2

MASTER

150 kWe SOLAR-POWERED DEEP-WELL IRRIGATION FACILITY
PHASE I PRELIMINARY DESIGN STUDY

FINAL REPORT

prepared for
Acurex Corporation

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by

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Bechtel Corporation
Research and Engineering

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PREFACE

Bechtel Corporation is a subcontractor to Acurex Corporation in a Phase I study, the overall purpose of which is to develop a preliminary design of a 150 kWe solar-powered deep-well irrigation facility for ERDA over a seven-month period starting in February, 1977 (Subcontract No. HG68301A). Acurex is one of three contractors working on the Phase I study. ERDA intends to select one of the contractors for a follow-on Phase II program to finalize the design and to construct, startup, and demonstrate a prototype facility on an operating farm in Arizona.

In this Phase I study, Bechtel has the responsibility to design the power generation subsystem (consisting of a prime mover and its auxiliary systems), the water storage and delivery subsystem, and foundations for the irrigation facility. Bechtel is also responsible for the development of an overall plot plan for the facility, and cost and schedule estimates for the Phase II program as well as for the eventual mass production and deployment of these facilities. Sundstrand Corporation was engaged as a subcontractor to Bechtel to provide support in developing the design of the power generation subsystem. In addition, Bechtel has supported Acurex in system definition and optimization trade-off studies and analyses, in the design of the thermal energy storage subsystem, and in the development of a Phase II plan. Bechtel's tasks and schedule for Phase I are shown in Figure P-1.

JOB NO. 12177
2-11-77

TASK	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	BECHTEL TASK RESPONS.
1. PROGRAM PLANNING	—							SUPPORT
2. PROJECT MANAGEMENT AND DIRECTION	-----	-----	-----	-----	-----	-----	-----	SUPPORT
3. SYSTEM DEFINITION								SUPPORT
4. PRELIMINARY DESIGN PRIME MOVER/GENERATOR AND OTHER BOP		—	—	—	—	—	—	PRIME
5. FOUNDATION PRELIMINARY DESIGN				—	—	—	—	PRIME
6. CONSULTATION ON THERMAL STORAGE DESIGN	-----	-----	-----	-----	-----	-----	-----	SUPPORT
7. PRELIMINARY PLOT PLAN DEVELOPMENT				—	—	—	—	PRIME
8. COST AND SCHEDULE ESTIMATES				—	—	—	—	PRIME
9. PRODUCTION COST ESTIMATES					—	—	—	PRIME
10. DEVELOPMENT OF PHASE II PLAN					—	—	—	SUPPORT
11. PROGRAM REVIEWS				▲			▲	SUPPORT
12. 31-MONTHLY PROGRESS AND COST REPORTS		▲	▲			▲	▲	SUPPORT
13. FINAL REPORT						—	—	SUPPORT

Figure P-1 BECHTEL PROJECT SCHEDULE
SOLAR-POWERED DEEPWELL IRRIGATION FACILITY
PHASE 1

The objective of this final report is to describe work performed by Bechtel and its subcontractor, Sundstrand Energy Systems, throughout the course of this Phase I preliminary design study. The report is written in a format that will permit Acurex to insert Bechtel's sections directly into Acurex's final report to ERDA. The outline for Acurex's final report is given in Table P-1, with preparation responsibilities indicated in parentheses. It will be noted that all of Bechtel's inputs are to Volume I of the Acurex final report.

Bechtel Phase II planning will be provided separately in Bechtel's proposal for Phase II follow-on work.

TABLE P-1
OUTLINE FOR ACUREX'S FINAL REPORT

VOLUME I PHASE I PRELIMINARY DESIGN STUDY FINAL REPORT
150 kWe SOLAR-POWERED DEEP-WELL IRRIGATION FACILITY

1. INTRODUCTION AND SUMMARY (A)*
2. DESIGN CRITERIA (A)
 - 2.1 ERDA-Specified Generic Design Criteria (B)
 - 2.2 Site-Specific Design Criteria (B)
 - 2.3 Design Approach (A)
3. SYSTEM ANALYSES (A)
 - 3.1 Collector Subsystem (A)
 - 3.2 Thermal Storage Subsystem (A)
 - 3.3 Power Generation Subsystem (B)
 - 3.4 Water Storage and Delivery Subsystem (B)
 - 3.5 Power Distribution Subsystem (B)
 - 3.6 Overall System Performance and Economic Analysis (A)
4. PRELIMINARY DESIGN (A)
 - 4.1 Collector Subsystem (A)
 - 4.2 Thermal Storage Subsystem (A)
 - 4.3 Power Generation Subsystem (B)
 - 4.4 Cooling Water Subsystems (B)
 - 4.5 Power Distribution Subsystem (B)
 - 4.6 Control Subsystems (A)
 - 4.7 Data Acquisition Subsystem (A)
 - 4.8 Foundations (B)
 - 4.9 Site Layout and Improvements (B)
5. COST ANALYSIS OF PHASE II PROTOTYPE AND PRODUCTION UNITS (B)
 - 5.1 Summary of Cost Estimates (B)
 - 5.2 Bases for Estimates (B)
 - 5.3 Differences Between Prototype and Production Designs and Costs (B)
 - 5.4 Phase II Prototype Capital Costs (B)
 - 5.5 Production Unit Capital Costs (B)

VOLUME II PHASE II PROGRAM PLAN AND COST ESTIMATE
150 kWe SOLAR-POWERED DEEP-WELL IRRIGATION FACILITY

1. OBJECTIVES (A)
2. DESCRIPTION OF PHASE II PROGRAM (A)
3. PHASE II PROGRAM SCHEDULE (A)
4. PHASE II COST ESTIMATE (A)

* Report preparation responsibilities are noted in parentheses:
A-Acurex, B-Bechtel.

SECTION 1
INTRODUCTION AND SUMMARY

(to be prepared by Acurex)

SECTION 2

DESIGN CRITERIA

Design criteria for the solar-powered irrigation facility are necessary as the basis for development of the preliminary design. Ideally, these criteria should provide site data and facility operation requirements specific to a given site. In particular, these site data and requirements are important to (1) the design of an efficient power generation subsystem, (2) the design of cost-effective foundations suitable for site-specific soil and geology conditions, (3) the development of a facility layout suitable to site topography, (4) the design of a water storage and delivery subsystem required for site-specific, time-dependent irrigation demand, and (5) the sizing of collector and thermal storage subsystems for site-dependent insolation.

However, for this preliminary design study, a general (generic) design for a solar-powered irrigation facility was required so that the design can serve as the basis for eventual mass production and deployment at a number of sites in the southwestern U.S. To this end, ERDA specified a set of general (generic) design criteria using hypothetical general site conditions. These general design criteria and site conditions, as specified by ERDA, are summarized in section 2.1.

Additionally, in order to make it possible to adapt the generic design to a site designated by ERDA for Phase II implementation, site-specific

data are also necessary. Such data are provided in section 2.2 for the specific site selected by ERDA.

2.1 ERDA-SPECIFIED GENERIC DESIGN CRITERIA

2.1.1 Operation Requirements

The solar-powered irrigation facility will supply 150 kWe, at 3 phase, 440 volt, and 60 Hz to the well pump motor(s). The facility must be capable of operating continuously (24 hours per day) during the peak irrigation season. In operating continuously, the facility must utilize a cost-effective combination of solar energy, electric utility off-peak power, water storage, and/or other types of storage, subject to the constraint that whenever insolation is greater than 600 watts per square meter, the 150 kWe output must be supplied by solar energy alone.

ERDA specified that the generic site has electric utility power available. Therefore, a stand-alone facility, separate from the utility grid, was not considered in the design study.

The generic irrigation demand varies throughout the year, with 100% of well capacity required in July, dropping off to a low of 40% in December, January, and February, (see Figure 2.1-1).

The generic facility design must demonstrate reliable, trouble-free operation, over a 30-year life. With routine preventive maintenance, the reliability goal will be failure-free operation over the system life. If a failure should occur, the facility should be capable of being restored to operation quickly by farm personnel or by a locally based service organization.

Figure 2.1-1 ERDA - Specified Generic Irrigation Water Demand

The generic irrigation facility design must be based on existing processes and current technology to the greatest extent possible.

2.1.2 General Site Conditions

Insolation. ERDA specified that insolation data for Albuquerque, New Mexico, reduced by 10 per cent for conservatism, will be used.

Meteorology. The facility must be able to operate during, or survive, the following conditions:

<u>Parameter</u>	<u>Operation</u>	<u>Survival</u>
Minimum temperature	30°F	-20°F
Maximum temperature	140°F	140°F
Maximum wind speed (gust)	40 mph	100 mph

The solar-powered facility must be capable of withstanding environments that include rain, sleet, hail, and snow.

ERDA specified that precipitation and evaporation data for Wilcox, Arizona, and wind data for Phoenix, Arizona, will be used for performance evaluations. The annual precipitation is 11.6 inches and the ratio of precipitation to evaporation is 1:7.3.

The collectors must be designed to withstand 1/2-inch diameter hail stones and not degrade more than 2% in performance for a one-inch hail storm.

Hydrology. ERDA specified that pumping depths of 380 ± 100 feet should be assumed, and that groundwater temperature ranges from 75 to 100°F.

2.1.3 Economics

Utility Rates. The rates of several different electric utilities were given in Appendix A of the ERDA-Acurex contract; different utilities' rates vary significantly. No further guidance was given by ERDA concerning which rates to use in the preliminary design study; therefore, it was assumed that cost-effectiveness of the generic irrigation facility design is to be demonstrated based on the average current utility rate of 30 mills/kWh.

Economic Evaluation Parameters. The following economic evaluation parameters were specified by ERDA:

Inflation	6% per year
Energy Cost Escalation	10% per year (above inflation)
Interest Rate	8% per year
Investment Credit	10%

2.2 SITE-SPECIFIC DESIGN CRITERIA

The site selected by ERDA for the Phase II prototype demonstration of the solar-powered irrigation facility is located on the Dalton H. Cole & Son farm. This farm is located between Phoenix and Tucson, Arizona, about 40 miles southeast of Phoenix, 5 miles south-southwest of Coolidge, Arizona, in Section 7 of the Coolidge, Arizona, USGS topographical map quadrangle. The site is approximately square in plan with the southern boundary at an approximate coordinate of N 32°-55' and the eastern boundary at an approximate coordinate of 111°-33'-30". The site is approximately 1/2 mile due east of the Eleven Mile Corner Road.

2.2.1 Operation Requirements

ERDA specified that the Phase II prototype irrigation facility will be constructed by January 1, 1979.

2.2.1.1 Season, Crops, and Methods

The Cole farm occupies approximately 1100 acres, of which about 950 acres are arable and irrigated. Cotton and barley are the primary crops grown during the irrigation season, which extends from January through mid-September (see Figure 2.2-1). For the farm soil and prevailing environmental conditions, cotton and barley typically require 4 and 2 acre-ft/acre of irrigation water per season, respectively. Gravity (flood) irrigation is used exclusively, and irrigation water is pumped on a continuous 24-hour per day basis from eight wells during the irrigation season. Each well pump has a free uncontrolled horizontal discharge through a short length of pipe into an adjacent concrete-lined ditch or basin.

Figure 2.2-1 Site Specific Irrigation Water Demand

The water is distributed from the wells to the particular fields being irrigated via a system of concrete-lined ditches, diversion gates, and temporary canvas dams. Plastic pipe siphons of 2 inch diameter are used to lift water from the ditch to the head end of the field. A typical setting might use 30-40 siphons lifting about 30 gpm each, and may require the full output of 2-3 well pumps. Algae growth is a chronic problem in the ditches.

A typical field is about one-quarter mile long from head to foot and one-quarter mile wide, and is graded with multiple slopes toward the foot so as to minimize evaporation loss and foot run-off. The general slope of the land is down from south to north, with about one-third of the fields graded with slopes to the west as indicated in Figure 2.2-2.

Groundwater is not pumped for irrigation on the Cole farm from mid-September through December. Due to the heavy concentration of pumping from the underground aquifer system in the area, it is a standard practice of many farmers in the area to cease pumping during these months and permit the water table to be naturally restored. However, if it were feasible and desirable to continue the pumping, small crops of alfalfa or sugar beets could be grown by irrigation during the normal off-season from mid-September through December.

2.2.1.2 Electric Power Supply

Electric power for irrigation pumping is supplied to the farm and to most other farms in the area by the local electrical cooperative, Electrical District #2 (ED #2). ED #2 purchases power from various southwestern utilities and distributes the power at 12.5 kV over its own lines.

Legend:

- FARM ROAD
- CONCRETE-LINED IRRIGATION DITCH
- ➔ DIRECTION OF IRRIGATION FLOW

Scale: 0 1000 2000
Feet

Figure 2.2-2 Site Land Use Map

The current irrigation electricity cost is 10.5 mills/kWh, based on purchasing hydroelectric power at 6 mills/kWh and thermally generated power at 25-30 mills/kWh. Purchased power contracts are due to be renegotiated in the near future, and it is projected by ED #2 that the irrigation electricity cost may increase to about 40 mills/kWh by 1980. Summer peak load on the ED #2 system is about 50 MWe.

For electric irrigation pumps, ED #2 runs 12.5 kV, 3 phase, 60 Hz power to the location of each pump. The voltage is stepped down to 440 volt by pole-mounted transformers, which are normally owned by the user and located adjacent to each pump. A manual high voltage disconnect switch and a manually operated reduced voltage motor starter are also associated with each well.

The electric utility grid/irrigation facility interface for Phase II must conform to the ERDA specification that solar-electric power will be supplied to deep-well pump motors on power distribution lines separate from the local utility lines, and that the option to tie into the utility grid, when desired, will also be provided.

2.2.2 Phase II Site Conditions

2.2.2.1 Topography and Land Use Plan

The site is fairly level, at an approximate elevation of 1434 ft above mean sea level. The natural ground slope is down from south to north.

Figure 2.2-2 is the land use plan for a portion of the Cole farm showing locations of wells, irrigation ditches, cropland, and directions

of irrigation water flow. There are a total of eight wells on the Cole farm, four of which are shown in Figure 2.2-2. The solar-powered facility will supply electricity to Well C, located on the southeast corner of the proposed site, and to Wells D and E. The site lies within a subsidence region (believed to be caused by pumping groundwater) and further subsidence should be expected as the result of continued pumping.

2.2.2.2 Geology and Soils

Since site-specific soil data were not available for the preliminary design study, reasonable assumptions had to be made regarding soil properties. Although soil properties generally vary within a large selected area according to geologic formation and location, the most likely soil types representative of the southwestern U.S. include medium-to-coarse dry sands, clays, or silty clays with sand. For the purpose of the Phase I preliminary design, it was assumed that such soils extend to a depth of at least 30 feet below the surface. It was also assumed that soil properties at a depth of one foot are those given in Table No. 29-B of the Uniform Building Code (Reference 2.2-1) for Class 5 material (clay, sandy clay, silty clay, clayey silt), as follows:

Allowable Foundation Pressures	1000 lb/sq ft
Allowable Lateral Bearing Pressure	100 lb/sq ft/ft depth
Lateral Sliding Resistance	130 lb/sq ft

Values, recommended by Bowles (Reference 2.2-2), of 4000 lb/sq in and 0.3 for the modulus of elasticity and the Poisson's ratio, respectively, for sandy clay were used in the design. It was assumed that the value of the modulus of elasticity of the soil increases linearly with depth.

Lacking specific soil data, the soil bearing capacity was determined using Tables 29 B, C and D of the Uniform Building Code, 1976 Edition, as a guideline. It is anticipated that these assumptions will result in conservative designs. When site soil data are obtained during Phase II, foundation designs will be revised, as required.

2.2.2.3 Seismicity

The site is located in Seismic Zone 2 of the Uniform Building Code, 1976 Edition (Reference 2.2-1). Areas within Zone 2 can expect moderate damage due to earthquakes of magnitude VII on the Modified Mercalli Scale. Seismic design criteria as specified for UBC Seismic Zone 2 were used. This simplified equivalent static load approach of the UBC is considered to be adequate for the size of the plant and the seismic zone. A more sophisticated dynamic analysis was not performed because the facility does not have tall structures and is not located in a highly seismic zone.

2.2.2.4 Meteorology

The site has a desert climate. Precipitation is light in all months; therefore, crops require irrigation. The wettest months are July and August, when brief but moderately heavy thunderstorms are experienced.

Mid-winter temperatures are mild, normally ranging from 30-40°F at night to 65-70°F in the day. At night the temperature frequently dips below freezing for a few hours, but rarely below 20°F. Summer days are hot; the mean daily maximum temperature in July is 107°F.

Dust storms are common. Winds are generally greater than 20 mph and from the west during these occurrences. Tumble weeds are often carried by the wind onto the cropland.

Mean annual evaporation ranges from 80 to 100 inches. Maximum evaporation occurs during the months of June and July when monthly evaporation ranges from 10 to 15 inches.

Climatological summaries for Phoenix and for Casa Grande Ruins National Monument, which is approximately five miles north of the site, were given for the design.

The Uniform Building Code (UBC) was used to define design wind pressures for structures. Figure 4 of the Uniform Building Code, 1976 Edition, indicates that the site is located in wind pressure map area 20. From UBC Table No. 23-F, the resulting wind pressures for various height zones of interest were determined to be as follows:

<u>Height Zone (in feet)</u>	<u>Design Wind Pressure (lb/sq ft)</u>
Less than 30	15
30 to 49	20

Wind tunnel test data were provided by Acurex to determine wind loads on parabolic trough collectors for use in the design of the collectors and their foundations. In addition to the UBC, it was also necessary to use ANSI A58.1, 1972 for the purpose of scaling down wind load data (see section 4.8.1).

2.2.2.5 Hydrology

ERDA provided data concerning Wells C, D and E (see Figure 2.2-1 for location), to which the solar facility will deliver electric power. These data are given in Table 2.2-1. Note that the pump discharges for the three wells are significantly different despite similar power requirements. It

is not clear why this is so. Also note that the total electric power requirement of the 3 pumps is 184 kWe which is 34 kWe greater than the ERDA-specified 150 kWe net output to the pump motors.

Groundwater quality data obtained from Wells C, D and E are shown in Table 2.2-2. At times during well pump operation, settleable materials (sand and sediment) may be pumped to the surface. Preventative measures must be taken to avoid fouling of the solar plant condenser equipment by such contaminants.

TABLE 2.2-1 IRRIGATION FACILITY WELL DATA

Paramater	Well C	Well D	Well E
Power Requirement (kWe)	63	61	60
Motor Data			
RPM	1770	1465	1485
Current (amps)	150	154	--
Horsepower	125	150	75
Well Cased Depth (ft)	600	350	450
Water Temperature (°F)	80	80	80
Estimated Lift (ft)	300	300	300
Estimated Water table depth (ft)	210	210	210
Estimated Drawdown (ft)	90	90	90
Discharge (gpm)	410	780	285

TABLE 2.2-2 SITE GROUNDWATER QUALITY

Paramter	Well C	Well D	Well E
Date of Sample	3-23-77	3-02-77	3-23-77
Electroconductivity (micro-mho/cm)	1250	2490	990
Total Dissolved Solids (ppm)	658	777	551
pH	7.6	7.6	7.8
Ion Concentrations (mg/l)			
Calcium	98	110	55
Magnesium	12	12	5
Sodium	102	112	106
Chloride	107	164	95
Sulfate	171	189	114
Bicarbonate	163	181	132
Fluoride	0	0	0
Nitrate	0.55	0.43	0.55
	3.95	5.20	3.65

2.3 DESIGN APPROACH

(to be prepared by Acurex)

SECTION 3

SYSTEM ANALYSES

The objective of the system analysis portion of the preliminary design study was the definition and optimization of each major subsystem and the overall facility from the standpoint of the ERDA-specified design objectives and the design approach described in section 2.

The irrigation facility was considered as a system, consisting of the following major subsystems:

- collector subsystem
- thermal storage subsystem
- power generation subsystem
- water storage and delivery subsystem
- power distribution subsystem

Figure 3.0-1 shows in a schematic diagram these major subsystems and their relationships to each other.

Figure 3.0-1 Schematic Diagram — 150 kWe Solar-Powered Deep-Well Irrigation Facility

3.1 COLLECTOR SUBSYSTEM

(to be prepared by Acurex)

3.2 THERMAL STORAGE SUBSYSTEM

(to be prepared by Acurex)

3.3 POWER GENERATION SUBSYSTEM

The function of the power generation subsystem is to convert thermal energy which is available from either the solar collector or thermal storage subsystems (see Sections 3.1 and 3.2), to 150 kW of electrical power which drives one or more deep-well irrigation pumps. A number of evaluations were conducted during the systems analysis phase of the preliminary design study to support baseline decisions regarding the options available for the following aspects of the power generation subsystem design:

- Power cycle type,
- Working fluid,
- Thermodynamic state points,
- Prime mover vendor.

The primary objective of the power generation subsystem analysis was to define a baseline design which could be implemented with state-of-the-art hardware, and which optimally satisfies the project requirements for high efficiency, low design risk, high reliability, low facility cost, and low maintenance. A second major objective during the systems analysis phase was the selection of a qualified vendor to perform the Phase I preliminary design of the major components of the power generation subsystem, and who would also subsequently supply these components for the Phase II prototype facility. The systems analysis effort in support of these two objectives was conducted with full recognition of the need to meet ERDA's schedule goal to have the Phase II prototype facility designed, fabricated, and constructed by January 1, 1979.

3.3.1 Selection of Power Cycle

The Rankine cycle was selected as the basis for the heat engine to be used for converting solar thermal energy to mechanical shaft power which would then be transformed to electrical power. The Rankine cycle was further specified as being an "organic" Rankine cycle, using an organic working fluid. Alternative power cycles which were considered included a steam Rankine cycle, the Stirling cycle and the Brayton cycle. Selection of the organic Rankine cycle was dictated primarily by consideration of the thermal efficiency of state-of-the-art heat engines for the alternative power cycles, given the available temperature range between heat source and heat sink.

3.3.1.1 Temperature Constraints

The temperature of the heat source for the heat engine is constrained by the efficiency of the line-focus concentrating solar collectors, which become less efficient with increasing receiver temperature. It is also constrained by the stability of the collector heat transfer fluid if an organic heat transfer fluid is used. As discussed in Section 3.1, Therminol-66 was selected during the system analysis phase of the preliminary design study as the collector heat transfer fluid, and the maximum bulk temperature of the fluid was set at 600°F for design purposes. Although a decision was made later in preliminary design to use Caloria HT-43 rather than Therminol-66, the maximum bulk temperature of the Caloria HT-43 was also set at 600°F. Therminol-66 is referenced in this section for consistency in reporting the systems analysis work as accomplished. Given a heat source temperature of 600°F, a 50°F terminal temperature difference was assumed for the heat exchanger used to transfer heat from the Therminol-66 to the heat engine

working fluid. As a result, a peak heat engine working fluid temperature of 550°F was selected for comparison of the alternative power cycles. The minimum temperature of the heat engine working fluid was assumed to be 100°F, for an assumed heat sink temperature of approximately 80°F. A heat sink temperature of 80°F is within the ERDA-specified temperature range for irrigation groundwater which might be used for cooling (see Table 2.2-1), and is also representative of average daytime ambient dry-bulb temperatures in the Southwest for much of the year.

3.3.1.2 Power Cycle Efficiencies

For a heat engine operating with maximum/minimum working fluid temperatures of 550°F/100°F, the maximum cycle efficiency of the ideal Carnot cycle is 44.55%. In practice, commercial configurations of real power cycles such as the Rankine, Stirling, and Brayton cycles that are optimized for maximum efficiency have not achieved efficiencies greater than about two-thirds of the ideal Carnot efficiency. Thus, for the 550°F/100°F temperature constraints involved for this design, a power cycle efficiency greater than about 30% should not be expected even with an optimized design. A simple cycle configuration might result in a realistic maximum power cycle efficiency of approximately 25% at a 550°F peak cycle temperature. Figure 3.3-1 shows the variation in efficiencies of state-of-the-art heat engines for the alternative power cycles considered, and for peak cycle temperatures ranging from 400°F to 1800°F. As indicated, the characteristics of the Stirling and Brayton cycles are such that these two cycles must operate with peak cycle temperatures of at least 1000°F in order to compete with the Rankine cycle efficiency at 550°F. Efficiencies in excess of 20% are obtainable from organic Rankine cycle heat engines operating at 550°F (Ref. 3.3-1).

Figure 3.3-1 Comparison Of Power Cycles

Recent calculations of Stirling cycle engine efficiency (Ref. 3.3-2) show engine shaft efficiency increasing from a value of about 12% at 480°F to about 38% at 1560°F. Stirling cycle engine efficiencies obtained in operating experiments are 10% at a peak temperature of 750°F, and 30% at 1080°F (Ref. 3.3-3, 3.3-4). Primarily because of low efficiency at 550°F, it was concluded that state-of-the-art Stirling cycles would not be suitable for this design.

The characteristics of Brayton cycle heat engines are well known. As indicated in Figure 3.3-1, heat engines for the Brayton cycle must operate at a temperature above 1200°F in order to achieve efficiencies of 20%. At the 550°F peak cycle temperature, the compressor in the Brayton cycle would consume very nearly all the power produced by its drive turbine. With a resulting cycle efficiency on the order of 6%, the Brayton cycle is impractical for this design.

With the selection of the Rankine power cycle, the further specification of a working fluid for the cycle was determined based on Bechtel's analysis of the performance of working fluids.

3.3.2 Selection of Rankine Cycle Working Fluid

Selection of the optimum Rankine cycle working fluid is critical to the design and performance of the power generation subsystem. Many chemical compounds are potentially suitable for use as working fluids in Rankine cycles. Candidate fluids for the solar-powered irrigation facility include a number of organics and water.

Candidate working fluids should be compared on the basis of the following criteria:

- Rankine cycle efficiency
- Thermal stability
- Toxicity
- Flammability
- Cost
- Availability

The ideal fluid would offer high cycle thermal efficiency and would be stable, non-toxic, non-flammable, low in cost, and plentiful in supply. Unfortunately, real fluids do have undesirable characteristics; therefore, it is important to compare advantages and disadvantages of these fluids and choose one fluid that optimally satisfies the particular design requirements.

3.3.2.1 Comparison of Steam and Organic Working Fluids

Steam. Many thermal electric power plants use steam (water) as the working fluid in a Rankine power cycle. The reasons are many. Water is available and plentiful in most places. It is cheap, non-toxic, non-flammable, and has well-known physical, thermodynamic, and handling properties.

On the other hand, water has certain disadvantages. Its freezing point is not as low as is desirable for some applications. High water quality is required to minimize fouling and corrosion. Also, as shown in Figure 3.3-2(a) expansion of saturated steam from state point 1 to state point 2 results in wet vapor in the expander, which reduces expander efficiency and can result in the erosion of turbine blades. The potential problem of blade erosion can be reduced by superheating the vapor before expansion, as indicated by path a-b in Figure 3.3-2(a). However, for a given peak cycle temperature, superheating reduces cycle thermal efficiency.

Figure 3.3-2 TS Diagrams For Water & a Typical Organic Fluid

Another disadvantage of water as a working fluid in small turbines is its low molecular weight. The low molecular weight of steam results in a high energy release during expansion; i.e., high adiabatic head. Because of the high adiabatic head, the turbine nozzle spouting velocity is high. When steam, even at relatively low pressure, is expanded through a nozzle to a condenser at near ambient temperature, the velocity of the efflux is over 3000 ft/sec. Since the theoretical optimum wheel speed for an impulse turbine is about one-half the spouting velocity, the optimal bucket tip speed for a single wheel impulse steam turbine would be about 1500 ft/sec, which is about twice the practical limit. When a single wheel steam turbine is operated at practical speeds, the bucket velocity ratio is considerably off optimum, resulting in poor turbine efficiency. In order to maintain reasonable steam turbine efficiency at practical speeds, the number of turbine stages could be increased; thereby reducing the adiabatic head per stage. This results in a more complex machine, which has not been economical for small steam turbines. Moreover, velocity compounding is not very efficient in small size turbines, and pressure compounding is prohibitive due to windage and disc losses in the high pressure stages. Thus, the total losses for a small 150 KWe steam turbine for this design would be relatively high as compared to the larger multi-stage turbines normally used for electric power generation.

In general, the turbine expansion efficiency of small state-of-the-art steam turbines is about 50%. On the other hand, with the proper choice of working fluid for the specific application, a small single-stage organic turbine might achieve an efficiency of 80% because of the properties of some organic fluids as explained below.

Organics. Because the slope of the saturated vapor line of a typical organic fluid on the T-S diagram is positive as shown in Figure 3.3-2(b), a saturated organic vapor becomes superheated (dry) upon expanding through a turbine. This circumstance avoids efficiency losses and potential erosion problems associated with wet vapor encountered in steam turbines. However, sending the superheated vapor directly to the condenser will reduce cycle efficiency. Therefore, a regenerator is often used to improve cycle efficiency by transferring superheat from the turbine exhaust to the high pressure boiler feed fluid as shown in Figure 3.3-3.

Single stage organic Rankine cycle turbines can be built with good mechanical and stage efficiencies if the correct working fluid is selected for the application. This is of special importance in the irrigation facility design, where a simple, reliable and low cost turbine is desirable. Although the best fluid for a given application is determined by trade-offs of turbine speed and size for the required power level, it is easier to adapt a turbine for lower power levels using a high molecular weight organic fluid instead of steam because the organic's lower adiabatic head permits the use of turbine tip speeds which are within practical limits, at the optimum bucket velocity ratios for best efficiency.

Organic Rankine cycle working fluids have another advantage over steam in this application because the lower latent heat of vaporization of most organics permits a greater temperature drop of the solar collector heat transfer fluid in the boiler heat exchanger. With a greater collector fluid temperature drop between boiler inlet and outlet, more heat is extracted per pound of collector fluid and the collector fluid mass flow rate is reduced for a given power output. Therefore, for a fixed collector outlet temperature

Figure 3.3-3 Schematic Organic Rankine Cycle With Regeneration

(600°F), collector inlet temperature is reduced, thereby decreasing average collector temperature and increasing collector efficiency. And, because more heat is extracted per pound of collector fluid, the size of the thermal energy storage subsystem for a given energy storage capacity is reduced.

Organic working fluids do have disadvantages, however. Some organic compounds are unstable at temperatures below 550°F. Some organic fluids are also toxic and flammable; however, safety-conscious engineering designs are feasible to minimize such hazards.

With the identification of several significant advantages to using an organic working fluid for this design, an evaluation of the performance of organics versus steam in terms of overall Rankine cycle efficiency was conducted as part of a comparison of several candidate organic fluids.

3.3.2.2 Comparison of Candidate Organic Working Fluids

Various organic fluids have been used in Rankine cycle systems. The choice of working fluid depends upon the specifications of the given application, especially operating temperatures and allowable pressures. In a 1974 study, Monsanto Research Corporation evaluated ten organic fluids for use in Rankine cycles for solar energy applications over a range of cycle operating temperatures spanning 150°F to 800°F (Ref. 3.3-5). Four organics - benzene, toluene, pyridine, and chlorobenzene - consistently delivered the highest cycle efficiencies for operating temperatures in the range of 100°F to 550°F. Of these fluids, benzene was eliminated from further consideration for the irrigation facility because its freezing point of -42°F is higher than the ERDA-specified low ambient temperature of -20°F. Fluorinol-85 was included in the evaluation for this design because studies by Thermo Electron

Corporation have shown it to be an efficient working fluid (Ref. 3.3-6).

The thermophysical properties of the four candidate organic working fluids - toluene, pyridine, chlorobenzene, and Fluorinol-85 - are summarized in Table 3.3-1.

Thermal stability temperature limits of the candidate organics range from 600 to 750°F. Saturation pressure at 90°F is low and varies from 0.3 to 2.5 psia. Therefore, condensation in the power cycle would occur at sub-atmospheric pressure for any of these organics, which would require that the engine to be sealed to minimize air in-leakage, and that a non-condensables removal system be provided to maintain low condenser pressure and the low saturation temperature of heat rejection necessary for best cycle efficiency. Steam, with a saturation pressure of 0.7 psia at 90°F, would require similar provisions.

Table 3.3-2 displays additional data concerning the four candidate organic working fluids. Toluene is the least expensive of the fluids, and Fluorinol-85 is 14 times more expensive than toluene. All four are toxic and flammable to some degree and will require special design considerations to ensure safe operation. Toluene is the least toxic of the fluids. The fact that there is no OSHA standard for Fluorinol-85 is due to the fluid's relatively infrequent use.

TABLE 3.3-1 THERMOPHYSICAL PROPERTIES OF SEVERAL CANDIDATE ORGANIC WORKING FLUIDS

Name of Fluid	Toluene	Pyridine	Chloro- benzene	Fluorinol-85
Molecular Weight	92	79	113	87.7
Normal Boiling Point, °F	231	239	270	166
Freezing Point, °F	-139	-41	-49	-82
Liquid Density, g/cc @ 30°C	0.86	0.97	1.11	1.32
Sat. Pres. @ 350°F, psia	62	60	39	265
Sat. Pres. @ 90°F, psia	0.8	0.6	0.3	2.5
Thermal Stability, °F	700	600	750	625

TABLE 3.3-2 ADDITIONAL DATA ON CANDIDATE ORGANIC WORKING FLUIDS

Name of Fluid	Toluene	Pyridine	Chloro- benzene	Fluorinol-85
Supplier	Monsanto	Koppers	Allied	Halocarbon
Cost, \$/gal	2.50	4.80	2.80	35.00
Availability	Large	Large	Large	Medium (22,000 lb/yr)
Flammability				
Flash Point, °F	40	82	85	105
Fire Point, °F	40	82	85	160
Auto Ignition Point, °F	1025	no data	1180	900
Toxicity (threshold limit value) ppm	200	5	75	10
OSHA Limits on Concentration, a/b, ppm	200/300	5/n.s.	75/n.s.	No standard

a: 8-hour time-weighted average concentration.

b: Acceptable ceiling concentration at any time during 8-hour shift.

Calculations of the performance of the candidate organic fluids and steam in a Rankine cycle were made, and the results are shown in Table 3.3-3. With a uniform set of assumptions as indicated in Table 3.3-3, the results indicate that toluene is the best of the candidate working fluids in terms of cycle efficiency with a calculated value of 23.8% for a cycle with a regenerator and with turbine inlet conditions of 550°F, saturated. The next best fluid is chlorobenzene with a cycle efficiency of 22.3%. Following is pyridine, at a cycle efficiency of 21.9%. Fluorinol-85's efficiency was calculated to be 20.1% in a supercritical cycle, almost 4 percentage points below toluene's. Steam has a low cycle efficiency of 13.0% assuming a 50% turbine expansion efficiency quoted by a number of manufacturers. Even if the steam turbine efficiency could be increased (by multiple turbine stages and reheating) to the 80% value that might be achieved with simple single-stage turbines operating on organic fluids, the calculated cycle efficiency is 20.9%, almost 3 percentage points below toluene's 23.8%.

Given that any one of the four candidate organics would yield Rankine cycle efficiencies significantly better than could reasonably be obtained with steam at 550°F, and that the costs of the organic and steam Rankine cycle equipment were judged to be comparable, the use of an organic working fluid was clearly indicated for this design. Toluene was selected as the optimal organic fluid for this design based on its high calculated cycle efficiency, low toxicity, low cost, and availability. With the selection of toluene as the Rankine cycle working fluid, an evaluation was made to select the optimal boiler pressure/temperature state points.

TABLE 3.3-3

RANKINE CYCLE EFFICIENCIES FOR CANDIDATE WORKING FLUIDS

Working Fluid	With Regener- ation ?	Max/Min Cycle Pressures (psia)	Cycle Efficiency (%)	Comments
Toluene	Yes	407.2/1.0	23.8	Saturated
	No	"	19.8	"
	Yes	300/1.0	23.3	Superheated
	Yes	200/1.0	23.0	Superheated
	Yes	100/1.0	21.3	Superheated
Pyridine	Yes	400/0.9	21.9	Saturated
	No	"	19.9	Saturated
Chlorobenzene	Yes	300/0.5	22.3	Saturated
	No	"	18.8	"
Fluorinol-85	Yes	800/3.1	20.1	Supercritical
	No	"	17.7	"
	Yes	300/3.1	19.8	Superheated
	No	"	16.5	"
Steam	No	200/0.9	13.0	50% expansion eff.
	"	"	20.9	80% expansion eff.

Assumptions

1. Peak cycle temperature = 550°F
2. Condensing temperature = 100°F
3. Regenerator effectiveness = 80%
4. Turbine expansion efficiency = 80%
unless noted otherwise
5. Mech. eff.
(turbine + gearbox) = 90%
6. Generator eff. = 90%
7. Feed Pump eff. = 60%
8. Pressure drops neglected

3.3.3 Selection of Boiler Thermodynamic State Points

The boiler is a key component of the power generation subsystem because it is the interface with the collector and thermal storage subsystems. Optimization of the irrigation facility for cost effectiveness requires an evaluation of the effects of the boiler operating conditions on the overall facility cost.

The definition of optimum boiler operating conditions requires a trade-off of:

- Rankine cycle net thermal efficiency
- Solar collector efficiency
- Thermal storage size
- Collector fluid pumping power

The optimum irrigation facility design would provide the required electric power to the deep-well pump motors at minimum cost. Since operation and maintenance costs would be small compared to the capital cost of the facility, minimum cost of generated electricity requires a minimum capital cost facility. Preliminary estimates indicated that the solar collector and thermal storage subsystems would constitute about three-fourths of the total facility cost. Therefore, reducing collector area and thermal storage volume requirements should tend to minimize total facility cost.

The overall system efficiency is a useful parameter to use in system optimization because it can be related to facility capital cost. System efficiency is defined as the ratio of net electric power output to incident solar radiation. Since collector cost is directly proportional to collector

area, as is total incident insolation, collector subsystem cost can be minimized by maximizing overall system efficiency.

System efficiency, however, is proportional to the product of collector efficiency and Rankine cycle efficiency. A trade-off must be made in optimizing the toluene boiler operating conditions, because increased Rankine cycle efficiency is obtained at the expense of a reduction in collector efficiency.

Figure 3.3-4 illustrates Rankine cycle, solar collector, and overall system efficiencies versus boiler toluene pressure for a peak cycle temperature of 550°F. The figure indicates that Rankine cycle efficiency increases with increasing boiler pressure. The reason is that the mean temperature of heat addition to toluene is increased by higher boiler pressures as shown in Figure 3.3-5. However, collector efficiency decreases with increasing boiler toluene pressure as shown in Figure 3.3-4. The reason for this is that, as boiler toluene pressure increases, the Therminol-66 temperature drop between boiler inlet and outlet decreases as shown in Figure 3.3-5. Therefore, for a fixed collector outlet Therminol-66 temperature of 600°F, the collector inlet temperature is increased, thereby increasing average collector temperature and decreasing collector efficiency. Because the Therminol-66 mass flow rate is inversely proportional to its temperature drop across the boiler for a given heat input to the boiler, this flow rate increases with increasing boiler toluene pressure as indicated in Figure 3.3-6. The marked increase in Therminol-66 flow as boiler pressure increases results in increasing parasitic pumping power requirements which would require additional collector areas unless the improvement in Rankine cycle efficiency

Figure 3.3-4 Solar Collector , Rankine Cycle , And Overall System Efficiency
As a Function Of Boiler Pressure

Figure 3.3-5 Effect Of Boiler Pressure On Boiler Operating Temperatures

Figure 3.3-6 Boiler Mass Flow Rates As a Function Of Toluene Boiler Pressure

at higher boiler pressure more than compensates for the combined effects of decreased collector efficiency and increased parasitic power.

A decision was made at this point in the systems analysis work to select a value for boiler pressure based on a reasonable compromise between collector and Rankine cycle efficiencies, and which results in a significant collector fluid temperature drop so as to reduce the size of the thermal storage subsystem and also reduce collector fluid pumping power.

A boiler operating pressure of 200 psia was selected for further systems analysis and for the development of a preliminary design for both the generic and Phase II site specific conditions. At 200 psia, boiler toluene saturation temperature is 460°F. Thus for a peak toluene temperature of 550°F, the toluene at the boiler outlet and turbine inlet will be superheated by approximately 110°F as was indicated in Figure 3.3-5. Given a Therminol-66 collector outlet and boiler inlet temperature of 600°F, and assuming a 15°F boiler pinch point temperature difference (closest approach of Therminol and toluene temperatures), the Therminol-66 temperature drop through the boiler is approximately 200°F.

3.3.4 Estimated Rankine Cycle Efficiency for Systems Analysis

As discussed in more detail subsection 3.3.5, Sundstrand Corporation was selected to provide not only the prototype Rankine cycle prime mover (turbine), but also a complete and fully developed prototype Rankine cycle "package" consisting of turbine, generator, regenerator, condenser, boiler, auxiliary equipment and controls. The single-stage toluene turbine in an existing Sundstrand package was designed for a 600 kWe application and operated with a turbine expansion efficiency of approximately

73%. When the turbine is operated with reduced toluene flow for this 150 kWe application, its expansion efficiency is approximately 70%. Although the turbine efficiency can be increased, as will be discussed in section 4.3, the lower efficiency was used for further systems analysis and preliminary design in order to take advantage of equipment which is part of an existing state-of-the-art design package.

An initial estimate was made of the parasitic power required by the irrigation facility to support generation of 150 kWe net output. An allowance of 6.8% of net power was made for Therminol-66 pumping and Rankine cycle parasitic power. No allowance was made for condenser cooling water pumping power on the tentative assumption that cooling water would be pumped directly from a deep-well irrigation pump. Allowing for parasitic power, the initial estimate for gross output of the Rankine cycle was 160.3 kWe. Gross Rankine cycle efficiency for Sundstrand's design was calculated at 21.5% as the ratio of gross electrical output to heat input, based on 550°F peak cycle temperature, 200 psia boiler pressure, and 100°F condensing temperature. Net cycle efficiency is 20.1%, based on 150 kWe net output for the same heat input. The gross cycle efficiency of 21.5% may be compared to the 23% value which was calculated for a 200 psia toluene cycle in Table 3.3-3, and reflects the effect of losses due to pressure drops and a lower turbine efficiency.

The value of 20.1% for net Rankine cycle efficiency was used for condenser cooling optimization studies (section 3.4) and for the overall system performance and economic analysis (section 3.6).

3.3.5 Selection of Power Generation Subsystem Vendor

The selection of a Rankine cycle equipment vendor during system analysis was essential to meeting the overall project schedule and design objectives. The Rankine cycle equipment is the heart of the power generation subsystem, and requires a longer lead time for design and fabrication than any of the other equipment in the irrigation facility.

The criteria for selecting a power generation subsystem and vendor are related to four basic ERDA-specified irrigation facility design requirements:

- Low risk
- Low facility cost
- High reliability
- Low maintenance

In addition, safety and environmental impact must be considered. These project design requirements can be translated into specific vendor selection criteria as summarized in Table 3.3-4 and as further discussed in the following paragraphs.

Low Risk. The Phase II prototype subsystem, when installed, must operate successfully and must meet performance specifications with minimal risk of failure. This requirement dictates two vendor selection criteria. First, the selected vendor should have considerable experience with electric power generation systems of the size and type required for this 150 kWe solar-powered application, with toluene as a working fluid. Second, since successful operation is dependent on successful integration of components into a system, it is

TABLE 3.3-4

POWER GENERATION SUBSYSTEM VENDOR SELECTION CRITERIA

Project Design Requirements	Vendor Selection Criteria
<ul style="list-style-type: none"> ● Low Risk 	<ul style="list-style-type: none"> ● Experience with similar proven system design that can be adapted easily to project requirements ● Capability and expertise to supply prototype and production "package" systems on schedule
<ul style="list-style-type: none"> ● Low Facility Cost 	<ul style="list-style-type: none"> ● Power generation subsystem cycle efficiency ● Cost of power generation subsystem in prototype and production quantities ● Credibility of cost estimates
<ul style="list-style-type: none"> ● High Reliability 	<ul style="list-style-type: none"> ● System design and operation simplicity ● Operation experience
<ul style="list-style-type: none"> ● Low Maintenance 	<ul style="list-style-type: none"> ● Maintenance requirements and schedule by manufacturer representative and by farmer
<ul style="list-style-type: none"> ● Other Requirements 	<ul style="list-style-type: none"> ● Safety ● Environmental Impact

desirable that the selected vendor be capable of and have considerable experience in providing an integrated power generation subsystem "package" based on existing designs of similar components. The project schedule does not allow time for development of new components.

The selected vendor must be able to demonstrate that engineering development and testing of substantially similar systems have already been done. The vendor must be able to meet the schedule requirements of Phase I and Phase II.

Low Facility Cost. The cost of the power generation subsystem will have a significant impact on the cost of the entire irrigation facility. One of the major objectives adopted for this design study is the production of realistic cost estimates for the Phase II prototype facility to which ERDA can attach a high level of confidence in planning for and funding the Phase II program. Therefore, the selected subsystem vendor should be capable of demonstrating the credibility of the cost estimated for the Phase II prototype, preferably by reference to current design and production experience for similar applications. Although the cost of the power generation subsystem itself is an important criterion, the overall cycle efficiency of the power generation subsystem is a more important factor in determining total facility cost because the size (and cost) of the collector and thermal storage subsystems are directly related to cycle efficiency. For this reason, the vendor should have experience with the organic Rankine cycle, and with toluene, the top-ranked working fluid for this application.

High Reliability. The total facility must be designed to operate with minimal outages over the ERDA-specified design life of 30 years with routine scheduled maintenance. The selected power generation subsystem vendor must be capable of demonstrating that his equipment will provide this kind of reliability, preferably by virtue of the simplicity of the design and prior successful extended operating experience.

Low Maintenance. The system must operate successfully over its life with minimal maintenance. Scheduled yearly maintenance could be performed by a manufacturer's representative. If more frequent maintenance is required, a farmer or a locally based service organization should be able to do the maintenance.

Other Requirements. Safety of operation and environmental impact must be considered. With the use of organic working fluids, the vendor must demonstrate that his design has sufficient safety protection features.

Concurrent with the systems analysis effort leading to selection of the Rankine cycle working fluid (section 3.3.2), a survey to determine the qualifications of some 19 potential Rankine cycle equipment vendors was accomplished. In an initial screening, thirteen of the potential vendor candidates were dropped from further consideration, primarily because of their lack of experience with organic working fluids, and/or lack of existing designs scalable to the required 150 kWe size for this application. However, among the six vendor candidates remaining, one advocating a steam Rankine cycle with a reciprocating engine was included to permit further assessment of this popular concept. With the selection of toluene as the working fluid for an organic Rankine cycle, the qualifications of the remaining six vendor candidates were evaluated in detail and judged with respect to

the previously discussed vendor selection criteria. As a result of the final evaluation process, Sundstrand Energy Systems Division of Sundstrand Corporation was selected as the Rankine cycle equipment vendor for the Phase II prototype and the production version of the power generation subsystem of the generic design. The preliminary design of the Sundstrand organic Rankine cycle (ORC) package is discussed in section 4.3.

3.4 WATER STORAGE AND DELIVERY SUBSYSTEM

The water storage and delivery subsystem of the solar-powered deep-well irrigation facility has three potential functions:

- Delivery of water from the underground aquifer to the cropland to be irrigated.
- Storage of water pumped during periods of low irrigation water demand for use later during high demand periods.
- Delivery of cooling water to the condenser of the power generation subsystem to dissipate heat from the power cycle.

The first function of this subsystem, the delivery of groundwater to the irrigated fields, is out of the scope of the current preliminary design study. It is assumed for the preliminary design that the well, pump, irrigation ditches, pipe, and other irrigation system components are either already existing or supplied by others.

The feasibility of using a water reservoir as a means of storing water pumped during low irrigation water demand periods for use later during high irrigation water demand periods was studied by Bechtel. The most cost-effective water reservoir design was determined and, based on the cost of this reservoir, the economic feasibility of water storage was evaluated. As will be discussed in section 3.4.1, the use of a water reservoir for water storage was found to be uneconomical.

Provision of condenser cooling water is the third function of the water storage and delivery subsystem. Several condenser cooling schemes, including once-through cooling using pumped groundwater and various closed-loop cooling systems, were investigated by Bechtel. As discussed in section 3.4.2, depending on site-specific conditions, either once-through cooling using pumped

groundwater, or closed-loop cooling using a spray pond, is the economic alternative for condenser cooling.

3.4.1 Water Reservoir

One potential function of the water storage and delivery subsystem is to store excess water pumped during periods when irrigation water demand is relatively low so that it can be used at a later time when water demand exceeds the rate at which water can be pumped by the solar facility. The application of a water reservoir to serve such a function was considered for the generic facility design in order to supply the ERDA-specified irrigation water demand, which varies throughout the year as was shown in Figure 2.1-1.

Figure 3.4-1 compares by month this irrigation water demand (percent of continuous rated well output) to the solar facility power generation subsystem capacity factor (the ratio of actual kilowatt-hour generation to the maximum possible with continuous, 24 hour per day, rated output of 150 kWe). The power generation subsystem capacity factor was determined based on insolation data from Albuquerque and the calculated performance of the solar facility (see section 3.6, Overall System Performance and Economic Analysis).

Note that in order to supply the irrigation water demand, the equivalent well output must be 40 percent of capacity in the winter months and greater than 90 percent during the month of August. However, the solar facility can supply the energy equivalent of only 20 percent of well capacity during the winter months and a maximum of 70 percent in the month of June. Only during the months of April, May, and June is there sufficient electric power generation from the solar facility to meet the irrigation water demand. During the

Figure 3.4-1 Comparison Of Generic Demand With Supply From Solar Energy

remaining nine months of the year, solar energy would have to be supplemented with other sources of energy to provide the irrigation water requirement.

One source is the electric utility power grid. Electric power could be purchased to supply the deficit between demand and supply by solar energy (areas B and C of Figure 3.4-1).

Note from the figure that more electric power than is required to meet irrigation water demand could be generated from solar energy during the months of April, May, and June (area A). If feasible, excess generation could be distributed and sold to the local electric utility. Therefore, the sale of electricity represented by area A of Figure 3.4-1 could potentially offset the cost of electricity that the farmer must purchase later in the year (e.g., area B). If the farmer can sell excess generated electricity to the utility at a reasonable price, it would be to the farmer's advantage to do so. This, in effect, would be using the electric grid for energy storage at no additional cost to the farmer. It is not clear whether an electric utility would permit or encourage this kind of interfacing, particularly if a large number of facilities were to be deployed.

If it were not feasible or desirable to distribute excess electric power to the utility grid, the farmer would have the following two basic alternatives. First, he could de-steer the solar collectors part of the time during April, May, and June so that electric power generation matched that required for the irrigation water demand. Second, he could find another use for the solar thermal energy, electricity, and/or pumped groundwater represented by area A. For example, he could use thermal energy for heating buildings or crop drying, or electricity for other farm power demands. Or, as was mentioned previously, he could use the excess electric power to pump water which would be stored in a

water reservoir for later irrigation use. Excess groundwater could be pumped during April, May, and June and stored in a water reservoir for use during July, August, and September to meet peak irrigation demand. With this approach the amount of electric energy purchased from the local utility could be reduced by the amount represented by area B. However, it should be noted that all the energy represented by area A would not be recovered because of (1) losses of water due to evaporation and seepage and (2) supplemental electric energy required to pump water from the water reservoir to the cropland.

In order to assess the economic feasibility of the use of the water reservoir as a means of meeting the peak irrigation water demand, the capital cost of a water reservoir sized for this purpose must be traded off against the cost of purchasing electricity equivalent to area B of Figure 3.4-1. The electric energy represented by area A of Figure 3.4-1 was calculated by graphical integration to be 42,000 kWh. Therefore, if a water reservoir were used, the annual purchase of electricity (area B) could be reduced by at most 42,000 kWh. The actual reduction in purchased electricity would be somewhat less than 42,000 kWh because of water evaporation and seepage and additional water pumping energy requirements as noted previously; however, it was assumed in these trade-off calculations that the full 42,000 kWh saving could be achieved.

In order to determine the size of a water reservoir necessary to store the water equivalent of 42,000 kWh of pumping power, the groundwater pumping rate must be known. Well pump discharges were calculated for three ERDA-specified pumping depths of 280, 380, and 480 feet assuming a 150 kWe input

to the pump motor(s). For this calculation, an overall pump efficiency was assumed to be 65% which accounts for electric motor losses, mechanical linkage losses, pipe friction losses, inlet/outlet losses, and the hydraulic efficiency of the pump impeller stages. Table 3.4-1 summarizes the ground-water pumping rates equivalent to 150 kW of electric power input to the deep-well pump motor and the total water volume equivalent to 42,000 kWh.

TABLE 3.4-1 EFFECT OF PUMPING DEPTH ON FLOW RATES AND WATER RESERVOIR SIZE

<u>Pumping Depth (ft)</u>	<u>Pumped Groundwater Flow Rate @ 150 kWe (gpm)</u>	<u>Water Reservoir Size Requirement (acre-ft)</u>
280	1854	97
380	1366	70
480	1082	56

Note that with a pumping depth of 380 feet the groundwater pumping rate is 1366 gpm and the water reservoir capacity must be 70 acre-feet. The capital cost of a 70 acre-foot water reservoir designed for a flat site with soil conditions typical of the southwestern U.S. was estimated to be \$200,000. Such a reservoir would be lined with a 20 mil poly-vinyl chloride impermeable membrane, would be surrounded by earth banks with a 3:1 slope constructed from excavated material, and could have a depth of from 8 to 20 feet.

To convert this water reservoir capital cost to an equivalent annual cost, over the assumed 30-year life of the facility, the \$200,000 was multiplied by the 30-year, 8% interest capital recovery factor of 0.089 to obtain an annual cost of \$18,000. This converts to an equivalent cost for electric energy of 420 mills/kWh. Since this cost is significantly higher than current

and projected electricity costs in the Southwest (10-40 mills/kWh), the investment in a water reservoir to supply peak irrigation water demand was judged to be unwarranted for the near future.

For the Phase II site-specific design a water reservoir could be used in a similar manner to that described for the generic site to store water pumped by the solar facility during the irrigation off-season from mid-September through December for later use during the irrigation season (see Figure 3.4-2). The electricity that can be generated by the solar facility during the off-season (see area A of Figure 3.4-2) was calculated to be 102,000 kWh; thus, for an assumed pumping depth of 380 feet, this electric energy could pump 170 acre-feet of water (equivalent to area B of Figure 3.4-2). The cost of a water reservoir this size was estimated to be \$400,000. The equivalent electric power cost is 380 mills/kWh, still considerably higher than current and projected electric power costs in the southwestern U.S. Again, it should be reiterated that in these cost comparisons, for simplicity, the losses resulting from water evaporation and seepage during the storage period and supplemental pumping power requirements were ignored. If these additional factors were accounted for, the water reservoir would be even less cost-effective.

It was recognized that, depending on the site-dependent irrigation techniques employed, such as gravity, sprinkler, or drip irrigation, a small water reservoir may be required to handle surges in water supply or demand, but since the method of delivery of irrigation water to the cropland is out of the scope of this preliminary design study, such a requirement was not addressed.

Figure 3.4-2 Comparison Of Phase II Site - Specific Demand With Supply From Solar Energy

To summarize, the concept of storing water in a reservoir for later use was found to be technically feasible but not economically viable when compared to alternatives. For this reason, the water storage function of the water subsystem was eliminated, and in the further preliminary design activities the "water storage and delivery subsystem" has been re-named simply as the "cooling water subsystem."

3.4.2 Condenser Cooling

The most important function of the cooling water subsystem in terms of the solar facility performance is that of supplying cooling water for the condenser of the power generation subsystem.

The temperature of cooling water will depend on the site and on the cooling method (e.g., closed-loop or once-through) and may have daily and seasonal fluctuations. Since the cooling water temperature determines the condensing temperature, which, in turn, affects the Rankine cycle efficiency, for design purposes it is desirable to establish a design condensing temperature as a baseline. Once this design temperature has been established, the effect of variations in condensing temperature from the baseline can be determined.

As discussed in section 3.3, for the preliminary design of the generic 150kWe solar-powered irrigation facility, a baseline design condensing temperature of 100°F was selected. This temperature was selected on the basis that 80°F cooling water is supplied to the condenser, cooling water temperature rise is 10°F, and condenser approach is 10°F.

The 80°F cooling water temperature was selected because:

- The range of temperatures given by ERDA for groundwater for the generic design is 75-100°F.

- The measured temperature of groundwater at the site for the Phase II demonstration near Coolidge, Arizona is 80°F.

Assuming full load operation (150 kWe net output) of the power generation subsystem at a net cycle efficiency of 20.1%, the condenser heat rejection rate is approximately 600 kWt and the cooling water flow rate required to reject this heat with a 10°F water temperature rise is about 400 gpm.

Two basic methods of supplying this cooling water requirement were considered:

- Once-through
- Closed-loop (cooling tower, spray pond, cooling pond, or cooling canal)

The term, once-through cooling, refers to the fact that cooling water is pumped through the condenser only once. If once-through cooling were used for the irrigation facility, pumped groundwater would be pumped through the condenser and then would be used for irrigation. Closed-loop cooling systems recycle water that has been pumped through the condenser so that it may be re-used for cooling. Closed-loop cooling systems use some method for dissipating heat to the atmosphere in order to cool the water before it is pumped back to the condenser. Four methods of closed-loop heat dissipation were considered for the irrigation facility: wet cooling towers, spray ponds, cooling ponds, and cooling canals.

Wet cooling towers and spray ponds dissipate heat from the cooling water to the atmosphere largely by latent heat transfer resulting from partial evaporation of small droplets. In a cooling tower, hot water is pumped to the top and is then allowed to fall through a fill where it is broken up into small droplets to create a large surface area for air-water

contact. A fan is generally employed to blow ambient air through the cascading water droplets. A small portion of the water evaporates, cooling the balance. In a spray pond, cooling is achieved by pumping hot water to upward-facing nozzles to produce a fine spray of water droplets. The water droplets are cooled by evaporation as they fall to the surface of the pond. The spray pond occupies a larger area than a cooling tower but may have lower costs, if land costs are minimal, because the capital, operating, and maintenance costs associated with the cooling tower's structure and fan are avoided. Since both the cooling tower and the spray pond cool water by the process of evaporation, the lowest temperature to which the water can be cooled is the ambient wet bulb temperature. Generally, an economically optimum approach to the wet bulb temperature is 10°F at a 70°F wet bulb temperature.

The cooling pond transfers heat from hot cooling water to the atmosphere over the surface area of the pond. Since this method does not produce fine droplets of water to increase the air-water contact area, a larger land area is required for this alternative. A rule of thumb is that 1 to 2 acres of cooling pond area is required per megawatt of installed electric generating capacity. Heat is dissipated from the hot water surface by a combination of conduction, convection, long-wave radiation, and evaporation. The cooling canal is a variation of the cooling pond in which the surface area is provided by a long, narrow "canal." The advantage of the cooling canal over the cooling pond is that lower water temperatures can be achieved with the same surface area because, by virtue of the plug flow through the canal network, hot and cool water do not mix, whereas in most cooling ponds there is some mixing of hot and cold water.

Water in a cooling pond or canal will approach an equilibrium temperature. The equilibrium temperature depends on the site meteorological conditions and is generally higher than the wet bulb temperature. As is the case with the cooling tower or spray pond approach to wet-bulb temperature, with the cooling pond or canal the equilibrium temperature is approached but generally not achieved. Depending on the size of the pond or canal and ambient conditions, the cooling water temperature will be 10-20°F higher than the equilibrium temperature.

The choice of alternate condenser cooling methods - once-through, cooling tower, spray pond, cooling pond, cooling canal - for the irrigation facility should be based on economics and on the site-specific ambient meteorological conditions, groundwater temperature, irrigation requirements, and local electric utility interface conditions. A trade-off must be made between (1) the incremental capital and operating costs of the given cooling alternate above a baseline design and (2) the additional electric power output that the cooling alternate makes possible through increased cycle efficiency of the power generation subsystem or through extended periods of operation. For example, if irrigation water is not required year-round at a given location, and electricity generated on-site may be sold to the local utility, a closed-loop cooling method may have two advantages over a once-through cooling scheme. First, cooling water temperatures lower than groundwater temperature may be achieved, thereby reducing condenser temperature and increasing power generation subsystem cycle efficiency. Second, the closed-loop cooling system would permit the facility to operate during the irrigation off-season and to distribute electricity to the local electric utility grid. The trade-off must consider whether the additional kilowatt-hours generated by the solar facility equipped with the given condenser

cooling design justifies the incremental capital and operation costs of the given design above that of the baseline design.

For the analysis of alternate condenser cooling methods, the baseline design is once-through cooling, using 80°F pumped groundwater.

Figure 3.4-3 shows the monthly average cooling water temperatures that can be obtained by alternate condenser cooling methods. The condenser cooling water temperature obtained by using once-through cooling with 80°F pumped groundwater, available at the site selected for the Phase II facility, is a constant 80°F throughout the year. However, the cooling water temperatures obtained using one of the four closed-loop cooling methods vary throughout the year as ambient meteorological conditions vary. The performance of the cooling pond and canal was calculated using Phoenix, Arizona meteorological data and techniques from Reference 3.4-1. Cooling tower and spray pond performance was calculated based on a frequency distribution of wet-bulb temperatures in Phoenix, Arizona (Ref. 3.4-2) and on the calculated thermal performance of a tower or a pond sized to provide a 10°F approach to a 70°F wet-bulb temperature. It can be observed from the figure that about half of the year cooling water temperatures obtained from the cooling pond or canal exceed the 80°F groundwater temperature; however, with the cooling tower or spray pond, the monthly average water temperature exceeds 80°F only during July. In the economic analysis of alternate cooling methods, it was assumed that if a closed-loop cooling method were utilized and cooling water temperature were to exceed 80°F, a switch-over to once-through cooling would be made during these hot periods.

Figure 3.4-4 shows the effect of condensing temperature on gross cycle efficiency of the power generation subsystem based on Bechtel thermodynamic

Figure 3.4-3 Monthly Average Condenser Cooling Water Temperatures Obtainable by Alternative Cooling Schemes

3.4-15

Figure 3.4-4 Effect of Cycle Condensing Temperature on Rankine Cycle Efficiency

calculations and Sundstrand organic Rankine cycle (ORC) state points. Note that significant increases in cycle efficiency result when condensing temperatures lower than the baseline 100°F can be obtained.

Table 3.4-2 shows the results of an analysis of the net increase in the solar-powered facility's electric power output resulting from the utilization of alternate condenser cooling methods. The first column shows the total auxiliary power requirement for each of the cooling alternatives. The 7.8 hp requirement for the cooling tower includes 2 hp for fan power and 5.8 hp for pump power. Auxiliary power requirements for all other alternatives are pumping power only. The second column gives the auxiliary power requirement of each alternative above that required for once-through cooling. The third column shows the increase in ORC power output for each cooling method, resulting from reduced cooling water and ORC condensing temperatures averaged over the period that the given cooling method is used. It is assumed that a given closed-loop cooling alternative is used only during the months of year when that given alternative achieves cooling water temperatures lower than the 80°F groundwater temperature. For example, the cooling pond or canal would be used only during the coldest five or six months of the year, respectively, whereas the cooling tower or spray pond would be used throughout the entire year, except July. The fourth column of the table gives the net average increase in power output from the facility, which is the increase in ORC output minus the auxiliary power requirement. Note that using the cooling tower or spray pond results in an average increase in net power output of 1.6 hp over the 11-month period that these cooling methods would be used. Using either the cooling pond or the cooling canal results in an average increase in net power output of greater than 5 hp; however, these increases are averaged over shorter periods of five and six months, respectively.

TABLE 3.4-2 TRADE-OFF OF ELECTRIC POWER OUTPUT AGAINST AUXILIARY POWER REQUIREMENTS WITH ALTERNATE CONDENSER COOLING METHODS

Condenser Cooling Method	Auxiliary Power Requirement (hp)		Increase (above base) in ORC Output (hp)	Increased ORC Output minus Aux. Power Req't (hp)	Yearly Increase in Power Output (kWh)
	Absolute	Above Base			
Once-through (base)	3.9	0.0	0.0	0.0	0
Cooling Tower	7.8	3.9	5.5	1.6	3500
Spray Pond	7.8	3.9	5.5	1.6	3500
Cooling Pond	3.9	0.0	5.1	5.1	4600
Cooling Canal	4.7	0.8	6.4	5.6	6600

3.4-17

The last column of Table 3.4-2 shows the yearly increase in kilowatt-hours generated by the ORC resulting from the use of the given cooling alternative. Note that by using the cooling canal scheme, the largest increase in ORC power output (6600 kWh/year) is obtained. If a cooling pond is used, a 4600 kWh/year power output increase is obtained. With either the cooling tower or spray pond, there is an increased ORC power output of 3500 kWh/year above that obtained using once-through cooling with 80°F pumped groundwater. These increases in power output must be traded off against the incremental costs of the alternate cooling methods.

Table 3.4-3 shows the cost trade-off of the condenser cooling alternatives. The first column gives the capital cost (above base) of each of the cooling methods. The cooling pond and canal are the most expensive alternatives, with once-through cooling being least expensive and the spray pond and cooling tower \$7000 and \$8000 above the cost for once-through cooling, respectively.

TABLE 3.4-3 COST TRADE-OFF OF ALTERNATE CONDENSER COOLING METHODS

Condenser Cooling Method	Capital Cost (above base)	Present Worth of increased OCR output	Net Savings
Once-through (base)	\$0	\$0	\$0
Cooling Tower	\$ 8,000	\$1,600	- \$6,400
Spray Pond	\$ 7,000	\$1,600	- \$5,400
Cooling Pond	\$50,000	\$2,100	-\$47,900
Cooling Canal	\$50,000	\$3,000	-\$47,000

The second column gives the present worth of the 30-year savings in electricity costs resulting from the increase in ORC power output obtained from the use of the given alternative, assuming the equivalent electricity cost is 40 mills/kWh (the estimated electricity cost in the 1980 time frame). The last column shows the net savings. At the assumed 40 mills/kWh electricity cost, none of the closed-loop cooling alternatives provides sufficiently increased ORC electric power output to justify the additional investment. Electricity costs would have to increase to 175 mills/kWh to make the spray pond economically more attractive than once-through cooling.

Therefore, for the generic design of the irrigation facility for deployment in the 1980 time frame, the cost-effective condenser cooling method is once-through cooling using pumped groundwater. This choice, however, is site-specific to the extent that it is based on the following assumptions:

- Groundwater is 80°F or cooler.
- Meteorological conditions at the site are similar to Phoenix, Arizona conditions.
- There is a year-round irrigation demand, or, if there is not, electricity generated by the facility during the irrigation off-season cannot be sold to the local electric utility.
- Levelized, 30-year electricity cost is less than 175 mills/kWh.

At a site where there is not a year-round irrigation water demand and where electricity generated by the facility during the irrigation off-season may be sold to the local electric utility, the economics change. For example, at the site selected by ERDA for the Phase II prototype near Coolidge, Arizona irrigation water is not needed from mid-September through the end

of December, and officials of the local utility, Electrical District #2, have stated that they would be willing to purchase electricity generated by the solar facility during the irrigation off-season.

In such a situation, a problem would result if only once-through cooling water were provided for condenser cooling of the facility. At least one deep-well pump would have to be operated to provide condenser cooling to permit the facility to generate electricity during the irrigation off-season, thereby reducing electric power output available for distribution to the utility. Also, after being pumped through the condenser, water would have to be disposed of in some manner. Therefore, at a site where it is desirable to generate and sell electricity during the irrigation off-season, some kind of closed-loop cooling should be provided.

The economic feasibility of investing in a closed-loop condenser cooling scheme to permit electricity generation during the irrigation off-season was investigated using the specific conditions of the Phase II site. The electricity that can be generated by the solar facility during the off-season from mid-September through December was calculated to be 102,000 kWh. Assuming a 40 mills/kWh electricity cost (selling price), the present worth of a 30-year series of 102,000 kWh/year electricity sales is \$46,000. If this revenue is added to the net savings shown in Table 3.4-3, the spray pond becomes the economically favored condenser cooling method, as shown in Table 3.4-4. Thus, the use of a spray pond would result in a net savings of \$40,600, while the cooling tower would be a close second with a net savings of \$39,600.

To summarize, for the generic facility, installed at a site with 80°F groundwater and a year-round irrigation demand, a once-through condenser

cooling scheme is recommended. For the facility at the Phase II site (or similar sites) a closed-loop cooling scheme using a spray pond is recommended.

TABLE 3.4-4 COST TRADE-OFF OF ALTERNATE CONDENSER COOLING METHODS, ASSUMING ELECTRICITY SALES DURING IRRIGATION OFF-SEASON

Condenser Cooling Method	Capital Cost (above base)	Present Worth at increased ORC output	Revenue from Electricity Sales During Off-Season	Net Savings
Once-through (base)	\$0	\$0	\$0	\$0
Cooling Tower	\$ 8,000	\$1,600	\$46,000	\$39,600
Spray Pond	\$ 7,000	\$1,600	\$46,000	\$40,600
Cooling Pond	\$50,000	\$2,100	\$46,000	-\$1,900
Cooling Canal	\$50,000	\$3,000	\$46,000	-\$1,000

3.5 POWER DISTRIBUTION SUBSYSTEM

The primary function of the power distribution subsystem is to distribute the solar derived 150 kWe net output of the power generation subsystem to the electric motor driven deep-well irrigation pump(s). A second major function of this subsystem is to distribute auxiliary power to electrical loads within the solar powered generating facility, as may be required during normal operation, for collector tracking drives, collector and thermal storage fluid pumping, Rankine cycle working fluid pumping, cooling water pumping, control power, etc. The supply of auxiliary power required for daily startup and shutdown of the facility and for emergency conditions is also a function of this subsystem.

The method of delivering 150 kWe net generator output to the electrical load is site dependent, being affected by such factors as: number and sizes of the pumps to be served; proximity of the pumps to each other and to the location of the solar generating facility; and the characteristics of the existing local electric utility distribution system.

3.5.1 Basis for Generic Design

For generic design purposes, ERDA has specified that electric power as delivered to the deep well pump motor(s) shall be 440 volt, 3-phase, 60 Hz.

On a generic basis, the most straightforward method of distributing power from the power generation subsystem to the deep-well pumps is to feed the power directly into the existing electrical grid. Conventional provisions would be included in the controls for the power generation subsystem

for electrically synchronizing the generator with the utility every day, or whenever the solar generating facility is brought on-line. A watt-hour meter would indicate the amount of energy delivered to the utility. Credit would be given for any excess power generated over that required for irrigation pumping during periods of minimum water demand, and would be applied to any shortfall made up by the utility during periods of maximum water demand.

Power generated by the solar facility would be at 480 volts, which is suitable for internal distribution to auxiliary loads, and would be increased to the utility transmission voltage through a step-up transformer. Startup power for the facility would come from the low side of the step-up transformer.

The approach taken for the generic design of the power distribution subsystem is simple, inexpensive, and reliable; and it provides maximum operating flexibility with no disruption of operating practices for existing electric deep-well pumping applications.

3.5.2 Basis for Phase II Site-Specific Design

For the Phase II site-specific preliminary design of the demonstration facility, ERDA has specified that power from the solar generating facility shall be distributed to the well pumps by wiring which is separate from the existing ED#2 wiring, in order that the ability of the pumps to run only on solar generated electricity can be easily demonstrated. ERDA has also specified that provisions shall be included in the Phase II preliminary design to permit connecting the well pump motors and/or the output of the solar generating unit to the ED#2 grid.

The capability of feeding the electrical output of the solar facility directly to the ED#2 system is desirable in that it would permit continued operation and testing of the facility during the irrigation off-season months (mid-September through December) when the irrigation pumps are not operated. Retaining the capability of powering the irrigation pumps from the ED#2 grid is necessary to permit continued 24 hour per day pumping during the irrigation season when power is not available from the solar generating facility. The ERDA-specified criteria regarding the electrical interface between the electrical grid and the solar generating facility form the basis for the preliminary design of the power distribution subsystem which is presented in section 4.5.

One additional criterion which was adopted for the preliminary design is that the design shall not result in a requirement to shut down the irrigation pumps when transferring from ED#2 power to solar generated power, or when transferring back to ED#2 power from solar generated power. This criteria would not necessarily be applicable if the solar collector and thermal storage subsystems are sized to provide uninterrupted 24-hour per day operation of the irrigation pumps on solar generated power. The criterion would apply, however, if the solar generating facility is not sized to provide 24 hour per day operation. For the latter case, uninterrupted pump operation during power transfer is desirable because it precludes the necessity of a twice-daily stop and restart of each of the three pumps to be powered by the solar facility. Under general operating practice the pumps are run 24 hours per day for months without stopping.

3.6 OVERALL SYSTEM PERFORMANCE AND ECONOMIC ANALYSIS

(to be prepared by Acurex)

SECTION 4
PRELIMINARY DESIGN

(to be prepared by Acurex)

4.1 COLLECTOR SUBSYSTEM

(to be prepared by Acurex)

4.2 THERMAL STORAGE SUBSYSTEM

(to be prepared by Acurex)

4.3 POWER GENERATION SUBSYSTEM

The preliminary design of the power generation subsystem is based on the use of an existing design for a 600 kWe organic Rankine cycle (ORC) power conversion system developed by Sundstrand Corporation. Preliminary design of the 150 kWe power generation subsystem for Phase II therefore involved the identification and evaluation of appropriate modifications to the baseline Sundstrand 600 kWe ORC design, and a determination of the performance of the modified 600 kWe ORC design when operating at a 150 kWe net output.

4.3.1 Baseline 600 kWe Organic Rankine Cycle (ORC) Design

The 600 kWe ORC design was developed by Sundstrand Corporation as a bottoming power cycle for use in waste heat recovery applications with gaseous waste heat streams at temperatures of 600°F and higher. Development of the 600 kWe ORC design was initiated by Sundstrand in mid-1975.

In September 1976, Sundstrand and ERDA entered into a cooperative agreement which encompasses the production and field testing of five 600 kWe units (ERDA Cooperative Agreement No. EX-76-A01-2132). Assembly of the development unit for the 600 kWe ORC program was completed in mid-July 1977.

Initial checkout and a 4000 hour test of the development unit will be started in mid-August 1977 in a dedicated ORC test facility at Sundstrand's Rockford, Illinois plant. The Sundstrand-ERDA schedule calls for having the five field test units installed and operational by early 1979.

Major aspects of the 600 kWe ORC design are discussed in the following paragraphs. Preliminary design modifications to the basic 600 kWe design, appropriate for the 150 kWe solar application, are discussed in section 4.3.2.

4.3.1.1 General Description

The 600 kWe ORC is a complete electric power generating system consisting of a boiler, Rankine cycle package, generator, controls, switchgear and all necessary auxiliaries. Figure 4.3-1 is an isometric view of the 600 kWe ORC as configured for a waste heat recovery application. The power conversion module is a skid-mounted arrangement of the turbine, cycle pumps, regenerator, condenser, gearbox, electric generator, and auxiliaries. The approach taken in designing the system was to keep it as simple as possible, using as much off-the-shelf hardware as possible, thus minimizing problems of a developmental nature associated with accessory and peripheral equipment. The ORC was optimized to minimize overall system cost for waste heat recovery using toluene as a working fluid. Toluene was selected as the most cost effective working fluid for the bottoming cycle application based on Sundstrand's prior experience and a thorough review of potential working fluids and cycle conditions.

4.3.1.2 Design Conditions

Design point conditions for the 600 kWe ORC are with a gaseous heat source at 800°F and with an available cooling water temperature of 86°F for heat rejection. The corresponding toluene turbine inlet conditions are 300 psia/550°F. Toluene condenser temperature is 140°F. The 600 kWe ORC design is also adaptable to the requirement that the cycle should be efficient at lower heat source temperatures. With a 600°F heat source, efficient operation is obtained when turbine inlet conditions are adjusted to 200 psia/465°F, and minor changes are made to the components.

4.3.1.3 Turbine and Feed Pumps

The turbine and feed pump for the 600 kWe ORC are of Sundstrand design and are based on Sundstrand's experience with other ORC systems using toluene

Figure 4.3-1 Sundstrand 600 kWe ORC for Waste Heat Recovery

and other working fluids. The turbine and pump are an integral unit, with the two-stage feed pump impeller mounted at one end of the turbine shaft. This arrangement eliminates the need for a high pressure seal on the pump shaft and eliminates the inefficiency associated with an electric motor drive for the feed pump. The turbine is supported on journal bearings lubricated by toluene, which eliminates the need for a pump, seals, and a cooling loop if a separate lubricant is used. This arrangement also precludes the potential of fouling the working fluid with lubricating oil, or of diluting the lubricating oil with the working fluid, and results in a close approximation to a hermetic system. The turbine is single-stage, supersonic axial flow, with a pitch diameter of 20.5 inches and blade height of 2.35 inches. The turbine speed is 9300 rpm.

4.3.1.4 Regenerator and Condenser

The regenerator and condenser heat exchanger cores are plate-fin designs mounted inside a common pressure vessel housing which includes a hotwell sump. This arrangement permits large frontal areas for the heat exchanger cores, resulting in a very low toluene vapor pressure drop through the regenerator and condenser cores and a negligible pressure drop in the passage between the cores. The ORC design includes an automatic non-condensable gas removal system for the condenser to remove any entrained air prior to startup and any non-condensable gas which may be generated by degradation of the toluene.

4.3.1.5 Off-the-Shelf Components

The control valves, start pump, boost pump, filters, generator, and all plumbing and control components, with the exception of some of the printed circuits, are off-the-shelf hardware. The gear box is a single reduction

unit supplied by Cotta Transmission Co., and is similar in design to other gear boxes which they currently manufacturer.

4.3.1.6 Code Compliance and Safety Features

In order to provide compliance with national, state, and local codes, all working fluid plumbing meets the requirements of the ANSI B-31.1 Power Piping Code. The regenerator heat exchanger core and the regenerator/condenser pressure vessel housing are designed and stamped per Section VIII of the ASME Boiler and Pressure Vessel Code. The heat recovery boiler is designed and stamped per the requirements of Section I of the ASME Boiler and Pressure Vessel Code.

Because of toluene's low flash point (40°F), the electrical design of the power conversion module and boiler are in accordance with the requirements for a Class I, Division 2, Group D location as defined in the National Electric Code. To meet these requirements all wiring is approved cable or is run in sealed, rigid conduit, and all electrical devices are either intrinsically safe or are located in housings which meet the requirements for this type of location. All electric motors are totally enclosed, fan-cooled.

In addition to meeting Class I, Division 2, Group D requirements the ORC unit is equipped with a flammable gas detector which will shut the unit down if a concentration of 25% of the flammable limit of toluene is sensed. Installation of the unit under a sun shade without walls, or in a building which has walls that do not extend all the way to the ground, will provide adequate natural ventilation to prevent a hazardous build-up of toluene fumes should a leak occur. All of the ORC equipment is weather-proof and suitable for outdoor installation.

4.3.1.7 Control System Features

The ORC control system contains six functional solid-state analog control modules and a solid-state programmable controller. The programmable controller performs all start-stop sequence logic and safety logic for determining shutdowns and enunciating the causes for shutdowns. The six functional analog modules are designed to permit rapid fault diagnosis and replacement in the event of malfunction. A programmable controller was selected over hardwired logic for several reasons: lower cost; increased flexibility, both during development and for production units requiring control variations based on application; proven reliability; and because the programmable controller can be easily interfaced for communication with remotely located control terminals. The generator circuit breaker control includes an automatic synchronizer unit for applications in which the ORC is to be operated with the generator in parallel with an electric utility system.

4.3.1.8 Maintenance Requirements

All ORC components which cannot be readily repaired in the field are easily replaced as a unit. The ORC is designed for a life of 20 years with a minimum of 50,000 hours of operation and 2,000 starts between overhauls, when operated at 90% of the design output of 600 kWe. Major periodic inspections are to be performed once a year. All routine maintenance required at intervals of less than 120 days can be performed with the unit operating. All maintenance which must be done at 120 day intervals can be accomplished in four hours or less.

Toluene can be added to the system while it is operating, and under normal circumstances this will be necessary only once per year. Normal leak-

age will be approximately 1/4 pound of toluene vapor per day, mainly through shaft seal losses. Approximately 1/4 pound of toluene vapor will also be expelled from the system when the unit is started if the condenser pressure has risen to atmospheric pressure. This will only occur if the system has been opened up for repair, or if there is an air leak into a portion of the system which is below atmospheric pressure. Without such leaks, the system will hold a vacuum for several days after it is shut down.

4.3.2 Preliminary Design of the Phase II 150 kWe Power Generation Subsystem

4.3.2.1 Design Conditions and Performance

The design conditions for the 150 kWe power generation subsystem are shown in Table 4.3-1. Gross electrical generating capacity is 183 kWe based on supplying a net output of 150 kWe to irrigation pump motors while also supplying 33 kWe of auxiliary power. A breakdown of the auxiliary power loads is given in the discussion of the power distribution subsystem in section 4.5. Caloria HT-43 was selected as the collector and thermal storage heat transfer fluid as discussed in sections 4.1 and 4.2. The remaining design conditions were established during system analysis as discussed in section 3.

Figure 4.3-2 is a schematic of the 150 kWe version of the modified 600 kWe organic Rankine cycle, and indicates the flows, pressures, and temperatures throughout the cycle for a gross output of 183 kWe. The indicated 211.8 kW turbine shaft power is reduced to 183 kWe generator output on the basis of gearbox and generator efficiencies of 96% and 90%, respectively. Overall performance of the ORC is summarized in Table 4.3-2. Part load performance with constant auxiliary power is indicated in Figure 4.3-3.

4.3.2.2 Modifications to Basic 600 kWe ORC Design

The modifications required to adapt the existing 600 kWe ORC design for use in the Phase II 150 kWe application are described in the following paragraphs.

Feed Pump. The two stage feed pump will be modified to efficiently deliver the lower head and flow required by reducing the impeller diameter, vane widths, and diffuser flow areas. These changes can be made to the existing castings.

TABLE 4.3-1 FIXED DESIGN PARAMETERS FOR THE
POWER GENERATION SUBSYSTEM

● Net Power to Deep-Well Pumps	150 kWe
● Gross Power Generation	183 kWe
● Collector Heat Transfer Fluid	Caloria HT-43
● Heat Transfer Fluid at Boiler Inlet	600°F
● Boiler Pinch-point	15°F
● Condenser Cooling Water Inlet	80°F
● Toluene Condensing Temperature	100°F
● Turbine Inlet Temperature	550°F

Figure 4.3-2 Cycle Diagram and State Points for 150 kW_e Phase II ORC

TABLE 4.3-2 PHASE II POWER GENERATION SUBSYSTEM ORGANIC RANKINE CYCLE PERFORMANCE

Gross Power Generation	183 kWe
Auxiliary Power	33 kWe
Net Power to Deep-Well Pumps	150 kWe
<u>HEAT TRANSFER FLUID</u>	<u>CALORIA HT-43</u>
● Flow	7.019 lb/sec
● Boiler inlet temperature	600°F
● Boiler outlet temperature	408.8°F
● Heat input	3,044,000 Btu/hr
<u>WORKING FLUID</u>	<u>TOLUENE</u>
● Flow	3.490 lb/sec
● Boiler pressure (in vaporizer)	200 psia
● Turbine inlet temperature	550°F
● Condenser temperature	100°F
<u>CYCLE EFFICIENCY</u>	
● Based on Gross Output (183 kWe)	20.52%
● Based on Net Output (150 kWe)	16.82%
● Gross Heat Rate	16,636 Btu/kWh

4.3-11

Figure 4.3-3 150 kW_e ORC Part Load Performance

Boost Pump. A new electrically driven boost pump will be procured to deliver the lower flow requirements efficiently.

Turbine. The turbine nozzle ring will be modified to control the new flow conditions. Since the nozzle pressure ratio is increased and the flow rate is reduced, the new nozzle ring will have larger area ratio nozzles of smaller throat area which will result in approximately 1/3 of the nozzle annulus being unoccupied. The nozzle ring will fit into the existing turbine housing. There is sufficient flow area available in the 600 kWe wheel which will be retained for the Phase II demonstration unit. Using the existing wheel will result in a loss of only 3 percentage points in turbine efficiency.

Gearbox. In order to reduce the shaft tare losses, an off-the-shelf gearbox rated for the lower power will be procured.

Generator. For the same reason as the gearbox change, a new off-the-shelf generator will be procured.

Air Compressor. The pneumatic control power will be provided by a separate electrically driven air compressor. Estimated power requirement is 0.7 kWe for a 15 scfm, 100 psig unit.

Power Conversion Module. The component modifications just discussed will not alter the overall physical dimensions of the ORC power conversion module. The dimensions of the 600 kWe module are shown in the outline drawing, Figure 4.3-4, and are applicable for the 150 kWe ORC in the Phase II demonstration facility.

Boiler. The boiler is designed specifically for the 150 kWe solar powered application with Caloria HT-43 as the heat transfer fluid from the thermal

Figure 4.3-4 Outline Drawing, Sundstrand 600 kWe ORC Power Conversion Module

storage subsystem. The boiler is made up of a preheater section, evaporator, vapor separator, and superheater. Figure 4.3-5 shows the arrangement of the boiler components. The preheater section consists of three Graham #10-345 helical coil heat exchangers in series, with a total heat transfer surface of 327 sq ft. The evaporator is a standard TEMA-E single-pass, shell-and-tube heat exchanger design, with 490 sq ft of heat transfer surface, and is arranged for thermosiphon recirculation from the vapor separator. The superheater is a single Graham #30-28LL heat exchanger. The boiler and the piping for toluene flow between the boiler and the power conversion module will be insulated for minimal heat loss.

4.3.2.3 Additional Analysis in Phase II Final Design

There are several areas which will be investigated in depth during the Phase II detail design of the ORC to reduce parasitic loads and improve the efficiency of the power generation subsystem.

Several possibilities exist for reducing parasitic loads. These include the identification and use of higher efficiency motors for the boost pump, vacuum pump, and air compressor, and the reduction of control power requirements. Any increase in generator or gearbox efficiency would directly improve overall system efficiency. The generator and gearbox efficiencies of 90% and 96% which have been used are based on commercially available components and could possibly be improved without impacting the schedule for Phase II of this program.

It may also be possible to redesign the condenser heat exchanger core to reduce the pressure drop on the water side without reducing capacity, thus reducing cooling water pumping power requirements. While this may require

PRE-HEATER:
GRAHAM 10-34S

EVAPORATOR
AMERICAN STANDARD CPK 19144

SUPER-HEATER:
GRAHAM 30-28LL

- [A] 4" SCH 40
- [B] 3" SCH 40
- [C] 3" SCH 40
- [D] 3" SCH 40

4.3-15

Figure 4.3-5 Outline Drawing, 150 kW_e ORC Boiler Module

slightly more heat transfer area, the overall impact on system cost should be beneficial.

4.3.3 Power Generation Subsystem Controls

A simplified control block diagram for the ORC is shown in Figure 4.3-6. Major elements of the ORC controls are discussed in the following paragraphs.

4.3.3.1 Heat Flow Controls

The heat flow controls regulate the energy into the boiler by controlling the flow of the Caloria HT-43 from thermal storage. During startup, the flow control will limit the heat flow, determined by separator temperature and level, to prevent thermal expansion of the toluene from overflowing the separator. When the ORC is running in parallel with the utility grid, the flow control valve will be wide open and will be used to limit heat flow only in the event of high separator outlet temperature or high generator output power over a preset value. When powering the irrigation pumps independent of the utility grid, the heat flow controls will modulate the heat into the boiler to maintain control of the boiler separator temperature.

4.3.3.2 Throttle Valve Controls

The throttle valve controls regulate the energy to the turbine by controlling the position of the throttle valve. During startup, the throttle valve will open to accelerate the turbine, but once the turbine reaches operating speed, the throttle valve position will be modulated to provide constant speed control. In order to operate in parallel with the utility grid, the turbine speed will be controlled to provide synchronism between the generator output and the utility bus. Once the paralleling breaker has been closed, the throttle

Figure 4.3-6 150 kW ORC Control Block Diagram

valve control will shift to a temperature control mode, which modulates throttle valve position to maintain a constant boiler outlet temperature.

4.3.3.3 Liquid Level Controls

The liquid level controls regulate the toluene flow into the boiler by controlling the position of the level valve. During startup, the level valve maintains the separator liquid level at the start level, which is 40 inches below the full power running level, in order to provide for thermal expansion, while bringing the toluene up to temperature. During normal running, the liquid level controls will maintain the liquid level in the separator based on the generator output power. At no-load the liquid level will be maintained 24 inches below the full load liquid level. This is done to compensate for the volumetric expansion that would be caused by an increase in vapor generating rate.

4.3.3.4 Turbine Bypass Valve Controls

The bypass valve is used only during startup to provide a controlled toluene path around the turbine. The bypass valve controls provide the appropriate bypass valve position to act as a vapor flow limiter while the boiler is being heated up to temperature.

4.3.3.5 Non-condensable Removal Controls

The non-condensable removal controls detect the condenser temperature difference between the non-condensables and the toluene and provides a timed on/off cycling of the vacuum pump and solenoid valve to remove the non-condensables. The timed cycling of the vacuum pump is required to prevent flashing the hotwell due to reducing the condenser pressure too rapidly. During startup, the vacuum pump is turned on and off based on condenser

pressure until the condenser temperature rises to establish the non-condensable temperature difference.

4.3.3.6 Start Sequence

When power is first applied to the controls, the controls will prevent the system from starting until all start safeties indicate a safe condition and there is sufficient heat source temperature to run the system. The system safeties then reset. The annunciator will indicate what caused the previous shutdown until the safeties are reset.

Once the start requirements are met and when a start signal is received, the controls enable the non-condensable controls to pump down the condenser and turn on the appropriate cycle pumps and valves (lube pump, start pump, by-pass valve, level valve) to fill the boiler. When the condenser pressure is established and the boiler has been filled to the start level, the heat flow valve is partially opened to start heating the toluene in the vaporizer. When the boiler temperature reaches 300°F, the heat flow valve is allowed to open all the way and the turbine bypass valve is partially opened. When the boiler outlet temperature reaches 500°F, the bypass valve is closed, and the turbine stop valve and throttle valve are opened to accelerate the turbine to speed. When the turbine reaches operating speed, the start pump is turned off and the running safeties are enabled. The automatic synchronizer then temporarily takes over turbine speed control to synchronize the generator to the utility grid and close the paralleling breaker.

Figure 4.3-7 is a typical startup sequence diagram for the Sundstrand ORC.

Figure 4.3-7 Typical ORC Startup Sequence

4.3.3.7 Shutdown Sequence

Two shutdown modes are used in the ORC control system. The first mode is an emergency shutdown that is initiated in situations which require the turbine to be shut down immediately. When the immediate shutdown is initiated, all the valves are closed, the main breaker is opened, the start pump is turned on and the boost pump and lube pump are left on to provide spin-down lubrication for the gearbox and turbine. The second shutdown mode closes only the heat flow valve immediately and delays shutting down the turbine until the thermal energy in the boiler has been dissipated to the point of initiating a boiler under-temperature signal, which in turn initiates the turbine shutdown. The delayed shutdown mode is also initiated when the stop switch is used to shut the unit down. Five minutes after the turbine shutdown is initiated, the control power is turned off.

Figure 4.3-8 is a typical shutdown sequence diagram for the Sundstrand ORC.

4.3.3.8 Instrumentation

The ORC is fully instrumented for normal control and monitoring purposes. The Phase II prototype unit will be provided with additional instrumentation as necessary to provide the flow, pressure, and temperature data required for determining the efficiency of the unit for various operating conditions which may be imposed during field testing of the solar-powered deep-well irrigation facility.

4.3.4 Preliminary Design for a 150 kWe Production Version ORC

The design and performance of a commercial production version of the 150 kWe ORC suitable for the generic design application was developed as

Figure 4.3—8 Typical ORC Shutdown Sequence

the basis for making the production quantity unit price estimates which are in section 5. The basic configuration of the production version ORC is the same as that of the Phase II demonstration unit. However, the 150 kWe power conversion module would be physically smaller than the basic 600 kWe module due primarily to a smaller regenerator/condenser pressure vessel housing. Dimensions of the production 150 kWe power conversion module are shown in Figure 4.3-9. The boiler for the production version would be essentially the same as the boiler for Phase II which is shown in Figure 4.3-5.

The optimum configuration for the production unit was developed by Sundstrand using a computerized optimization routine which varies the system design to arrive at the minimum cost system within the limits of a given set of fixed parameters. This computer routine includes cost models of the turbine, feed pump, vaporizer, collector subsystem, thermal storage subsystem, condenser core, regenerator core and the condenser/regenerator housing. The ORC state points are varied and the effect on total system cost is determined. The program optimizes the cycle conditions to achieve the minimum total system cost. The fixed design parameters used in the optimization are as follows:

- Gross generator output 183 kWe
- Net system output 150 kWe
- Heat transfer fluid Caloria HT-43
- Heat transfer fluid temperature at boiler inlet 600°F
- Condenser cooling water inlet temperature 80°F

The resulting ORC state point conditions for the production unit are shown in the cycle schematic of Figure 4.3-10, and are very similar to the Phase II ORC conditions. The flow requirements for Caloria HT-43, toluene,

Figure 4.3-9 Outline Drawing, Sundstrand Production Version 150 kW ORC Power Conversion Module

4.3-25

Figure 4.3-10 Cycle Diagram and State Points for 150 kW_e Production Version ORC

and cooling water are substantially less than for the Phase II ORC due to changes which increase the efficiency of production unit. Performance of the production unit is summarized in Table 4.3-3 alongside the performance of the Phase II ORC for comparison.

Changes similar to those made for the Phase II demonstration ORC would be applied to the feed pump, boost pump, gearbox, generator and control valves. Other changes are described below.

4.3.4.1 Turbine

The single stage, supersonic impulse turbine configuration would be retained on the basis of its simplicity, relatively low cost, easy development and relatively high efficiency. Changes to the design for the 150 kWe production version would involve a new, smaller diameter, higher speed wheel design, and a new nozzle ring compatible with the wheel. The higher speed will necessitate a double reduction gearbox. The new turbine design will restore the turbine efficiency to 73%, the level predicted for the Sundstrand 600 kWe machine.

4.3.4.2 Regenerator

The thermal effectiveness of the regenerator would be increased from 94% to 95% by upsizing. This has the effect of reducing the heat load on the condenser and increasing cycle efficiency.

4.3.4.3 Condenser

The production version system was optimized at a condenser temperature of 100°F. The condenser core would be smaller due to the reduced heat rejection from the more efficient cycle.

TABLE 4.3-3 PRODUCTION VERSION POWER GENERATION SUBSYSTEM ORGANIC RANKINE CYCLE PERFORMANCE

	Phase II ORC	Production Unit ORC
Gross Power Generation (kWe)	183	183
Auxiliary Power (kWe)	33	33
Net Power to Deepwell Pumps (kWe)	150	150
<u>HEAT TRANSFER FLUID</u>	<u>CALORIA HT-43</u>	<u>CALORIA HT-43</u>
● Flow (lb/sec)	7.019	6.536
● Boiler inlet temperature (°F)	600	600
● Boiler outlet temperature (°F)	408.8	409.8
● Heat input (Btu/hr)	3,044,000	2,834,000
<u>WORKING FLUID</u>	<u>TOLUENE</u>	<u>TOLUENE</u>
● Flow	3.490	3.229
● Boiler pressure (psia)	200	200
● Turbine inlet temperature (°F)	550	550
● Condenser temperature (°F)	100	100
<u>CYCLE EFFICIENCY</u>		
● Based on gross output (183 kWe)	20.52%	22.03%
● Based on net output (150 kWe)	16.82%	18.06%
● Gross heat rate (Btu/kWh)	16,636	15,488

4.4 COOLING WATER SUBSYSTEM

The primary function of the cooling water subsystem is to provide condenser cooling for the power generation subsystem. A closed loop cooling arrangement using a spray pond for heat dissipation was selected for preliminary design of the site-specific Phase II demonstration facility as previously discussed in section 3.4. The use of a spray pond for the Phase II site provides a means for condenser cooling and continued power generation during the off-season from mid-September through December when irrigation pumping ceases and groundwater is not available for cooling. Once-through condenser cooling using pumped groundwater was selected as the baseline cooling method for the generic application in which irrigation pumping occurs year-round.

The preliminary design as developed for the site-specific Phase II cooling water subsystem is presented and discussed in detail in this section. The major effects of altering the design to use once-through cooling for generic application are also briefly discussed.

4.4.1 Cooling Requirements

The heat rejection duty for the cooling water subsystem is 2.5 million Btu/hr for full load operation at 183 kWe gross power output (150 kWe net). The design duty includes condenser cooling and allowances for the following auxiliary cooling loads: collector and boiler Caloria pumps stuffing boxes; organic Rankine cycle (ORC) turbine gearbox; ORC turbine bearings; and the ORC non-condensables cooler. Based on a 10°F temperature rise above a 80°F cold water temperature, the total cooling water flow for the design duty is 500 gal/min. A cold water temperature of 80°F, with a 10°F rise and a

10% condenser approach, results in the baseline toluene condensing temperature of 100°F selected during systems analysis of the power generation subsystem.

4.4.2 Cooling Water Subsystem Preliminary Design

The preliminary design of the cooling water subsystem is shown schematically in Figure 4.4-1. Cooling water is pumped from the spray pond, through piping to the condenser and equipment coolers, and back to the spray pond where it sprays upward into the air through spray nozzles. Heat transferred to the water in the condenser and equipment coolers is dissipated by evaporation of a small fraction of the water as it returns to the surface of the pond from the spray nozzles. Details on various aspects of the design are discussed in the following paragraphs.

4.4.2.1 Spray Pond Design

The spray pond is designed to cool 500 gal/min of water from 90°F to 80°F at a 70°F ambient wet bulb temperature. Ten spray nozzles are used in order to obtain the desired 10°F approach to wet bulb. The ten nozzles are grouped in two clusters of five nozzles each at a height of 5 feet above the pond surface. With a nozzle spray pressure of 7 psi, the conical spray pattern from each nozzle will rise to a height of 12 feet above the pond surface and will return to the surface on a diameter of 32 feet. The arrangement and spacing of the ten nozzles is such that the tangential perimeter of the total spray pattern at the pond surface is rectangular. A 10 foot clearance is provided between the spray perimeter and the banks of the pond to reasonably minimize drift losses, and results in pond dimensions of 60 feet wide by 73 feet long at the waterline. A pond depth of 3 feet was selected to reasonably minimize daytime ambient reheating of the water,

4.4-3

4.4-1 Phase II Cooling Water Subsystem P&ID

and results in a pond capacity of about 100,000 gallons. For preliminary design purposes it was assumed that a spray pond liner of 30 mil PVC will be required. The site soil survey and analysis which will be conducted at the outset of the Phase II program will determine whether a pond liner is necessary to control seepage loss.

4.4.2.2 Cooling Water Pumps

Two cooling water pumps are used in the preliminary design, each having a different function. The spray pond pump (P-201) starts automatically in the daily ORC startup sequence and provides the full 500 gal/min cooling flow required for normal power generation operation. P-201 is also stopped automatically as one of the last steps in the ORC shutdown sequence.

The auxiliary cooling water pump (P-202) starts automatically in the start sequence of the collector or boiler Caloria pumps and provides stuffing box cooling water for the Caloria pumps. P-202 stops automatically when normal full load cooling water flow from the spray pond pump is established. The small auxiliary cooling water pump was included in the preliminary design in order to avoid most of the larger power consumption that would be associated with running the spray pond pump during the hour or more of daily morning startup when the thermal storage tank is being charged prior to starting the ORC. During the Phase II final design an effort will be made to identify a standard design for the Caloria pumps capable of tolerating the 400-600°F fluid temperatures without water cooling. If that effort is successful, the auxiliary cooling water pump can be eliminated.

Both of the cooling water pumps are of a standard vertical-wet pit spump pump design, and take suction from a basin in the corner of the spray

pond nearest the power generation building. The pumps are protected against dry running by a float type level switch which will trip the pumps on low suction water level.

4.4.2.3 Spray Pond Makeup

With a 500 gal/min cooling water flow and a 10°F cooling effect, the maximum evaporation loss during operation of the spray pond is about 5 gal/min. The combined blowdown and drift losses from the spray pond should not exceed 1/2% of circulating water flows; therefore, the maximum cooling water loss is about 7.5 gal/min. On this basis, and assuming 12 hours per day operation, one-half of the spray pond water inventory would be lost in about 6 days. Makeup to the pond is provided from the discharge of deep-well pump C. The full output of well pump C would be required for about 90 minutes every 6 days during the off-season to refill the spray pond. During the irrigation season when well pump C operates continuously, the makeup to the spray pond can be accomplished at a much lower rate over a longer period of time without disrupting the normal irrigation operation. If well pump C is inoperable, makeup can also be supplied by gravity flow from the irrigation ditch supplied with water from either well D or E.

4.4.2.4 Water Treatment

Due to aeration of the cooling water in the spray pond, there is a high probability of condenser tube fouling and reduced heat transfer by the formation of aerobic bacterial slime. A small hypochlorinator is included in the preliminary design as the simplest means of controlling condenser fouling. A one hour per day dose of 5 ppm chlorine equivalent is considered adequate for the control of bacterial slime, and results in a 5 gallon per hour feed rate of a 3% solution of sodium hypochlorite at the condenser

cooling water inlet. A 50 gallon (10 day capacity) 3% solution is mixed periodically as needed from a 50 gallon (30 day capacity) 15% sodium hypochlorite drum. In addition, the water treatment system will be designed to control any algae growth which would otherwise occur in the spray pond.

4.4.3 Cooling Water Subsystem for a Generic Application

As discussed in section 3.4, the baseline cooling water subsystem for a generic application would involve once-through condenser cooling. With once-through cooling, some of the water pumped by the deep-well pump(s) passes through the condenser enroute to either the irrigation ditches for gravity (flood) irrigation, or to spray heads for sprinkler irrigation. Because of the year-round irrigation water demand associated with the ERDA-specified generic application, groundwater would be continuously available for condenser cooling, and a spray pond or other means of off-season cooling would not be necessary.

The design of the once-through cooling system is site-dependent to the extent that several deep-well pumps having different pumping capacities may be involved, as is the case for the Phase II demonstration site. In that case, it may be that the output of more than one deep-well pump would be required in order to supply the 500 gal/min cooling requirement. Combining the outputs of two pumps and piping the flow to the condenser would be impractical unless the two pumps are located close to each other and close to the space available for the solar-powered irrigation facility. Redistribution of the water to the desired points of use may also be impractical, especially for sprinkler irrigation systems.

Alternatively, if a single 150 kWe (200 hp) deep well-pump is involved, its output would be in the range of 1000 to 2000 gal/min for the ERDA-specified range of pumping depths to be considered. Passing the full output of a single 200 hp pump through a condenser designed for 500 gal/min cooling flow is impractical due to the much higher pressure drop which would occur. Given a limit on the total pumping power available, any increase in pumping power required to overcome increased condenser pressure drop effectively reduces the amount of irrigation water which could otherwise be delivered.

In view of these practical considerations regarding the use of once-through cooling, it is reasonable to define a generic design which uses a dedicated condenser cooling water pump having the same function as the spray pond pump in the Phase II preliminary design. The once-through cooling water pump could take suction from an irrigation ditch for gravity flow irrigation applications, or from a small basin supplied with water from the sprinkler header pipe, for sprinkler applications. In the latter case the head developed by the cooling water pump must be sufficient to supply the sprinkler pressure required.

4.5 POWER DISTRIBUTION SUBSYSTEM

The 150 kWe net output of the Phase II solar generating facility will be used to power three deep-well irrigation pumps, designated as Wells C, D and E, which are presently receiving power from the local electrical cooperative, Electrical District No. 2 (ED #2). Power from ED #2 will continue to power the pumps at night, or at any other time during the irrigation season when the solar generating facility is not operating. However, when the facility is operating, it must be capable of supplying power to the three pumps, independent of the utility supply. Given that the solar collector and thermal storage subsystems for the Phase II demonstration facility are not sized to provide electrical output for 24 hour per day operation of irrigation pumps, the design criterion discussed in section 3.5 is applicable, and the design for transferring of power supply to the pumps shall not require a pump shutdown and restart. As was also discussed in section 3.5, provisions must be included in the system design to permit feeding the generator output directly into the ED #2 grid during the irrigation off-season when the irrigation pumps are not operated. Auxiliary power required for normal startup and shutdown of the facility is available from the ED #2 grid.

The preliminary design of the power distribution subsystem as developed to satisfy the above criteria is presented in this section. Included within the scope of the power distribution subsystem is the electrical switching interface between the facility and ED #2; new power distribution lines from the facility to pumps at Wells C, D, and E; internal distribution of auxiliary power; and provisions for emergency power supply.

4.5.1 Existing Power Supply

Electric power is presently supplied to deep-well pumps at Wells C, D, and E via the ED #2 12.5 kV, 60 Hz, 3-phase overhead distribution lines. These lines are energized from the ED #2 115 kV/12.5 kV Signal Peak Substation, located approximately two miles distant from the wells. The 12.5 kV distribution voltage is stepped down to 440 volts by a 3-phase pole-mounted transformer located adjacent to each pump, and is delivered to each pump motor via a manually operated reduced voltage starter at each pump.

All pump motors are 440 volt 3-phase, with motor ratings as follows:

- Well Pump C - 125 hp
- Well Pump D - 150 hp
- Well Pump E - 75 hp

4.5.2 Electrical Interface and Power Distribution

The power distribution subsystem preliminary design is shown in the electrical single line diagram, Figure 4.5-1. Major components of the system are the generator circuit breaker; the generator step-up transformer; the 12.5 kV utility tie circuit breaker; the 12.5 kV, 3-phase distribution feeder to the well pumps; and the 12.5 kV double-throw disconnect switch located at each well pump.

The double-throw disconnect switches at the well pumps permit the connection of any pump motor to either the existing ED #2 supply feeder or to the new 12.5 kV dedicated facility distribution feeder. Each switch is rated at 14.4 kV, 600A, and is pole-mounted hook-stick operated. Power

4.5-3

Figure 4.5-1 Power Distribution Subsystem - II last Single-Line Diagram

is delivered to the motors from either 12.5 kV feeder via the existing step-down transformer and motor starter at each pump.

The new 12.5 kV distribution feeder receives power from the high side of the generator step-up transformer, which is in turn energized by the generator of the power generation subsystem via the generator circuit breaker as previously discussed in section 4.3. The generator transformer is pole-mounted; rated at 480 V/12.5 kV, 225 kVA, 3-phase, 60 Hz; and is oil-immersed, self-cooled. The high side of the transformer is protected by current limiting fuses and surge arresters.

Interconnection of the new facility distribution feeder and the existing ED #2 supply feeder is accomplished via the utility tie circuit breaker. The tie circuit breaker is rated 14.4 kV, 600A; and is 3-phase, oil filled. A circuit breaker was selected as the switching device between the solar facility and ED #2 because its stored energy type operator is required for coordination with the automatic synchronizing equipment in the power generation subsystem. The synchronizer ensures that the solar-powered generator is not connected in parallel with the utility grid unless the two systems are operating in synchronism.

The new 12.5 kV feeder to the well pumps consists of three overhead pole-mounted conductors, routed in a radial fashion from the facility to the three well pumps, as was shown in Figure 4.5-1. The most economical method of running the new feeder would be to under-hang it on the existing ED #2 pole line. This would not be permissible, however, due to minimum ground clearance requirement of 35 ft. The existing ED #2 feeder is hung at the minimum ground clearance height, and it will be necessary to replace

the existing poles with taller ones which will permit under-hanging the new feeder, or to run the new feeder on a new string of poles. The latter method may require encroachment on cropland, which would not be desirable. Therefore, the preliminary design is based on the assumption that the new feeder will be under-hung on new taller poles. The validity of this assumption will be further investigated during initial stages of the Phase II final design.

4.5.3 System Operation

During the irrigation season all three well pumps are normally connected to the new 12.5 kV distribution feeder via the manually operated disconnect switch at each pump. When the solar facility has been shut down at night, the generator breaker is open and the utility tie breaker is closed, thereby supplying ED #2 power over the new feeder to the running pumps. During morning startup, as soon as sufficient thermal energy is available, the turbine-generator is brought up to rated speed, and is synchronized with the utility. The generator breaker is then closed, paralleling the generator with the utility system. Generator load is then increased until it slightly exceeds the load demand of the running pumps. This condition activates a reverse power relay on the utility side of the tie-in and causes the utility tie breaker to be opened. The solar generating facility then powers the deep-well pumps independent of the ED #2 system, with the turbine speed controls maintaining generator frequency approximately equal to ED #2 frequency. This normal operating condition would continue until a predetermined lower limit of thermal energy storage capacity is reached. When the predetermined lower limit of available thermal energy is reached, indicating that turbine-generator shutdown is imminent, the turbine-generator is re-synchronized with the utility system, and the utility tie breaker is closed. The generator

breaker is then opened as part of the power generation subsystem shutdown sequence. These switching operations are automatically initiated by logic signals generated by the facility instrumentation and control systems and accomplish the transfer of power supply between the solar-powered generator and the utility system with no interruption of service at the pumps.

Any one of the well pumps may be disconnected from the new 12.5 kV feeder and connected directly to the existing utility feeder by stopping the pump, manually operating the double-throw disconnect switch at the pump, and manually restarting the pump. This provision is included primarily for operational testing flexibility.

During the non-irrigation season the well pumps are not running and the utility tie breaker is maintained closed by a mode selector switch. When sufficient thermal energy is available to run the turbine-generator, the unit is brought up to rated speed and synchronized with the utility. The generator breaker is then closed, and the generator is controlled to supply maximum power to the utility system.

4.5.4 Auxiliary Power Supply

The auxiliary electrical power requirements of the facility are summarized in Table 4.5-1 for startup, daytime operation, and evening operation modes of operation, as well as for emergency shutdown situations.

The auxiliary power distribution system, which is also shown in Figure 4.5-1 consists of a 480 volt motor control center, a 480 V/120-240 volt step-down transformer, and a 120-240 volt distribution panel. A 15 kWe,

TABLE 4.5-1 AUXILIARY POWER REQUIREMENTS

Load Description	Startup		Daytime Operation		Evening Operation		Emergency Shutdown	
	Load (kWe)	Duration (min)	Load (kWe)	Duration (min)	Load (kWe)	Duration (min)	Load (kWe)	Duration (min)
Collector Field Tracking Motors	7.3	60	7.3	Continuous	0	-	12.1	15
Collector Field Caloria Pump	3.7	60	3.7	Continuous	0	-	0	-
Boiler Caloria Pump	0	-	2.2	Continuous	2.2	Continuous	0	-
Cooling Water Spray Pond Pump	0	-	8.7	Continuous	8.7	Continuous	0	-
Auxiliary Cooling Water Pump	0.25	60	0	-	0	-	0	-
Controls and Instrumentation	3	60	3	Continuous	3	Continuous	2	15
Power Generation Subsystem	0	Continuous	6.4	Continuous	6.4	Continuous	0	-
Total*	14.3	-	31.3	-	20.3	-	14.1	-

* Represents maximum coincident demand

120-240 volt gasoline engine powered emergency generator set is included to provide a source of emergency power.

4.5.4.1 Normal Auxiliary Power Supply

During normal facility operation, at which time the facility is operating with the main generator breaker closed and the utility tie breaker open, all auxiliary power is supplied by the main generator via the 480 volt motor control center. The 480 volt motor control center bus is connected to the line side of the main generator circuit breaker and is protected by a 70 amp circuit breaker. Power is delivered directly to the individual auxiliary loads via 480 volt combination motor starters, 480 volt circuit breakers, or is stepped down to 120-240 V for delivery to those loads on the 120-240 volt distribution panel. All circuit feeders are installed in conduit, which may be either above or below ground depending on the location of the load.

The emergency generator transfer switch connects the collector field drives, and critical instrumentation and control supply circuits to the normal power supply as long as adequate voltage is present at the 120-240 volt distribution panel.

4.5.4.2 Startup and Normal Shutdown Auxiliary Power Supply

During facility startup, at which time the main generator circuit breaker is open, or during normal shutdown, when main generator output may be insufficient to supply the auxiliary load demand, auxiliary power is supplied by the ED #2 grid. The utility tie breaker is closed at these times, to supply utility power to the well pumps during the irrigation season, or to connect the facility directly to the utility grid during the off-season.

The utility power is back-fed through the main generator transformer and is distributed to the loads in the same manner as described above for normal operation.

4.5.4.3 Emergency Power Supply

In the event of the loss of all normal power supply (i.e. main generator and utility supply) the emergency generator transfer switch senses the loss of voltage at the 120-240 volt distribution panel and initiates an automatic start of a 15 kWe gasoline engine powered emergency generator. The transfer switch contains time delay relays which delay the engine start signal by about one second to prevent unnecessary starts. When the generator is up to rated speed and is ready to accept load (about 10 to 15 seconds), the transfer switch operates to isolate the collector field and critical control and instrumentation supply circuits and to connect them to the emergency generator output. The generator supplies sufficient power to stow all collectors and accomplish a safe and orderly facility shutdown. A small battery charger is included to recharge the engine cranking battery. An exerciser timer periodically starts and runs the engine-generator set to ensure its availability when needed.

4.5.5 Grounding and Lightning Protection

Electrical grounding for the facility is accomplished via direct buried copper conductors and driven ground rods. All facility equipment, including pumps, motors, storage tanks, heat exchangers, and metal structures, are connected to the grounding system. Metal reinforcing bars in all concrete pads and foundations are also bonded to the ground grid.

Metal air terminals are located on the thermal storage tank to provide protection against direct lightning strikes.

(to be prepared by Acurex)

4.7 DATA ACQUISITION SUBSYSTEM

(to be prepared by Acurex)

4.8 FOUNDATIONS

Foundation designs were developed for the generic designs of the collectors, the thermal storage tank, the power conversion module, boiler, and the buildings. Owing to the lack of soil data, site-specific designs could not be developed for the Phase II application.

4.8.1 Collector Foundation Design

Because the collector foundations will be a significant portion of the total facility cost, the major effort in the foundation design task was directed toward arriving at a cost-effective collector foundation design suitable for economical mass production in the field. A total of 918 collector foundations will be required of which 102 are for the drive supports and the remaining 816 are for the non-drive supports (see Section 4.1). The drive supports have higher design loads than the non-drive supports. Seven different collector foundation types for both the drive and non-drive supports were investigated. Cost-sensitive parameters were identified and relative costs determined. Based on the results of this investigation, a drilled cast-in-place caisson (pier) was selected.

4.8.1.1 Generic Design Criteria for Collector Foundation Design

The design criteria that determined the generic collector foundation design are those related to wind pressure.

Two basic criteria were used in the collector foundation design:

- Collector sway at a height of 4 feet above ground resulting from foundation rotation must be limited to less than 0.5 inch during operational periods when wind speeds are less than 40 mph.

- No significant permanent displacement of the collector foundation should occur under the maximum loading condition, which occurs with the survival wind of 100 mph.

The first criterion is required to maintain collector deflections within an acceptable limit so that a standard group of eight collectors can be driven by a common tracking mechanism and motor. Also, minimal deflection is necessary to maintain the focussed beam on the concentrating collector's receiver tube.

An Acurex standard group of collectors consists of eight trough-type concentrating reflectors, each approximately 10 feet long and 6 feet wide, separated by a gap of approximately 6 inches. At each gap is a support. There is one drive support at the center of the group and four additional supports on either side of the central drive support for a total of nine supports per group. During operation the drive motor and gear mechanism exert a torque on the drive support on which they are located, hence the design axial and lateral loads for the collector foundation for the drive support are greater than those for the non-drive supports. Although the non-drive supports at the ends of each collector group theoretically carry a lesser load than the non-drive supports in the middle of the group, all non-drive support loads were assumed to be equal for foundation design purposes. Each collector support post consists of a 4 inch square, 1/4 inch wall, 42 inch long steel tube welded at the bottom to a pair of 4 inch x 4 inch, 1/4 inch thick angles. The angles are located approximately 6 inches above the top of the foundation to allow for levelling of the collector modules and are connected to the foundation by four bolts spaced 8 inch on centers.

Depending on the spatial and temporal variation of wind speed and direction integrated over the surfaces of the eight connected collectors, it is possible for support posts to be deflected in different directions. Such differential deflections, if large enough, could cause deflections of the receiver tube relative to the concentrating reflector surface resulting in the displacement of the focussed image away from the receiver tube. Therefore, it was decided that collector sway at 4 ft above ground resulting from foundation displacement should be limited to 0.5 inch.

It should be noted that the total sway of the collector results not only from foundation displacement but also from:

- elastic elongation and compression of the anchor bolts
- warping of the base angles, and
- elastic deflection of the 4 inch square tubular support post, acting as a cantilever beam.

The maximum loading condition (maximum bending moment) occurs with the survival wind speed (100 mph) when collectors are in a stowed position (face down). The collectors are stowed when the wind speed exceeds 50 mph. Moments and forces on the collector foundations were computed by Acurex based on wind tunnel test data for collectors similar in design to those proposed for this facility. Wind tunnel tests were conducted at wind speeds of 100 mph.

Maximum loading conditions on collector foundations for the 100 mph survival winds are summarized below:

Load	Non-drive Support	Drive Support
Maximum Vertical Force	1,870 lb	1,870 lb
Maximum Lateral Force	660 lb	660 lb
Maximum Bending Moment	4,360 ft lb	14,879 ft lb

The forces and moments at the 40 mph operational wind speed were computed by scaling down from the survival loads using the wind equation 4 of ANSI A58.1 1972.

4.8.1.2 Collector Foundation Design Alternatives

The following seven alternative designs for collector foundations were considered:

- Drilled caisson
- Spread footing
- Precast concrete pile
- Steel pipe pile
- Steel H-pile with cap
- Steel H-pile without cap
- Timber pile

Design details were developed for each of the foundation alternatives so that each alternative would meet the design criteria described above. Then, based on the design details, cost estimates were made to compare the installed costs of each alternative. The results of this comparison are summarized in Table 4.8-1. The drilled, cast-in-place concrete caisson was found to be the lowest cost foundation, slightly less expensive than the second best alternative, the timber pile, and significantly less expensive

than any of the other foundations. On the basis of cost and other factors discussed below, the drilled, cast-in-place concrete caisson was selected as the design for the irrigation facility's collector foundations.

A brief summary of design details of each of the collector foundation design alternatives is presented below.

TABLE 4.8-1 COLLECTOR FOUNDATION COST RATIOS

Foundation Description	Cost Ratio
Drilled Caisson	1.00
Spread Footing	1.26
Precast Concrete Pile with Cap	1.55
Steel Pipe Pile with Cap	1.94
Steel H-Pile with Cap	1.80
Steel H-Pile without Cap	1.49
Timber Pile	1.03

Drilled Caisson. The drilled, cast-in-place concrete caisson was found to be the most cost-effective foundation design. One design was developed for both the drive and non-drive supports. This design is illustrated in Figure 4.8-1. The caisson is 2 ft in diameter and is drilled 12 ft deep into the ground. The top projects 6 inches above the natural ground surface to protect the base from moisture, corrosion, and wind-driven sand. The caisson is reinforced with steel reinforcement bars as shown in the figure.

Spread Footing. The spread footing foundation for the drive support as shown in Figure 4.8-2 is a 7 ft long, 4 ft wide, 2 ft deep, cast-in-place con-

Figure 4.8-1 Drilled Concrete Caisson

Figure 4.8-2 Spread Footing

crete footing resting 18 inches below the ground with the 7 ft face perpendicular to the axis of rotation of the collectors. The spread footing for the non-drive support is slightly smaller due to the lower design overturning moment. To provide resistance to temperature and shrinkage stresses, the footings for both the drive and non-drive supports are nominally reinforced with preassembled steel reinforcing bars.

Precast Concrete Piles. This foundation is shown in Figure 4.8-3. It consists of a single 12 inch square precast concrete pile driven to a tip elevation which is 13 ft below the ground surface for the non-drive supports and 15 ft 6 inches below the ground surface for the drive supports. The top of the pile is cut off at 6 inches below the ground and is provided with a 2 ft 6 inch square cast-in-place reinforced concrete cap. The concrete cap is required to set the anchor bolts accurately and to provide a transition for the transfer of vertical and lateral forces from the support to the pile. The prestressed reinforcing would have to have adequate embedment in the cap, and the cap would have to be provided with nominal reinforcing to resist shrinkage and temperature stresses.

An alternate concept was considered of embedding anchor bolts directly in the pile so as to eliminate the cap; however, it is extremely difficult to drive piles to close tolerances. Consultation with pile driving contractors revealed that the usual tolerances for the short lengths of piles being considered would be 2 inches.

Steel Pipe Pile. This alternative is very similar to the previous one. The only difference is that the precast pile is replaced with a 12 inch diameter open-ended standard-weight steel pipe (see Figure 4.8-4). The required

Figure 4.8-3 Precast Prestressed Concrete Pile Foundation

Figure 4.8-4

Steel Pipe Pile Foundation

pile embedments are 16 ft 6 inches for the drive supports and 12 ft 3 inches for the non-drive supports.

One of the major problems with this type of foundation is the possibility of corrosion. As a conservative assumption, the relative cost estimates summarized in Table 4.8-1 included the cost of cathodic protection.

Steel H-Pile With Cap. This alternate is also similar to the precast concrete pile. Here the precast concrete would be replaced with a 12 inch steel H-pile weighing 53 lb/ft (see Figure 4.8-5). This alternate may also require cathodic protection for protection against corrosion. The estimated pile embedment lengths are 17 ft for the drive supports and 12 ft for the non-drive supports.

Steel H-Pile Without Cap. This alternative is a variation of the steel H-pile foundation with cap previously described. As shown in Figure 4.8-6 this pile has the same dimensions and tip elevation; however, the overall pile length is 1 ft 9 in longer and is assumed to project 1 ft 3 inches above the ground. The attempt here was to eliminate the cost of the cast-in-place concrete cap and its reinforcing cage. This concept has the same potential corrosion problem as the two previous alternatives. The cost of cathodic protection has been accounted for in the cost estimate although it may not be required depending on the pH and resistivity of the soil.

The other advantage of this concept over the steel H-pile concept is the elimination of the pair of angles at the base of the support and a reduction in the number of bolts from four to two. However, as mentioned earlier, the top of the pile could be 2 inches off the actual centerline of the support

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Figure 4.8-5 Steel H-Pile with Cap

Figure 4.8-6 Steel H-Pile Without Cap

and a considerable amount of labor in shimming and levelling would be added if the piles deviate from the correct support locations.

Timber Pile Foundation. This foundation consists of a timber pile with a minimum diameter of 14 inches at the top. This pile would conform with the requirements of ASTM D25-70 "Standard Specifications for Round Timber Piles" for friction piles. The minimum recommended embedment length below ground for both drive and non-drive supports is 13 ft. The pile extends 18 inches above the ground for a total length of 14 ft 6 inches. To connect the pile to the collector support, the pile is provided with a 16 inch square, 3/8 inch thick cap plate, at the bottom of which are welded four 15 inch x 6 inch x 1/4 inch thick straps as shown in Figure 4.8-7. The top of the pile is dapped to accommodate the cap plate and is connected to it with two 1 inch diameter, 15 inch long bolts.

There are several disadvantages to this concept. The pile would have the same alignment problems as the steel H-pile without cap. These alignment problems could be eliminated by proper dapping and drilling of the cap plate mounting holes in the field; however, this would increase the field labor costs. The timber would be exposed to the weather and hence be subjected to expansion and contraction due to changes in moisture content, and the cap plate mounting bolts may require periodic inspection tightening.

4.8.1.3 Advantages of Caissons

Economy. As previously mentioned, the principal reason for using drilled caissons in preference to other types of deep foundations is to minimize cost. In ground where soil, rock, and groundwater conditions are suitable for their use, caissons cost less than other types of foundations

Figure 4.8-7 Timber Pile Foundation

per unit of load carried. The potential economic advantage of drilled caissons comes from the fact that rotary drilling is a rapid and inexpensive way of excavating, provided:

- a circular excavation, usually with its length substantially greater than its diameter, can be adapted to the proposed structural requirements;
- the soil to be excavated can be cut readily with rotary drilling tools; and
- the soil does not cave or flow into the hole.

As any one of these conditions diminishes, the cost of drilled caissons increases. However, there are ways of circumventing difficulties due to ground conditions, and even in the absence of ideal conditions, drilled caissons often retain an effective cost advantage.

Rapid Completion. The rapid completion of caisson construction not only expedites the foundation phase of the project, but can also expedite subsequent operations because of minimal interference with other construction operations.

The caisson is small enough in diameter and length to permit the use of a truck-mounted drill rig with an open helix auger with a knife cutting edge. This foundation system permits use of an assembly line technique in the field. The drill rig would be followed by:

- A truck to remove the excavated material to the plant area where it will be reused for the fire protection berm construction around the thermal storage tank;
- A truck carrying the pre-fabricated reinforcing cages attached to the anchor bolt assemblies;
- A concrete mixer carrying an elephant trunk type of funnel to prevent segregation of concrete as it is poured down the hole.

Concrete Formwork is Minimized. In reinforced concrete work, the cost of formwork usually exceeds the cost of the concrete and reinforcing. The minimization of costly formwork is the main reason for the savings in cost and time when compared to conventional excavation and footing construction. For the selected configuration, formwork will be required only near the top 6 inch portion projecting above the ground.

Heave and Ground Displacement is Eliminated. When piles are driven, ground heave and lateral displacement of previously driven piles becomes a major problem. This is eliminated in drilled caissons because the drilled material is excavated and hauled away for use in backfilling operations.

Ability to Resist Lateral Loads. Drilled caissons can be designed with a much higher ultimate resistance to lateral deflection than can be obtained with an economical equivalent spread footing or pile foundations.

Availability of Drilling Rigs. Since the job site is located in an area where drilling rigs are commonly used for wells, this type of foundation system will be time and cost effective due to the of local availability of equipment.

4.8.1.4 Disadvantages of Caissons

Drilling should be stopped in bad weather. Wet weather interferes with caisson drilling and concreting to a much greater extent than with pile driving.

More complete soil exploration is needed. For drilled caisson applications the soil investigation needs to be more thorough than for most other types of deep foundations.

Inspection and technical supervision are critical. This is especially true for the concreting phase to ensure that the hole is clean and no pockets of soil are entrapped within the concrete.

Prior preparation for possible unfavorable conditions. Metal casings or cardboard sono-tube type forms should be kept on hand in case unfavorable soil conditions are encountered.

Prevention of quantity overrun. Failure on the part of the driller to stop the drilling operation when specified depth is reached can cause major increases in caisson costs due to the increased quantity of concrete to be poured in the hole. The method of reimbursement of the driller should be based on specified depths rather than actual depths drilled in the field.

4.8.2 Turbine/Generator Foundation

The foundation consists of a 23 ft long and 17 ft wide concrete pad which is 3 ft thick. It projects 6 inches above the normal grade. The concrete strength was assumed to be 3000 psi at 28 days. The foundation has a top and bottom mat of reinforcing bars as shown in Figure 4.8-8 to resist shrinkage and temperature stresses.

The foundation design approach was based on two Bechtel design guides (see references 4.8-1 and 4.8-2).

The turbine and generator will be mounted on separate skids, comprising the power conversion module, and the skids bolted down to the foundation. The main objective of the design was to limit vibrations

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Figure 4.8-8 Power Generation Components Foundation

amplitudes to values that are permissible. Excessive motions of a machine cause distress to couplings, wear of bearings and may result in unsafe operation or necessitate shutting down the machine for repairs. Rigidity of the machine foundation is essential, since a deflection of a few thousandths of an inch may cause a bearing disturbance. Machines with operating speeds greater than 1000 rpm, as is the case here, are classified as high-speed machines. In such cases, a flexible or low-tuned foundation with sufficient stiffness to maintain alignment, is necessary. The first natural frequency of the system must be 40 to 50 percent lower than the forcing frequency, corresponding to the operating speed of the machine.

Since the foundation is comparatively rigid in the two horizontal directions, the foundation design for this condition will not be critical. In order to minimize transmission of vibrations to the building structure it was deemed advantageous to isolate the foundation from the building slab by a construction joint.

4.8.3 Boiler Foundation

The boiler is supported on a concrete pad 8 ft long and 6 ft wide as shown in Figure 4.8-8. It is 2 ft deep and has a rebar mat at the bottom, mainly to resist shrinkage and temperature. A total boiler weight of 24,000 lb was used in the design. Since the power generation building is an "open" type design, wind pressure was more critical than seismic forces in the design of the boiler foundation. The design wind pressure was conservatively assumed to be 35 lb/sq ft.

4.8.4 Foundation for Thermal Storage Tank

The foundation (see Figure 4.8-9) is constructed of a 17 ft top octagon on a 28 ft bottom octagon each having a thickness of 2 ft. The dimension of the top octagon was selected to accommodate the 11 ft diameter tank which is supported by a skirt. The tank has insulation which is approximately 1 ft thick. The top octagon will provide for an approximately 2 ft wide path around the tank perimeter for maintenance and access. The dimension of the bottom octagon was selected such that the whole bottom of the foundation is always subjected to compressive soil pressure, even for the adverse load combination of dead and seismic loads. The seismic (rather than wind pressure) overturning moment governed the design, because of the tank's weight and high center of gravity.

The allowable soil pressure at a depth of 4 ft is estimated to be in excess of 3000 lb/sq ft. The maximum net soil bearing pressure under the worst loading condition is less than 2150 lb/sq ft, which is less than the estimated allowable value. For this all-compressive soil-foundation interface pressure and low soil bearing pressure condition, the soil may be considered to remain in the elastic range. This therefore precludes a permanent uneven settlement of the foundation. Assuming a concrete strength of 3000 psi at 28 days and grade 60 (ASTM A615) reinforcing with a yield point of 60 ksi, the required reinforcing to resist the bending moment, shear and punching shear are as indicated in the Figure 4.8-9.

The temperature of the skirt at the base of the thermal storage tank is expected to vary from 400°F to 600°F during a period of 24 hours. This will result in radial and circumferential expansion and contraction of the

tank and skirt. A pair of Lubrite plates and Sauereisen F-100 grout will be provided at the skirt-foundation interface to prevent deterioration of the top of the foundation due to the high temperatures and thermal cycling. This combination has typically been used by Bechtel in refinery applications under similar loading conditions and found to be satisfactory. Sauereisen grout resists temperatures to 1000°F with minimal change in physical properties.

Other foundation systems considered included:

- a square spread footing of uniform depth
- a caisson foundation with 24 caissons and a cap.

However these were found to be uneconomical.

4.8.5 Building Foundations

4.8.5.1 Control Building

The control building has load-bearing exterior and interior walls which rest on a nominally thickened edge of the concrete slab as shown in Figure 4.8-10. This thickened edge serves as the building's foundation.

4.8.5.2 Power Generation Building

This is a Butler type SBF II building with a 35 ft clear span. The building has an open design and is provided with cross-bracing to resist lateral forces. The building is 40 ft long in plan and has 6 supporting columns. The columns are supported on 2 ft square concrete pilasters which extend 2 ft 6 inches above the ground as shown in Figure 4.8-11. The foundations at each of the 6 column locations consist of a 4 ft. square and 2 ft deep spread footing with nominal reinforcing to resist shrinkage and temperature stresses (see Fig. 4.8-8).

Figure 4.8-10 Control Building Foundation

Figure 4.8-11 Power Generation Building Foundation

4.9 SITE LAYOUT AND IMPROVEMENTS

In this section the layout of the subsystem components of the irrigation facility on the site selected by ERDA for Phase II is discussed. Also discussed are general site improvements of the balance-of-plant, including roads, drainage, and buildings.

4.9.1 Site Layout

4.9.1.1 Architectural Considerations

An artist's concept of the solar-powered deep-well irrigation facility was prepared under the project architect's supervision and is shown in Figure 4.9-1. The uniqueness of this plant is identifiable by the major elements of the plant--the collectors and the vertical thermal storage tank. The symmetrical and axial relationship of these elements forms the principal architectural design feature. The design goal was to meet the functional requirements and to make the plant aesthetically compatible with the environment.

The thermal storage tank is the point of visual orientation to the site, and the main road into the plant site is aligned with its north/south axis. The approach to the site provides an uninterrupted view of the collector field, the thermal storage tank, and the control and power generation buildings. The complete process of electric power generation from solar energy, including the collectors, thermal storage tank, boiler, turbine-generator, and power distribution lines to the deep-well pump, is perceived in one panorama.

Figure 4.9-1
Artist's Concept - 150 KWe Solar - powered
Deep-well Irrigation Facility

4.9.1.2 Site Plan

As mentioned in section 2.2, the site for the Phase II prototype solar-powered irrigation facility is located on the Dalton Cole farm approximately 40 miles southeast of Phoenix and 5 miles southwest of Coolidge. The 40-acre parcel of land available for the facility is square in plan, with Well C located on its southeast corner. The actual plant occupies a total of about 8 acres (550 ft by 620 ft) at the southeastern quarter of the site near Well C. The western boundary of the site is approximately 2000 ft from the Eleven Mile Corner Road which runs north to south as shown in Figure 4.9-2. The entrance to the plant is in the southeastern corner and will require an access road running east-west, approximately half a mile long, to connect the plant with the Eleven Mile Corner Road. The balance-of-plant is located on the eastern face of the site to minimize the piping lengths and overhead power distribution lines to Wells C, D, and E. Another reason for this location is to locate the spray pond in the prevailing downwind direction from the collector field, so as to minimize drift deposition on the collector surfaces.

4.9.1.3 Plot Plan

Figure 4.9-3 shows the key features of the plot plan. The arrangement is dictated by the orientation of the collectors which rotate about north-south axis tracking the sun from east to west. The collectors are arranged in 18 rows at 20 ft on centers. Each collector group consists of 8 collector modules and there are six groups per row, except for the two back rows which have three groups per row. The east-west central axis of the collector field has a clear space of 15 ft 6 inches, in which supply and return piping headers for the collector heat transfer fluid are located. Except for this central

Figure 4.9-2 Site Plan

4.9-5

Figure 4.9-3 Plot Plan

axis, spacing between collection groups is 5 ft 6 in. The collectors occupy an area of about 4 acres, 545 ft 6 inches in length and 346 ft in width.

The thermal storage tank is located approximately 50 ft away from the nearest collector. It is provided with a nominal 3 ft high containment berm with 2:1 side slope to contain accidental leakage. Oil spills will be drained away from the tank and building area to a catch basin or burn-off pond located 100 ft to the north through a gravity-flow open channel. The necessity for a drainage basin for the oil is dictated by the high temperature of the oil and the need to drain it away from the tank, buildings and the turbine/generator. The flash point temperature for Caloria HT-43 is 400°F. Since the oil will be more than 200°F above this temperature, exposure to a spark or flame will cause ignition of the oil. The possible burning of the total tank oil inventory of about 8000 gallons within a short distance of the buildings should be avoided. Without the drainage basin, more expensive design features for protection of equipment and building materials would be required. Storm drainage will also be directed to the same catch basin. The capacity of the catch basin is 13,000 gallons. The capacity of the diked area around the thermal storage tank is approximately 18,000 gallons.

The north-south paved road provides convenient access to all the equipment areas, the control building, the power generation building, the spray pond and the thermal storage tank. Trucks supplying oil for the thermal storage tank will have to back into the space adjacent to the control building before driving out. This space will normally be used for parking cars for plant maintenance and Phase II operating personnel and visitors. Parking space for six automobiles has been provided.

A peripheral 6 ft galvanized chain link wire fence surrounds the entire plant for the dual purpose of providing security and preventing the intrusion and buildup of tumbleweeds.

4.9.2 Site Improvements

4.9.2.1 Roads

The plant access road is designed to accommodate heavy vehicular traffic during construction and initial operation of the facility. This road has a 24 ft wide asphaltic concrete pavement and 4 ft wide shoulders (see Figure 4.9-4). The geometric design is based on a vehicle operating speed of 10 mph within the plant limits. The road pavement has been designed for a service life of 30 years. If the upper 4 inches of in-place material has a relative compaction of less than 90 percent in the paving area or area under the roadway, it will have to be compacted until the minimum relative compaction of 90 percent is achieved.

Paved roads within and around the collector field have not been provided, to minimize environmental impact and cost. The collector rows are spaced 20 ft apart to minimize shadowing losses and to permit access for washing, testing and maintenance. The anticipated circulation for maintenance vehicles is shown in Figure 4.9-5. The maintenance vehicles are assumed to be 2-axled and provided with low profile, wide, low pressure tires. Access to the collectors will be possible only at every alternate row of collectors from the north and south sides as shown because of above ground interconnecting piping. Above ground piping at the center of the collector field will also make it necessary for the maintenance vehicles to back out after completing the maintenance operation. Since the collector field is not paved, some deterioration

Figure 4.9-5 Vehicle Circulation Plan

can be anticipated on the north and south accesses due to the scrubbing action of the maintenance vehicles turning around the corners. However, in view of the anticipated low frequency of maintenance, it was not economically justifiable to pave these areas. Instead, some periodic maintenance on the north and south sides of the collector field is recommended.

4.9.2.2 Drainage

The site has a minimal slope of 0.25 percent in a northerly direction. From the limited topographic information provided by the USGS map for the Coolidge quadrangle (see Figure 4.9-6), it appears that only a minimum of surface grading will be required to prevent a concentration of storm water runoff and surface erosion and to provide for maintenance vehicle travel through the collector field.

Culverts will be provided where the access road intercepts a drainage path or irrigation ditch.

4.9.2.3 Power Generation Building

The power generation building is a pre-fabricated Butler building with an eave height of 16 ft 6 in, as shown in Figure 4.9-7. This provides a minimum of 2 ft clearance between the roof framing and the top of the boiler. This building has a flat roof to match the control building and to keep the overall appearance of the buildings low-profile. The main purpose of providing a roof over the turbine and generator is for the comfort of the operating personnel and for shielding from the sun.

The building has an "open" design with no exterior walls. Cross-bracing between the columns will provide the required lateral stiffness against wind.

The building is approximately 40 ft long and 35 ft wide to provide the minimum working space and clearances between the building structure and the equipment.

This building is located 30 ft clear of the thermal storage tank and the control building for safety reasons described in section 4.9.2.4 below. Its centerline is in line with the center of the plant to minimize the cost of piping.

The power generation building would not be necessary for the production or commercial version of the plant due to the absence of operation testing plant personnel. The power generation subsystem equipment is designed so that protection from weather is not necessary.

4.9.2.4 Control Building

The control building (see Figure 4.9-8) is a one-storied structure located 30 ft clear and to the south of the power generation building. This separation distance was required for three reasons:

- fire protection,
- vibration isolation,
- noise isolation.

Since toluene has a flash point of 40°F, it is a potential fire hazard. The separation distance will provide safety for operation testing personnel in the event of fire. The 8-inch load-bearing concrete block wall on the exterior of the building will have a 4-hour fire rating and serves the dual role of fire protection and energy conservation by cutting down on the air conditioning requirements during the hot summer months.

Figure 4.9-8 Control Building

The control building is approximately 20 ft long and 15 ft wide. The main function is to provide space for:

- an office for operation testing personnel,
- a toilet,
- the master control console,
- the generator control console,
- the main circuit breaker and,
- the wall mounted electrical switchgear.

Windows have been provided facing the collector field and facing the power generation building and thermal storage tank so that an operator can see the major components of the plant. The toilet is located in the north-east corner of the building and has a separate access from outside. The toilet is provided with a sink and a toilet connected to an underground septic tank.

It should be noted that the control building would not be necessary in the commercial or production version of the irrigation facility where the controls would be housed in a weather-protected cabinet near the power generation equipment. The prototype facility needs a control room because of the extended occupancy anticipated during testing, and the need to provide a controlled environment for data acquisition and recording equipment.

4.9.3 Personnel Safety and Fire Protection

Potential personnel hazards associated with the Phase II demonstration facility include the following:

- Electrical shock;
- Heat from high temperature surfaces;

- Heat from high temperature liquid or vapor leaks;
- Fire and/or explosion of toluene or Caloria HT-43 because of leakage or sudden mechanical rupture;
- Health effects from excessive contact with toluene.

The preliminary design of the facility and its components was developed on the basis of a "minimum risk" approach with respect to protecting both personnel and equipment. All structures and equipment will be electrically grounded, and high temperature piping and equipment will be insulated. All pressure piping and vessels are designed per nationally accepted engineering codes and with provisions for thermal expansion so as to preclude leakage or rupture. Any spill of Caloria HT-43 from the thermal storage tank will be contained within a berm and drained off to a catch basin at a safe distance. Natural ventilation of the open-sided power generation building will reduce the probability of a buildup of an explosive or toxic concentration of toluene in the event of a spill or leakage.

One of the inherent hazards associated with the facility is the possibility of a toluene fire. The maximum operating temperature of the toluene is 550°F, which is well below its auto-ignition temperature of 1025°F; thus a source of ignition must be present at the same time a leak or spill occurs in order for a fire to start. Possible ignition sources in the power generation building are minimized by the use of sealed electrical conduit and gas tight electrical devices. The fire protection system for the power generation building includes combustible gas detectors which will activate to shut down operating equipment and sound an alarm if a major spill occurs. Rate-of-rise temperature

switches are also included which will activate an automatic, nitrogen-pressurized, foam deluge system in the event of a fire.

With these safety features, the hazards associated with the use of toluene in the facility should be less than the hazards associated with the common use of gasoline or diesel fuel in a farming operation.

SECTION 5

COST ANALYSIS OF PHASE II PROTOTYPE AND PRODUCTION UNITS

This section presents Bechtel capital cost estimates for the 150 kWe solar-powered deep-well irrigation facility. Estimates were made for the Phase II prototype facility and for a generic facility when built in production quantities of 10, 100, and 1,000 total units.

Section 5.1 presents a summary of prototype and production costs. Section 5.2 outlines the bases for cost estimates. The differences between the first Phase II prototype and the production versions in terms of facility design, equipment cost, and scope and cost of engineering and construction services are described in section 5.3. Details of capital cost estimates for the Phase II prototype and the production units are presented in sections 5.4 and 5.5, respectively.

5.1 SUMMARY OF COST ESTIMATES

The estimated capital costs of a 150 kWe solar-powered irrigation facility, based on the preliminary design described in section 4, are summarized as follows:

<u>Production Quantity</u>	<u>Total Unit Capital Cost</u>	<u>Normalized Capital Cost</u>
1 Phase II Prototype	\$3,850,000	\$26,000/KWe
10 Production Units	\$2,710,000	\$18,000/KWe
100 Production Units	\$2,390,000	\$16,000/KWe
1,000 Production Units	\$2,300,000	\$15,000/KWe

The breakdown of these costs by cost category (field construction, engineering services, and allowance for uncertainty) and by cost component of the field construction cost (collector subsystem, thermal storage subsystem, power generation subsystem, and balance-of-plant) is illustrated in Figure 5.1-1.

It can be clearly seen from this figure that the capital cost of the irrigation facility, when constructed in relatively large quantities, can be reduced significantly from the cost of the first prototype facility. This conclusion is based on the assumption that a generic design is developed so that irrigation facilities can be constructed at a number of sites without significant engineering re-design. However, unit capital costs for the facility, even when constructed in quantities of up to 1,000 units, are still greater than half of the cost of the first prototype. Significant reductions in the cost per facility of the power generation subsystem and engineering services result by constructing large numbers of generic facilities. However, the construction costs of the collector and thermal storage

Figure 5.1-1 Capital Cost Estimate Summary for Prototype and Production Versions of Solar - Powered Irrigation Facility

subsystems and the balance-of-plant do not change significantly when a large number of facilities are constructed. It may be noted that even if produced in large numbers the capital cost of the solar-powered irrigation facility would be greater than \$15,000/kWe.

5.2 BASES FOR ESTIMATES

5.2.1 General

The estimates are based on the engineering information developed during the preliminary design study for the 150 kWe solar-powered deep-well irrigation facility, on formal and informal vendor contacts, and on extrapolation from Bechtel historical information.

The following items are excluded from the project scope and are therefore not included in the estimate:

- Irrigation wells, deep-well pumps, and other irrigation system systems compenents
- Cost of land
- Allowance for interest on funds during construction
- Training of plant operators
- Plant startup, operation, and testing.

The total estimated facility capital cost is the sum of field construction costs, engineering services costs, and an allowance for uncertainty. The largest category, field construction costs, comprises the direct cost of permanent plant equipment, materials and labor for construction, and the indirect cost of temporary construction facilities, supervision, etc. It was assumed for this estimate that the prototype and production facilities will be built by a direct-hire contractor employing field construction labor forces.

5.2.2 Pricing Levels and Escalation

The estimate is at second quarter, 1977, price and wage levels. No allowance has been made for escalation.

5.2.3 Field Construction Costs

The direct field construction costs of permanent plant equipment, materials, subcontracts, and construction labor have been included in the estimate on the basis of the following discussion.

The cost of collectors installed in place (excluding foundations) was estimated by Acurex Corporation based on experience with fabrication and installation on previous experimental facilities and on projections of larger-scale economies for fabrication and installation techniques. The installed collector cost includes cost of materials; cost of fabrication; cost of freight to the jobsite; cost of jobsite materials, temporary facilities, construction equipment and services; and direct and indirect field labor and supervision required to support the assembly and installation of the collectors. The cost of installation and supporting field indirect costs for the collector foundations were estimated by Bechtel.

The cost of the organic Rankine cycle equipment in the power generation subsystem was estimated by Sundstrand Corporation considering engineering and manufacturing requirements. The cost of installation and supporting field indirect costs were estimated by Bechtel. The cost of other equipment was estimated using Bechtel data and vendor contacts.

Quantity evaluations were made from preliminary design drawings for identifiable bulk materials such as concrete, steel, piping, wire, and

cable, and these quantities were priced using current unit prices from Bechtel sources. Other materials that would be delineated on the final engineering drawings have been evaluated by experience as percentages of the installed costs of the identified materials.

Subcontracts for equipment and materials commonly installed by subcontractors were estimated and priced in accordance with Bechtel experience from current sources.

The direct construction labor costs for the installation of the plant equipment and materials were estimated using recent productivity experience and wage rates based on labor contracts and fringe benefits for the southern Arizona area.

The indirect field costs were estimated as a function of direct field labor, based on field construction experience. These indirect field costs were distributed among direct labor components.

The items covered by indirect field costs are as follows:

- Temporary construction facilities: temporary buildings, working areas, utilities, and general purpose scaffolding.
- Miscellaneous construction services: general job clean-up, maintenance of construction equipment and tools, material handling, and surveying.
- Construction equipment and supplies: construction equipment, small tools, consumable supplies, and purchased utilities.
- Field office: craft supervision, engineering, procurement, scheduling, personnel administration, warehousing, first aid, and the costs of operating the field office.
- Normal check-out and acceptance testing of materials to ensure that components and systems are operable.

- Project insurance: public liability, property damage, and builder's risk insurances.
- Taxes and permits: state and local taxes and permits.

The field construction cost components included in the estimates are briefly defined as follows:

- Collector Subsystem: The collector subsystem includes the installed cost of the collectors, collector foundations, interconnecting piping between collectors and thermal storage tank, including piping insulation and supports.
- Thermal Storage Subsystem: The thermal storage subsystem includes the installed cost of the thermal storage tank and foundation, spill containment berm, catch basin and drain line, tank rock packing, and Caloria HT-43 heat transfer fluid sufficient for charging the tank and collector field piping.
- Power Generation Subsystem: The power generation subsystem includes the Sundstrand organic Rankine cycle equipment (toluene boiler; power conversion module, which includes the turbine, generator, condenser, regenerator and associated instruments and controls); boiler Caloria circulation pump; interconnecting piping; and insulation for piping and equipment.
- Cooling Water Subsystem: The cooling water subsystem includes cooling water piping from the irrigation water basin to the condenser (and other equipment cooling points) and back to the basin and condenser cooling water and auxiliary cooling water pumps. Also, for the Phase II prototype, a spray pond, auxiliary piping, and spray nozzles are included in the cost.
- Controls Subsystem: The controls subsystem includes all control valves, and other control devices and instruments, excluding instruments and controls supplied with the Sundstrand organic Rankine cycle equipment.
- Data Acquisition Subsystem: The data acquisition subsystem includes computer hardware with control cabinet instruments, and interconnecting cabling (not required for production facilities).
- Power Distribution Subsystem: The power distribution subsystem includes the main transformer and circuit breakers; distribution equipment; a standby emergency gasoline-powered generator; power lines and poles; and wire, cable and conduits to serve all plant auxiliary loads.
- Site Improvement and Buildings: Included in this category is the cost of minimal site preparation and storm runoff provisions,

foundations and pads for the power generation and distribution equipment, and fire protection facilities for the power generation unit. For the Phase II prototype unit, this category also includes a prefabricated structure over the power generation equipment, a control building, and an allowance for a paved parking area.

5.2.4 Engineering Services

The estimated cost of engineering services includes design and engineering costs, other home office costs, and fee. Engineering includes detailed engineering, specification writing, vendor drawing review, and site soil investigations. Other home office costs include procurement and expediting, estimating and scheduling services, quality assurance, and construction and project management.

5.2.5 Allowance for Uncertainty

Included in the estimate is an allowance for the uncertainty that exists within the estimate in quantity, pricing, or productivity. It is not an allowance for changes to the project scope such as would be the case if (1) the design undergoes significant revision, (2) the design duty of plant components proves to be more severe than anticipated, or (3) additional major subsystems are ultimately found to be necessary.

An allowance of 10% was used for the collectors supplied by Acurex, and an allowance of 15% was used for all other components of the facility cost.

5.3 DIFFERENCES BETWEEN PROTOTYPE AND PRODUCTION DESIGNS AND COSTS

The preliminary design developed for the Phase II prototype irrigation facility is the basis for the design assumed to be applicable for production versions. Some differences in the design features of the Phase II prototype and those of the production versions do exist, however, and since they affect costs, they are described in this section. Also described in this section are the reductions in costs of various subsystems that would result from mass production and deployment of large numbers of irrigation facilities. Finally, for the Phase II prototype design, a data acquisition system and a building were included for the purpose of the operation testing during Phase II, while these items would not be included in production versions.

Details of design and cost differences are outlined in the following sections.

5.3.1 Power Generation Subsystem

As discussed in section 4.3, the organic Rankine cycle (ORC) power generation equipment to be supplied by Sundstrand for the Phase II prototype facility is a modification of Sundstrand's standard 600 kWe waste heat recovery ORC package. There are several advantages to using an existing design, modified for the specific requirements of the irrigation application: (1) the cost of Phase II is minimized, (2) Phase II schedule goals can be met, and (3) realistic commercial production cost projections can be obtained.

The gross cycle efficiency of the modified 600 kWe ORC unit for the 150 kWe Phase II prototype application is 20.5 percent. When production quantities of the ORC are required for irrigation applications, an additional

investment in engineering design and ORC equipment development would be justified in order to increase cycle efficiency to an estimated 22.0%, and to further optimize equipment design, including decreasing the physical size of the condenser-regenerator pressure vessel. However, the cost of such a development program would not be justified until such time as a market for a generic irrigation facility has developed, and production quantities would be ordered if available.

The cost of supplying the ORC power generation equipment for the Phase II program was estimated by Sundstrand to be \$735,000.

The cost of supplying the further optimized production version ORC power generation equipment was also estimated by Sundstrand. The development of the first production unit was estimated to cost \$1,617,000 in 1977 dollars. After the development expenditure for the first production unit, unit costs for the production ORC power generation equipment would then be as follows:

Lot of 10 units	\$445,000
Lot of 100 units	\$334,000
Lot of 200 units	\$295,000
Lots of 10 or more after an initial lot of 200 units	\$274,000

The production unit cost estimate for the power generation subsystem is based on the costs that have actually been incurred in designing and procuring the hardware for the Sundstrand 600 kWe waste heat power generation system. These costs were then adjusted to reflect the differences between the existing 600 kWe design and the design of the optimum 150 kWe

irrigation production system. In addition, economies associated with various size production lots have been included.

5.3.2 Collector Subsystem

As noted above, the production version of the ORC power generation equipment is expected to have a gross cycle efficiency of 22.0%, compared to the 20.5% cycle efficiency for the Phase II prototype. As a result of the production system's higher cycle efficiency, the collector area required for the production facility is less than that for the Phase II facility. The number of collector rows would decrease from 17 for the Phase II prototype to 16 for the commercial production version. The corresponding collector aperture areas are 48,960 and 46,080 sq ft, respectively.

The unit installed cost of the Acurex concentrating solar collector in dollars/sq ft of collector aperture area, excluding interconnecting piping and foundations, was estimated by Acurex to decrease by about 10% when manufactured and installed in quantities necessary for 100 or more facilities.

For the special steel hoses and fittings connecting collector groups, which would be required in substantial quantities of identical specification, it was assumed that the purchase cost would be lower by 10 percent if ten irrigation facilities were built, and by 15 percent if 100 or more facilities were built, considering the expanded market for the particular items. For production quantities of 100 or more facilities, it was also estimated that the cost of prefabricated piping would be 10 percent lower. It was assumed that all other materials and services would be procured

unit by unit from competitive bidders in the various locales where construction would occur.

Bechtel estimated the collector foundation costs. No saving in foundation cost is expected to result from constructing large numbers of facilities.

5.3.3 Thermal Storage Subsystem

Theoretically the volume of the thermal storage tank would decrease in the same proportion as the collector area requirement (6%). However, this reduction in volume would translate into a smaller percentage reduction in total field construction cost of the thermal storage subsystem; therefore, it was assumed that tank volume remains the same. It was also assumed that for production quantities of 100 or more, the cost of the tank itself would drop by 10 percent.

5.3.4 Balance-of-Plant

The differences between prototype and production version balance-of-plant designs that affected cost estimates are briefly outlined as follows:

- Cooling Water Subsystem: The Phase II prototype facility cooling water subsystem uses a spray pond for water cooling. The generic production unit would use once-through cooling.
- Data Acquisition Subsystem: The data acquisition subsystem required for the Phase II prototype facility was assumed not to be required for production units.
- Power Distribution Subsystem: Minor features required for the prototype facility to enable isolated switching from facility power to utility power at each well pump were considered not to be typical of a production facility.

- Site Improvements and Buildings: The detached control building housing the data acquisition equipment, the building over the power generation equipment, and the visitor parking area would not be required for a production unit.

5.3.5 Engineering Services

Significant reductions in the cost of engineering services are expected to occur when a generic irrigation facility design is deployed at a number of sites. These cost reductions are based on the assumption that significant design revisions would not be required for a given application. Design drawings and specifications would be given to a construction contractor who would purchase equipment, manage construction, and start up the facility.

The engineering services cost for the Phase II prototype facility is estimated to be \$780,000. For production versions the engineering services costs is estimated to be \$50,000, assuming the irrigation facility contractor can use the generic design developed during Phases I and II. The \$50,000 cost includes the cost of: (1) site soil testing; (2) selection of a site-specific, optimum condenser cooling method; and (3) evaluation of site-specific interfaces with the deep-well pump(s) and the electric utility power grid.

The cost of engineering services for a facility at a given site would increase if any of the following additional services were necessary:

- Economic studies of pay-back time, rate-of-return, etc.
- Optimization of collector field and thermal storage tank sizes for local insolation conditions
- Significant re-design necessary for interfacing with deep-well pumps and the electric utility grid or for changes in power output and for site-specific soil conditions and topography.

5.4 PHASE II PROTOTYPE CAPITAL COSTS

The estimated total capital cost of the Phase II prototype irrigation facility and the breakdown by cost categories and field construction cost components are summarized in Table 5.4-1. A further breakdown of the field construction cost is given in Table 5.4-2.

TABLE 5.4-1 CAPITAL COST ESTIMATE FOR PHASE II PROTOTYPE - 150 kWe SOLAR POWERED DEEP-WELL IRRIGATION FACILITY

<u>Cost Category</u>	<u>Thousands of Dollars</u>	<u>Percent of Total</u>
Field Construction Cost	2,692	70
Collector Subsystem	1,423	37
Thermal Storage Subsystem	156	4
Power Generation Subsystem	693	18
Cooling Water Subsystem	83	2
Controls Subsystem	40	1
Data Acquisition Subsystem	38	1
Power Distribution Subsystem	159	4
Site Improvements and Buildings	100	3
Engineering Services	700	18
Allowance for Uncertainty	<u>458</u>	<u>12</u>
TOTAL INSTALLED COST	3,850	100

TABLE 5.4-2 FIELD CONSTRUCTION COST DETAILS OF PHASE II FACILITY

	\$ THOUSANDS			
	Materials	Installation	Subcontracts	Total
Collector Subsystem	129	162	1,132	1,423
Collectors	-	-	1,091	1,091
Foundations	91	120	30	241
Interconnecting Piping	38	42	11	91
Thermal Storage Subsystem	53	84	19	156
Tank and Insulation	32	29	19	80
Foundation	7	27	-	34
Thermal Storage Medium	11	-	-	11
Containment Facilities	-	4	-	4
Ullage Maintenance	3	24	-	27
Power Generation Subsystem	664	26	3	693
Power Generation Unit	660	16	2	678
Circulation Pump and Piping	4	10	1	15
Cooling Water Subsystem	29	50	4	83
Spray Pond and Pumps	6	6	4	16
Piping and Valves	23	44	-	67
Controls Subsystem	20	20	-	40
Collector Subsystem Controls	11	14	-	25
Other Subsystem Controls	9	6	-	15
Data Acquisition Subsystem	32	6	-	38
Power Distribution Subsystem	37	102	20	159
High Voltage Transmission	-	-	20	20
Collector Field Distribution	13	72	-	85
Other Power and Control Distribution	24	30	-	54
Site Improvements and Buildings	23	54	23	100
Control Building	2	4	5	11
Generation Unit Structure	13	29	4	46
Site Civil Work	8	21	14	43
TOTAL FIELD CONSTRUCTION COST	987 =====	504 ====	1,201 =====	2,692 =====

5.5 PRODUCTION UNIT CAPITAL COSTS

Capital cost estimates for the production version of the irrigation facility when constructed in large numbers are summarized in Table 5.5-1.

TABLE 5.5-1 CAPITAL COST ESTIMATES FOR PRODUCTION UNITS

(Estimated Costs in Thousands of Dollars)

<u>Cost Category</u>	<u>Total Number of Units</u>		
	<u>10</u>	<u>100</u>	<u>1,000</u>
Collector Subsystem	1,292	1,235	1,235
Thermal Storage Subsystem	156	151	151
Power Generation Subsystem	597	380	297
Cooling Water Subsystem	74	74	74
Controls Subsystem	40	40	40
Power Distribution Subsystem	140	140	140
Site Improvements and Buildings	50	50	50
Engineering Services	50	50	50
Allowance for Uncertainty	<u>311</u>	<u>270</u>	<u>263</u>
TOTAL INSTALLED COST	2,710	2,390	2,300

APPENDIX A
ACUREX DRAWINGS

(to be prepared by Acurex)

APPENDIX B
BECHTEL DRAWINGS

Drawing No.	Title	Page
P-1001	Site Plan	B-2
P-1002	Plot Plan	B-3
C-1003	Grading, Roads, Drainage & Underground Lines	B-4
P-1004	Power Generation Building and Thermal Storage Tank Layout - Plan and Section A-A	B-5
P-1005	Power Generation Building - Section B-B Control Building - Plan and Section	B-6
C-1006	Drilled Cast-in-place Collector Foundation for Drive and Non-drive Support	B-7
C-1007	Foundation Schedule and Details	B-8
C-1008	Thermal Storage Tank Footing Plan and Section	B-9
M-1009	P&ID - Cooling Water and Fire Protection	B-10
E-1010	Electrical Single-line Diagram	B-11
C-1011	Collector Foundation Location	B-12
C-3001	Site Topography	B-13
C-3002	Land Use Plan	B-14
C-3003	Index Map for Geologic Cross-sections	B-15
C-3004	Geologic Cross-sections	B-16
C-3005	Site Hydrology	B-17

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SYMBOLS

- WOOD TRANSMISSION POLE, SINGLE CIRCUIT
- WOOD TRANSMISSION POLE, DOUBLE CIRCUIT
- EXISTING 12.5 KV UTILITY DISTRIBUTION FEEDER
- DEDICATED 12.5 KV DISTRIBUTION FEEDER
- 12.5KV OIL FILLED CIRCUIT BREAKER
- / 12.5KV OVERHEAD AIR BREAK DISCONNECT SWITCH, 3 POLE SINGLE THROW
- / 12.5KV FUSED OVERHEAD AIR BREAK DISCONNECT SWITCH, 3 POLE SINGLE THROW
- / 12.5KV OVERHEAD AIR BREAK DISCONNECT SWITCH, 3 POLE DOUBLE THROW

NOTES:

1. OIL CIRCUIT BREAKER AND DISCONNECT SWITCHES ARE SHOWN HERE FOR CLARITY ONLY. SEE DWG 12177-C-1003 FOR ACTUAL LOCATION.
2. STEP-DOWN TRANSFORMERS AND MOTOR CONTROLLERS ARE OMITTED HERE FOR CLARITY. FOR DETAILED SINGLE LINE DRAWING SEE DWG 12177-E-1010.
3. FOR PLOT PLAN SEE DWG 12177-P-1001.
4. FOR SITE LOCATION SEE DWG 12177-C-3001.

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△	TH-77	ISSUED FOR REPORT	2	2	2
△	DATE	REVISION	BY	CHKD	APPR
△	BECHTEL SAN FRANCISCO ACUREX CORPORATION 150 KW SOLAR POWERED DEEPWELL IRRIGATION FACILITY				
△	SITE PLAN				
△	JOB No.	DRAWING No.	REV.		
△	12177	P-1001	0

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- NOTES
1. FOR SITE PLAN SEE DWG 12177-P-1001
 2. FOR ROAD, POND AND CIVIL SEE DWG 12177-C-1003
 3. FOR COLLECTOR LOCATIONS SEE DWG 12177-C-1010

7-77	ISSUED FOR PERMIT	BY	DATE	REVISION	BY	DATE	REVISION	BY	DATE	REVISION
7-77	ISSUED FOR PERMIT	BY	DATE	REVISION	BY	DATE	REVISION	BY	DATE	REVISION
BECHTEL SAN FRANCISCO										
ACUREX CORPORATION 150 kW SOLAR POWERED DEEP WELL IRRIGATION FACILITY										
PLOT PLAN										
JOB No. 12177 DRAWING No. P-1002 REV. 0

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PLAN

SECTION A-A

- NOTES:
1. FOR SITE PLAN SEE DWG. 12177-P-1001
 2. FOR PLOT PLAN SEE DWG. 12177-P-1002
 3. FOR FOUNDATIONS SEE DWG. 12177-F-1001 & 12177-F-1002
 4. FOR THERMAL STORAGE TANK SEE ACUREX DWG. 7301-001
 5. POWER CONVERSION MODULE BY SUNSTAND

12177	ISSUED FOR REPORT	BY	DATE
12177	1-1-01	REVISIONS	BY
BECHTEL SAN FRANCISCO ACUREX CORPORATION 150 KWE SOLAR POWERED DEEPWELL IRRIGATION FACILITY POWER GENERATION BUILDING AND THERMAL STORAGE TANK LAYOUT - PLAN AND SECTION A-A			
JOB No.	DRAWING No.	REV.	
12177	P-1004	0

[illegible]

FOUNDATIONS FOR	L	B	D	REINFORCING EACH WAY			
				BOTTOM		TOP	
	FT.	FT.	FT	SIZE	SPACING	SIZE	SPACING
TURBINE-GENERATOR	23'	17'	3'	# 8	6"	# 4	6"
BOILER	8'	6'	2'	# 6	9"	—	—
POWER GENERATION BUILDING FOOTINGS	4'	4'	2'	# 4	6"	FOR PILASTER REIN- SEE DWG. P1005	

NOTES:

1. FOR POWER GENERATION BUILDING SEE DWG 12177-P-1004
2. ALL REINFORCING IS ASTM-A-615
3. CONCRETE STRENGTH
 $f_c = 3000 \text{ PSI AT 28 DAYS}$
4. PROVIDE MIN. 3" CONCRETE COVER OVER REINFORCING STEEL.
5. LAP ALL WIRE MESH TWO MODULES

GRAPHIC SCALE

	7-11-77	ISSUED FOR REPORT				£	£	£	<i>Murphy</i>
No.	DATE	REVISIONS			BY	CHKD	DESIGN SUPV	ENGR	PROJ. ENGR
SCALE 1:ONE		DESIGNED SHUKLA			DRAWN <i>[Signature]</i>			CHEF BAIR	

BECHTEL
SAN FRANCISCO

ACUREX CORPORATION
150 KWe SOLAR POWERED DEEPWELL
IRRIGATION FACILITY

FOUNDATIONS SCHEDULE AND DETAILS

JOB No.	DRAWING No.	REVISION
	12177	C-1007	0

NOTE

AUTOMATIC TRANSFER SWITCH, TO BE SUPPLIED WITH STAND-BY GENERATOR SET, INCLUDES:

- MAGNETICALLY OPERATED, INTERLOCKED CONTACTORS
- AUTOMATIC ENGINE START CIRCUIT
- TIME DELAY ON ENGINE START
- TIME DELAY ON RESTORATION TO NORMAL SERVICE
- BATTERY CHARGER (FOR ENGINE CRANKING BATTERY)
- AUTOMATIC SERVICE TIMER

SYMBOLS

AIR-BREAK DISCONNECT SWITCH, SINGLE THROW
AIR-BREAK DISCONNECT SWITCH, DOUBLE THROW
FUSE
FUSED DISCONNECT SWITCH
GROUND CONNECTION
LIGHTNING ARRESTER
POWER TRANSFORMER
3-PHASE WINDING, WYE CONNECTED
3-PHASE WINDING, DELTA CONNECTED
GENERATOR
OIL-CIRCUIT BREAKER NON-DRAW-OUT TYPE
AIR CIRCUIT BREAKER DRAW-OUT TYPE
AIR CIRCUIT BREAKER MOLDED CASE TYPE
COMBINATION MOTOR STARTER
INDUCTION MOTOR WITH RATED HORSEPOWER SHOWN

△										
△										
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7-17 ISSUED FOR EXPORT						#	#	#	#	APR
No.	DTE	REFERENCE:				BY	DATE	PROJECT	SECTION	APPD.
MADE IN U.S.A.		ISSUED BY C. BULL		RECEIVED		Good				
BECTEL SAN FRANCISCO ACUREX CORPORATION 150 kWe SOLAR POWERED DEEPWELL IRRIGATION FACILITY ELECTRIC SINGLE-LINE DIAGRAM
JOB No.		DRAWING No.				REV.		
		12177		E-1010				0

TEQUAL SPACES @ 20'-0" = 340'-0"

15 EQUAL SPACES @ 20'-0" = 300'-0"

NOTES:

1. FOR FOUNDATION SEE DWG 12177-C-1006
2. SWD CIRCUITS DETAIL & DRIVE FOUNDATION
& REMAINING FOUNDATIONS ARE NON DRIVE
3. FOR SITE PLAN SEE DWG 12177-P-1001
4. FOR PLOT PLAN SEE DWG 12177-P-1002

GRAPHIC SCALE
1/16" = 1'-0"

[illegible]

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△	7/4/77	ISSUED FOR REPORT							
DATE	REVISION	BY	DATE	REVISION	BY	DATE	REVISION	BY	DATE
<p align="center">BECHTEL SAN FRANCISCO</p> <p align="center">150 kWe SOLAR-POWERED DEEP WELL IRRIGATION FACILITY PHASE I</p> <p align="center">LAND USE PLAN</p>									
JOB NO.		DRAWING NO.		REV.					
12177		C-3002		0

[illegible]

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