Optimization and Preconceptual Design of a 5 MWe Salt-Gradient Solar Pond Power Plant at Great Salt Lake

**M. K. Drost
L. M. Brown
J. S. Barnhart**

**R. G. Cavola
S. G. Hauser
B. M. Johnson**

May 1983

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISCLAIMER

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, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents 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 or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

OPTIMIZATION AND PRECONCEPTUAL DESIGN
OF A 5 MWe SALT-GRADIENT SOLAR POND
POWER PLANT AT GREAT SALT LAKE

M.K. Drost
L.M. Brown
J.S. Barnhart
R.G. Cavola
S.G. Hauser
B.M. Johnson

May 1983

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

FOREWORD

This report documents the optimization and design of a solar salt pond power plant located at the Great Salt Lake in the state of Utah. The study was performed by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy and was part of a series of solar pond engineering studies conducted at PNL. The entire Solar Pond Engineering Program consisted of four tasks.

Truscott Brine Lake Feasibility Study - Working with the U.S. Army Corp of Engineers, PNL evaluated the technical and economic feasibility of building a solar pond power plant at Truscott Brine Lake. Truscott Brine Lake is part of Area VIII of the Arkansas-Red River Chloride Brine Control Project.

Great Salt Lake Feasibility Study - This task consisted of investigating the economic feasibility of constructing a power generating facility using solar salt pond in the Great Salt Lake region.

Site Comparison - The major sites proposed for the location of a large solar salt pond test facility were to be compared based on economics, performance and site characteristics.

Design Handbook - PNL was to assemble a design handbook for solar salt ponds which reflect the site-specific aspects of design and cost.

Task No. 1 is reported elsewhere (Tulsa District, U.S. Army Corp of Engineers, 1982) while Tasks 3 and 4 were to have been completed in FY 1983, but were closed out due to a change in the total project direction. This document reports some of the results of Task 2, the Great Salt Lake Feasibility Study, with particular emphasis on the method and results of the optimization study.

SUMMARY

This report documents the results of an optimization study for a solar salt pond (SSP) power plant located at the Great Salt Lake in the state of Utah. This work was part of a larger study sponsored by the U.S. Department of Energy which compared potential sites for the construction of a large solar pond engineering test facility. As part of the site comparison, PNL developed a preconceptual design of a solar pond power plant located at the Great Salt Lake. This design would then be compared to designs developed for construction at the Salton Sea in California and Truscott Brine Lake in west Texas.

In order to simplify the comparison of the Great Salt Lake design with other designs for a large engineering test facility, a series of ground rules and design constraints were established by the National Solar Pond Steering Committee. The most important ground rules limited the design to a 5 MWe gross plant with a capacity factor of 0.228. These ground rules were set primarily to match the existing Salton Sea design.

The first step in the design of the Great Salt Lake Power Plant was the selection of a site and the collection of meteorological and hydrological data at that site. This task was to be accomplished by researchers from Utah State University, University of Utah, and Weber State University, and funded by Utah Power and Light. Funding limitations prohibited completion of the data collection task. As a result, PNL used existing data to select a surrogate site. The selection of the surrogate site was based on the results of two previous surveys of the Great Salt Lake region for potential solar pond sites (Riley and Batty, 1981). Assistance was provided by the AMAX Corporation in the selection process. The site selected in this study was located on the southwest shore of the lake between its extreme southern point and Rowley, Utah.

As part of the preparation of the design specifications, PNL developed optimization techniques for investigating the effects of component design on the total SSP power plant cost. This report describes these optimization techniques and the results when applied to a site near the Great Salt Lake. A separate document will present the functional criteria for a conceptual design which resulted from the preconceptual design study.

The optimization procedure developed for this study (see Figure 1) began by optimizing the pond configuration. The pond configuration optimization selected optimum values for the gradient zone and storage zone thicknesses. This was conducted using both the SOLPOND computer model developed at the Solar Energy Research Institute (SERI) and the GCOST computer model developed at PNL. The SOLPOND computer code models the thermal performance of a solar salt pond. The major outputs for each simulation were the average annual pond storage temperature, the maximum heat extraction rate, and the ratio of evaporation pond to solar pond size. These were used as an input to the GCOST computer code along with assumed heat engine parameters. First, a series of pond configurations were simulated using SOLPOND. The GCOST code then evaluated the effects of changing pond configuration on the performance and cost of the heat engine, ponds and piping. These capital costs were used with appropriate operation and maintenance costs to calculate a levelized energy cost (LEC). The pond configuration with the lowest LEC was chosen as the pond design and used in the total system optimization.

The total systems optimization was conducted using the GCOST computer code, which includes a heat engine model, a piping systems design model, and an economic model. The heat engine model calculates the Rankine cycle performance, including cycle efficiency, brine, working fluid, and cooling water flowrates, pond sizing and capital costs, and heat engine capital costs. The piping systems design model (ETTRANS) determines the optimum pipe size and insulation thickness, parasitic power consumption, and piping system capital costs. The economic model receives capital costs from the other models and calculates total installed capital, operation and maintenance, and levelized energy costs.

This optimization consisted of selecting the working fluid and four key heat engine parameters that resulted in the lowest levelized energy cost. These parameters include the vapor generator approach and pinch point temperatures, and condenser approach and range temperatures. By selecting the working fluid and these four parameters, the plant cycle was defined. GCOST would then determine the heat engine performance and capital costs and then calculate the LEC.

FIGURE 1. Total System Optimization Methodology

The results of the optimization study indicated that the least cost pond design consisted of a 1.25 m gradient zone and a 1.0 m storage zone. The optimum heat engine used ammonia as the working fluid. The characteristics of the optimum design are presented as Table 1.

Sensitivity studies were conducted to examine the impact of varying the ground rules and design assumptions. The results indicated that increasing the plant capacity factor and choosing a site with more favorable meteorology would result in a substantial reduction in plant levelized energy costs.

TABLE 1. Optimum Plant Characteristics (For a 5 MWe Engineering Test Facility at Great Salt Lake)

Solar Pond	
Area (m ²)	618,000.
Upper Convecting Zone Thickness (m)	0.4
Gradient Zone Thickness (m)	1.25
Storage Zone Thickness (m)	1.0
Average Annual Storage Zone Temperature (°C)	86.
Evaporation Pond Area (m ²)	182,000.
Heat Engine	
Working Fluid	Ammonia
Vapor Generator Approach Temperature (°C)	8.3
Pinch Point Temperature (°C)	4.4
Condenser Approach Temperature (°C)	8.3
Condenser Range (°C)	5.6
Brine Flow Rate (kg/sec)	829.
Working Fluid Flow Rate (kg/sec)	47.
Cooling Water Flow Rate (kg/sec)	2192.
Gross Cycle Efficiency (%)	8.63
Net Power Output (MWe)	4.53
System Capital Costs (x10 ⁶ , 1982 dollars)	
Solar Pond	3.9
Evaporation Pond	1.0
Land Costs	0.1
Site Costs	0.7
Heat Engine Costs	3.7
Piping System Costs	1.5
Electrical Plant Costs	0.5
Miscellaneous Cost	0.1
Indirect Cost	2.8
Total Capital Cost	14.3
Levelized Energy Cost (mills/kWhr)	288

CONTENTS

FOREWORD.....	iii
SUMMARY.....	v
1.0 INTRODUCTION.....	1.1
1.1 SALT GRADIENT SOLAR POND.....	1.1
1.2 BACKGROUND OF GREAT SALT LAKE STUDY.....	1.3
2.0 GROUND RULES.....	2.1
3.0 SITE SELECTION AND CHARACTERISTICS.....	3.1
3.1 SITE SELECTION.....	3.1
3.2 SITE CHARACTERISTICS.....	3.3
3.2.1 Insolation.....	3.3
3.2.2 Ambient Temperatures.....	3.3
3.2.3 Net Evaporation.....	3.4
3.2.4 Brine Transmissivity.....	3.4
3.2.5 Brine Concentration.....	3.5
3.2.6 Lake Temperature.....	3.6
3.2.7 Soil Thermal Conductivity.....	3.6
3.2.8 Soil Permeability.....	3.6
4.0 OPTIMIZATION METHODOLOGY.....	4.1
4.1 FIGURE OF MERIT.....	4.1
4.2 GENERAL APPROACH.....	4.2
4.3 SOLAR POND SIMULATION MODEL (SOLPOND).....	4.5
4.4 SYSTEM SIMULATION MODEL (GCOST).....	4.10
4.4.1 System Description.....	4.10
4.4.2 Optimization Methods.....	4.13

4.4.3	G COST Computer Code.....	4.15
4.4.4	Code Inputs.....	4.16
4.4.5	Piping Optimization.....	4.16
4.5	ECONOMIC MODEL.....	4.20
5.0	OPTIMIZATION RESULTS FOR GREAT SALT LAKE.....	5.1
5.1	POND CONFIGURATION OPTIMIZATION.....	5.1
5.2	TOTAL SYSTEM OPTIMIZATION.....	5.2
5.2.1	Working Fluid Prescreening.....	5.2
5.2.2	Results of Optimization Study.....	5.4
5.3	PIPING OPTIMIZATION.....	5.7
6.0	SENSITIVITY STUDIES.....	6.1
6.1	POND DESIGN SENSITIVITY STUDIES.....	6.1
6.2	GROUND RULE SENSITIVITY STUDY.....	6.4
7.0	DESIGN SUMMARY.....	7.1
7.1	SITE LAYOUT.....	7.1
7.2	FLOW DIAGRAMS.....	7.1
7.3	COMPONENT CHARACTERISTICS.....	7.4
8.0	CONCLUSIONS.....	8.1
8.1	CONCLUSIONS ON POND DESIGN.....	8.1
8.2	CONCLUSIONS ON HEAT ENGINE DESIGN.....	8.3
8.3	CONCLUSIONS ON PIPING DESIGN.....	8.4
	REFERENCES.....	R.1
	APPENDIX A: SITE COMPARISON CRITERIA.....	A.1
	APPENDIX B: GSL SITE SELECTION CRITERIA.....	B.1
	APPENDIX C: EFFECTS OF WORKING FLUID SELECTION ON TURBINE DESIGN.....	C.1

FIGURES

1	Total System Optimization Methodology.....	vii
2	Solar Salt Pond Schematic.....	1.2
3	Possible Locations for a Solar Salt Pond Power Plant Around Great Salt Lake.....	3.2
4	Percentage of Solar Radiation Transmitted Through Saline Waters.....	3.5
5	Total System Optimization Methodology.....	4.3
6	One-Dimensional Solar Pond Thermal Network.....	4.6
7	Solar Pond Simulation Model (SOLPOND).....	4.9
8	Rankine Cycle.....	4.11
9	Rankine Cycle with Regenerator.....	4.12
10	Definition of Key Heat Engine Design Parameters.....	4.14
11	Heat Engine Model (GCOST).....	4.14
12	Schematic of Solar Pond Power Plant Piping.....	4.19
13	Piping System Model (ETTRANS).....	4.21
14	Economic Model.....	4.21
15	Effect of Working Fluid Heat Transfer Characteristics on Levelized Cost.....	5.8
16	Hot Brine Transport Piping.....	5.9
17	Condenser Cooling Water Piping.....	5.10
18	Flushing Water Supply Piping.....	5.11
19	Flushing Water Drain Piping.....	5.12
20	Cool Brine Transport Piping.....	5.13
21	Pond Minimum Temperature Sensitivity Study.....	6.2
22	Effects of Changing Capacity Factor on the Optimization of a SSPP.....	6.6

23	Effect of Changing Pond Location on Optimum Pond Configuration.....	6.7
24	Plant Layout.....	7.2
25	Plant System Flow Diagram.....	7.3
26	Heat Engine Flow Diagram.....	7.3

TABLES

1	Optimum Plant Characteristics.....	viii
2	Site Ambient Conditions.....	3.4
3	Pond Optimization Parameters.....	4.7
4	Heat Engine Performance Parameters.....	4.17
5	Economic Parameters for GCOST.....	4.22
6	Average Monthly Operation for Variable Duty Cycle.....	5.1
7	Pond Configuration Optimization.....	5.3
8	Total System Optimization (R-113).....	5.5
9	Total System Optimization (R-114).....	5.5
10	Total System Optimization (N-BUTANE).....	5.6
11	Characteristics of Optimum Plant Design.....	5.7
12	Load Cycle Sensitivity Study.....	6.4
13	Results of High Capacity Factor Pond Configuration Optimization.....	6.5
14	Plant Characteristics.....	7.4

1.0 INTRODUCTION

A solar salt-gradient pond provides a method of collecting and storing solar energy. When coupled with a heat engine, the collected solar energy in the form of hot brine can be used to produce electric power. This report describes the techniques used to optimize and design a solar salt-gradient pond (SSP) power plant for installation at the Great Salt Lake. In this section, the solar salt pond will be described, followed by a discussion of the background of the Great Salt Lake study.

1.1 SALT GRADIENT SOLAR POND

To understand how a solar salt-gradient solar pond works, it is first important to understand why an ordinary pond (i.e. a fresh water pond or a saline pond with uniform density) cannot collect large amounts of solar energy. In an ordinary pond, when the water absorbs solar energy, its temperature increases and its density decreases. The water near the surface is cooled as heat is dissipated to the atmosphere, increasing its density. The warmer, less dense water from the bottom of the pond rises to the surface, causing a fluid circulation known as natural convection. At the surface, heat contained in the warmer water is again dissipated to the atmosphere. Thus an ordinary pond is constantly turning over, losing most of the solar energy it absorbs.

In a salt-gradient solar pond, the process of natural convection is suppressed by the construction of a salt gradient in the pond. Concentrated salt water at the bottom of the pond heats up due to the absorbed solar energy but still remains heavier than the fresher water above it, preventing natural convection. In practice, a salt-gradient pond would consist of three layers; a storage zone of highly concentrated brine, a gradient zone with salt concentration gradually decreasing from bottom to top, and an upper convective zone of light brine or fresh water (Figure 2). The purpose of the storage zone is to absorb and store solar energy. The purpose of the gradient zone is to insulate the storage zone and to prevent natural convection. The upper convective zone

FIGURE 2. Solar Salt Pond Schematic

forms naturally by wind, evaporation, precipitation and diurnal heating and cooling. Since it has no positive benefit for the pond, the depth of this layer is kept at a minimum.

Heat trapped in the storage zone can be extracted by in-pond or out-of-pond heat exchangers. Because of corrosion and maintenance problems and because of the large pond size, out-of-pond heat exchangers are typically recommended. The hot brine is extracted from near the top of the storage zone and used to vaporize a working fluid. The cold brine is returned to the bottom of the storage zone usually on the opposite end of the pond from the extraction. The heated working fluid can be used to generate electricity using a Rankine cycle engine or as a source of process heat.

Over time, the salt concentration difference between the storage zone and the upper convecting zone would naturally disappear as salt diffuses upward. This is prevented by flushing the pond surface with low salt concentration water and adding high concentration brine to the storage zone.

Small solar ponds (less than 1 hectare) have been operated successfully at several locations in the United States and overseas. The Ein Bokek facility in Israel, which includes both a solar pond and an organic Rankine cycle heat engine for power generation, has operated for several years.

1.2 BACKGROUND OF GREAT SALT LAKE STUDY

Based on the operating experience gained with existing ponds in the United States and in foreign countries, several studies have been conducted in the U.S. on the feasibility of a large (10 to 25 hectares) solar pond power plant. The original feasibility study concentrated on the Salton Sea as a potential site for a large solar pond (Ormat Turbines, 1981, Peelgren, 1982). The Salton Sea study was jointly funded by the U.S. Department of Energy (DOE), the State of California, and Southern California Edison. A second feasibility study was conducted by the U.S. Army Corp of Engineers and focused on the Truscott Brine Lake located in northwest Texas (SERI Truscott Brine Lake Task Force, 1981). In order to determine the best location for a large Engineering Test Facility, the U.S. Department of Energy funded a comparison of potential sites to be conducted by the Pacific Northwest Laboratory (PNL). As part of this study, PNL was to develop a preconceptual design of a solar pond power plant located at the Great Salt Lake. This design would be compared to the designs developed for the Salton Sea and the Truscott Brine Lake.

The Great Salt Lake Feasibility Study consisted of a preconceptual design and cost estimate for a large solar pond located at the Great Salt Lake. In order to simplify the comparison of the Great Salt Lake design with the other designs for a large engineering test facility, a series of ground rules and design constraints were established by a National Solar Pond Steering Committee. A surrogate site for the solar pond facility was selected at the Great Salt Lake which was then used by PNL for the development of design specifications. The design specifications were to be given to an Architect/Engineering firm, as the basis for a conceptual design and cost estimate. As part of the preparation of the design specifications, PNL developed an optimization methodology for use in the design of solar pond power plants. This report

documents the methodology and the results obtained for the Great Salt Lake. A subsequent document will present the functional criteria for a conceptual design which resulted from the preconceptual design study.

2.0 GROUND RULES

The Great Salt Lake SSP power plant feasibility study was part of a larger study which compared the Great Salt Lake, Truscott Brine Lake and the Salton Sea as a site for a large solar pond power plant. To justly compare between the three sites, a series of ground rules were established. These ground rules defined major aspects of the plant and the plant's operating conditions. The ground rules were developed by the National Solar Pond Steering Committee which consisted of participants from the major design studies and other interested parties. The ground rules of the site comparison are discussed here because they have a major impact on the design of the Great Salt Lake SSP power plant.

It should be emphasized that the site comparison study was to identify the site for a large engineering test facility. The facility design requirements were defined by the need for both engineering test and demonstration. The design developed for Great Salt Lake was optimized for the lowest life-cycle cost within the ground rules of 5 MW (gross output) and 0.228 capacity factor. These costs should not be compared with other commercial energy sources with different sizes, constraints and levels of development.

The recommendations of the Steering Committee were summarized as ground rules and evaluation criteria. The ground rules are constraints on the design of the Large Scale Engineering Test Facility to insure that the designs for each site are comparable and meet certain minimum requirements necessary to demonstrate solar pond performance. The evaluation criteria are the list of attributes used to discriminate between designs. The ground rules will be discussed in this section because they influenced the design developed for the Great Salt Lake SSP power plant. The evaluation criteria also influenced the design development but to a lesser extent. The evaluation criteria are presented in Appendix A.

The design of the Great Salt Lake facility conforms to these ground rules:

- Available Technology - The Engineering Test Facility was constrained to only include commercially available components or components available in the near term. This ground rule prevented the

inclusion of components such as direct contact heat exchangers, non-Rankine cycle energy conversion subsystems and saturated solar salt ponds. It was anticipated that a test facility might ultimately include advanced components but for comparison purposes the designs were limited to available technology.

- Power Level - The plant was to include a single turbine/generator with a gross output of 5 MWe. The energy extraction equipment was to be sized to allow the plant to operate at its rated capacity. The 5 MWe turbine size was selected because it was the minimum size that utilities would accept as demonstrating the technology. A net output was not specified because good engineering judgement would balance capital costs against operating costs to dictate the parasitic loads.
- Duty Cycle - The solar salt pond was to be sized to allow the energy conversion subsystem to operate for at least 36 hr in essentially steady-state conditions. The pond was to be of sufficient size to allow the annual extraction of 10,000 MWhre for an indefinitely long period. The actual cycle was not specified, allowing the designer to select an optimum cycle with summer-only operation, year long operation, or something in between.
- Pond Size - The SSP subsystem was to be sized to allow demonstration of the essential characteristics of pond performance, including heat and mass extraction, non-convecting zone stability and wind-induced mixing of the upper convecting zone. This implied that one large pond would be preferred over several small ponds.
- Design Life - The equipment design and materials selection of the test facility were to be suitable for an operating life of 10 years in the operating environment associated with the solar salt pond.
- Design Features - The Engineering Test Facility was to be designed to demonstrate a variety of solar pond features including:
 - Brine Production
 - Dike Construction

Electrical Conversion

Brine Disposal

Heat Rejection

Pond maintenance (including wave suppression, salinity gradient maintenance, water treatment and clarity maintenance)

Pond instrumentation

Pond operating strategies.

- Code of Accounts - The results of the cost evaluation of the Great Salt Lake solar power plant were to be reported using a standard code of accounts developed as part of the National Solar Pond Steering Committee's activities.

3.0 SITE SELECTION AND CHARACTERISTICS

The selection of the specific site at the Great Salt Lake for the location of the SSP power plant was to be funded by Utah Power & Light and conducted by Utah State University, the University of Utah and Weber State University. The site selection process was to consist of three phases.

Phase One - Examination of general areas for overall suitability and selection of most promising general area

Phase Two - Selection of specific site within the most promising general area

Phase Three - Collection of detailed data on the selected site for use in detailed pond design.

The first phase of the study was conducted by Weber State University and Utah State University (Riley and Batty, 1981). The second phase of the study was to be conducted concurrently with the pond design tasks with the results being available early in the design process. Due to funding constraints, Utah Power & Light was unable to fund the Phases Two or Three. This forced PNL to select a surrogate site based on the results of the Phase One study. Section 3.1 will describe the method and results of the Phase One study and the selected surrogate site. Section 3.2 will summarize the characteristics of the selected site.

3.1 SITE SELECTION

The two investigation teams from Weber State and Utah State identified potential sites around the lake and compared them according to a selection criteria discussed in Appendix B. The sites studied in the Phase One effort are shown on Figure 3. The general areas explored by Utah State are identified by the letters A through H and the general areas explored by Weber State are identified by the numbers 1 through 7.

The two site evaluations reached essentially the same conclusions which indicated that the two best general areas are those identified in Figure 3 by 5 and C on the southwest shore, and by 1 and H near Willard Bay.

FIGURE 3. Possible Locations for a Solar Salt Pond Power Plant Around Great Salt Lake

The site selected as the surrogate site for the Engineering Test Facility was on the southwest shore of the lake at site 5 on Figure 3. A more detailed evaluation will be required before a final site selection can be completed. After consultation with representatives of the AMAX Corporation, another site was identified for consideration. This site is located just west of a large impoundment basin (see Figure 3), which is a convenient source of both flushing and cooling water. In addition, concentrated brine from the AMAX ponds may be available for makeup.

3.2 SITE CHARACTERISTICS

After the surrogate site was selected, data on relevant site characteristics was collected. In many cases data was not available for the specific site but it did exist for some locations on the Great Salt Lake. In other cases no data existed and the characteristics had to be assumed. Each of the site characteristics are discussed below.

3.2.1 Insolation

Solar insolation is a fundamental data requirement. Data on insolation were required in two forms. Monthly data on total insolation (direct and diffuse radiation) were required for the solar pond optimization while hourly data were required for performance calculations using the SOLSTEP computer program. Hourly insolation data were developed from meteorological data collected at the Salt Lake City International Airport. The insolation data represented a 5 year average. Monthly data were an aggregation of hourly data and are presented on Table 2 (Cingemoni et al., 1978).

3.2.2 Ambient Temperatures

Ambient air temperature affects both the thermal losses from the pond and the efficiency of the energy conversion subsystem. Monthly and hourly data were taken from a 5 year average of meteorological data collected at the Salt Lake City International Airport. Both wet bulb and dry bulb temperatures were collected. Monthly average dry bulb temperature data used in the pond configuration optimization are presented on Table 2 (Cingemoni et al., 1978).

TABLE 2. Site Ambient Conditions

<u>Month</u>	<u>Insolation (w/m²)</u>	<u>Dry Bulb Temperature (°C)</u>	<u>Wet Bulb Temperature (°C)</u>	<u>Lake Temperature (°C)</u>
January	72.7	-2.0	-3.9	4.0
February	116.7	0.8	-1.4	4.0
March	181.8	4.2	1.1	14.0
April	241.4	9.6	5.0	14.0
May	302.9	14.6	8.9	14.0
June	328.3	19.0	11.7	19.0
July	332.0	24.8	14.4	19.0
August	288.3	23.6	14.4	19.0
September	232.6	18.2	11.1	19.0
October	156.6	11.3	6.7	19.0
November	89.7	3.9	1.4	19.0
December	62.8	-0.9	-2.2	4.0

3.2.3 Net Evaporation

Net evaporation affects the fresh water requirements for evaporation make-up and the size of evaporation ponds for initial pond filling and make-up brine concentration. Excellent evaporation data exists at the Great Salt Lake due to the large scale industrial evaporation being conducted in the area. For this study an average annual net evaporation rate of 1.14 m/yr was used (Arnow, 1980).

3.2.4 Brine Transmissivity

The transmissivity of the brine used in the solar pond has the greatest impact on pond performance of any site characteristic. Clear brine will allow a maximum amount of insolation to enter the storage zone where it can be utilized for power generation. Reduced transmissivity means that more insolation is absorbed in the upper convecting zone where it will be lost to the environment. Unfortunately, transmissivity data was not available for Great Salt Lake brines at the beginning of this study. For this study, transmissivity characteristics similar to the Salton Sea were assumed (Peelgren, 1982).

During the study brine samples were collected from settling ponds operated by AMAX for a variety of brine concentrations. The results of transmissivity measurements conducted at PNL indicated that the optical properties of Great Salt Lake brines were substantially superior to those reported for Salton Sea. The more conservative values were used because of areas of uncertainty inherent in the transmissivity measurement process. Figure 4 shows the optical properties assumed for the Great Salt Lake as compared to other types of brines. Long term degradation of brine transmissivity due to wind blown particulate or soil/brine interactions was not considered.

3.2.5 Brine Concentration

The size of the evaporation ponds for initially filling the solar pond and for brine make up production is a function of brine concentration. A relatively concentrated brine will require small evaporation ponds. The Great Salt Lake has a variety of brines available (Sturm, 1980). The northern portion of

FIGURE 4. Percentage of Solar Radiation Transmitted Through Saline Waters

the lake consists of saturated brine and would require no concentration. The brine concentration in the southern portion of the lake ranges from highly concentrated brines in the deeper sections to lower concentration brines near fresh water sources. For this study, it was assumed that brine would be available with a specific gravity of 1.10 and a salt loading of 134 Kg/m^3 , typical of the southern portion of the lake, near the site.

3.2.6 Lake Temperature

The base case energy conversion scheme consists of a heat engine which uses once through cooling with water from the Great Salt Lake. The efficiency of the heat engine will depend on the temperature of the lake which is acting as a heat sink for waste heat from the power plant. Quarterly average lake temperatures were taken from (Sturm, 1980) and are shown in Table 2. An average lake temperature of 19°C (during plant operation) was assumed for heat engine performance calculations.

3.2.7 Soil Thermal Conductivity

The conductivity of the soil has a major impact on pond performance because soil conductivity influences heat loss through the bottom of the pond. A sensitivity study conducted at PNL has shown that soil conductivity has the second greatest impact on pond performance, i.e. next to pond transmissivity. Unfortunately, conductivity depends on the type of soil, the moisture content of the soil, ground water movement and other factors. These data were to have been determined during Phase 3 of the Site Selection Task. A soil thermal conductivity of $1.0 \text{ W/m-}^\circ\text{K}$ was assumed for the design optimization. This is representative of some types of dry soil. Variations in soil type and soil moisture can substantially change soil conductivity.

3.2.8 Soil Permeability

Soil permeability affects the requirements for brine used to replace brine lost by seepage. A low permeability will reduce the requirements for make-up brine production evaporative ponds and will minimize ground water contamination. A value of 5.56 cm/yr was assumed in this study, which is representative of a pond lined with a bentonite liner.

4.0 OPTIMIZATION METHODOLOGY

The optimization of a SSP power plant involves the selection of a large number of variables used to describe the plant. The best approach would involve the simultaneous optimization of all the major plant variables. A survey of available computer codes indicated that there was not a solar salt pond power plant optimization code available for use in this study. While the development of an optimization code was beyond the scope of this study, it was still necessary to develop an optimization methodology that would approximate the ideal case. The following sections will describe the figure of merit used in the study, the general optimization approach, and the specific optimization method used for each subsystem.

4.1 FIGURE OF MERIT

After investigating various criteria for optimization, the primary figure of merit selected for this study was the levelized cost of power produced by the facility. This approach calculates the present value of all costs associated with the plant, and converts this present value to an annualized cost which, over the lifetime of the plant, has exactly the same present value. Dividing this annualized cost by the annual energy output of the plant produces an energy cost which is constant, or levelized, over the plant's operating lifetime. One interpretation of the levelized energy cost (LEC) is that it is the price (at which the plant energy output could be sold) which, over the plant's lifetime, would exactly recover all costs associated with the plant. An alternative expression of the same concept is that the present value of all energy sold at the LEC over the life of the plant would exactly equal the present value of all plant costs. The use of a LEC to compare alternatives is a powerful tool because it condenses the required revenue to recover all project costs into a single unit-cost of energy. If all other factors of consideration (such as operating characteristics, capacity factor, risk, etc.) between two alternative plants are identical, the plant with the lowest LEC can be clearly judged to be the most economic alternative.

It is important to note that the LEC calculated for a plant has no direct connection with the price the utility would actually charge for the electricity from the plant. By definition, the LEC is a fixed unit cost for electricity over the plant's operating lifetime. In actual practice, utilities do not fix electricity prices for the lifetime of a plant, but allow them to increase to cover increases in operating costs. Because they are developed as a figure of merit rather than a pricing tool, LEC's cannot easily be meaningfully compared to current utility rates to judge solar pond economic feasibility. Another important point is that the LEC is not necessarily equivalent to the worth of the energy to the utility. The actual value to the utility of the energy from any plant is determined both by the cost of producing energy from the plant, and how operating the plant interfaces with the rest of the generating grid. Power plants which can reduce the need to operate expensive peak generation plants have a higher value to a utility than plants which would primarily replace energy generated from less expensive base-loaded plants.

4.2 GENERAL APPROACH

The optimization procedure used in this study (Fig. 5) began by separating the pond configuration optimization (i.e. the non-convecting zone and storage zone thickness) from the total system optimization (i.e. the pond sizes, heat engine parameters, working fluid selection and piping optimization). The pond configuration optimization was conducted using both the SOLPOND computer code developed at Solar Energy Research Institute (SERI) and the GCOST computer code developed at PNL. First a series of pond configurations was simulated using SOLPOND which models the thermal performance of a solar salt pond. The major outputs for each of these runs were an average annual pond storage temperature, the maximum heat extraction rate to maintain the pond above the minimum temperature during heat engine operation, and the ratio of required evaporation area to solar pond area. These were input to the GCOST computer code along with assumed average heat engine parameters. The GCOST code then evaluated the effects of changing pond configuration on the performance and cost of the heat engine, solar and evaporation ponds and the piping network. Finally, these costs were used to calculate a levelized energy cost (LEC) and the pond configuration with the lowest LEC was chosen for total system optimization.

FIGURE 5. Total System Optimization Methodology

The total system optimization was conducted using the GCOST computer code, which includes a heat engine model, solar and evaporative pond sizing model, a piping system model and an economic model. The five significant heat engine parameters were varied (working fluid, vaporizer approach, condenser approach, condenser range and the pinch point) over a normal range of values. Numerous runs were made to determine the optimum combination of parameters. Again GCOST computed capital costs for the significant components and combined them into a LEC for each system configuration. The cases with the lowest LEC were identified as the optimum design.

It should be noted here that the significant assumption in this optimization methodology lies in the selection of the "average" heat engine parameters. Conceivably, a poor choice of heat engine parameters could result in an optimized pond configuration which is different from the true optimum design. Due to the relative insensitivity of the pond design to heat engine parameters, it was felt that the risks associated with choosing average heat engine characteristics were small.

It is important to note that the different segments of the system (i.e. pond, heat engine, piping, etc.) should not be optimized separately. The pond configuration determines the average annual storage temperature which affects the heat engine operation and, therefore, the piping system. The heat engine parameters determine the cycle efficiency and, therefore, the required solar and evaporative pond sizes and costs. The piping system trades off capital cost versus parasitic power requirements and affects the LEC. Because of the interrelationships between segments, it is crucial to optimize the system as a whole.

The method described above, using average monthly input data, provides an adequate optimization for a plant using once-through cooling from Great Salt Lake. If other heat rejection schemes, such as dry cooling, are to be modeled, hourly time steps would be required. The solar pond itself will not exhibit significant variations with hourly time steps but the heat engine will normally operate with varying heat rejection temperatures and part load operation. This will result in significant hourly variation in plant performance. PNL has developed SOLSTEP-SSP which can simulate solar pond power plant performance on

an hourly basis using SOLMET format data tapes. SOLSTEP-SSP was not available during the current study so average monthly performance was used, but any future detailed optimization studies which include alternate cooling options should be based on hourly performance using a method similar to that used in SOLSTEP-SSP.

While the study ground rules (5 MWe gross capacity and 10,000 MWe-hr output per year) fix the plant capacity factor at 22%, they do not specify when the plant would operate during the year. The selection of a duty cycle for a commercial plant would be determined by the requirements of the operating utility. When considering an engineering test facility, the selection of a duty cycle is arbitrary.

In this optimization study, a variable load cycle was selected on the basis of a sensitivity study reported in Section 6.0. The variable cycle consists of operating from April to November, with the number of days of operation per month approximately proportional to the insolation rate. This load cycle satisfied the ground rule of a 22% capacity factor and permitted economic operation of the power plant, while demonstrating operation during 8 months of the year.

4.3 SOLAR POND SIMULATION MODEL (SOLPOND)

The performance of the pond was simulated using SOLPOND. The code was supplied with zone depths, load data, optical properties of the brine, simulation time step, meteorological data, and thermal properties of the brine and underlying soil. It calculated the pond storage zone temperature, the maximum heat extraction rate, and the ratio of evaporation pond area to solar pond area for a steady-state periodic solution. SOLPOND can use either a one-dimensional or a three-dimensional analysis depending on the pond size. Due to the large size of the Great Salt Lake facility, edge losses would be insignificant; therefore the one dimensional model was appropriate.

The SOLPOND code is described by Henderson and Leboeuf (1980) and the features of the code will only be summarized here. The electrical analogy one dimensional model is shown in Figure 6 (SERI Truscott Brine Lake Task Force, 1981). The pond is modeled as a series of nodes. Each node describes

FIGURE 6. One-Dimensional Solar Pond Thermal Network (Electrical Analogy)

the temperature at the related position within a pond. Due to convection, the storage zone and upper convecting zone were modeled as being isothermal and were represented by one node. Several nodes were included in the gradient zone and the soil below the pond so that the temperature profiles could be computed. In the electrical analogy the absorbed insolation is modeled as a current input with the appropriate magnitude. The extraction of thermal energy from the pond is also modeled as a current output for the storage zone node.

Table 3 presents the inputs to the code for the primary pond configuration optimization. Other sensitivity studies were conducted and will be discussed in Section 6. Several input variables merit a more detailed discussion.

TABLE 3. Pond Optimization Parameters

Upper Convecting Zone	0.4 m
Gradient Zone Thickness	
1	1.0 m
2	1.25 m
3	1.5 m
Storage Zone Thickness	
1	1.0 m
2	2.0 m
3	3.0 m
Heat Capacity of Salt Solution	$4.05 \times 10^6 \text{ J/m}^3\text{°C}$
Heat Capacity of Soil	$2.09 \times 10^6 \text{ J/m}^3\text{°C}$
Thermal Conductivity of Salt Solution	$0.68 \text{ w/m}^\circ\text{C}$
Thermal Conductivity of Soil	$1.0 \text{ w/m}^\circ\text{C}$
Minimum Temperature allowed in the storage zone during heat engine operation	70°C
Time Step	7 days
Heat Transfer Coefficient to Air	$300 \text{ w/m}^2\text{°C}$
Evaporation Rate	1.14 m/yr
Salt Concentration of Available Brine	134 Kg/m^3
Years to Evaporate	2.0 years
Evaporation Pond Depth	1.75 m
Salt Concentration Gradient Criteria	$166 \text{ Kg/m}^3/\text{m}$
Brine Optical Properties	Salton Sea, 0.15 concentration
TTD Vaporizer	5°C
TTD Condenser	5°C

- Upper Convecting Zone Thickness - In this study, an upper convecting zone thickness of 0.4 m was assumed. Other studies have assumed a thinner upper convecting zone thickness (0.2 m). The 0.4 m thickness has been obtained in practice and was felt to be a conservative but fair assumption. A thinner zone thickness would improve the pond's performance, but is difficult to maintain in practice.
- Thermal Conductivity of Soil - The thermal conductivity of the soil was assumed to be 1.0 W/m°C which is representative of dry soil.
- Salt Concentration - A salt concentration of 134 kg/m³ was assumed. This is representative of the less concentrated surface water in the south section of the lake.
- Brine Evaporation Time - The brine evaporation time affects the size of the evaporation ponds. This parameter was not optimized; instead, a brine concentration period of 2 years was assumed. This figure can be compared to the 7.25 years required by the Salton Sea design and the 10.8 years required by the Truscott Lake design to produce enough salt for the full pond depth.
- Salt Concentration Gradient Criterion - The criterion for a stable gradient zone was assumed to be 166 kg/m³/m. This value was derived from the Truscott Lake design (SERI Truscott Brine Lake Task Force, 1981).
- Brine Optical Properties - The brine optical properties were assumed to be similar to those at Salton Sea. The preliminary evaluation of water samples indicates that the optical properties of Great Salt Lake brines may be substantially better than those actually used.

The SSP simulation model is summarized on Figure 7 where the major inputs, optimization variables and simulation outputs are presented.

INPUTS:	OPTIMIZATION VARIABLES:	OUTPUTS:
<ul style="list-style-type: none"> • CLIMATE (AMBIENT TEMPERATURE, INSOLATION, EVAPORATION) • BRINE THERMAL PROPERTIES • BRINE OPTICAL PROPERTIES • EARTH THERMAL PROPERTIES • LOAD PROFILE • STORAGE ZONE MINIMUM TEMPERATURE • CAPACITY FACTOR • TIME TO PRODUCE INITIAL BRINE FILL • UPPER CONVECTING ZONE DEPTH 	<ul style="list-style-type: none"> • NON-CONVECTING ZONE DEPTH • STORAGE ZONE DEPTH 	<ul style="list-style-type: none"> • AVERAGE ANNUAL STORAGE ZONE TEMPERATURE • MAXIMUM HEAT EXTRACTION RATE • RATIO OF EVAPORATION TO SOLAR POND SIZE

FIGURE 7. Solar Pond Simulation Model (SOLPOND)

4.4 SYSTEM SIMULATION MODEL (GCOST)

With the completion of the pond configuration optimization, it was now possible to conduct the optimization of the complete system using the results of the pond configuration analysis. This section describes the method used to optimize the entire power plant system.

The system optimization consisted of using the PNL-developed computer code GCOST to calculate the performance and cost of specific plant designs. For this study it was assumed that the thermodynamic design could be defined by a set of five parameters. By selecting one set of parameters, a given plant was defined and GCOST was used to calculate average annual performance, plant capital cost, and, finally, levelized energy cost. The plant with the lowest levelized energy cost was selected as the optimized design. The details of the system, the performance model, the cost model, and code inputs will be discussed in the following subsections.

4.4.1 System Description

The system considered in the optimization procedure is shown in Figure 5. The major components are the solar pond, the evaporation pond, the piping, and the heat engine.

As described in Section 4.3, the SSP zone thicknesses were optimized separately from the system optimization. Once the optimum combination of pond zone thicknesses was identified, it was not allowed to vary during the system optimization. Although this section will primarily discuss the heat engine subsystem, the optimization procedure did consider the performance and cost impacts of the other system components such as solar and evaporation pond costs and piping costs.

The heat engine was modeled as a Rankine cycle power plant. Due to the low temperature of the heat source, steam was not a suitable working fluid and alternative fluids were considered. In general, working fluids can be divided into fluids which become supersaturated as they expand through a turbine (wetting fluids) and fluids which become superheated as they expand through the turbine (non-wetting fluids). A cycle arrangement for a wetting fluid is shown in Figure 8. A non-wetting working fluid cycle often includes a regenerator which

FIGURE 8. Rankine Cycle

extracts energy from the superheated vapor leaving the turbine and uses it to preheat the liquid about to enter the vapor generator's heat exchanger train. Figure 9 shows a Rankine power cycle arrangement with a regenerator. The GCOST code has the option of including a regenerator in the cycle.

Many working fluids considered for low temperature Rankine cycle applications are non-wetting fluids, and the proposed cycle arrangements for these working fluids normally include a regenerator. As part of a series of preliminary screening studies, the impact of the regenerator on the cost and performance of a Rankine cycle SSP power plant using a non-wetting working fluid was assessed. As expected, the regenerator did improve performance substantially, but the regenerator also represents a substantial cost component. When the improved performance and higher costs were both considered, the addition of the regenerator had an insignificant impact on plant levelized energy cost. Due to the insignificant cost advantage of the regenerator, it was decided that a

FIGURE 9. Rankine Cycle with Regenerator

regenerator would not be included in the cycle even for non-wetting working fluids; therefore, the cycle arrangement shown in Figure 8 was used for all working fluids.

Both cycle arrangements shown in Figures 8 and 9 reject heat through the condenser to water from the Great Salt Lake. The annual average temperature of the lake during heat engine operation, which was estimated to be 19°C, was used as the ultimate heat rejection temperature. With the availability of the Great Salt Lake for heat rejection, the question of selecting the most cost effective heat rejection scheme was avoided. At other sites, or if environmental constraints preclude the use of the Great Salt Lake for heat rejection, an alternative heat rejection system must be considered. While the analysis of alternative heat rejection schemes was beyond the scope of this study, the impact of heat rejection technology on plant performance and cost should not be underestimated, particularly considering new wet and dry cooling technology which can operate with very high salt concentration brines.

4.4.2 Optimization Methods

The optimization methodology consisted of selecting values for five primary design variables which define the Rankine cycle power plant. With these variables selected, the plant performance and cost is determined using the GCOST computer code. The design with the lowest levelized energy cost is the optimum design.

The five parameters used to define the power cycle are the working fluid, the vapor generator approach, the vapor generator pinch point, the condenser approach and the condenser range. For a particular set of temperatures the choice of working fluid determines the state point pressures, the required flow rates, and the cycle efficiency. In addition, the heat transfer properties of the working fluid affect the heat exchanger design. The four temperature parameters are illustrated in Figure 10. A small approach temperature implies large vapor generators, preheaters, and condensers, and result in an efficient cycle due to the high working fluid temperature at the turbine inlet and the low working fluid temperature in the condenser. A high approach temperature results in a small heat exchanger and a relatively inefficient power cycle.

Varying the vapor generator approach temperature is significant because the corresponding variations in cycle efficiency result in variations in solar pond size. Therefore, the cost of the vapor generator is traded off against the cost of the solar salt pond. The condenser approach temperature variation results in a similar tradeoff between condenser cost and solar salt pond size.

In addition to affecting the size of the vapor generator, the pinch point temperature determines the brine flow rate. This results in trading off brine piping and pumping power cost versus heat exchanger cost. Similarly, the condenser range determines the cooling water flow rate, which allows a trade-off of cooling water pumping power and piping cost versus condenser cost.

Other important design characteristics could have been considered as design variables, but the limited scope of this study required that the number of variables be kept to a minimum. The optimization methodology is summarized in Figure 11.

FIGURE 10. Definition of Key Heat Engine Design Parameters

INPUTS:	OPTIMIZATION VARIABLES:	OUTPUTS:
<ul style="list-style-type: none"> • GROSS POWER OUTPUT • CAPACITY FACTOR • AVERAGE ANNUAL POND STORAGE TEMPERATURE • HEAT EXCHANGER CONFIGURATIONS • CLIMATE • FOULING FACTORS 	<ul style="list-style-type: none"> • WORKING FLUID • VAPOR GENERATOR APPROACH TEMPERATURE • PINCH POINT TEMPERATURE • CONDENSER APPROACH TEMPERATURE • CONDENSER RANGE 	<ul style="list-style-type: none"> • CYCLE EFFICIENCY • BRINE, WORKING FLUID, & COOLING WATER FLOW RATES • HEAT EXCHANGER AREAS • HEAT ENGINE INSTALLED CAPITAL COST

FIGURE 11. Heat Engine Model (GCOST)

4.4.3 GCOST Computer Code

The performance and cost of the various designs were estimated using the GCOST computer code. GCOST simulates the production of electricity from thermal energy collected in a solar salt pond and calculates the potential cost of the solar thermal power. GCOST provides the flexibility to individually or collectively evaluate the impacts of heat engine design, pond design, piping design and the economic climate on the cost of power from the SSP power plant.

The GCOST computer code can simulate and cost both subcritical and supercritical Rankine cycles for a variety of working fluids including isobutane, n-butane, R-11, R-12, R-22, R-113, R-114, and ammonia. Various cycle arrangements can be simulated, including the addition of a superheater and a regenerator to the basic cycle arrangement shown in Figure 8.

The performance model consists of a straightforward thermodynamic analysis of the Rankine power cycle. The turbine is modeled as an isentropic expansion with a turbine efficiency used to determine the exit conditions. The condenser is assumed to produce saturated liquid which is pressurized in a feed pump with an assumed pump efficiency. The vapor generator is assumed to produce saturated vapor for non-wetting working fluids. For wetting fluids, superheating is assumed, with the exit temperature being selected to prevent the formation of saturated liquid in the turbine exhaust. Thermodynamic state points were determined at various locations in the power cycle, and the cycle efficiency was calculated. The cycle efficiency is the amount of power produced by the generator divided by the thermal energy transferred to the working fluid in the preheater, vapor generator and superheater. The thermodynamic properties of the working fluid at the state points are calculated using empirical equations of state. The Starling equation of state is used for the hydrocarbons (Starling, 1973). The Martin-Hou equation of state is used for the fluorocarbons and ammonia (Martin, 1967; Downing, Milora, 1973). Physical properties of working fluids at the state points are calculated using polynomial functions of phase and temperature correlated to data in the literature by least-squares curve fits.

After identifying cycle state points, significant mass flow rates are calculated based on the requirement that the gross plant output be 5 MWe. Mass flow rates are calculated for the working fluid, solar pond brine, and cooling water. Major components are sized based on appropriate parameters. The heat exchangers are sized using calculated heat duty and heat transfer coefficients. The turbine size is based on required working fluid flow rate and enthalpy drop. The pumps are sized based on the required pressure rise across the pump. The solar salt pond, evaporation pond, and brine piping are sized based on the required energy input to the heat engine to produce a gross output of 5 MWe.

GCOST is a modified version of GEOCOST (Huber et al, 1976; Bloomster, 1975), which has been used for many applications. The thermodynamic analysis results have agreed with other published data, so the performance results can be used with some confidence. The main area of concern is in estimating heat exchanger overall heat transfer coefficients. While a substantial effort was made to insure the accuracy of the heat transfer coefficients, the novel combination of low temperature differences and unusual working fluids presented a problem. This is particularly true of the vapor generator, where the low heat flux may not be sufficient for nucleate boiling. Predicting initial occurrence of nucleate boiling is difficult and has a large impact on the heat transfer coefficient.

4.4.4 Code Inputs

In addition to the five primary design parameters, a large number of other performance characteristics were specified. Table 4 lists the performance characteristics common to all designs.

4.4.5 Piping Optimization

Previous studies (SERI Truscott Brine Lake Task Force, 1981, ORMAT Turbines, 1981) indicated that piping represents a major component of the solar pond power plant capital cost. In order to minimize the expenses associated with piping, the piping systems were designed using the ETRANS computer code (Barnhart, 1980). This code was originally developed at PNL for optimizing pipe sizes and insulation thicknesses for distributed fields of solar collectors. The following section describes the assumed piping layout and the

TABLE 4. Heat Engine Performance Parameters

Turbine Isentropic Efficiency (%)	78.
Feed Pump Isentropic Efficiency (%)	90.
Turbine Exit Moisture Limit (%)	6.
Sink Temperature (Cooling Water) ($^{\circ}\text{C}$)	19.
Heat Exchanger Fouling Resistance ($\frac{\text{m}^2\text{ }^{\circ}\text{C}}{\text{W}}$)	
Working Fluid Side	0.0002
Water or Brine Side	0.0002

optimization method. Although this section will describe the piping optimization as if it were a separate procedure, this optimization was actually nested inside the system optimization. The effects of all the design parameters on piping system capital cost and pumping power were taken into account in a levelized cost for each design.

4.4.5.1 Piping Systems Description

The piping layout was designed after the preliminary plant arrangement was developed. The major piping systems include:

- Brine Piping - The brine piping includes the piping required to extract brine from and return it to the storage zone. Hot brine is withdrawn from the storage zone through a system of inlet diffusers manifolded together. The brine is pumped to the power plant, where heat is extracted in the vapor generator. The cooler return brine is injected into the storage zone through a series of outlet diffusers which are manifolded together. The brine piping is assumed to be fabricated from carbon steel. The inlet and outlet diffusers were based on the linear design model tested by the U.S. Army Corps of Engineers (Bohan and Grace, 1973).
- Cooling Water Piping - The power plant is assumed to be cooled by water taken from the Great Salt Lake. Due to the low conversion efficiency of the heat engine, the heat rejection load is quite high, requiring a high cooling water flow rate. Water is removed from the Great Salt Lake, pumped through the power plant's

condenser, and returned to the lake. Due to the level of dissolved oxygen in the water, fiberglass-reinforced plastic (FRP) piping was used in place of carbon steel.

- Brine Makeup Piping - Brine makeup piping consists of the piping required to provide concentrated makeup brine to the solar pond. Piping runs from the Great Salt Lake to the evaporation pond and from the evaporation pond to the brine return piping are included. Due to the high oxygen content of the brine, FRP piping was used.
- Surface Flushing Piping - The surface flushing piping consists of the piping necessary to provide fresh water for flushing the solar pond's surface and to remove the brine flushed from the surface. The fresh water piping includes diffusers to spread the fresh water over the surface of the pond. The brine removal piping removes low concentration brine from the surface of the opposite side of the pond. The brine is then returned to the lake rather than recycled. This is because the salt concentration of the removed surface brine is well below the lake salt concentration and not worth concentrating for makeup. Note that the flushing water is currently assumed to be provided from the impoundment basin of the AMAX corporation through the west canal, and drained to the Great Salt Lake. If at some future time prior to pond filling, it is deemed necessary to conserve water, the flushing water could be recycled. This would require a redesign of the salt concentrations of the gradient and storage zones to maintain a stable pond. Surface flushing piping is assumed to be fabricated from carbon steel.

The assumed piping layout is shown schematically in Figure 12. Due to the uncertainties introduced by the surrogate site and preliminary site arrangement, the actual piping layout was not extensively optimized. It was assumed that brine extraction and removal piping could be run through the pond rather than along the dikes. This arrangement would complicate piping maintenance if maintenance was required but it minimizes the length of the large brine piping.

FIGURE 12. Schematic of Solar Pond Power Plant Piping

4.4.5.2 Optimization Technique

The goal of the piping optimization task was to select the pipe size and insulation thickness which would minimize the costs associated with the piping. The optimization was done using the ETRANS code (Barnhart, 1980). This code is designed specifically to select piping and insulation for solar thermal applications. The optimization procedure consists of analyzing the costs associated with a range of discretely sized pipe, each with a variety of insulation thicknesses. The combination of piping size and insulation thickness which produces the lowest lifetime cost was then selected. The figure of merit was levelized energy cost, which included both the amortized capital cost of the pumps and piping and the operating costs associated with pumping power and thermal losses where appropriate. Of vital importance in the optimization is the cost assigned to the pumping power. A low cost will produce an optimized design with small piping and high pumping power while a high cost will produce a design with large pipes and low pumping power. In this study it was

assumed that the solar pond power plant provided the pumping power, therefore the cost of pumping power should approximate the levelized energy cost of power produced by the solar pond power plant. All piping was assumed to have a life of 20 years. The piping optimization methodology is summarized on Figure 13.

4.5 ECONOMIC MODEL

The economic model is an integral part of GCOST and was used to develop levelized cost estimates for both the pond configuration optimization and the total system optimization.

Most previous optimization studies have been based on thermodynamic considerations. In this study, it was required that an economic comparison be completed for both the pond configuration optimization and the system optimization. First, a heat engine and piping system were sized for each pond configuration design considered. Capital costs were estimated by GCOST for each component. These costs were used to calculate the levelized cost for each design. The levelized costs were compared and the most attractive pond configuration design was selected.

A similar procedure was followed for the total system optimization. Each GCOST performance simulation provided component characteristics which were used to estimate the capital cost of the various components. These costs were used along with the operation and maintenance costs to calculate the levelized energy cost for each design. The levelized energy costs were compared and the most attractive design was selected. A summary of the inputs and outputs from the economic model is presented in Figure 14.

Baseline capital costs for a number of different solar pond configurations were estimated using standard construction-cost information, unit costs from vendor files, and equipment cost information from previous solar pond studies (Ormat Turbines, 1981, SERI Truscott Brine Lake Task Force, 1981). These cost estimates were then used to derive capital cost correlations for major components of the plant. Cost correlations for the operations and maintenance cost of the plant (as a fraction of the initial capital investment cost) were also developed.

INPUTS:	OPTIMIZATION VARIABLES:	OUTPUTS:
<ul style="list-style-type: none"> • BRINE & COOLING WATER FLOW RATES • SOLAR POND AREA • PIPING LAYOUT 	<ul style="list-style-type: none"> • PIPING SIZES • INSULATION THICKNESSES 	<ul style="list-style-type: none"> • OPTIMUM PIPE SIZES & INSULATION THICKNESSES • PIPING SYSTEM INSTALLED CAPITAL COST • PARASITIC POWER REQUIREMENTS

FIGURE 13. Piping System Model (ETRANS)

INPUTS:	OUTPUTS:
<ul style="list-style-type: none"> • GROSS POWER OUTPUT • NET POWER OUTPUT • SOLAR POND AREA • SOLAR POND DEPTH • EVAPORATION POND AREA • EVAPORATION POND DEPTH • CAPACITY FACTOR • SOLAR POND WARMUP TIME • ECONOMIC ASSUMPTIONS 	<ul style="list-style-type: none"> • INSTALLED CAPITAL COST OF SOLAR SALT POND POWER PLANT • OPERATION AND MAINTENANCE COSTS • LEVELIZED ENERGY COST

FIGURE 14. Economic Model

Correlations for the capital and O&M costs for the plant were used in GCOST during the plant optimization procedure. As described previously, GCOST used these cost inputs to calculate a levelized energy cost for each plant configuration. The levelized energy costs were calculated based on net plant output, or the amount of energy which could be potentially delivered by the plant to a utility grid. The net plant output was derived for each configuration by subtracting plant parasitic loads (such as brine pumping power, cooling water pumping power, and the feed pump load) from the gross plant capability of 5 MWe.

The levelized cost calculations required information on general economic conditions. These assumed economic parameters are shown in Table 5.

The cost model and cost data used in the pond optimization study were kept simple because of the preconceptual nature of the design and the overall scope of the project. The method did identify significant cost variation between designs, but the uncertainties in cost data mean that great care should be used in interpreting the levelized costs. Specifically the levelized energy cost values calculated in this optimization study should not be considered as an indication of the economic feasibility of solar ponds. The second phase of the Great Salt Lake study will include a detailed cost estimate developed by an architect/engineer, which should aid in determining economic feasibility.

TABLE 5. Economic Parameters for GCOST

Fraction of Initial Investment in Bonds (%)	50
Common (%)	38
Preferred (%)	12
Bond Interest Rate (%)	8
Equity Earning Rate (% after taxes) common	13.5
preferred	8.5
Depreciable Life of Plant (yr)	15
Plant Construction and Licensing (yr)	4
Effective Tax Rate (%)	50
Property Tax Rate (%)	2
Plant Operating Life (yr)	30
Investment Tax Credit	7
General Inflation Rate (%)	6
Capital Escalation Rate (%)	6
O&M Escalation Rate (%)	7

5.0 OPTIMIZATION RESULTS FOR GREAT SALT LAKE

The results of the three optimization studies will now be presented. Section 5.1 will discuss the pond configuration optimization. Section 5.2 will present the results of the total system optimization and Section 5.3 will describe the piping optimization.

5.1 POND CONFIGURATION OPTIMIZATION

Two types of results were produced by the pond optimization study. The most important was the thickness optimization of the two controllable zones, the storage zone and gradient zone. The second set of results reports the conclusions of several sensitivity studies and will be discussed in Section 6.

The zone thickness optimization considered different combinations of storage zone and gradient zone thicknesses. The upper convecting zone thickness is essentially uncontrollable and was assumed to be constant at 0.4 m. Storage zone thicknesses of 1.0, 2.0 and 3.0 m were considered, as were gradient zone thicknesses of 1.0, 1.25 and 1.50 meters.

A variable load cycle was selected on the basis of a sensitivity study reported in Section 6.0. The variable cycle consists of operating from April to November, with the number of days of operation per month approximately proportional to the insolation rate. This load cycle satisfied the ground rule of a 22% capacity factor and permitted economic operation of the power plant while demonstrating operation during 8 months. The average monthly output for the variable duty cycle is given in Table 6.

TABLE 6. Average Monthly Operation for Variable Duty Cycle

<u>Month</u>	<u>Average Monthly Operation (days)</u>	<u>Month</u>	<u>Average Monthly Operation (Days)</u>
January	0	July	18
February	0	August	19
March	0	September	8
April	8	October	5
May	11	November	3
June	11	December	0

The results of the 9 evaluations are summarized in Table 7. The pond design with the lowest levelized energy cost consisted of a 1.25 m gradient zone and a 1.0 m storage zone. Note that the average annual storage zone temperature goes down as either the gradient zone or the storage zone gets deeper. This results in a lower heat engine efficiency and, therefore, a larger and more expensive pond. In addition, the deeper the solar pond, the more expensive the construction and the larger the evaporation pond area required to supply the initial brine fill. In contrast to these trends, which tend to indicate that the shallowest solar pond is the best, there is a significant trend to balance them. The deeper the solar pond, the more thermal capacity it has, which allows a higher maximum heat extraction rate without falling below the allowed minimum temperature. This results in a smaller pond area for the deeper ponds. The interactions between different components and the balance achieved between these trends makes it impossible to predict an optimum design for the SSP system without a similar optimization study.

The study limitations should be remembered, however: While we selected the pond configuration with the lowest levelized energy cost, the uncertainties in the performance and cost estimates make the selection of a design point configuration with similar LECs arbitrary. Within the accuracy of the study, cases 4, 7 and 1 all are equally attractive.

5.2 TOTAL SYSTEM OPTIMIZATION

The total system optimization developed an optimized design for four different working fluids. The four fluids were R-113, R-114, N-butane and ammonia. These were selected based on a preliminary prescreening of potential working fluids. The results of each optimization will be discussed below, in addition to a description of the prescreening procedure.

5.2.1 Working Fluid Prescreening

In order to reduce the number of simulations, a wide variety of working fluids was screened for application in the Great Salt Lake SSP power plant. The prescreening process simulated a plant design with a variety of working fluids using the conditions representative of the Great Salt Lake. Isobutane,

TABLE 7. Pond Configuration Optimization

Run No.	SOLPOND RESULTS						GCOST Results LEC (mills/kWhr)
	Non-convecting Zone Thickness (m)	Storage Zone Thickness (m)	Minimum Temperature of S.Z. (°C)	Avg. Annual Storage Temperature (°C)	Maximum Heat Extraction Rate (W/m ²)	Evaporative/ Solar Pond Area	
1	1.0	1.0	70.	90.	56.56	0.1148	397
2	1.0	2.0	70.	85.	63.27	0.2196	426
3	1.0	3.0	70.	83.	64.20	0.3243	469
4	1.25	1.0	70.	86.	90.25	0.2938	375
5	1.25	2.0	70.	81.	97.68	0.5344	424
6	1.25	3.0	70.	78.	99.08	0.7750	474
7	1.50	1.0	70.	83.	107.94	0.5068	384
8	1.50	2.0	70.	77.	188.10	0.8832	446
9	1.50	3.0	70.	75.	119.44	1.2596	501

n-butane, R-11, R-12, R-22, R-113, R-114, and ammonia were used. The pre-screening indicated that n-butane, R-113, R-114, gave the highest efficiency; therefore, these three were selected for the more detailed optimization.

Isobutane, n-butane, R-113 and R-114 are non-wetting fluids; that is, they superheat upon expansion through the turbine. Ammonia was not selected at this time because of its lower efficiency. Being a wetting fluid, its efficiency suffered under the constraint of no moisture at the turbine exit. As a part of the heat engine study, a turbine consultant was contracted to look at the effects of working fluid selection on turbine design and cost (see Appendix C, Bergmann, 1982). The report indicated that an ammonia turbine could operate with 6% moisture at the outlet. When analyzed under the new constraints, the ammonia cycle efficiency was almost as high as the other fluids and it was subsequently added to the list.

5.2.2 Results of Optimization Study

The results of the optimization simulations for R-113, R-114, and n-butane are presented in Tables 8, 9 and 10, respectively. The values selected for each variable were determined by an efficient search method, which reduced the number of required simulations for each fluid.

The analysis of ammonia as a working fluid was limited in scope because GCOST as currently configured can not simulate working fluids which expand into the vapor dome. Because the ammonia cases could not be simulated using GCOST, manual calculations were completed for three cases and the least cost case is presented in Table 11. Even with the limited optimization, the results indicated that ammonia is an attractive choice for working fluid with a levelized energy cost of 288 mills/kWh, as compared to n-butane with a levelized energy cost of 341 mills/kWh. The ammonia cycle efficiency is slightly below that for other working fluids. This is offset by the excellent heat transfer properties of ammonia which lead to a substantial reduction in heat exchanger costs. The net effect is to reduce the levelized energy cost of an ammonia cycle when compared to other working fluids.

Based on the results of the four optimization studies, ammonia was selected as the working fluid for the SSP power plant heat engine. The cycle operates with a vapor generator approach temperature of 8.3°C, a pinch point temperature

TABLE 8. Total System Optimization (R-113)

Run No.	Pond Configuration No.	Vaporizer Approach (°C)	Pinch Point (°C)	Condenser Approach (°C)	Condenser Range (°C)	LEC (mills/kWhr)
301	4	25	13	19	15	432
302	4	25	13	21	15	434
303	4	25	13	17	15	434
304	4	25	13	19	14	430
305	4	25	13	19	12	429
306	4	25	13	19	10	431
307	4	25	12	19	12	428
308	4	25	10	19	12	429
309	4	22	12	19	12	442
310	4	26	12	19	12	430
311	4	24	12	19	12	436

TABLE 9. Total System Optimization (R-114)

Run No.	Pond Configuration No.	Vaporizer Approach (°C)	Pinch Point (°C)	Condenser Approach (°C)	Condenser Range (°C)	LEC (mills/kWhr)
53	4	20	7.5	15	10	424
101	4	20	7.5	15	9	425
102	4	20	7.5	15	11	425
103	4	20	7	15	10	425
104	4	20	8	15	10	425
105	4	20	6	15	10	426
106	4	20	10	15	10	429
107	4	20	7.5	14	10	425
108	4	20	7.5	16	10	425
109	4	20	7.5	18	10	427
110	4	19	7.5	15	10	425
111	4	21	7.5	15	10	424.2
112	4	23	7.5	15	10	424.4

TABLE 10. Total System Optimization (N-BUTANE)

Run No.	Pond Configuration No.	Vaporizer Approach (°C)	Pinch Point (°C)	Condenser Approach (°C)	Condenser Range (°C)	LEC (mills/kWhr)
201	4	24	13	26	18	414
202	4	24	15	26	18	432
203	4	24	11	26	18	406
204	4	24	9	26	18	403
205	4	24	7	26	18	407
206	4	24	9	26	17	403
207	4	24	9	26	15	403
208	4	24	9	26	14	404
209	4	24	9	26	19	404
210	4	24	9	24	17	398
211	4	24	9	21	17	393
212	4	24	9	20	17	393
213	4	24	9	18	17	399
214	4	23	9	21	17	393
215	4	25	9	21	17	394
216	4	20	9	21	17	396
217	4	23	7	21	17	396
218	4	23	10	21	17	394
219	4	23	9	21	17	393
220	4	23	9	21	15	390
221	4	23	9	21	13	390
222	4	23	9	21	12	390
223	4	23	9	19	14	387
→ 224	4	23	9	17	14	386 ←
225	4	23	9	16	14	387
226	4	22	9	17	14	387
227	4	24	9	17	14	387

TABLE 11. Characteristics of Optimum Plant Design

Power Plant Characteristics	Ammonia
Vapor Generator Approach Temperature (°C)	8.3
Pinch Point Temperature (°C)	4.4
Condenser Approach Temperature (°C)	8.3
Condenser Range (°C)	5.6
Brine Flow Rate (kg/sec)	829.
Working Fluid Flow Rate (kg/sec)	47.
Cooling Water Flow Rate (kg/sec)	2192.
Gross Cycle Efficiency	8.63
Net Power Output (MWe)	4.53
System Capital Investment Cost (\$ x 10 ⁶)	
Solar Pond Cost	3.9
Evaporation Pond Cost	1.0
Land Cost	0.1
Site Cost	0.7
Heat Engine Cost	3.7
Piping System Cost	1.5
Electrical Plant Cost	0.5
Miscellaneous Costs	0.1
Indirect Costs	2.8
Total Capital Cost	14.3
Total Levelized Energy Cost (Mills/kWh)	288

of 4.4°C; a condenser approach temperature of 8.3°C and a condenser range of 5.6°C. The design characteristics and estimated costs of the facility are summarized on Table 11. To illustrate the approximate impact of heat transfer characteristics on system cost, Figure 15 presents levelized energy cost as a function of average heat transfer coefficient for the four fluids considered. The apparent correlation indicated the importance of the working fluids' heat transfer properties in the overall performance and cost of the system.

5.3 PIPING OPTIMIZATION

The results of the piping optimization study include approximate sizes for each run of piping (excluding working fluid piping which is costed in the heat engine optimization). Figures 16-20 list characteristics of each of the five major piping systems. Pumps were sized and costed on the basis of the flow rates and pressure drops estimated for each system (Figures 16-20). In addition, one spare pump was included in each system to improve reliability

FIGURE 15. Effect of Working Fluid Heat Transfer Characteristics on Levelized Cost

(e.g., (3) 50% capacity pumps on the hot brine system). Only the hot brine transport piping required insulation; the optimal thickness was 3.8 cm.

The large impact of pumping power cost on piping selection suggests that it is not appropriate to use pipe sizing rules of thumb developed for low-cost energy sources. In particular, the use of design velocities developed for steam power plant and refinery design may be based on low estimates for pumping power costs which would produce non-optimum designs with undersized piping and excessively high pumping power.

The low capacity factor of the plant also affected piping selection because of the limited running time. To some extent this mitigated the impact of high pumping power costs; as running time decreases, capital expenses begin to dominate the life-cycle cost and smaller pipe sizes become cost-effective.

SECTION	DIAMETER		LENGTH	SYMMETRY	TOTAL
	(in.)	(cm)	(M)	FACTOR	LENGTH (M)
①	20	(47.8)	844	1	844
②	16	(38.1)	209	2	418
③	12	(30.3)	195	4	780
④	12	(30.3)	195	4	780
⑤	16	(38.1)	209	2	418
⑥	18	(42.9)	10	1	10
⑦	12	(30.3)	6	3	18

MATERIAL: CARBON STEEL

PUMPS: 3, 50% CAPACITY

BRINE FLOW RATE: 44,100 LIT./MIN.

PRESSURE DROP: 248 KPa

FIGURE 16. Hot Brine Transport Piping

SECTION	DIAMETER		LENGTH	SYMMETRY	TOTAL
	(in.)	(cm.)	(M)	FACTOR	LENGTH (M)
①	20	(47.8)	6	3	18
②	36	(87.6)	100	1	100
③	36	(87.6)	100	1	100

MATERIAL: FIBERGLASS REINFORCED PLASTIC

PUMPS: 3, 50% CAPACITY

COOLING WATER FLOW RATE: 120,000 LIT./MIN.

PRESSURE DROP: 20 KPa

FIGURE 17. Condenser Cooling Water Piping

SECTION	DIAMETER		LENGTH	SYMMETRY	TOTAL
	(in.)	(cm)	(M)	FACTOR	LENGTH (M)
①	8	(20.3)	5	2	10
②	10	(25.5)	100	1	100
③	8	(20.3)	200	2	400
④	6	(20.3)	195	4	780

MATERIAL: FIBERGLASS REINFORCED PLASTIC

PUMPS: 2, 100% CAPACITY

FLUSHING WATER SUPPLY FLOW RATE: 4334 LIT./MIN.

PRESSURE DROP: 28 KPa

FIGURE 18. Flushing Water Supply Piping

SECTION	DIAMETER		LENGTH (M)	SYMMETRY FACTOR	TOTAL LENGTH (M)
(in.)	(cm)				
①	6	(15.4)	195	4	780
②	8	(20.3)	200	2	400
③	8	(20.3)	2	1	2
④	6	(15.4)	6	2	12
⑤	10	(25.5)	100	1	100

MATERIAL: FIBERGLASS REINFORCED PLASTIC

PUMPS: 2, 100% CAPACITY

FLUSHING WATER DRAIN FLOW RATE: 3140 LIT./MIN.

PRESSURE DROP: 20 KPa

FIGURE 19. Flushing Water Drain Piping

SECTION	DIAMETER		LENGTH	SYMMETRY	TOTAL
	(in.)	(cm)	(M)	FACTOR	LENGTH (M)
①	3	(7.8)	6	2	12
②	4	(10.2)	100	1	100
③	2	(5.3)	6	2	12
④	3	(7.8)	100	1	100

MATERIAL: FIBERGLASS REINFORCED PLASTIC

PUMPS: 2, 100% CAPACITY FOR MAKEUP FROM GREAT SALT LAKE
 2, 100% CAPACITY FOR MAKEUP FROM EVAPORATION POND

MAKEUP BRINE FLOW RATE (FROM GSL): 473 LIT./MIN.

MAKEUP BRINE FLOW RATE (FROM EVAP. POND): 212 LIT./MIN.

PRESSURE DROP: 28 KPa

FIGURE 20. Cool Brine Transport Piping (makeup)

6.0 SENSITIVITY STUDIES

After the completion of the optimization study, several sensitivity studies were conducted. The first set of sensitivity studies checked the appropriateness of the various design assumptions used in the pond configuration optimization. The second set of sensitivity studies investigated the impact of changing plant location and capacity factor. Additional hydrodynamic investigations using the PNL developed TEMPEST computer code were also completed but they will be documented in a subsequent report.

6.1 POND DESIGN SENSITIVITY STUDIES

In addition to the zone thickness optimization, a series of sensitivity studies were conducted both to check the appropriateness of various design assumptions and to examine other aspects of the pond design. The sensitivity studies include:

Pond Minimum Temperature - The pond minimum temperature is the lowest temperature that the storage zone was allowed to reach during heat engine operation. This is accomplished in SOLPOND by setting the desired minimum temperature, the capacity factor and load cycle, and the initial heat extraction rate, and then calculating an annual solution for pond storage temperature. The heat extraction rate is then raised or lowered in an iterative procedure to achieve the specified pond minimum temperature at the lowest point during operation. Note that the heat extraction rate is not varied during the yearly cycle, but held constant to assure that 5 MW_e is produced any time the heat engine is operating. A lower pond minimum temperature allows a higher heat extraction rate per acre which, in turn, allows a smaller solar pond for the same size power plant. In opposition, though, a lower minimum temperature produces a lower average annual storage temperature and, therefore, a lower average heat engine efficiency. In order to look at the tradeoff between these two opposing trends, a sensitivity study was performed to analyze the same pond and heat engine with four different minimum storage

temperatures (50°C, 60°C, 70°C, 80°C). The results of the study are shown in Figure 21 and 80 °C appeared to be the most cost-effective within the range tested. The optimization was performed using a 70°C minimum temperature based on previous information.

Load Cycle - Although the gross power output of 5 MW_e and the capacity factor of 0.228 were specified by the ground rules of this design, the actual load cycle was left up to the designer. In order to evaluate the effects of load cycle on power plant size and cost, a sensitivity study was done to look at a specific pond and heat engine operating under different load cycles. It is important to note at this point that the selection of the load cycle in this way

FIGURE 21. Pond Minimum Temperature Sensitivity Study

only applies to an Engineering Test Facility. The selection of a load cycle for a commercial power plant would be determined by the requirements of the operating utility. The load cycles that were considered in this study were:

- 1) operation during the summer months only; 83 days of operation starting June 1.
- 2) operation during 12 months of the year, with the number of days/month approximately proportional to insolation
- 3) operation during 8 months of the year, starting in April, with the number of days/month approximately proportional to insolation.
- 4) operation during 6 months of the year, starting May, with the number of days/month approximately proportional to insolation.

The straightforward load cycle where the heat engine is operated for about 7 days/month was initially considered for this study. It was eliminated because operation during the cold months made a very large pond necessary and the same pond could not be prevented from boiling in the summer months. The results of this study are shown in Table 12. There was no statistically significant effect on the LEC, so load cycle 3 was actually chosen for the optimization study.

- Heat Engine Model - The use of a minimum pond temperature may not be the optimum method of operating the facility. An alternative heat engine model assumed that the heat engine would operate regardless of pond temperature but the design would be penalized by a decrease in Carnot efficiency and a resulting increase in brine mass flow rate. This model did result in lower levelized energy costs but the heat engines were operating over a wide range of temperature differences (pond temperature minus heat rejection temperature) with high values of approximately 60°C and low values of approximately 25°C. Such a wide swing in operating conditions was considered an unreasonable operating scenario, i.e., a single heat engine design probably could not handle this range of conditions; but the results

TABLE 12. Load Cycle Sensitivity Study

	<u>Load Cycle</u>	<u>Lec</u>
1)	Summer only, 83 day straight operation, starting June 1	447
2)	Operation during 12 months, number of days/month approx. proportional to insolation	445
3)	Operation during 8 months, starting April 1, number of days/month approx. proportional to insolation	446
4)	Operation during 6 months, starting May 1, number of days/month approx. proportional to insolation.	437

implied, however, that future studies should consider other heat engine operating strategies in addition to simply using a minimum operating temperature.

- Time Step - The SOLPOND code can use a range of time steps. In order to determine the impact of time step on the results, daily, weekly and monthly were simulated. The results indicated that weekly time steps adequately modeled all transient effects while minimizing computational time.

6.2 GROUND RULE SENSITIVITY STUDY

The impact of changing ground rules was investigated by considering the effect of increasing plant capacity factor and changing the location of the facility from the Great Salt Lake to the Salton Sea. The second evaluation had the advantage of allowing a meaningful comparison between the design developed for the Great Salt Lake and the design developed by JPL and Ormat for the Salton Sea.

- The investigation of the impact of capacity factor on levelized energy cost consisted of conducting a system optimization of a plant with a capacity factor of 0.628. Following the procedure used in the primary optimization, the pond zone thicknesses were optimized so that the average annual pond temperature and other factors could be supplied to a system optimization study. The pond zone thickness optimization considered seven cases shown in Table 13. The minimum pond temperature was reduced to 60°C for several cases because the low flow rates associated with a high capacity factor plant resulted in many pond designs boiling the brine in the storage zone. The pond design selected for the high capacity case consisted of an upper convecting zone of 0.4 m (arbitrarily set), a non-convecting zone of 1.5 m, and a storage zone of 1.0 m (Case 5).

The capacity factor sensitivity study was limited to one working fluid, R-114. The results presented indicated that an optimized high capacity factor design would have levelized energy cost of 214 mills/kWh. The selected design operates with a vapor generator approach temperature of 11°C, a pinch point temperature of 7.2°C, a condenser approach temperature of 9.4°C, and a condenser range of 5.6°C.

TABLE 13. Results of High Capacity Factor (0.628)
Pond Configuration Optimization

Case No.	Nonconvecting Zone Thickness (m)	Storage Zone Thickness (m)	Minimum Pond Temperature (°C)	Levelized Energy Cost, (mills/kWh)
1	1.5	2.0	70	277
2	1.50	3.0	70	309
3	1.25	2.0	60	312
4	1.25	3.0	60	272
→ 5	1.50	1.0	60	230 ←
6	1.50	2.0	60	262
7	1.50	3.0	60	297

The results of the sensitivity study indicated that an increase in capacity factor from 0.228 to 0.628 reduces the levelized energy cost from 375 mills/kWh to 214 mills/kWh. The rapid reduction in levelized energy cost with capacity factor confirms results from other design studies for Salton Sea and Truscott Lake. The results are summarized on Figure 22.

- In addition to varying the capacity factor, the effect of changing the pond location from the Great Salt Lake to the Salton Sea was investigated. It was anticipated that the higher ambient temperature and the improved insolation would result in a deeper storage zone, but offsetting the improved performance of a deeper zone was the economic impact of producing brine from the low salt concentration water of the Salton Sea. The sensitivity study was limited to an optimization of the pond because it was felt that the location would not have a significant impact on the heat engine. The pond design

PARAMETER	0.228 C.F.	0.628 C.F.
POND CONFIGURATION:		
UPPER CONVECTING ZONE DEPTH	0.4 m	0.4m
NON-CONVECTING ZONE DEPTH	1.25m	1.5m
STORAGE ZONE DEPTH	1.0m	1.0m
TOTAL SYSTEM:		
AVERAGE BRINE STORAGE TEMPERATURE	86°C	82°C
BRINE MASS FLOW RATE	1500 KG/sec	2800 KG/sec
NET POWER OUTPUT	4.46 MW	4.29 MW
SOLAR POND SIZE	615,000 M ²	1,627,000 M ²
EVAPORATION POND SIZE	202,350 M ²	826,000 M ²
TOTAL SYSTEM INSTALLED CAPITAL COST	\$17.96 M	\$28.95 M
LEVELIZED ENERGY COST	375 MILLS/KWHR	214 MILLS/KWHR

FIGURE 22. Effects of Changing Capacity Factor on the Optimization of a SSPP

selected for the Salton Sea is similar to that proposed for the Great Salt Lake. A low capacity factor design (0.228) consisted of a 1.5 m convecting zone and a storage zone thickness of 2.0 m. The 2.0 m storage zone was the thinnest zone that avoided boiling. The high capacity factor design (0.628) at Salton Sea consisted of a 1.25 m nonconvecting zone and a 1.00 m storage zone. The results differed from the Salton Sea design developed by Ormat, which used a 3.5 m storage zone. It should be emphasized that the shallow storage zone thickness is based on an economic optimization. Hydrodynamic considerations might require a thicker zone, particularly for the low capacity factor design, which would have a particularly high flow rate. The results of this evaluation are summarized on Figure 23.

PARAMETER	GREAT SALT LAKE	SALTON SEA
• UPPER CONVECTING ZONE DEPTH	0.4 m	0.4 m
• NON-CONVECTING ZONE DEPTH	1.25 m	1.5 m
• STORAGE ZONE DEPTH	1.0 m	2.0 m
• RELATIVE SOLAR POND SIZE (ASSUME: GROSS OUTPUT = 5 MW HEAT ENGINE CYCLE EFFICIENCY = 8%)	692,000m ²	376,000m ²

FIGURE 23. Effects of Changing Pond Location on Optimum Pond Configuration

7.0 DESIGN SUMMARY

The results of the optimization studies used to develop design specifications for the Great Salt Lake SSP power plant are included here. The design specifications were in sufficient detail to allow an engineering consulting firm to develop a preconceptual design and cost estimate for comparison with other sites for large solar salt ponds. This section summarizes the design details used in the preparation of the design specifications.

7.1 SITE LAYOUT

The design is based on the assumed surrogate site located on the southwest shore of The Great Salt Lake. The acquisition of detailed site specific information was beyond the scope of the study. This limited the information available for developing a site layout, therefore a schematic site layout was prepared rather than a detailed plot plan. Figure 24 presents the schematic site layout with the major ponds, piping and facilities arranged to minimize pipe lengths and pumping requirements. A detailed arrangement would require extensive site-specific information including soil borings and soil properties.

The layout consists of one large solar pond constructed on land adjacent to the lake with the evaporation pond located close to the salt pond. The power plant is located as close to the cooling water supply as possible to minimize cooling water piping. All ponds include, where necessary, diversion diking to divert runoff.

7.2 FLOW DIAGRAMS

Two flow diagrams are included. Figure 25 shows the major flow streams associated with the brine transport, brine production, surface flushing and cooling water systems. Figure 26 is a flow diagram for the ammonia Rankine cycle heat engine. Both figures show mass flow rates while Figure 26 also indicates the working fluid properties at significant locations in the cycle.

FIGURE 24. Plant Layout

FIGURE 25. Plant System Flow Diagram

FIGURE 26. Heat Engine Flow Diagram

7.3 COMPONENT CHARACTERISTICS

Table 14 summarizes the characteristics of the plant and of major subsystems and components. The heat exchangers are a major cost item and substantial effort was spent on attempting to estimate the heat transfer coefficients for each heat exchanger. The turbine design and cost were based on information from a turbine manufacturer. Other components were sized based on appropriate mass flow rates and fluid properties.

TABLE 14. Plant Characteristics

Overall Plant Characteristics	
Plant Gross Rating (MW_e)	5.
Plant Net Rating (MW_e)	4.53
Capacity Factor (%)	22.8
Pond Characteristics	
Solar Salt Pond Area (m^2)	618,000.
Upper convecting zone depth (m)	.4
Gradient zone depth (m)	1.25
Storage zone depth (m)	1.0
Upper convecting zone salt concentration (kg salt/ m^3 brine)	0.5
Storage zone salt concentration (kg salt/ m^3 brine)	208.
Flushing water flow rate (lit/min)	4334.
Makeup brine flow rate (lit/min)	212.
Average annual storage zone temperature ($^{\circ}C$)	86.
Evaporation Pond	
Area (m^2)	182,000.
Depth (m)	1.75
Makeup Pond (Part of Evaporation Pond)	
Area (m^2)	121,000.
Depth (m)	1.75
Flow Rates	
Brine flow rate (kg/sec)	829.
Cooling water flow rate (kg/sec)	2192.

TABLE 14. (contd)

Pumping Power	
Brine pump (KWe)	230.4
Cooling water pump (KWe)	42.7
Other pumps (not including ammonia feed pump) (KWe)	10.5
Heat Engine Characteristics	
Working Fluid	Ammonia
Net cycle efficiency (%)	8.63
Ammonia flow rate (kg/sec)	47.
Preheater	
Heat duty (W)	9.6×10^6
Heat transfer coefficient (W/m°C)	440.
Area (m ²)	392.
Vapor Generator	
Heat duty (W)	44.25×10^6
Heat transfer coefficient (W/m°C)	342.
Area (m ²)	4215.
Pinch point (°C)	4.4
Brine range (°C)	16.
Superheater	
Heat duty (W)	1.8×10^6
Heat transfer coefficient (W/m°C)	303.
Area (m ²)	148.
Approach temperature (°C)	8.3
Condenser	
Heat duty (W)	$51. \times 10^6$
Heat transfer coefficient (W/m°C)	500.
Area (m ²)	6140.
Cooling water range (°C)	5.6
Approach temperature (°C)	8.3
Feed pump power (KW _e)	184.6
Turbine	
Efficiency (%)	80.
Speed (rpm)	13,500
Gear box required?	Yes
Gross output (MW _e)	5.
Enthalpy drop (KJ/KG)	106.
Wheel diameter (cm)	46.
Outlet flange size (cm)	66.

8.0 CONCLUSIONS

In addition to producing the optimized design of a SSP power plant for the Great Salt Lake, the studies described in this report identified significant conclusions concerning optimization results and methodology. Three general conclusions are presented regarding the overall system design, and then specific conclusions are presented on each of the three major subsystems; ponds, heat engine and piping.

- Economic optimization of a SSP power plant yields significantly different results than thermodynamic optimization. Thermodynamically, deeper gradient and storage zones were more cost-effective. Similarly, a regenerator made a significant improvement in thermodynamic performance, but was not included after an economic assessment.
- The relationships between the different major subsystems of the SSP power plant (i.e., ponds, heat engine and piping) are far too complex to specify each independently. A systems optimization is required to tradeoff parameters that affect several subsystems. A primary trade off, for example, is the pond cost versus the heat exchanger cost.
- The optimization of a SSP power plant is dramatically affected by many factors including location, climate, plant size, capacity factor, and load cycle. A given plant must be individually designed for a specific set of initial conditions in order to assure optimum design.

8.1 CONCLUSIONS ON POND DESIGN

The conclusions on the pond design are taken from the results of the pond optimization study and they include:

- Based on performance and cost the optimum pond consists of a 1.25 m thick gradient zone and a 1 m thick storage zone. Practical considerations related to brine extraction may make this design unattractive. The shallow storage zone would experience high brine

flow rates with the possibility of erosion of the gradient zone. Because of the small cost penalty associated with using a 2.0 m thick zone this approach could be used if the risk of using a shallower storage zone was too great. A successfully operating 1.0 m storage zone was reported at the Ein Bokek facility in Israel (Lin, 1982).

- The optimum storage zone thickness of 1 m is thinner than that used for other SSP power plant conceptual designs (Peelgren, 1982, SERI Truscott Brine Lake Task Force, 1981). The specific pond output did increase slightly with storage zone depth but the added costs of dike construction and evaporation ponds more than offset the increased output, producing an increase in levelized energy cost. The specific output was influenced by ambient conditions. The low winter ambient temperature seems to push an optimum design towards a peaking unit with a shallow storage zone which can warm up quickly in the spring. The relatively poor transmissivity assumed for Great Salt Lake brine may have contributed to optimizing with shallow zone thicknesses. It is anticipated that other sites with more expensive salt than that used for Great Salt Lake would optimize with even shallower zone thicknesses unless there was a major improvement in performance.
- The impact of brine transmissivity on specific outputs is very great. It was originally felt that water sampling was beyond the scope of a first order feasibility study but the sensitivity of the results to brine transmissivity was so great that samples were acquired and tested at PNL. The results indicated optical properties substantially better than for Salton Sea brines, but due to sampling uncertainties, the conservative assumption of assuming Salton Sea optical properties was used. In any future feasibility studies it is strongly recommended that brine sampling be included early on in the study and that actual optical properties be used where appropriate.
- The heat engine operating strategy used in this study assumes that the power plant is always producing 5 MW (constant output), but that it is operated for a different number of days each month. This load profile was selected to approximate the insolation profile and to extract the most energy without allowing the storage zone temperature

to fall below 70 °C. This may not be the most practical strategy. A more reasonable strategy may be to operate the heat engine until the net output (gross output minus auxiliary loads) fell below a value determined by plant economics.

8.2 CONCLUSIONS ON HEAT ENGINE DESIGN

The conclusions on the heat engine design are based on both the results of this study and a review of other similar heat engine evaluations. The conclusions include:

- A meaningful heat engine optimization must include costs and heat transfer aspects of the design. Most previous studies have consisted of strictly thermodynamic analysis. This results in an overestimation of performance-improving modifications and an underestimation of the importance of heat transfer characteristics.
- This study has shown ammonia to be an attractive working fluid for low temperature applications. This conclusion conflicts with a previous study based on a thermodynamic analysis. The beneficial impact on heat exchanger performance and cost of using ammonia as a working fluid offsets the slightly lower efficiency of an ammonia cycle. Due to the limited scope of GCOST, the ammonia cycle could not be optimized in the same detail as the other working fluids. Therefore the proposed ammonia cycle arrangement may not be optimum. The results of this study indicate that ammonia should be considered in future evaluations and that further optimization of the ammonia cycle should be completed.
- The heat exchangers are the dominant cost component in the heat engine and they directly impact the heat engine performance. Solar pond applications represent unusual operating conditions because of the unusual fluids and small temperature differences. Additional research is required to develop designs optimized for these conditions. Particular emphasis should be placed on previous work done in the design of geothermal heat exchangers and OTEC heat exchangers.

- When cost factors are included, a regenerator does not offer a significant advantage for Rankine cycles using "nonwetting" fluids for the cycle working fluid. This further emphasizes the importance of including cost factors in a heat engine design because most previous studies have included a regenerator based on performance improvements.
- The assumed availability of the Great Salt Lake for cooling the power plant avoided the problem of heat rejection which may be important at other sites. The cost of cooling a low efficiency power plant such as a solar pond power plant can be quite high. Advanced dry cooling and wet cooling systems using high concentration brine should be considered if once-through cooling is not available.
- While the design of the turbine for any of the working fluids does not represent a major problem, the working fluid selection can result in significant variation in turbine design and cost. The turbine for the ammonia cycle is a small, high speed machine which requires a gear box for driving the generator. Other designs result in larger and more expensive turbines which do not require a gear box. The working fluid selection was detailed by other factors but the impact of the working fluid on the turbine design and cost should not be underestimated.

8.3 CONCLUSIONS ON PIPING DESIGN

The piping optimization study was limited in scope; therefore it was not possible to draw many conclusions. The primary conclusion is that the use of normal piping design rules of thumb are inappropriate for designs with a very high energy cost. An optimized piping design produced pipe flow areas larger than for other designs; this is probably because of the high value of energy from the small peak-load SSP power plant.

REFERENCES

- Arnow, Ted. 1980. "Water Budget and Water-Surface Fluctuations of Great Salt Lake." In Great Salt Lake: A Scientific, Historical and Economic Overview, pp. 255-263. Utah Geological and Mineral Survey, Salt Lake City, Utah.
- Barnhart, J. S. 1980. ETRANS: An Energy Transport System Optimization Code for Distributed Networks of Solar Collectors. PNL-3327, Pacific Northwest Laboratory, Richland, Washington.
- Bergmann, Duane. 1982. A Study of Expansion Turbines for a 5 MW Solar Salt Pond Power Plant. Prepared for the Pacific Northwest Laboratory by Bergmann Engineering, Inc., Glendora, California.
- Bloomster, C. H. et al. 1975. GEOCOST-A Computer Program for Geothermal Cost Analysis. BNWL-1888, Battelle-Northwest Laboratories, Richland, Washington.
- Bohan, Joseph, P. and J. L. Grace, Jr. 1973. Selective Withdrawal From Man-Made Lakes. Technical Report H-73-4, U.S. Army Engineering Waterways Experiment Station, Vicksburg, Mississippi.
- Cinguemoni, et al. 1978. SOLMET Rehabilitated Data, Salt Lake City, Utah.
- Downing, R. C. Refrigerant Equations, No. 2313, Dupont Company, Freon Products Division.
- Henderson, J. and C. M. Leboeuf. 1980. SOLPOND-A Simulation Program for Salinity Gradient Solar Ponds, SERI/TP-351-559, Solar Energy Research Institute, Golden, Colorado.
- Huber, H. D., R. A. Walter and C. H. Bloomster. 1976. User Manual for GEO-COST: A Computer Model for Geothermal Cost Analysis. BNWL-1942-V2, Battelle, Northwest Laboratories, Richland, Washington.
- Lin, E. I. H. 1982. A Review of the Salt-Gradient Solar Pond Technology. JPL 81-116, Jet Propulsion Laboratory, Pasadena, California.
- Martin, J. J. 1967. "Equations of State." Ind. Eng. Chem., Vol. 59, No. 12, pp. 34-52.
- Milora, S. L. 1973. Application of the Martin Equation of State to the Thermodynamic Properties of Ammonia. ORNL-TM-4413, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Ormat Turbines. 1981. A Study of the Feasibility of a Solar Salt Pond Generating Facility in the State of California, U.S.A., Vol. I and II. Prepared for the Southern California Edison Company by Ormat Turbines, Yavne, Israel.

Peelgren, M. L. 1982. Salton Sea Project-Phase 1, Final Report. DOE/JPL-1060-44, Jet Propulsion Laboratory, Pasadena, California.

Riley, J. Paul and J. Clair Batty. 1981. The Potential for Solar Pond Development in Utah. Utah State University, Logan, Utah.

SERI Truscott Brine Lake Task Force. 1981. Conceptual Design of the Truscott Brine Lake Solar Pond System - Volume 1, Utility-Independent Scenario. Prepared for the U.S. Army Corps of Engineers, Tulsa District by Solar Energy Research Institute, Golden, Colorado.

Starling, K. E. 1973. Fluid Thermodynamic Properties for Light Petroleum Systems. Gulf Publishing Co., Houston, Texas.

Sturm, Paul. A. 1980. "The Great Salt lake Brine System." In Great Salt Lake: A Scientific, Historical and Economic Overview, pp. 147-162. Utah Geological and Mineral Survey, Salt Lake City, Utah.

Tulsa District, U.S. Army Corps of Engineers, and the Pacific Northwest Laboratory. 1982. The Technical and Economic Feasibility of Salt-Gradient Solar Ponds at the Truscott Brine Lake of the Red River Chloride Control Project. Pacific Northwest Laboratory, Richland, Washington.

APPENDIX A

SITE COMPARISON CRITERIA

APPENDIX A

SITE COMPARISON CRITERIA

In order to decide between the sites considered in this study it is necessary to determine which attributes are desirable in a solar salt pond Engineering Test Facility. The criteria described below were developed by the Ad Hoc Steering Committee. These are described here because the decision criteria had a major impact on the design of the Great Salt Lake solar pond power plant. The decision criteria include:

- Capital Cost - The capital cost of the Engineering Test Facility was a major evaluation criterion. The lowest cost facility which met the design requirements would be most attractive.
- Schedule - The sites which allowed rapid design, construction, brine concentration and startup were to be viewed favorably.
- Specific Output - The base load sustainable output per acre of pond area was used as a measure of the commercial potential of a given site because this attribute includes the impact of insolation, water clarity, ambient temperature, heat losses and pond efficiency. Sites with a high specific output were considered to be most attractive.
- Size of Potential Resource - The ultimate installed power generating capacity at a given site was used as a criterion to indicate the importance of a site to possible investors.
- Site Characteristics - Site characteristics other than specific output were also considered as a criterion. These included such factors as salt availability, land availability, makeup water availability, ground water, soil permeability and other site characteristics.
- Potential User Involvement - The involvement of potential users and investors such as electric utilities, industrial users and others was viewed as being an advantage for a given site.

- Environmental Impact - The environmental impact of a solar salt pond power plant installed at a given site was included as a major evaluation criterion. These impacts include site contamination, groundwater contamination and other environmental impacts.

APPENDIX B

GSL SITE SELECTION CRITERIA

APPENDIX B

GSL SITE SELECTION CRITERIA

In order to allow a comparison of the 14 general areas around Great Salt Lake, an evaluation criteria were developed. The criteria consisted of 11 components which include:

- Topography - It was assumed that an attractive pond site would have a relatively flat topography in order to minimize excavation. The availability of flat land around the Great Salt Lake was not considered a problem, because there are literally hundreds of square miles of land with a slope of less than one foot per half-mile. The major difficulty was in finding a flat site which was at a sufficient distance from the lake so that variations in lake level and wind-driven waves would not threaten the pond's dike.
- Fresh Water - A successful site must have convenient access to a source of fresh water. Considerations include the closeness of the source, the quality of the water at the source, particularly with respect to salinity and nutrients that might promote radiation absorbency or biological activity in the pond, and the cost of conveying the water to the actual pond site.
- Brine - Brine must be obtained for initial pond filling and to provide make-up brine to replace salt lost by surface flushing and seepage. The brine should be highly concentrated and free of sediments and organic material. The cost of conveying the brine from its source to the site must be minimized in addition to any costs associated with evaporation ponds necessary to concentrate the brine to a level suitable for use in the pond.
- Accessibility - The site must be accessible to the existing transportation network and utilities. This criterion includes access to roads, proximity to electric power, water, telephones, and perhaps

sewage disposal. The proximity and access to utilities will minimize the costs associated in providing these services and in supplying power to the utility grid.

- Soil Conditions - Desirable soil conditions at and in the general area of the pond are: low permeability to seepage of brine from the pond, high resistance to erosion from both surface winds and wave action, and sufficient stability for stable dike construction to be maintained at a reasonably steep slope.
- Groundwater Conditions - Groundwater flow into a solar pond can significantly reduce energy storage efficiency by reducing temperature and salinity at the bottom and edges, in addition to carrying brine into underlying aquifers. The contamination of aquifers is not considered a problem near the Great Salt Lake because the flow gradient carries water into the lake. At the Great Salt Lake percolation from the pond would, however, cause a loss of the energy contained in the brines. The attributes of this criterion include groundwater level, variations in groundwater level and groundwater movement.
- Wind Conditions - The site should be sheltered from winds of high velocity or long duration. Both wind velocity and duration increase wave energy which can enlarge the upper convective zone. In addition, it is advantageous for a site to be sheltered from winds likely to carry fine sediments or other particulates. It is expected that winds blowing off the lake would carry less suspended materials than winds blowing off cultivated lands.
- Exposure to Lake - While current lake levels are about 4199 ft above sea level, a horizontal level as high as 4205 ft above sea level could well be reached during the next five years. Oscillatory waves and seiches during periods of high winds could cause lake levels at specific locations to be even higher for short periods. These contingencies were considered in the original pond location and design investigations.

- Land Cost - Land below the meander line (a line established by surveys varying between an elevation of 4202 feet and 4212 feet) is owned by the State of Utah. Some of this land is leased to private interests. The land immediately above the meander line is held by a variety of owners. Generally the lands near the lake have low agricultural productivity and are not suited for other uses, consequently, those lands usually can be obtained at a reasonable cost. Lands occupied by the mineral industry or preserved for public use such as recreation or water fowl refuge areas would not be available.
- Expansion Potential - It is expected that the proposed engineering test facility will lead to larger and more efficient salt gradient solar pond electrical energy production in the future. It thus would be advantageous to select a site where substantial expansion could occur over nearby land area, and possibly into adjacent areas of the lake. Other factors being equal, a location in a large area with favorable conditions is more desirable than an isolated small site.
- Environmental Impact - Adverse environmental impacts include: discharge of chemicals used to inhibit biological activities in the pond, contamination of ground water, biological or chemical effects on bird refuge areas and esthetic effects on established or proposed recreational areas. Sites which minimize these impacts will be more attractive than other sites with greater environmental impacts.

APPENDIX C

EFFECTS OF WORKING FLUID SELECTION ON TURBINE DESIGN

APPENDIX C

EFFECTS OF WORKING FLUID SELECTION ON TURBINE DESIGN*

Solar salt ponds, as described in Reference 1, can be used to generate electrical power by utilizing the temperature difference which exists between the bottom of the pond and an available cooling medium. The power cycle typically used for this application is the Rankine cycle.

It is the purpose of the study reported here to examine the effect that the choice of working fluid has on the design and construction of the expander/generator subsystem for a representative 5 MW_e solar salt pond power plant. The working fluids considered are: R-12, R-113, R-114, R-500, propane, normal-butane, iso-pentane and ammonia.

TECHNICAL DISCUSSION

General

The objective of the present study is to examine the design details and, therefore, size and complexity of expansion turbines for a 5 MW (gross) solar salt pond power plant. As the basis for comparison, the expander inlet temperature has been set at 176 F in all cases. The expander outlet pressure has been set at the value corresponding to 80 F saturated conditions. Expander inlet conditions correspond to saturated vapor unless excessive liquid formation at the expander outlet requires some superheat.

A summary of the properties of the working fluids for this process is presented in Table C.1. It can be noted from this data that the isentropic enthalpy drop and expander outlet specific volume vary over a wide range. Therefore, the expander designs are likely to be considerably different for each fluid.

* In 1982, PNL hired Duane Bergmann, P.E., a turbine consultant, to investigate the effects of working fluid selection on turbine/generator design for a 5 MWe SSP power plant. The following pages are excerpts from his final report (Bergmann, 1982).

TABLE C.1.

Fluid	R-12	R-113	R-114	R-500	C3	nC4	iC5	NH3
Mole Weight	120.9	187.4	170.9	99.3	44.1	58.1	72.2	17.03
Ratio of Spec Heats	1.14	1.08	1.084	1.14	1.14	1.097	1.078	1.29
Exp Inlet Press,psia	334.3	38.9	134.2	397	504	147.5	65	400
Exp Outlet Press, psia	98.9	6.9	32.7	116.7	143.8	37.1	14.0	153
Isentropic Enth Drop Btu/lb	8.65	10.51	9.00	10.16	20.4	25.5	26	46
Exp Outlet Spec Vol., ft ³ /lb	0.405	4.39	0.962	0.417	0.739	2.48	5.54	1.9
Liquid Dens lb/ft ³	81.5	97.5	90.9	71.9	30.7	35.6	39.0	37.5
Source of Prop Data	*	*	*	*	*	*	**	***

* Reference 1

** Data Generated by Simulation sciences, Inc.

*** Reference 2.

Once the process conditions and required power output have been set for an expander, it is possible to determine the type and size of design which produces optimum efficiency. The preliminary design of the expander for each working fluid was accomplished using the optimizing technique outlined in Reference 3 and data from Reference 4. A key element of this approach is that only four dimensionless parameters are needed to describe the characteristics of gas expanders; specifically, the Mach number, the Reynolds number and two characteristic velocity ratios. By combining this data with mechanical considerations, such as minimizing the number of stages of expansion and eliminating gear boxes, the objective has been to create a simple, cost effective and efficient expander/generator system.

Thermodynamic/Aerodynamic Design

Expansion turbines, whether axial or radial flow in design, operate on the principle of converting potential energy to kinetic energy in a nozzle and then producing shaft power by momentum transfer from the gas to a rotating wheel.

It can be shown that the required wheel tip speed is directly related to the isentropic enthalpy drop across the stage. It is also true that for geometrically similar wheels, the material stress in the wheel increases with the square of the tip speed. Consideration of these two facts tends to set the minimum number of stages of expansion for a given process. Employing modern design methods and materials of construction allows expansion of 60 Btu/lb and more, per stage, even for very conservative designs. Since solar salt pond Rankine cycles operate with a relatively low enthalpy drop, all of the expander designs studied are optimized with a single stage of expansion.

All expanders are subject to Mach number limitations associated with "choking" at the outlet of the wheel. This consideration can be particularly important in cases of high gas velocity (high isentropic enthalpy drop) and low sonic velocity (high molecular weight). Depending on the details of design, the outlet Mach number becomes a limiting criterion for values greater than approximately 0.70. Outlet Mach number is not a particularly important parameter in the present study as all of the selected single stage designs have outlet Mach numbers between 0.20 and 0.40.

As outlined above, the approach of this study has been to do the preliminary design of both an optimized radial and axial flow expander for each working fluid. The results indicate that single stage designs of both radial and axial configuration are capable of producing approximately the same efficiency. The shaft power produced by each expander is 6,700 horsepower. A summary of design details for each fluid is shown in Table C.2.

Mechanical Design

The mechanical design of the expander must consider a wide range of parameters, such as: casing design pressure; corrosive and/or toxic fluid properties; optimum shaft speed; and physical size and complexity of manufactured parts.

TABLE C.2.

Fluid	R-12	R-113	R-114	R-500	C3	nC4	iC5	NH5
Exp wheel dia, in.	29.3	65.	60.	25.8	20.5	33.0	50.9	18.0
Shaft speed, rpm x 10 ³	3.6	1.8	1.8	4.43	7.9	5.5	3.79	13.5
Exp out vol. flow, cfm x 10 ³	16.2	158.4	38.5	13.7	12.2	35.4	77.0	14.3
Adiabatic eff, %	82	82	82	82	82	82	82	82
Mass flow rate, lb/sec	668	550	642	569	283	227	569	126
Outlet liquid, %	1.5	0	0	3.6	2.7	0	0	5.7
Specific speed,-	80	108	60	80	80	80	80	80
Outlet Mach No.-	0.28	0.31	0.32	0.27	0.26	0.33	0.36	0.23
Wheel tip speed, ft/sec	461	508	470	500	708	792	800	1063
Outlet flange dia, in.	28	90	44	26	24	42	62	26
Feed pump power, HP	674	63	250	774	1159	246	101	290
No of pump stages	1	1	1	2	4	1	1	2

With respect to casing design pressure, it is the author's experience that machinery casings of acceptable structural rigidity will generally be suitable for expander inlet pressures of 200 to 400 psig and, therefore, no additional cost or complexity allowance need be included up to this level.

The expander outlet pressure affects the design of the expander shaft sealing arrangement, as this is generally the working fluid pressure on the shaft seal. It is desirable to maintain this pressure between atmospheric and approximately 100 psig to obtain maximum seal life at minimum cost. A vacuum at the expander outlet can result in leaks of air into the system at shaft seals and flanges. The air will act as a non-condensable and degrade the performance of the cycle and/or result in explosive mixtures of gases in the system.

A review of commercially available, synchronous generators, in the size range of interest, indicates that the least expensive and efficient generators operate at 1,800 rpm. Therefore, if optimum expander efficiency could be obtained at, or near, 1,800 rpm, the expander was designed for this speed, eliminating the need for a gear box. If another shaft speed was required, the speed was set by optimizing the expander design. Of the eight working fluids studied, two have direct drive expanders and six require a gear box. All of the required gear boxes are of conventional design and are readily available from several manufacturers.

All of the commonly used construction materials, such as carbon steel, stainless steel, aluminum alloys and brass, are acceptable for the construction of the studied expanders, except that brass or other copper-containing alloys should not be used with ammonia.

Cycle Boost Pump Considerations

As a logical adjunct to consideration of the expander, it is also of interest to briefly consider how the choice of working fluid affects the design and operation of the cycle boost pump. Of particular interest here is the pump power required for a given expander power and the number of pump stages required. From the point of view of the boost pump, the best choice is R-113 where only one stage is required and the pump power is only 63 horsepower (0.94% of the expander shaft power). The other extreme is represented by propane, where at least a four-stage pump of 1,159 horsepower (17.3% of the expander shaft power) is required. The estimated pump power and number of pump stages are shown in Table C.2 for each of the studied fluids.

CONCLUSIONS

Selection of an optimum working fluid is very difficult to quantify and is, therefore, largely a subjective judgement involving cost, reliability, safety and maintainability.

Table C.3 presents a summary of the advantages and disadvantages of each working fluid as related to the expander/generator system.

TABLE C.3.

R-12	<ol style="list-style-type: none"> 1. Moderate machine size 2. Moderate exp pressure 3. Simple boost pump 	<ol style="list-style-type: none"> 1. Requires gear box 2. Expensive fluid
R-113	<ol style="list-style-type: none"> 1. Minimum boost pump power 2. Simple boost pump 3. Does not require gear box 	<ol style="list-style-type: none"> 1. Large expander size 2. Vacuum at exp outlet 3. Expensive fluid
R-114	<ol style="list-style-type: none"> 1. Moderate exp pressure 2. Does not require gear box 3. Low boost pump power 4. Simple boost pump 	<ol style="list-style-type: none"> 1. Large exp size 2. Expensive fluid
R-500	<ol style="list-style-type: none"> 1. Moderate exp size 2. Moderate exp pressure 	<ol style="list-style-type: none"> 1. High boost pump power 2. Two-stage boost pump 3. Expensive fluid 4. Requires gear box
C3	<ol style="list-style-type: none"> 1. Small exp size 2. Inexpensive fluid 	<ol style="list-style-type: none"> 1. Flammable fluid 2. High exp pressure 3. High boost pump power 4. Four-stage boost pump 5. Gear box required.
nC4	<ol style="list-style-type: none"> 1. Moderate exp size 2. Low boost pump power 3. Simple boost pump 4. Inexpensive fluid 5. Moderate exp pressure 	<ol style="list-style-type: none"> 1. Flammable fluid 2. Gear box required
ic5	<ol style="list-style-type: none"> 1. Low boost pump power 2. Simple boost pump 3. Inexpensive fluid 	<ol style="list-style-type: none"> 1. Flammable fluid 2. Gear box required 3. Large exp size 4. Vacuum at exp outlet
NH3	<ol style="list-style-type: none"> 1. Small exp size 2. Low boost pump power 3. Inexpensive fluid 	<ol style="list-style-type: none"> 1. Toxic and flammable fluid 2. Gear box required 3. High exp pressure 4. Two-stage boost pump

After consideration of the above data, it is the opinion of the author (Bergmann) that the best combination of expander/generator system features is provided by either R-12, R-114 or normal-butane. The principal advantages of R-12 are that the expander is of moderate size and pressure, and the fluid is not flammable.

The key features of R-114 are that the generator is direct-driven and the fluid

is not flammable. The principal advantage of normal-butane is that the expander is of moderate size and pressure and the working fluid is inexpensive and readily available.

In the end, the final selection between R-12, R-114 and normal-butane is a very subtle judgement. It is the author's opinion that, in the absence of overriding considerations, the most cost effective and reliable choice of fluid is normal-butane. This opinion is based partially on the many years of successful operation of butane production and distribution systems combined with some concern about the ready availability of the large quantities of "Freon" for recharging the R-12 and R-114 systems, if required.

REFERENCES

- ASHRAE. 1969. "Thermodynamic Properties of Refrigerants."
- Scheel, L. F. 1972. "Gas Machinery." Gulf Publishing Co.
- Balje, O. E. 1960. "A Study on Design Criteria and Matching of Turbo-machines." 60-WA-230, ASME Publication.
- Balje, O. E. 1981. "Turbomachines." John Wiley and Sons, 1981.

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

	<u>U.S. Department of Energy</u> Mr. G. W. Braun, Director Division of Solar Thermal Technology U.S. Department of Energy 1000 Independence Avenue Washington, DC 20585	Mr. Frank Wilkins, Program Manager Division of Solar Thermal Technology U.S. Department of Energy 1000 Independence Avenue Mail Stop CE-314 Washington, DC 20585
20	Mr. Clifton McFarland Systems Testing and Evaluation Branch Division of Solar Thermal Technology U.S. Department of Energy 1000 Independence Avenue Mail Stop CE-134 Washington, DC 20585	Mr. Robert W. Hughey Deputy Director San Francisco Operation Office U.S. Department of Energy 1333 Broadway Oakland, CA 94612
	Mr. James E. Rannels, Program Manager Systems Testing and Evaluation Branch Division of Solar Thermal Technology U.S. Department of Energy 1000 Independence Avenue Mail Stop CE-314 Washington, DC 20585	Mr. Mike Lopez San Francisco Operation Office Department of Energy 1333 Broadway Oakland, CA 94612
	Mr. Sam Schweitzer Division of Solar Thermal Technology U.S. Department of Energy 1000 Independence Avenue Washington, DC 20585	Mr. Steve Sargant DOE/SERI Site Office Solar Energy Research Institute 1617 Cole Boulevard Golden, CO 80401
		<u>U.S. Army of Corps of Engineers</u>
		Mr. Jack Bickley Construction Operations Division U.S. Army-Corps of Eng. Command DAEN-CWO-M Washington, DC 20314
27	DOE Technical Information Center	Mr. Paul Boldan Programs Division U.S. Army-Corps of Eng. Command DAEN-CWB-C Washington, DC 20314

No. of
Copies

Mr. Norman T. Edwards
Planning Division
U.S. Army-Corps of Eng. Command
DAEN-CWP-G
Washington, DC 20314

Mr. Bob Kinsel
Engineering Division
U.S. Army-Corps of Eng. Command
DAEN-CWE-E
Washington, DC 20314

Mr. Alex Shwaiko, Chief
Office of Policy
U.S. Army-Corps of Eng. Command
DAEN-CWR
Washington, DC 20314

Mr. Bill Banks, Program Manager
Red River Chloride Control
Project
Corps of Engineers
P.O. Box 61
Tulsa, OK 74121

Mr. Harvey Bolinger, Program
Manager
Planning Section
Corps of Engineers
P.O. Box 61
Tulsa, OK 64121

Colonel Jim Harmon, District
Engineer
Corps of Engineers
P.O. Box 61
Tulsa, OK 74121

J. L. Matthews
Design Branch
Corps of Engineers
P.O. Box 61
Tulsa OK 74121

Fred Munsell
Economics Branch
Corps of Engineers
P.O. Box 61
Tulsa OK 74121

No of
Copies

Mr. Ken Perry
Engineering Division
Corps of Engineers
1114 Commerce Street
Dallas, Texas 75242

Mr. Charles Ringenberg, Chief
Program Development Office
Corps of Eng. - Southwestern
Division
1114 Commerce Street
Dallas, Texas 75242

Major General Hugh Robinson
Division Engineer
U.S. Army Corps of Engineers
1114 Commerce Street
Dallas, TX 75242

John Sparlin Chief
Economics Branch
Corps of Engineers
P.O. Box 61
Tulsa OK 74121

Steve Wilhelm
U.S. Army Corps of Engineers
Waterways Experimental Station
P.O. Box 631
Vicksburg, MS 39180

Argonne National Laboratory
John Hull
Building CT-308
Argonne TL 60439

Barber Nichols Eng. Company
Kenneth E. Nichols, President
6325 West 55th Avenue
Arvada, CO 80002

Colorado River Basin Salinity
Control Forum
Jack A. Barnett, Exec. Director
220 South 2nd East, Suite 320
Salt Lake City, Utah 84111

No. of
Copies

Department of Interior
Bureau of Reclamation

Mr. Michael B. Bessler
Colorado River Water Quality
Office
Bureau of Reclamation
Engineering & Research Center
P.O. Box 25007
Denver Federal Center
Denver, CO 80225

Mr. Mike Clinton, Chief
Colorado River Water Quality
Office
Bureau of Reclamation
U.S. Department of the Interior
P.O. Box 25007
Denver Federal Center
Denver, CO 80225

Mr. Stanley J. Hightower
Colorado River Water Quality
Office
Bureau of Reclamation
U.S. Department of the Interior
P.O. Box 25007
Denver Federal Center
Denver, CO 80225

Desert Research Institute
C. G. Stojanoff
1500 Buchanan Blvd.
Boulder City, Nevada 89005

Flow Industries, Inc.
Dr. Michael Edesess
444 Sherman Street
Denver, CO 80203

Jet Propulsion Laboratory
Dr. M. Apler
4800 Oak Grove Drive
Mail Stop 502-307
Pasadena, California 91109

No. of
Copies

Jet Propulsion Laboratory
Mr. Robert L. French
4800 Oak Grove Drive
Pasadena, CA 90041

Los Alamos Scientific Laboratory
Mr. Ken A. Meyer
Solar Energy Group
Mail Stop K-571
P.O. Box 1663
Los Alamos, NM 87545

Massachusetts Institute of
Technology
Dr. Donald Harleman
Ralph M. Parsons Laboratory
Department of Civil Engineering
Cambridge, MA 02139

Monsanto Research Corporation
Layton Wittenberg
Mound Laboratory
P.O. Box 32
Miamasburg, OH 43542

Department of Physics
Dr. Carl Nielsen
Ohio State University
Columbus, OH 43210

Ralph M. Parsons
Engineering Company
John Brehany
100 W. Walnut Street
Pasadena, CA 91124

Purdue University
Dr. Frank Incropera
Department of Mechanical
Engineering
West Lafayette, IN 47907

Sandia National Laboratories
Ms Joan Woodard
Technology Program Integrator
Solar Thermal Project
P.O. Box 969
Livermore, CA 94550

No. of
Copies

Solar Energy Research Institute

Dr. David H. Johnson,
Group Manager
Solar Thermal Research Branch
1617 Cole Boulevard
Golden, Colorado 80401

Solar Energy Research Institute
Dr. Frank Kreith, Chief
Solar Thermal Research Branch
1617 Cole Boulevard
Golden, CO 80401

Solar Energy Research Institute
Mr. Ken May
1617 Cole Boulevard
Golden, CO 80401

Solar Energy Research Institute
Ms. Cecile Leboerg
1617 Cole Boulevard
Golden, CO 80401

Dr. Federica Zangrando, Senior
Engineer
Solar Thermal Research Branch
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Southwest Power Administration
Mr. Warren Jamison
Deputy Administrator
P.O. Box 1619
Tulsa, OK 74101

Southwest Power Administration
Mr. Ed Lindsey
P.O. Box 1619
Tulsa, OK 74101

No. of
Copies

Southern California Edison
Company

Mr. Igal Meitlis, Project
Engineer
Salton Sea Project
P.O. Box 800
Rosemead, CA 91770

Stanford University
Professor S. Kline
Department of Mech. Eng.
Palo Alto, CA 94303

Tennessee Valley Authority
Mr. Graham R. Segel, Program
Manager Electrical Utilization
Group
1850 Commerce Union Bank
Building
Chattanooga, TN 37401

Trends Publishing Inc.
Evelyn Didier
233 Nort Press Building
Washington, DC 20045

University of New Mexico
Howard C. Bryant
Department of Physics of
Astronomy
Albuquerque, NM 87131

University of Utah
Dr. Robert F. Boehm
Department of Mechanical
Engineering
Salt Lake City, UT 84112

Utah Power and Light Company
Mr. Lynn Rasband
Supervising Research Engineer
P.O. Box 899
Salt Lake City, UT 84110

No. of
Copies

Utah State University
Dr. J. Clair Batty, Professor
Department of Mechanical
Engineering
UMC-41
Logan, UT 84322

Utah State University
Dr. L. Douglas James
Utah Water Research Laboratory
Logan, Utah 84322

Utah State University
Dr. J. Paul Riley
Water Resource and Hydrology
College of Engineering
UMC-41
Logan, UT 84322

ONSITE

DOE Richland Operations Office

H. E. Ransom
D. R. Segna

No. of
Copies

41 Pacific Northwest Laboratory

J. S. Barnhart
C. H. Blomster
D. R. Brown
L. M. Brown
M. K. Drost
K. Drumheller
S. G. Hauser
A. J. Haverfield
D. S. Jackson
W. W. Laity
R. P. Marshall
D. E. Olesen
D. L. Styris
T. A. Williams
File-B. M. Johnson (20)
Technical Information (5)
Publishing Coordination (2)