BOEING
ENGINEERING &
CONSTRUCTION
THE BOEING ENERGY
AND ENVIRONMENT DIVISION

Solar Energy Water Desalination System Design

Final Report Volume I

System Requirement Definition
System Analysis

SERI Contract AF-1-9115-2

August, 1981

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401
(303) 231-1000

SERI

81-270.1-3371

24 August 1981

Mr. John Anderson
Sandia National Laboratories
Division 8452
P. O. Box 969
Livermore, CA 94550

Dear Mr. Anderson:

Subject: Solar Energy Water Desalination Project

Attached please find 4 volumes of the draft final report by Boeing for your review and scoring according to the attribute list sent to you earlier. The remaining volumes Nos. 2 and 3 will be sent to you when they become available.

Sincerely,

WLuft

Werner Luft
Project Manager
Solar Energy Water Desalination

WL:ml
Attachment

cc: M. Al-Nemer
B. Martin

1. Final Report Volume III
Phase 2 Definition Study

2. Final Report Volume IV
Commercial Plant Cost Study

3. System Performance Specification
Commercial Plant

4 System Specification
Performance, Design and Quality Assurance
Requirements For a Solar Powered
Reverse Osmosis Water Desalination
System Pilot Plant.
Specification No S277-102431

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401
(303) 231-1000

81-270.1-3381

27 August 1981

Mr. John Anderson
Sandia National Laboratories
Division 8452
P.O. Box 969
Livermore, CA 94550

Dear Mr. Anderson:

Subject: Solar Energy Water Desalination Project

Attached please find the remaining draft final report volumes Nos. 1 and 2 by Boeing. Volumes 3 and 4, together with the system specification and systems performance specification, were sent to you on 24 August 1981.

The final format of the attribute list will be sent to you early next week.

Sincerely,

Werner Luft
Project Manager
Solar Energy Water Desalination

WL:ml
Attachment

cc: M. Al-Nemer
B. Martin

1. Final Report Volume I
System Requirement Definition
System Analysis

2. Final Report Volume II
Pilot Plant Preliminary Design.

A Division of Midwest Research Institute

Boeing US Gypsum - Repower.

Air receiver 1335°F

Rec out put 11.92 MW_t

electric ~~12.54~~ mw 1.3 mWe

Process power 10.54 MW_t

Annual energy product 16.8 GWh_t

Capital cost \$9 m \$230/m² heliostat

Annual energy/m² area = .814 MWh_t/m²

Cost/fuel displace \$427/MWh_t

469 heliostats 44 m² 20636 m² land

65,000 m² land .065 (km)²

1100

Desal

436 heliostats 46.9 m² 20448 m² mirror

84700 m² land

Annual Insolation 5.44 kWh/m² dy × 20448 m² × 365 = 40.6 GWh

(39.5 GWh) in report

Receiver annual 19,974 MWh - 20.04

Receiver at design point 13.1 MW_t

SOLAR ENERGY WATER DESALINATION SYSTEM DESIGN

FINAL REPORT VOLUME I

SYSTEMS REQUIREMENTS DEFINITION

SYSTEM ANALYSIS

Prepared by

SOLAR SYSTEMS GROUP
BOEING ENGINEERING AND CONSTRUCTION COMPANY
A Division of The Boeing Company
Seattle, Washington 98124

Program Technical Leader
John H. Laakso

Program Manager
Donald K. Zimmerman

Prepared for

SOLAR ENERGY RESEARCH INSTITUTE

SERI Subcontract AF-9115-2

August, 1981

Water production 2.11×10^6 m^3 pg 138

Solar incident on field 39, 520 mwh_t —— 19 KWh/m^3

Receiver output 20 200 mwh_t —— 10 KWh/m^3

Heliostat reflector surface 20448 m^2

103 $\frac{m^3 \text{ of water}}{m^2 \text{ of mirror area}}$

Commercial plant capital Investment \$ 28.369 M. → \$ 13.445/m^3 of water.

ABSTRACT

The system design for a future commercial solar energy brackish water desalination plant is described. Key features of the plant are discussed along with its configuration selection rationale, design objectives, operation, and performance.

The water treatment technology used in the plant is ion exchange pretreatment and single stage reverse osmosis desalination utilizing high-flux membranes. Electrical power needed for plant operation is produced by a solar energy system, which is based on the Brayton cycle having air as the working fluid. Primary solar system components are: heliostat field, central cavity-tube receiver, receiver support tower, thermal energy storage, and a commercial gas turbine generator set. The thermal energy storage subsystem is of the sensible heat brick type and provides a capability for continuous day/night power generation during most weather conditions.

This system design was selected in a study of various system alternatives and their life cycle product water costs for a representative site in western Texas.

TABLE OF CONTENTS

Appendices

ACRONYMS

BEC	Boeing Engineering and Construction Company
BMSR	Bench Model Solar Receiver
BPGS	Backup Power Generation Subsystem
CRT	Cathode Ray Tube
CRTF	Central Receiver Test Facility
EDS	Energy Delivery Subsystem
EPRI	Electric Power Research Institute
ISO	International Standards Organization
IWT	Illinois Water Treatment
JPL	Jet Propulsion Laboratory
MCS	Master Control System
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NOAA	National Oceanic & Atmospheric Administration
RCC	Resources Conservation Company
RO	Reverse Osmosis
SERI	Solar Energy Research Institute
SOA	State of the Art
S/M	Solar Multiple
STI	Solar Turbines International
TDS	Total Dissolved Solids
TES	Thermal Energy Storage
UPS	Uninterruptable Power Supply
USG	United States Gypsum Company
WAC	Weak Acid Cation

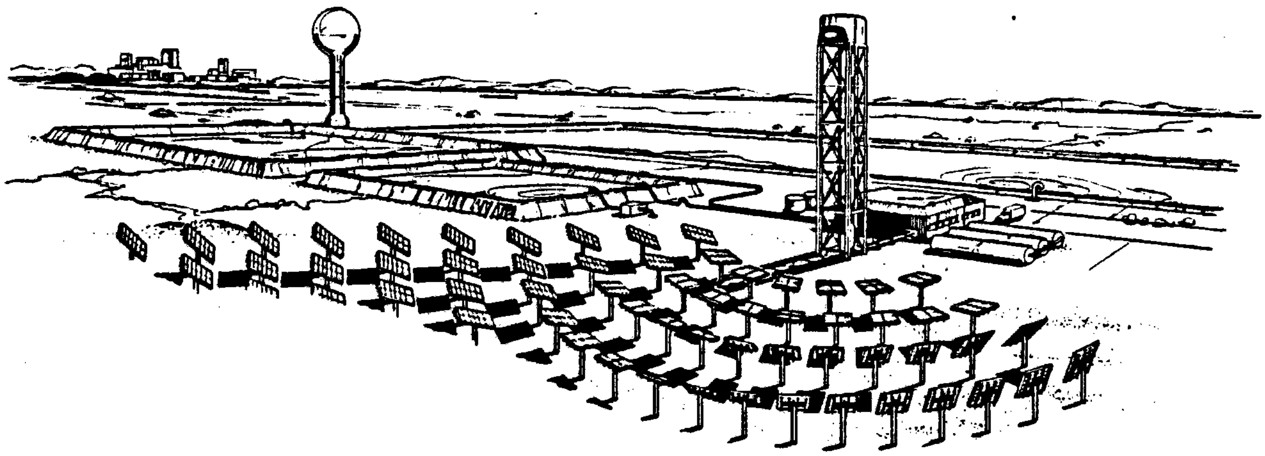
1.0 SUMMARY

Boeing Engineering and Construction (BEC) under subcontract from the Solar Energy Research Institute (SERI) has prepared a design for a solar energy water desalination system that would transform brackish well water into potable water for a community in southwest Texas. BEC performed overall project management, system engineering and solar subsystem design; Resources Conservation Company (RCC), a partly owned subsidiary of BEC, provided designs for the water related subsystem.

The work is reported in four volumes. Volume I (this document) describes work under Task 2, System Requirements Definition, and Task 3, System Analysis, dealing with selection of requirements and a system configuration and definition of the design, costs, and operational characteristics for a commercial solar energy water desalination plant. Volume II describes the Task 4 Pilot Plant design, Volume III presents results of the Phase 2 definition study, (part of Task 5) and Volume IV contains commercial plant cost analyses from both Task 3 and Task 5. Details of the system requirements definition for both the commercial plant and pilot plant are contained in separate documents (System Performance Specifications).

1.1 DESIGN CONCEPT SELECTION

The design concept forming the basis for the studies reported here was developed prior to the contract and has been refined to fully meet the design requirements and to achieve the best overall combination of product water cost, technical readiness, complexity, and risk. The concept is based on selecting the best combination of the two areas of technology involved - Solar and Desalination - leading to an optimum integrated system. Reverse Osmosis (RO) desalination was selected over other desalting methods because of its acceptable capital cost, low power consumption, and mature technology. A solar-thermal electric power plant was chosen to provide energy compatible with the RO requirements and based on its relative economics, maturity of technology, and availability of equipment. A sketch of the plant showing its major elements is shown in Figure 1-1.



BOEING ENGINEERING & CONSTRUCTION
THE BOEING ENERGY AND ENVIRONMENT DIVISION

Figure 1-1. Solar Energy Water Desalination System

The baseline (design concept at initiation of the program) utilized a two-stage RO design, similar to a desalting plant recently completed by RCC, with 90 percent recovery. After studying the operation of this plant in conjunction with the stand-alone solar power plant, it became evident that several features of the system, particularly the feedwater pretreatment subsystem, were not conveniently adaptable to the expected intermittent operation with stand-alone solar power. This led to trade studies of several alternatives to the two-stage RO. While the changes in design concept were primarily in the water processing subsystems, the trade studies addressed the entire system including the considerable variation in size of the solar subsystems.

Results of these trades are summarized in Table 1-1. Concept II featuring weak acid cation (WAC) ion exchange feedwater pretreatment, single-stage RO, and 72 percent overall recovery was selected. The WAC ion exchange provides simple on-off operation but limits the allowable concentration of precipitable ions; only single stage RO may be used, resulting in the lower recovery. The selected system was then developed to describe the subsystems, evaluate plant operations and performance, and determine capital, operating, and product water costs.

Table 1-1. System Concept Evaluation Summary

Candidate	Levelized Product Water Cost $/m^3$	Technology Readiness	Complexity	Application Limitiations	Risk Factors	Overall Selection Rating Based on SOLERAS Requirements
I 2-Stage RO Lime-soda pretreatment Simple cycle Centaur	4.86	High	Low	Minimal	Low	3
II Single Stage RO WAC ion exchange Simple cycle Saturn	3.39	High	Low	Minimal (except for large evaporation pond)	Low	1
III Single Stage RO WAC and NaZ ion exchange Combined cycle Saturn	3.22	Low	Medium	Minimal	Medium	2
IV RO and vapor compression WAC ion exchange Combined cycle Centaur	4.95	Low	High	Some	High	4

1.2 SYSTEM DESCRIPTION

A schematic of the selected system is shown in Figure 1-2. Modularity in the energy storage water pretreatment, and desalination subsystem is shown. Ancillary equipment has been added to fully meet the design requirements regarding stand-alone, non-fossil fuel normal operation. This equipment includes a small turbo-generator for standby electric power; the turbine is powered by residual heat in the thermal energy storage units. A bottoming cycle is shown as an option; based on performance and cost of currently available units, this is not currently recommended, although a well-matched combined cycle turbine generator set would substantially improve solar plant efficiency and power production. A plant air supply is also shown; it is used for operating pneumatically actuated valves and for the Saturn turbine startup.

Subsystems which comprise the selected system are listed below:

Solar Energy Collection Subsystem - Solar thermal central receiver system has a collector field of 436 heliostats in a north field array. Energy is concentrated in a tower mounted air-cooled receiver with aperture at 54 m elevation.

Energy Delivery Subsystem - Saturn gas turbine generator set has a peak electric power output of 713 kW at system design conditions. Electric power distribution within plant is at 480 volts. Plant air supply is provided for valve actuation and turbine start.

Energy Storage Subsystem - Three Thermal Energy Storage (TES) units operate in parallel. Storage media is MgO bricks of 1.68×10^6 kg total weight. Air flow recirculation through TES and back to the receiver inlet is accomplished by a centrifugal type booster compressor.

Backup Power Subsystem - Fossil fuel is stored for emergency operation of the main turbine. Standby power (non-emergency) is produced by an organic Rankine cycle turbine using heat from TES. Standby power (emergency) is supplied by a small diesel generator.

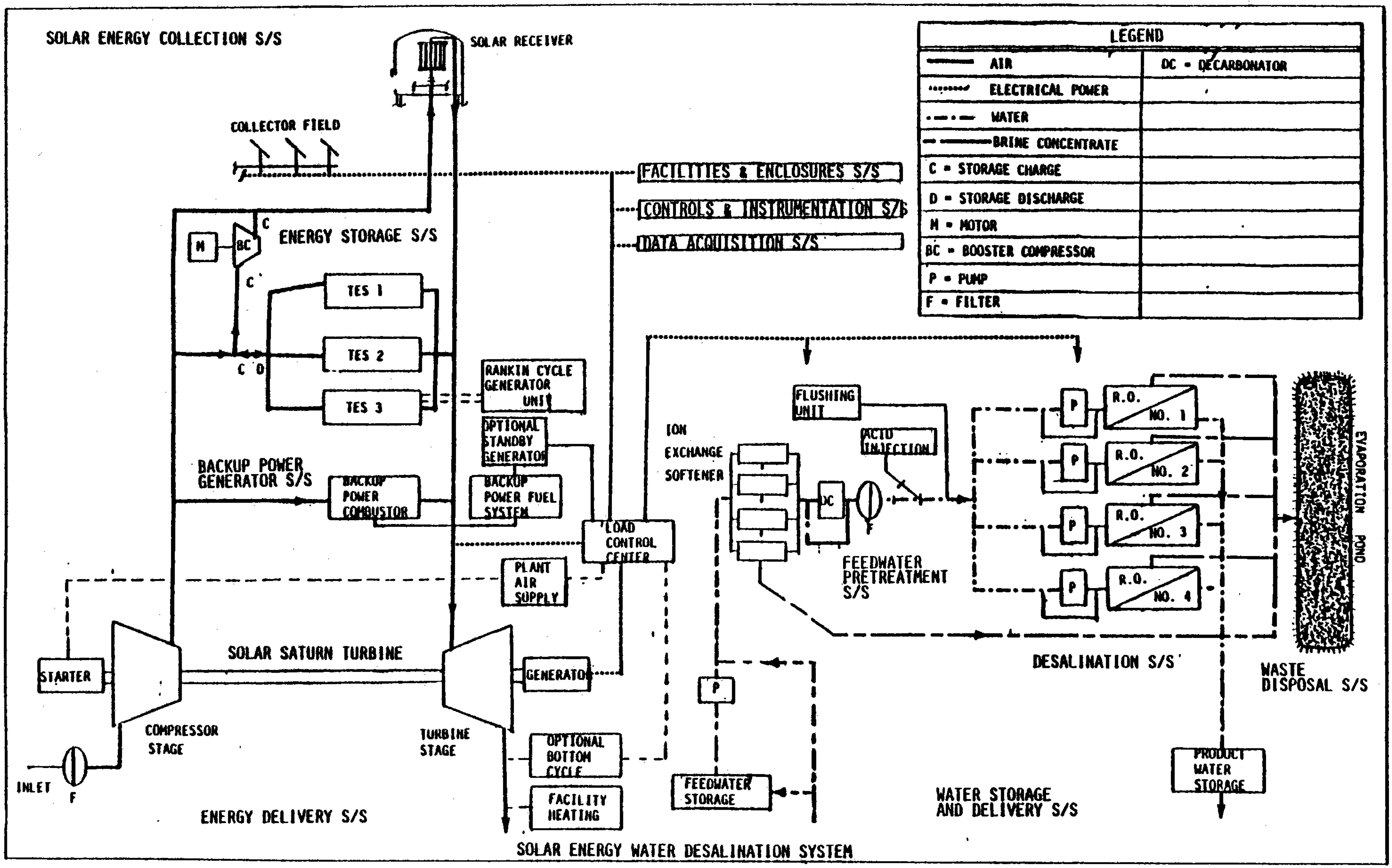


Figure 1-2. Commercial Soleras Solar Energy Water Desalination System

Feedwater Pretreatment Subsystem - Four WAC units are in parallel; three can pretreat the maximum feedwater flow while the fourth is regenerated by the acid flush regeneration equipment. A decarbonation/pH control unit, in parallel with the feed line to the RO, removes CO_2 resulting from the reaction in the WAC units.

Desalination Subsystem - Four RO trains are connected in parallel. The number of trains operating can be varied according to power available. Each train consists of two sections of modules in series with a 2:1 taper. The modules contain non-cellulosic, high flux membranes. A positive displacement, high pressure pump provides flow to each RO train. Recovery in the RO units is 75 percent; total system recovery is 72 percent.

Controls and Instrumentation Subsystem - A master control computer is linked to distributed digital controllers, with separate computers for solar collection and power generation and for water process control.

Data Acquisition Subsystem - There are measurement provisions and a storage device for plant operating parameters and computed data.

Water Storage and Delivery Subsystem - Feedwater and product water reservoirs are 8.2×10^3 m^2 and 2.65×10^4 m^2 area, respectively. The product water reservoir would be covered with a plastic film to prevent large evaporation losses.

Waste Disposal Subsystem - A plastic film lined evaporation pond prevents release of wastes back to the feedwater source. Area of the pond is 5.19×10^5 m^2.

Site and Facilities - Reasonably level site of 8.1×10^5 m^2 is required. Industrial type of building, with 2195 m^2 floor area, contains office, control room, water processing equipment and maintenance area.

1.3 PLANT OPERATIONS

The plant is designed to operate as continuously as possible within the limits of the solar resource available in west Texas and an economical choice of equipment to effectively utilize this resource. Plant performance is based on assuming the variability in product water demand does not constrain production. Plant electric power requirements vary between 347 kW and maximum capability during water production and about 33 kW during standby.

Analysis of the plant operations shows that a total of 14 employees would be required to operate the plant. Some of the administration and maintenance personnel would not be needed full time; reduction in the personnel could result if they could be shared with other plants.

A preliminary analysis of the mean time between failures and the mean time to repair for all the major elements in the plant results in an overall plant availability of 0.93. Performance analysis have been based on a somewhat lower value of 0.91.

1.4 PLANT PERFORMANCE

Annual plant performance has been analyzed using a system operations model based on quasi-steady simulation of the various components in the plant. The model utilizes ambient temperature and direct normal insolation measurements obtained at Midland-Odessa, Texas, in 1978 and 1979. The model operating strategy maximizes the turbine inlet temperature at all times to produce the most electricity. A more sophisticated strategy, including anticipatory logic might improve plant performance.

The hourly performance results provide confidence that the plant will operate as intended. During a succession of clear days with occasional cloudiness, the plant will operate 24 h/d. When TES is exhausted during extended cloudiness, the water production is curtailed and demand is met by extracting from product water storage. Operation during several representative episodes of varying insolation is described in Section 8. Annual performance of the plant is summarized in Table 1-2.

1.5 CONCLUSIONS

The system analyses have shown that the selected Solar Energy Water Desalination System design has the potential to desalinate water with attractive levelized product water cost and would have the simplicity and operational flexibility needed for isolated applications.

Table 1-2. Solar Desal Plant Annual Performance—1978 Midland Data

Month	Water production ($10^6 m^3$)	Operation time (hr)			Insolation MWh			RCR heat absorption (MWh)
		Total	Direct solar	TES	Collector field	Max avail at RCR	Actual input at RCR	
J	0.145	473	132	341	2,345	1,613	1,480	1,295
F	0.181	503	181	322	2,977	2,024	1,858	1,626
M	0.192	598	207	391	3,359	2,252	2,022	1,769
A	0.264	720	277	443	4,600	2,884	2,534	2,217
M	0.205	666	242	424	3,993	2,394	2,153	1,884
J	0.157	535	202	333	3,128	1,869	1,700	1,488
J	0.246	734	311	423	5,007	2,977	2,452	2,146
A	0.145	545	202	343	3,042	1,868	1,740	1,523
S	0.101	432	163	269	2,330	1,561	1,459	1,277
O	0.205	641	214	427	3,549	2,397	2,141	1,873
N	0.102	413	127	286	2,085	1,443	1,330	1,164
D	0.186	591	184	407	3,105	2,131	1,958	1,713
Year	2.129	6,851	2,440	4,411	39,520	25,414	22,827	19,974

- **Adjustment for 30-year average**

  $2.129 \times 1.09 \times 0.91 = 2.11 \times 10^6 m^3$

  ("1978 data") x (30 year factor) x (Plant availability)

2.0 INTRODUCTION

BEC under subcontract from the SERI has prepared a design for a solar energy water desalination system that would transform brackish well water into potable water for a community in southwest Texas. BEC performed overall project management, system engineering and solar subsystem design; Resources Conservation Company, a partly-owned subsidiary of BEC, provided designs for the water-related subsystem.

The 10-month contract which began in October, 1980 covers Phase 1 of a 3-phase program that is (1) sponsored jointly by the governments of Saudi Arabia and the United States as part of the SOLERAS agreement and (2) administered by SERI. An objective of the SOLERAS agreement is to advance the development of solar energy technology in the two countries. The system analysis and pilot plant preliminary design activities of Phase 1 are described further in the remainder of this section. Phase 2 will involve detailed design and construction of a pilot plant and Phase 3 will cover pilot plant operation and training of personnel. Operation of the pilot plant will provide verification of the design features and performance of the large-scale commercial plant.

This report documents the work done in Phase 1 under Task 2, System Requirements Definition, and Task 3, System Analysis, dealing with selection of requirements, system trade studies, and definition of the design, costs, and operational characteristics for a commercial solar energy water desalination plant. The objectives of the study were to define a system that has near-term practicability, operational flexibility, and overall system simplicity.

The work flow during Tasks 2 and 3 is illustrated in Figure 2-1. A preliminary System Performance Specification was prepared at the start of the contract to document the system design requirements. A performance model of the plant was developed to allow system performance to be determined on both an hourly and an annual basis. Using this model along with subsystem design evaluations and cost analyses, four candidate systems were chosen and evaluated, leading to selection of the preferred system. All candidates used similar central receiver solar collection, Brayton cycle energy conversion, and reverse osmosis water treatment. One of the candidates was the originally proposed system, which served as a baseline. The preferred system was refined and described in further detail during the remainder of Task 3. Design, performance, and cost analyses were performed to further characterize the selected system. The cost analyses are reported in Volume IV, along with the Task 5 cost analyses.

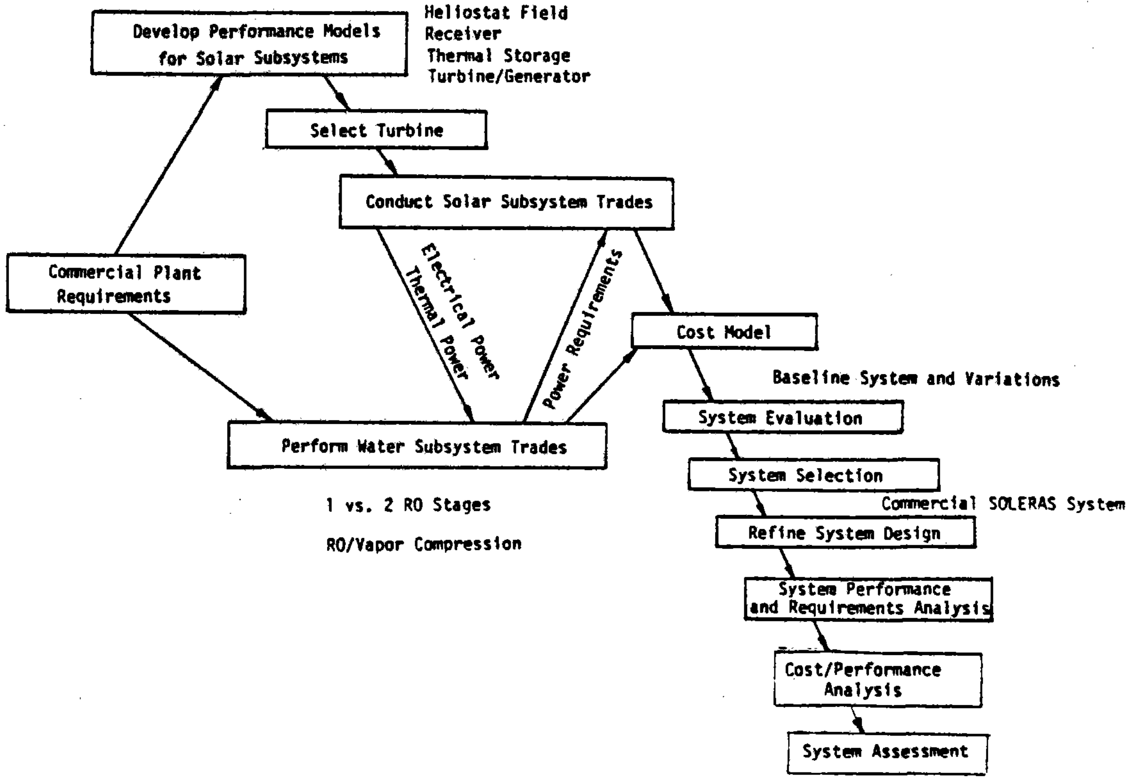


Figure 2-1. General System Analysis Approach

3.0 SYSTEM REQUIREMENTS

Details of the system requirements are contained in the subcontract Statement of Work [1] and in the System Performance Specification [2]. The general system requirements that govern the system design are listed below:

Brackish water desalination based on
    SERI's before/after chemistry standards
1,800,000 m^3/year product water production rate
Minimum levelized product water cost
    using SERI economic parameters
20 year plant life
High reliability/maintainability
Independent from fossil fuel in normal operations
Technical readiness
Low risk
Minimum overall water recovery factor: 0.70
Minimum plant availability factor: 0.82
Feedwater storage: 3 d
Product water storage: 10 d
Fuel storage for backup power: 7 d
Minimum process chemical storage: 30 d
Zero leakage evaporation pond

In addition to these requirements, the system is designed to meet several other conditions. First, water production is based on electrical power generation capability. This condition offers independence from having to design the system to meet unusual local water demand profiles and allows easier assessment of plant performance in various locations.

The plant is designed for a location in the Midland-Odessa area of West Texas. SOLMET and 30 year average weather data [3] is available for Midland-Odessa and is suitable for plant design and performance analysis. This region has good solar insolation and has wide spread water quality problems and thus could benefit from commercial availability of solar water desalination plants.

Several conditions were specified that influence product water cost. Feedwater is assumed to be groundwater and is pumped to the plant at no cost. After desalination, the consumers will draw product water from plant storage for purification in their own treatment facilities. Finally, the plant is assumed to be the "Nth" constructed which implies initial design and development costs have already been amortized.

4.0 GENERAL SYSTEM CONCEPT

4.1 Candidate System Concepts

The system design is based on Brayton cycle solar power generation and reverse osmosis water desalination. All electrical power needed for normal plant operation is provided by a Brayton cycle engine (gas turbine) having compressed air as a working fluid. Primary solar system components are: heliostat field, central cavity tube heat exchanger receiver, receiver support tower, thermal energy storage, and a commercial gas turbine generator set. Most of these components utilize technology being developed in separate U.S. Department of Energy and Electric Power Research Institute projects. A simplified schematic applicable to all candidates is shown in Figure 4-1.

Air is used as a solar system working fluid in order to (1) simplify design of the receiver, thermal storage units, fluid lines, and interfaces; (2) allow use of commercial turbomachinery; and (3) simplify interfaces between these components because of the common working fluid. Also with this type of system, fossil fuel can be burned in a modified turbine combustor to provide emergency standby power at low additional system cost.

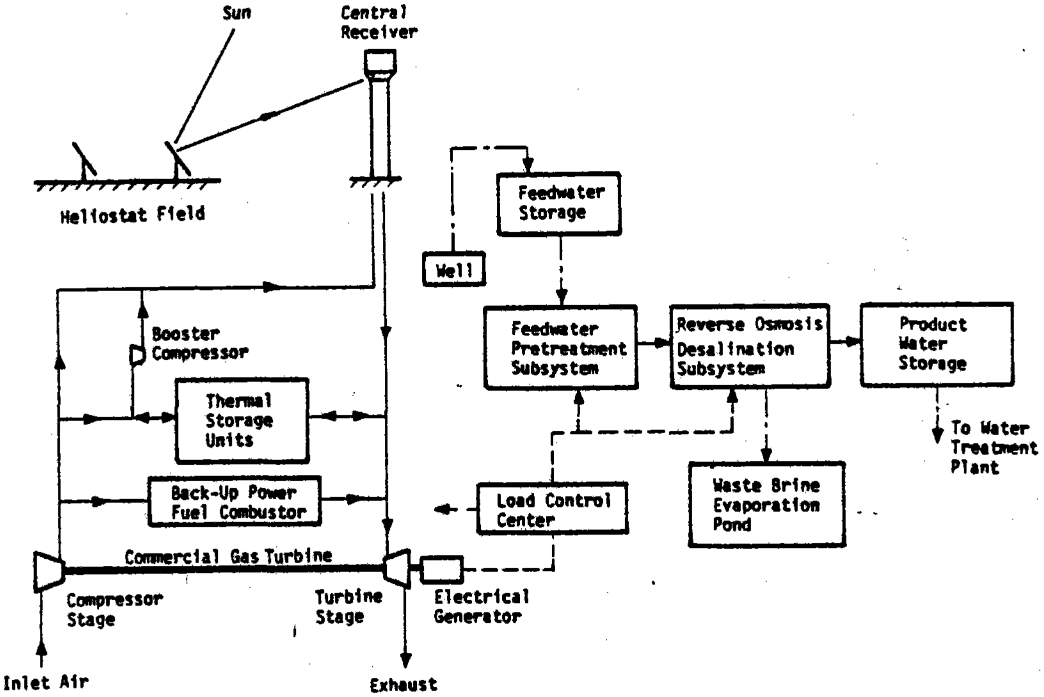


Figure 4-1. General System Schematic

An important operational aspect of the system is that the water subsystems should be run as continuously as possible to minimize product water cost. This, combined with a SERI requirement that normal operation shall not use fossil fuel, suggests that some form of thermal energy storage be used to accomplish continuous day/night power generation. The thermal storage concept selected utilizes simple sensible heat units having brick checkerwork construction contained in an internally insulated pressure shell. This storage scheme is very compatible with the air Brayton cycle. With this type of energy storage, charging is accomplished by routing heated air from the receiver to the thermal storage units during daytime conditions. When the solar resource becomes inadequate, the compressor flow is diverted away from the receiver and is routed through the thermal storage units where it is heated to the required turbine inlet temperature.

Reverse osmosis is selected as the basic water desalination method. Compared to other desalination technologies, the reverse osmosis process has low power demand which minimizes the solar subsystems size and costs. Also the reverse osmosis process has a simple electrical interface with the solar side of the system.

A more detailed system schematic, shown in Figure 4-2, describes the baseline commercial plant, as proposed and studied during the early weeks of the contract. This concept featured a 2-stage water desalination system and lime-soda softening for pretreatment. It was selected as the optimal approach after considerable study during the proposal effort. However, as the design, cost, and operational aspects of this configuration were being defined, it became evident that several concerns might best be resolved by revising the water treatment portion of the plant. The concerns were based primarily on high capital, membrane replacement, and chemical costs and adaptability of lime-soda pretreatment to intermittent operation. While the conceptual approach for the solar power portion remained the same, its power requirements and size were affected by power demands of the water system. Four candidate system concepts were defined that all employ RO desalination technology and satisfy the requirements of product water production rate and before/after water chemistry. These candidate systems, shown in Figure 4-3, differ in (1) the method of feedwater pretreatment, (2) number of reverse osmosis stages,

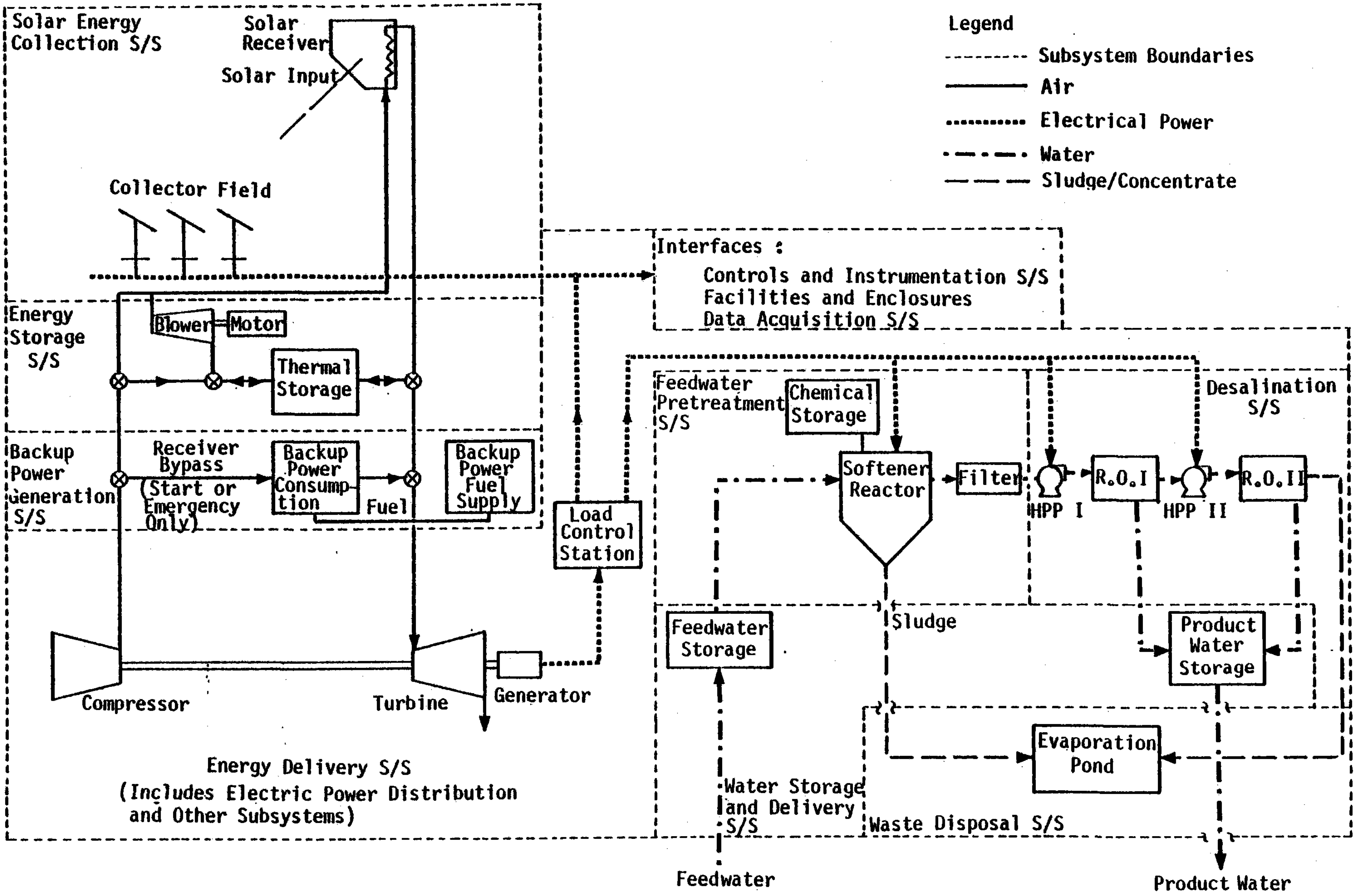


Figure 4-2. Solar Energy Water Desalination System Schematic Baseline Commercial Plant

(3) use of standard flux vs. high flux reverse osmosis membranes, and (4) use of multiple effect vapor compression for increased water recovery. The systems consequently have varying water recovery ratios, electrical power demands, and water subsystem costs.

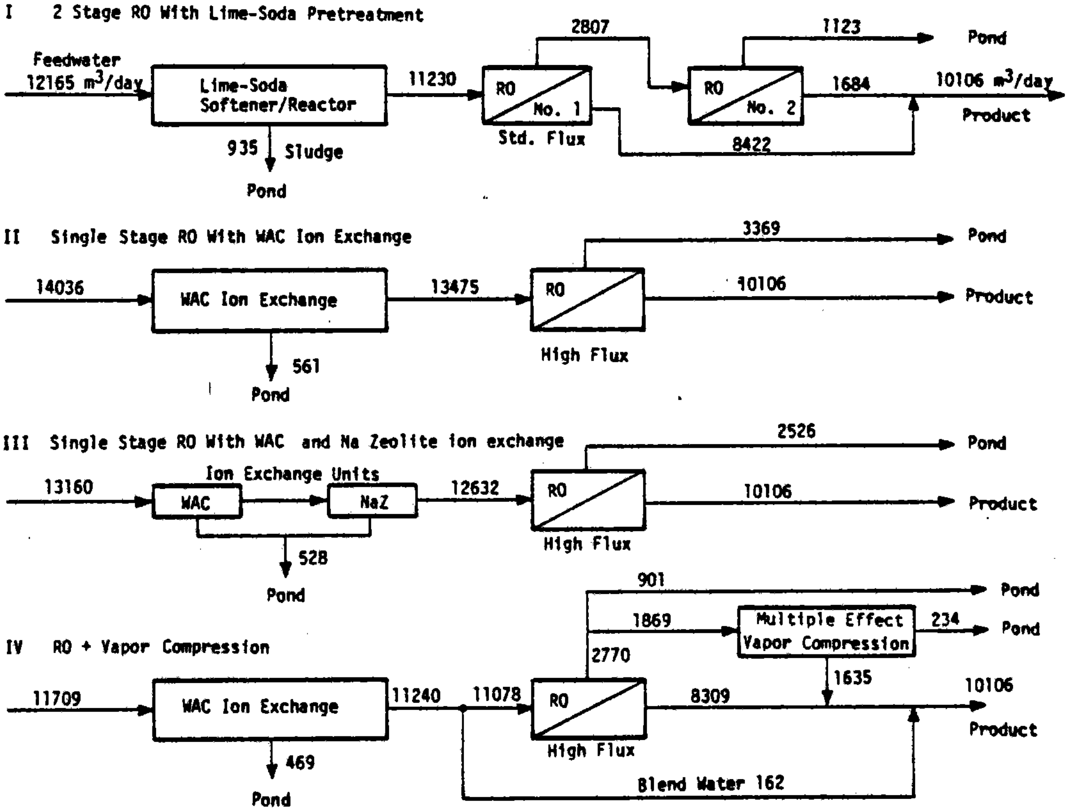


Figure 4-3. Candidate Water Treatment Systems

Configuration I (2 stage RO with lime-soda pretreatment) was the proposed system and the baseline shown in Figure 4-2. It also served as a baseline configuration in a preliminary systems analysis study that defined sizes of the primary solar subsystem components. This baseline system was analyzed for performance on a seasonal basis using 30 year averaged weather data for Midland-Odessa, Texas. The DELSOL code [4] was used to design the heliostat field and predict seasonal energy inputs to the central receiver. A general plant performance computer model was used to predict daily electrical power production of this design on an hourly basis.

Table 4-1 lists the predicted seasonal electrical output for the baseline system. This performance, together with sun availability (weather factor) and a conservative assumption for plant availability, forms a basis for defining the peak water production design point for the water subsystems. The peak rate of 10106 m^3/year was used to size the water related components of each candidate system.

Table 4-1. Daily Design Water Production Rate

	March	June	Sept	Dec	Average
Net plant electrical output (MWh)	22.2	18.3	17.9	15.4	18.45
Clear day plant performance					
Baseline system					
Relative electrical output E	1.21	0.99	0.97	0.83	
Sun availability S	0.72	0.80	0.79	0.74	
Plant availability A					0.82
Annual water production rate (m^3/day) Vo					4945
Required daily production (m^3/day)					
Vo(E)/(AS)	10106 Peak Design Flow	7472	7400	6796	
Basic assumption:					
Water-production follows daily energy production in each season					

4.2 Candidate System Design Features

After establishing pump and plant parasitic power requirements for each system, the respective solar system components could then be sized. Also, evaporation pond sizes were determined for each system based on their respective water recovery ratios and a mean pond evaporation rate of 1.35 m /year. A summary of the candidate system size parameters appears in the following table.

Table 4-2. Candidate System Features

		Water Recovery Ratio %	Evaporation Pond Size Ha	Peak Power Demand kW		Turbine	Number of Heliostat	Thermal Storage Media Mass Gg
				Water Systems	Total Plant			
I	2-Stage RO with lime-soda pretreatment	90	13.3	724	1034	Simple Cycle Centaur	600	2.5
II	Single stage RO with WAC ion exchange	72	51.9	512	731	Simple Cycle Saturn	436	1.68
III	Single stage RO with WAC and NaZ ion exchange	76.5	41.0	607	867	Combined Cycle Saturn	436	1.68
IV	RO + vapor compression with WAC ion exchange	86.3	21.2	1459	2083	Combined Cycle Centaur	600	2.5

A survey of commercial gas turbines indicated the Saturn and Centaur turbines, produced by Solar Turbines International, are a good match to the candidate systems. These turbines are currently available, are in widespread use, and have sufficiently high pressure ratios and low turbine inlet temperature to be compatible with current receiver technology. To meet the higher power demands, the turbines for systems III and IV require combined cycle equipment in which the gas turbine reject heat is used to produce steam for a turbine-generator set. The combined cycle turbines, since they utilize reject heat, do not require larger heliostat fields or more massive thermal storage than their respective simple cycle systems.

4.3 System Evaluation Factors

In evaluating the candidate systems, five areas were considered:

Levelized (life cycle) product water costs
Technology readiness
Complexity
Application limitations
Implementation risks

Product water cost is a dominant evaluation factor and can be treated quantitively. The other areas are of a qualitive nature but are, never-the-less, important to system evaluation and selection.

The levelized product water costs for 1.8 million m^3 annual production were computed by the method for sum-of-the-years-digits depreciation given in reference [6] using economic parameters specified by SERI [1]. The primary parameters are:

System operating lifetime	20 years
Accounting lifetime	16 years
Cost of capital (and rate of return on capital)	0.086
Base year for constant dollars	1980
Price year for cost information	1980
First year of commercial operation	1983
Rate of general inflation	0.060
Escalation rate for capital costs	0.060
Escalation rate for operating costs	0.070
Escalation rate for maintenace costs	0.070
Escalation rate for fuel costs	15%
Insurance + "other tax" fraction	0.020
Investment tax credit	0.100
Tax rate	0.5
Raw land cost	$1.25/m^2$
Cost for lined evaporation ponds	$25/m^2$
Cost for fuel oil (31 GJ/m^3)	$157/m^3$

The resulting computed cost parameters that were used to calculate levelized product water costs are:

Capital recovery factor (8.6%, 20yrs)	0.1064
Present value of sum-of-the-years-digits depreciation	0.6376
Fixed charge rate	0.1437

4.4 System Evaluations

Costs for the candidate systems are listed in Table 4-3. These costs are engineering estimates for an "Nth" plant. Major equipment costs are based on information obtained from suppliers and cost estimates prepared for a recent Department of Energy project for industrial process heat involving similar heliostat field and central receiver concept[5]. The heliostat costs are assumed to be \$200/m^2 (based on nominal reflector area) for system comparison purposes. Water subsystem costs are based on information from suppliers obtained by RCC for prepackaged skid-mounted assemblies. A sizeable portion of the operation and maintenance costs are due to plant personnel (14 total) and costs related to the water subsystems, particularly reverse osmosis membrane replacement at 3 year intervals.

	Cost Account	I 2-Stage RO ($1000)	II 1-Stage RO	III 1-Stage RO	IV RO & Vapor Compression
5101	Site	184	220	220	184
5102	Facilities & Enclosures	400	416	450	400
5103	Solar Energy Collection	6,828	5140 ?	5,140	6,828
5104	Energy Storage	2,900	210 2100 ·	2,050	2,900
5105	Energy Delivery	1,528	600	900	2,528
5106	Back-Up Power	134	95	100	175
5107	Feedwater Pretreatment	6,570	1,600	600	1,600
5108	Desalination	9,550	3,240	3,000	15,740
5109	Water Storage & Delivery	2,600	2,600	2,600	2,600
5110	Waste Disposal	3,483	13,000	10,240	5,300
5111	Controls & Instrumentation				
	Solar Subsytems	350	343	410	350
	Water Subsytems	350	296	400	450
5112	Data Acquisition	150	150	150	150
5120	Maintenance Support	50	50	50	50
5130	Technical Data	20	20	20	20
	Total Capital Costs	35,274	29,870	26,159	39,334
	Annual Operating Costs	1,070	563	670	960
	Annual Maintenance Costs	815	351	387	635
	Annual Back-Up Fuel Costs	25	18	22	51

Table 4-3. Cost Model Data for Candidate Systems

Table 4-4 presents levelized product water costs for the candidate systems using the respective system cost data given in the previous table. Systems II and III, while having lower water recovery ratios, have levelized product water costs that are relatively low and comparable. System III has a slightly lower product water cost than System II primarily because of the evaporation pond size reduction allowed by the higher water recovery ratio. Systems I and IV have significantly higher product water costs due to higher capital, operation and maintenance costs; these higher costs are not offset by the associated higher water recovery ratios.

In the area of technology readiness, Table 4-5, the water subsystems are all state-of-the-art and commercially available. On the solar system side, development is required for a production receiver design. The Electric Power Research Institute (EPRI) is currently funding BEC in a project called the Full System Experiment; this project is providing technical background in the areas of receiver design, receiver-turbine integration, and operation and control of a hybrid solar/fossil fuel central receiver as a power generation system. This program follows another EPRI/BEC program, the Bench Model Solar Receiver, in which a 1 MW receiver was successfully designed, fabricated, and tested. Heliostats are in an advanced stage of development at BEC as part of the Department of Energy's Second Generation Heliostat program. The turbomachinery components are currently available except for the combined cycle Saturn turbine configuration which requires development. From an overall viewpoint, all of the candidate solar systems require design development of a similar nature prior to commercialization.

Assessment of candidate systems with respect to complexity, which relates to reliability, appears in Table 4-6. System II is the simplest system because of operational ease and flexibility, simple cycle power generation, and small energy collection subsystem size.

As indicated in Table 4-7, there are no significant limitations on locations for the candidate systems, other than the basic requirements for good solar insolation. System IV, because of its combined cycle power generation and vapor compression features (not a simple on/off system) is judged to be unsuitable for remote sites.

	Overall Water Recovery Ratio %	Costs Capital $M	 Annual Operating $M	 Annual Maintenance $M	Levelized Water Cost $\$/m^3$
I Two Stage RO Lime soda pretreatment Std. membranes Simple cycle Centaur	90	35.3	1.07	0.82	4.86
II Single Stage RO WAC Ion exchange pretreatment High flux membrane Simple cycle Saturn	72	29.9	0.56	0.35	3.39
III Single Stage RO WAC + NaZ ion exchange High flux membrane Combined cycle Saturn	76.5	26.2	0.64	0.39	3.22
IV RO + Vapor Compression WAC ion exchange High flux membrane Combined cycle Centaur	86.3	39.3	0.96	0.64	4.95

Table 4-4. Product Water Cost Comparisons

	Candidate	
I	2-Stage RO with lime-soda pretreatment. Simple cycle Centaur.	S.O.A.[1] water systems-standard membranes. Simple cycle Centaur is available.
II	Singe stage RO with WAC ion exchange. Simple cycle Saturn.	S.O.A. water systems-high flux membranes are now in service. Simple cycle Saturn is readily available.
III	Single stage RO with WAC + NaZ ion exchange. Combined cycle Saturn.	S.O.A. water systems-high flux membranes are now in service. Combined cycle Saturn needs development.
IV	RO + vapor compression with WAC ion exchange. Combined cycle Centaur.	S.O.A. water systems-high flux membranes are now in service. Combined cycle Centaur is available.
	General	All systems require similar solar subsystem design development.

---

[1] S.O.A. - State of the Art

Table 4-5. System Concept Evaluations — Technology Readiness

Candidate	
I 2-Stage RO Lime-soda pretreatment Simple cycle Centaur	Lime-soda process requires close control
II Single Stage RO WAC ion exchange Simple cycle Saturn	Simple on/off water systems - Minimal chemical controls smallest power demand - Smallest and simplest solar subsystems
III Single Stage RO WAC and NaZ ion exchange Combned cycle Saturn	- Requires more controls than above - Increased complexity with combined cycle
IV RO and vapor compression WAC ion exchange Combined cycle Centaur	- Highest water system complexity due to V.C. - Difficult to turn on/off - Complex combined cycle power generation - Largest solar subsystems

Table 4-6. System Concept Evaluations — Complexity/Reliability Factors

Candidate	
I 2-Stage RO Lime-soda pretreatment Simple cycle Centaur	- Can treat wide range of feedwaters
II Single Stage RO WAC ion exchange Simple cycle Saturn	- Requires certain concentration of ions in feedwater - Opportunity for continued cycle power generation - Requires largest pond
III Single Stage RO WAC and NaZ ion exchange Combined cycle Saturn	- Requires certain concentration of ions in feedwater
IV RO and vapor compression WAC ion exchange Combined cycle Centaur	- Can treat wide range of feedwaters - Requires skilled operators

Table 4-7. System Concept Evaluations — Application Factors

The candidate systems have varying implementation risks as shown in Table 4-8. System II, because it has the simplest solar subsystems, appears to have the least risk for successful implementation and operation.

	Candidate	
I	2-Stage RO Lime-soda pretreatment Simple cycle Centaur	- Widely used processes - Lime-soda process not normally used in intermittent operations
II	Single Stage RO WAC ion exchange Simple cycle Saturn	- New applications of WAC ion exchange and high flux RO, but suppliers will guarantee - Small solar system, size lessens development risk
III	Single Stage RO WAC and NaZ ion exchange Combined cycle Saturn	- New application of WAC and NA ion exchange, but suppliers will guarantee - Combined cycle Saturn needs development
IV	RO and vapor compression WAC ion exchange Combined cycle Centaur	- New application of WAC ion exchange, but suppliers will guarantee - Vapor compression not normally used in on/off operation
	General	- Solar receiver technology under development in separate programs - Heliostat costs dependent on developing market

Table 4-8. System Concept Evaluations — Risk Factors

4.5 System Selection

The preceding evaluations are summarized in Table 4-9. Based on these evaluations, overall ratings were determined that rank the candidate systems according to responsiveness to the system requirements specified by SERI. The resulting ratings indicate that System II, single stage reverse osmosis with weak acid cation exchange, is the preferred system concept. System II was selected for the on-going Task 3 project activities consisting of additional system design definition, operating availability analysis, plant performance analysis, and cost analysis of the selected commercial plant concept.

Candidate	Levelized Product Water Cost $/m^3$	Technology Readiness	Complexity	Application Limitiations	Risk Factors	Overall Selection Rating Based on SOLERAS Requirements
I 2-Stage RO Lime-soda pretreatment Simple cycle Centaur	4.86	High	Low	Minimal	Low	3
II Single Stage RO WAC ion exchange Simple cycle Saturn	3.39	High	Low	Minimal (except for large evaporation pond)	Low	1
III Single Stage RO WAC and NaZ ion exchange Combined cycle Saturn	3.22	Low	Medium	Minimal	Medium	2
IV RO and vapor compression WAC ion exchange Combined cycle Centaur	4.95	Low	High	Some	High	4

Table 4-9. System Concept Evaluation Summary

As a result of the subsystem trade-off study, a system configuration was selected that meets the SOLERAS project requirements for a commercial solar energy water desalination plant. The configuration consists of a heliostat/central receiver energy collection subsystem, air Brayton cycle power generation subsystem, sensible heat thermal energy storage, weak acid cation feedwater pretreatment, single stage reverse osmosis water desalination, and other subsystems. A preliminary systems analysis of the plant shows indirectly that it has the potential to desalinate water with attractive levelized product water cost and would have the simplicity and operational flexibility needed for isolated applications. The plant's economics are enhanced by the simple system configuration and capability for continuous day/night operations during normal weather conditions without using fossil fuel. The selected configuration has a low power requirement and thus allows continuous operation using sensible heat thermal energy storage of reasonable size.

5.0 COMMERCIAL SOLERAS PLANT CONFIGURATION

5.1 General System Description

A schematic of the selected commercial plant configuration, consistent with the candidate concept II in Section 4, but with more detail resulting from the design definition effort, is shown in Figure 5-1. System features which differ from the baseline schematic (Figure 4-2) are primarily the type of water pretreatment and use of a single stage RO instead of two stage RO. The additional detail in Figure 5-1 includes definition of the modularity in the energy storage, water pretreatment, and desalination subsystems. Also, ancillary equipment has been added to fully meet the design requirements regarding stand-alone, non-fossil fuel normal operation. This equipment includes a small turbo-generator for standby electric power that is powered by residual heat in the thermal energy storage units. A bottoming cycle is shown as an option; based on performance and cost of currently available units, this in not currently recommended, although a well-matched combined cycle turbine generator set would substantially improve solar plant efficiency and power production. A plant air supply is also shown; it is used for operating pneumatically actuated valves and for the Saturn turbine startup.

A more detailed schematic/flow diagram of the water storage, treatment, and waste disposal subsystems is shown in Figure 5-2. The pumped well water goes directly to the water pretreatment system without a break in the pressurization. The feedwater storage is parallel to this line and is normally maintained in a full condition, a nominal three day supply. Water pretreatment consists of four parallel weak acid cation units which soften the feedwater by reducing its calcium content and removing all the bicarbonate. At full production rate three of these units are in operation while the fourth is regenerating. Most of the softened feedwater is then passed through the decarbonator where carbon dioxide (a product of the bicarbonate reaction in the softening process) is removed. Following pretreatment, the feedwater is filtered and pumped at high pressure to the four parallel reverse osmosis units. Any combination of these units can be on-line, depending on the electric power available and the water production rate desired. The permeate

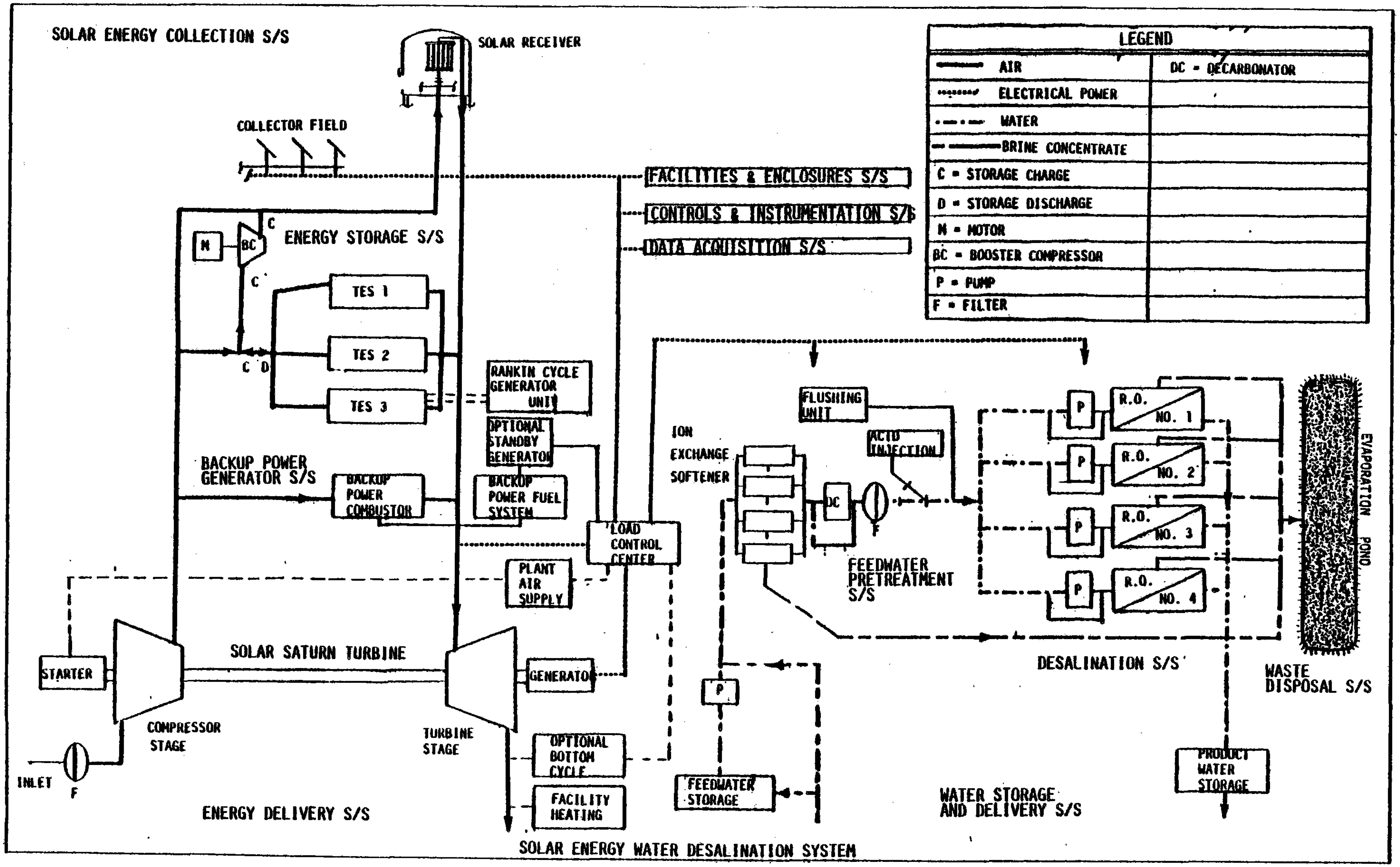


Figure 5-1. Commercial Soleras Solar Energy Water Desalination System

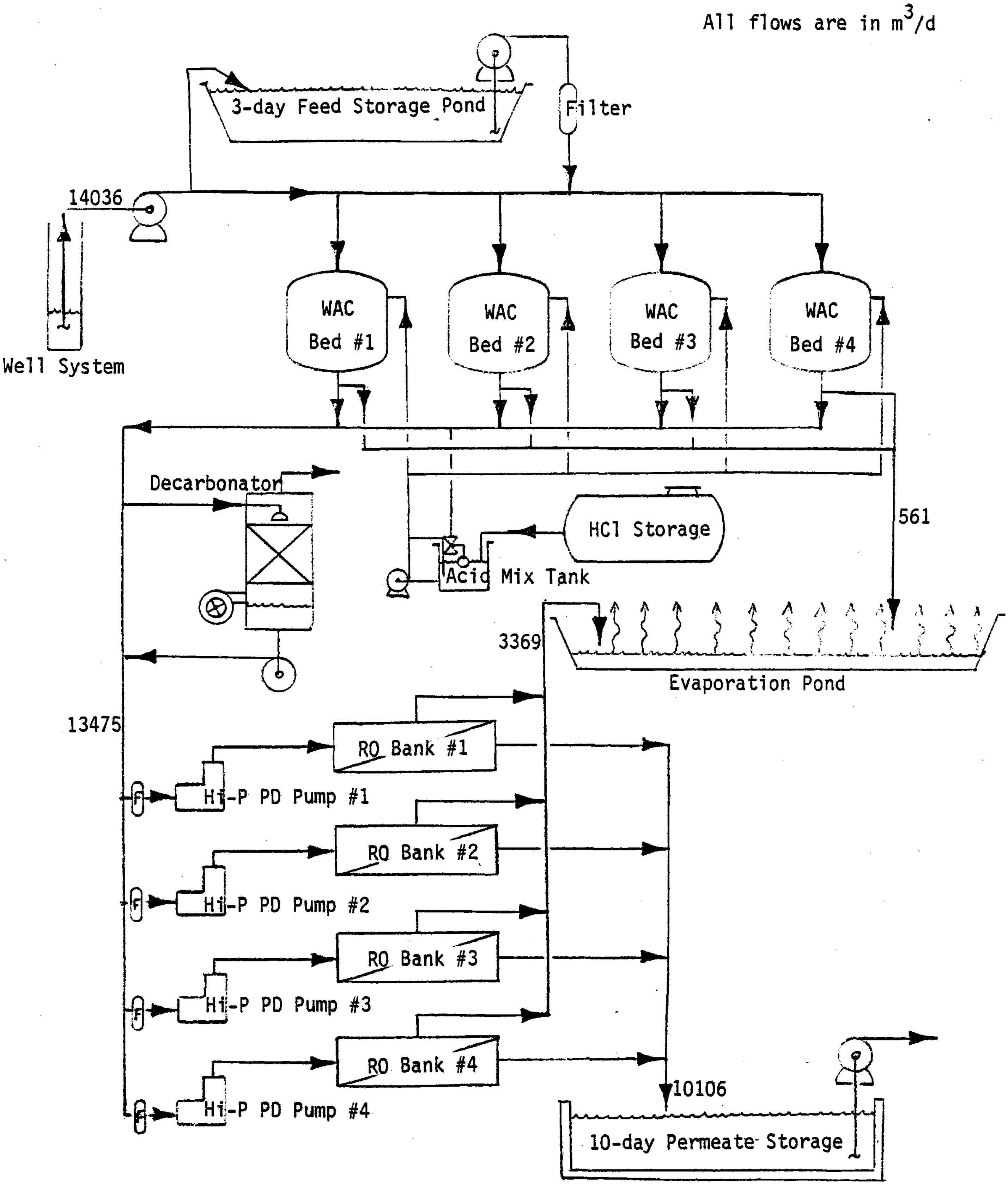


Figure 5-2. Water Treatment and Desalination Process Flow Diagram

(i.e., product water) from the RO units is sent to the ten day product water storage pond or to the distribution system. Reject from the RO units and waste from the pretreatment equipment flows to the waste disposal pond for eventual evaporation. The RO desalination subsystem recovers 75 percent of the water supplied to it; overall recovery including pretreatment losses is 72 percent. Water chemistry at several points of the flow through the system are listed in Table 5-1.

5.2 General Plant Layout

A general site plan, Figure 5-3, shows the major elements of the commercial plant. The evaporation pond is the largest (and costliest) element of the system, occupying over half the site area. The site has been laid out so that the evaporation pond is downwind of the collector field and product water storage in prevailing wind conditions. However, the site plan is flexible and can be tailored to land availability, terrain features, and prevailing wind direction as needed. The plant building and energy storage subsystem are located near the base of the tower to minimize piping, electric power distribution lines, and control cabling lengths.

The general arrangement within the plant building is defined in Figure 5-4. This building provides space for the feedwater pretreatment and desalination subsystems, backup power systems, the controls, and other facilities.

5.3 Plant Design Features

Detailed design features of the selected plant are listed below:

Site

Location	Near Midland-Odessa, Texas Latitude 31.9°N Longitude 101.9°W
Altitude	579 m
Total Area	9.6×10^5 m^2

Ion Concentrations in mg/liter

	Raw Feed	RO Feed	Predicted Reject	Predicted Product	Required Product
Calcium (Ca^{++})	500	274	1060	<20	-
Magnesium (Mg^{++})	75	75	290	< 5	-
Sodium (Na^{+})	1500	1500	5525	<200	-
Potassium (K^{+})	120	120	442	< 20	-
Iron (Fe)	0.1	0	0	0	≤ 0.3
Manganese (Mn)	0.1	0	0	0	≤ 0.05
Bicarbonate (HCO_3^{-})	690	0	0	< 2	-
Carbonate ($CO_3^{=}$)	0	0	0	0	-
Chloride (Cl^{-})	2000	2000	7367	<250	≤250
Sulfate ($SO_4^{=}$)	1100	1100	4259	< 50	≤250
Nitrate (NO_3^{-})	1	1	4	< 0.5	≤ 10
Phosphate ($PO_4^{=}$)	0	0	0	0	-
Fluoride (F^{-})	40	40	147	< 1	-
Silica (SiO_2)	35	35	90 - 130	< 10	-
TDS	6000	5150	19200	<500	≤ 500
pH (dimensionless)	7 - 7.5	4.5 - 5.5	4.5 - 5.5	~6	-

Table 5-1. Water System Chemistry

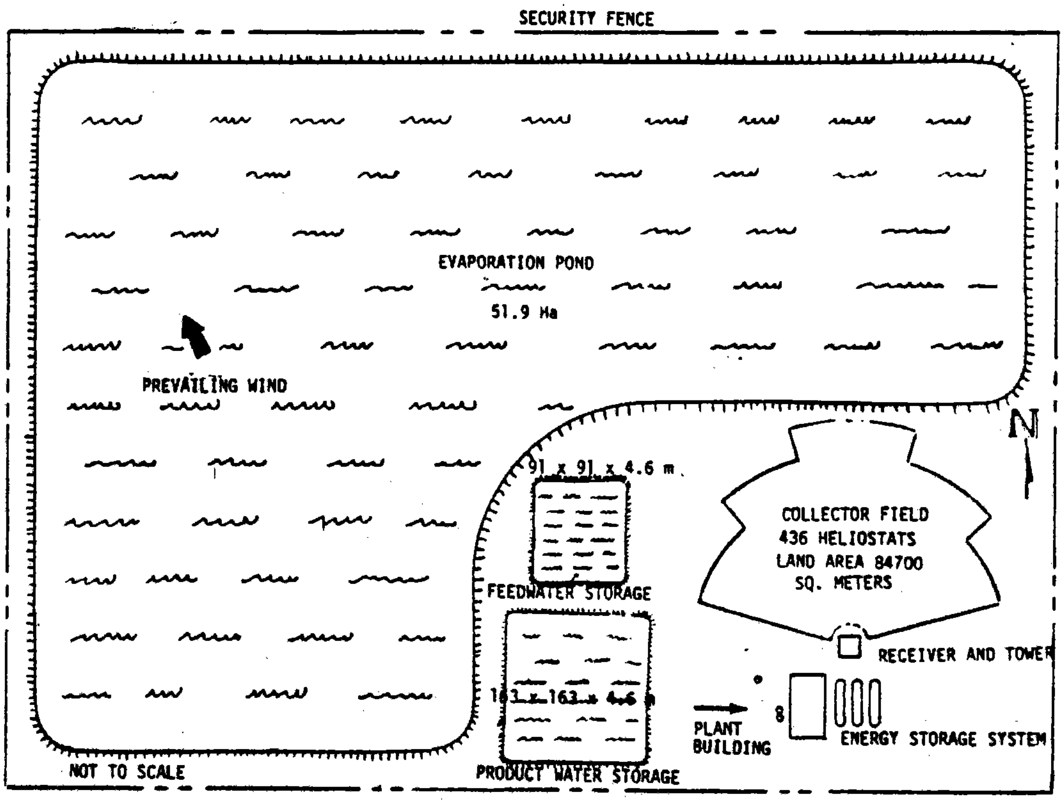


Figure 5-3. Solar Energy Desalination General Site Plan

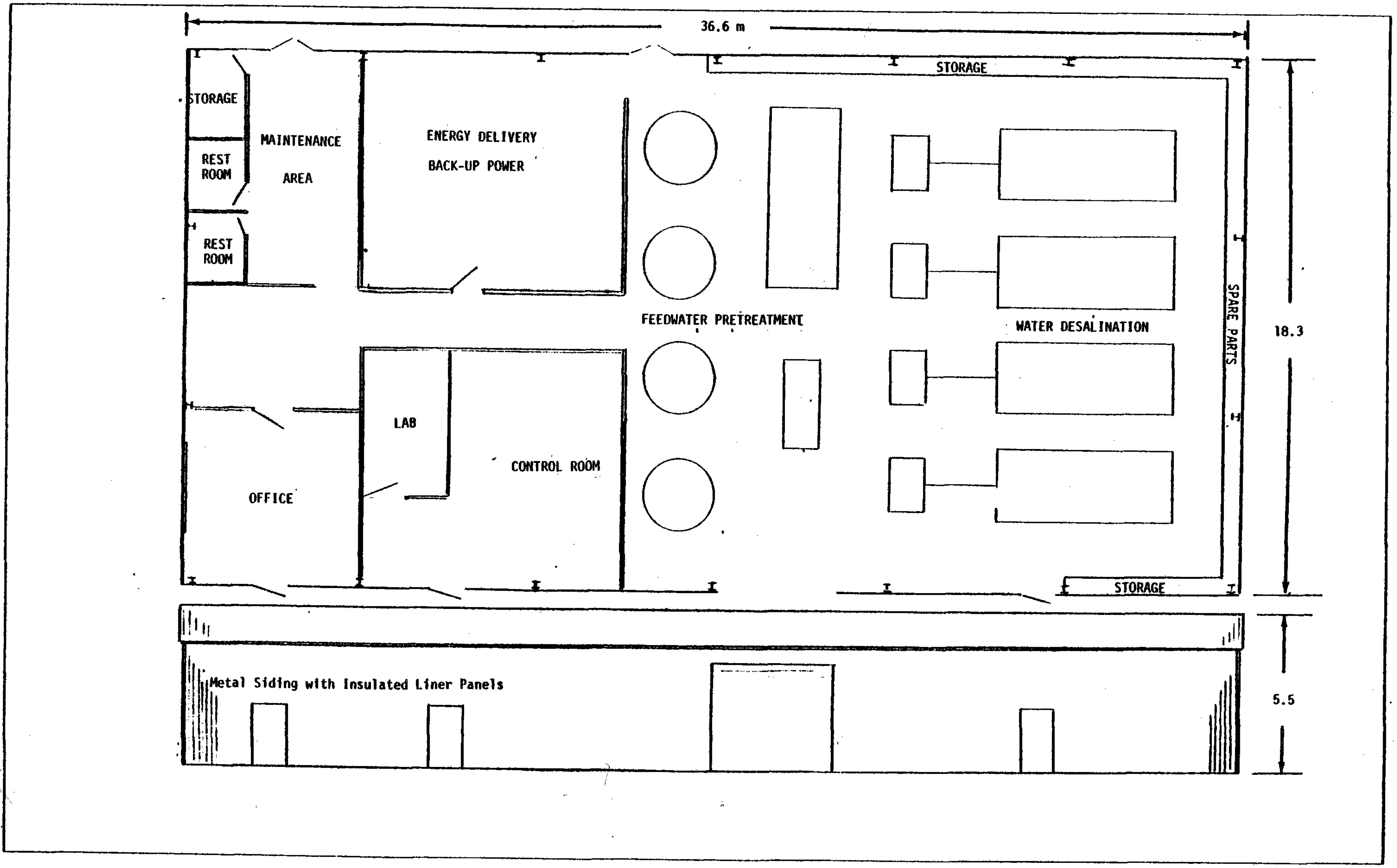


Figure 5-4. Solar Energy Water Desalination Control and Maintenance Building Plan and Evaluation

Facilities

Industrial-type warehouse/office building
Plan area: ~~2195~~ 670 m^2 errata

Energy Collection Subsystem

System Spec has 49 m^2

Heliostats :	
Type	BEC Second Generation
Heliostat mirror area	46.9 m^2
Heliostat surfaces	Cylindrical focus glass/ foamglas sandwich
Heliostat design life	20 years
Field configuration	North of tower with staggered heliostats
Field dimensions	
- Depth	300 m
- Width	390 m
Field area	84700 m^2
Heliostat number	436
Heliostat total reflective surface	20448 m^2 .241
Heliostat spacing	
- Radial (average)	11.5 m
- Azimuth (average)	7.5 m
Receiver :	
Receiver cavity width	14 m
Receiver height	68 m
Aperture area	42 m^2
Aperture height	54 m
Aperture inclination from vertical	40°
Cavity wall insulation thickness	0.30 m
Heat exchanger panel number	7
Heat exchanger tubes per panel	139/167
Heat exchanger tube material	Incoloy 800H

Heat exchanger tube dimensions	
- Length	9 m
- Outside diameter (direct/indirect)	1.95/1.60 cm
- Wall thickness	0.12 cm
- Tube pitch ratio (direct/indirect)	1.58/1.62
Panel width	4.29
Header material	321 CRES
Header dimensions	
- Inside diameter	27.9 cm
- Wall thickness	1.27 cm
Manifold material	321 CRES
Manifold dimensions	
- Inside diameter (inlet/outlet)	45.7/48.3 cm
- Wall thickness	0.63 cm

Tower :

Tower type	Structural steel
Tower height to aperture centerline	54 m
Foundation type	Concrete piers
Tower taper ratio	Straight
Tower materials	ASTM A36 steel
Riser, downcomer materials	321 CRES
Riser, downcomer dimensions	
- Inside diameter	45.7 cm
- Wall thickness	0.63 cm
- Pipe length (riser/downcomer)	50/63 m
Insulation material	Kaowool
Insulation thickness	20 cm

Energy Storage Subsystem

Storage tank number	3
Storage tank material (steel)	ASTM A516
Storage tank dimensions	3.6 m dia x 33.9 m
Insulation materials	Kaowool

Insulation dimensions	38 cm
Storage media material	MgO refractory (98%)
Storage media weight	1.68 x 10^6 kg
Storage media dimensions	
- Length	33.9 m
- Flow passage diameter	1.89 cm
-. Number of flow passages	2716
Booster compressor	
- Single stage centrifugal unit driven by AC electrical motor	
Peak power requirement	556 kW
Candidate equipment	
Elliot type	40 PH
Roots type	01B

Energy Generation Subsytem

Gas Turbine Generator Set -

Solar Saturn manufactured by Solar Turbines International

Modified for external fuel combustor using existing ductwork from recuperated prototype. Combustor is a standard Saturn combustor (not hybrid solar/ fossil burner). Electrical output rating is 731 kW at design point conditions

Standard pneumatic starter

Plant Air Supply -

Industrial air compressor with storage tank

Provide pressurized air for turbine starter and system control valves

Back-Up Power Generation

Standby Power Generator -

Rankine cycle unit using toluene as a working fluid. Heat energy is supplied from the thermal energy storage units. (The unit would be an adaptation of a unit being developed for Jet Propulsion Laboratory (JPL). Provides power during standby periods to power essential plant environmental and control equipment. Rating at design point: 40 kW

Diesel Generator Set -

Automatic cylinder diesel generator manufactured by Alturdyne for emergency panels.

Design point rating: 40 kW

Batteries -

Minimal battery supply for motor starting and fail-safe control system power.

Fossil fuel supply to turbine -

Capacity for 7 days operation = 62.51m^3 (16515 gal).

Plant will normally operate using thermal storage. During periods of extended low solar insolation and low thermal storage, plant will be maintained in a standby condition using power generated by a standby power system. In case of emergency servicing of solar energy collection or thermal energy storage subsystems, the turbine can be operated at normal power levels using an external fossil fuel combustor.

Feedwater Pretreatment Subsystem

Weak acid ion exchange

Candidate suppliers
  - U.S. Filter
  - Die-Sep
  - Illinois Water Treatment (IWT)
  - Graver

Design capacity raw water	14167 m^3/d

Acid injection for pH control

Desalination Subsystem

Reverse osmosis unit with a four module configuration -

Product water design capacity 10200 m^3/d

High flux polymeric membrane candidate suppliers

- Fluid Systems
- Envirogenics
- Hydronautics

High pressure pump on each RO module (positive displacement type) -

Pump pressure rating 2.94 MPa

Waste Disposal Subsystem

Earth excavation with plastic film liner and sand/gravel fill -

Area: 5.19×10^5 m^2

Water Storage and Delivery Subsystem

Feedwater Storage Tank -

Earth embankment with plastic film -

Size: 91 x 91 x 4.6 m

Area: 8.2×10^3 m^2

Capacity: 4×10^4 m^3

Product Water Storage -

Earth embankment with reinforced concrete liner -

Size: 163 x 163 x 4.6 m

Area: 2.65×10^6 m^2

Capacity: 1.2×10^5

Controls and Instrumentation Subsystem

Central control system concept color Cathode Ray Tube (CRT) displays

Master control linked to:

- Heliostat controllers
- Power generation controllers
- Process (water treatment) control computer

6.0 SUBSYSTEM DESCRIPTIONS

6.1 Solar Energy Collection Subsystem

The Solar Energy Collection Subsystem includes all the components for collecting solar energy, transforming it to thermal energy, and transferring it to the Energy Delivery Subsystem. Major components in this subsystem are the solar receiver, the receiver tower, riser and downcomer piping, and the collector field consisting of an array of heliostats and the power distribution and control system wiring associated with the heliostats.

6.1.1 Receiver, Tower, and Riser/Downcomer

Elevation views of the receiver and tower are shown in Figure 6-1. The receiver is supported at an elevation of 54 m from the ground to the center of the receiver aperture. The tower is an open steel truss structure; guy lines at the four corners improve the tower rigidity and reduce overall tower material usage and cost. Concrete pier foundations spread the loads into the surrounding soil and provide tower stability with or without the guide lines. In addition to supporting the receiver, the tower provides intermediate supports for the riser and downcomer and incorporates a ladder and walkway for personnel access.

External dimensions of the receiver are shown in Figure 6-2. The aperture geometry required is a function of both the heliostats reflected image sizes on the aperture plane and the positioning of heliostats (collector field shape). The aperture dimensions are determined interactively with the collector field sizing described in Section 8.3.3. Overall receiver dimensions are governed by several factors: limiting solar flux on interior walls to acceptable levels, reducing reradiation out the aperture to an acceptable level, and providing the required heat exchanger area. The top of the receiver supports lightning protection and a warning light.

Cutaways of the receiver, Figure 6-3, show its major features. Seven panels of heat exchanger tubing are located around the interior walls, except directly above the aperture. Incoming air is provided to the heat exchangers

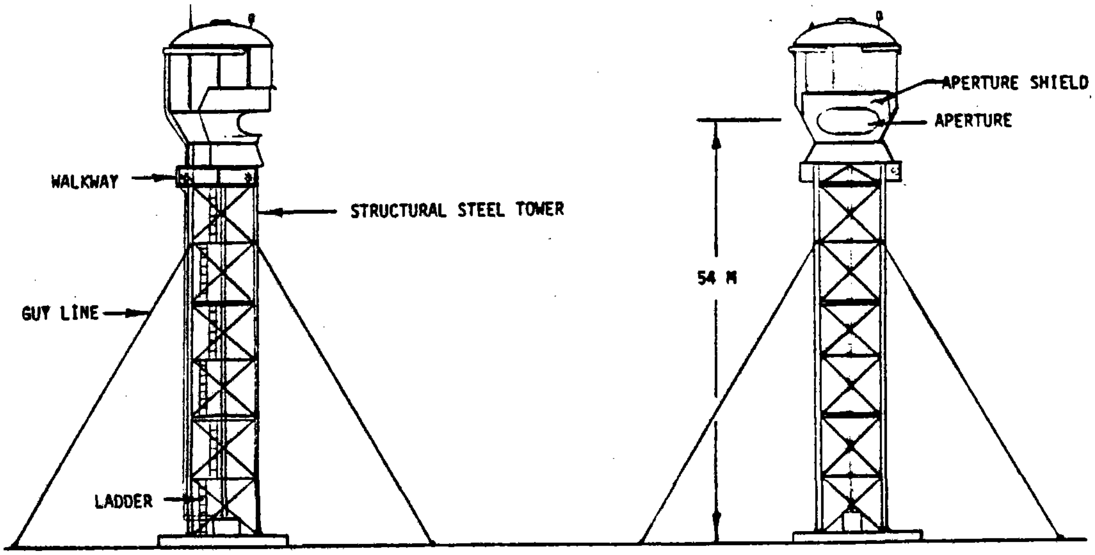


Figure 6-1. Receiver Tower Concept

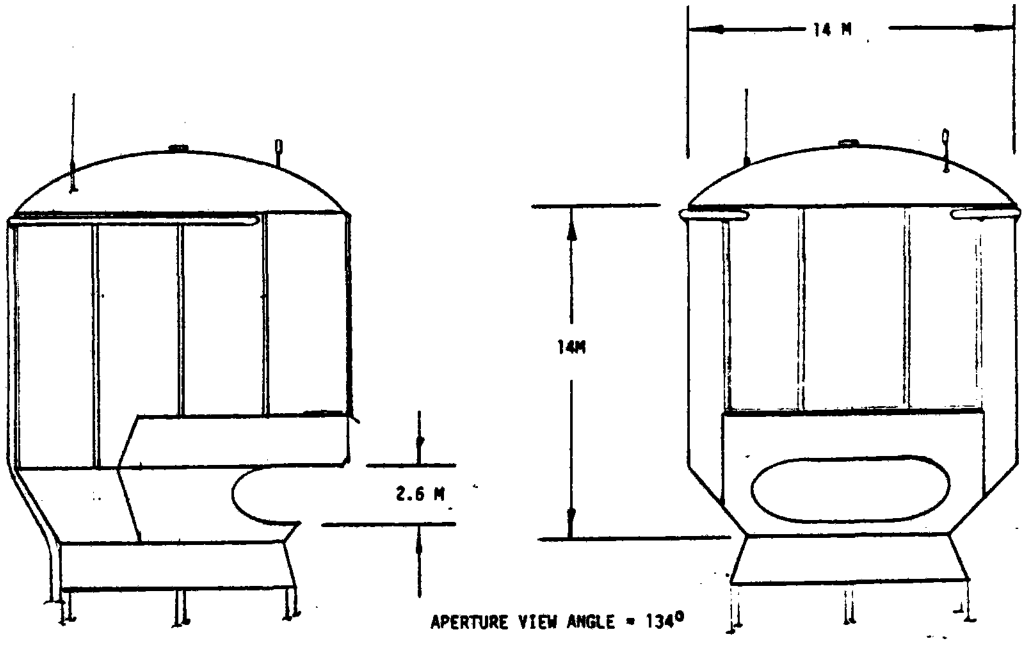


Figure 6-2. Receiver Configuration

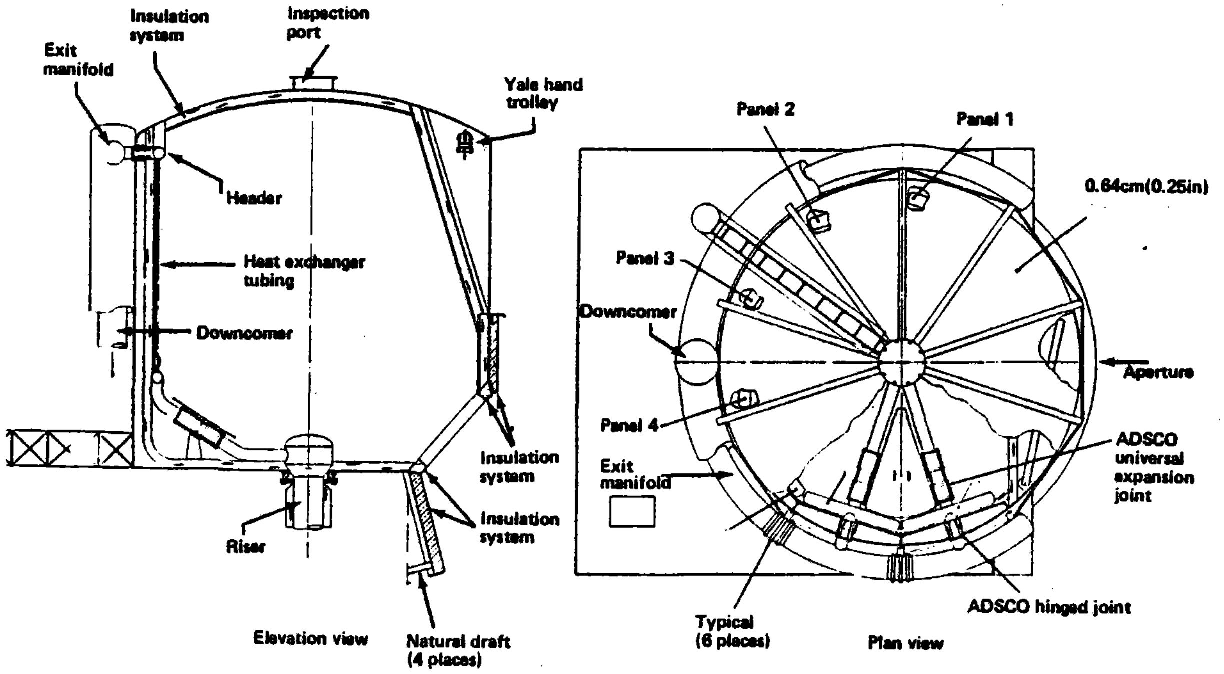
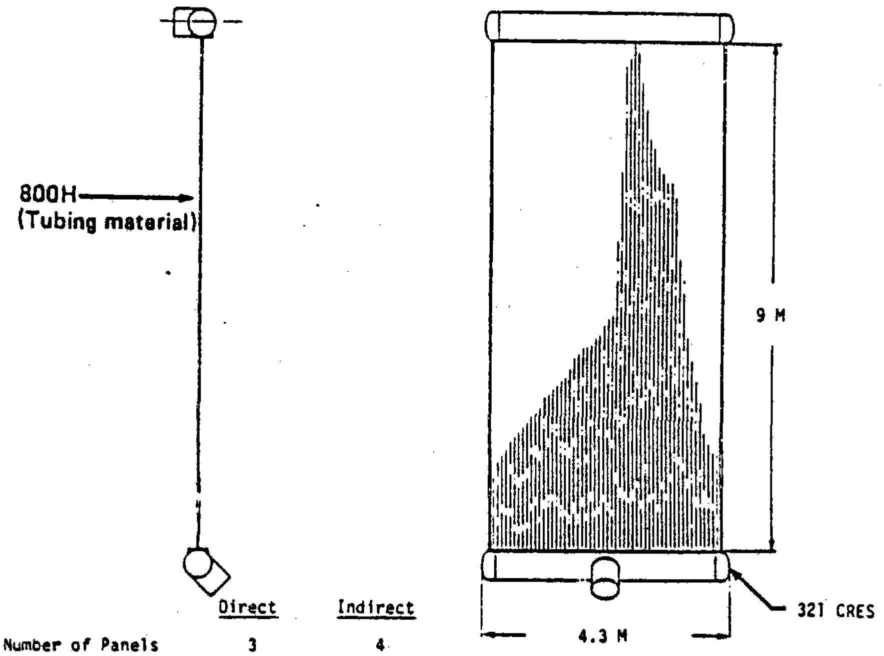


Figure 6-3. Central Receiver



	Direct	Indirect
Number of Panels	3	4
Tube No. per Panel	139	167
Outside Diameter	1.95 cm	1.60 cm
Wall Thickness	0.12 cm	0.12 cm

Figure 6-4. Heat Exchanger Panel

by the riser, which enters the cavity through the floor, and a plenum with a spider arrangement of ducts to the lower end of the headers on each panel. Air is extracted through the exit headers at the top of the panels, collected in the exit manifold mounted on the exterior of the receiver, and then ducted through the downcomer on the south side of the receiver. Flexible joints are incorporated in the ducts on each side of the heat exchanger panels to allow free movement of the panel due to thermal gradients and thus minimize thermal stresses.

Dimensions of the heat exchanger panel are given in Figure 6-4. The solar flux impinges directly on three of the panels (those opposite the aperture) and is transmitted indirectly to the remaining panels by reflections and reradiation. Therefore, the heat exchanger dimensions differ slightly for the two conditions. This helps balance the flow to achieve uniform exit temperatures from each panel. The flow can be further balanced with adjustable orifices in the duct to each panel. These would be adjusted initially and then remain fixed.

The riser and downcomer are stainless steel pipes, 45.7 cm diameter, insulated on their exterior with a 20 cm thickness of Kaowool. The pipes will incorporate anchors at each end and intermediate expansion joints and spring hangers to permit thermal expansion under operating conditions.

6.1.2 Collector Field

The collector field design is based on the production version of the BEC Second Generation Heliostat, shown in Figure 6-5, modified to curve the mirror panels in the horizontal direction. Performance of the heliostat as required by the Sandia design specification (see System Performance Specification [2]) is used in the collector field analysis. Tests of the two prototype versions of this heliostat at the Central Receiver Test Facility (CRTF), Albuquerque, New Mexico, show that the specified performance is met or exceeded. The mirror curvature provides a degree of focusing, required in small collector fields to limit spillage at a small receiver aperture. Curving the mirrors does not significantly impact heliostat cost based on BEC analysis of production tooling and processing requirements.

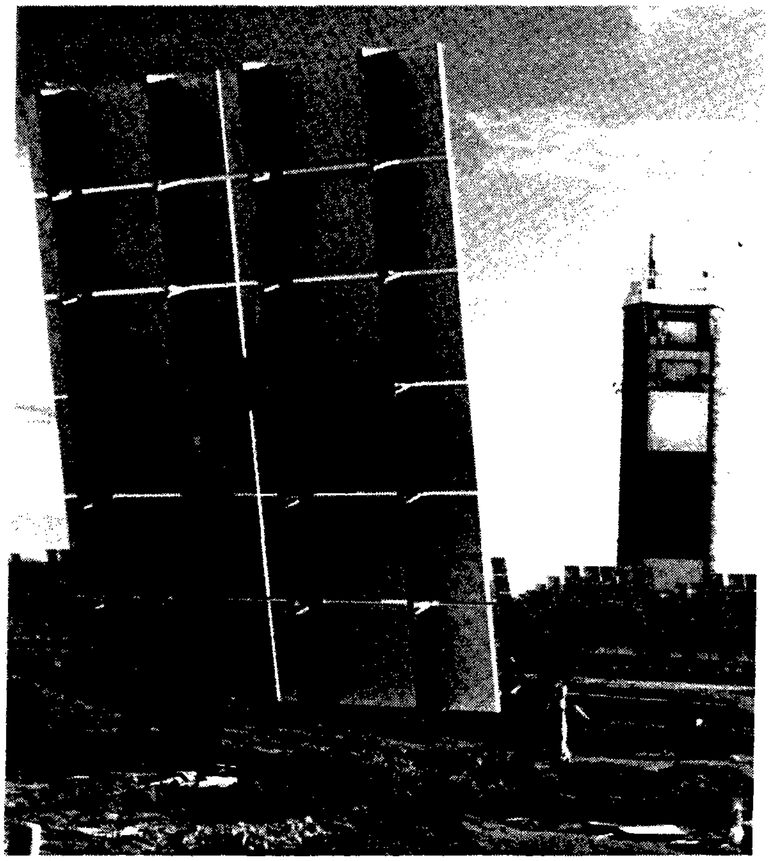


Figure 6-5. Heliostat

In determining annual performance, mirror reflectivity has been degraded by four percent to account for the long-term average effects of soiling on reflectivity experienced with the test facility heliostats at CRTF. This is the maximum reduction in long-term average reflectivity in the upper three curves of Figure 6-6. These heliostats were positioned to take advantage of natural precipitation for periodic cleaning of the mirrors. The heliostat represented by the fourth curve showing a lower reflectivity was always positioned face down so that no cleaning took place. Annual average rainfall in the Midland-Odessa area of Texas is 70 percent higher than in Albuquerque (0.34 m versus 0.20 m) so natural cleaning and average reflectivity should exceed the assumed values.

The geometry of the collector field is shown in Figure 6-7. Heliostats within each section of the field are arranged in uniform radial-stagger patterns over the area of that section. The radial-stagger pattern minimizes the shadowing and blocking caused by adjacent heliostats. Density of the field (reflector area divided by ground area) decreases from the maximum value of 48% nearest the tower to a minimum of 12% at the furthest section from the tower. Typical spacings are shown in Figure 6-8.

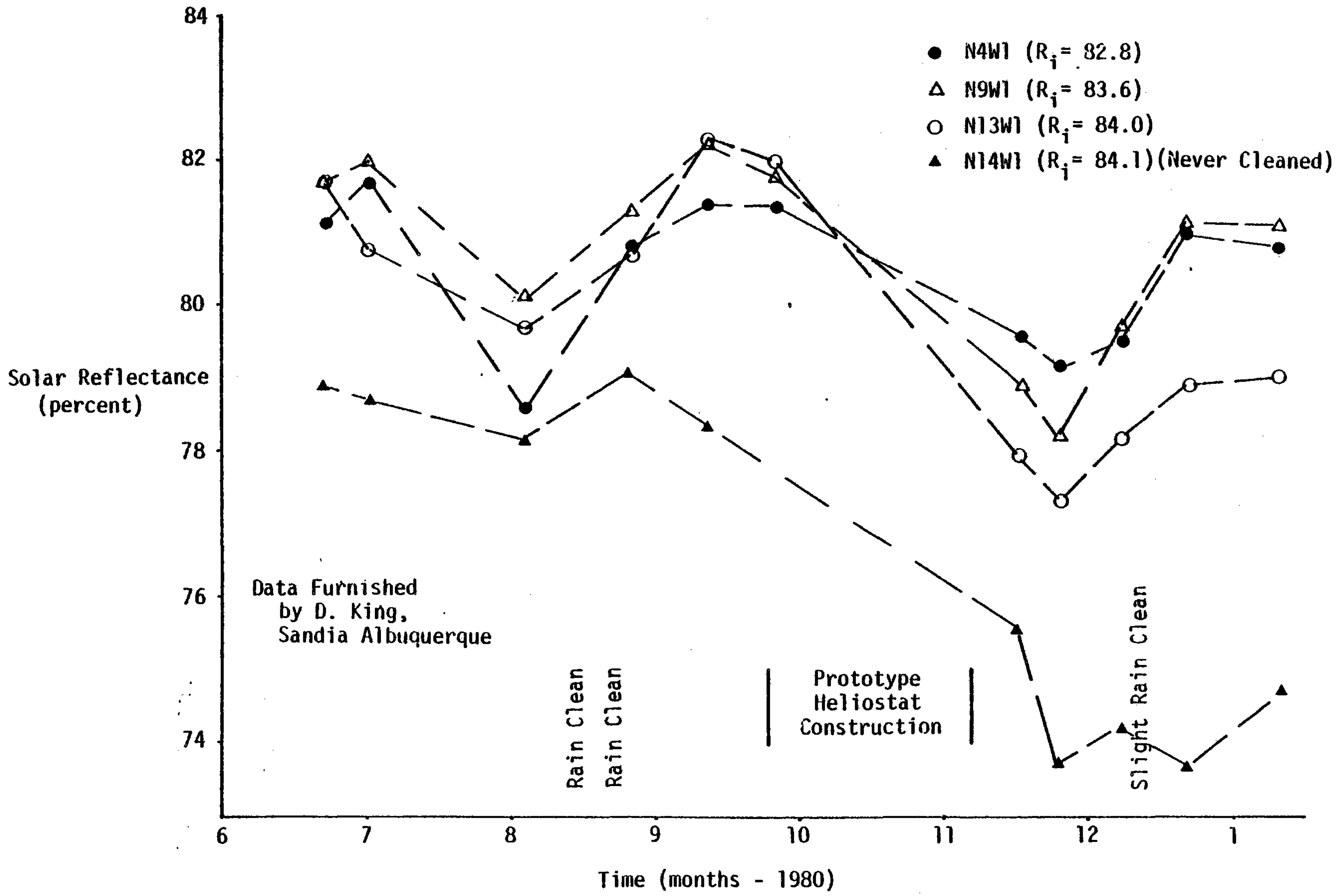


Figure 6-6. CRTF Heliostat Reflectance

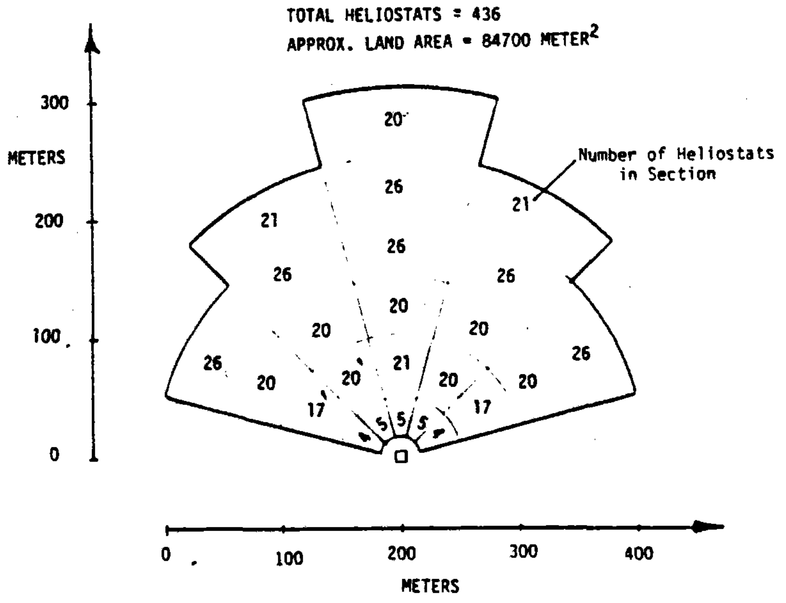


Figure 6-7. Heliostat Field Design

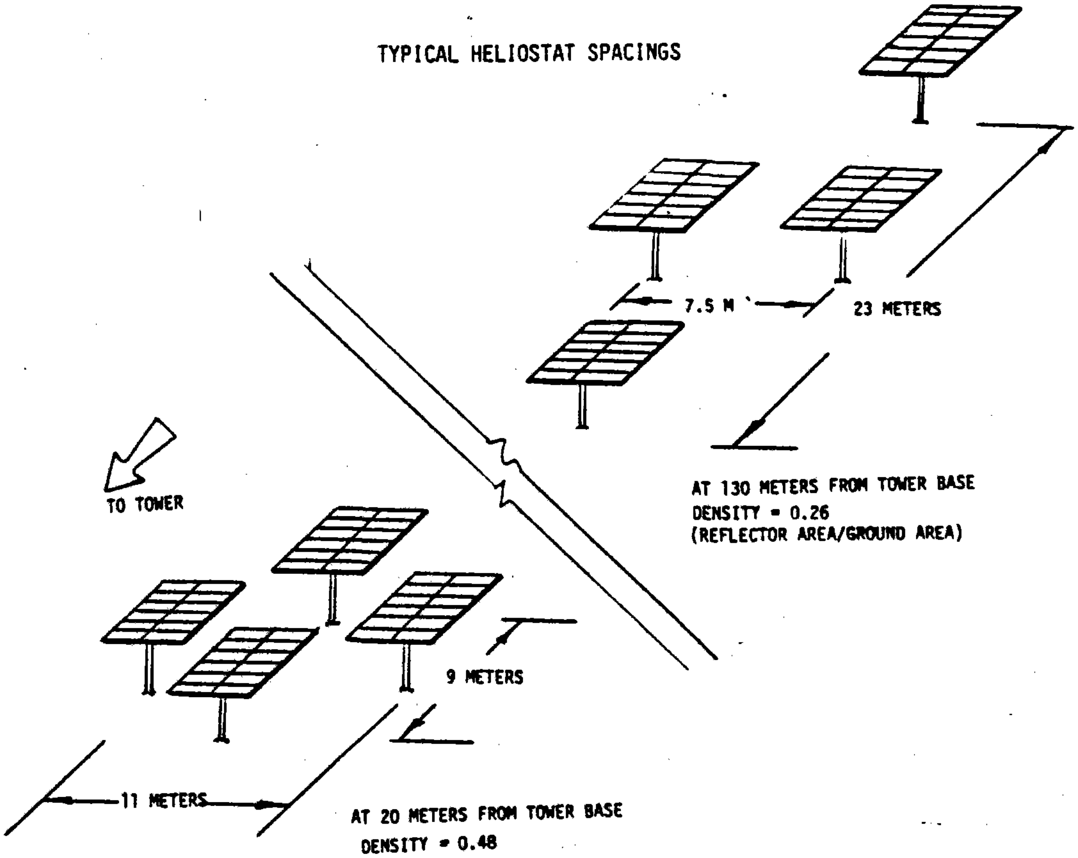


Figure 6-8. Typical Heliostat Spacings

6.2 Energy Delivery Subsystem

The Energy Delivery Subsystem consists of a gas turbine generator set, electric power distribution, and plant air storage and distribution.

6.2.1 Turbine Generator Set

The gas turbine generator set, the primary power conversion equipment, is a Saturn turbine manufactured by Solar Turbines International of San Diego, California. The skid-mounted unit is depicted in Figure 6-9; photographs of the Saturn and an installation of multiple units are shown in Figure 6-10 and 6-11. The International Standards Organization (ISO) base rating of this turbine for continuous service is 800 kW; under the design conditions for this plant, the maximum output is 731 kW. Physical specifications of the Saturn turbine are listed in Table 6-1. The table specifies an annular combustion chamber. However, a version with flanged ports for an external combustor is available (see Figure 6-12) and would be used in this application. A sketch of the ducts interfacing with these ports is shown in Figure 6-13.

Both electro-hydraulic and pneumatic starter systems are available for the Saturn turbine. The pneumatic system is selected since a plant air supply will be needed to operate pneumatically actuated valves in the water subsystems.

Efficiency, equipment cost, and equipment availability (of the appropriate size) are the major considerations in selection of the energy conversion system. The Saturn machine qualifies with respect to the latter two considerations. However, its efficiency is relatively low, typical of industrial gas turbines of conservative and not too recent design. The relatively high exhaust temperature suggests further energy recovery, either with a bottoming cycle or some plant process. During the design definition, several candidate processes were considered to utilize the exhaust heat. These included a thermally powered desalination process and, to reduce evaporation pond size, a waste stream spray drier. The candidates studied had additional costs that outweighed the benefits.

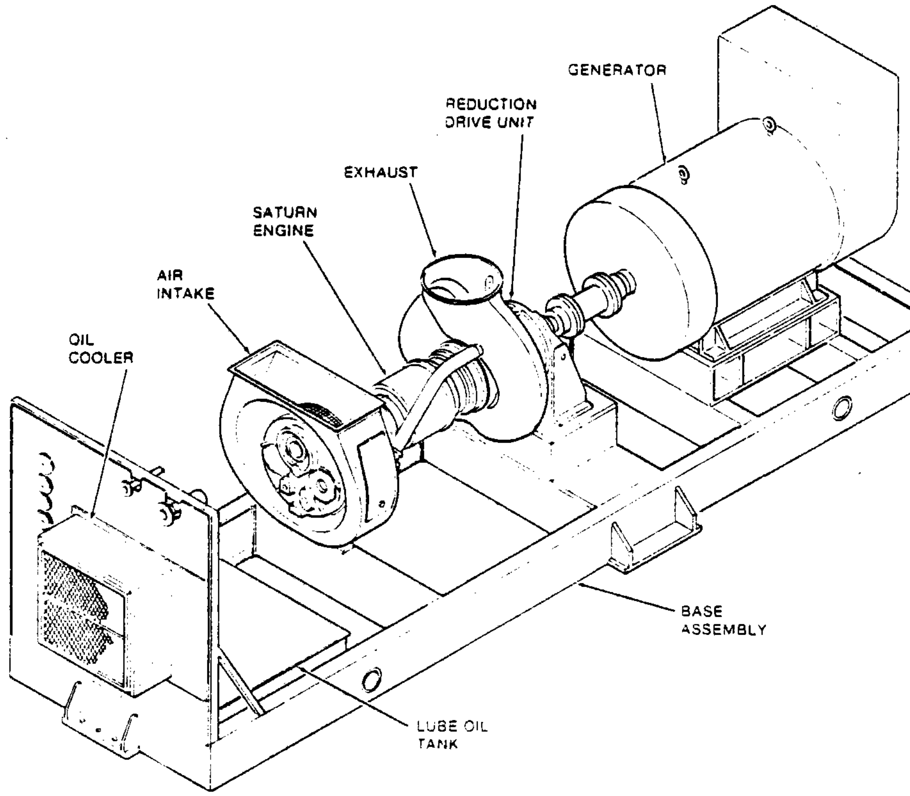


Figure 6-9. Saturn Turbine Generator Set

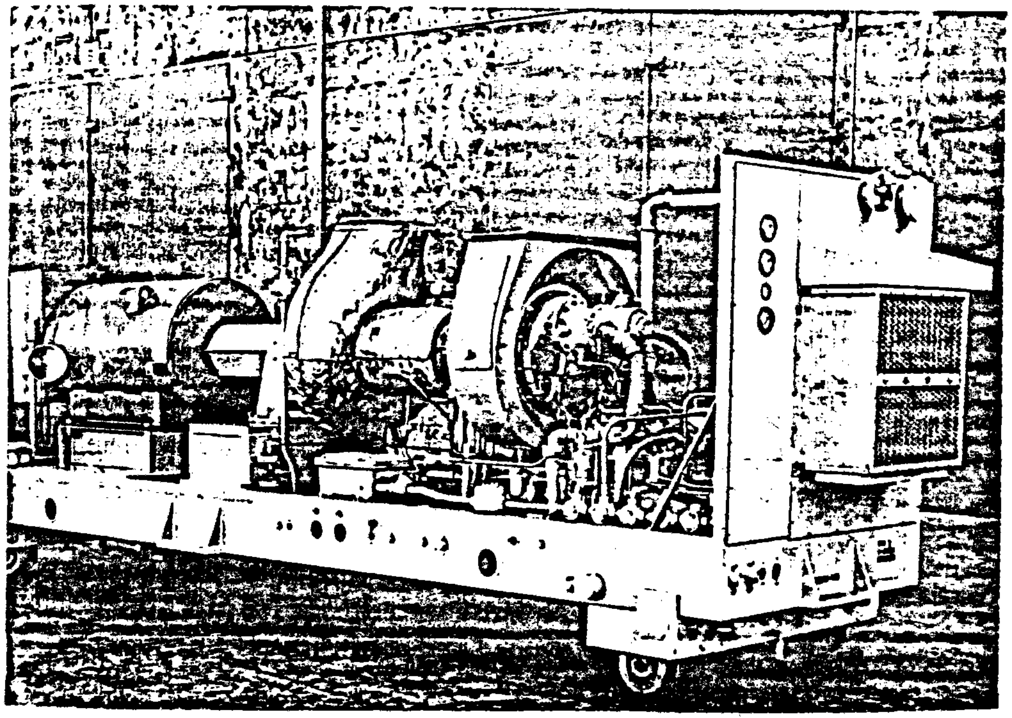


Figure 6-10. Solar Saturn Turbine Continuous Duty Generator Set

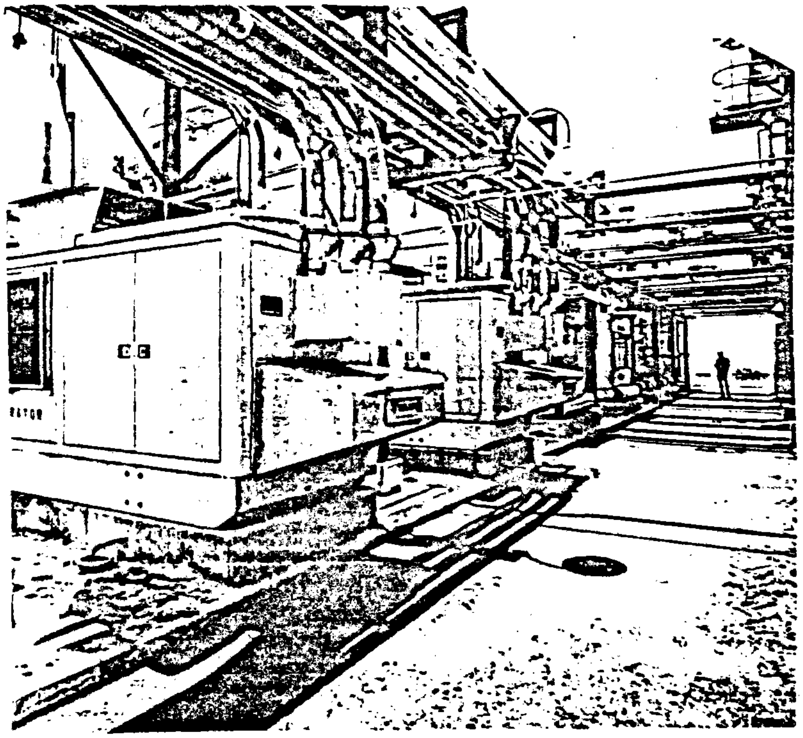


Figure 6-11. Typical Gas Line Compressor Station Using Solar Saturn Turbines

Compressor	
Type	Axial
Number of Stages	8
Compression Ratio	6.2:1
Flow	5.8 kg/sec (12.8 lb/sec)
Speed	22,300 rpm
Combustion Chamber	
Type	Annular
Ignition	Single igniter plug
Number of Fuel Nozzles	9
Turbine	
Number of Stages	3
Speed (Design)	22,300 rpm
Bearings	Sleeve
Materials of Construction	
Air Intake Housing	Aluminum
Compressor Case	17-4PH stainless steel
Compressor Blades	17-4PH cast stainless steel
Combustor Liner	N155 high-temperature alloy
Combustor Case	N155 high-temperature alloy
Turbine Case	422 AISI stainless steel
Turbine Nozzles, First-Stage	X45M high-temperature alloy
Turbine Nozzles, Second- and Third-Stage	N155 high-temperature alloy
Turbine Discs	A286 stainless steel
Turbine Blades, First- and Second-Stage	S816 alloy steel
Turbine Blades, Third-Stage	713 cast alloy steel
Exhaust Diffuser	17-4 PH stainless steel
Exhaust Collector	321 stainless steel
Accessory Gear Housing	Nodular iron
Oil Tank Capacity	416 liters (110 gallons) Operating capacity: 284 liters (75 gallons)
Main Oil Pump	
Driver	Hydraulic motor
Type	Gear
Rating (At Design Speed)	190 liters/min at 310 to 379 kPa gage (50 gpm at 45 to 55 psig)
Pre/Post Lube Pump	
Driver	DC electric motor
Type	Gear
Rating	38 liters/min at 83 to 103 kPa gage (10 gpm at 12 to 15 psig)
Oil Cooler	
Type	Air-to-oil radiator
Fan Drive Type	Hydraulic motor
Filter	
Type	Full flow
Number	1
Element	Replaceable

Table 6-1. Saturn Turbine Specifications

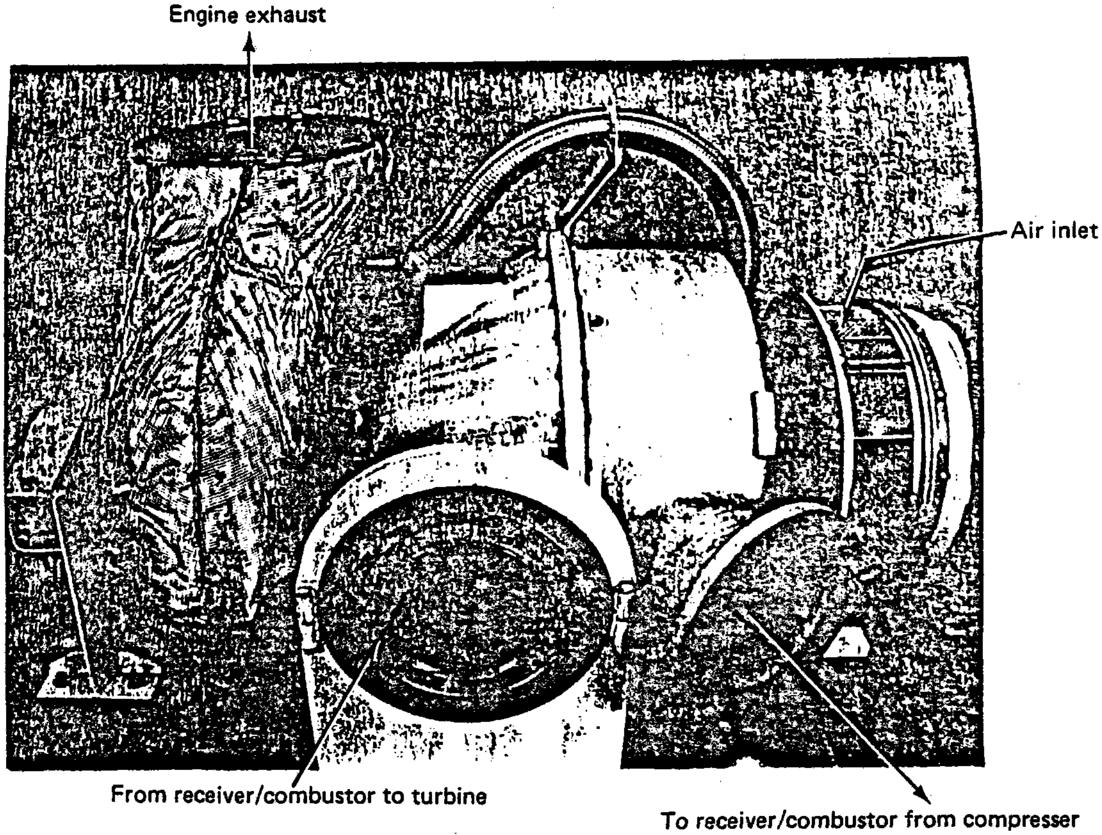


Figure 6-12. Saturn Gas Turbine Engine with In/Out Hardware for Recuperator

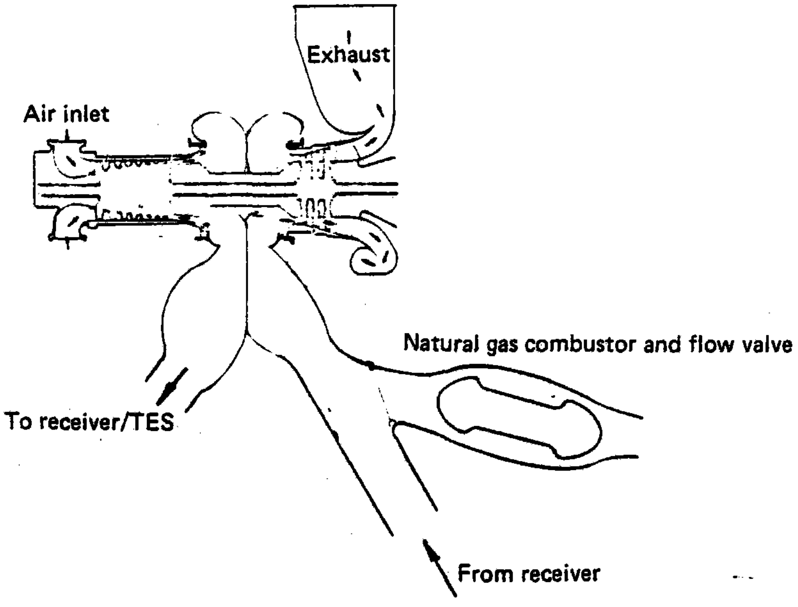


Figure 6-13. Saturn Gas Turbine with In/Out Hardware

A bottoming cycle was examined and found to be a promising means of utilizing the gas turbine waste heat. Plant efficiency and power production can be substantially increased with no increase in the solar collection subsystem. However, such a combined cycle package is not commercially available in the size needed for the 6000 m^3/d plant; the smallest unit presently available as a package is the Solar Turbines International Centaur CC with an ISO rating of 4MW. Custom units might be constructed but at additional cost. Adaptation of a Sundstrand organic Rankine cycle turbine for use with the Saturn was examined and found to be feasible, although the Sundstrand unit had to be derated about 50 percent. Again, costs exceeded the benefit (primarily due to the high cost of the oversized bottom cycle), and the extra power was not needed in the 6000m^3/d plant. Addition of a bottom cycle to the commercial plant design was rejected primarily because available equipment of the appropriate size could not be identified. Some benefit can be expected from a combined cycle well matched to the plant size. This is examined in the study of a range of plant sizes in Volume IV of this report.

6.2.2 Electric Power Distribution

Figure 6-14 shows the one-line diagram for the plant electric power distribution. Plant electrical power will be distributed by a central power transformer and switchgear station. Power will be provided to the station by the main generator, an emergency diesel generator, and a standby Rankine generator set. Selection and distribution of power will be controlled by a power generation controller which is linked to the master computer. Uninterruptable power supplies (UPS) will be used to maintain plant control during short term power interruptions or transfer of power sources. The primary plant power voltage is 480 volts, selected to achieve high efficiency of the main generator, the large motors and general power distribution and in accordance with general industrial practice.

6.2.3 Plant Air Supply

Compressed air is provided for the Saturn turbine pneumatic starter, and pneumatic valve actuators on air ducts and water treatment system lines. The Saturn air start equipment, shown in Figure 6-15, will provide storage for all compressed air functions in the plant.

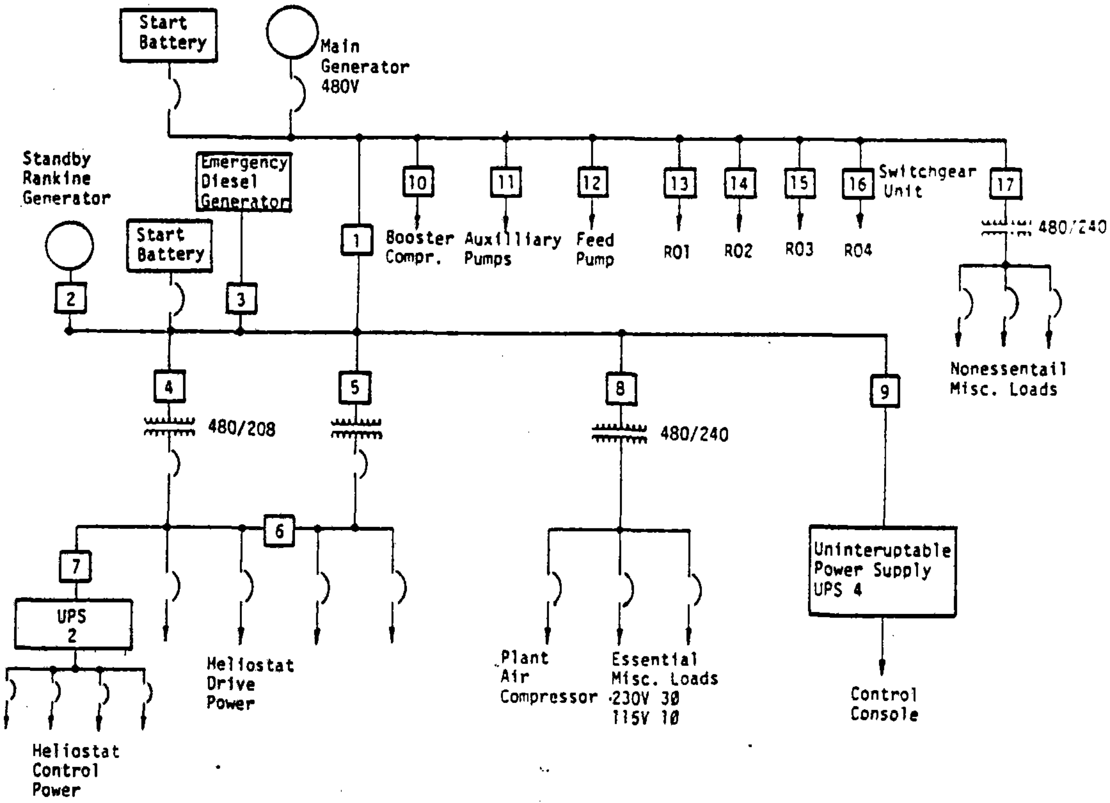


Figure 6-14. Power Distribution One-Line Diagram

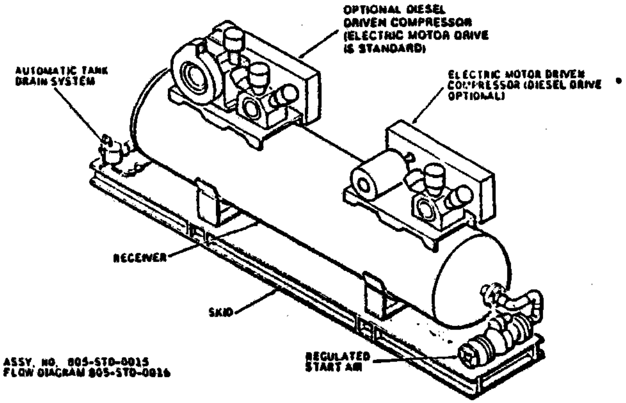


Figure 6-15. Typical Saturn Air Start System

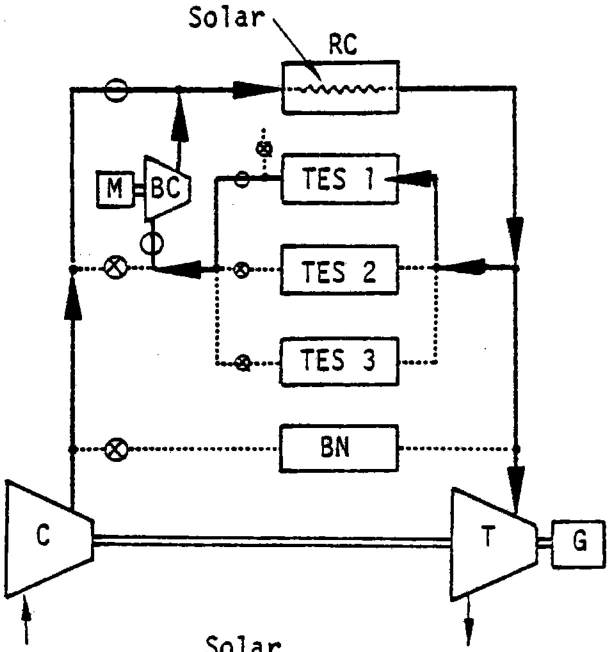
6.3 Energy Storage Subsystem

As previously shown in Figure 5-1, the thermal energy storage subsystem is located in an air flow path parallel to the receiver and between the compressor outlet and turbine inlet on the Saturn turbine. The major components of the subsystem are the three parallel TES units, an electric motor driven booster compressor, ducting, and valves to permit a variety of operating modes.

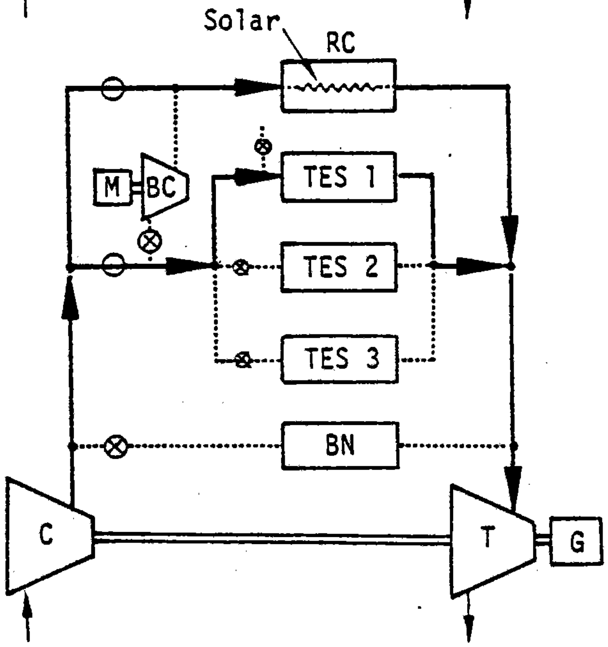
6.3.1 Thermal Energy Storage Operation

The main operating modes involving the thermal energy storage subsystem are shown in Figure 6-16. Solar energy received in excess of that required to operate the turbine is circulated through one or more of the three parallel TES units in the TES charge mode, Figure 6-16(a). The number of units being charged at any time depends on the amount of solar power available. After starting the booster-compressor, the units to be charged are selected by opening the valves downstream of the unit. A thermocline in the heated storage medium advances along the length of the storage unit (from right to left in the schematic) as the unit is charged. The TES units when fully charged have the bulk of the storage medium at or near 816°C (1500°F) . However, a portion of the medium near the valve end remains downstream of the thermocline and serves as a buffer at reduced temperature to limit the valve temperature during charging. At the fully charged condition the air leaving the TES, flowing through the valve and entering the booster compressor is at a maximum temperature of 385°C (725°F).

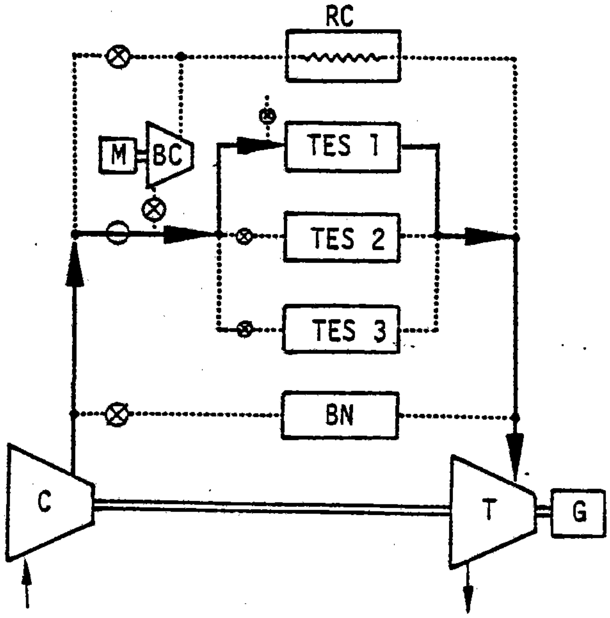
Flow through the TES is reversed for discharge as shown in Figure 6-16(b) and (c). The TES may be operated in parallel with the receiver to supplement the available solar energy, or the TES can supply all the thermal energy to the turbine. The flows through the receiver and TES are adjusted for these modes by the valves between the Saturn's compressor and these components. In the discharge mode, flow is through one TES unit at a time.



(a) TES Charging



(b) Parallel Receiver and TES Discharge



(c) TES Discharge

Figure 6-16.

Alternate Thermal Energy Storage Operating Modes

6.3.2 Thermal Energy Storage Design

The TES units are arranged conceptually as shown in Figure 6-17. Further design effort would be directed toward reducing the length of piping runs depicted in this arrangement. Each of the units has a cylindrical pressure vessel with dimensions as shown in Figure 6-18. The vessel is supported at intervals to allow natural convective cooling of the vessel exterior. As shown in Figure 6-19, standard pressure vessel construction practice is used. Insulation inside the vessel separates the storage media from the shell to minimize energy loss and to limit the maximum shell temperatures to 104°C (220°F). The storage medium is magnesium oxide bricks designed to provide airflow channels at the required size and spacing.

One of the commercially available booster compressors which meets the requirements of the TES design is described in Figure 6-20.

6.4 Backup Power Subsystem

The backup power subsystem includes several components which can provide electrical power when the main turbine-generator set is not operating on either solar or stored energy.

6.4.1 Main Power Emergency Backup

A fossil fuel supply and external combustor allows operation of the Saturn turbine-generator for abnormal or emergency conditions, when the desalination subsystem must be operated and solar or stored energy is not available. The annual product water output of the plant does not include water production in a fossil fuel mode.

6.4.2 Standby Power

Power generation components provide a lower power level needed for the plant in the standby mode (i.e., when the desalination subsystem is not operating). A nonfossil fuel power generation system is necessary to meet the design requirements. Choices considered are shown in the upper part of Table 6-2.

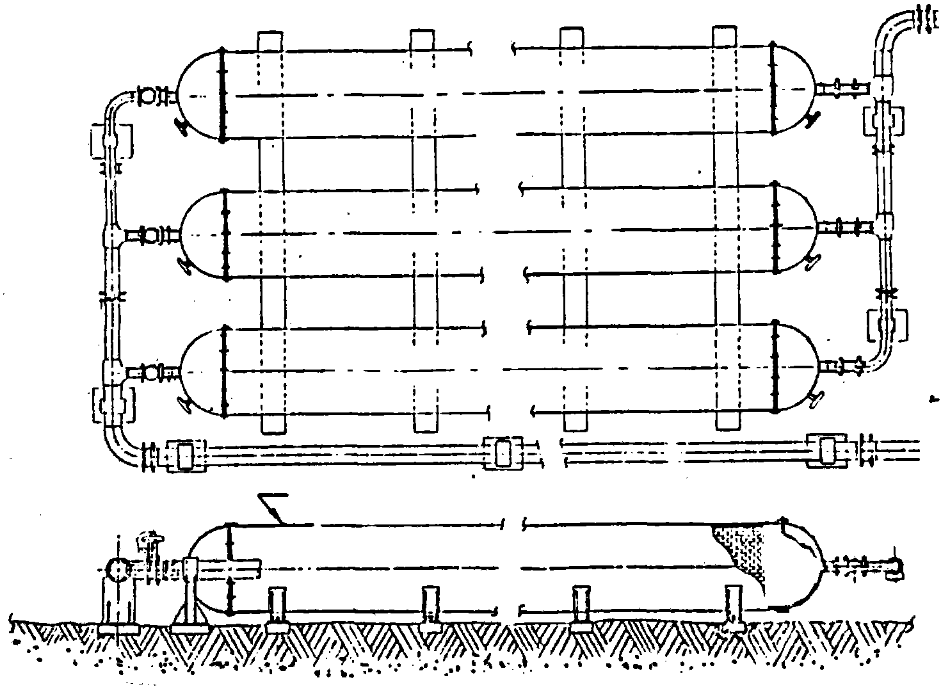


Figure 6-17. Thermal Storage Unit Arrangement

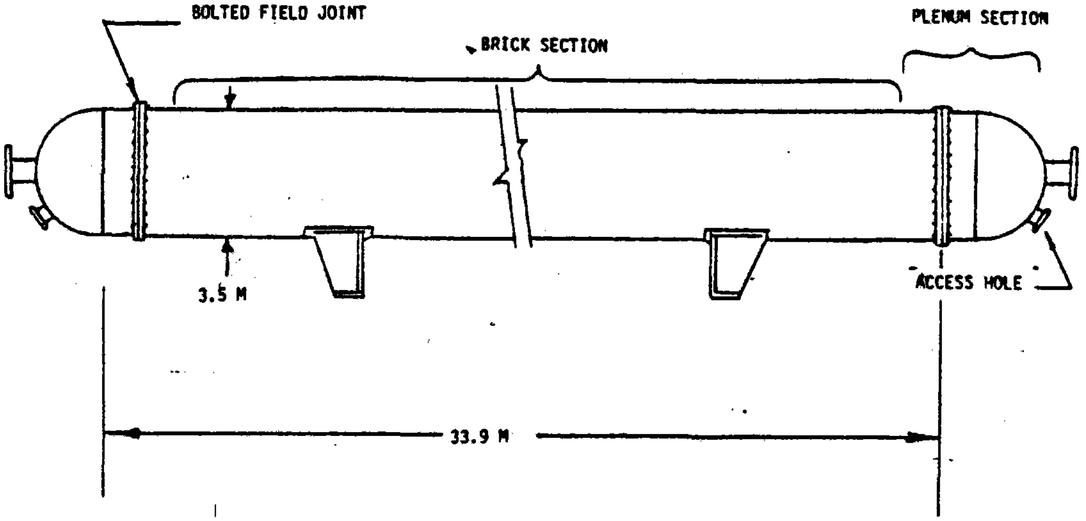


Figure 6-18. TES Unit Features

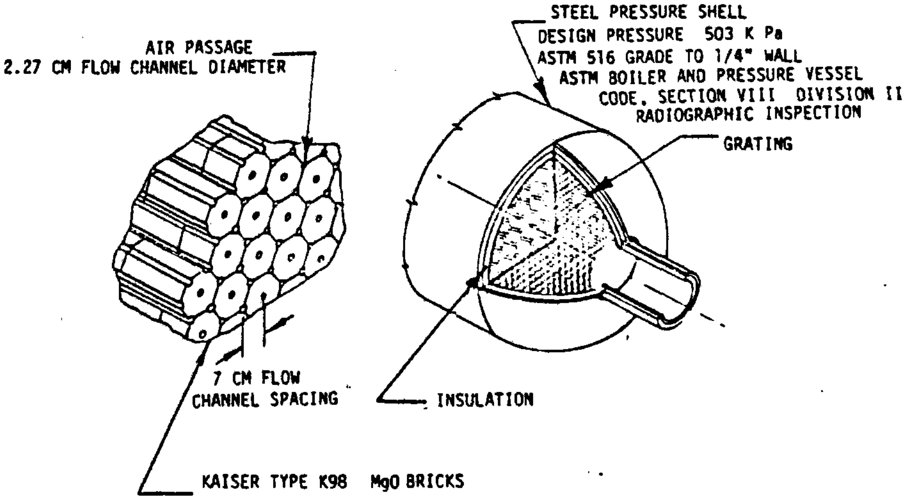
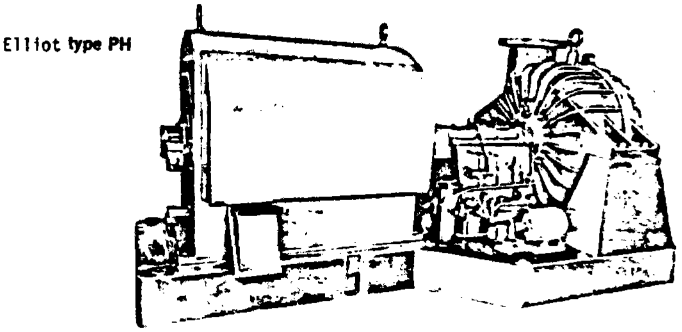


Figure 6-19. TES Unit Section



- o SINGLE STAGE RADIAL CENTRIFUGAL TECHNOLOGY
- o OUTLET TEMPERATURE 315°C
- o AC MOTOR DRIP PROOF WITH GEARBOX - OIL SYSTEM - ANTISURE CONTROL
- o 20% TURNDOWN IN CONVENTIAL APPLICATIONS
- o 63.5 CM ROTOR DIAMETER
- o 948 STANDARD M^3/MIN
- o ELECTRICAL POWER REQUIRED FOR PEAK STEADY-STATE OPERATION: 556 KW

Figure 6-20. Applicable Booster Compressor

Table 6-2. Standby Power System Candidates

Function	Candidate System	Rating	Estimated Production Price	Status
Standby wait power	Organic Rankine/TES	40 kW	$ 50,000	Being developed by Barber Nichols/FACC for JPL
Standby wait power	Lead acid batteries 48V	30 kW 72 hrs	$288,000	Available from Gould
Emergency fossil fueled standby power	Diesel - generator set			Available from Alturdyne
		40 kW	$ 25,000	6 cyl. VW Diesel
		24 kW	$ 18,000	4 cyl. VW Rabbit Diesel
Emergency fossil fueled standby power	Gas turbine - generator set	90 kW	$ 46,000	Available from Alturdyne Solar Titan turbine

The small organic Rankine turbine operating with heat from the TES was selected based on cost. In addition, a fossil fueled emergency power system is provided for the rare condition where the TES is cold or depleted below 150°C.

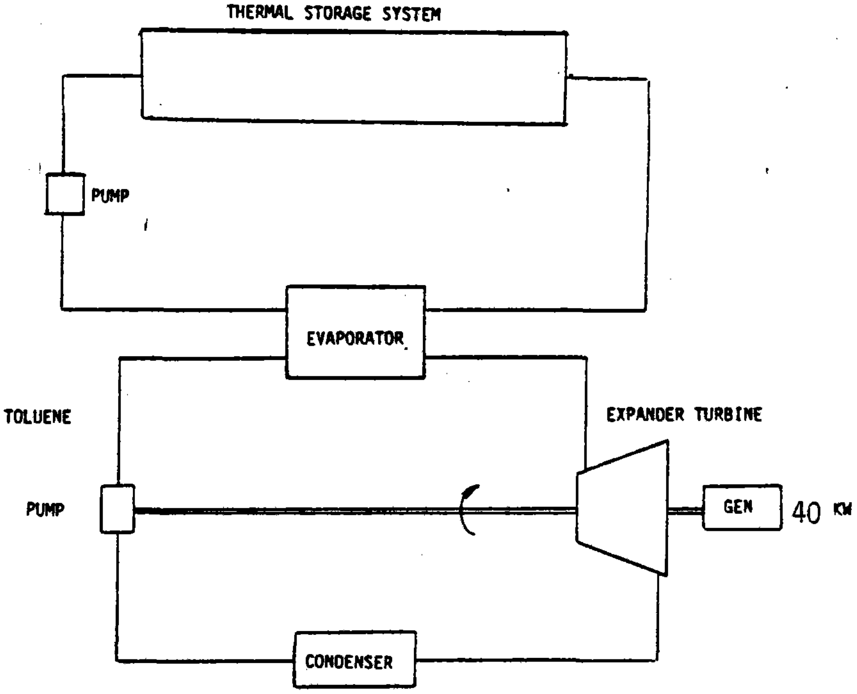
The Rankine cycle turbine concept is shown in Figure 6-21. Heat would be extracted from one or more of the TES units and circulated through a heat exchanger that would evaporate and superheat the toluene working fluid. The heat transfer fluid for the heat extraction system has not been selected; candidates include air and the organic heat transfer fluids. The latter choice would require a drainable section within the TES to prevent excessive temperatures in the fluid. The size of the turbine generator being developed by Barber Nichols for JPL, Figure 6-22, is approximately the size required for the standby power demands of the plant. The lightweight, but more expensive, ancillary components in this design would be replaced by more conventional condensers and regenerators.

The emergency standby power system is pictured in Figure 6-23. This is a commercially available unit, employing a Volkswagen Rabbit diesel engine as the power source.

6.5 Feedwater Pretreatment Subsystem

The function of the feedwater pretreatment subsystem is to provide a quality feed supply to the RO units. Because the specified water has relatively high hardness content, it has to be treated by a softening process to prevent scaling in the desalination equipment. This pretreatment subsystem removes the hardness in the form of calcium and bicarbonate ions from the feedwater and prevents the scaling that would otherwise occur as concentrations of these ions increase on the reject side of the RO membrane.

As previously shown in Figure 5-2, the feedwater pretreatment subsystem consists of four WAC exchange units in parallel, a regeneration system for these units, and a decarbonation/pH control system. This type of pretreatment was selected because of its flexibility and compatibility with intermittent operation (particularly important to integration in a solar dependent power system), its relatively simple control and operation, and its minimal impact to the waste streams.



ADAPTATION OF JPL/FORD AEROSPACE/BARBER NICHOLS UNIT

Figure 6-21. Adaption of JPL/Ford Aerospace/Barber Nichols Unit

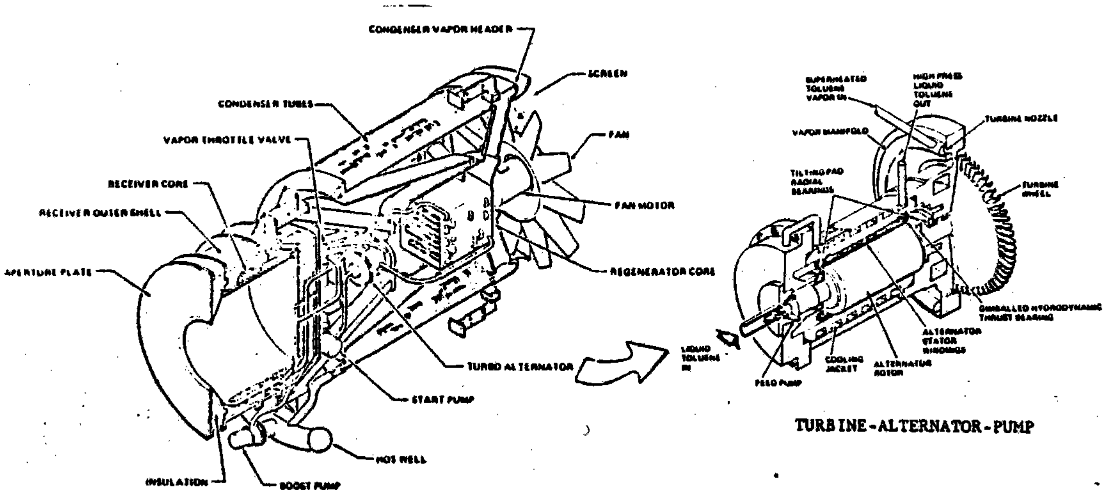
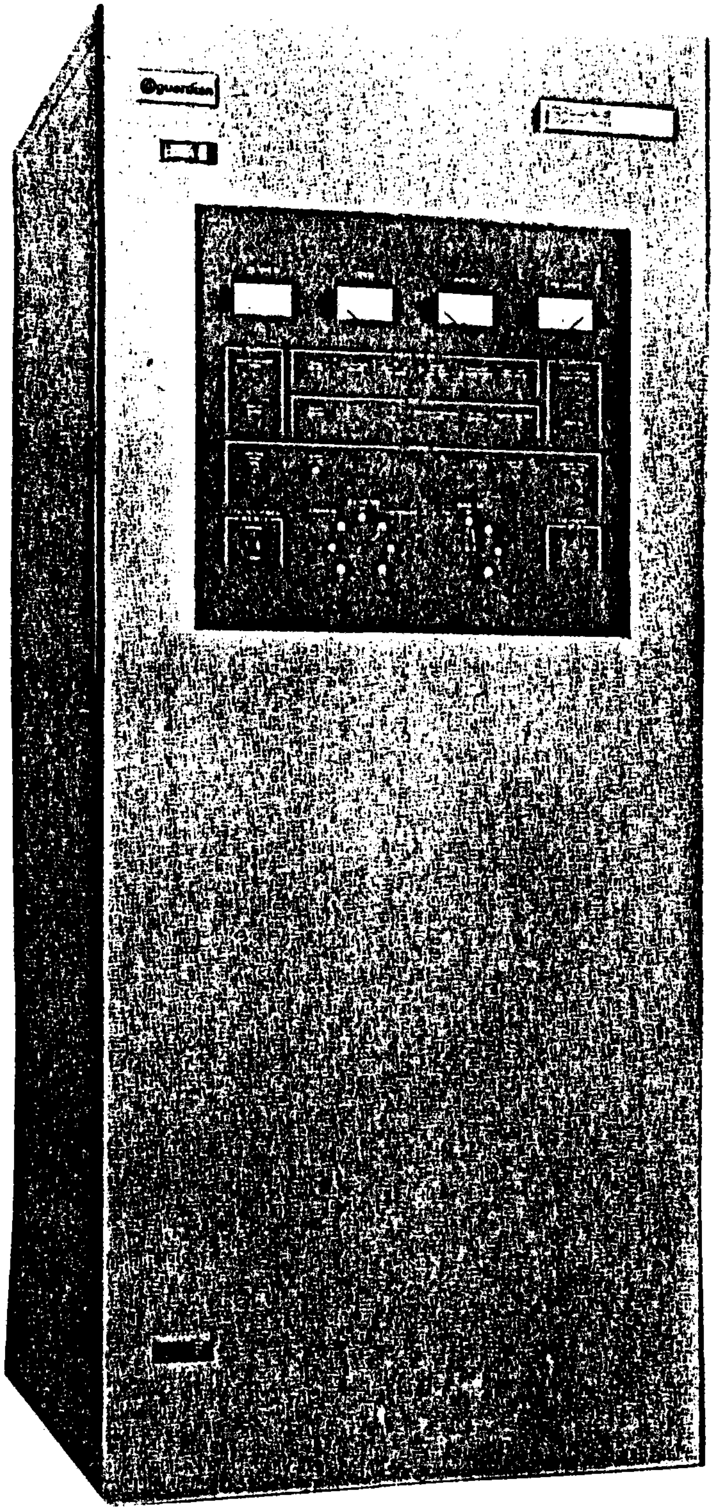
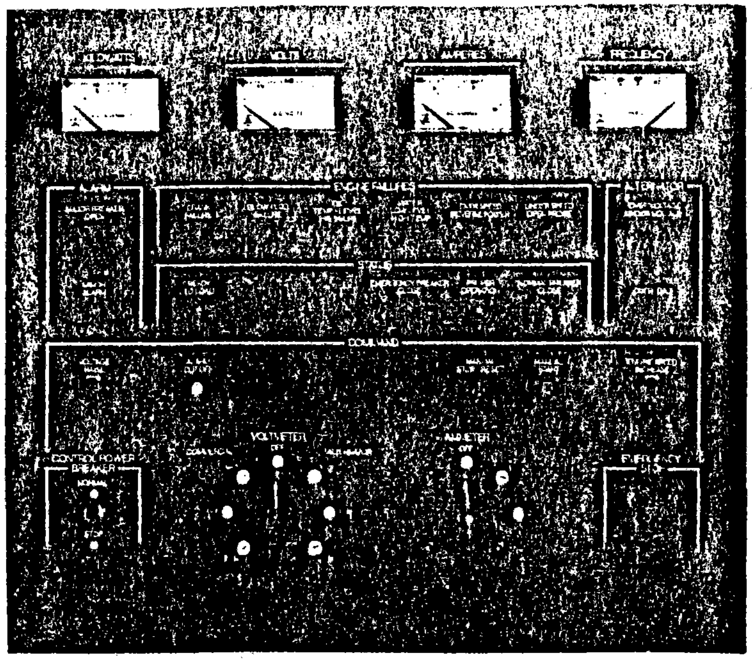


Figure 6-22. SCSE Organic Rankine Engine.



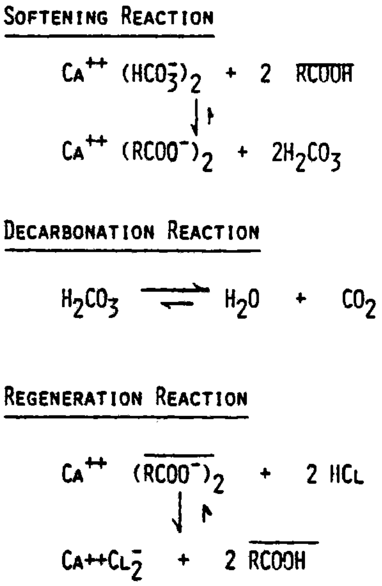


- New vertically-mounted design.
- Occupies less than 9 sq. ft. (0.8 sq. m) of floor space.
- Self-contained.
- Microcomputer-controlled for automatic, unattended, reliable operation.
- Less ductwork and piping to clutter walls and ceiling.
- Does not require separate external battery stand or alarm unit.
- Quiet operation with less vibration.

Figure 6-23. Guardian 24 kW Diesel Engine-Alternator

6.5.1 Weak Acid Cation Exchange Units and Regeneration System

In the softening reaction, the calcium ion is absorbed on the WAC resin and displaces a hydrogen ion. This hydrogen ion combines with the bicarbonate ion in the feedwater to form carbonic acid, which is subsequently removed downstream in the decarbonation subsystem. The chemical reactions are identified in Figure 6-24. This reaction continues until no further calcium can be absorbed and regeneration of the bed is required. Regeneration of the resin in the WAC exchange unit is accomplished by flushing the resin bed with hydrochloric acid, which removes calcium ions and replaces the hydrogen needed in the softening reaction.



NOTE: $\overline{\text{RCOO}}$ IS THE RESIN BACKBONE AND ─── SIGNIFIES RESIN PHASE.

Figure 6-24. Weak Acid Cation Ion Exchange

A schematic of one of the WAC exchange units and the regeneration system is shown in Figure 6-25. Normally one of the four WAC units is kept in a standby or regeneration status with the other three beds in production operation. This provides for the continuous operation of feed supply to the RO units. In normal operation the feedwater is distributed over the resin bed and flows down to the underdrain headers where it is collected and directed to the decarbonation system. The softening reaction occurs as soon as fresh resin is encountered; thus, the reaction front moves uniformly down through the bed, and the amount of softening remains constant as long as the reaction front remains above the drain headers. After a predetermined quantity of feedwater has flowed through the unit, it is replaced on-line by a fresh unit and is then regenerated. The regeneration cycle is automatically controlled through precalibrated timer instrumentation and is accomplished by valving the unit out of the system, flushing for a specified time period with dilute hydrochloric acid, and rinsing with product water. The flushing and rinsing fluids are drained to the evaporation pond. The regeneration of each WAC bed will occur daily at system specification production capacity and will require an estimated one hour to complete.

The WAC exchange units would be purchased skid mounted, complete with regeneration system. Several companies including Die-Sep, U.S. Filters, Graver and I.W.T. are candidate vendors for this equipment. A cross section of a typical unit is shown in Figure 6-26.

6.5.2 Decarbonation/pH Control Unit

The dissolved carbon dioxide (CO_2) or carbonic acid produced by the WAC subsystem must be removed to lower the acidity of the softened water feed to the RO units. The decarbonation unit removes the carbon dioxide by desorption within a packed bed column. The WAC product water containing the dissolved CO_2 is distributed down through the packed bed. A counterflow of air from an external blower then sweeps the CO_2 to the vent system. The decarbonation/pH control unit is shown in Figure 6-27. Acidity/pH control for the feed to the RO units is provided via a bypass loop around the decarbonation unit. The required 4.5 - 5.5 pH feedwater to the RO is obtained by adjusting the ratio of WAC water flowrates through the decarbonator and bypass. The controls are fully automatic and have been proven in commercial applications.

WEAK ACID CATION EXCHANGE SYSTEM

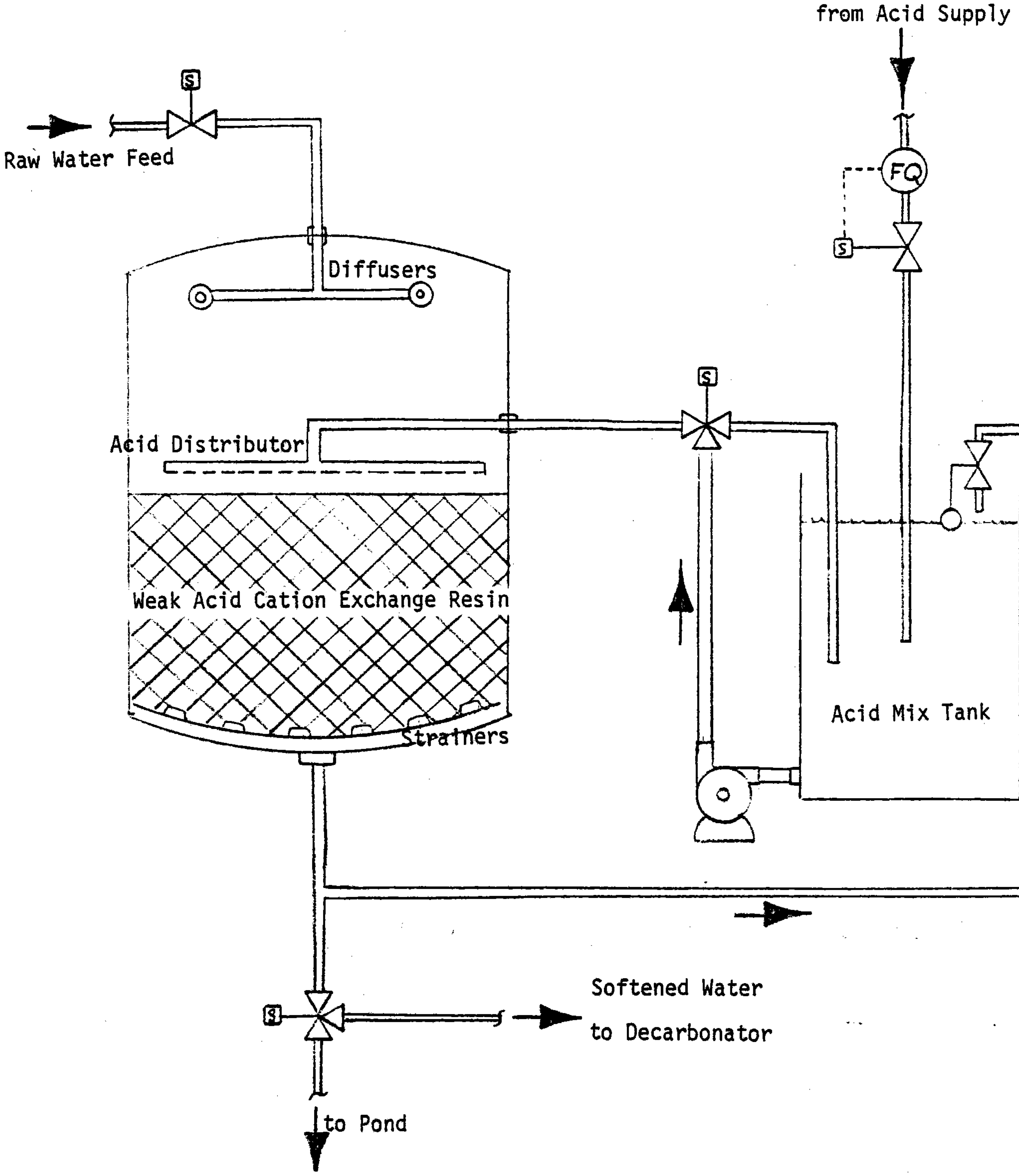


Figure 6-25. Weak Acid Cation Exchange System

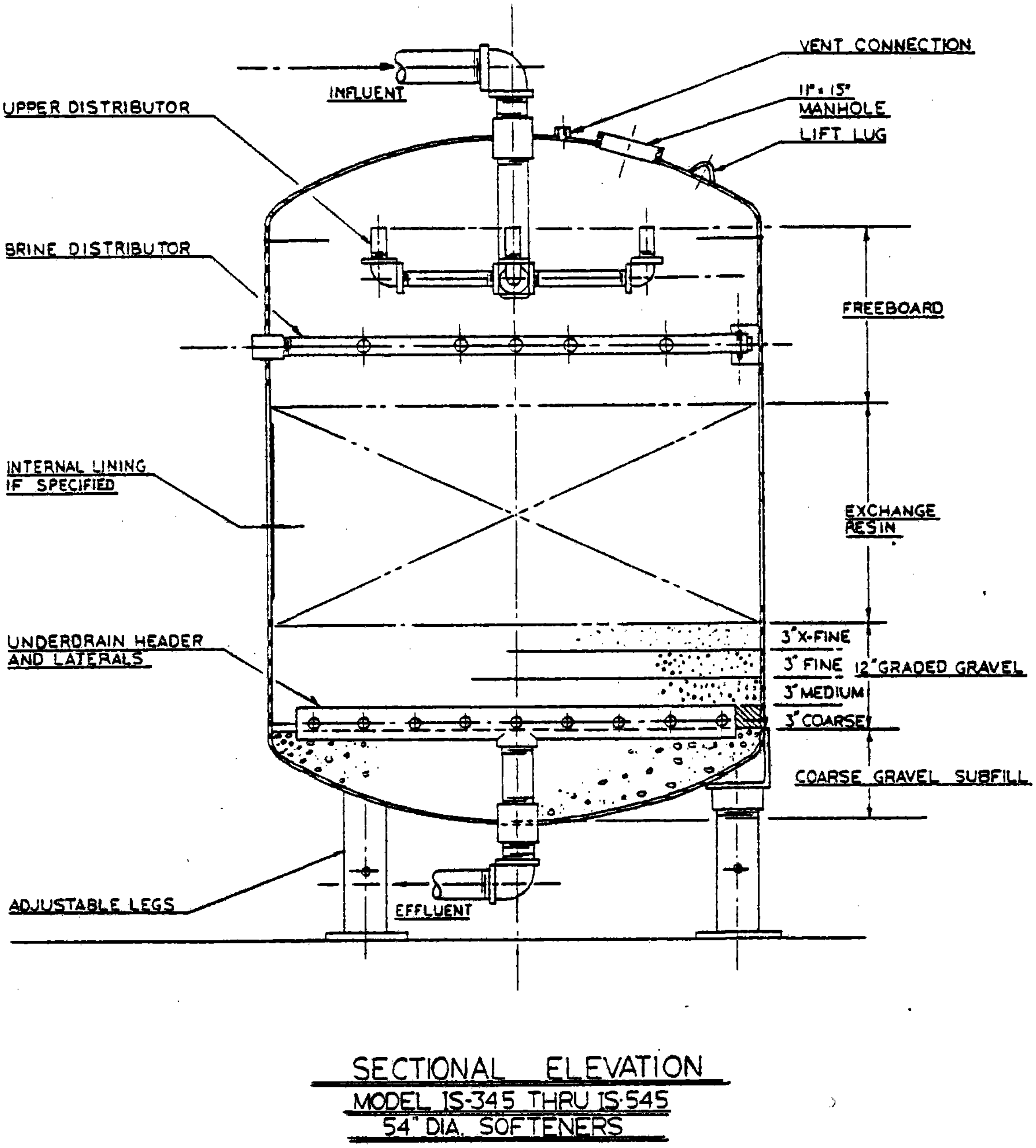


Figure 6-26. Weak Acid Exchange Resin Bed

The selected pretreatment process is capable of essentially single step reduction of calcium and bicarbonate with pH effluent control, utilizing approximately the same quantity of acid that would have been required for bicarbonate destruction alone.

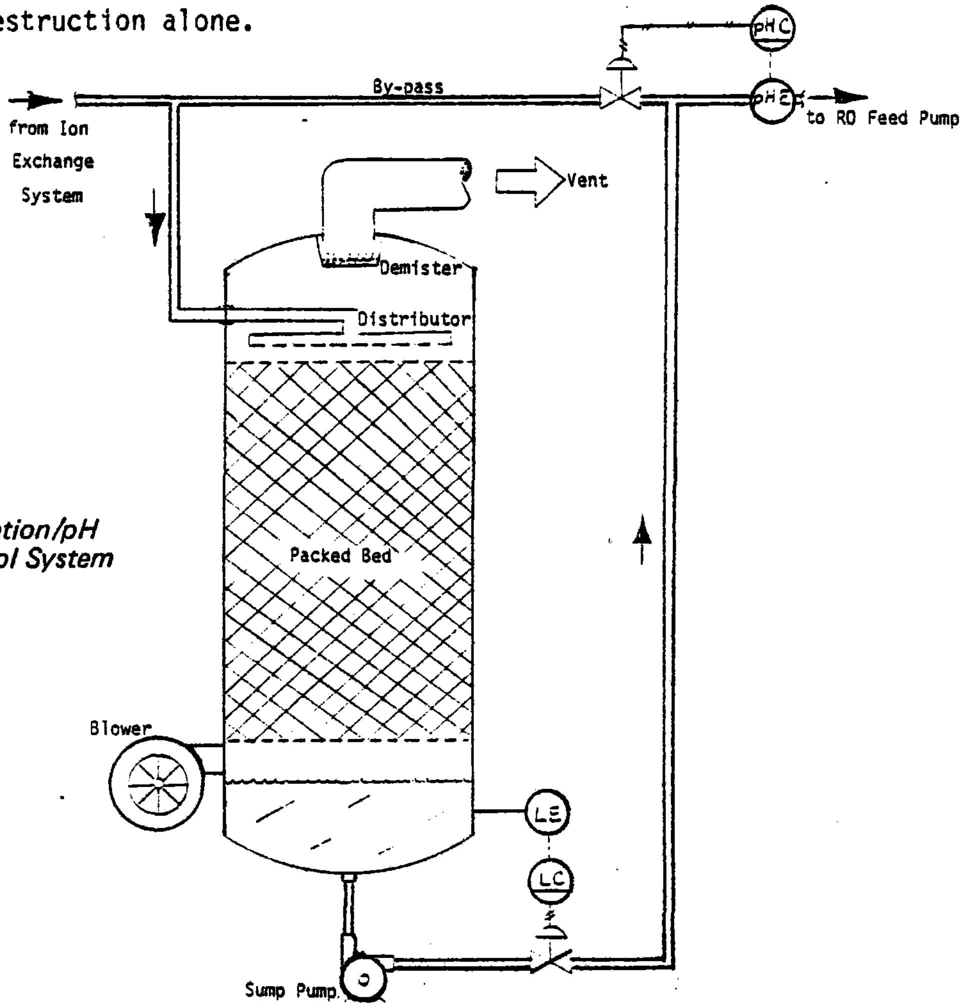


Figure 6-27. Decarbonation/pH Control System

6.6 Desalination Subsystem

The desalination subsystem consists of four parallel sets of RO trains with 10 µm cartridge filters and high pressure pumps as illustrated in Figure 5-2. The process of reverse osmosis and the rejection of dissolved materials takes place under pressure with the feed solution passing across the semi-permeable membrane. The products flow through the membrane in the reverse osmosis units generally proportional to the applied pressure differential across the membranes. The selected RO units will operate at feedwater nominal gage pressures of 2895 kPa providing a product recovery rate of 75%. The passage of dissolved salts through the membrane is proportional to the concentration differential across the membrane. For this particular application, recovery rates greater than 80% could cause the dissolved salts to exceed their solubility limits and precipitate, causing membrane fouling, lower recovery rates, and reduced plant availability. The pretreatment system has been designed to eliminate this possibility by reducing the calcium content to less than 300 ppm by weak acid cation exchange.

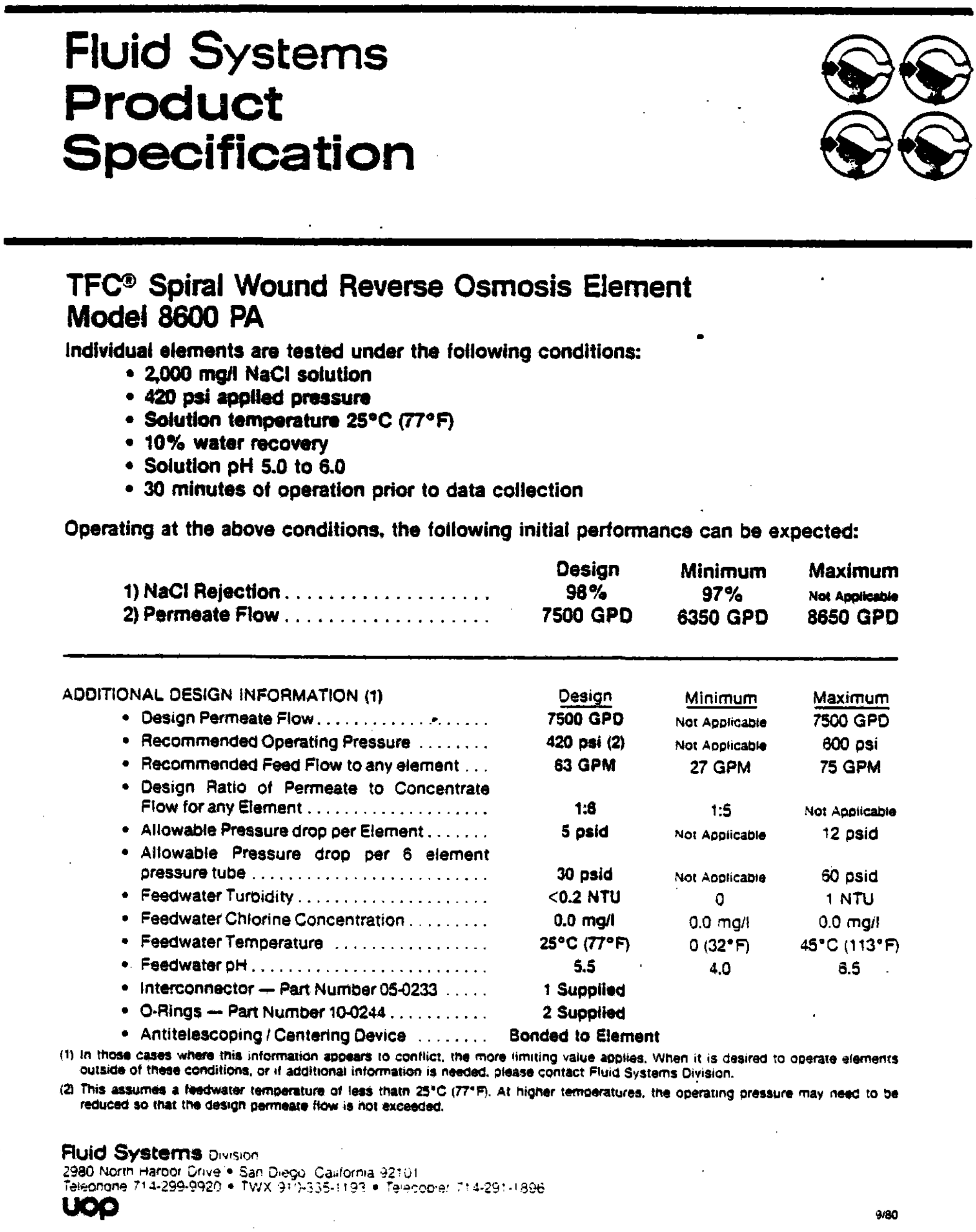
Three basic criteria for the selection of the RO units were applied against the system requirements. They were as follows: capacity in terms of system flow; performance in terms of product composition; and stability in terms of operating life, i.e., membrane replacement.

The membrane type selected for the RO units is Fluid System's Model 8600 PA, TFC® Spiral Wound Reverse Osmosis Element; the supplier's data for this non-cellulosic element are shown in Figures 6-28 and 6-29. The element operates at high flux (flow) levels and is proven in commercial applications. The expected normal membrane life is three years. The predicted product chemistry is stated in Table 5-1. The expected total dissolved solids (TDS) of the product water is almost 370 mg/l which is well within the 500 mg/l potable water requirement.

Each RO train will be comprised of modules each containing six elements. The modules are connected in series so that the reject from two modules becomes the feed for one module. The train will have the requisite number of these 3-module sets in parallel to meet the capacity requirement for the train.

Because RO units operate most efficiently under specific steady state conditions, a parallel RO train arrangement is required to balance the number of units being operated with electric power availability. This arrangement also allows for the service and maintenance of the individual RO unit including the periodic clean-out and flush and membrane replacement without affecting other RO units.

Positive displacement plunger pumps are selected for the high pressure pumps because of their high efficiency compared to centrifugal pumps. A candidate pump for this application is the Series 300 line manufactured by the Wheatley



Fluid Systems Product Specification

TFC® Spiral Wound Reverse Osmosis Element
Model 8600 PA

Individual elements are tested under the following conditions:

- **2,000 mg/l NaCl solution**
- **420 psi applied pressure**
- **Solution temperature 25°C (77°F)**
- **10% water recovery**
- **Solution pH 5.0 to 6.0**
- **30 minutes of operation prior to data collection**

Operating at the above conditions, the following initial performance can be expected:

	Design	Minimum	Maximum
1) NaCl Rejection	98%	97%	Not Applicable
2) Permeate Flow	7500 GPD	6350 GPD	8650 GPD

ADDITIONAL DESIGN INFORMATION (1)	Design	Minimum	Maximum
• Design Permeate Flow	7500 GPD	Not Applicable	7500 GPD
• Recommended Operating Pressure	420 psi (2)	Not Applicable	600 psi
• Recommended Feed Flow to any element	63 GPM	27 GPM	75 GPM
• Design Ratio of Permeate to Concentrate Flow for any Element	1:8	1:5	Not Applicable
• Allowable Pressure drop per Element	5 psid	Not Applicable	12 psid
• Allowable Pressure drop per 6 element pressure tube	30 psid	Not Applicable	60 psid
• Feedwater Turbidity	<0.2 NTU	0	1 NTU
• Feedwater Chlorine Concentration	0.0 mg/l	0.0 mg/l	0.0 mg/l
• Feedwater Temperature	25°C (77°F)	0 (32°F)	45°C (113°F)
• Feedwater pH	5.5	4.0	6.5
• Interconnector — Part Number 05-0233	1 Supplied		
• O-Rings — Part Number 10-0244	2 Supplied		
• Antitelescoping / Centering Device	Bonded to Element		

(1) In those cases where this information appears to conflict, the more limiting value applies. When it is desired to operate elements outside of these conditions, or if additional information is needed, please contact Fluid Systems Division.

(2) This assumes a feedwater temperature of less thatn 25°C (77°F). At higher temperatures, the operating pressure may need to be reduced so that the design permeate flow is not exceeded.

Fluid Systems Division
2980 North Harbor Drive • San Diego California 92101
Telephone 714-299-9920 • TWX 910-335-1193 • Telecopier 714-291-1896
UOP

9/80

Figure 6-28. TFC Spiral Wound Reverse Osmosis Element Model 8600 PA – Product Specification

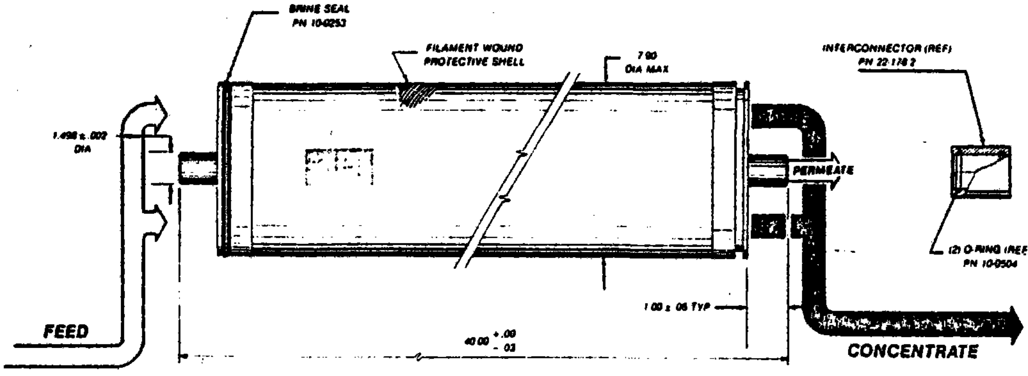


Figure 6-29. TFC Spiral Wound Reverse Osmosis Element – Model 8600 PA

Company of Tulsa, Oklahoma. Pump installation will include a pressure control arrangement for controlling pump discharge pressures. A back pressure valve will be installed in a bypass line from each pump discharge to the pump section. An accumulator will be required to dampen pump pulsations.

In normal operation, the recovery of potable water is 75% of the feed to the RO. The RO unit will remove 95% of the monovalent ions present and 98% of the polyvalent ions present in the feed to the RO. Seventy percent of the dissolved solids entering the RO system are monovalent ions and 30% are polyvalent. The expected TDS of the potable water is 370 mg/l, well below the specified TDS of 500 mg/l. The net pressure across the RO membrane is 2137 kPa. RO permeators utilize 2896 kPa water as feed, with an osmotic pressure of 621 kPa and a membrane pressure drop of 138 kPa being the contributors to the pressure reduction.

6.7 Controls and Instrumentation Subsystem

The plant operations will be controlled automatically by a master control computer linked to distributed digital controllers. A control system block diagram is shown in Figure 6-30; Figure 6-31 identifies the primary control system functions. The control system includes the following key features:

- Daily operating strategy will be programmed by an operator with keyboard data entry.
- The operator can override automatic operation in test, emergency or service conditions.
- Subsystem operating algorithms will be pre-programmed to minimize operator workload and skill requirements.
- Weather data and process parameters will be transmitted to the master computer for process control and performance analysis.
- Control instructions will be transmitted to distributed controllers that control the heliostats, power generation, and water treatment subsystems. Having distributed controllers will allow independent subsystem operation if necessary.

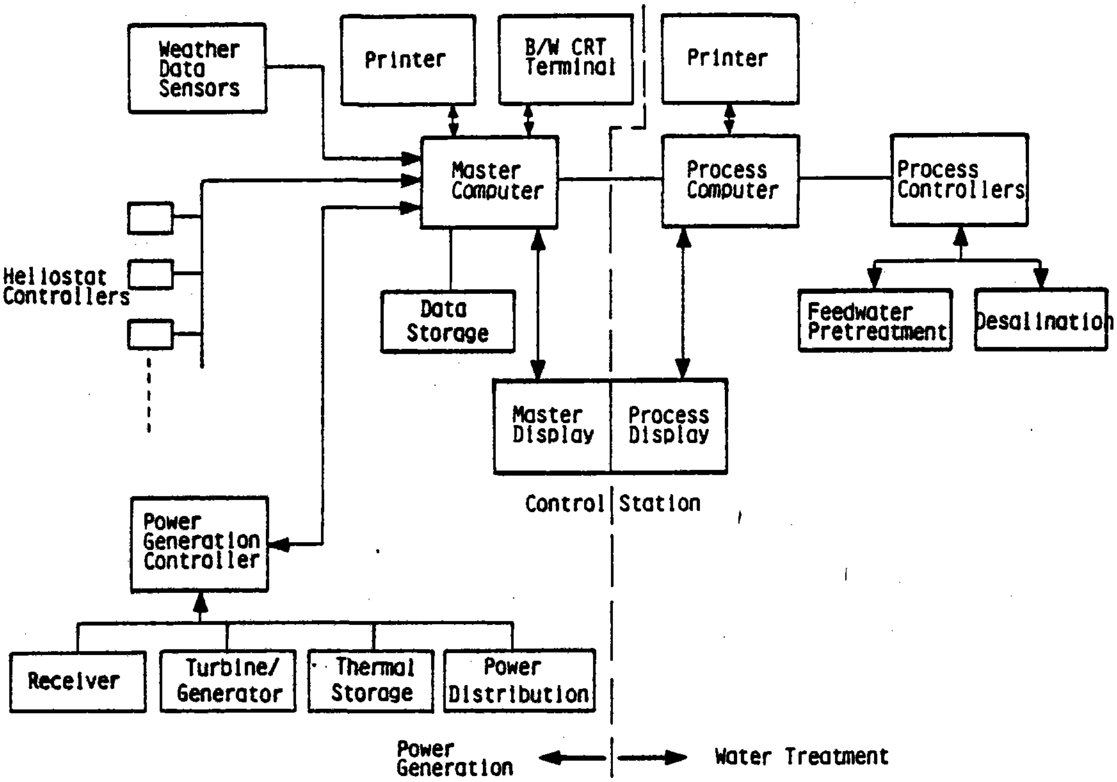


Figure 6-30. Plant Control System Function Block Diagram

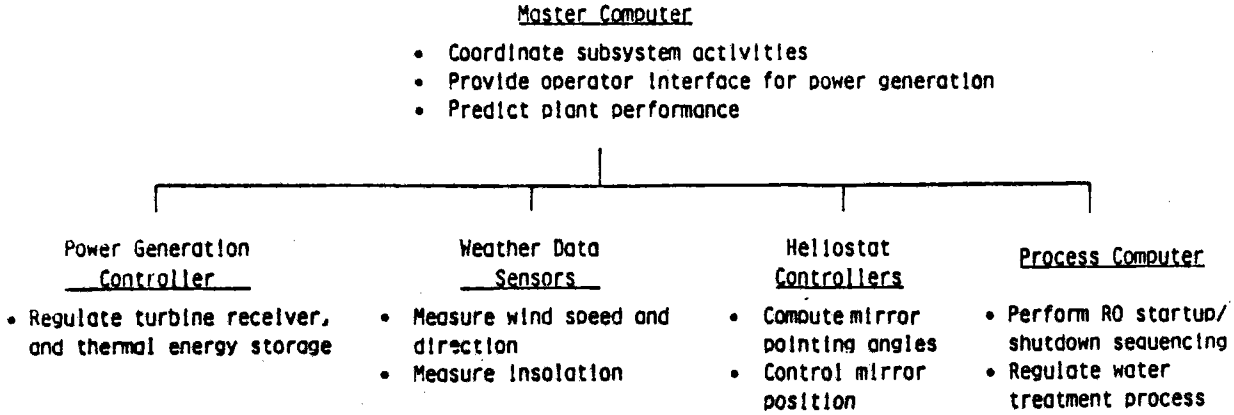


Figure 6-31. Control System Functions

- Commercially available solid state control consoles and color CRT displays will be used to simplify programming operation and maintenance. The solid state control units will have low power consumption.

Equipment candidates for the control system are identified in Table 6-3; these candidates would be evaluated in a subsequent detail design phase. A representative master control console is shown in Figure 6-32. These controllers are commercially available and have the necessary software, peripherals, and interfaces needed for adaptation to the commercial plant.

The control system will acquire and control operating parameters that are identified in Table 6-4. Except for weather data, the measured and controlled parameters will be transmitted via the distributed controllers using conventional analog and serial digital data protocol.

6.8 Data Acquisition Subsystem

A data storage device will be provided to record the plant operating parameters listed in Table 6-4. In addition, computed data from the master computer, such as efficiencies and capacity factors, will be recorded. At selected intervals, the recorded data will be printed for analysis and archiving along with the operator's logs.

6.9 Water Storage and Delivery Subsystem

Feedwater and product water storage concepts for the commercial plant are excavated lined reservoirs. The respective sizes of the reservoirs are:

<u>Feedwater Reservoir</u>:

91 x 91 x 4.6 m deep
8.2×10^3 m^2 area
40,000 m^3 capacity

Master Control Computer	Process Control Equipment
Digital equipment corporation (16-bit)	Fisher controls - Provox line (baseline)
PDP 11/23	• distributed controllers
PDP 11/34	• HP-1000 process computer
PDP 11/44 (baseline)	• sequencing capability
	• color displays
Systems engineering labs (32-bit)	• flexibile programming
32/27	
32/30A	Taylor Mod III
32/57	• distributed controllers
	• Varian computer
Hewlett Packard (16-bit)	• sequencing capability
HP 1000L	• monochrome displays - color optional
HP 1000E	
Selection Criteria	Selection Criteria
1. performance	1. performance and flexibility
2. reliability/error detection	2. ease of operation
3. maintainability	3. reliability and failure mode operation
4. cost	4. fault isolation/ease of repair
	5. compatability with master
	6. cost

Table 6-3. Candidate Controllers

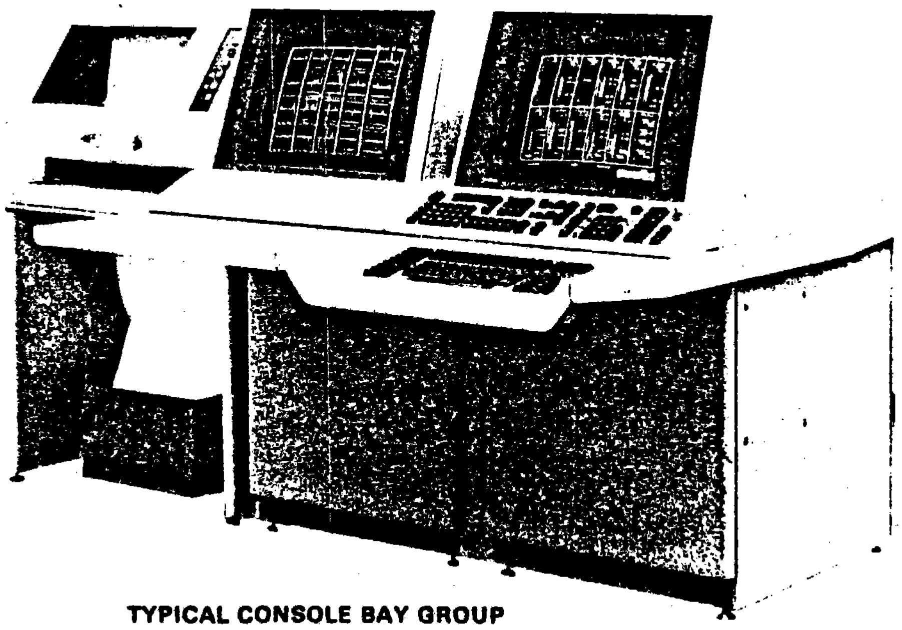


Figure 6-32. Fisher Control Console

Subsystem	Measured Parameter	Primary Control Function (If Any)
Feedwater	Storage level	Storage pump shutoff
	Water flow	Chemical injection rates
	Conductivity	
	Temperature	
	pH	Acid injection
	Filter pressure drop	
RO Units	Pump inlet pressure	Pump shutdown
	Pump outlet pressure	
	Pump temperature	Pump shutdown
	Membrane inlet pressure	Pump shutdown
	Concentrate pressure	Pump shutdown
	Concentrate conductivity	
	Concentrate flow	Concentrate flow valve
	Permeate pressure	Pump shutdown
	Permeate conductivity	
	Permeate flow	Maintain flow ratio with respect to concentrate via feed valve
	Membrane pressure drop	
	Bypass valve position	Used for pump startup
Power generation	Compressor inlet temperature	
	Compressor outlet pressure	
	Compressor outlet temperature	
	Compressor flow	
	Receiver inlet temperature	
	Receiver inlet pressure	
	Receiver outlet temperature - each panel	Heliostat control
	Receiver outlet temperature	Heliostat control
	Receiver outlet pressure	
	Combustor fuel flow	Generated power
	Turbine inlet temperature	Power control
	Turbine inlet pressure	
	Thermal energy storage pressure	
	Thermal energy storage temp.	Storage control
	Thermal energy storage flow	
	Turbine vibration	Failure shutdown
	Turbine speed	Speed governor
Power generation (cont'd)	Turbine exhaust temperature	
	Turbine exhaust pressure	
	Bleed valve position	Turbine overspeed control
	Generator frequency	
	Generator phase voltage	
	Generator phase current	
	Generator watts	
	Generator KVA	
Miscellaneous	Water storage levels	
	Turbine fuel level	
	Weather data	

Table 6-4. Measured/Controlled Parameters

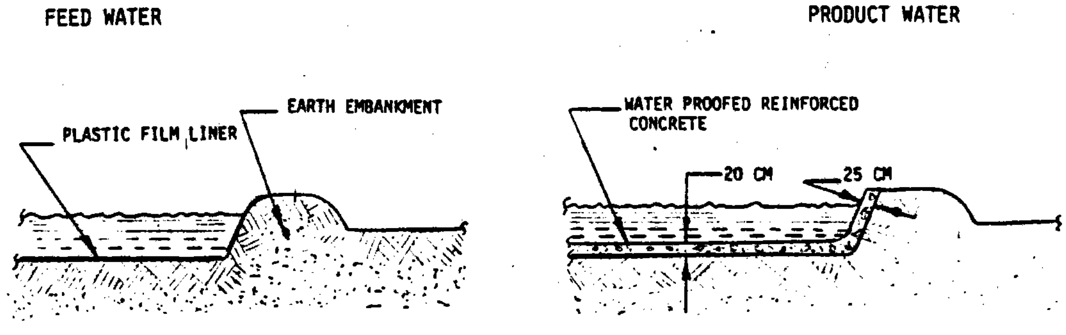
Product Water Reservoir:

163 x 163 x 4.6 m deep
2.65×10^4 m^2 area
120,000 m^3 capacity

These sizes correspond to peak production conditions (10106 m^3/d product water) and storage ratings of 3 days feedwater and 10 days product water.

The feedwater as shown previously in Figure 5-2 can go directly to the ion exchange system without any break in pressurization. The feedwater reservoir will be connected in parallel such that a bypass will always keep the reservoir full. In case of interrupted supply, the water for treatment would be furnished by the feedwater reservoir.

Figure 6-33 illustrates the general features of the reservoir cross-sections. Both feedwater and pretreatment water reservoirs are lined to prevent leakage. The feedwater reservoir has a simple flexible plastic film liner. The product water liner is reinforced concrete with a waterproof coating. This type of structural liner is commonly used in product water reservoirs to prevent leakage and contamination by ground water.


FEED WATER

PRODUCT WATER

3 DAY STORAGE
8.3 Ha x 4.6 M DEEP
37900 M^3 CAPACITY

10 DAY STORAGE
26.6 Ha x 4.6 M DEEP
121000 M^3 CAPACITY

Figure 6-33. Reservoir Features

The feedwater reservoir is uncovered for minimum construction cost. (There are no known regulations for the Upton County, Texas area that would require covered reservoirs.) Based on a mean annual lake evaporation rate for that area of 1.9 m/year, the estimated annual feedwater evaporation loss is only 0.5% of the feedwater supplied. Because of the product water value and the relatively large product water reservoir surface area, a covered product water reservoir is recommended. The cover could be a simple floating film, such as 0.8 mm Hypalon, which would result in a break-even cost saving in one year.

6.10 Waste Disposal Subsystems

Brine concentrate and ion exchange softening regeneration waste will be gravity fed to a zero-leakage solar evaporation pond having features as shown in Figure 6-34. The pond would be formed by surface grading and construction of an earth embankment. The excavation would be covered with a graded sand/gravel mix and an impermeable plastic film liner such as Hypalon. Additional sand would be placed over the film to protect it from sunlight and mechanical damage. The sand/gravel underlayment provides a cushion for the film and drainage paths to a grid of leakage sensors under the film. In case of leakage, the zone of damage can be found from the signaling leakage sensors.

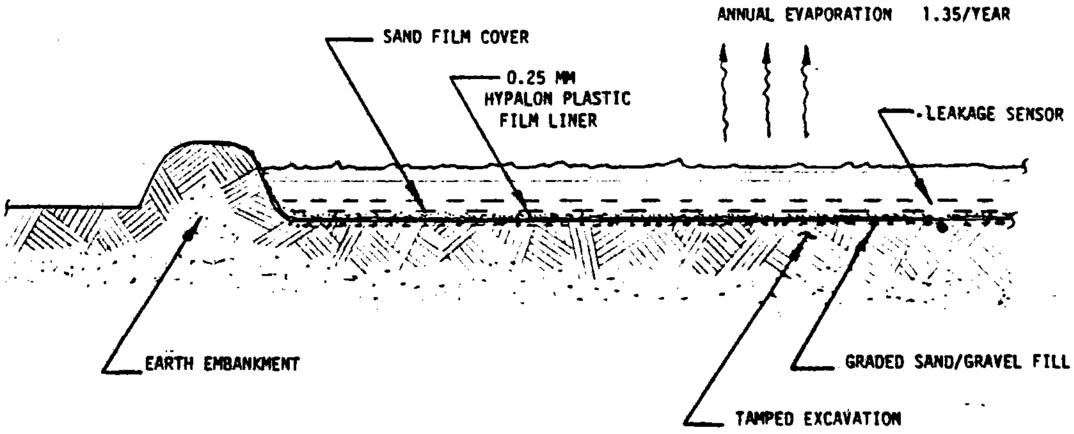


Figure 6-34. Evaporation Pond Features

Based on an estimated average saline pond evaporation rate of 1.35 m/year, an annual production of 2.0 million m^3, and a recovery ratio of 0.72, the required evaporation pond size is 5.78×10^5 m^2.

6.11 Site and Facilities

A general site arrangement was shown previously in Figure 5-3. By careful location of the subsystems (reservoirs, pond, etc.), the minimum required land area is 81×10^5 m^2. If the terrain is not reasonably level, the land area will increase somewhat as a result of terracing. The previous sections describe the various subsystems that would be located on the site and within a plant building.

The plant building (see Figure 5-4 for floor plan) would be a standard industrial type with insulated metal siding and floor area of 2195 m^2. Housed in the building are:

Office
Control room
Water quality laboratory
Energy delivery and back-up power subsystems in an isolated room
Feedwater pretreatment subsystem
Desalination subsystem
Maintenance shop
Spare parts and supplies storage
Lavatory

Heating and air conditioning would be provided to the office, laboratory and control room areas for personnel comfort and equipment protection.

7 OPERATIONS AND AVAILABILITY

7.1 GENERAL DESCRIPTION

7.1.1 Operational Concept

The solar energy water desalination system is expected to be used as the water production segment of municipal and agricultural water supply systems in the United States and Saudi Arabia. The system can be used to desalinate brackish water from either surface or ground water sources. Both potable water and water suitable only for irrigation may be produced by the process.

The operating scheme for the system must account for a variety of conditions: initial operation after construction; normal operation under various conditions of intermittent insolation; planned maintenance; and responses to unusual conditions, such as emergency generator shutdown and severe weather phenomena.

The system is designed to be deployed as a stand-alone plant (i.e., it is independent of power sources other than solar). The system could be deployed as one of several plants within a supply system network. The deployment mode can influence the final system design in several ways. First, the short-and long-term variation in product-water demand and (if present) supply system water storage will influence the requirements for plant product-water storage. Second, the variability in site insolation and the plant deployment mode will influence the requirements for product water storage, thermal storage, and weather prediction. If the plant is deployed in an isolated situation, there may be a need to predict insolation and other weather characteristics (temperature, storms, etc.) for short to moderately long time periods. Weather prediction capability would allow operating the plant in an optimal manner. For a more extensive discussion of this subject, see paragraph 4.10 of reference 7. Third, the deployment mode will influence the maintenance plan for the plant. For example, if the system is an isolated plant, scheduled maintenance normally might be performed only during periods of low water demand. However, if the plant is one of several in a larger supply network, scheduled maintenance planning will be integrated within the system so that plant scheduled downtime may occur at other times of the year.

Normally, water supply systems experience short-term (hourly, daily) and long-term (seasonal) demand fluctuations. The seasonal demand profile for the Rankin/McCamey, Texas, customer group has been estimated from a variety of sources and is illustrated in Figures 7-1a and 7-1b. Based on these estimates, a typical synthetic demand profile for the commercial system has been derived; it is shown in Figure 7-2. The ratio of maximum to minimum demand in this profile is about 2.4. Seasonal water production capability may not match the demand profile. Early studies by BEC indicated the solar powered plant's production and demand are very similar, but excess capacity would exist at times. To remove local site effects on the mismatch between these profiles, SERI specified that the demand could be regarded as equal to the production - all of the product water would be used.

Daily and seasonal demand fluctuations can be accomodated in the system in three ways: product water storage, variable output capability, or a combination of both. Since the system specification requires 10 days of storage at the nominal production rate (6,000 m^3/d), a variable output capability has also been provided to account for the seasonal demand fluctuation shown in Figure 7-2. The reverse osmosis system provides incremental outputs of 2525 m^3/d per train in four steps, up to the maximum output of 10,100 m^3/d. This gives a turn down ratio of 4 to 1, which is compatible with the seasonal ratio depicted in Figure 7-2, as well as the hourly variation in available electric power.

7.1.2 Expected Operating Hours

The nature of the energy-conversion/water-purification process suggests that it should be operated in a manner analagous to a base-load electric power plant, i.e., subject to scheduled maintenance considerations, it should be operated twenty-four hours per day, 365 days per year.

Based on the system performance evaluation model (described in Section 8.1), it is expected that the system would produce water over 7000 hours per year, assuming insolation characteristics similar to those described in Section 8.2. Without accounting for scheduled and unscheduled maintenance downtime, this would produce the expected subsystem operating and non-operating hours shown in Table 7-1. The hours shown in Table 7-1 are used as the basis for all subsequent operations and availability analyses.

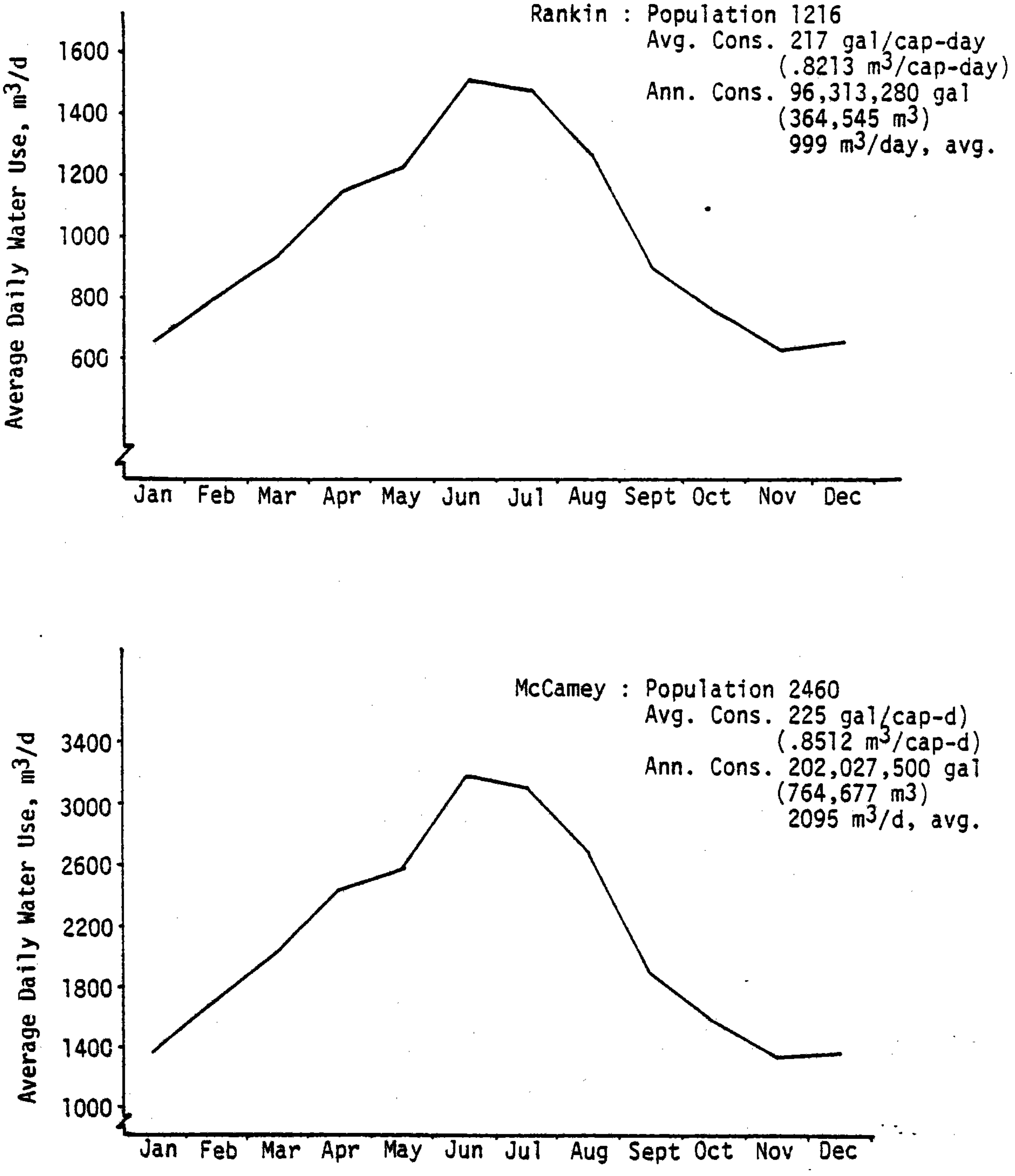


Figure 7-1. Estimated Potable Water Use Profiles, Rankin and McCamey, Texas, 1980

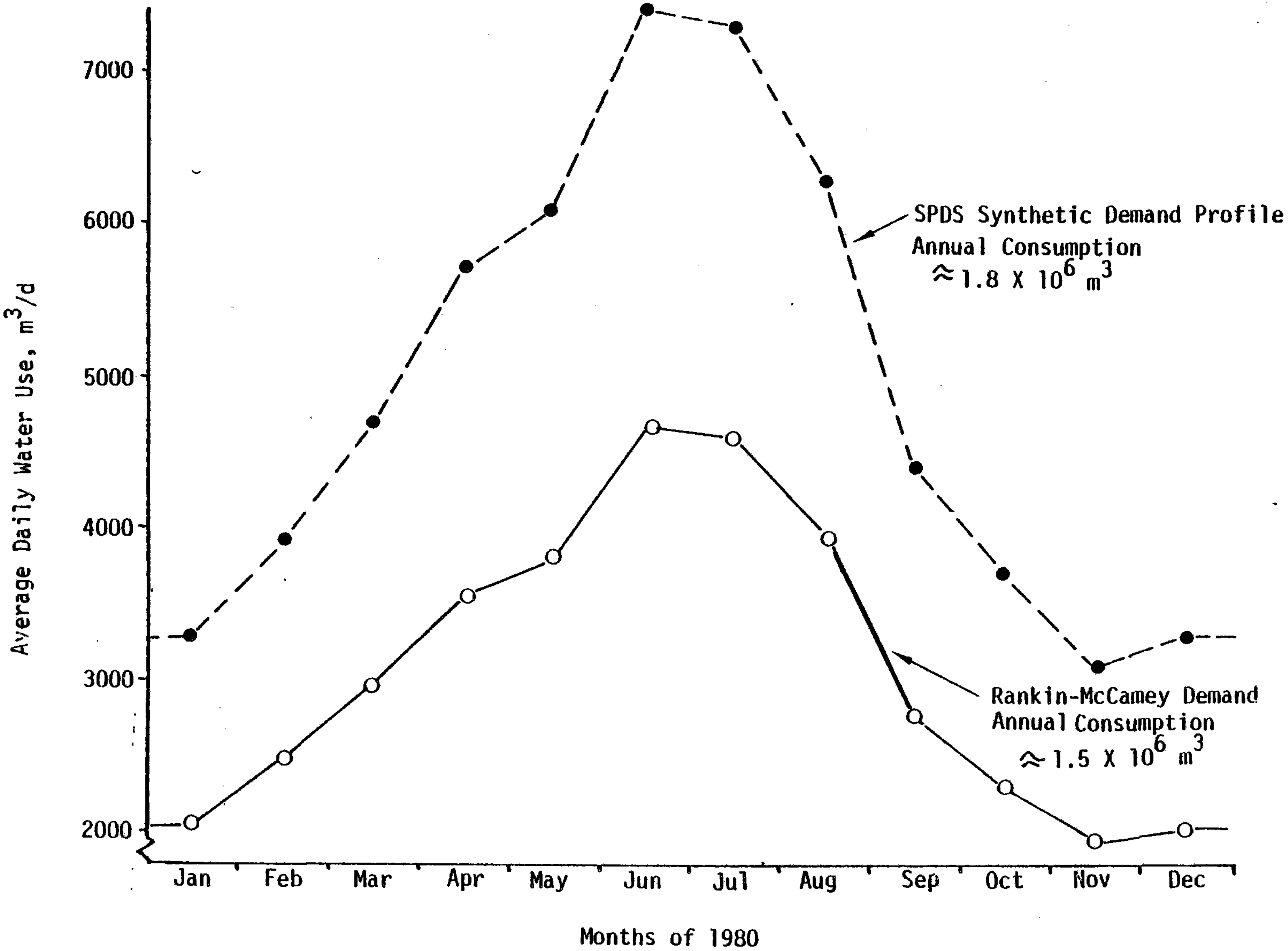


Figure 7-2. Estimated Potable Water Demand, m^3/day, Rankin-McCamey, Texas, 1980, and Synthesized Demand Profile

SUBSYSTEM	EXPECTED YEARLY NUMBER OF		
	OPERATING HOURS	NON-OPERATING HOURS	STARTS/OTHER
Collector Subsystem			
Heliostat			
Gimbal	3080	5680	
Frame/Ped./Facet	8760	-	
Control	8760	-	
Controls/Data/Power	8760	-	
Receiver	3080	5680	365 Starts
Thermal Energy Storage	5260	3500	
EPGS (APU)	7950 (810)	810 (7950)	100 Starts
Controls/Communication	8760	-	
Maintenance Support	2500	6260	
Water Desalination	7950	810	

Table 7-1. Expected Operating and Nonoperating Hours

7.1.3 Normal Operational Sequence

The system is expected to operate up to twenty-four hours per day once the plant has been delivered to the operating utility. The normal operational sequence is depicted in Figure 7-3.

7.2 INITIAL PLANT OPERATION

7.2.1 Initial Heat-Up of Thermal Energy Storage

Because the storage subsystem uses a very large mass of refractory brick, it is anticipated that it would take several months of normal plant operation to bring it to equilibrium conditions if only receiver heat is used. Feasible alternatives might be to burn fuel in heaters temporarily connected to the storage inlet to perform some initial heating.

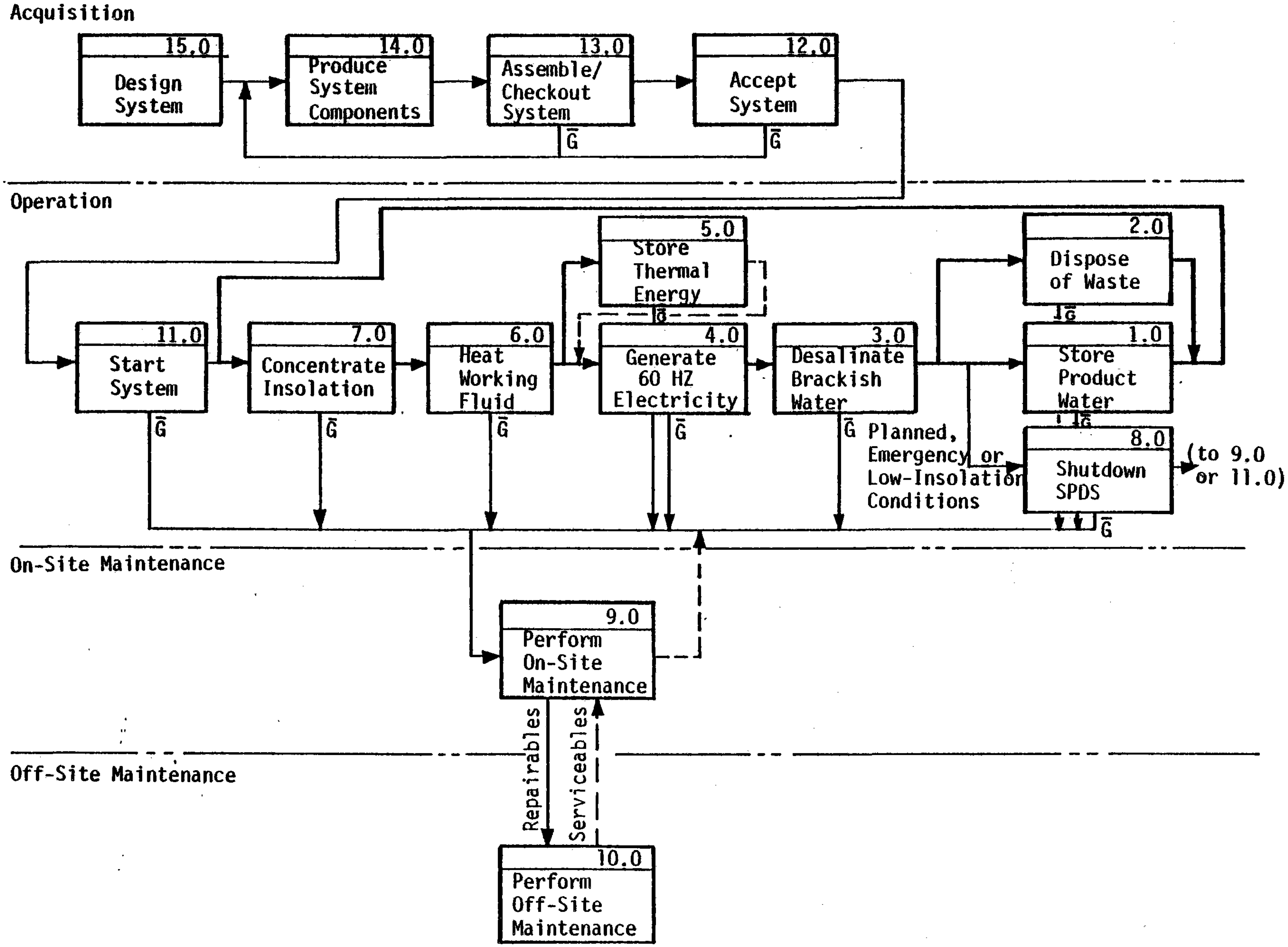


Figure 7-3. Top Functional Flow Diagram

A more feasible alternative, and the approach chosen, will be to temporarily route the turbine exhaust through the storage tanks during the plant construction phase. It is planned that the turbine will be delivered in time to supply electric power for some portion of the plant construction activities. In particular, electric power is required for subsystem checkout activities prior to plant delivery: see construction schedule shown in Figure 7-4. This technique would raise the medium temperature to approximately 260 -320°C. Allowing for heat losses in the ducting and storage tanks, it is estimated that a period of twelve to fifteen days of intermittent (eight h/d) turbine operation would be required to achieve high temperature equilibrium. If the turbine was operated continuously, equilibrium would be achieved in about four days. The actual technique used will be a function of overall plant integration and checkout requirements, which are shown generically in Figure 7-4.

7.2.2 Initial Fill-Up of Product Water and Feed Water Ponds

During initial plant integration and checkout in the acquisition (construction) phase, the product and feed water storage ponds will be filled, if possible. Again, construction activity phasing, as illustrated in Figure 7-4, will allow time for these operations, subject to minimizing the overall construction time period.

7.3 PLANT OPERATION AND MAINTENANCE

7.3.1 Clear-Day Operating Cycle

During clear weather conditions, the plant will be operating twenty-four hours per day. A plant control algorithm will be iterated by computer hardware and software under the control and overall supervision of the plant operator. The significant operating parameters which need to be set or adjusted throughout a normal 24 h running period are:

a. Collector start and stop times, and operating conditions (number of heliostats required, etc.);
b. Receiver start and stop times, and operating conditions (operating temperatures, ramp rates, etc.);
c. Disposition of working fluid thermal energy (amount to be used directly, amount to be stored, etc.);

REFERENCE ________ **GENERAL PURPOSE SCHEDULE ▶** SOLAR POWERED DESALINATION SYSTEM CONSTRUCTION ORGN K-6110 DATE 1-20-81

TITLE Rev. A 3-3-81

Ground Rules:

- o 8 hr day/5 day week/21 days/months
- o No overtime
- o No bad weather allowance

MAJOR MILESTONES

1. Mobilize & Initial Site Survey/Layout

2. Site Work

2.1 Clear & Grub (240 acres)

2.2 Rough Grade Site

2.3 Detail Site Layout/Survey

2.4 Site Storm Water Provisions

2.5 Access Controls/Roads and Dust Control

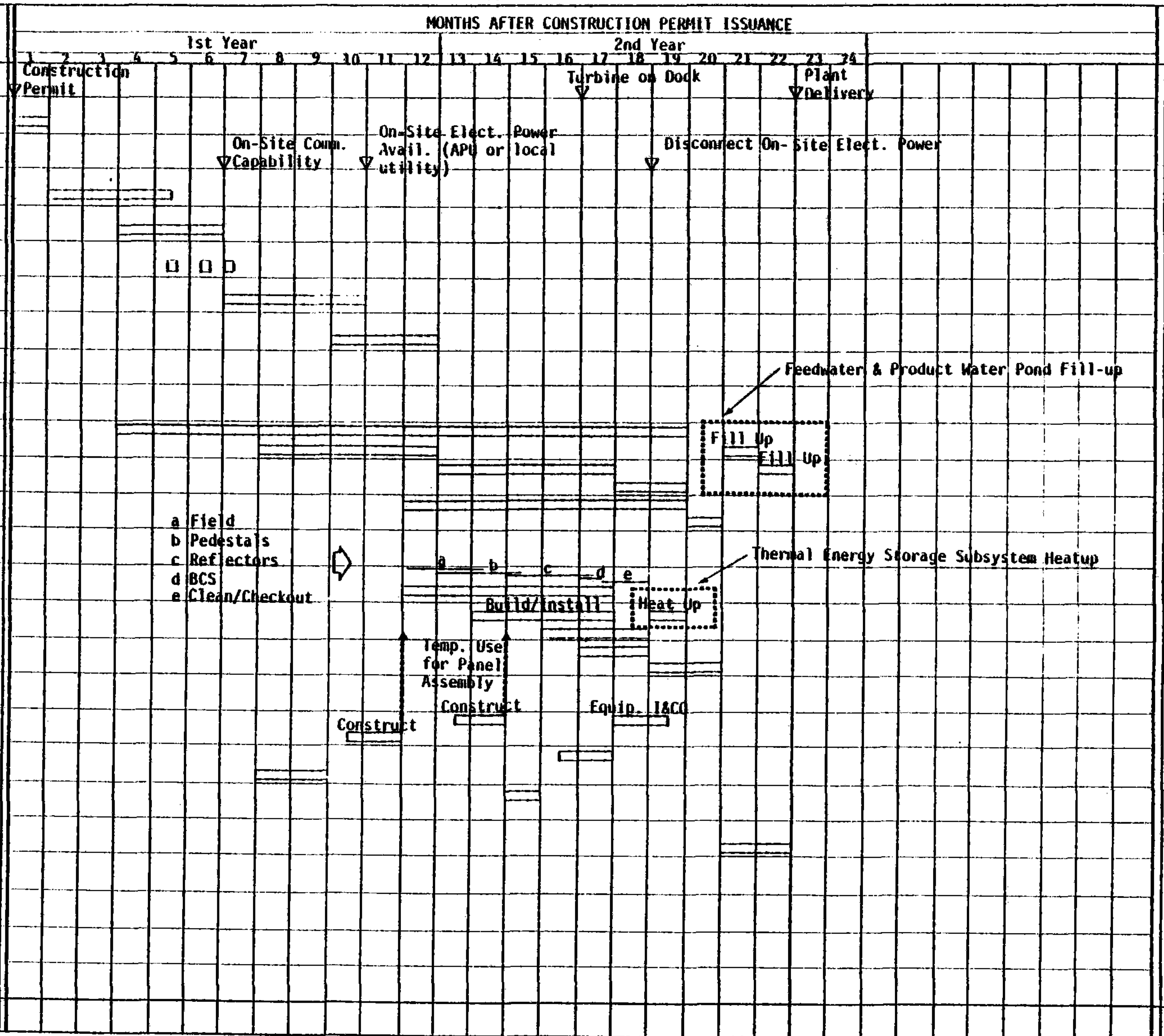
3. SPDS Construction

3.1 Water Desalination Segment
3.1.1 Evaporation Pond (1.84 x 10^6 c.y.)
3.1.2 Feed Water Pond (50,000 c.y)
3.1.3 Prod. Water Pond (52,800 c.y.)
3.1.4 Pond/Desal Plant Piping
3.1.5 Desal Plant Installation
3.1.6 Desal Plant Checkout

3.2 Solar Energy Conversion Segment
3.2.1 Collector Subsystem
3.2.2 Tower, Receiver & Heat Transport Subsystems
3.2.3 Storage Subsystem
3.2.4 EPGS and Power Distribution
3.2.5 Controls
3.2.6 Solar Segment Checkout

3.3 System Support Facilities
3.3.1 OPS/Maintenance Building
3.3.2 Desal Equipment Building
3.3.3 Emergency/Backup Power
3.3.4 Site Septic Sewer/Waste Treatment
3.3.5 Command/Control Capability

4. System Integrated Checkout & Delivery



D1 4066 5000 REV. 7/78

FLAGNOTES:

Figure 7-4. Generic Plant Construction Schedule

d. Water production profile (number of RO units to be operated); and,
e. Thermal-energy-storage operating times and storage/withdrawal rates.

To establish the preferred values for the above parameters, an optimizing control strategy similar to the dispatch of power in an electric utility generation network would be developed in the design phase; the concept is depicted in Figure 7-5. The objective of the operating strategy is to maximize (within demand and storage limits) the expected amount of water produced for a specified time period, for example, over the next several days. In order to determine the preferred operating strategy, the operators, in conjunction with the plant master computer and software, will develop the next period's operating parameters based on updated weather and plant performance data. The desired sophistication in this predictive capability will depend on the degree of excess capacity, product water storage, and reliability of insolation at the plant. A simple strategy would suffice if all these characteristics are present; however, its implementation should still be similar to the generic approach shown in Figure 7-5. Multiple day look-ahead capability requires weather predictions, which may be of questionable reliability. This uncertainty is largely avoided in the simplest strategy, prepared for just the current day's operation. Thus, the strategy can be tailored to the predictive capability available.

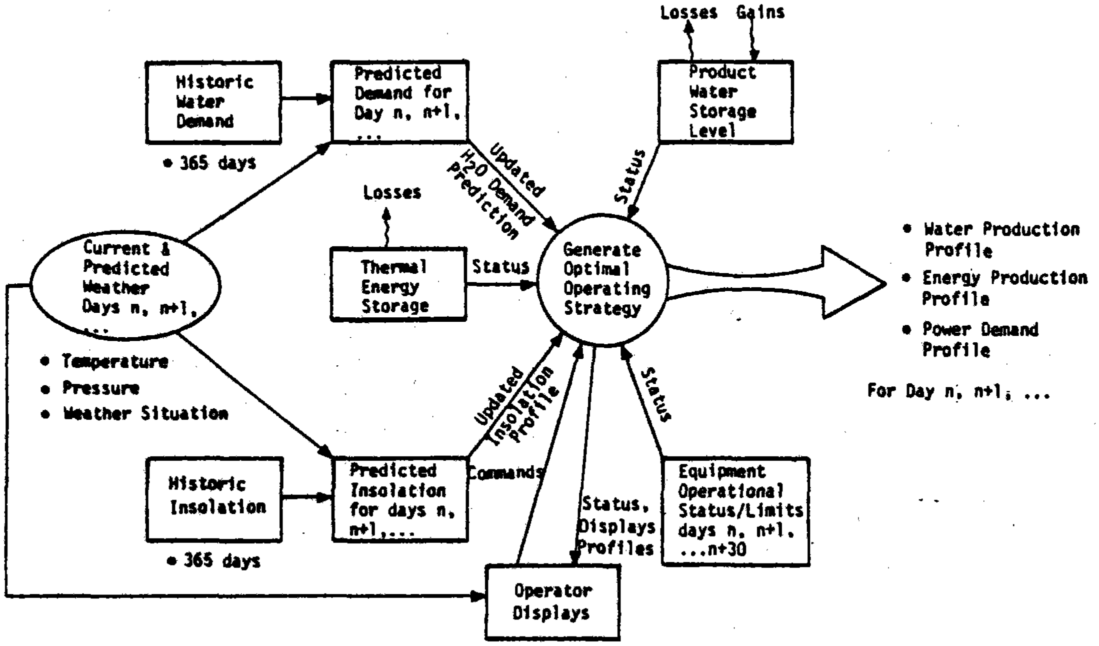


Figure 7-5. Operating Strategy Mechanization

Normally, the plant will operate from direct insolation, converting enough energy to electricity to run the desired number of RO units, and, depending on thermal storage levels, storing thermal energy as required. As sunset approaches, the collector field and receiver will be shutdown in an orderly manner, with heliostats arranged for the next day's run in a near-vertical, overnight stow position. Energy extraction from the TES will be increased as field power decreases so that the receiver is shut down as the prescribed level of turbine operation from the TES is achieved. Water production will continue during the night at the desired rate. As the threshold sun angle above the horizon approaches, the collector field will be powered up, brought to standby, and then receiver heat-up begun. As power output from the receiver increases, energy extraction from the TES will be decreased until the turbine is once again operating directly from the receiver. This completes the normal diurnal cycle.

7.3.2 Intermittent Cloudiness Operations

During periods of intermittent cloudiness or partial cloud-shadowing of the collector field, thermal energy will be extracted from the TES. The control system will automatically determine the need for TES energy based on receiver outlet temperature. The amount of compressor flow and position of valves to the receiver and TES will be adjusted to maintain the required turbine inlet temperature and mass flow for the electrical load. The impact of cloudiness on insolation is illustrated in Figure 7-6.

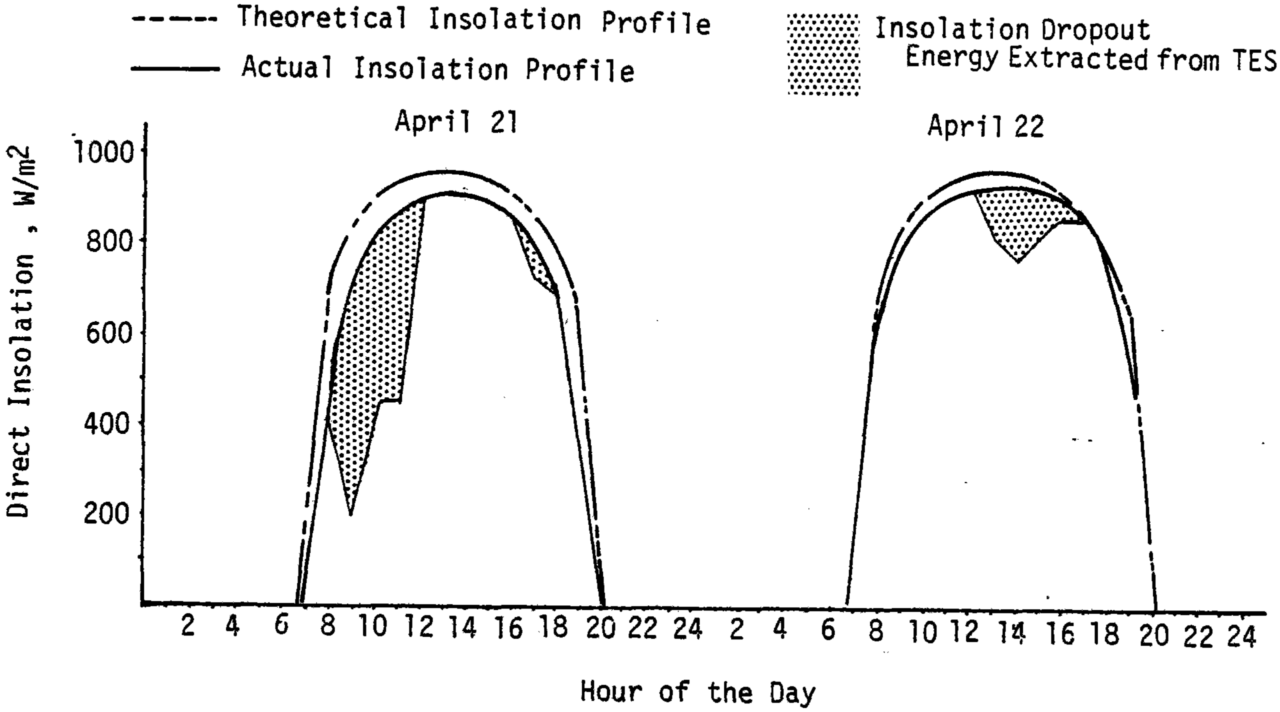


Figure 7-6. Insolation Profiles during Intermittent Cloudiness

The control system detects changes (e.g., decreasing or increasing temperature) in receiver outlet conditions caused by cloud blockage or passage. To maintain stable system conditions, the receiver mass flow rate will be adjusted (increased for decreasing insolation, decreased for increasing insolation) by diverting more or less flow through storage. Depending on the energy and temperature conditions of TES, the plant load may also be adjusted (e.g., one or more RO units shut down or started). Variable power demands for the collector subsystem will be accommodated by the master control system. The control system will also automatically determine the preferred plant operating parameter values throughout the day.

7.3.3 Extended Cloudiness Operation

In some deployment areas, there may be periods of extended cloudiness, which, for convenience, is defined as two or more consecutive overcast days. When this condition occurs, the plant will continue to operate as needed until the TES is depleted to a specific level. Then the plant will be configured for standby (non-water-production) operations and shut down in a normal manner.

To avoid backup operation of the main turbine on fossil fuel, all nonessential electrical loads will be turned off. Power will be supplied to all essential loads (master control, plant work-area lights, etc.)from the standby power generator. Operation and maintenance personnel will continue to perform their normal duties. Maintenance which could not be performed during normal operations will be performed during these periods.

Depending on the length of the extended cloudiness period, it will be necessary to perform certain maintenance on the RO units. For periods of two to seven consecutive days of nonoperation, chlorine or chlorine dioxide must be injected into the RO units for fifteen minutes every twenty-four hours. These injections are performed automatically by the RO unit hardware as initiated by the master control system.

For extended cloudiness periods in excess of seven days, a dilute solution of formaldehyde must be injected into the RO units. This process can be mechanized or performed manually depending on the frequency of extended cloudiness weather sequences at the plant site.

If the plant is down for fourteen days or more, it will be necessary to remove the membranes from the RO units and store them. This activity will be performed by plant maintenance personnel.

7.3.4 Power Requirements

The system will require electrical power for a variety of loads during startup, over the normal diurnal cycle, during emergency shutdown conditions, and during periods of extended cloudiness. Table 7-2 shows the power consumption and average coincident peak loads for the various operating modes. Table 7-3 shows the maximum peak loads for various conditions, and the power supplies and their associated nameplate ratings which satisfy these requirements.

Table 7-2. Plant Electric Power Requirements

Source	Power Consumption	Average Coincident Peak Load, kW			
		Startup	Normal OPS	Emergency Shutdown	Extended Cloudiness
Water Desalination Segment	4 units @ 128 kW +0.5 kW	0.5	128.5-512.5	0.5	0.5
Solar Energy Segment					
Collector	25.5 kW	5.0	25.5	71.8*/41.8**	5.0
TES	0 - 300 kW	-	150.0	-	-
Miscellaneous	1.0 kW	1.0	1.0	1.0	-
EDS/BPGS	8.6 kW	2.5	8.6	2.5	1.5
Plant Master Control	14.7 kW	14.7	14.7	14.7	5.7
Miscellaneous Plant Loads					
Air Conditioned	10.0 kW	10.0	10.0	10.0	10.0
Lighting	2.5 kW (avg)	1.5	1.5	1.5	2.5
Maintenance Mach.	2.0 kW	-	-	-	3.7
Other	4.5 kW	-	-	-	4.5
	TOTALS	35.2	347.3-731.3	101*/72**	33.4

* For 15 seconds, helio scram

** High wind stow during quiescent operations

EDS-Energy Delivery Subsystem

BPGS-Backup Power Generation Subsystem

Table 7-3. *Power Supplies for the Solar Powered Desalination Plant*

Condition	Peak Load kW	Power Source	Nameplate Rating kW
Startup	35.2	APU	40
Normal Operations	745.2[1]	Main Turbine	800
Emergency Shutdown	95[2] /80[3]	EDS + BPGS.[4]	100
Extended Cloudiness	30-38	APU	40

[1] TES pump at maximum power, 3 R-O units running; daylight hours

[2] Helio scram

[3] High wind stow during quiescent operations

[4] EDS-Energy Delivery Subsystem
BPGS-Backup Power Generation Subsystem

7.3.5 Maintenance Concept

A conventional 2-level maintenance concept has been developed for the system: on-site and off-site maintenance. Both scheduled and unscheduled maintenance will be performed.

It is expected that the on-site maintenance capability will be adapted to suit the deployment mode and actual plant site. Stand-alone plants in remote areas would be expected to have considerably more extensive on-site capabilities than a similar plant located in a developed region, such as the southwestern United States. Initial maintenance planning has been based on deployment in the west Texas area.

The important scheduled maintenance requirements for the plant have been summarized in Table 7-4. The unscheduled maintenance scheme is depicted in Figure 7-7.

Subsystem/Component	Maintenance Requirement	Interval
Collector		
Heliostat	- Clean reflective surface, inspect gimbal for leaks	1 year
Receiver	- Inspect insulation, HX tubes, expansion joints	1800 hrs
	- Insulation major refurbishment	10 years
Heat transport	- Inspect valves/piping	1 year
Thermal energy storage		
	- Lubricate blower motor & gearbox	1 year
	- Overhaul blower	5 years
Electric power generation		
Generator	- Lubricate bearings, voltage & frequency control check	3600 hrs
Generator - turbine coupling	- Check/lubricate	3600 - 4000 hrs
Turbine	- Visual inspection, oil sample, calibrate instruments	1000 hrs
	- Hot section inspection	4000 hrs
	- Major tear down/overhal	30 - 40,000 hrs
APU	- Startup/checkout	monthly
	- Inspections/lubrications	(similar to main turbine)
Water desalination		
Pumps	Check/maintain oil levels	Daily
RO units	Replace membrane	Every 3 years
Pretreatment	Drain, flush, calibrate	Monthly
Instruments	Check operation, calibrate/standardize	Daily
Product water	Check pond for integrity & contamination	Monthly
	Water quality checks	As required*
Plant control	None expected	
Miscellaneous plant systems	TBD	

Table 7-4. Scheduled Maintenance Requirements

7.3.6 Personnel Requirements

Personnel will be required for both operation and maintenance of the plant; a typical organizational structure is illustrated in Figure 7-8.

Depending on the plant deployment mode (stand-alone, integrated, etc.), and the organizational and personnel policies of the plant operator/owner, it may be possible to reduce the number of on-site personnel. For example, if the plant is one of several in an integrated water supply system, it may be feasible to share management, clerical, and some maintenance personnel may also be shared among several plants. However, it is expected that a minimum cadre of full-time on-site personnel will be required to ensure reliable daily plant operation. The number required for a stand-alone plant is shown in Table 7-5.

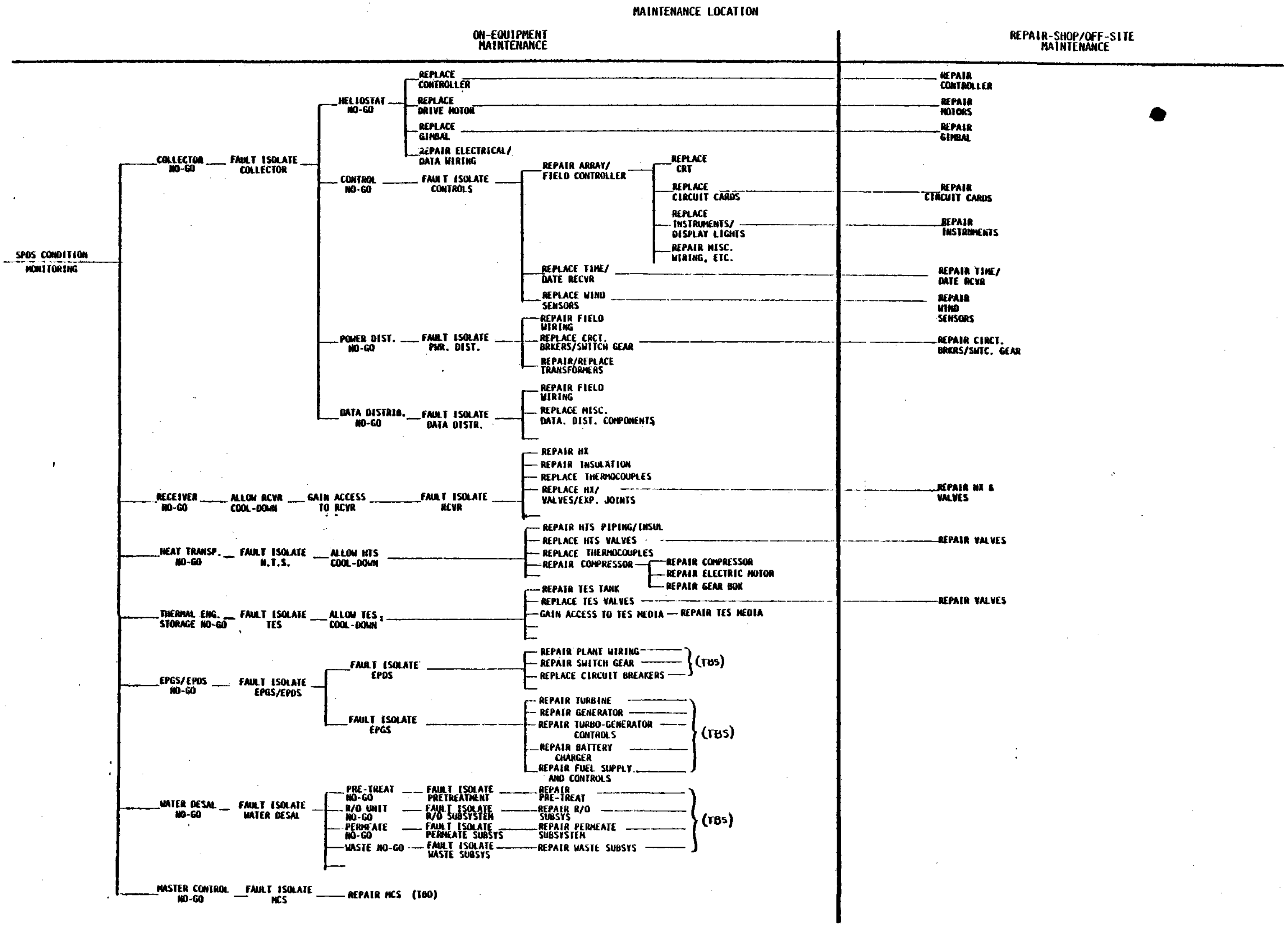


Figure 7-7. Unscheduled Maintenance Diagram

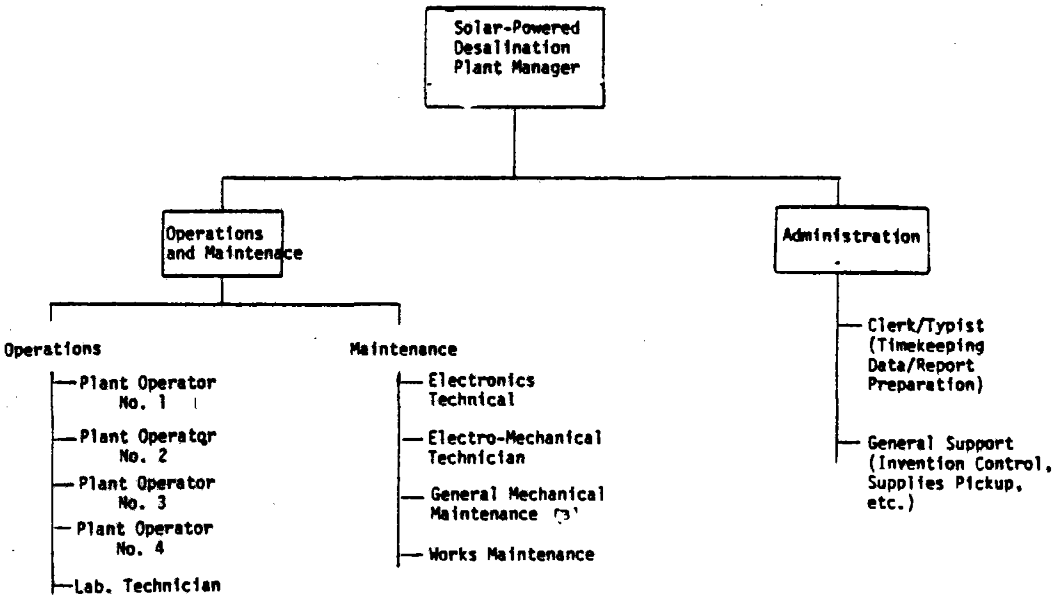


Figure 7-8. Organizational Structure

Personnel Type	No. Assigned to Shift				Total
Operations	#1	#2	#3	Relief	
Operator	1	1	1	1	4
Lab. Technician	1	-	-	-	1
Maintenance					
Electronics Technician	1	-	-	-	1
Electro-Mechanical Tech.	1	-	-	-	1
General Mecahnical Tech.	1	1	1	-	3
Works Maintenance	1	-	-	-	1
Administration					
Works Manager	1	-	-	-	1
Clerk	1	-	-	-	1
General Support	1	-	-	-	1
TOTALS	9	2	2	1	14

Table 7-5. Number of Personnel Required by Shift

7.4 RESPONSE TO UNUSUAL CONDITIONS

The system will be designed for safe response to a variety of unusual conditions, such as generator trip, severe weather phenomena, etc. In each instance, the event will be detected and announced by the control system to the system operator. In addition, automatic data logging will be performed to provide a record of events during the excursion. In some cases, the master computer will automatically initiate certain actions (e.g., collector field defocus, load shedding). Other events may require operator responses only, or operator responses in conjunction with control system actions.

7.4.1 Main Generator Trip

Certain faults in the electric power distribution subsystem or other subsystems may initiate a main generator trip, i.e., the generator main circuit breaker must be opened. In this event, power to the turbine must be reduced immediately to prevent an overspeed condition. This is accomplished with a dump valve in the TES piping; it is rapidly opened, thus causing the working fluid to vent through the storage tanks. This procedure allows recovery of some thermal energy from the receiver working fluid in an emergency shutdown. Also, the dump valve design is simplified owing to its lower temperature location.

Electrical power for the system during and subsequent to the generator trip will be furnished by the backup power subsystem. Sufficient power will be available to permit a safe shutdown of the plant, including (should the generator trip occur during active solar power operations) defocusing the collector field. After safe shutdown, the plant will be operated in a minimum power profile mode until repairs can be made. No water production will occur during such standby conditions.

7.4.2 Solar Energy Conversion Segment Failures

Failures in the solar energy conversion segment (solar energy collection and energy storage subsystems) will be fault isolated by the master control subsystem. The most critical failure would be the loss of pressure and/or mass flow through the receiver during solar heating operations. Such conditions might occur due to rupture of piping or receiver heat exchangers.

In this event, the collector field will be rapidly defocused, and the piping or receiver isolated so that normal generation may continue from the TES.

In responding to this condition, the master control subsystem will automatically configure the plant for the power levels sustainable by the TES. If the failure is such that it is not possible to automatically isolate the leak, the backup power subsystem will be activated, the solar segment shutdown, and the plant will be placed in a standby condition until repairs are completed.

Failures in the collector subsystem electric power or data networks may cause unbalanced power conditions in the receiver. Depending on the magnitude of the unbalance, it may be necessary to place the field in standby and switch entirely to the TES. In this event, power generation and plant configuration will be established in the same manner as described above.

7.4.3 Water Desalination Segment Failures

The most significant failures in the water desalination segment would be RO unit pump or motor running failures. Since each motor is 112 kW (150 horse-power) loss of one or more of these units will impose significant power transients on the electric power generation and distribution subsystems. However, such load excursions are well within the control stability limits of the overall solar thermal and electric power conversion systems. Thus, the normal response will be to shut down the failed RO unit, and activate one or more units which may be in standby. During load switching, the control subsystem will automatically control power input to the turbine to maintain the required electrical output levels.

7.4.4 Severe Weather Phenomena

There are several severe weather phenomena which must be considered in the design and operation of the system: sustained high wind speeds, thunderstorms, tornadoes, vigorous frontal activity, and hail. During severe weather involving sustained or gusting high speed winds (generally at or above 22 m/s) the collector field must be in a "feathered" or high-wind stow position, i.e., all heliostat mirrors must be parallel to the ground. It is not necessary to orient the heliostat azimuthally.

Since the heliostat drive systems have been designed for certain wind loads, it will be necessary to have wind-speed sensors near the collector field. This will enable the system operator, in conjunction with other weather data and control system software, to anticipate when to initiate high-wind stowage. The field must be stowed before the wind speed reaches 22 m/s.

Hail activity is normally associated with thunderstorms. A map showing hailstone regions of the United States is shown in Figure 7-9 with probability distribution data shown in Table 7-6; comparable data for Saudi Arabia is not available.

The heliostats have been designed to withstand one-inch hailstones impacting at 23 m/s. Thus, in most locations where the system would be deployed, hail is not expected to be a problem. If severe hail activity (hailstones larger than one inch) is expected, it may be prudent to position the heliostats in a vertical stow position; this will minimize surface-area exposure and reduce the probability of damage.

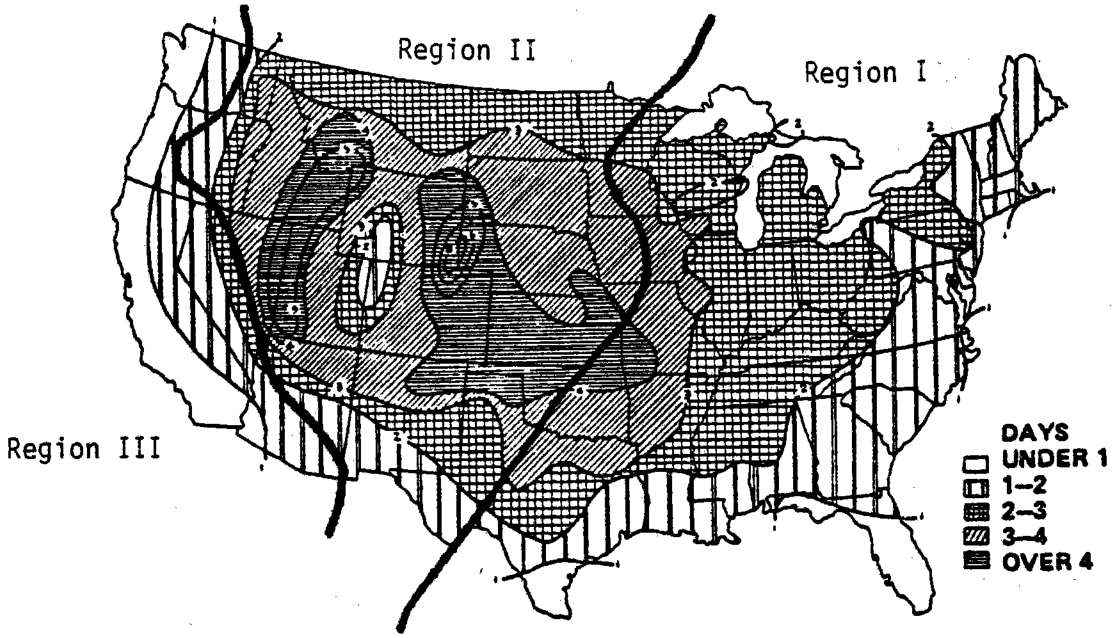


Figure 7-9. Hailstone Occurrences in the United States (Excluding Alaska and Hawaii)

*Table 7-6. Cumulative Probability of Obtaining Hailstones of a Given Diameter or Greater**

HISTORICAL WEATHER CHARACTERISTICS

OCCURENCE OF HAIL

- **Cumulative Probability of Obtaining Hailstones of a Given Diameter or Greater***

Diameter (inches)	Cumulative Probability				
	Region I		Region II		Region III
	Upper Limit	Lower Limit	Upper Limit	Lower Limit	
≥0.25	0.94	0.50	1.0	0.88	0.58
≥0.50	0.75	0.20	0.96	0.58	0.14
≥0.75	0.46	0.085	0.65	0.30	0.075
≥1.00	0.26	0.030	0.40	0.15	0.05
≥1.25	0.15	0.006	0.25	0.06	
≥1.50	0.07	0.0012	0.16	0.017	
≥2.00	0.008	0.00011	0.03	0.0017	
≥3.00	0.00025	4×10^{-6}	0.0013	0.00007	
≥4.00	0.00002	3.5×10^{-7}	0.0001	7×10^{-6}	

Table 1 is obtained from the envelope curves in Figures 6-8 and is to be used in conjunction with Figure 5.

NOTE: Data is based on hailpad and observer data.

*Given that a hailstorm is occurring.

7.5 AVAILABILITY OF PLANT

7.5.1 Availability Model

The availability of the system is defined as the long-term probability that the system will be capable of performing its intended function, given adequate insolation has been and is available during any 24-hour period. This probability statement may be represented as

$$A_{\text{system}} = \left[\begin{array}{c|c} \text{Prob. system capable of} & \text{Adequate} \\ \text{Functional Performance} & \text{Insolation} \end{array} \right] . \qquad (7.1)$$

Removing the conditioning event from the probability statement, we have

$$A_{\text{system}} = \frac{[\text{Expected up time}]}{[\text{Expected up time}] + [\text{Expected down time}]} , \qquad (7.2)$$

since the system is repairable.

The measures of up time and down time which are subject to design control are reliability (failure rate) and maintainability (repair rate). These measures are expressed as quantitative figures of merit:

R = reliability measure,
= probability that the system will perform its function for a specified time period under expected operating conditions, given it was available at the beginning of the time period;

and,

M = maintainability measure,
probability that the system
= can be restored to a serviceable condition within a specified time, given the correct maintenance resources are available at the time the failure occurs.

These figure-of-merit probabilities are quantified according by standard mathematical expressions:

$$R = e^{-\lambda t}$$

and

$$M = e^{-\alpha t}$$

where

λ = the system failure rate,
α = the system maintenance rate,
t = time period of interest.

If we assume exponentially distributed times between failure and repair,

$$\lambda = \frac{1}{\text{MTBF}}$$

and

$$\alpha = \frac{1}{\text{MTTR}}$$

where

MTBF = the mean time between failures,

and

MTTR = the mean time to repair.

Given the foregoing definitions and equations, the availability of the system becomes

$$A_{\text{system}} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \quad . \qquad (7.3)$$

The expressions for system availability (identity 7.1 and equation 7.3) can be evaluated by use of a system availability block diagram; this is shown in Figure 7-10.

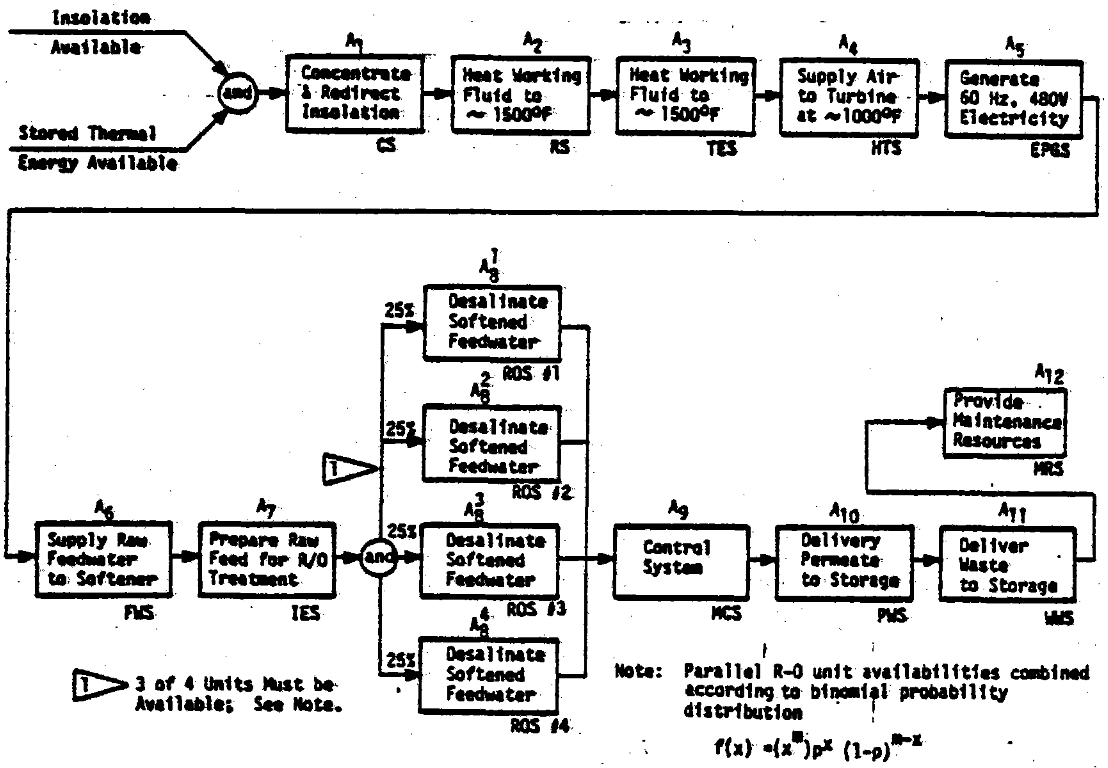


Figure 7-10. Availability Block Diagram

To evaluate the system availability, Figure 7-10 is simplified by consolidating the parallel blocks representing the reverse osmosis units. This is accomplished by considering the specified performance requirement of 6000 m^3 of product water per day. This output level is achievable when three or four RO units are available; therefore, the A_8' availabilities may be combined by the binomial (Bernoulli) probability distribution:

$$f(x) = \binom{n}{x} p^x (1-p)^{n-x} \qquad (7\text{-}4)$$

Thus, the probability of 3 or 4 units functioning, defined as A_8' is given by:

$$P_x(x=3) = \left[\frac{4!}{(3!)(4-3)!}\right](A_8^i)^3(1-A_8^i)^1 ;$$

and

$$P_x(x=4) = \left[\frac{4!}{(4!)(0)!}\right](A_8^i)^4(1-A_8^i)^0$$
$$= (A_8^i)^4 ;$$

thus

$$A_8' = (4)(A_8^i)^3(1-A_8^i) + (A_8^i)^4 .$$

With the expression for A_8' determined, we may now evaluate the system availability as a series expression.

7.5.2 Failure and Maintenance Rate Estimates

For the conceptual design, the reliability and maintainability characteristics of each of the major subsystems were evaluated and characterized by their MTBF and MTTR values. The values used are summarized in Table 7-7, and are based on available data from various sources within BEC and other industry sources. Due to the conceptual nature of the design, the values are based on available data for similar equipment, rather than a detailed analysis of the design.

To establish an effective failure rate for the collector subsystem, it is necessary to define what constitutes a failure of the heliostat field (the array of 436 heliostats). Under normal operating circumstances the field output will fluctuate somewhat due to changes in the insolation falling on the collector. Since the field has been designed for approximately 940 W/m^2 on December 21st, a collector field failure could be defined as any condition which does not provide enough thermal energy to the receiver so that a total of 6000 m^3 of product water is produced on a typical day, given that approximately 3000 m^3 of water had been produced by 0700 of the typical day. This event (3000 m^3 produced by 0700 of a typical day) is the condition expected based on the performance predicted by the system model for the insolation conditions described in the system availability definition (identity 7.1).

In the worst case (no insolation during daylight hours of the typical day), the system model predicts that the minimum total water produced would be 8750

Table 7-7. Reliability and Maintainability Values

		UNIT MTBF, HOURS				REPAIRABILITY		
SUBSYSTEM SEGMENT	NUMBER PER EPDS	OPERATING	NON-OPERATIING	MTTR, HRS.		REPAIR-ABLE	NON-REPAIR-ABLE	REMARKS
COLLECTOR SUBSYSTEM								
HELIOSTAT	436	24,654		3.4		X		
A/F CONTROLLER	1	50,000	-	4.0		X		REPAIR IN PLACE
TIME/DATE RECEIVER	1	80,000	-	1.0		X		REMOVE/REPLACE
WIND SENSORS	1 SET	35,000	-	3.0		X		
DATA DIST. LINK	1 SET	150,000	-	16.0		X		FIELD REPAIR
POWER DIST. SYSTEM	1 SET	100,000	-	8.0		X		FIELD REPAIR
RECEIVER SUBSYSTEM								
TOWER	1	876,000	-	24.0		X		
RECEIVER	1	4,000	50,000	120.0		X		8 HR AVG. C-D
HEAT TRANSPORT SUBSYS.								
PIPES AND VALVES	1 SET	30,000	50,000	24.0		X		
THERMAL ENERGY STORAGE								
STORAGE TANKS/MEDIA	3	200,000	400,000	192.0		X		
STORAGE BLOWER	1	8,000	25,000	96.0		X		
ELECTRIC POWER GEN DIST.								
MAIN TURBO-GEN.	1	4,285	10,000	96.0		X		
480/208 TRANSFORM	1	200,000	-	8.0		X		REMOVE/REPLACE
POWER SWITCHING	1 SET	125,000	-	6.0		X		
PLANT POWER DISTR.	1 SET	150,000	-	4.0		X		
APU (RANKINE)	1	3,000	15,000	48.0		X		
EBUP (DIESEL)	1	5,000	8,000	24.0		X		
WATER DESAL SEGMENT								
FEEDWATER SUBSYSTEM	1 SET	25,000	50,000	12.0		X		
DESAL UNITS	4	10,000	30,000	4.0		X		
PERMEATE SUB.	1 SET	30,000	60,000	6.0		X		
WASTE TRMTN SUB.	1 SET	15,000	30,000	12.0		X		
MASTER CONTROL SEGMENT	1	3,778		16.0				
MASTER COMPUTER	1	60,000	-	8.0		X		
PROCESS COMPUTER	1	60,000	-	8.0		X		
DISPLAYS	3	40,000	-	4.0		X		
PRINTERS	2	35,000	-	12.0		X		
DATA STORAGE	1	60,000	-	4.0	6.5	X		
CONTROLLERS	2	50,000	-	6.0		X		
MISC. INTERCON.	1 SET	50,000	-	2.0		X		
DATA FINALS	1 SET	80,000	-	4.0		X		
SOFTWARE	1 SET	100,000	75,000	8.0		X		
SYSTEM FAULT ISO.	-	-		9.5		-		
MAINT. RESOURCE SEG.								
MAINT. SYS. EQUIP.	1 SET	7,000	30,000	24.0		X		
PERSONNEL SEGMENT								
OPERATORS	4	5,600	-	1.0		X		
MAINTENANCE	4	4,000	-	1.0		X		
STRUCTURE AND SITE								
AIR CONDITIONING	1	10,000	-	8.0		X		

m^3. In a sense then, the collector field does not have a failure event corresponding to unavailability as defined by the availability model (identity 7.1). However, to be conservative, one could assume that such a condition could occur whenever there is a failure event which causes all heliostats to fail (or be out of commission).

The probability of this event may be estimated by evaluating the probability that all 436 heliostats will fail, converting this probability to an equivalent failure rate, and adding the derived rate to the failure rates for the array/ field controller, time/date receiver, power distribution network, and data distribution network. These latter elements can produce a condition where all heliostats are out of commission.

The probability of 436 heliostats failing may be evaluated with the Poisson probability mass function:

$$P_{x_o}(x) = \frac{(\lambda t)^x e^{-\lambda t}}{x!} ;$$

also,

$$\lambda t = (436)(39.2 \times 10^{-6})(10),$$

with

t = 10 hours, to be conservative;

thus

$$P_{x_o}(436) = \frac{(436)(39.2 \times 10^{-6})(10)^{436} e^{-(436)(39.2 \times 10^{-6})(10)}}{436!}$$

$$\approx 0.$$

This result is not surprising, since the expected number of failures in ten hours is

$$\lambda t = 0.37.$$

This corresponds to a very large MTBF, which, to be conservative, we shall value at 10^8 hours.

7.5.3 Availability Estimate

Using the expressions defined by equations 7.3 and 7.4, the availability estimate for the subsystem has been computed. The availability values are summarized in Table 7-8; these values yield the following estimate for the system:

$$\begin{aligned} A_{RO} &= (4)(A_{RO})^3(1-A_{RO})+(A_{RO})^4 \\ &= 0.999999 \quad ; \end{aligned}$$

and

$$A_{system} = 0.93$$

Because the commercial plant design is only conceptual at this time, some allowance must be made for uncertainty in assessing system availability. Therefore, in computing the expected water to be produced, an availability of 0.91 has been used.

Table 7-8. Subsystem Availabilities

Subsystem		Availability
A_1	Collector	0.999499
A_2	Receiver	0.988062
A_3	Thermal Energy Storage	0.989357
A_4	Heat Transport	0.999233
A_5	Electric Power Generation	0.972083
A_6	Feedwater Supply	0.999543
A_7	Ion Exchange	0.999543
A_8	Reverse Osmosis	0.999625
A_9	Master Control	0.995785
A_{10}	Product Water	0.999808
A_{11}	Waste Water	0.999233
A_{12}	Maintenance Resources	0.996230

8.0 PLANT PERFORMANCE ANALYSIS

This section describes the system level performance analysis of the selected solar desalination plant configuration. First, the general purpose system analysis computer code is briefly described. The available site ambient data is then summarized. Evaluations of the site solar resource character and availability are also presented. The determination of the solar desalination plant and subsystem size is discussed. Finally, data from an hour-by-hour yearly analysis of plant performance are summarized.

8.1 PLANT PERFORMANCE MODEL

8.1.1 Functions of the System Analysis Model

The functions of the solar desalination system analysis model (DESAL) are listed in Figure 8-1. The model has been devised as a flexible tool to be utilized throughout the solar desalination program. DESAL is a quasi-steady state model of the various components of the selected solar desalination plant. The model assumes the plant will proceed from one steady state point to another. This is accurate for slowly changing events where the minimum time increment is approximately 0.25 hours. For transient events less than 15 minutes time constant, the transient performance of the receiver/turbine/field is not adequately represented in DESAL. The short term transients are of importance for detailed design, but have little impact on plant sizing and annual performance results to be obtained with DESAL.

One of DESAL's great utilities is in exploring the effects of large numbers of potential system configurations and operating philosophies. Data for many combinations can be gathered quickly and inexpensively, allowing the system analyst to study the major operation parameters without becoming bogged down in extensive, tedious hand calculations.

Another important model usage is in the area of annual performance predictions with hour-by-hour data. This allows verification of subsystem component sizes and permits an accurate assessment of plant outages and startup requirements.

- Functions
  - Provide system performance for various system level configurations
  - Provide subsystem design point operating conditions
  - Provide annual performance predictions with hour-by-hour data
  - Provide a tool for evaluation of various operating strategies

Figure 8-1. Performance Model Functions

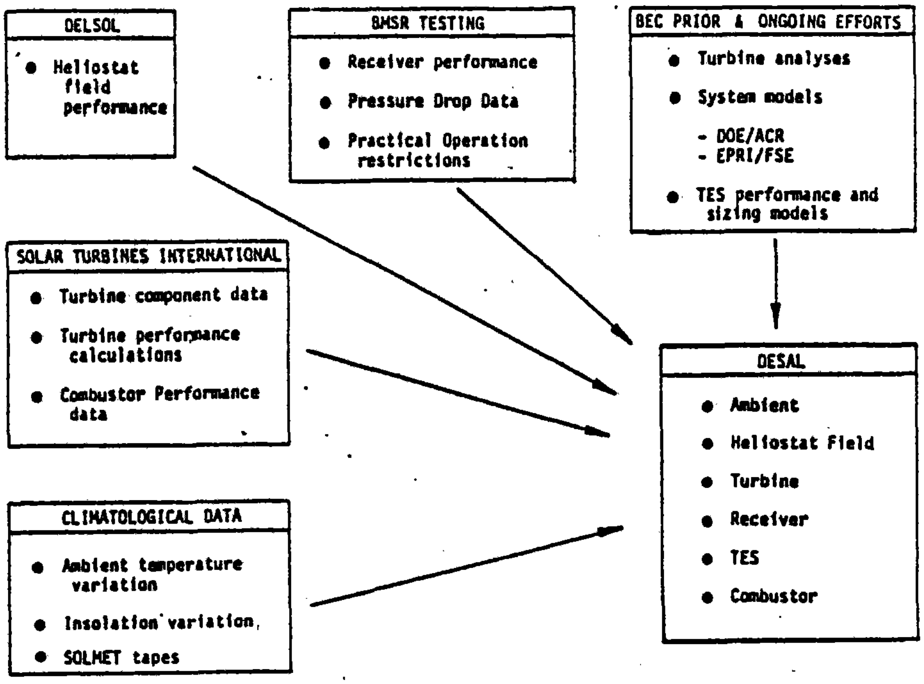


Figure 8-2. Data Sources

8.1.2 Data Sources

Figure 8-2 illustrates the data sources for this computer model. Climatological data used in the DESAL code are broken into two categories, clear day and annual hour-by-hour. The clear day data were generated to represent a cloudless day for each month of the year. Insolation values were generated for Rankin, Texas using Allen's clear air model [8]. Ambient temperature profiles were chosen to represent the 30-year average for each month. Annual hour-by-hour insolation and ambient temperature data were obtained from 1978-1979 SOLMET data for Midland-Odessa, Texas. The hour-by-hour data is more fully described in Section 8.2.1.

Solar Turbines International (STI) provided turbine component data, the turbine performance calculation method, and combustor performance data. Heliostat field performance was obtained with the DELSOL computer code. This field data consisted of the field efficiency multiplied by the mirror area as a function of solar hour for the 21st day of each month of the year. Performance on other days was interpolated from these 12 days' data. Data from the BEC/EPRI Bench Model Solar Receiver (BMSR) testing program (EPRI Research Project 377-3) were used as a basis for estimating receiver performance and pressure drop. A system analysis model (FSESAM) developed for the BEC/EPRI Full System Experiment program provided a base upon which the DESAL model was constructed. Adding to the limited solar hybrid operation capability of FSESAM, the DESAL model was embellished with previously developed plant/thermal storage models to produce both an extended solar hybrid and a storage integrated plant capability. DESAL was also greatly benefited by other system analysis model development at Boeing. The information from these data sources were combined into a consistent calculation methodology resulting in the DESAL program.

8.1.3 Model Capabilities and Limitations

The basic capabilities of the DESAL model are summarized in Figure 8-3. DESAL was written in FORTRAN on the Boeing Computer Services CDC 6600 System. The basic limitation in the use of the DESAL model is due to the quasi-steady state model. As stated before, the model assumes slowly varying ambient conditions, allowing the solar subsystems to equilibrate to a new steady

- FORTRAN Language
- Ambient
    - Ambient temperature
        - 30 year average (12 days)
        - 1978 actual hour-by-hour data
    - Insolation
        - Clear day profile (12 days)
        - 1978 actual hour-by-hour data
- Heliostat Field Performance
    - Clear day, diurnal data (12 days)
    - Annual data interpolated
- Turbine
    - STI - Titan
    - STI - Spartan
    - Garrett 831 - 800 (partial)
    - STI - Centaur
    - STI - Saturn
- Receiver
    - BMSR
    - Desal receiver
- TES
    - Sensible heat
    - Latent heat
- Cycle
    - Simple cycle
    - Recuperated cycle
    - Steam bottoming cycle
- Operation
    - Maximum solar
        - Constant turbine inlet temperature
        - Constant electric output (hybrid solar mode only)
    - Minimum solar-receiver flowrate
    - Charge TES
    - Parallel receiver/TES discharge
    - Discharge TES only
    - Fossil only

Figure 8-3. "Desal" Capabilities — as of Feb 13,1981

state. For rapid transients, e.g. time constants on the order of several minutes or less, the capacitive effects of the various solar components must be analyzed in a truly dynamic system model. Presently, the DESAL model is "resistive" in nature, containing "capacitance" only in the TES subsystem.

8.1.4 Model Organization

The organization of DESAL is illustrated in Figure 8-4. Subsystem performance is based on subroutine submodels. A main or executor program sequentially calls each subroutine as needed.

8.1.5 Model Operating Strategies

The DESAL model current operating strategies are illustrated in Figure 8-5. This list is not exhaustive in all of the operation modes that a solar desalination of this type could expect. The purpose of the list is to summarize the major operating strategies of the model. As new operating methods and refinements are developed, they can be added to the model.

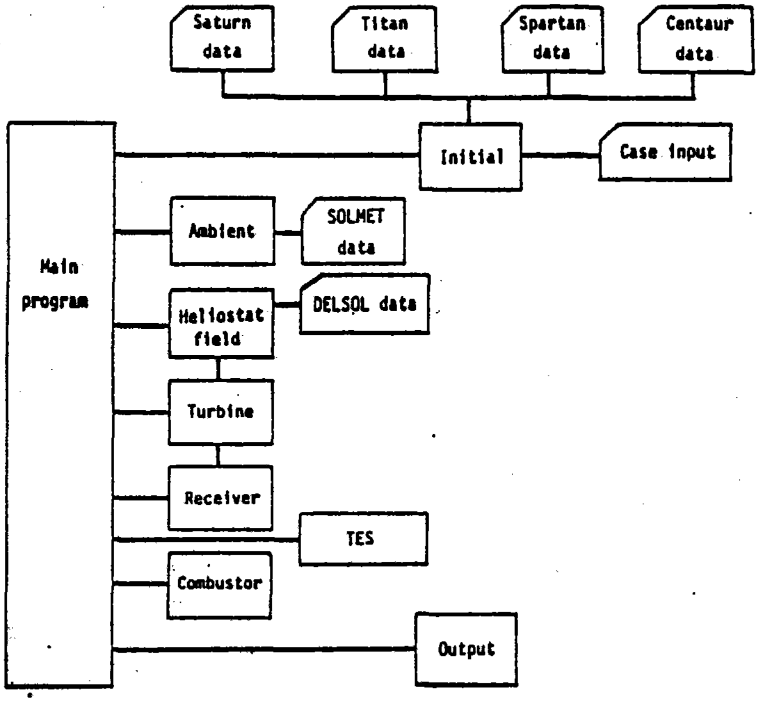


Figure 8-4. "Desal" Organization

- o Maintain turbine inlet temperature as close to 788°C as possible
  - solar only
  - solar and TES in parallel
  - TES only
- o Produce as much electricity as possible at all times
  - no anticipatory logic
- o Limits on solar input
  - design values
  - receiver subsystem pressure drop
  - TES pump power consumption
  - minimum receiver mass flow

Figure 8-5. "Desal" Model Operating Strategies

The major current operating strategy is to maintain at all times the turbine inlet temperature as high as possible but not above the design value of 788°C (1450°F). A corollary of this strategy is that the model attempts to operate the plant to produce as much electricity as possible at a given instant. No anticipatory logic is included. This results in some situations where the model may not produce the best long term plant performance. As an example, consider a mostly cloudy day that has usable direct insolation becoming available late in the operation day, e.g. an hour before the minimum solar elevation angle (10°). The model would attempt to start up the plant to capture that energy, whereas a plant operator would probably evaluate the nearness of the minimum elevation angle time and choose not to start the turbine. It is expected that using a nonanticipatory logic will produce conservative plant performance, actual performance being greater. Anticipatory logic should allow an increase in long term plant performance and a reduction in required plant starts.

Solar input control strategy is influenced by a number of factors. Potential solar input above the design value for maximum solar flux results in turning away some of the heliostats. This maximum solar input condition coincides with the maximum receiver pressure drop and TES pump power consumption at the plant design point. If the maximum receiver pressure drop and/or TES pump power consumption limits are encountered at lower solar input conditions, adjustments in the heliostat field are also made. As the minimum desirable pressure drop level is passed, additional heliostats are added, if available, to boost solar input and hence receiver thermal output. At the minimum receiver mass flow, the heat transfer capability of the receiver heat exchanger panels reaches a level where further receiver operation becomes unrealistic, and the heliostat field is shut down.

8.2 SOLAR RESOURCE ANALYSIS

The performance of a given solar plant is obviously affected by the ambient environment at the site for which it is intended. This section summarizes the various analyses performed on ambient data available for or typical of the solar desalination plant site. The basic data sources are described as well as conclusions available from statistical analyses of those data. The solar energy density (kWh/m^2-d) available at the site is presented. Finally, the site solar availability derived from long term data and hour-by-hour measurements is discussed.

8.2.1 Weather Data

Weather data for the Rankin-McCamey, Texas solar desalination plant site are adequately represented by National Oceanic & Atmospheric Administration (NOAA) data for Midland-Odessa, 50 miles to the north, which was utilized extensively for the plant performance analysis.

Weather data are broken into two broad categories: hour-by-hour data and long-term, i.e. "30-year", average data. The hour-by-hour data is useful for estimating detailed performance characteristics such as plant outage times, startup requirements, and TES utilization. The long-term data is used to size the plant components and predict the long term performance and economics.

The following subsections present the data sources for the hour-by-hour and long-term data.

8.2.1.1 SOLMET Data

A SOLMET data tape for Midland-Odessa, Texas was purchased from NOAA. This data tape provided hour-by-hour ambient data from January 1, 1978 to June 30, 1979. The specific ambient data of interest to the plant performance analysis were the ambient temperature and direct insolation. A separate file or tape was created containing ambient temperature and insolation data. The separate tape would represent an actual hour-by-hour record of ambient temperature and insolation representative of the variations expected at the site.

An analysis of the SOLMET data revealed that the ambient temperature data were complete for each hour of the year (8760 data points) and could be transferred directly to the separate file. However, the direct insolation data revealed gaps for January and February, 1978 and January, 1979. In order to produce a representative year's insolation variation, February, 1979 insolation data were substituted in the February slots. March through December data were taken directly from March through December, 1978 SOLMET data. January insolation data was taken symmetric about the winter solstice, i.e. Day 1 data taken same as Day 308, Day 2 as 307, etc. For the remainder of the plant performance analysis discussion, the separate file data thus formed is referred to as the "1978 Midland" data.

The SOLMET direct insolation data is recorded as the hourly energy density, i.e. kJ/m^2. By dividing these data by 3.6, i.e. (1000/3600), the hourly integrated solar power density in W/m^2 is obtained.

8.2.1.2 30-Year Average Data

Long term or "30-year" average temperature data for Midland-Odessa, Texas are presented in Table 8-1.

Table 8-1. Midland-Odessa, Texas Normal Ambient Temperature Data (1941-1970)

Month	Daily Maximum (°C)	Daily Minimum (°C)	Monthly Average (°C)
J	14.6	-1.1	6.8
F	17.1	+1.2	9.1
M	21.1	4.3	12.7
A	26.5	10.0	18.3
M	30.6	14.8	22.7
J	34.1	19.7	26.9
J	34.2	21.1	28.3
A	35.0	20.9	28.0
S	31.4	17.3	23.3
O	26.6	11.7	18.0
N	20.1	4.3	12.2
D	15.9	0.1	6.9
Year	25.7	10.4	18.1

Long term direct insolation data for Midland-Odessa are not directly available. Long term total insolation (direct plus diffuse) data for Midland-Odessa are presented in Table 8-2. The average long term yearly average direct insolation energy density or "solar resource" for Midland-Odessa, Texas has been estimated as 6.00 kWh/m^2-d.

Clear day insolation data for the 21st of each month of the year were generated for the selected solar desalination site using Allen's clear air model [8]. The insolation profiles are presented in Figure 8-6.

Table 8-2. Midland-Odessa, Texas Total Insolation Data

Month	Average Daily Total Solar Energy Density (kWh/m^2-d)
J	3.35
F	4.20
M	5.47
A	6.39
M	6.99
J	7.19
J	7.61
A	6.56
S	5.76
O	4.71
N	3.63
D	3.36
Year	5.44

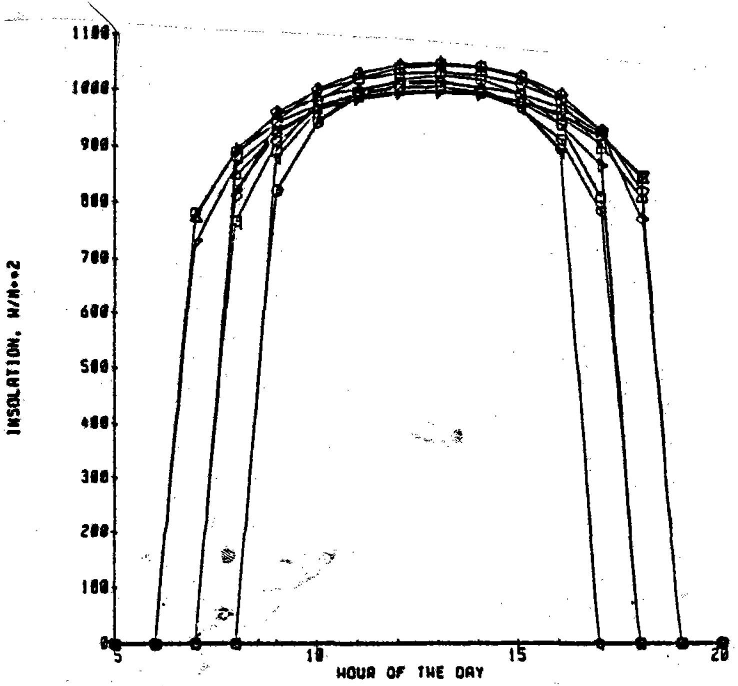


Figure 8-6. Clear Day Insolation Profiles

8.2.2 Ambient Temperature Data Results

By analyzing the 1978 Midland data, a histogram of the ambient temperature was constructed as shown in Figure 8-7. Presented are the number of occurrences in the 1978 Midland data year that a particular ambient temperature was encountered.

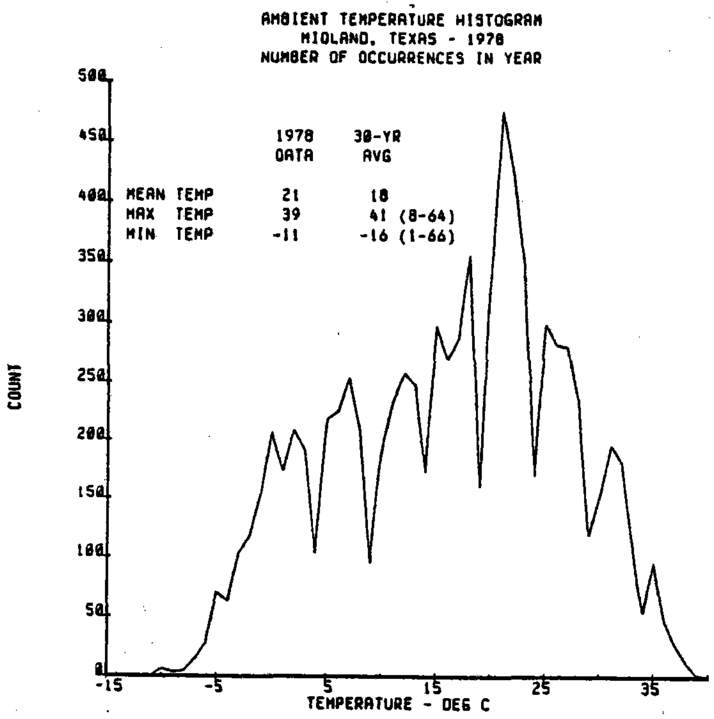


Figure 8-7. Ambient Temperature Histogram, Midland, Texas, 1978

8.2.3 Insolation Data Results

The maximum daily insolation level for each day of the year is presented in Figure 8-8. As can be seen, several periods of the year had no direct insolation indicating periods of extended cloudiness. An insolation histogram is shown in Figure 8-9. The fractional sum of the insolation distribution for the 1978 Midland data is presented in Figure 8-10. Of the time that direct insolation is available, 95% of the occurrences were at 940 W/m^2 and below, although insolation levels as high as 1030 W/m^2 were encountered occasionally. Also, 75% of the direct insolation occurrences were between 150 and 940 W/m^2.

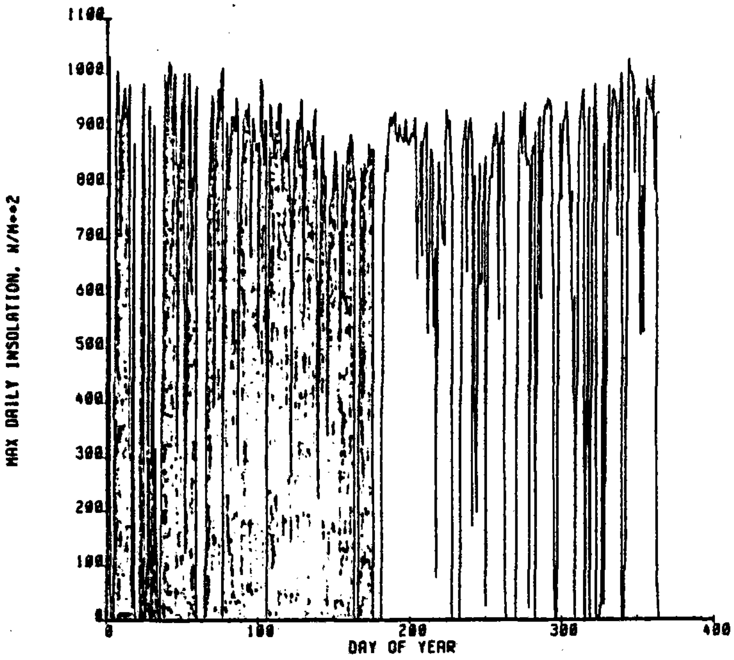


Figure 8-8. Maximum Daily Insolation Yearly Distribution

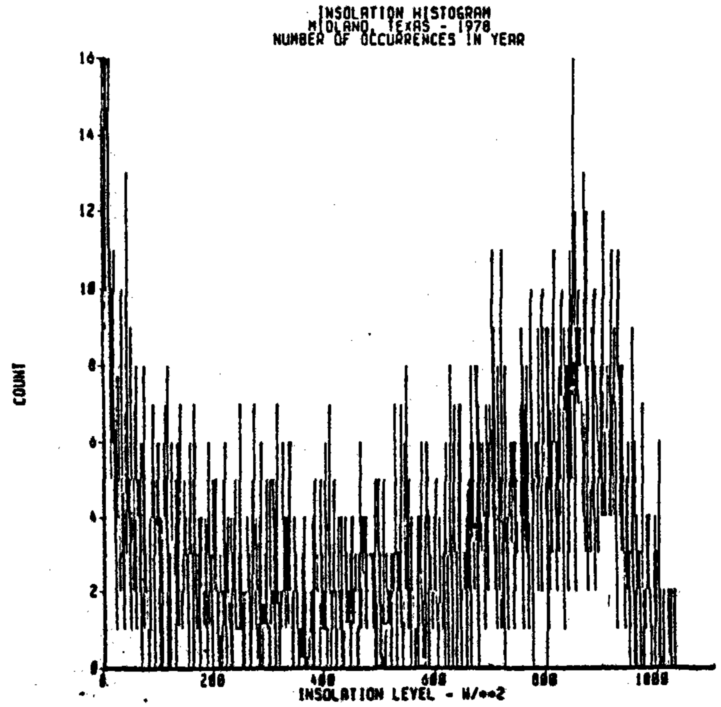


Figure 8-9. Insolation Histogram, Midland, Texas, 1978

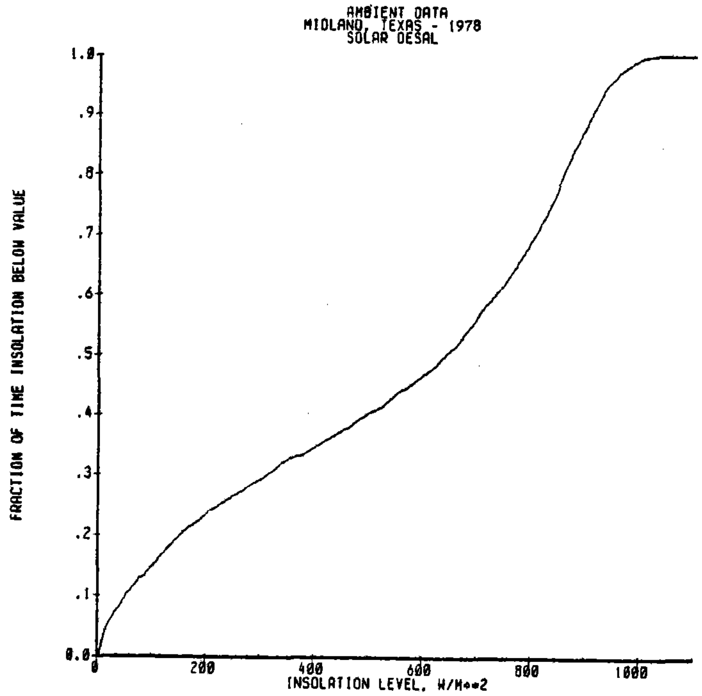


Figure 8-10. Insolation Fractional Distribution

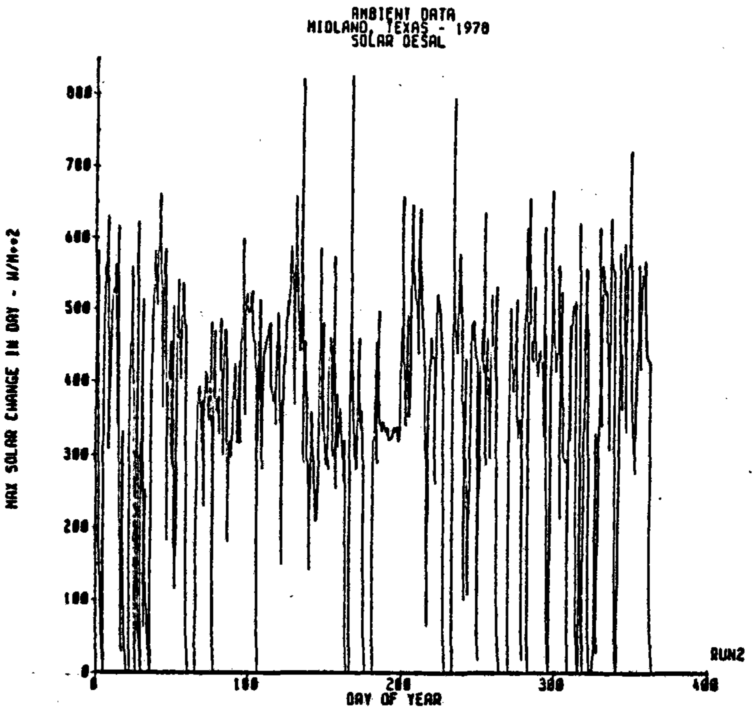


Figure 8-11. Maximum Solar Insolation Change per Day

The hour-by-hour solar variability is studied by calculating the change in insolation level from one hour to another. Figure 8-11 presents the maximum hourly insolation change for each day of the year. Figure 8-12 presents the spectrum of insolation changes as a function of their frequency of occurrence. The change distribution is nearly symmetric with "off-loading" changes (loss of insolation) as high as 900 W/m^2 and "on-loading" changes (gain of insolation) as high as 800 W/m^2. Considering the general concerns about thermal shock and thermal cycling in solar receivers, such solar change data should be useful in the pilot plant receiver design. For instance, Figure 8-12 suggests that rates of change are usually moderate and rarely approach the "black cloud" worst case condition.

8.2.4 Site Resource Data Results

The solar power density or insolation level in W/m^2 directly affects the sizing of the solar receiver and flow components. However, the TES system performance is influenced more by the energy density or "solar resource". This solar resource is generally expressed in terms of kWh/m^2-d. The long term solar resource data were discussed earlier. The day-by-day resource from the 1978 Midland data is presented in Figure 8-13. These data further demonstrate that there were several periods of extended cloudiness in the 1978 year data. A histogram of the solar resource data is presented in Figure 8-14. A significant number of occurrences were at 7.0 kWh/m^2 and above. The fractional distribution of the resource shown in Figure 8-15 demonstrates that although the yearly average resource value is 5.30 kWh/m^2, the mean value is 7.0 kWh/m^2. The mean includes only days that had direct normal insolation whereas the average includes all days.

It is obvious than one hour at 1000 W/m^2 contributes to the daily solar resource value 5 times the effect of an hour at 200 W/m^2. Figure 8-16 presents the insolation fractional distribution based on power and energy. These data demonstrate that although 75% of all the occurrences of insolation fall between 150 -940 W/m^2, that same 150 -940 W/m^2 range accounts for 90% of all the energy potentially available at the site. Furthermore, plant operation at less than 150 W/m^2 or greater than 940 W/m^2 is relatively unimportant because only small amounts of potential solar input energy are actually available at those insolation levels. These conclusions give some

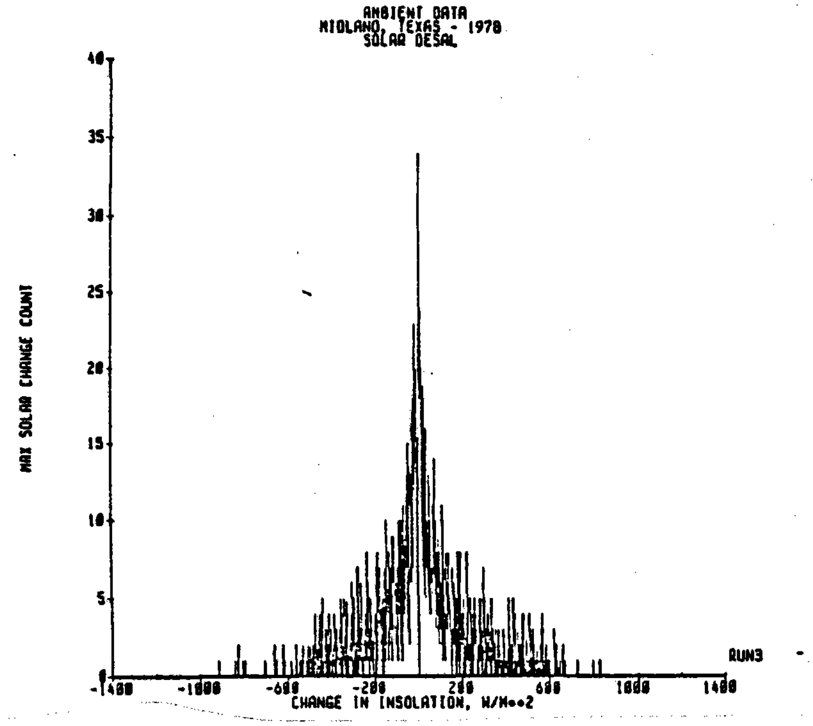


Figure 8-12. Insolation Change Distribution

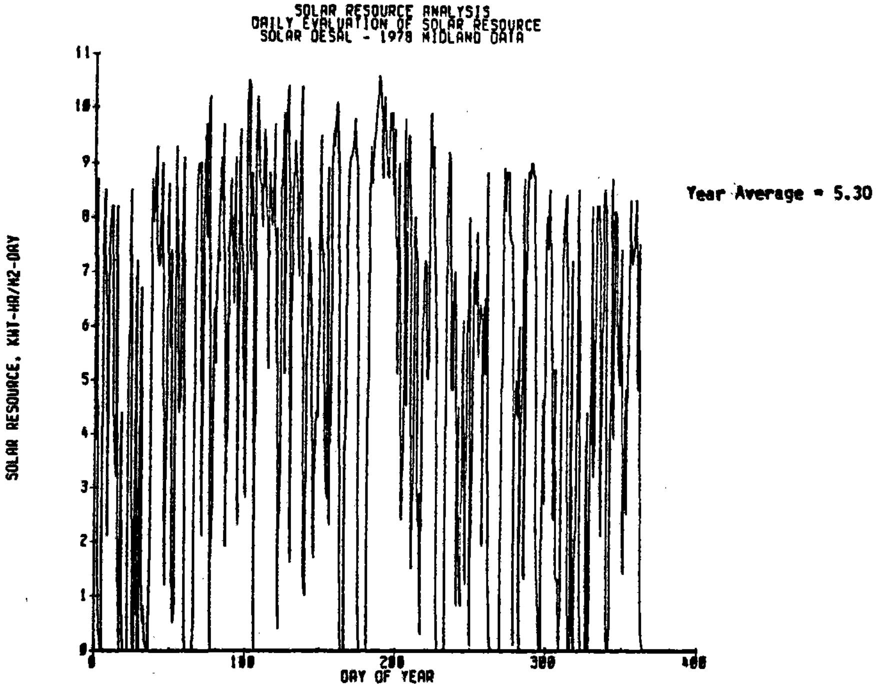


Figure 8-13. Solar Resource Yearly Distribution

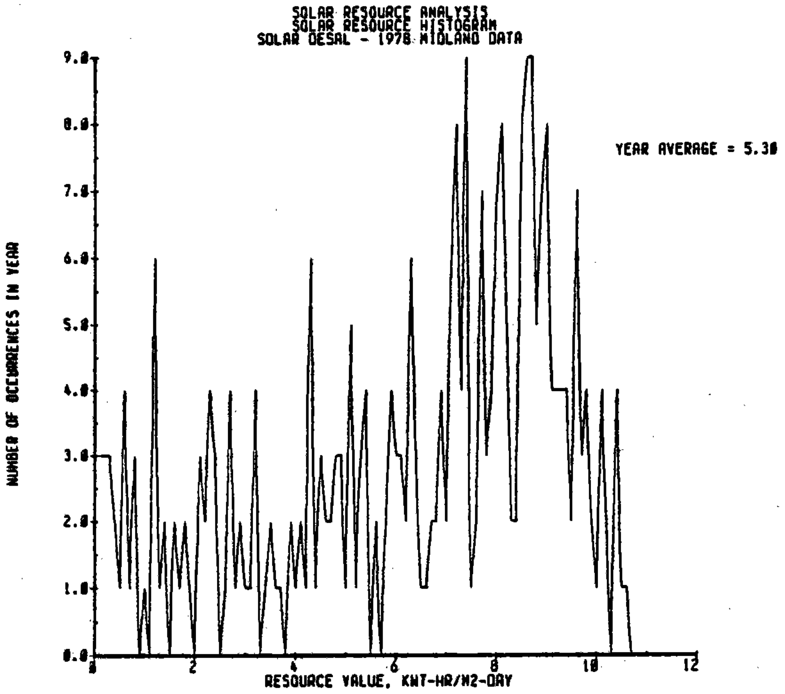


Figure 8-14. Solar Resource Histogram

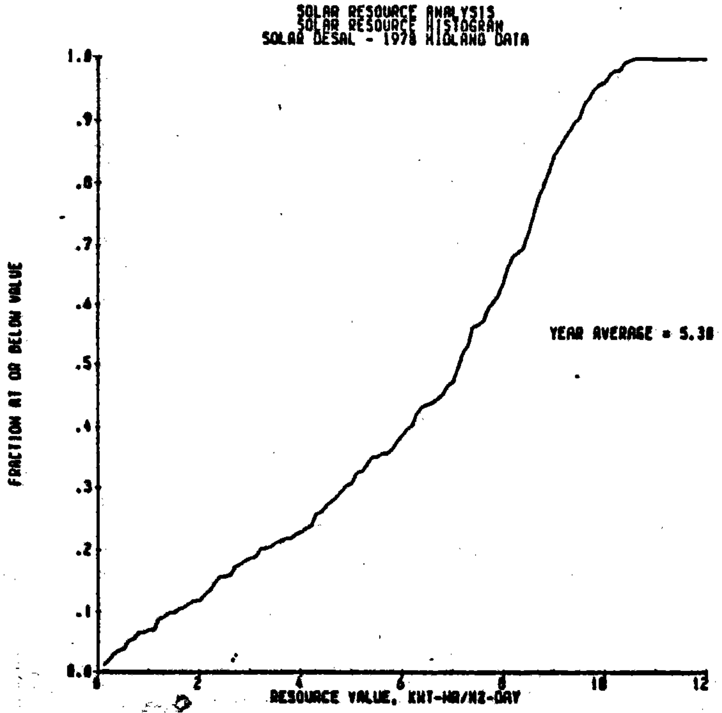
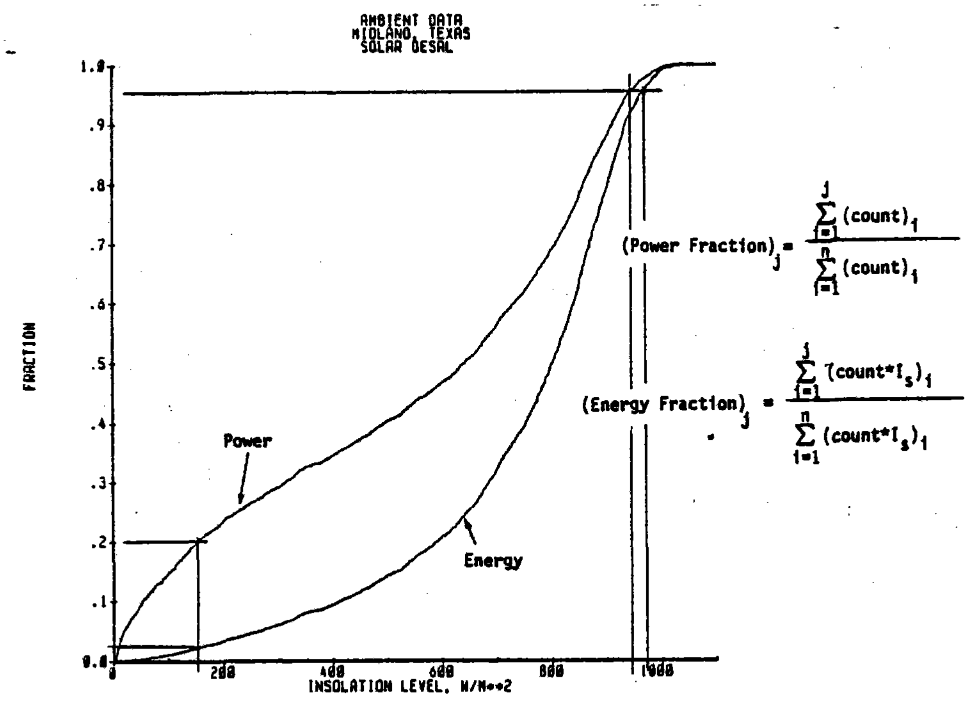


Figure 8-15. Solar Resource Fractional Distribution



$$(\text{Power Fraction})_j = \frac{\sum_{i=1}^{j} (\text{count})_i}{\sum_{i=1}^{n} (\text{count})_i}$$

$$(\text{Energy Fraction})_j = \frac{\sum_{i=1}^{j} (\text{count}*I_s)_i}{\sum_{i=1}^{n} (\text{count}*I_s)_i}$$

Figure 8-16. Insolation Fractional Power and Energy Distribution

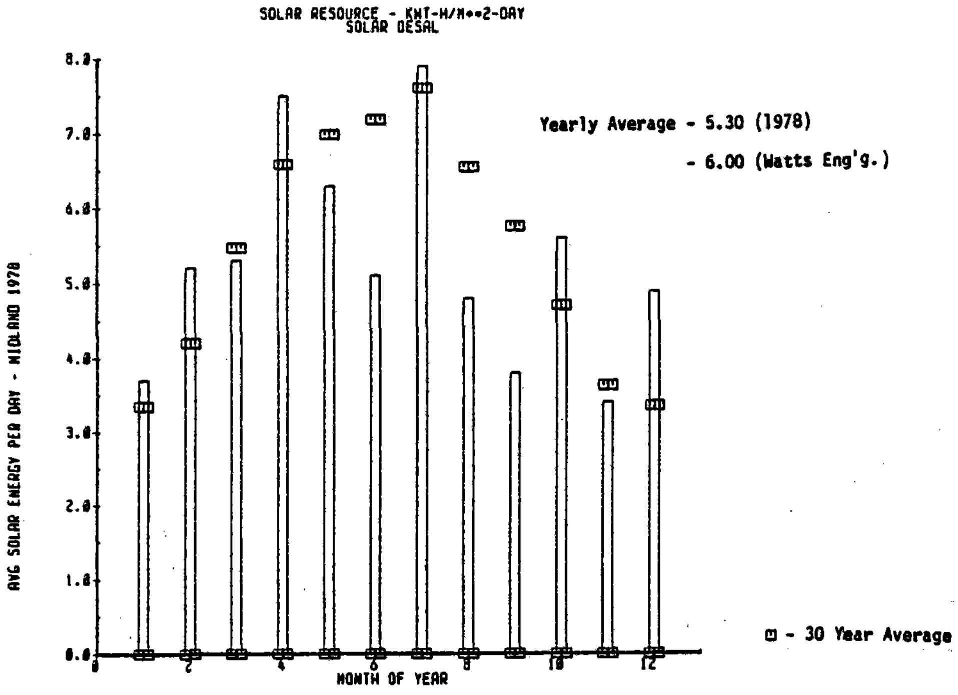


Figure 8-17. Monthly Average Solar Resource Distribution

guidance in plant operation strategy. At some minimum insolation level at the heliostat field design point efficiency, the solar input to the receiver will be at a minimum allowable level. This minimum allowable solar input level results from consideration of the heat transfer capability of the heat exchanger panels at low mass flows. The minimum flow condition for the solar desalination receiver occurs at roughly 150 W/m^2. The data shown in Figure 8-16 indicates that the annual performance penalty of not operating the receiver at levels below 150 W/m^2 is small.

On the other side, requiring the receiver to operate at the maximum expected insolation levels also imposes a receiver design capability that on an annual basis is fully utilized only occasionally. The strategy chosen for the solar desalination receiver is to turn away heliostats when the solar input is too large. This occurs at 940 W/m^2 at the heliostat field design point. Again, Figure 8-16 indicates the annual performance penalty for this operation is small. Higher insolation can be utilized (and is utilized in the DESAL program) at conditions other than design point, such as when TES is not approaching the fully charged condition.

The monthly average solar resource derived from the 1978 Midland data is presented in Figure 8-17. Also presented are the 30-year average total solar resource (direct and diffuse) data. Although the data do not compare directly, their month-by-month distributions indicate that the 1978 data had more month-by-month variation in solar resource than would be expected in the long term.

8.2.5 Solar Availability Analysis and Results

The solar availability is an important concern in sizing the TES subsystem. An analysis was performed to determine the most likely amounts of time that solar insolation would not be available. Figure 8-18 illustrates the process utilized. The number and length of occurrences of solar outage (below 150 W/m^2) were tallied for each hour of the year. The resulting data is displayed in Figure 8-19. By analyzing all hours of the year, outage caused by both cloudiness and nighttime are counted. Figure 8-19 shows a peak near 1-2 hours and another at 12-13 hours. It is expected that the 12-13 hour peak is caused largely by nighttime outage, whereas the 1-2 hour peak is caused by

- **Histogram**
- **Fractional Occurrences**

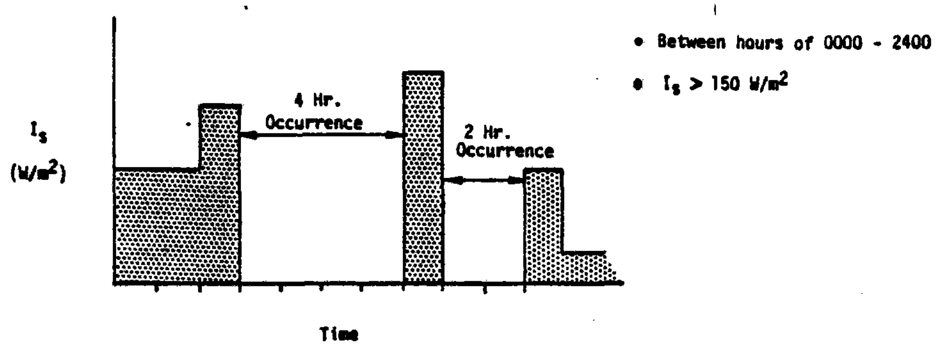
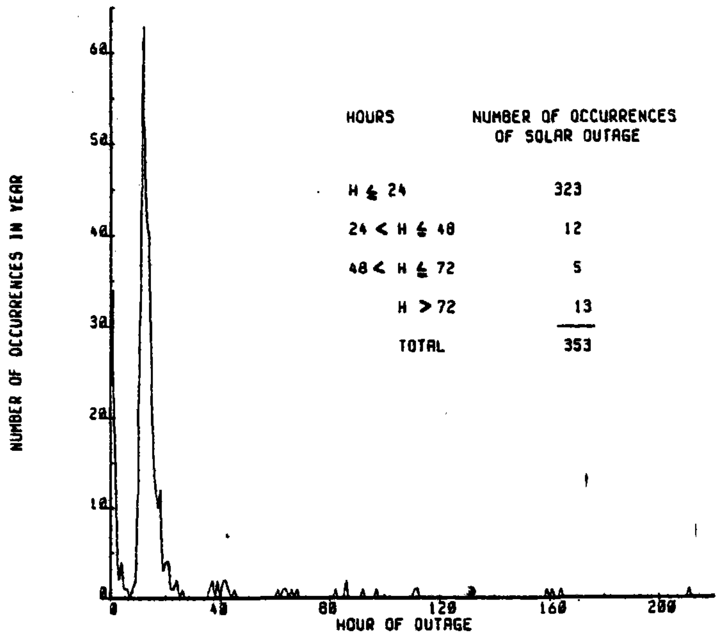


Figure 8-18. Solar Availability Analysis Schematic



HOURS	NUMBER OF OCCURRENCES OF SOLAR OUTAGE
$H \leq 24$	323
$24 < H \leq 48$	12
$48 < H \leq 72$	5
$H > 72$	13
TOTAL	353

Figure 8-19. Solar Availability Analysis Results

cloudiness. Solar outages as large as 210 hours were experienced. However, 323, or 91.3%, out of the total 353 solar outage hours were at or below 24 hours. These data indicate that storage times on the order of 24-48 hours would be most appropriate.

As an attempt to filter out the cloudiness effects from the nighttime effects, the average solar hours per clear day were calculated for each month of the year. The direct insolation data for each month was analyzed for the hours of potential solar operation. The number of hours of no insolation and for insolation at or below 150 W/m^2 were tallied for each month. The resulting data are presented in Table 8-3. As indicated, 1115 hours out of a potential 3777 were lost due to non-available insolation. This indicates a 70% "weather factor" from the 1978 Midland data. The long term "weather factor" for Midland is 75%.

8.3 PLANT SIZING

This subsection summarizes the major analyses employed to define the solar subsystem component sizes. Plant sizing is an iterative process requiring not only physical sizing but first order estimates of plant performance. The solar desalination plant sizing has been performed parallel to and interacting with the plant conceptual configuration selection, performance model synthesis, and annual performance calculations.

The plant sizing and subsequent plant performance analysis was largely influenced by two factors:

(1) The turbine selection
(2) The "stand-alone" plant specification

As presented earlier, the Saturn turbine was selected for the baseline electric power generation equipment. This turbogenerator set has an electric output of 650 - 750 kW for the solar desalination operation conditions. The peak water subsystem power demand is 512 kW. During charging of the TES system, the TES blower also must be powered from the generator output. This is accomplished by modularizing the RO subsystem allowing a stepping down of RO power consumption (and water production) to allow powering of the TES blower.

Table 8-3. Solar Availability Results — "1978 Midland" Data

Month	Avg. Solar Hour per Clear Day	Potential Solar Hours per Month	Hours* I_s=0	Hours* $I_s \leq 150$ W/m^2	Days with No I_s	Days with <0.1 kWh/m^2
Jan	8.44	262	138	186	8	9
Feb	9.36	262	64	134	2	2
Mar	10.41	332	83	120	7	7
Apr	11.40	342	31	87	1	1
May	12.10	375	38	120	0	0
Jun	12.36	371	176	215	9	9
Jul	12.10	357	19	71	0	0
Aug	11.40	353	128	198	6	6
Sep	10.41	312	145	208	7	7
Oct	9.36	390	72	128	2	3
Nov	8.44	353	142	186	6	9
Dec	8.06	250	79	129	3	4
Year	10.32	3777	1115	1782	51	57

*During daylight period

Assuming auxiliary plant power requirements approximately equal, the TES blower maximum power consumption is limited to about 500 kW with all the RO modules turned off. With commercially available blower efficiencies, the maximum TES blower power consumption for given pressure ratios dictates the TES maximum mass flowrate. The maximum receiver mass flow is the sum of the turbine and maximum TES mass flows. With the receiver maximum mass flow and inlet and outlet temperatures, the receiver "size" is given and subsequently the heliostat field solar power input requirements are specified. The ratio of the maximum receiver mass flow to the turbine mass flow roughly determines the solar multiple of the plant and in turn the maximum TES discharge time.

The turbine selection and the stand-alone plant requirement combine to limit the maximum operational time achievable with the plant. Increases in receiver/heliostat field size would be ineffective since there is no additional mass flow source with which to maintain the receiver at or below maximum outlet temperature. The maximum receiver flow rate limits the maximum TES charge rate so that increases in TES medium mass would provide rapidly diminishing benefits in extended plant operation.

Using the interactions discussed above, the plant sizing was accomplished by obtaining first order annual performance data based on four clear seasonal days and long term expected weather factors. Analysis of these data led to a definition of a solar subsystem design point. This design point corresponded roughly to the condition that maximum TES compressor power consumption equalled the peak RO subsystem power demand. This correspondence was accomplished iteratively. The various components were sized and performance and design point recalculated until the above mentioned correspondence was achieved. With this final design point definition, the physical sizing of the heliostat, receiver, and storage subsystems proceeded. The details of this sizing process are described in the following paragraphs. In the interest of brevity, the results of the "final iteration" are emphasized.

8.3.1 Clear Day Analysis

In calculating the performance of an "average" clear day with a storage integrated solar thermal system, the initial energy content or thermocline of the TES system affects the results. This effect becomes more important as the amount of TES increases. For example, the performance of a plant would be greatly different if a single clear day had been preceded by several completely overcast days. For TES discharge times of 24 to 48 hours as envisioned for this plant, it is impossible to determine apriori the initial TES thermocline. The approach chosen for the clear day analysis was to begin the TES system at a uniform TES medium temperature (316°C) (600°F) and repeat the clear day ambient data back-to-back to simulate several days operation. When the thermocline approached a periodic behavior, the performance of the last day was assumed to be appropriate for the average performance. This approach is illustrated in Figure 8-20, a plot of TES system energy content versus time. The charging and discharging behavior beginning from an initial condition is evident. After several repetitions of the same clear day ambient data, periodic behavior is approached.

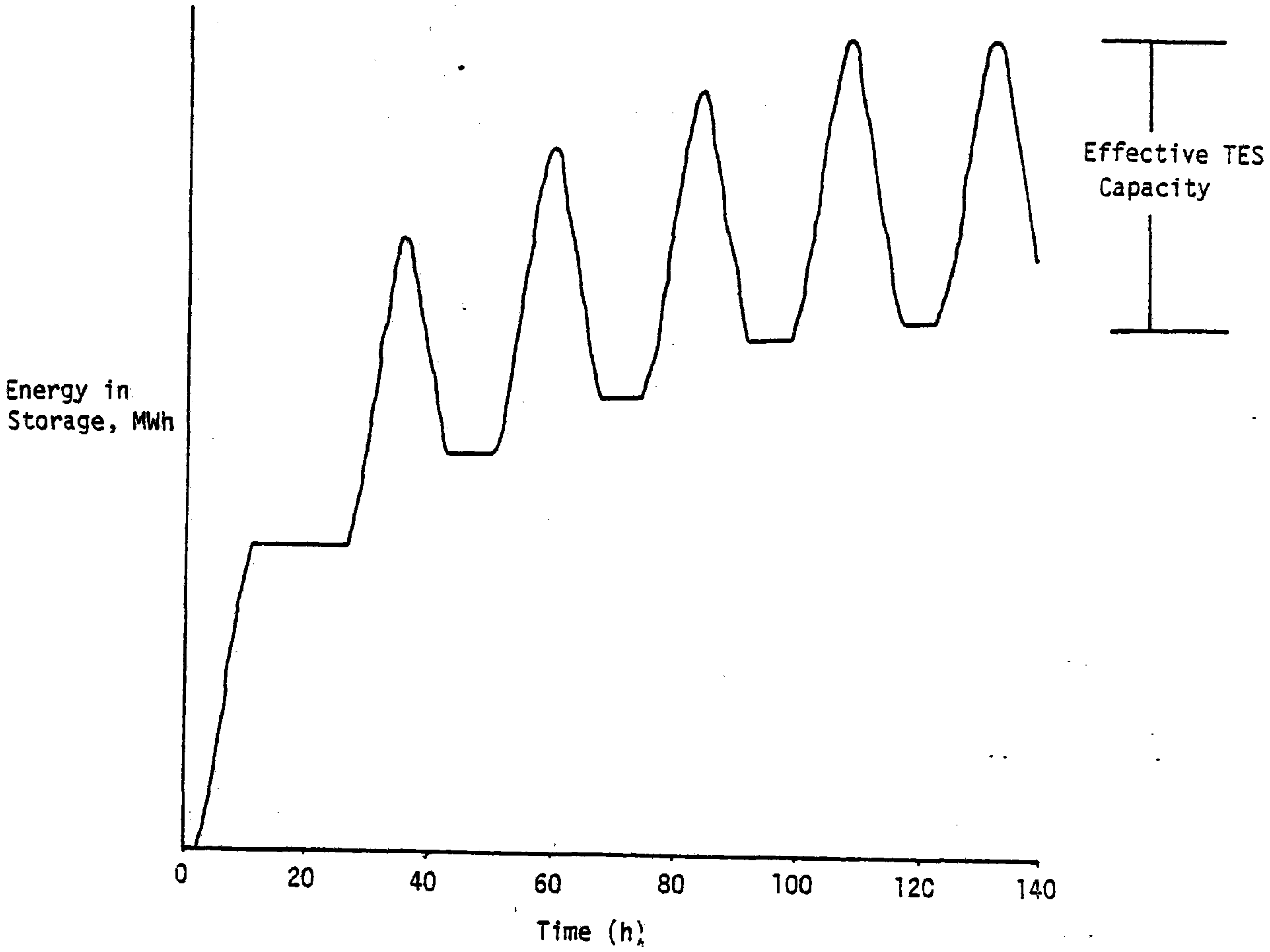


Figure 8-20. TES Medium Warm-up Cycle

The results from four clear seasonal days' analyses are summarized in Table 8-4. For the spring, summer, and fall days, the TES system became fully charged in the afternoon, resulting in a turning away of heliostats and a reduction in total solar energy input to the receiver. The fully charged condition was reached earliest for the summer day, then by the fall day and finally in late afternoon on the spring day. The combination of fully charging TES and relatively warmer ambient temperatures reduces summer and fall gross electrical outputs and in turn daily water productions. However, the annually averaged water production rate is 8047 m^3/d, which is close to the 8041 m^3/d required for at least 1.8 x 10^6 m^3 yearly water production.

8.3.2 Solar Subsystems Design Point Definition

The clear day data were also examined on an hour-by-hour basis to determine the maximum solar input condition to the receiver. The resulting maximum was 14.9 MW occurring on the winter day. Assuming this solar input is required at the design insolation level of 940 W/m^2 at solar noon on the winter solstice, the heliostat field could be sized.

The receiver design point must accommodate the maximum receiver mass flow rate. At this mass flow the receiver subsystem pressure drop would be the highest. For a given peak solar input level, the maximum receiver mass flow occurs when the temperature difference across the receiver is a minimum. For a given maximum receiver outlet gas temperature, the maximum mass flow occurs at maximum receiver inlet temperature. The maximum receiver inlet temperature occurs when the TES subsystem is nearly fully charged. Therefore, the solar subsystem design point occurs at solar noon, winter solstice for the TES approaching the fully charged condition. This condition is illustrated in Figure 8-21. The turbogenerator produces 654 kW with 88 kW consumed by the balance of plant parasitics (heliostat field, lighting, etc.) and 566 kW consumed in the TES compressor. As expected, the 566 kW is on the same order as the 512 kW peak RO system demand.

8.3.3 Heliostat Field Sizing

The primary analysis tool used for determining the size (quantity of heliostats) and configuration of the collector field was the DELSOL computer

Table 8-4. Clear Day Results

- $\eta_{RCR} = 0.85$ (conservative)
- $m_{TES} = 2.04 \times 10^6$ kg
- 436 Heliostats

Day	Solar Energy Resource (kWh/m^2-d)	Solar Energy Input to Receiver (MWh)	Gross Electricity Produced (MWh)	Total Water Production (m^3)
Spring (day=80)	10.7	94.2	16.7	8750
Summer (day=172)	11.3	85.1	14.7	8229
Fall (day=264)	9.5	87.4	14.7	7917
Winter (day=355)	7.7	92.6	14.8	7292
			Average =	8047

$\omega_{net} = W_T - W_c = (5.6)(1004.836)\left[.9(788-467) - \frac{(245-13)}{.9}\right] = 31.3 \text{ KW}_e$

289 — 258

31.1

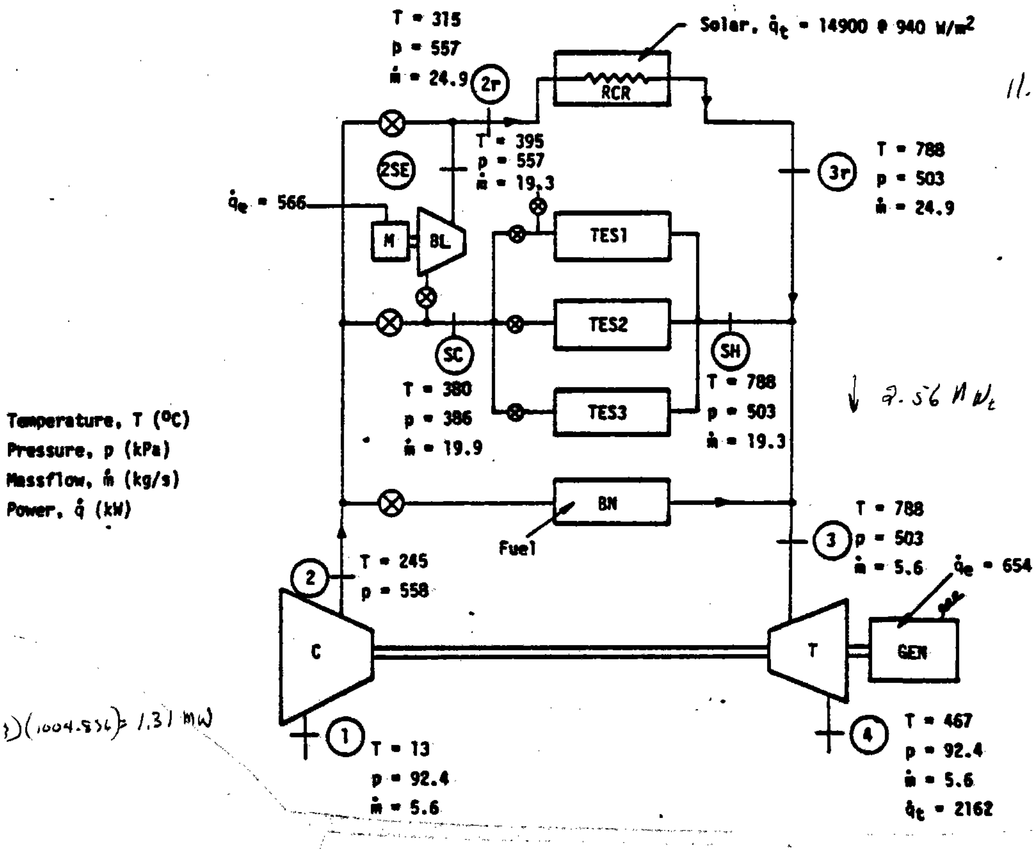


Figure 8-21. Solar Desal Design Point

11.8 MW .794

$\frac{5.6}{24.9} = .225$

↓ 2.56 MW$_t$

$5.6(788-467)\ 1004.836 = 1.81$ mWt

or 501 KW$_e$

$5.6(245-13)(1004.836) = 1.31$ MW

$5.6(467-13)(1004.836) = 2.55$ MW

code [4]. This code is one of several existing programs for analysis of central receiver heliostat fields; it is a good choice for iterative conceptual design because it is easy to use and relatively inexpensive in terms of computer costs.

DELSOL has options for automatically optimizing collector fields and receiver aperture elevation based on cost. However, the cost algorithms are not appropriate to smaller fields. The field for the present study was optimized by hand, based on experience and field configurations from previous work. The performance analysis computed by DELSOL compares well with results from other computer codes. Results indicate that a hand optimization can result in significantly smaller collector fields, for equivalent performance, compared to the automated optimization. A new version (DELSOL II) which is more appropriate to small collector fields became available after the completion of this analysis and was used in the pilot plant analysis.

The collector field developed and analyzed with the help of the DELSOL code was shown in Figure 6-7. The hour-to-hour efficiency of this field computed for one day of each month is used in the system performance model as part of determining overall plant performance. Hourly collector field efficiency for the solstices and equinox are shown in Figure 8-22. Solar collection initiation or cutoff for each clear day is at a sun angle of 10° above the horizon.

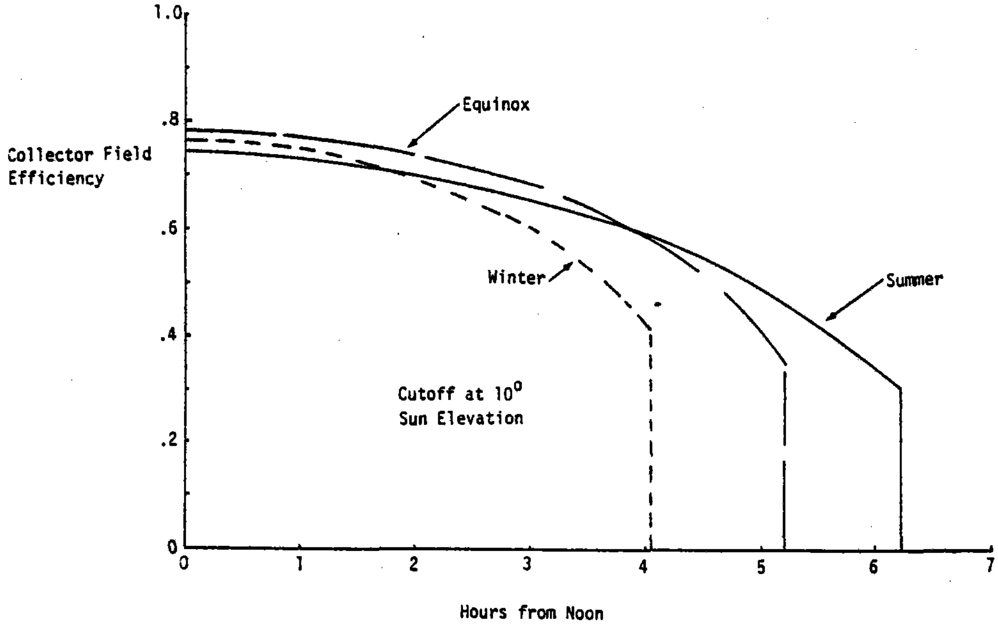


Figure 8-22. Daily Collector Field Efficiency

The collector field efficiency at any given time is the integrated effect of the efficiencies in each sector of the field. These efficiencies are all variable with time and location within the field. Figure 8-23 shows the factors which contribute to the efficiency of the total field on an annual average basis. These factors are:

- Insolation - Incident energy assuming heliostats are normal to sun rays;
- Reflectance - Expected average reflectance of the heliostat mirrors;
- Cosine Losses - Effective area loss because angle of incidence/ reflection on mirrors is not normal to the mirrors;
- Shadowing - Effective area reduction caused by shadows from adjacent heliostats;
- Blocking - Effective area reduction caused by reflected rays hitting adjacent heliostats;
- Atmospheric Alternations - Absorption and scattering of reflected energy before reaching receiver;
- Spillage - Energy incident on the receiver that misses the aperture.

Some of these factors depend on dimensions and performance of the heliostat. The analysis is based on the production version of the BEC Second Generation Heliostat; test data from the prototype versions has been used when possible, other parameters are taken from the performance verification.

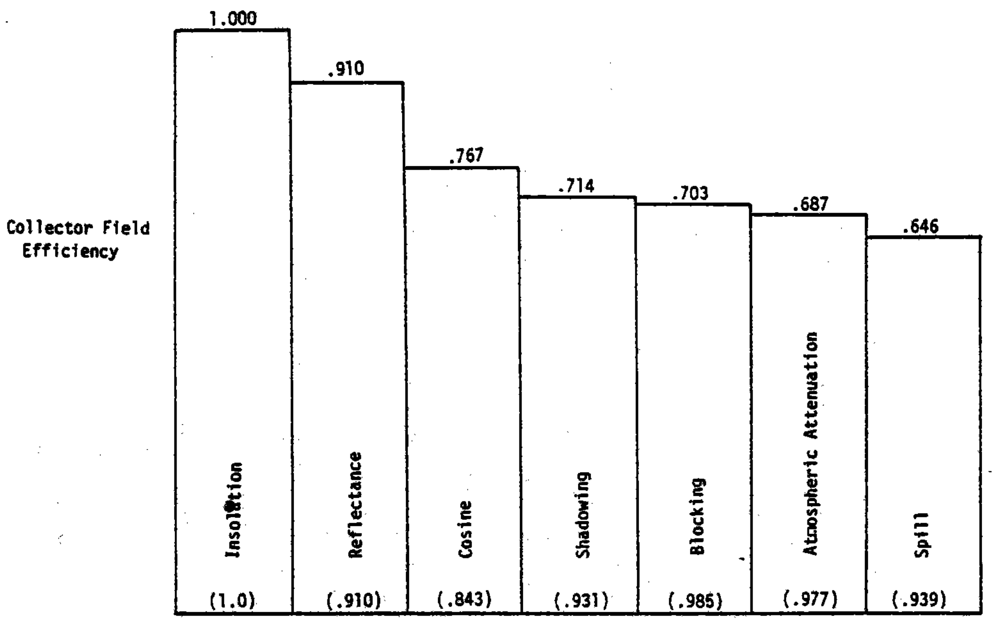


Figure 8-23. Yearly Average Collector Field Efficiency

8.3.4 Receiver Sizing

Table 8-5 presents a comparison between the BEC/United States Gypsum (USG) [5] and commercial desalination plant (Desal) receiver operating conditions. As indicated earlier, the two receivers are similar in design and in operating conditions. Notable differences are in the operating pressure and maximum tube temperatures.

Table 8-5. Comparison of Receiver Operating Conditions

	USG RCR	DESAL RCR
Inlet Pressure (kPa)	334	557
Pressure Loss	11%	10%
Inlet Temperature (°C)	227	315
Outlet Temperature (°C)	724	788
Total Mass Flow (kg/sec)	23.1	24.9
Maximum Tube Temperature (°C)	924	877
Combustor/RCR Arrangment	Series	Parallel

The approach used in sizing the Desal receiver was to scale the BEC/USG receiver design to the Desal conditions. The BEC/USG receiver design was accomplished with a considerable amount of detailed thermal analyses. These included solar flux mapping, cavity thermal radiative interchange, and tube thermal and structural nodal analysis. The thermal scaling relationships are presented as an appendix. The receiver scaling sensitivities are presented in Figure 8-24.

The non-dimensional receiver characteristic length is seen to be influenced by operating condition parameters in differing ways. Increases in pressure, pressure drop fraction, and tube-to-gas temperature difference decrease receiver size, whereas increases in average fluid gas temperature, mass flow rate, tube spacing and outlet-to-inlet gas temperature difference increase receiver size. Using these types of relations, the receiver was sized. The results are contained in the system specification and have been summarized earlier in Section 5.

The overall receiver size, mass, and cost have been determined. First order thermal analyses have determined the heat exchanger panel tube number, spacing

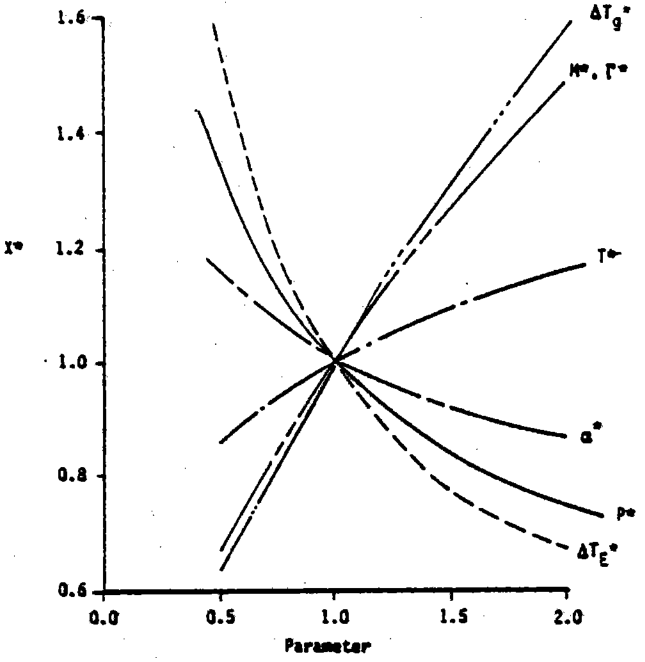


Figure 8-24. Receiver Scaling Sensitivities

and diameter. Results from parallel air receiver/gas turbine integration efforts such as the BEC/EPRI Full System Experiment project may impact the commercial Desal receiver heat exchanger design. Refinements in tube number, spacing and diameter may be required during detailed receiver design. However, these refinements are not expected to influence the overall receiver size, mass or cost.

8.3.5 Thermal Energy Storage Sizing

The TES sizing methodology used in this project is illustrated in Figure 8-25. As indicated earlier, choice of the turbine and its accompanying electrical production capability imposes some limitations on the ability to charge storage. After selection of the system design point, the heliostat and receiver subsystems could be sized. Preliminary annual performance calculations indicated the need for greater than one day's thermal storage capability to reduce the requirements for plant starts. Also, data from the solar availability or outage analysis indicated a storage time of 24-48 hours would be appropriate.

The TES system was sized by beginning with a storage medium mass larger than expected to be required based on preliminary performance calculations. A clear day analysis was performed for the winter solstice day. The clear day was followed by several days without insolation until the TES system was

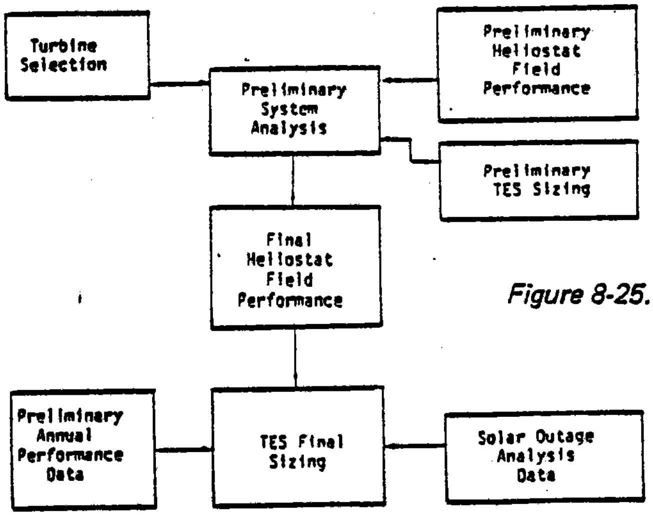


Figure 8-25. TES Sizing Methodology

depleted. The process was repeated with smaller TES masses. It was assumed that the relative clear day behavior of the differing TES medium sizes would be representative of the relative annual behavior. As indicated earlier, RO modules are switched off as required during TES charging to provide electrical power to run the TES compressor. During discharge, all four RO modules are initially operating. As TES is depleted, the turbine inlet temperature decreases, reducing the gross electrical output available. When there is not enough power to operate all four modules, one module is switched off and water production continues on three. This operation continues for three then two then one RO module. TES is considered depleted or "empty" when there is not enough electrical output to operate at least one RO module. Depending on how long insolation is unavailable, there remains enough TES energy at the "empty" point to return the gas turbine to the "no-load" condition during plant startup.

Table 8-6 presents the results from the TES sizing analysis. Presented in Table 8-6a are gross electricity and water production for the clear day and until the TES system was depleted. Figure 8-26 illustrates TES energy level through the entire process for the 1.68 x 10^6 kg case. As indicated, the hours of continuous operation from TES discharge are from 41 hours to 33 hours. A reduction of 0.36 x 10^6 kg from 2.04 x 10^6 kg is seen to reduce the TES discharge time from 41 to 39 hours, whereas a further reduction of 0.36 x 10^6 kg reduces the discharge time to 33 hours. Both the gross electrical production and water production indicate similar relatively small performance reductions in going to the 1.68 x 10^6 kg medium mass value, whereas a further reduction to 1.32 x 10^6 kg produces relatively larger performance losses. Because of these effects, the 1.68 x 10^6 kg value was considered the "knee of the curve" and was chosen as the most appropriate for the TES system.

Table 8-6.a TES Sizing Results

- Evaluation of TES Mass on Day = 355 (Winter) Performance
- η_{RCR} = 87.5%
- Clear day followed by no insolation until TES is depleted

M_{TES} (10^6 kg)	2.04	1.68	1.32
Gross Electricity - Solar (kWh)	5691	5691	5691
Gross Electricity - TES (kWh)	22618	22076	20144
Gross Electricity - Total (kWh)	28309	27767	25835
Water Produced - Solar (m^3)	2083	2083	2083
Water Produced - TES (m^3)	14957	14773	14092
Water Produced - Total (m^3)	17040	16856	16175
Hours of TES Continuous Operation (h) *	41	39	33

* At least one RO operating

Table 8-6b. Annual Performance in TES Size

TES Mass (10^6 kg)	Annual Water Production (10^6 m^3)	Operation Time, k			Produced Gross Electricity (MW-h)	Process Electrical Consumption (MW-h)
		Total	Direct Solar	TES		
1.32	1.818	6540	2440	4100	3538.7	2234.0
1.68	2.129	6851	2440	4411	3678.1	2615.7
2.04	1.784	6799	2440	4359	3543.2	2191.7

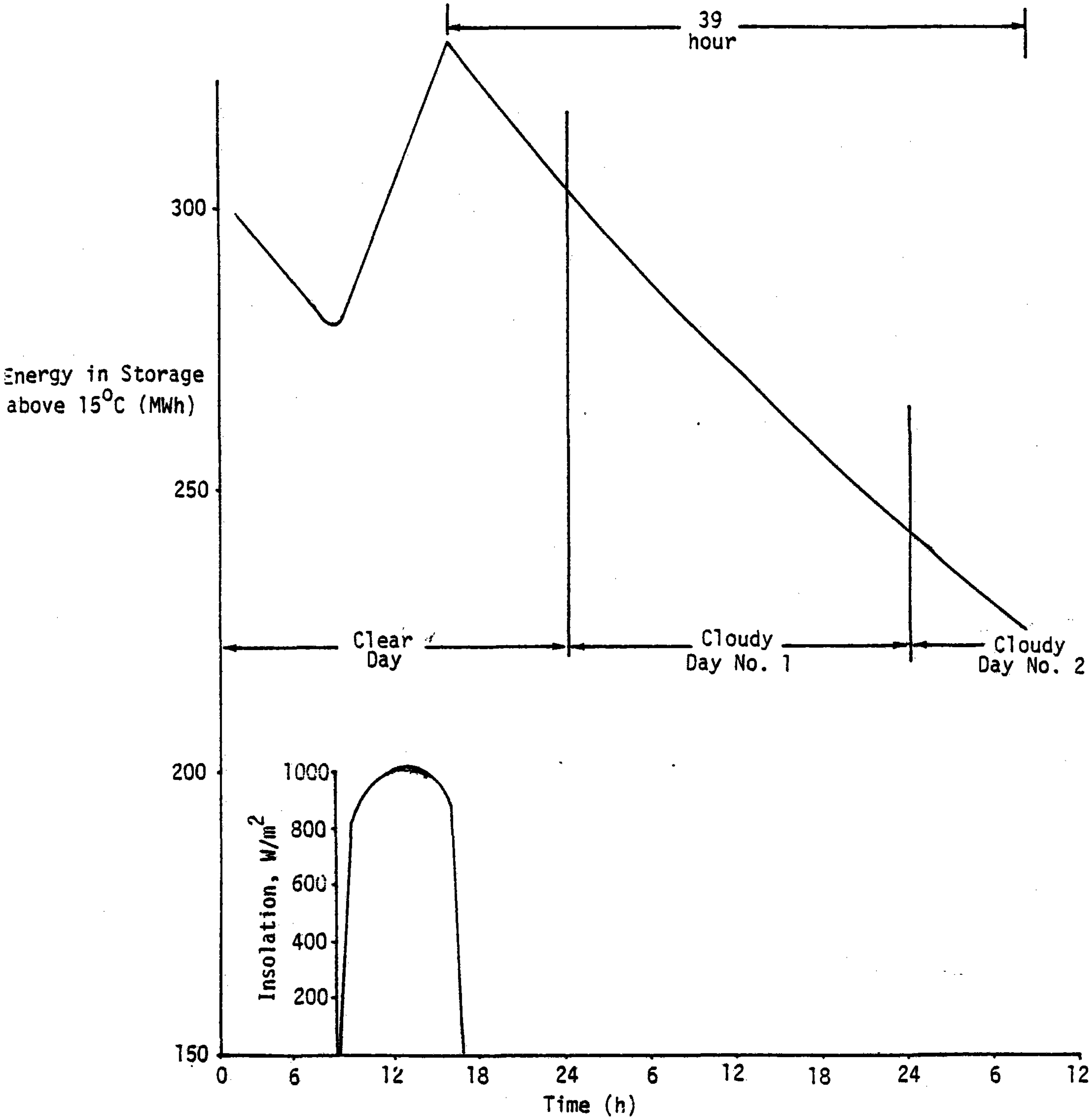


Figure 8-26. Energy in Storage Profile

Complete annual performance calculations were subsequently done; results are summarized in Table 8-6b. These results support the earlier conclusion that the 1.68 x 10^6 kg TES mass was optimal. Water production peaks sharply with TES size, so cost variation with TES size is not expected to move the optimum much from the size for peak water production.

8.4 PLANT ANNUAL PERFORMANCE

The solar desalination plant system analysis model (DESAL) was used to investigate the hour-by-hour performance for the selected plant configuration and sizes. The following subsections present the results from that analysis.

8.4.1 Monthly and Yearly Performance Predictions

Table 8-7 and 8-8 summarize the monthly and yearly performance results using the 1978 Midland ambient data as defined in Section 8.2. These data consider the solar availability as contained in the hour-by-hour insolation data. The data do not include plant availability (plant outage due to scheduled and unscheduled maintenance, etc.). As indicated, the plant operated for a total of 7220 hours and produced 2.05 x 10^6 m^3 of water.

7851 2.129

In order to predict the 30-year average annual performance, this "1978 Midland" data needs correction to the 30-year average insolation trend. The "1978 Midland" solar source data are 13% below average at that location. Multiplying the annual water production of 2.129 x 10^6 m^3 times the 1.13 weather correction factor times the minimum plant availability of 0.82 yields the minimum expected 30-year average water production of 2.0 x 10^6 m^3. Since the minimum water production expected is in excess of the 1.8 x 10^6 m^3 value, the water production specification has been met.

There is some question as to the most technically correct method of correcting to long term average performance. This is discussed further in Volume II Section 17.6. The more conservative method discussed there yields a 1.09 correction factor. Section 7 shows the plant availability estimate for the selected system is 0.91. Basing the water production on that availability value and the 1.09 correction factor results in a predicted annual water production capability of 2.1 x 10^6 m^3.

Month	Water production ($10^6 m^3$)	Operation time (hr)			Insolation MWh			RCR heat absorption (MWh)
		Total	Direct solar	TES	Collector field	Max avail at RCR	Actual input at RCR	
J	0.145	473	132	341	2,345	1,613	1,480	1,295
F	0.181	503	181	322	2,977	2,024	1,858	1,626
M	0.192	598	207	391	3,359	2,252	2,022	1,769
A	0.264	720	277	443	4,600	2,884	2,534	2,217
M	0.205	666	242	424	3,993	2,394	2,153	1,884
J	0.157	535	202	333	3,128	1,869	1,700	1,488
J	0.246	734	311	423	5,007	2,977	2,452	2,146
A	0.145	545	202	343	3,042	1,868	1,740	1,523
S	0.101	432	163	269	2,330	1,561	1,459	1,277
O	0.205	641	214	427	3,549	2,397	2,141	1,873
N	0.102	413	127	286	2,085	1,443	1,330	1,164
D	0.186	591	184	407	3,105	2,131	1,958	1,713
Year	2.129	6,851	2,440	4,411	39,520	25,414	22,827	19,974

- **Adjustment for 30-year average**

$2.129 \times 1.09 \times 0.91 = 2.11 \times 10^6 m^3$

("1978 data") x (30 year factor) x (Plant availability)

Table 8-7. Solar Desal Plant Annual Performance

Month	Gross electrical production (MW -h)	Process electrical consumption (MW -h)	Parasitics		
			Heliostat field (MW -h)	TES pump (MW -h)	Plant pump (MW -h)
J	261.4	178.6	7.6	19.4	55.8
F	303.9	222.0	7.1	24.4	50.4
M	328.3	235.6	7.9	29.0	55.8
A	426.0	324.1	7.8	40.1	54.0
M	343.7	252.2	8.1	27.6	55.8
J	276.9	193.4	7.6	21.9	54.0
J	401.2	302.5	8.1	34.8	55.8
A	262.7	177.8	7.9	21.2	55.8
S	203.6	123.6	7.5	18.5	54.0
O	348.3	251.7	7.9	32.9	55.8
N	203.9	125.2	7.3	17.4	54.0
D	318.2	229.0	7.8	25.6	55.8
Year	3678.1	2615.7	92.6	312.8	657.0

Table 8-8. Solar Desal Plant Annual Performance 1062.4

8.4.2 Representative Hourly Performance Data

Figures 8-27 to 8-29 illustrate results from the plant performance system analysis model for four days in April. Figure 8-27 presents the daily insolation profile. April 14 is seen to be a relatively clear day followed by an intermittent insolation day representative of the passage of several cloud banks. April 16 contained no direct insolation indicating complete cloud cover. Finally, April 17 is another clear day. The resulting plant component mass flows are illustrated in Figure 8-28. The turbine mass flow is seen to be nearly constant, affected only by ambient temperature variations. The receiver mass flow follows approximately the available insolation. The TES mass flow illustrates first charging with excess receiver heat absorption and equal to turbine mass flow during TES discharge. Figure 8-29 presents the TES hot and cold fluid temperatures and the TES energy level. The TES hot fluid temperature is equal to the turbine inlet temperature. During TES discharge, the cold TES fluid temperature is equal to the main compressor exit temperature. The TES energy level is measured relative to a uniform 15.6°C (60°F) medium temperature. The charging/discharging behavior is clearly evident. The TES system becomes fully charged at about the 320 MWh energy level. The TES system carries the plant through the intermittent insolation day followed by the completely cloudy day, until the clear day returns on April 17.

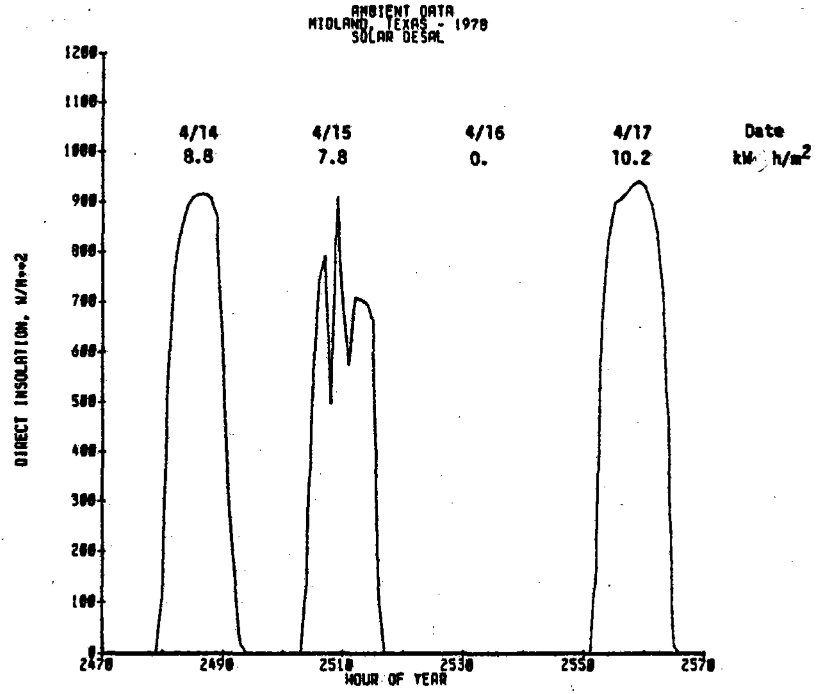


Figure 8-27. Insolation Profiles for April 14-17

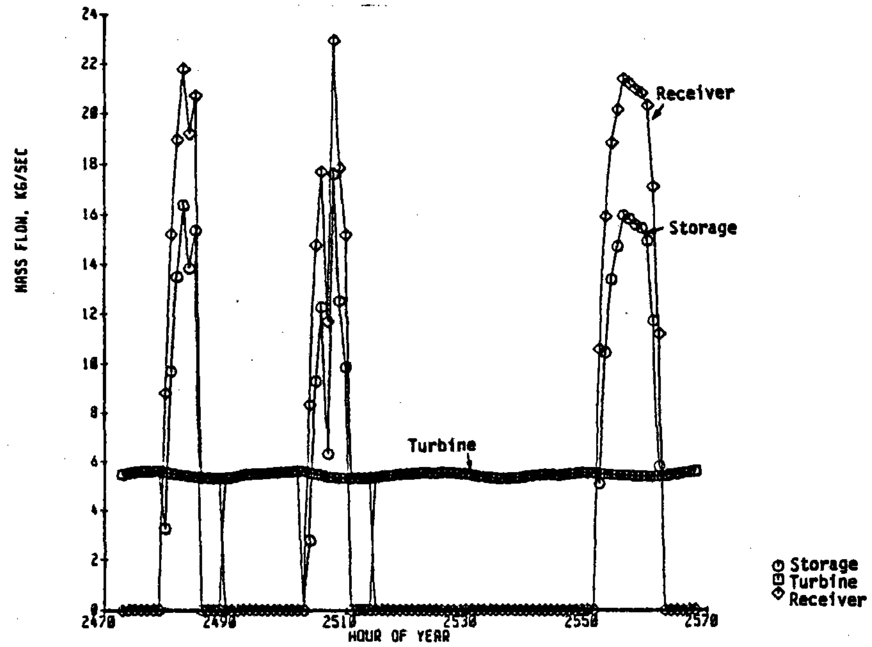


Figure 8-28. Mass Flows for April 14-17, 1978

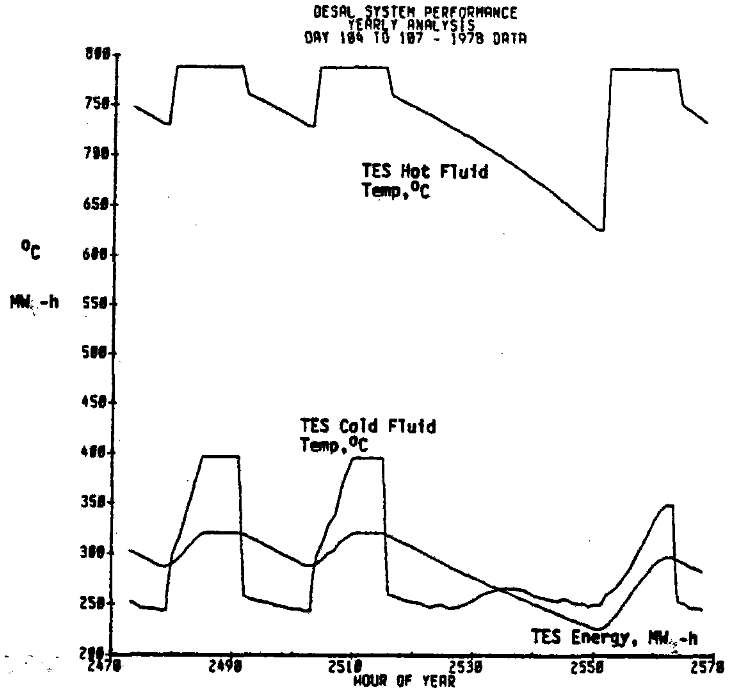


Figure 8-29. TES Fluid Temperatures and Energy Level for April 14-17, 1978

Figures 8-30 to 8-32 illustrate similar data from a series of days in June where the TES is depleted. The insolation profiles show several clear days followed by several overcast ones. The TES system is able to carry the plant for about 50 continuous hours from the loss of insolation on the fourth day in the series.

Figures 8-33 to 8-35 illustrate data for the month of April, the best operation month based on the 1978 Midland data. Figure 8-33 illustrates the month's insolation profiles. A number of clear day profiles are indicated, however, some cloudy effects are also evident. Figure 8-34 illustrates the TES energy level. The TES is seen to cycle through a relatively narrow range except when called upon to cover periods of longer cloudiness. The daily solar resource value is illustrated in Figure 8-35. The monthly daily average of 7.5 kWh/m^2-d is close to the winter design day value of 7.7 and the annual mean of 7.0.

Data for the poorest operating period, November, are illustrated in Figures 8-36 to 8-38. November insolation profiles show some clear days but several periods of extended cloudiness are present. The TES energy levels of Figure 8-37 show the TES continually at the low portion of the TES capacity. The solar resource data of Figure 8-38 show the month as a poor month for direct insolation. The daily average solar resource of 3.4 is significantly below the mean and average annual values.

8.4.3 Plant Outage and Startups

6857

Table 8-7 showed the plant operated 7220 hours on solar and/or TES. The remaining 1540 hours of plant outage were distributed over the year as shown in Figure 8-39. The number of occurrences of a particular hour of plant outage is given in Figure 8-40. Also presented is a monthly tally of hours of plant outage. The fractional distribution of plant outage is presented in Figure 8-41. Ninety-five percent of all the plant outages are 50 hours and less.

A plant startup, from the system analysis model's point of view, is required

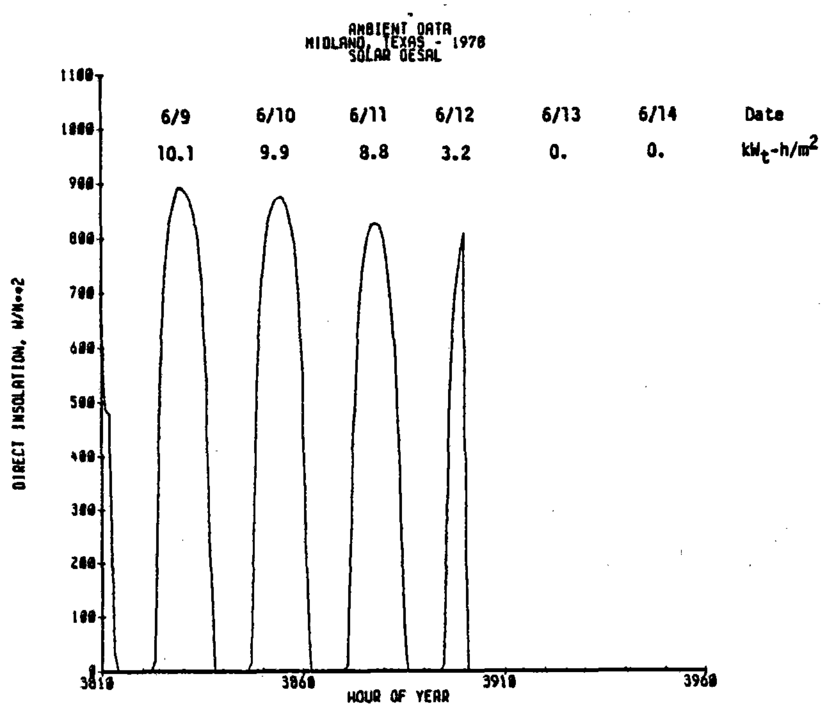


Figure 8-30. Insolation Profiles for June 9-14, 1978

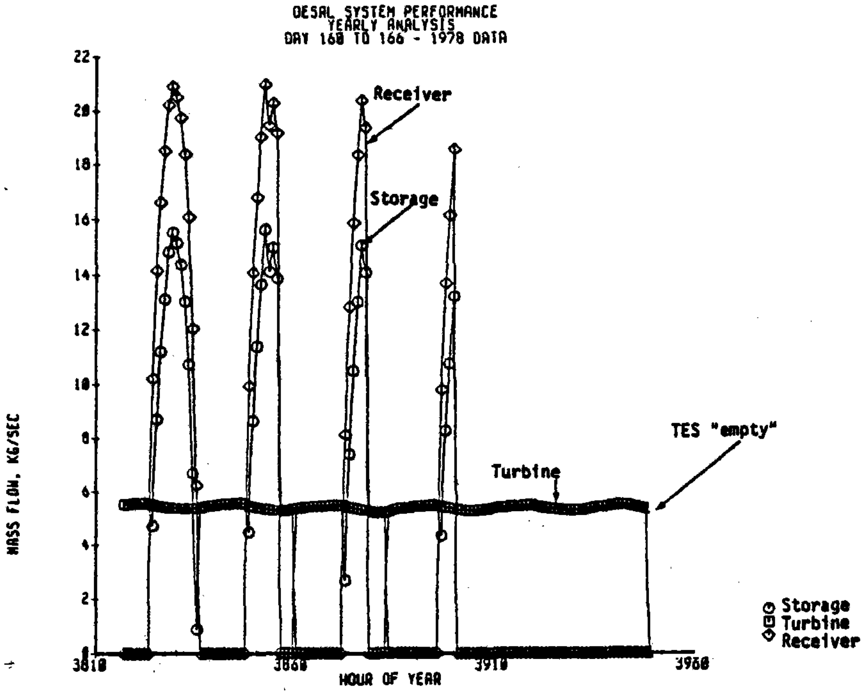


Figure 8-31. Mass Flows for June 9-14, 1978

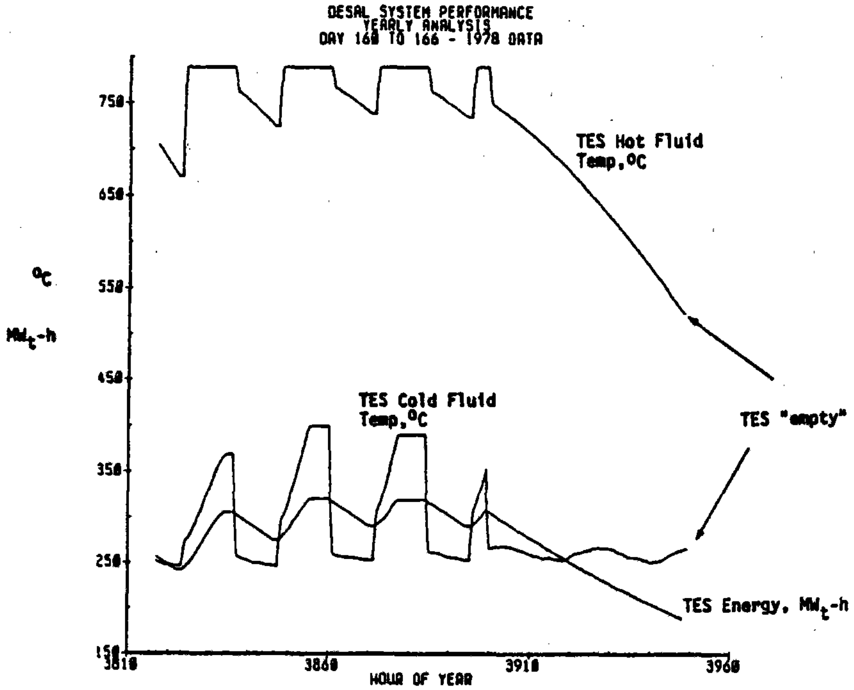


Figure 8-32. TES Fluid Temperatures and Energy Level for June 9-14, 1978

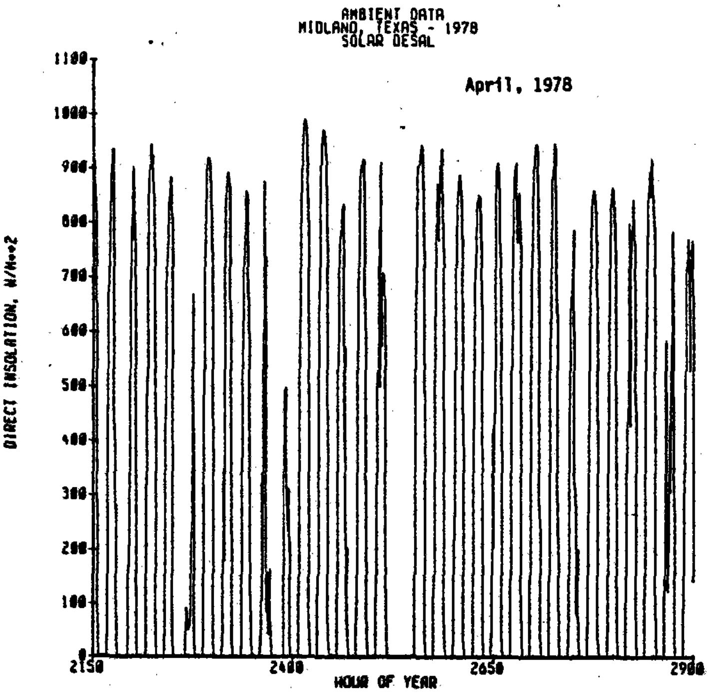


Figure 8-33. Insolation Profiles for April, 1978

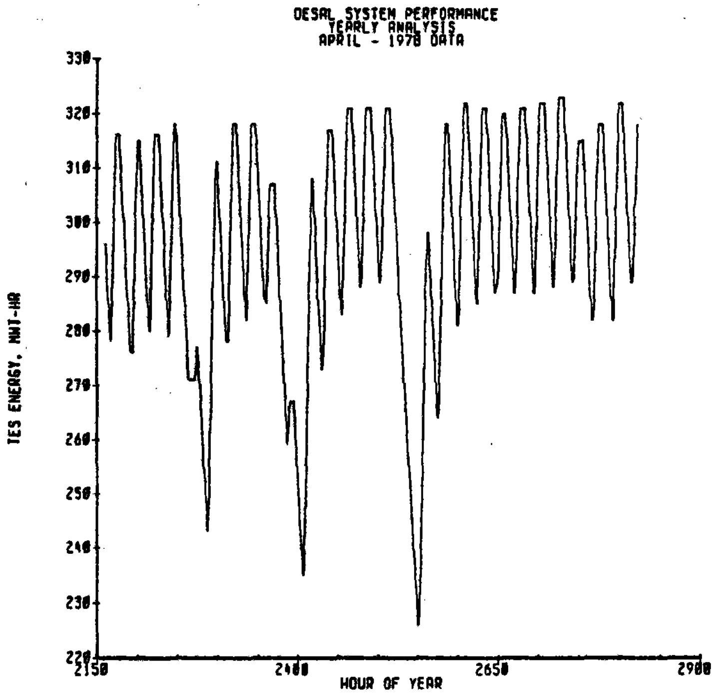


Figure 8-34. TES Energy Level for April, 1978

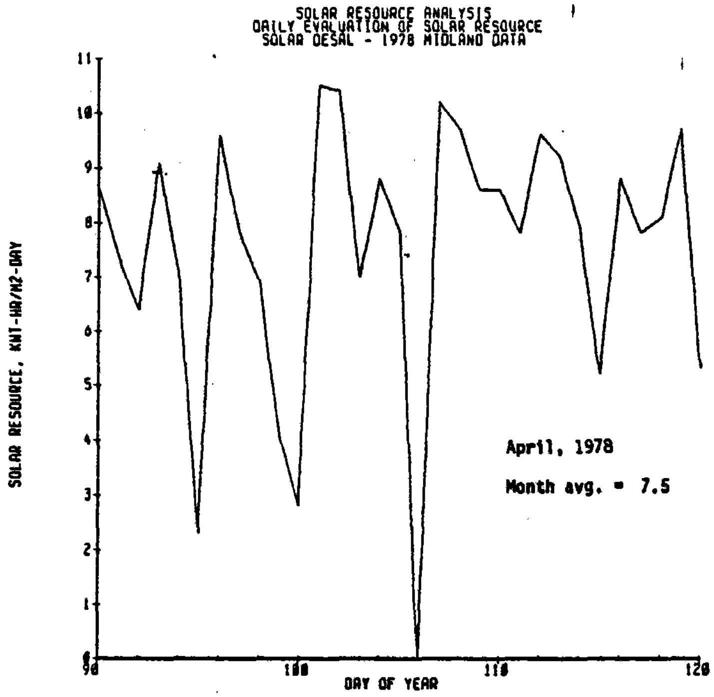


Figure 8-35. Daily Solar Resource Value for April, 1978

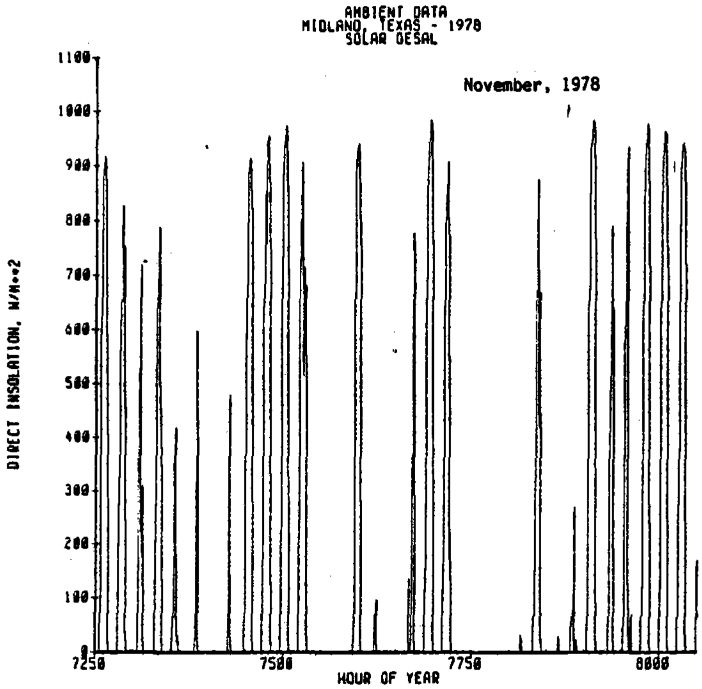


Figure 8-36. Insolation Profiles for November, 1978

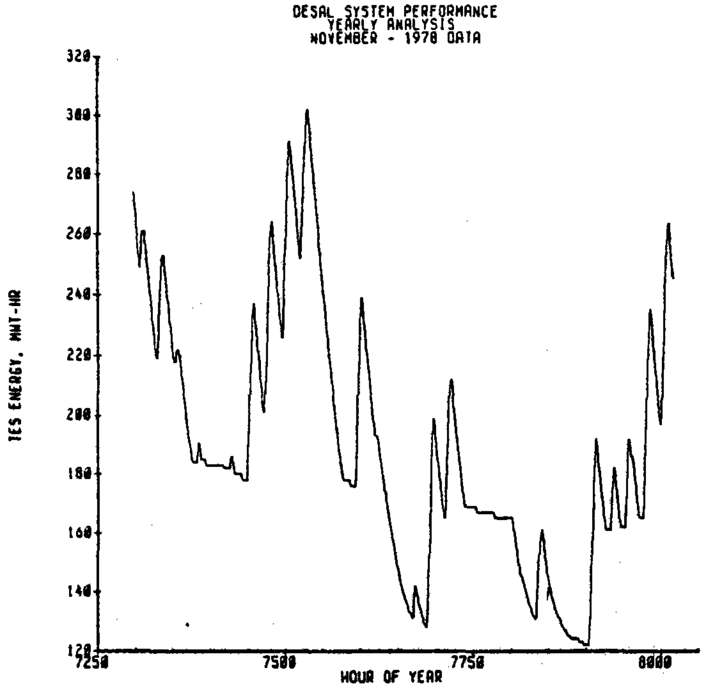


Figure 8-37. TES Energy Level for November, 1978

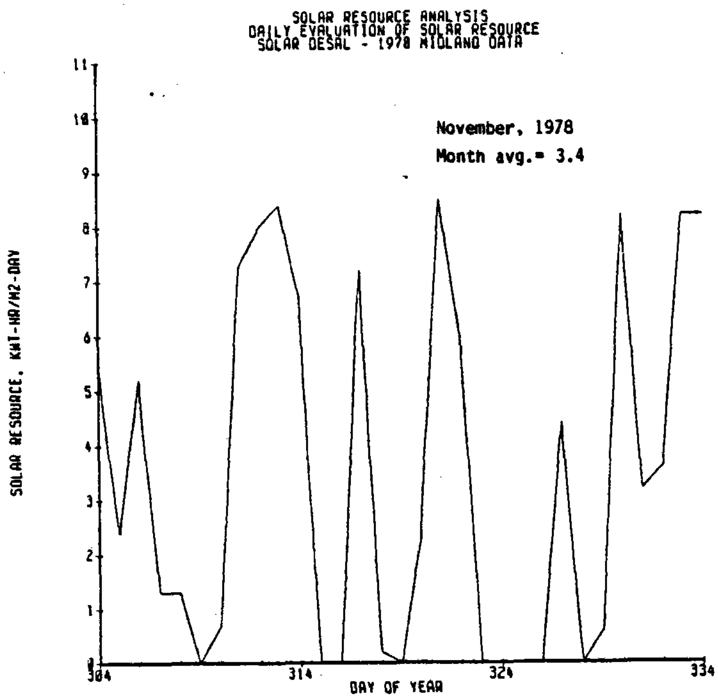


Figure 8-38. Daily Solar Resource Value for November, 1978

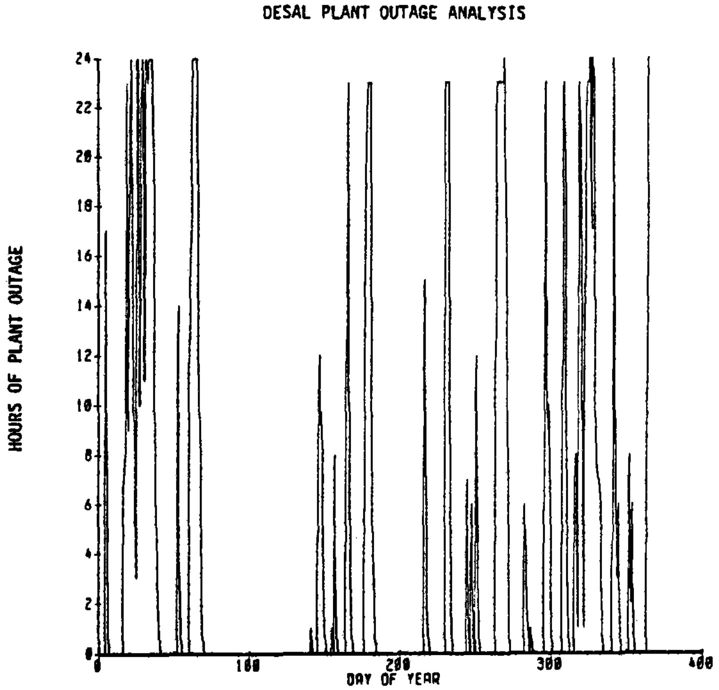
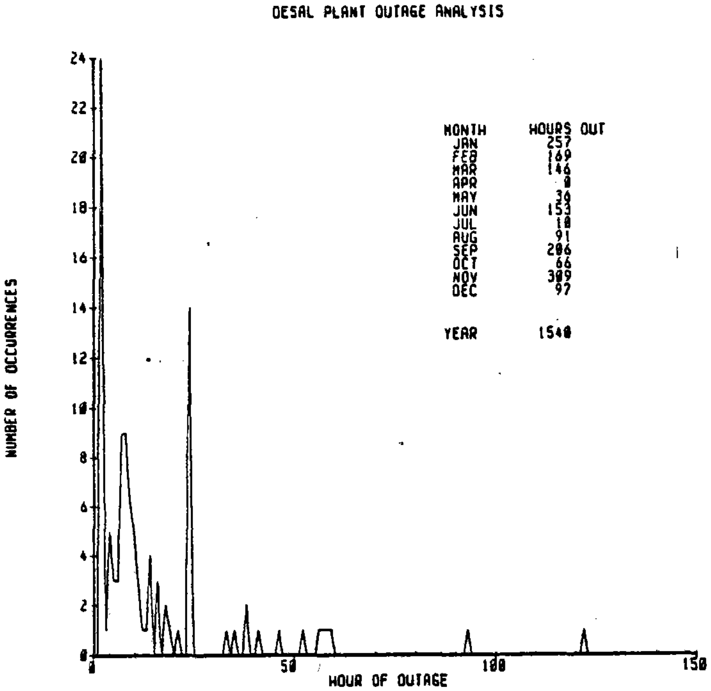


Figure 8-39. Plant Outage Yearly Distribution



MONTH	HOURS OUT
JAN	257
FEB	169
MAR	146
APR	0
MAY	36
JUN	153
JUL	10
AUG	91
SEP	206
OCT	66
NOV	309
DEC	97
YEAR	1540

Figure 8-40. Plant Outage Histogram

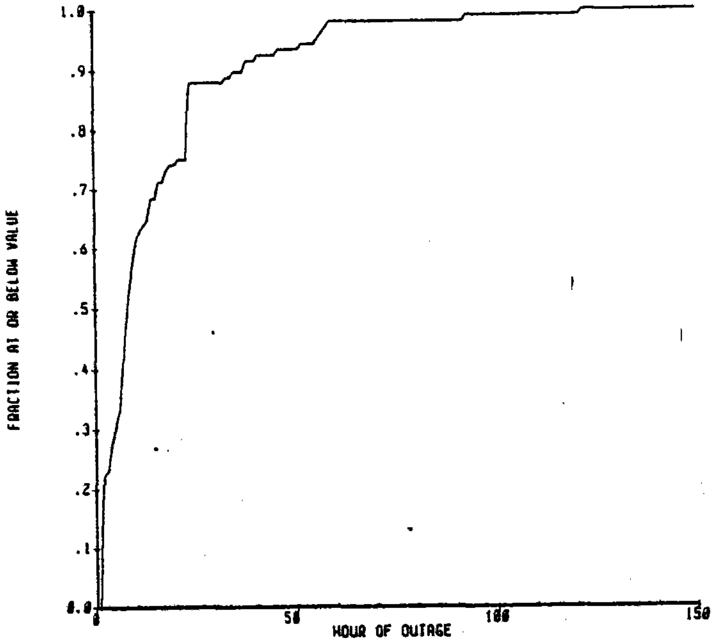


Figure 8-41. Plant Outage Fractional Distribution

whenever the TES is at the "empty" level and usable insolation becomes available, regardless of what hour of the day the usable insolation occurs. This process will produce a maximal number of required plant starts. Figure 8-42 presents a yearly distribution of plant starts as predicted by the system analysis model. A monthly summary of plant starts is presented in Table 8-9. No plant starts are required for April, whereas November required 21. 10? Anticipation of weather patterns should allow an experienced plant operator to avoid a significant number of plant starts, especially during periods of poor insolation characteristics, such as November.

8.4.4 Plant Efficiency

Predicted design point and annual performance in the form of a plant efficiency train are shown in Figure 8-43. The design point condition is based on all power being consumed by maximum TES charging, thus process (water production) efficiency under this condition is zero. For the annual performance, greater detail of the right end of the efficiency train is shown in Figure 8-44. The annual efficiency train shows that 39520 MWh of solar energy (based on projected area of the heliostats) is input to the system. Based on the predicted annual product water output of 2.1×10^6 m^3, the solar energy requirement for desalted water production with this system is 18.8 kWh/m^3.

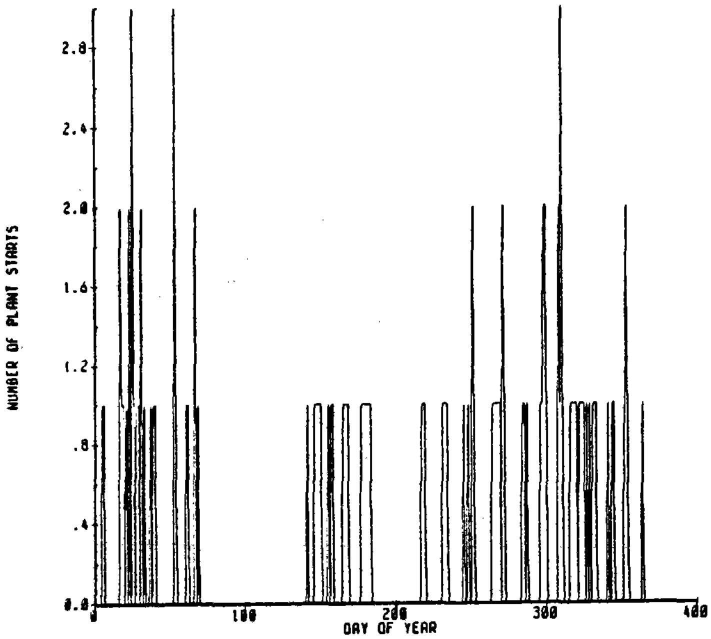


Figure 8-42. Plant Start-up Yearly Distribution

Table 8-9. Start-up Analysis

Month	Hours of plant operation	Required plant starts
J	473	6
F	503	5
M	598	2
A	720	0
M	666	7
J	535	6
J	734	1
A	545	9
S	432	6
O	641	7
N	413	10
D	591	7
Year	6,851	66

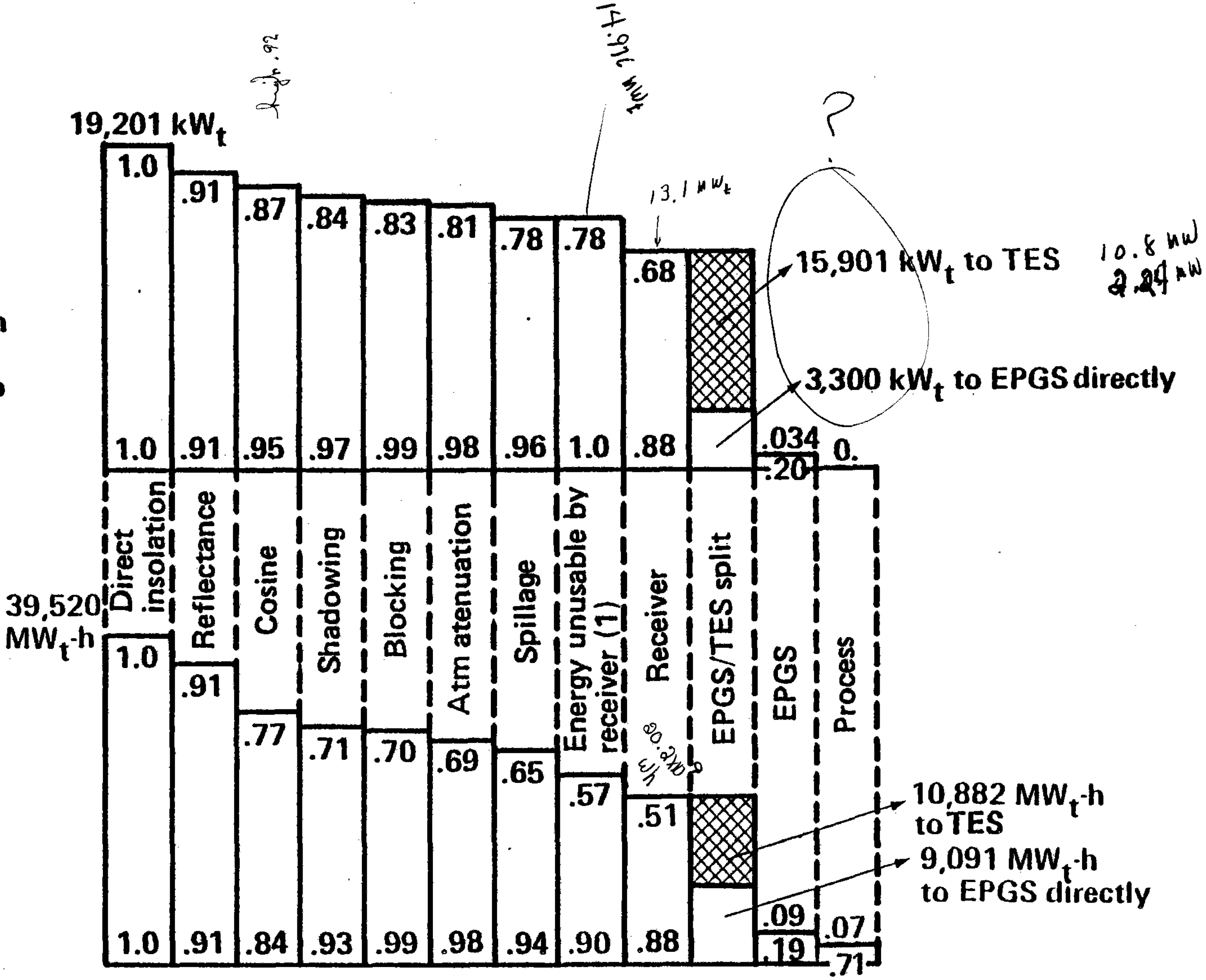
46.9 m^2 x 436 heli. x 940 w/m^2 = 19.22 mw

5.44 kWh/m^2 day x 365 days x 20448 m^2 = 40.60 x10^9 wh

.208 .29

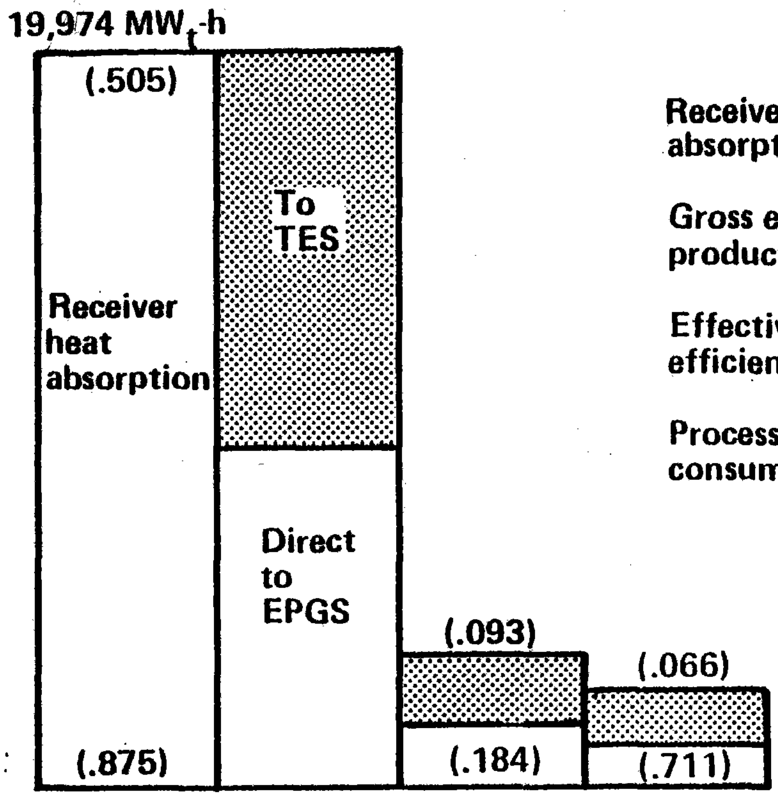
Design point
- Solar noon
- Winter solstice
- 940 W/m^2
- TES near fully charged condition
- Max. receiver flow
- Max. pressure drop
- T_{amb} = 13°C
- $T_{turb.in.}$ = 788°C

Annual
- 1978 midland data



(1) Energy below minimum receiver massflow condition or heliostats turn away.

Figure 8-43. DESAL Commercial Plant Efficiency Train



	TES	Direct to EPGS	Total
Receiver heat absorption (MW$_t$-h)	10,882	9,091	19,974
Gross electrical production (MW$_e$-h)	2,054	1,624	3,678
Effective electrical efficiency	.189	.179	.184
Process electrical consumption (MW$_e$-h)	1,461	1,155	2,615

Figure 8-44. **Efficiency Train Details**

9.0 REFERENCES

1. Statement of Work, Appendix A, SERI Subcontract No. AF-1-9115-2, October 10, 1980.

2. System Performance Specification, Solar Energy Water Desalination System Design, Prepared under SERI Contract AF-9115-2, Boeing Engineering and Construction, Seattle, Washington, November 1980.

3. Hourly Insolation and Meteorological Data Bases Including Improved Direct Insolation Estimates, Sandia Laboratories, Contract No.02-7837

4. A User's Manual for DELSOL: A Computer Code for Calculating the Optical Performance, Field Layout, and Optimal System Design for Central Receiver Plants, Report SAND 79-8215, Sandia Laboratories, Albuquerque, New Mexico, June 1979.

5. United States Gypusm Plant Solar Retrofit, Volume 2, System Requirements, Prepared under DOE Contract DE-AC03-79SF10742, Boeing Engineering and Construction Company, Seattle, Washington, July, 1980.

6. The Cost of Energy from Utility-Owned Solar Electric Systems, Jet Propulsion Laboratory Report 5040-29, Pasadena, California, June, 1976.

7. Technical and Economic Assessment of Solar Hybrid Repowering, Final Report, SAN/1608-4-1, Public Service Company of New Mexico, Albuquerque, New Mexico, September, 1978.

8. Methods for Estimating Total Flux in the Direct Solar Beam at any time, Lorin Vant-Hull, Joint Conference of the American Section of the International Solar Energy Society and the Solar Energy Society of Canada, Inc., 1976, Winnipeg, Canada, Vol. 1, pg. 369.

APPENDIX A

RECEIVER SCALING RELATIONSHIPS

- Assuming a detailed thermal design of a solar receiver exists, the effects of scaling from that design can be explored

- Example,

$$N = \frac{W}{D\Gamma}\,,$$

N = tube number
W = panel width
D = diameter
Γ = pitch ratio

$$N^* = \frac{W^*}{D^*\ \Gamma^*}\,, \quad \text{where} \quad (\ )^* = \frac{(\ )_{\text{new value}}}{(\ )_{\text{old value}}}$$

- Heat Transfer

$$\dot{m}\, N\, C_p\, \underbrace{(T_{in} - T_{out})}_{\Delta T_g} = h\, A_w\, \underbrace{(T_t - T_g)}_{\Delta T_E}$$

$$\boxed{\Delta T_E{}^* = \frac{Re^*\ Pr^*\ D^*\ \Delta T_g{}^*}{Nu^*\ \ L^*}}$$

- Pressure Drop

$$\alpha = \frac{\Delta p}{p} = \tfrac{1}{2}\,\frac{\rho\, v^2}{p}\,\left[f\left(\frac{L}{D}\right) + K\right]$$

$$\boxed{D^* = \left\{\frac{M^{*2}}{P^{*2}}\,\frac{T^*\ L^*\ \Gamma^{*2}}{\alpha^*\ W^{*2}}\right\}^{1/3}}$$

RECEIVER SCALING

$$\boxed{W^{*.87}\, L^{*.67} = \frac{\Delta T_g^*}{\Delta T_E^*}\; \frac{M^{*.87}\, \Gamma^{*.87}\, T^{*.33}}{P^{*.67}\quad \alpha^{*.33}}}$$

o Assuming W* and L* grow in same proportion, i.e.

W* = L* = X* = linear dimension of heat exchanger panel

$$\boxed{X^* = \left\{ \frac{\Delta T_g^*}{\Delta T_E^*}\; \frac{M^{*.87}\, \Gamma^{*.87}\, T^{*.33}}{P^{*.67}\quad \alpha^{*.33}} \right\}^{1/1.54}}$$