SAN/1109-8/1

SOLAR PILOT PLANT

PHASE 1, PRELIMINARY DESIGN REPORT

Volume 1, Executive Overview (Approved), CDRL Item 2

August 1, 1977

Work Performed Under Contract No. EY-76-C-03-1109

Energy Resources Center
Honeywell, Incorporated
Minneapolis, Minnesota

U.S. Department of Energy

Solar Energy

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SOLAR PILOT PLANT

Phase I

Preliminary Design Report

Volume I

Executive Overview

(Approved)

CDRL Item 2

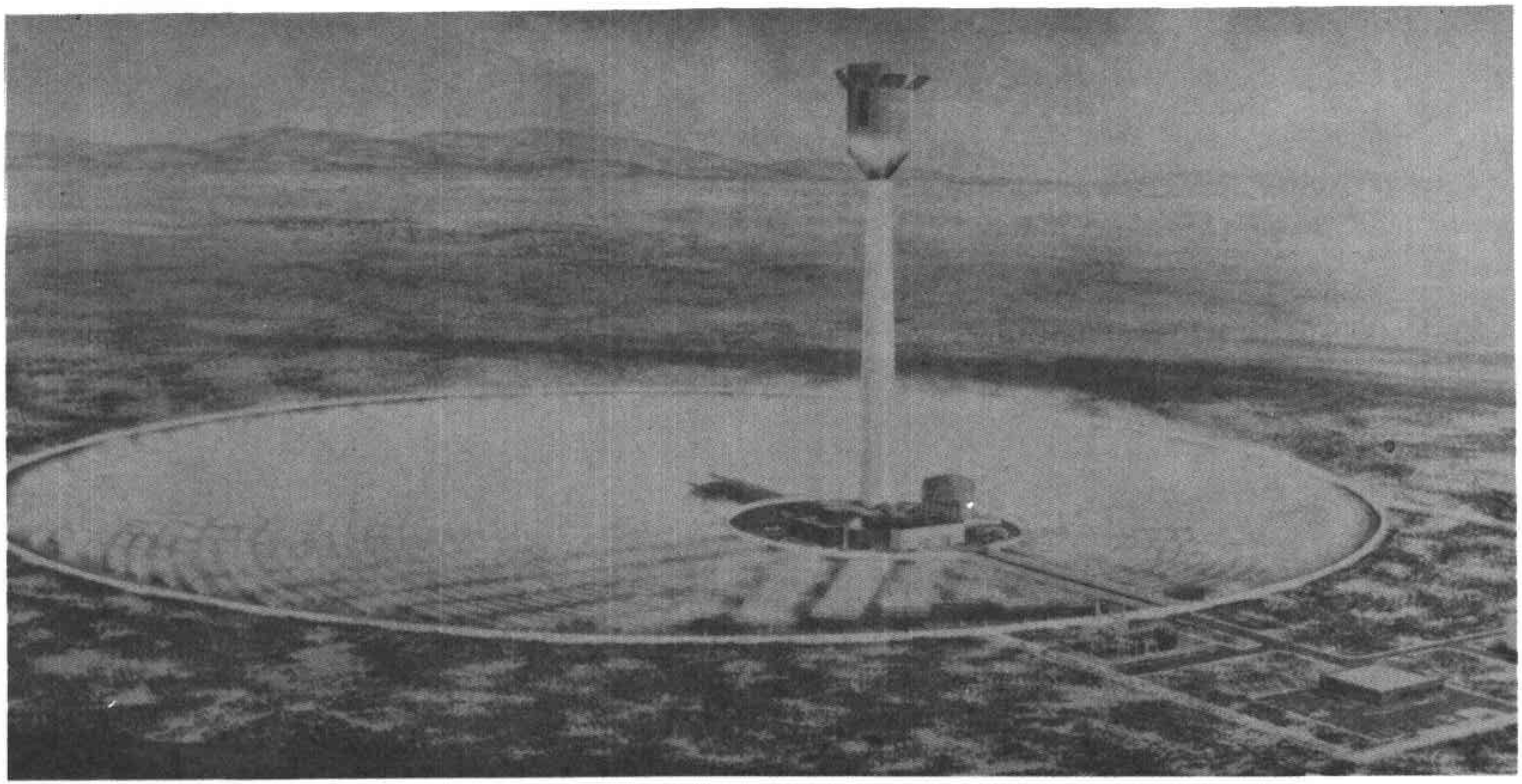
O. J. Bunnell
Contract Administrator

J. C. Powell
Program Manager

HONEYWELL, INCORPORATED
ENERGY RESOURCES CENTER
2600 RIDGWAY PARKWAY
MINNEAPOLIS, MINNESOTA 55343

FOREWORD

This is the final submittal of the Solar Pilot Plant Preliminary Design Report per Contract Data Requirement List Item 2 of ERDA Contract E(04-3)-1109. The report has been reviewed and approved by ERDA. This is Volume I of seven volumes.



10 MW(e) SOLAR PILOT PLANT

PRELIMINARY DESIGN REPORT

INTRODUCTION

BACKGROUND

Historically, the socio-economic pressures of exponentially growing demand in a closed ecosystem have been alleviated through technological breakthroughs. As it stands, the present energy situation appears to have the basic dimensions of an ecocrisis: exponentially growing demand and diminishing returns. To this problem, the national response has been along four fronts:

- Energy conservation to slow down the exponential curve
- Increased utilization of base load coal and nuclear fission power plants to stabilize the supply
- Accelerated pursuit of technological breakthroughs in nuclear fusion to fundamentally change the nature of the ecosystem from one with finite resources to one with essentially infinite fuel
- Research and development of alternate energy sources such as solar thermal, solar electric, wind, ocean and geothermal.

Studies in the early 1970's showed one of these alternate sources, namely, solar thermal to electric, to be feasible with present-day technology, thus avoiding a prolonged search for a breakthrough. The studies investigated a variety of concept configurations such as distributed and central receiver systems using thermodynamic cycles from organic Rankine to closed helium Brayton.

For large scale, utility level, generation capacity the central receiver system coupled to a water/steam Rankine cycle conventional turbogenerator emerged as the most promising concept primarily for the following two reasons:

- The high temperature/pressure capabilities of the concept promised high conversion efficiencies at conventional power plant sizes without the piping cost penalties of the distributed concepts
- Preliminary cost estimates promised eventual economic viability as compared with conventional power sources for intermediate and peak load applications.

The federal central receiver program that was initiated on the bases of the concept investigation studies is a multi-phased effort that attempts to lead the technology from concept to commercialization. These phases are:

Phase I - Pilot Plant Preliminary Design

Subsystem ResearchExperiments

Commercial Plant Conceptual Design

Phase II - Pilot Plant Detailed Design and Construction

Commercial Plant Preliminary Design

Subsystem In-situ Tests

Phase III - Pilot Plant Operation

Commercial Plant Detailed Design

Phase IV - First Commercial Plant Build and Operate

This document contains the Executive Summary of the Final Technical Report describing Honeywell's effort to perform Phase I of the Central Receiver Program.

PHASE I GOALS AND REQUIREMENTS

The Phase I project goals must be understood within the framework of the total program and its final objective: commercial solar electric power. Each major Phase I project effort attempts to establish the fundamental technical and economic operative factors and relationships between the Pilot Plant and the first Commercial Plant as well as the n^{th} solar power generating unit within a conventional network.

In detail, the Pilot Plant preliminary design effort had as its goal the specification of a plant that will demonstrate in operation the technical feasibility of a large scale application. Furthermore, the Pilot Plant design must be such as to allow scaling up to the first commercial plant that has as its goal the demonstration of economic viability under utility operation.

Therefore, the Pilot Plant Preliminary Design has to be closely coupled to the Commercial Plant design since their goals complement each other. In addition, the Subsystem ResearchExperiments design, build and test efforts of Phase I have to relate directly to the Pilot Plant goal of demonstrating technical feasibility. In a hierarchy of goals, the efforts then would appear as:

- Subsystem Research Experiments - Demonstrate technical feasibility at the subsystem level

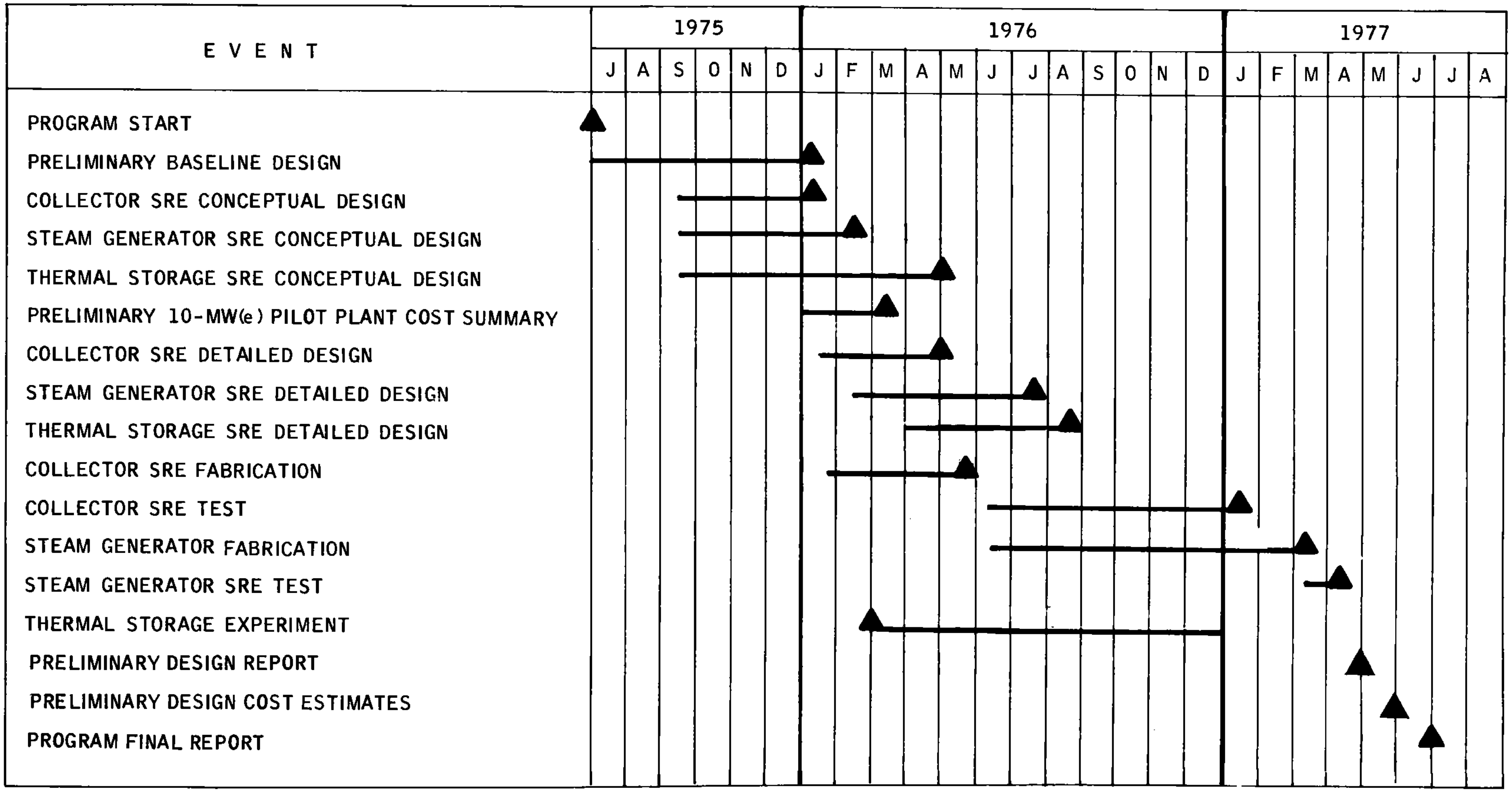
- Pilot Plant - Demonstrate technical feasibility at the system level

- First Commercial Plant - Demonstrate economic viability at the utility network level

Within the overall effort constraint of using conventional hardware as much as possible, the Pilot Plant preliminary design effort attempts to synthesize a configuration that, once implemented, will demonstrate technical feasibility and operating capability within the following envelope:

- Transient and periodic environmental conditions such as the solar insolation variation, the vagaries of weather, and earthquake disturbances
- Varying operational modes under different storage utilization strategies
- Emergency plant or network conditions

Within this framework, the design must attempt to resolve, upon implementation, such issues as diurnal start up and shut down, response to cloud transients, overnight stand by losses, scalibility, safety, expected life time performance, grid interface, as well as maintenance and repair requirements. Furthermore, the design must be such as to allow the identification of the primary economic factors: capital investment requirements and bus bar costs as related to annual performance under different operating strategies.

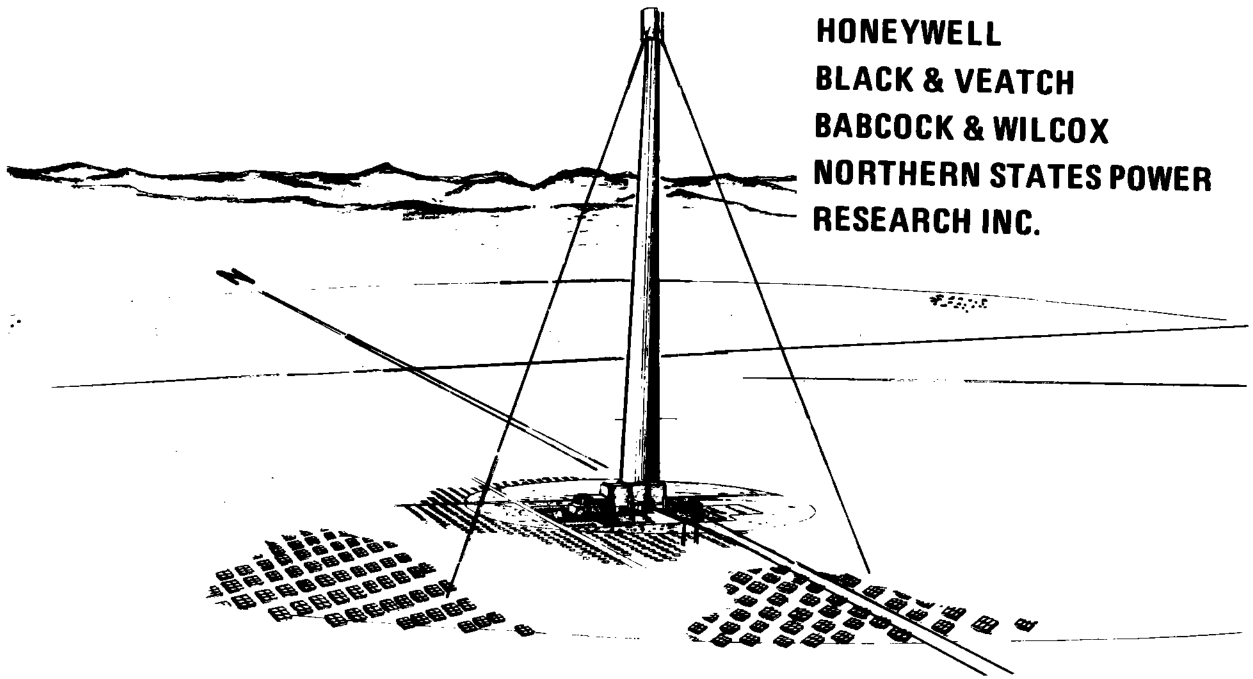


PROGRAM SCHEDULE

HONEYWELL SOLAR PILOT PLANT TEAM

The complexity of the undertaking dictated using a team approach to provide the technical and managerial skills required. The management focal point resided with Honeywell's Energy Resources Center, Minneapolis, Minnesota.

Northern States Power Company and Research Incorporated are also based in Minneapolis, Minnesota. Black & Veatch is located in Kansas City, Missouri, and Babcock and Wilcox in Alliance, Ohio. The Honeywell Avionics Division facility is in St. Petersburg, Florida.



HONEYWELL ENERGY RESOURCES CENTER
MINNEAPOLIS

- PROGRAM MANAGEMENT
- SYSTEMS ENGINEERING
- STORAGE SUBSYSTEM, DESIGN FAB AND TEST
- STEAM GENERATOR TEST

HONEYWELL AVIONICS DIVSION
ST. PETERSBURG

- COLLECTOR SYSTEM DESIGN, FAB AND TEST

BLACK & VEATCH
KANSAS CITY

- ELECTRICAL GENERATOR SUBSYSTEM
- RECEIVER SUBSYSTEM
- TEST FACILITY DESIGN SUPPORT

BABCOCK & WILCOX
ALLIANCE, OHIO

- STEAM GENERATOR DESIGN AND FAB
- TEST SUPPORT

RESEARCH INC.
MINNEAPOLIS

- SOLAR SIMULATOR

NORTHERN STATES POWER COMPANY
MINNEAPOLIS

- TEST FACILITIES
- TEST SUPPORT

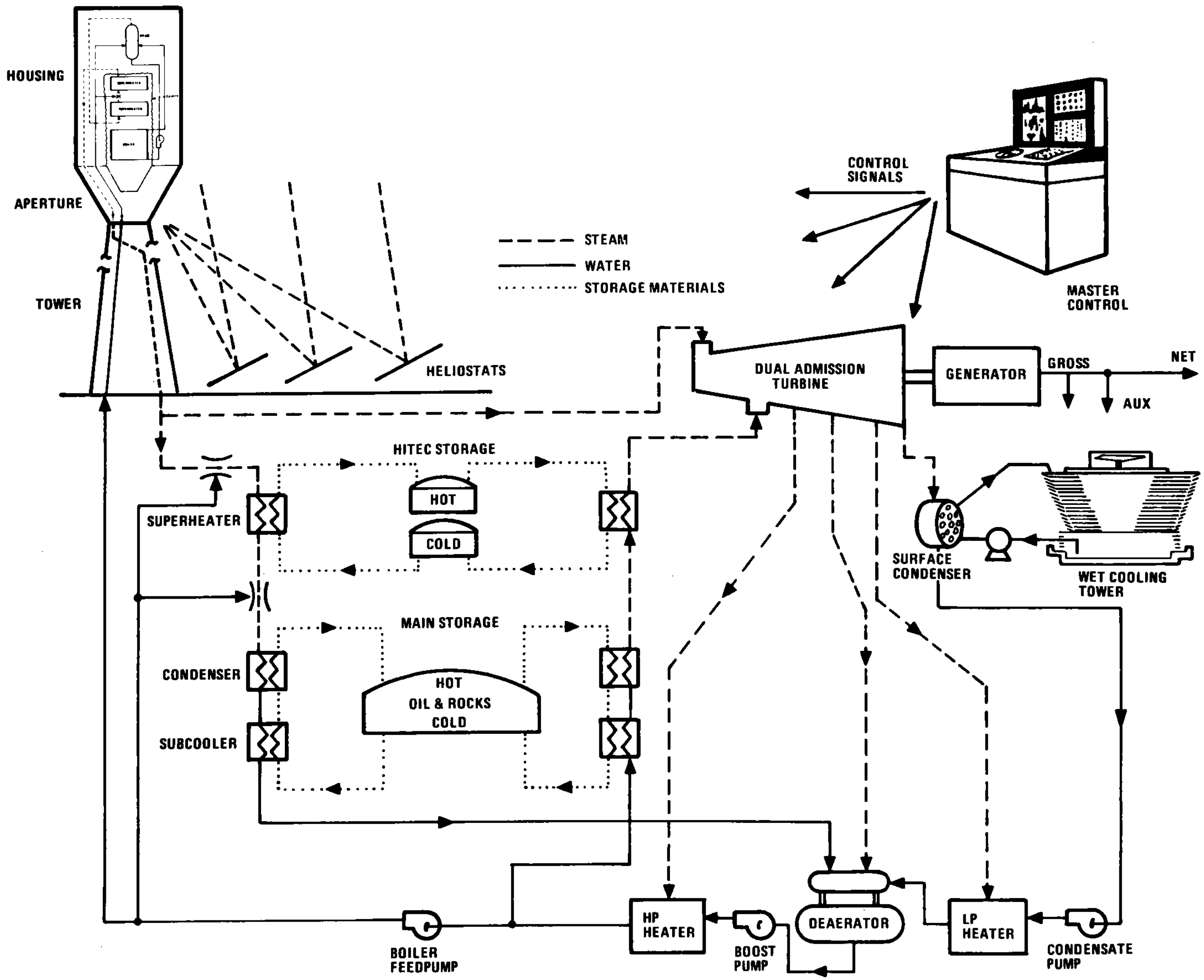
THE HONEYWELL TEAM

SOLAR PILOT PLANT PRELIMINARY DESIGN

The solar pilot plant consists of the following subsystems: collector field, receiver/tower, thermal storage, electrical power generation and balance of plant and controls.

Sunlight is redirected by the collector subsystem into the aperture of the receiver on top of a tower, where it heats water in a steam generator. The steam is piped directly to a turbine, or into storage if it is not needed immediately. The storage subsystem normally supplies steam to the turbine when the receiver subsystem is inoperative. If the load demand requires it, steam can be drawn from both subsystems simultaneously. The turbine generator, with a nameplate capacity of 15 MW(e), utilizes wet cooling.

Pilot plant operation is controlled through a coordinated master control that regulates subsystem controls to correspond to the load demand and the energy available. The control system features a manual override capability, and every precaution is taken to ensure the safety of operating personnel and equipment.



SOLAR PILOT PLANT SCHEMATIC

APPROACH TO THE PILOT PLANT DESIGN

The pilot plant performance specifications were the basis for the preliminary design. Honeywell's overall objective was to provide a pilot plant design that translates realistically to commercial scale in terms of performance and cost.

PILOT AND COMMERCIAL PLANT DESIGN PARAMETERS

	PARAMETER	PILOT PLANT	FIRST COMMERCIAL
1	Location	Barstow	TBD
2	Nameplate Capacity	15 MW(e)	120 MW(e)
3	Design Point	12/21, 2 PM	3/21, Noon
4	Design Point Net Power	10 MW(e)	100 MW(e)
5	Solar Multiple	1.23	1.7
6	Heliostat Size	$40 m^2$	Same
7	Number of Heliostats	1598	20,220
8	Total Mirror Area	$63{,}920 m^2$	$808{,}800 m^2$
13	Total Net Annual Energy (NAE)	2.22×10^4 MWhr(e)	2.89×10^5 MWhr(e)
14	NAE/Total Mirror Area	0.348 MWhr(e)/m^2	0.357 MWhr(e)/m^2
9	Storage Capacity	7 MW(e) for 3 hours	70 MW(e) for 3 hours
10	Turbine Cycle		
	– From Receiver	10.1MPa/510°C (1450 PSIA/950°F)	Same
	– From Storage	3.2 MPa/388°C (460 PSIA/730°F)	Same

PILOT PLANT DESIGN CRITERIA

The Pilot Plant design aimed itself at five critical issues:

- Control
- Performance
- Economics
- Flexibility
- Scaling to Commercial Size

The varying solar input and climatological conditions in contrast to the steady level output requirements of a utility network define the prime issue of controlled operation. The capital cost intensive nature of solar equipment demands high performance and cost minimization. The experimental nature of the Pilot Plant accounts for the flexibility and scaling requirements.

PILOT PLANT DESIGN FEATURES

COLLECTOR SUBSYSTEM

- FOCUSED MIRRORS
- MULTI-FACET, LOW-PROFILE HELIOSTAT
- CENTRAL COMPUTER CONTROL

RECEIVER SUBSYSTEM

- CAVITY RECEIVER
- PROVEN TOWER DESIGN/ CONSTRUCTION
- DRUM BOILER
- STANDARD ASME CODE PRACTICES

ELECTRICAL POWER GENERATION SUBSYSTEM

- TURBINE SIZED FOR MAXIMUM POWER
- SIMULTANEOUS STEAM SOURCE TRANSFER/OPERATION
- HIGH CYCLE EFFICIENCY

THERMAL STORAGE SUBSYSTEM

- SENSIBLE HEAT STORAGE
- STATE OF THE ART TECHNOLOGY
- INDEPENDENT CHARGE/DISCHARGE CAPABILITY

CONTROLS

- DIGITAL MASTER
- CONVENTIONAL ANALOG/DIGITAL SUBSYSTEM CONTROL

COLLECTOR SUBSYSTEM

The collector subsystem consists of the heliostat field, control, and calibration equipment. The critical element is the heliostat because it is the most important cost and performance factor in the Pilot Plant system.

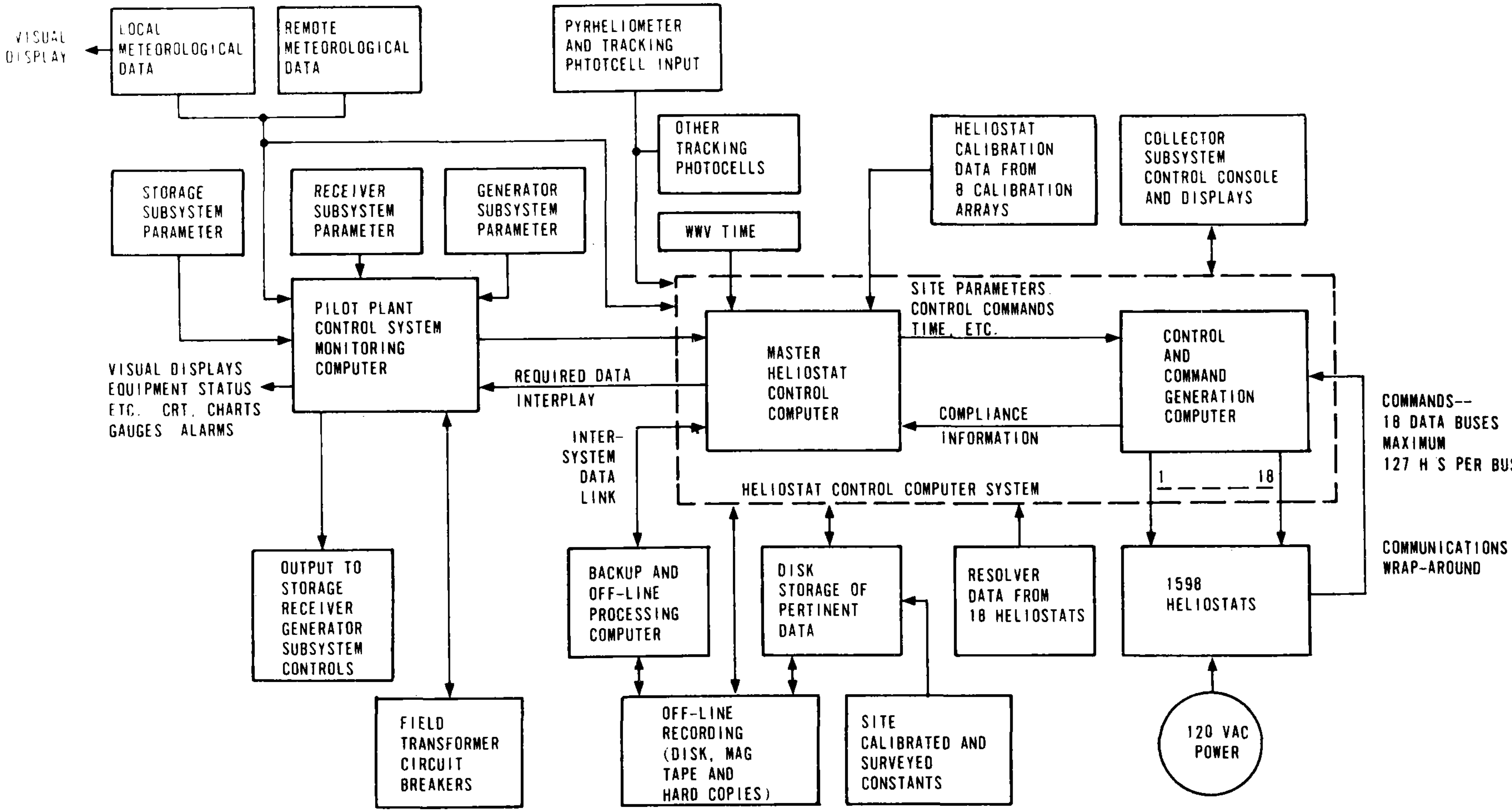
The heliostat is designed to provide high reflectivity and accurate angular and spatial positioning of the redirected energy. Other heliostat features are modularity for quick, easy installation and maintenance, and the use of dc motors and trickle charged batteries.

SRE HELIOSTAT

COLLECTOR SUBSYSTEM CONTROLS

The computerized control subsystem has the capability to address all of the heliostats simultaneously while performing calculations of sun position and pointing direction and compensating for known fixed errors. The Honeywell Level 6/45 computer permits cross-checking of input data, including weather conditions in the collector field, thereby enhancing reliability and safety in the collector subsystem.

The calibration sensor arrays, mounted on top of the receiver tower, provide the capability to measure both beam location and beam energy accurately. This information is used to correct minor pointing errors and determine when the mirrors need to be cleaned.



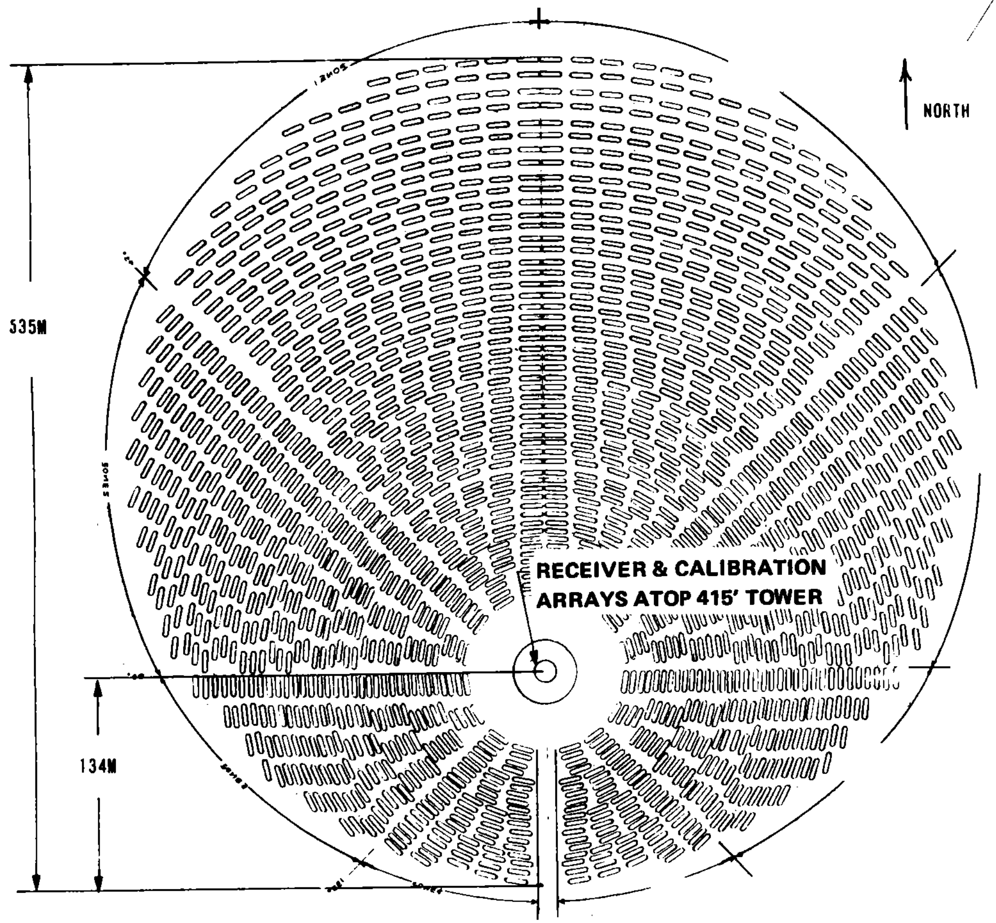
HELIOSTAT CONTROL SYSTEM

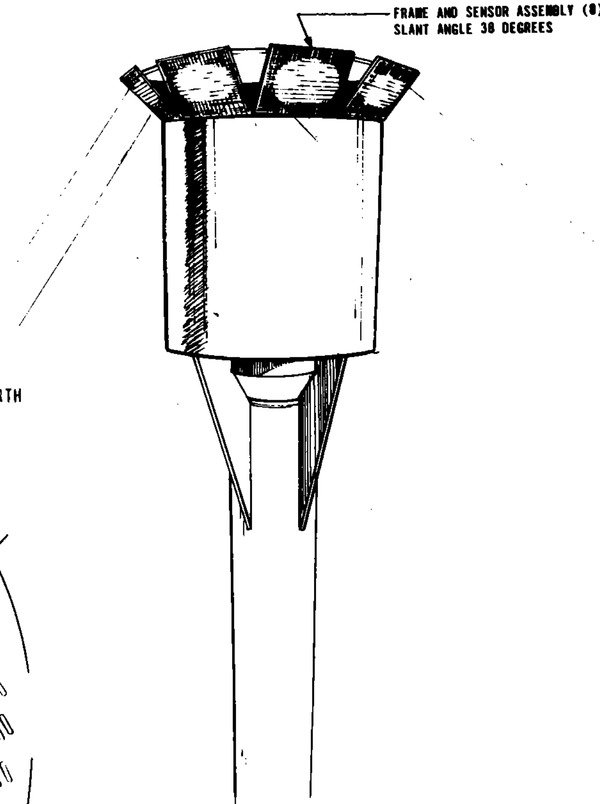
PILOT PLANT COLLECTOR FIELD

The pilot plant collector field configuration was determined by computer analysis, the criterion being maximum redirected solar energy collected during the year. The field is circular with the receiver one-half of the field radius south of field center. The field contains 1598 heliostats spaced radially and tangentially to minimize shading and blocking. Any heliostat can be placed in any given position in the field. The ratio of mirror surface area to collector field area is 0.29. Eight calibration arrays are fixed on top of the receiver tower. The control facility is housed near the base of the receiver tower.

The calibration array measures the redirected solar beam periodically. By moving the beam from the aperture of the receiver to the array, the computer detects differences between predicted and measured position and makes appropriate corrections. Information is accumulated to identify such long-term influences as foundation drift. More immediately, energy measurements show when mirror cleaning is required.

PILOT PLANT COLLECTOR FIELD





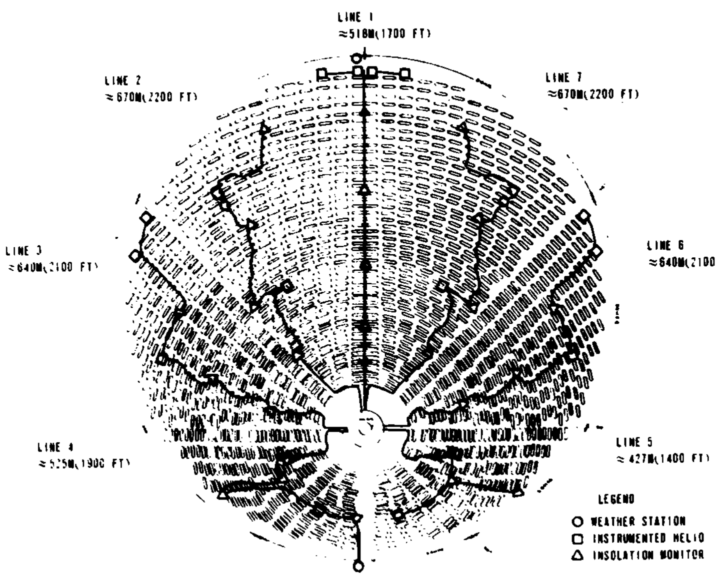
CALIBRATION ARRAY

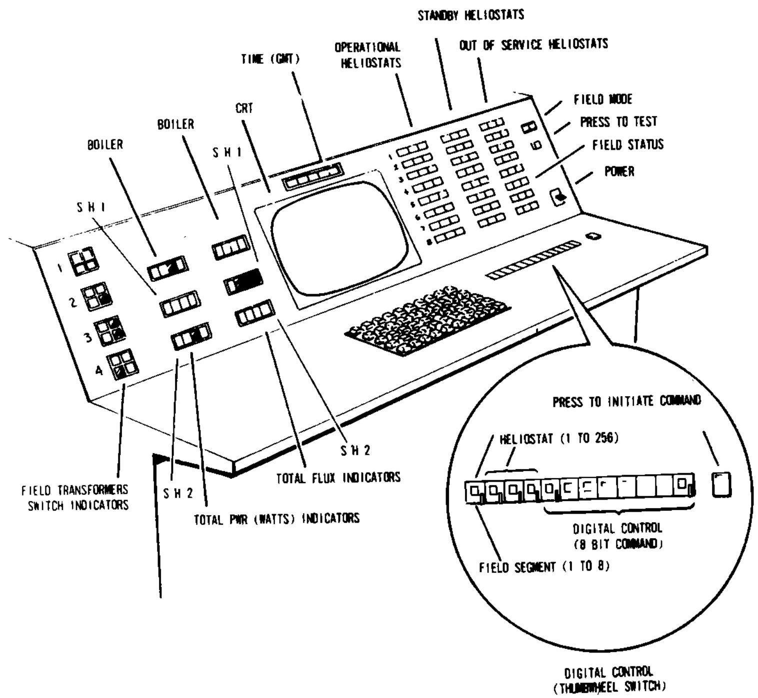
CONTROL OF THE COLLECTOR SUBSYSTEM

Using National Bureau of Standards time signals as a timing reference, the computer calculates time-dependent sun position at one-second intervals. From this, it computes gimbal tracking angles for all heliostats. Gimbal angle commands are transmitted to the heliostats via buried twisted shielded lines. Gimbal updates can be in one or fifteen step increments. One-step commands are for fine tracking while 15-step commands are for controlled speed slewing. In the tracking mode, the computer commands the redirected beam to track the receiver aperture or a secondary target, which can be the calibration array or simply a point in space.

Operation of a solar power plant requires knowledge of weather and solar radiation in the collector field at a given time. A number of remote weather stations are located in the field. They transmit data to the computer, which uses it in deciding when to alter operation to accommodate cloud cover or to stow heliostats against foul weather.

FIELD INSTRUMENTATION INTERCONNECT



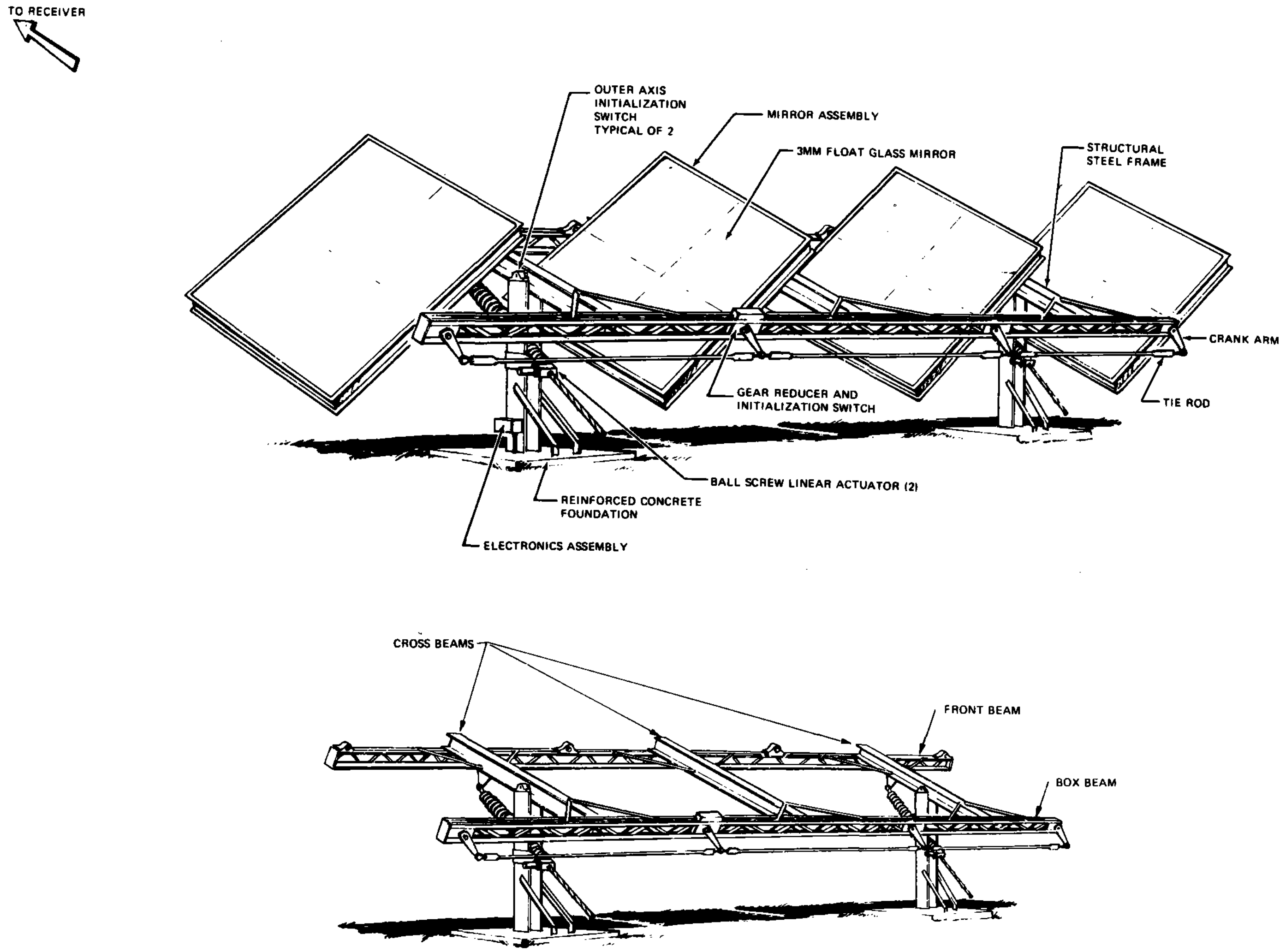


COLLECTOR CONTROL CONSOLE

PILOT PLANT HELIOSTAT DESIGN

Each heliostat facet consists of second surface glass mirror on an aluminum honeycomb panel faced on both sides with steel. The 4-facet, tilt-tilt, fixed focus heliostat has several unique features.

It has a low profile with all moving parts less than three feet above the support surface. This ensures cleanliness of the mirrors and moving parts, while at the same time it reduces structural exposure to high winds. The heliostat resists overturning moments by having its centers of gravity and wind resistance midway between two support posts - as opposed to being cantilevered. This reduces the foundation requirement. The second surface glass mirrors actually have no bending loads imposed on them. The heliostat gears, motors, and electronics are packaged, shielded, and grounded in such manner as to ensure maximum efficiency, safety, and life.

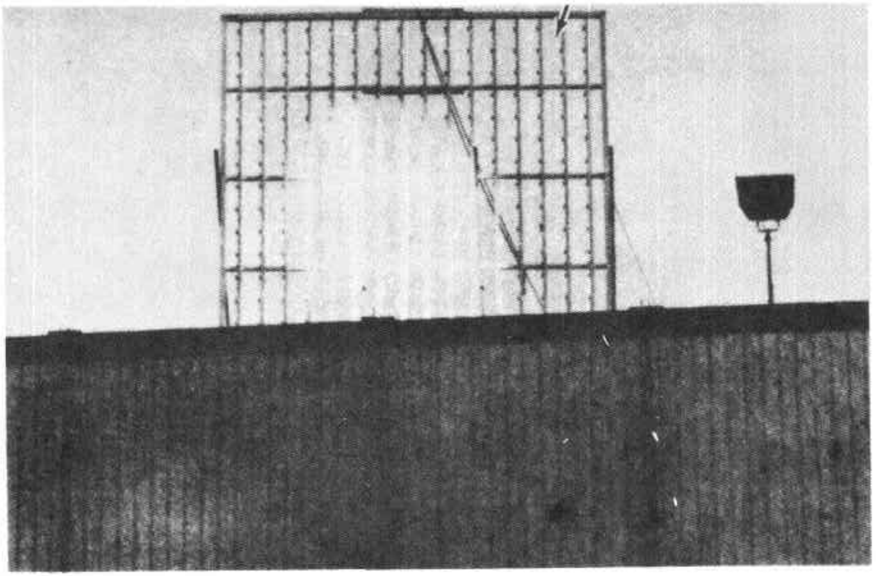


HELIOSTAT DESIGN FEATURES

SRE EVALUATION OF THE COLLECTOR SUBSYSTEM

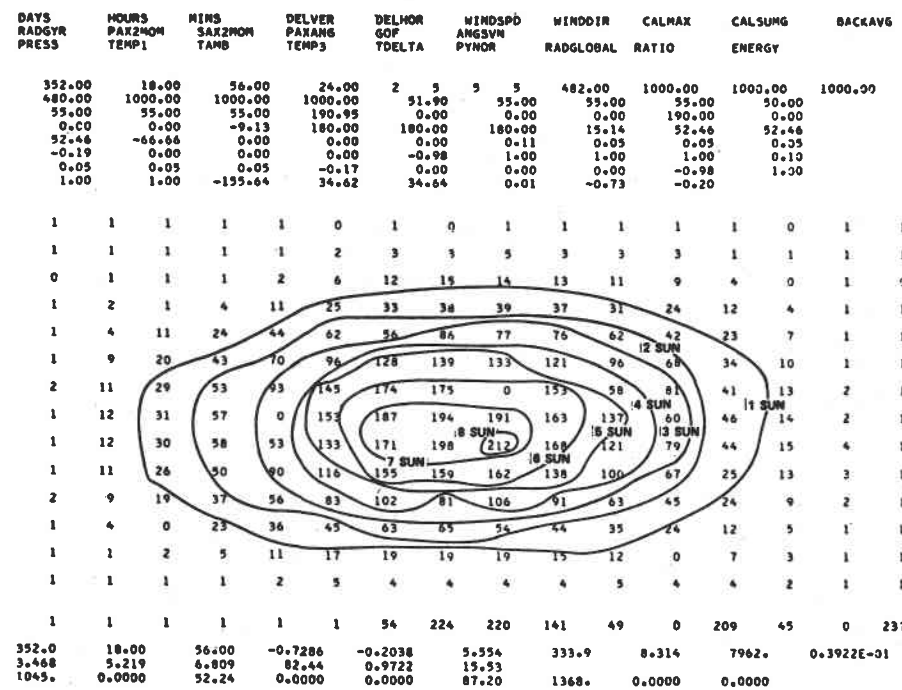
Results from the SRE tests provided a firm basis for confidence in the performance of the collector subsystem. Those successful tests extended over a 9-month period and included key components and the entire subsystem, operationally, and environmentally.

Flux density profiles of the reflected energy were measured with a calibration array. Energy balances of solar incident energy, losses and energy reaching the target were determined. Test results agreed remarkably well with results predicted by "ray trace" and atmospheric attenuation computer models. Tracking and optical accuracies met or exceeded requirements under all environmental test conditions.



CALIBRATION ARRAY

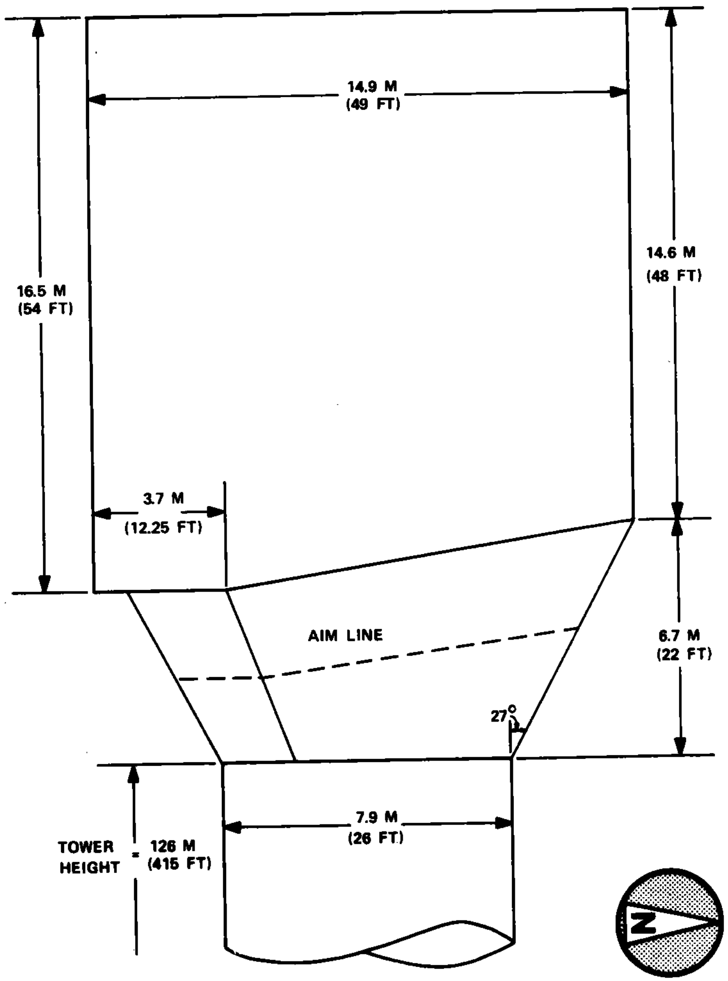
SRE HELIOSTAT FLUX PROFILE



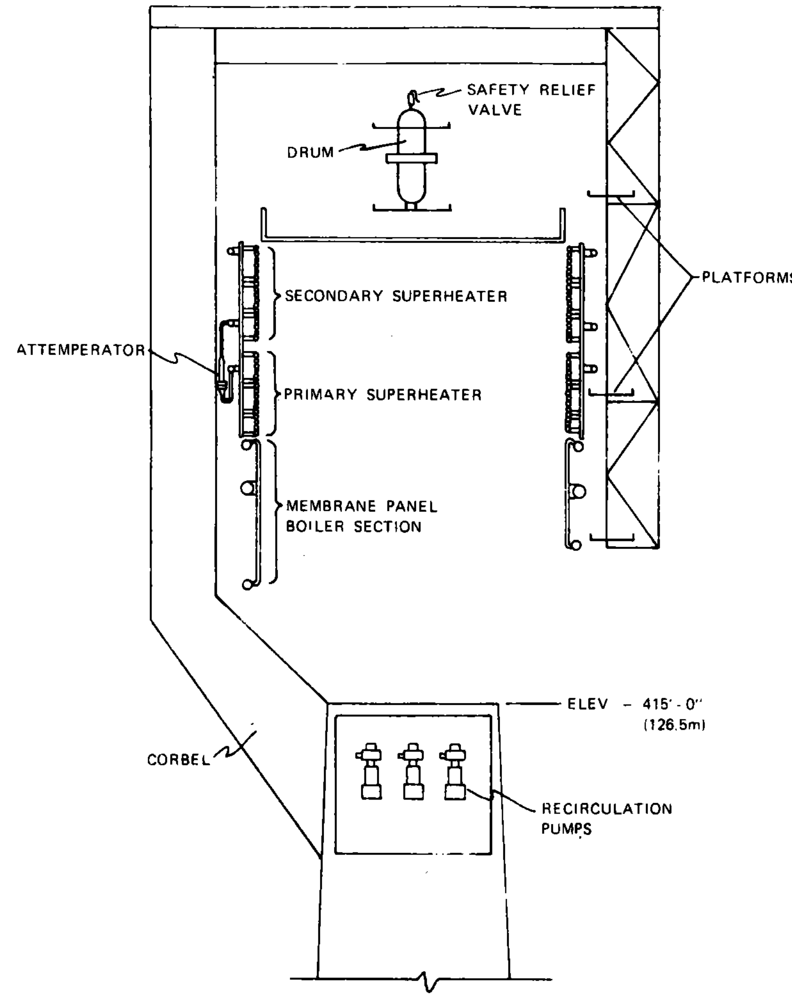
RECEIVER SUBSYSTEM

The receiver subsystem consists of a cavity receiver housing the steam generator, support tower, cavity barrier, piping, cables, protective shielding, and access provisions for maintenance and repair.

The design requirements for the subsystem are dictated largely by performance requirements for the solar steam generator. These in turn impose certain design requirements on the receiver tower support structure. In brief the steam generator is required to absorb solar energy efficiently and reliably and convert it to the steam-water working fluid that drives the system.



CAVITY



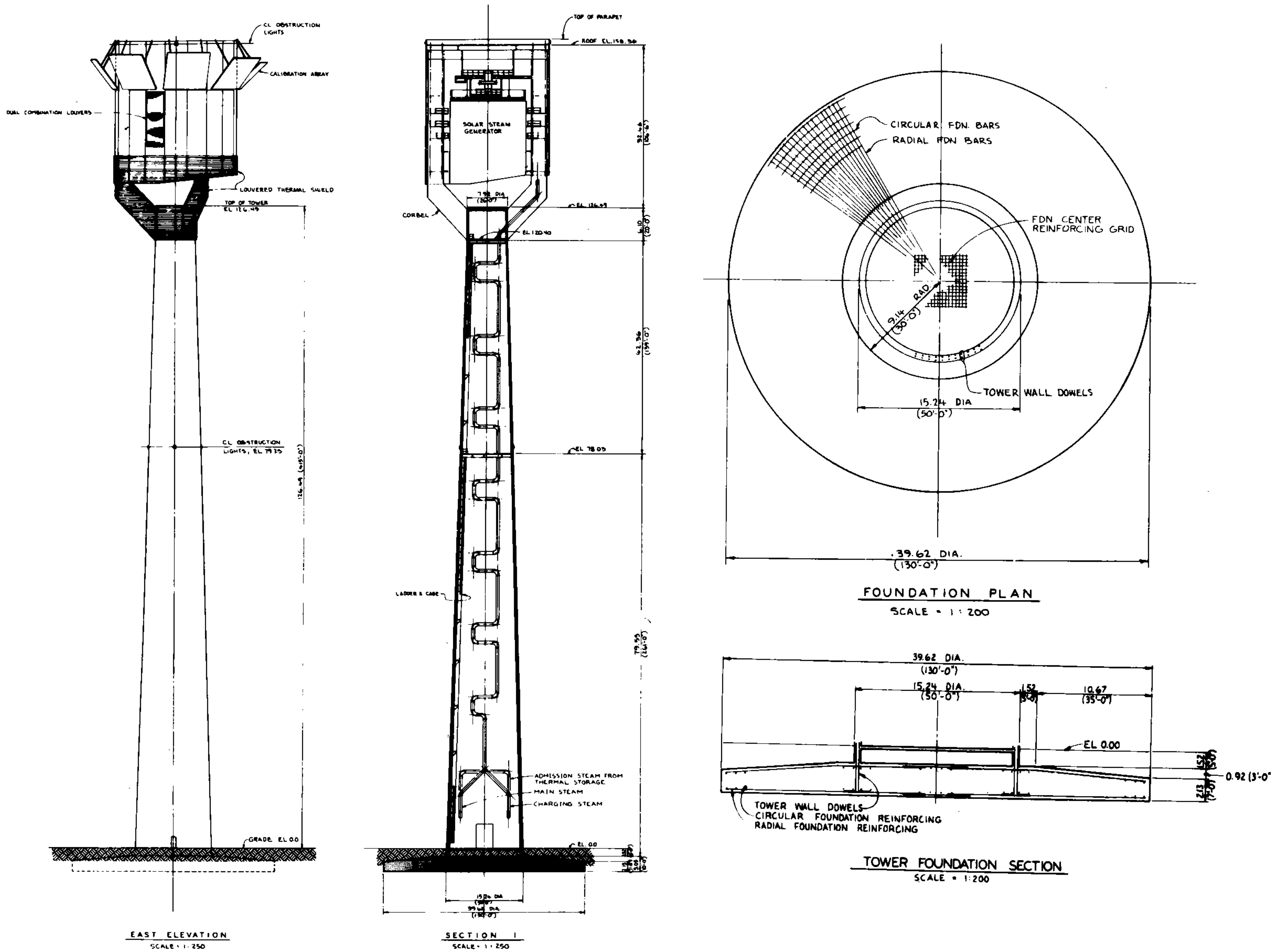
STEAM GENERATOR

PILOT PLANT RECEIVER

RECEIVER TOWER

Major elements of the tower are the foundation, tower structure, feedwater and steam piping, equipment interfaces, protective shielding, and accessways. The tower structure must resist support reactions, its own dead, live and wind loads, and seismic forces.

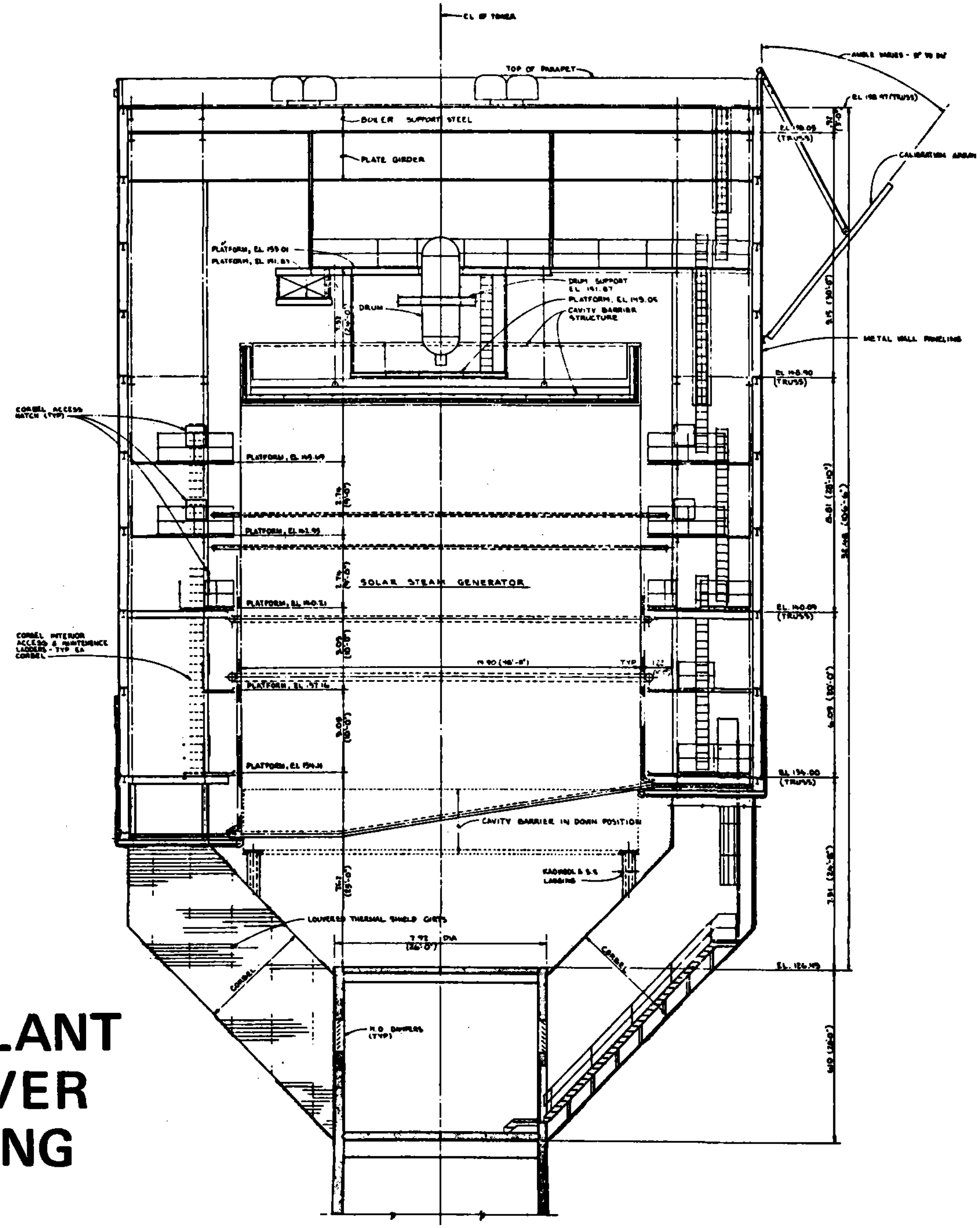
Access to the tower at its base is through a rolling steel door 3.66 meters wide and 4.88 meters high, and by a door for personnel that is 0.91 meter wide and 2.13 meters high. Personnel access up the tower is by elevator with ladder backup. The ladder is caged structural steel with bar grating landing platforms at 9-meter intervals. The elevator is enclosed and guided from rails along the tower shell.



PILOT PLANT RECEIVER TOWER

RECEIVER HOUSING

The housing provides a means of supporting the steam generator. It also serves as an environmental enclosure. It is composed of a series of horizontal and vertical trusses interconnecting the box beam steel corbels. The steam generator is suspended from the top to provide for growth due to thermal expansion in the downward direction. Personnel access for maintenance is provided through the corbels and between the housing and steam generator. Thermal losses are minimized during night time and periods of no solar radiation by lowering the cavity ceiling to close the upper aperture. The area between the steam generator and the housing is ventilated by forced air circulation.



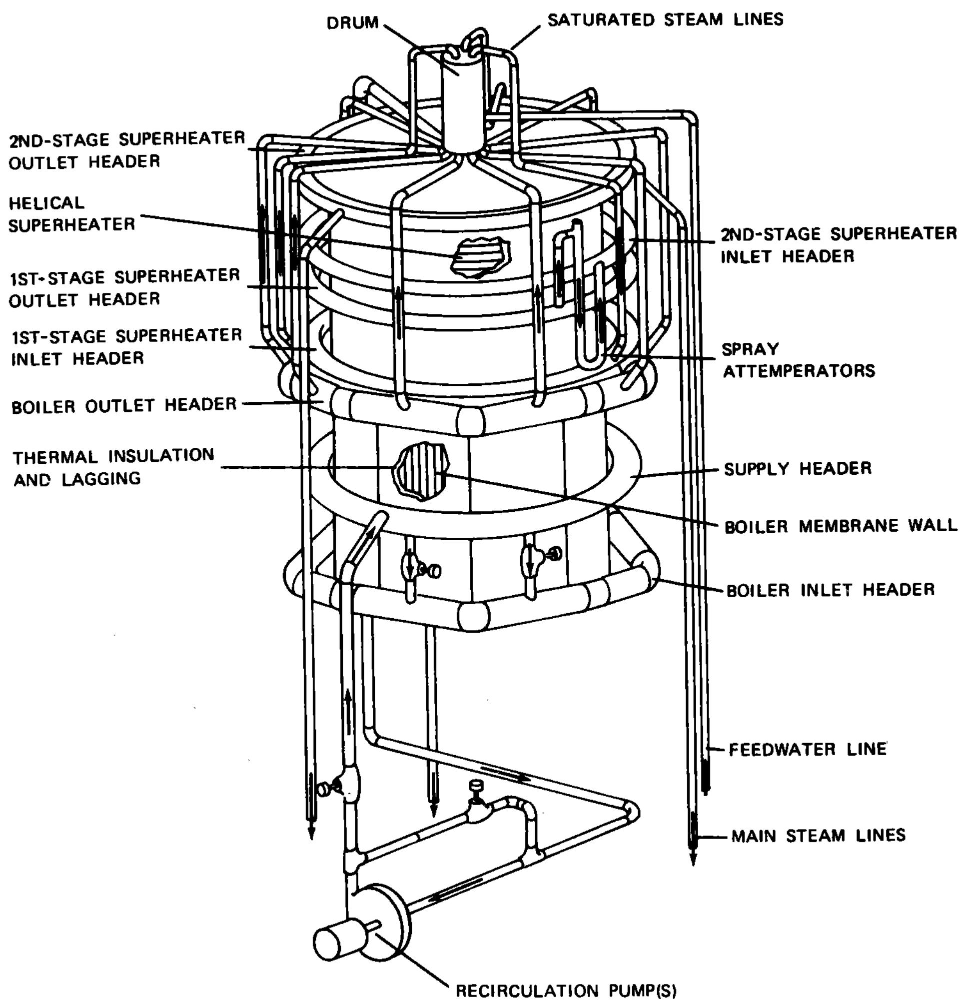
PILOT PLANT RECEIVER HOUSING

STEAM GENERATOR

The solar steam generator design is based on state-of-the-art fossil fuel boiler technology. Two considerations unique to solar central receiver steam generators had to be accommodated in the design:

- An unusually large number of stress cycles during 30-year design life
- Wind and seismic loads more severe than those at ground level

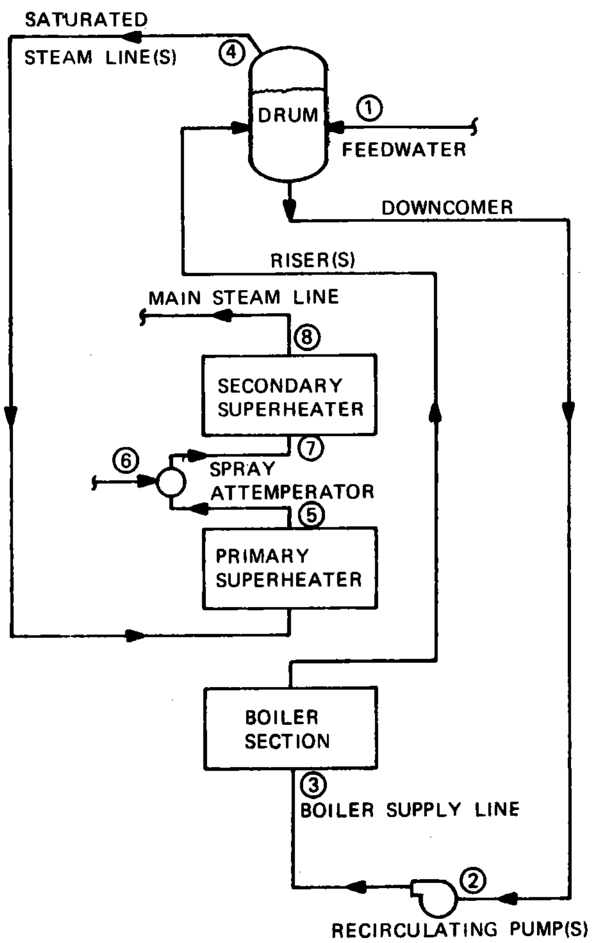
The steam generator configuration and the radiation properties of the heat transfer surfaces are designed to maximize absorptance and the efficiency of the receiver cavity. The steam generator heat transfer surface is an 18-sided polygon that forms the interior walls of the receiver cavity. The absorptance value is ~ 0.9.



PILOT PLANT STEAM GENERATOR

STEAM GENERATOR FLOW

The steam generator design features a pump-assisted recirculating drum boiler with two superheaters and a spray attemperator for controlling steam outlet temperature. Forced circulation ensures that DNB (departure from nucleate boiling) does not occur during cloud transients. A 10 to 1 recirculation ratio is nominal with steam/water separation taking place in the drum to ensure dry steam entering the first stage superheater.

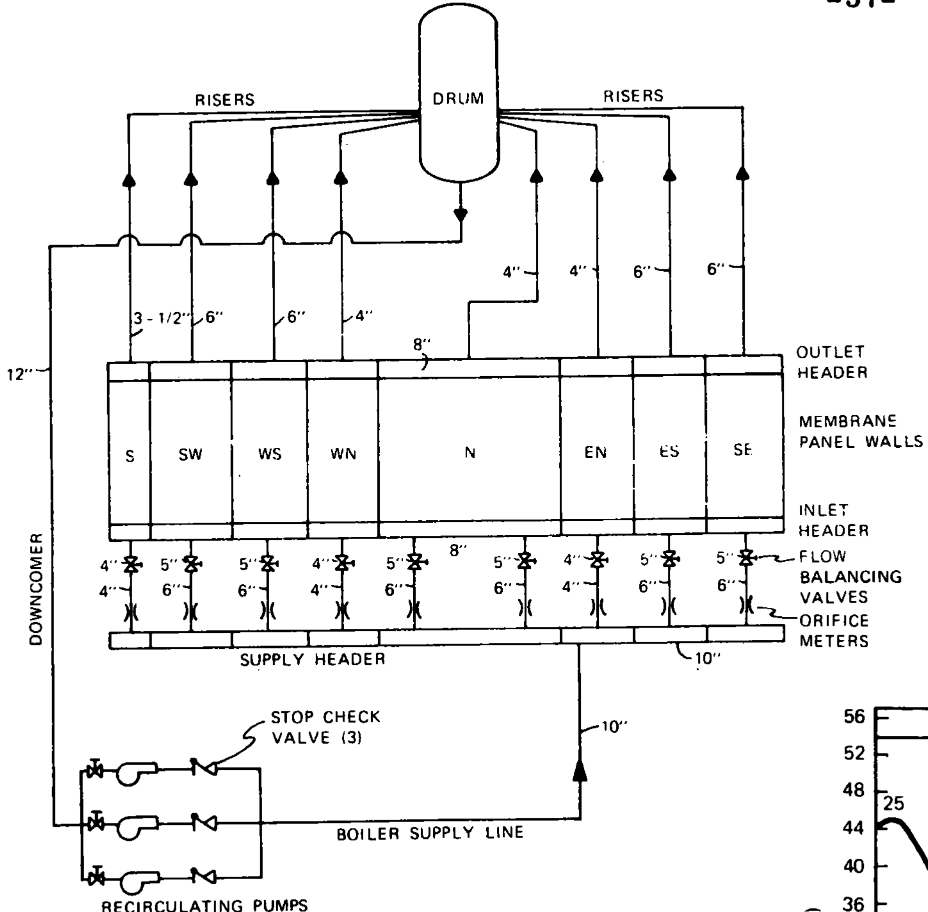


Location	P MPa (psia)	T C (F)	W kg/s (lb/hr)
	12/21/2p.m.		
① Feedwater		171 (339)	799 (105.6×10^3)
② Pump Inlet	11.36 (1649)	313 (594)	10280 (1358×10^3)
③ Pump Discharge	11.71 (1699)	313 (594)	10280 (1358×10^3)
④ Drum Discharge	11.23 (1630)	320 (608)	799 (105.6×10^3)
⑤ Primary Outlet	11.00 (1597)	461 (862)	799 (105.6×10^3)
⑥ Attemperator Spray		171 (339)	74 (9.8×10^3)
⑦ Secondary Inlet	10.97 (1592)	390 (733)	874 (115.4×10^3)
⑧ Secondary Outlet	10.77 (1563)	515 (960)	874 (115.4×10^3)

PILOT PLANT STEAM GENERATOR FLOW CIRCUIT

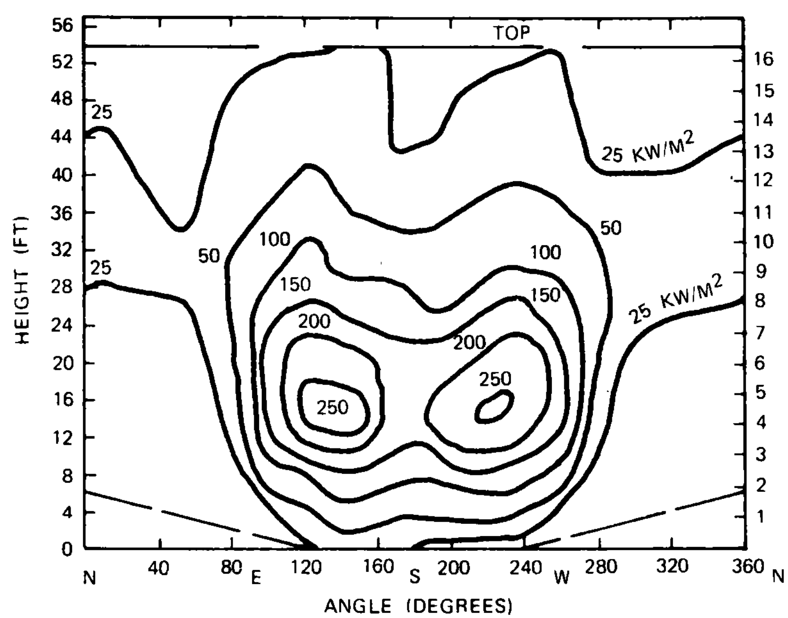
BOILER FLOW CIRCUITRY

The membrane panel section flows are matched to the cavity flux density azimuthal distribution. The flows are adjusted to achieve variable absorption resulting in uniform boiler wall temperatures. Flow and heat absorptance balancing is accomplished by eight (8) flow circuits. Each circuit includes a supply tube, a hand valve for initial adjustment of flow resistance, a flow orifice meter, an inlet header, membrane panel heat transfer surface, an outlet header, and a riser which returns the working fluid to the drum.



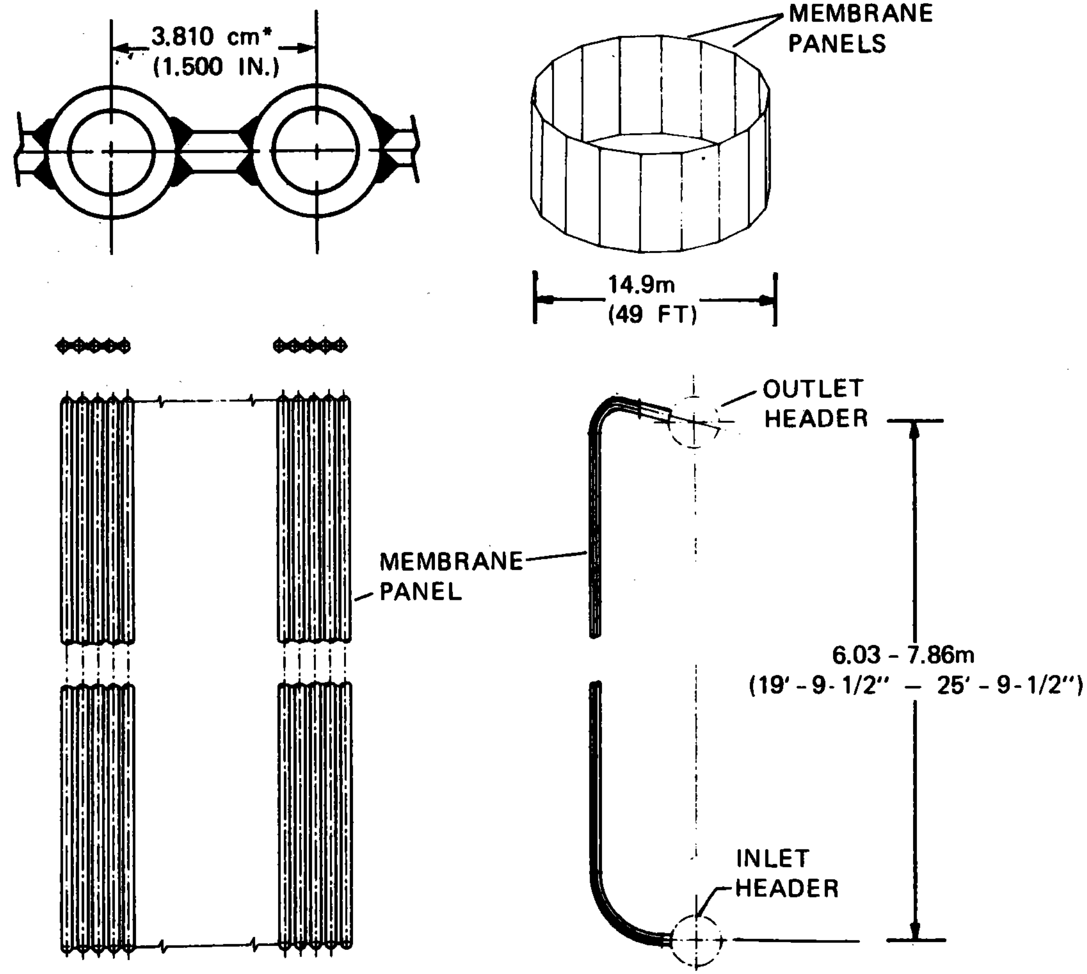
STEAM GENERATOR BOILER HYDRAULIC CIRCUIT

CAVITY FLUX DISTRIBUTION



BOILER WALL DESIGN

The steam generator employs standard fossil technology. The Pilot Plant membrane wall design is identical to the tested SRE design. The headers and heat transfer surfaces form one continuous welded structure to achieve strength and rigidity. The boiler section walls are constructed from flat membrane wall sections composed of panels of multiple rows of tubes connected by continuously welded membrane bars along the centerline of each tube. The inlet and outlet headers are attached at the factory.



SPECIFICATIONS:

TUBE:

O.D.	2.223 cm	(.875 IN.)
MIN. WALL	0.376 cm	(0.148 IN.)
MAT'L.	SA 210 GRADE A1CF	

WEB:

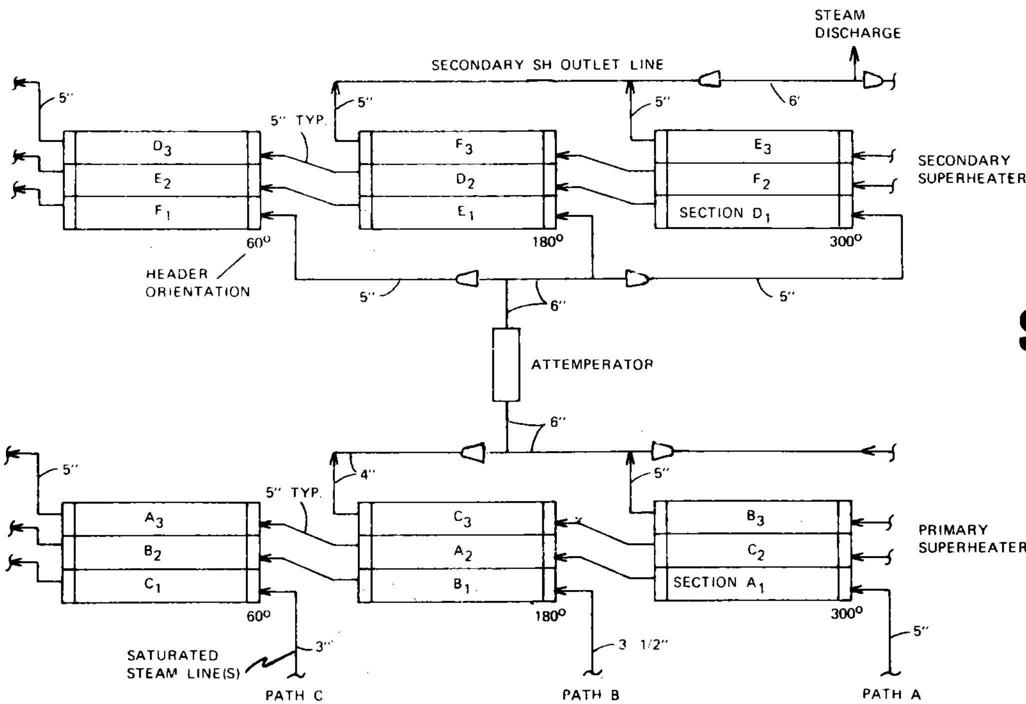
THICKNESS	.635cm (0.25 IN.)
MAT'L.	CARBON STEEL (C1015 C.F.)

*7.62cm (3.0 INCH) ON NORTH WALL

PILOT PLANT STEAM GENERATOR BOILER DESIGN

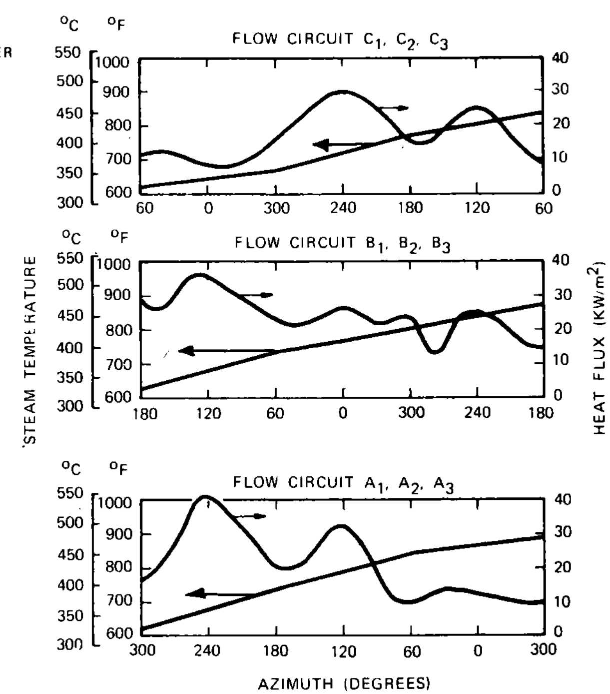
SUPERHEATER DESIGN

The Pilot Plant design utilizes prefabricated superheater tube panels, which are plumbed together to provide the functional equivalent of the SRE spiral design. This minor design change was made to obtain the cost reduction allowed by prefab construction methods versus on-site fabrication. The performance of this design is excellent, and it has the additional desirable feature of further reducing thermal stress levels.



SUPERHEATER FLOW CIRCUIT

SUPERHEATER FLUX AND FLUID TEMPERATURE



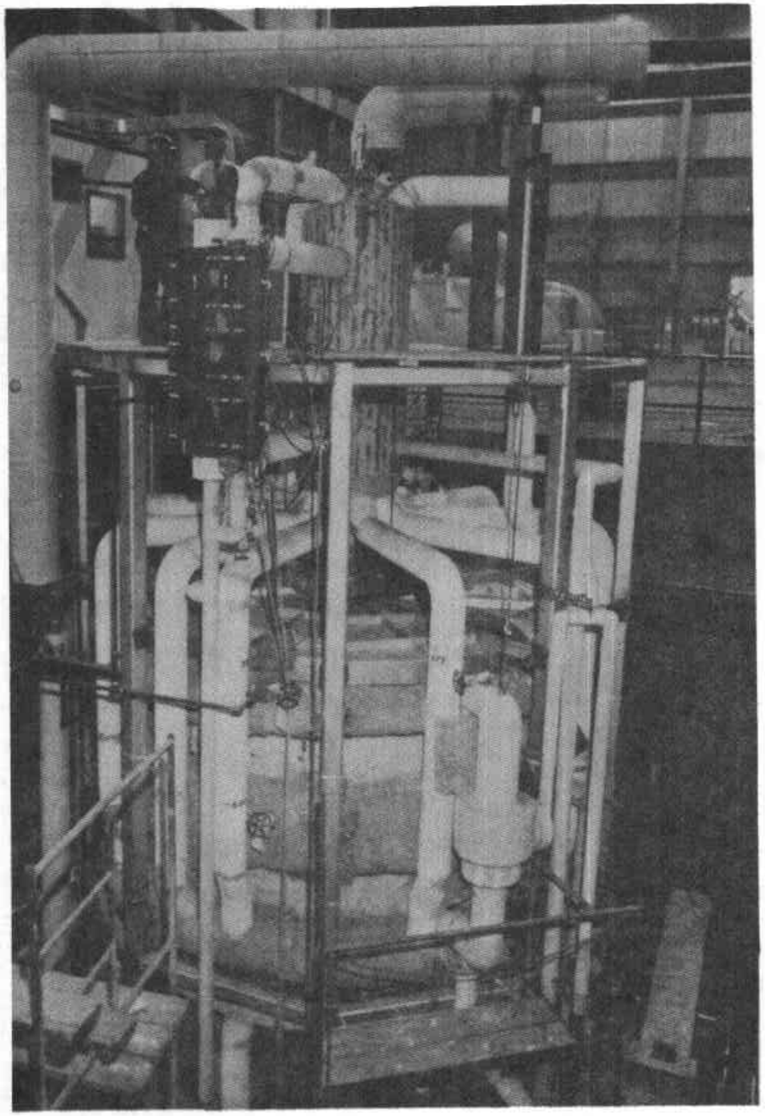
SRE STEAM GENERATOR TESTS

The steam generator was tested as a subsystem research experiment. The SRE steam generator, a one-tenth capacity version of the pilot plant design, was installed in an empty turbine well at the Riverside power plant of Northern States Power Company. A nine megawatt radiant heat source simulated the solar energy that the collector subsystem supplied in the pilot plant distribution system.

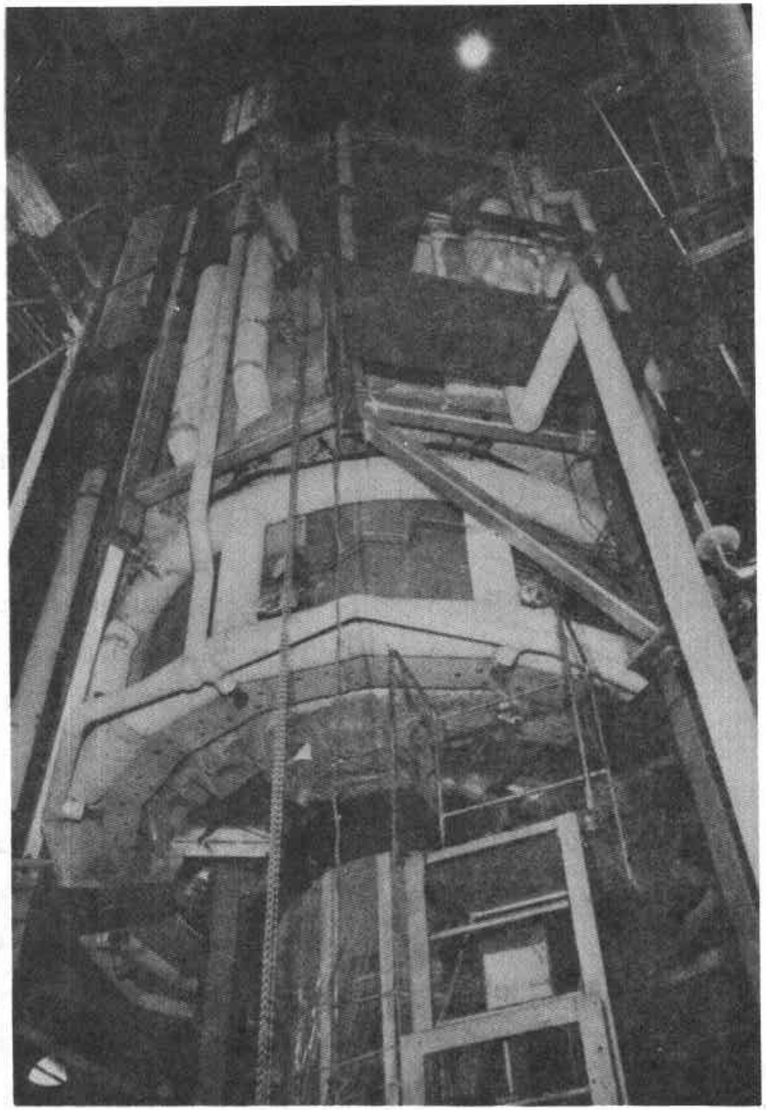
The test emulated typical power plant operations using power plant personnel under the guidance of Honeywell engineers. Feed water was supplied by a fossil boiler. The tests were successful, and results verify the pilot plant design.

Several groups, including foreign government representatives, interested in solar energy reviewed the steam generator. It was featured on television news programs and in newspapers.

The steam generator was selected as one of the seven wonders of engineering for 1977 by the Minnesota Society of Professional Engineers.



Side View



Cavity View

SOLAR BOILER

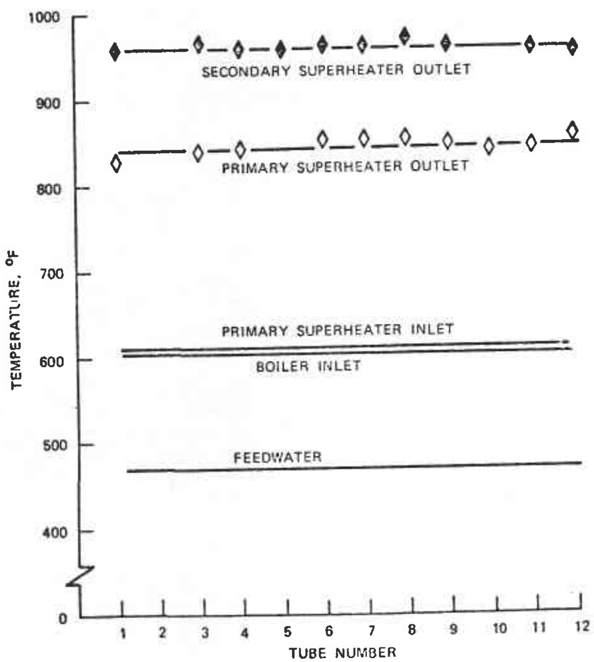
SRE TEST CORRELATION

Predicted performance data has been compared with actual measured data from the Riverside tests and they agree very very closely. While additional testing is highly desirable to gain additional insight into the steam generator operation, no questions remain as to the validity of the design methodology.

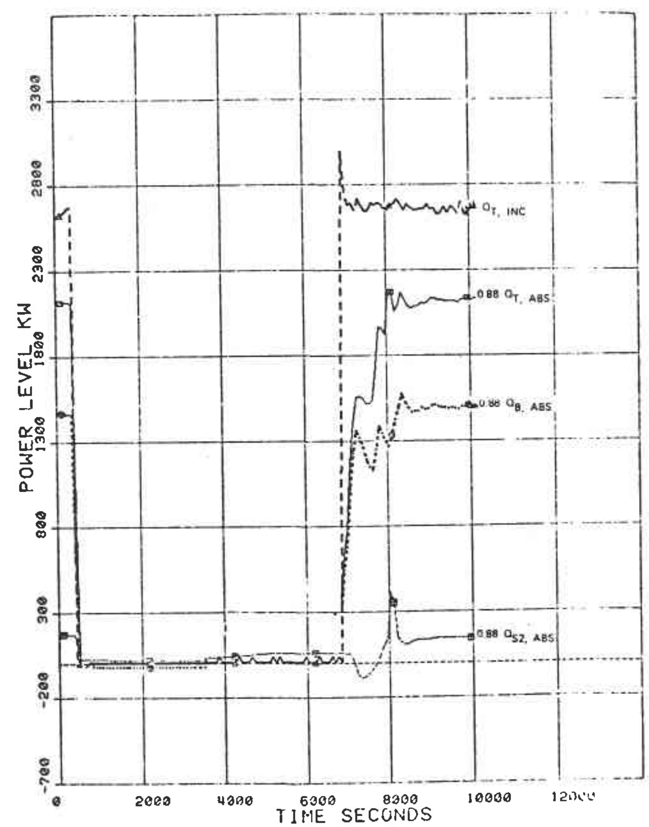
SRE STEADY STATE DATA APRIL 13, 1977 11:37 AM

INCIDENT ENERGY	3.2 MW
ENERGY LOSS	0.18 MW
ABSORBED ENERGY	3.0 MW
BOILER	2.1 MW
PRIMARY SUPERHEATER	0.67 MW
SECONDARY SUPERHEATER	0.22 MW

	MEASURED			PREDICTED
LOCATION	FLOW (LBM/HR)	TEMPERATURE (°F)	PRESSURE (PSIA)	PRESSURE (PSIA)
FEEDWATER	9924	469	1915	–
BOILER INLET	86900	603	–	–
BOILER OUTLET	86900	610	–	–
DRUM	10136	610	1670	1670
PRIMARY SH OUT	10136	843	1641	1642
SECONDARY SH OUT	10136	958	1601	1594



CLOUD TRANSIENT



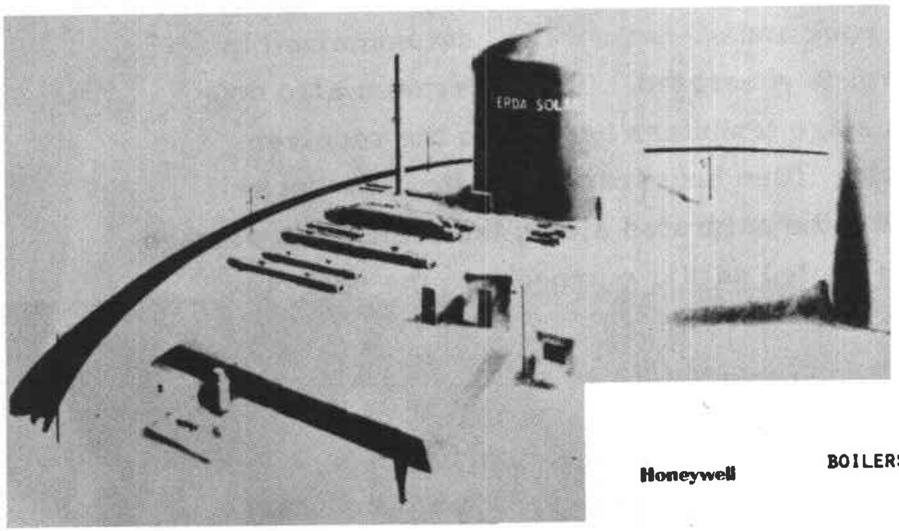
SRE TEST CORRELATION

THERMAL STORAGE SUBSYSTEM

The Honeywell pilot plant thermal storage subsystem is a two-stage sensible heat storage arrangement that uses rock and oil in the first stage and an inorganic salt mixture in the second stage. This design is based on a 100 MW(e) commercial configuration.

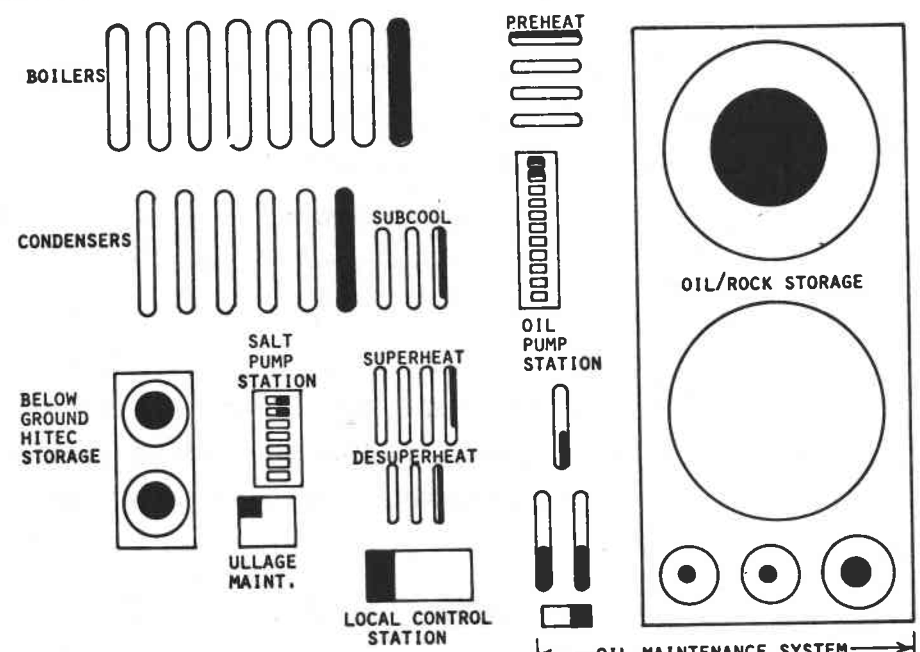
The guiding precepts used in the development of this design included modular equipment, standard components and materials of construction, and proven parts and components.

ARTIST'S CONCEPT



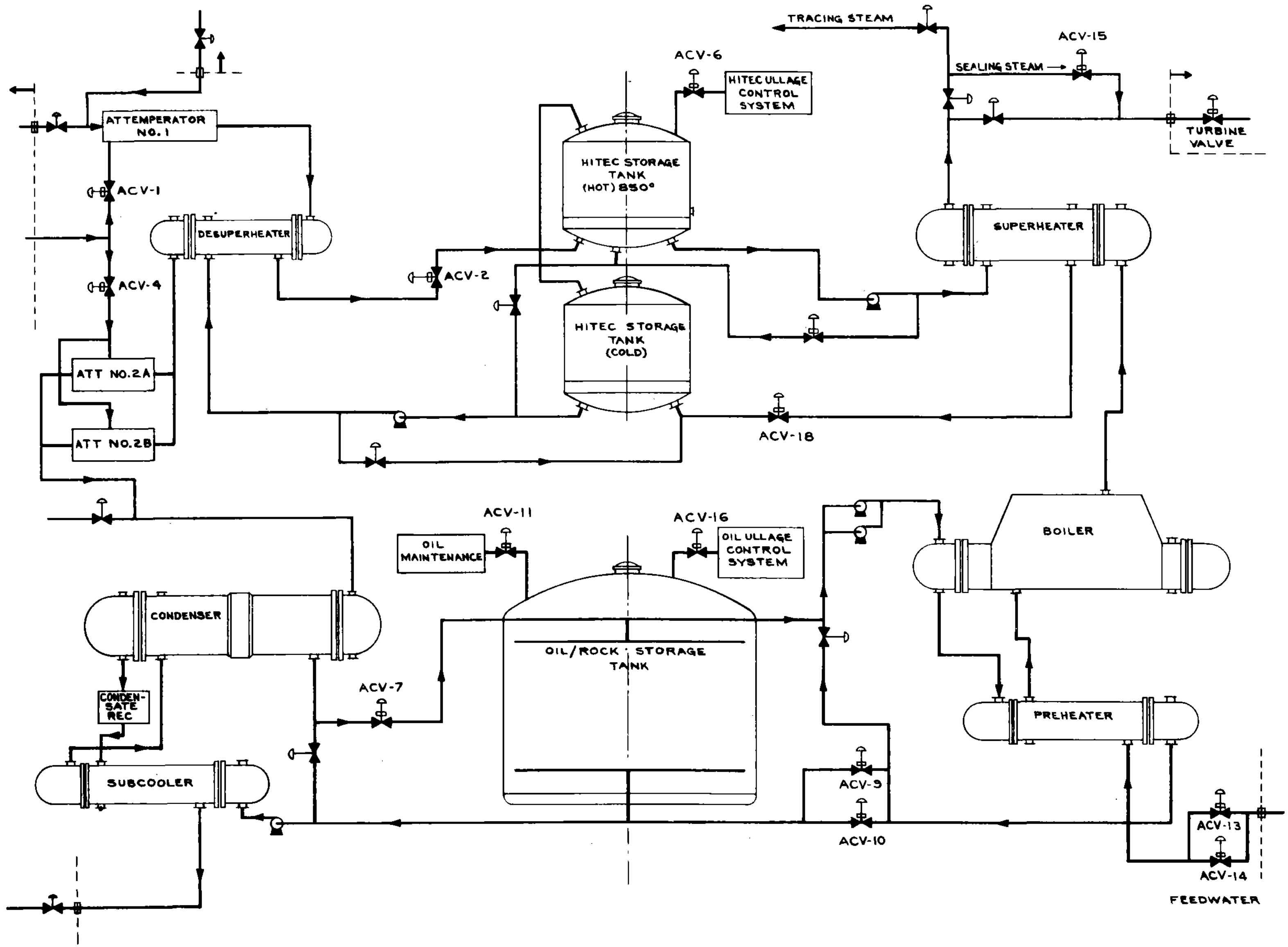
Honeywell

100 MW(e) COMMERICAL PLANT WITH PILOT PLANT OVERLAY



THERMAL STORAGE SUBSYSTEM DESIGN FEATURES

The subsystem contains a main storage stage that transfers the latent heat in steam to Caloria HT-43 oil and stores it in the rock and oil tank. The heat contained in the tank is discharged and saturated steam is generated. The subsystem also contains a superheater storage stage. This stage transfers heat from the receiver supplied steam into a hot storage tank using Hitec heat transfer salt. The hot salt energy is discharged and used to superheat the saturated steam from the main storage to the turbine admission conditions. The cooled salt is pumped into the cold tank. The maximum charge and discharge rate through storage is 31. 6 MW(t). The oil and rock tank and main boiler also supplies twenty hours of tracing steam via auxiliary control equipment.



THERMAL STORAGE SUBSYSTEM SCHEMATIC

THERMAL STORAGE SUBSYSTEM BASELINE CHARACTERISTICS

Eighty seven percent of the stored thermal energy is in the main stages. The rock and oil tank contains 7161 ton of granite, 12.5 mm in diameter and 828,000 litters of oil. The tank material is a high yield low alloy steel A-533 and is designed to withstand repeated cycling from 300°C to ambient. The superheater storage contains two tanks to transfer salt from one to the other. Below ground storage reduces the stresses due to thermal cycling, isolates the storage from the oil, and is the most economical solution for tank heat loss. The daily heat loss for the superheater storage alone is only 0.05% of total stored capacity. The 7.0 MW(e) net is available from storage within one minute of the demand signal. The increase in the gross thermal efficiency from pilot to commercial plant reflect the efficiency of scale. The charge efficiency accounts for the fact that high pressure water leaves storage as condensate with an enthalpy above that of the receiver feedwater. The Main Storage thermocline efficiency of 77.4% includes a 98% charge efficiency and 3% growth during hold and discharge resulting in a net 77.4% at discharge.

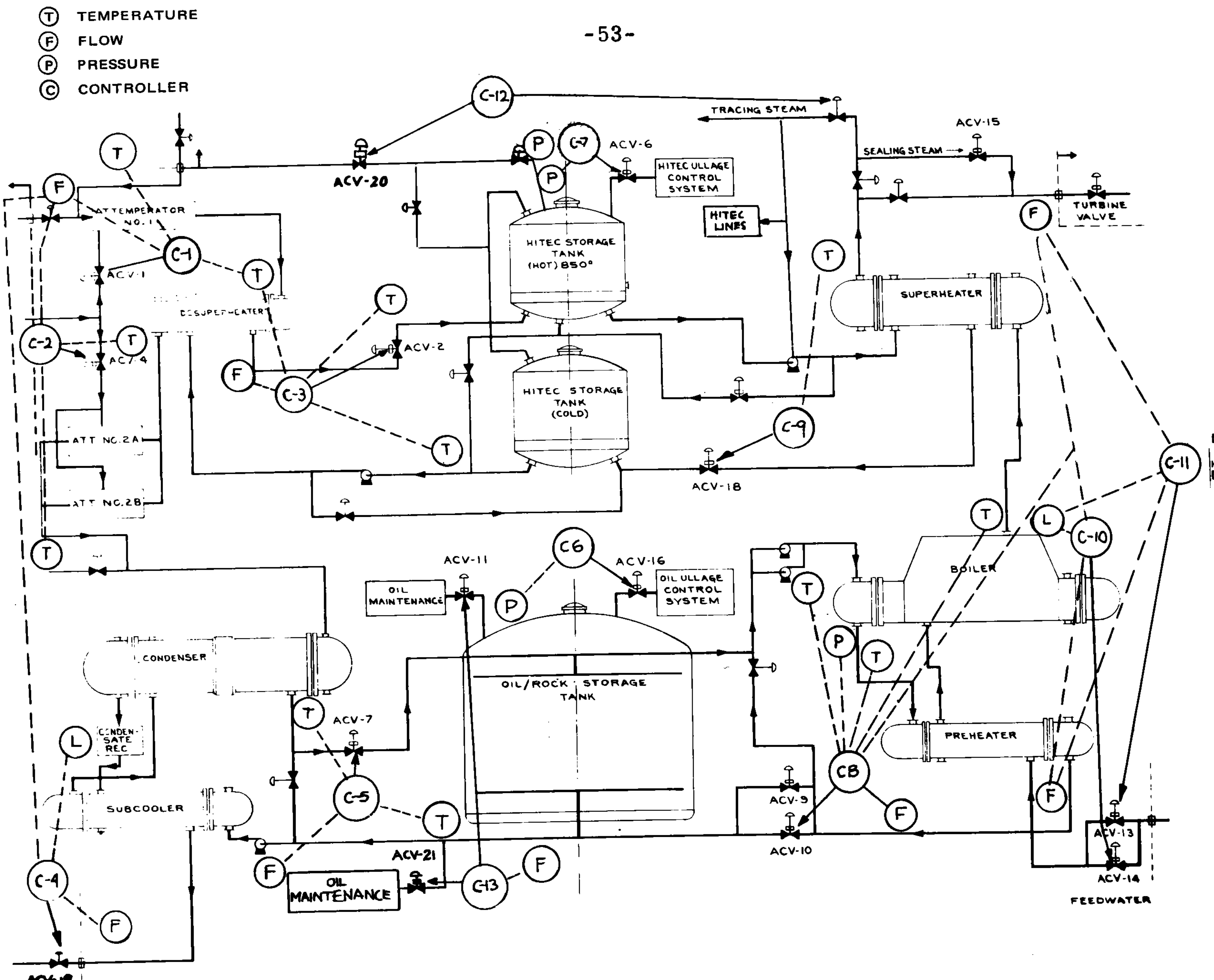
THERMAL STORAGE SUBSYSTEM BASELINE CHARACTERISTICS

Parameter	Pilot Plant	Commericial Plant
Storage Capacity, MWH(t)	133	961
Main Storage, MWH(t)	116	831
SH Storage, MWH(t)	17	130
Main Storage Media	Caloria Oil/Rocks	Caloria Oil/Rocks
Operational Availability	98%	98%
SH Storage Medium	Hitec Salt	Hitec Salt
Main Storage Tankage-Quantity	One	Two
Diameter, Meters	18.3	34.8
Wall Height, Meters	14.6	14.6
SH Storage Tankage	Two cylindrical tanks with dished heads-below ground	
Diameter, Meters	6.1	12.2
Wall Height, Meters	4.9	9.8
Heat Loss Rate, %Capacity/Day	5	5
Operating Temperatures		
Main Storage, °C	303→249	303→249
Min. Oil Temperature When Charged, °C	300	300
Discharged, °C	249	249
SH Storage, °C	454→299	454→299
Sealing & Tracing Steam, % of Capacity	6.0	2.3

Parameter	Pilot Plant	Commercial Plant
Net Elect. Output, MW(e)	7.0	70.0
Duration, hours	3	3
Charge P/T, kPa/°C	10101/510	10101/510
Discharge P/T, kPa/°C	3620/390	3620/390
Gross turbine H. R. WH(t)/WH(e)	3.512	3.145
Gross thermal efficiency	0.285	0.318
Net thermal efficiency	.221	.291
Max. Discharge Rate, MW(t)	31.6	284.5
Gross Charge Input Rate, MW(t)	37.7	247.3
Max. Charge Rate, MW(t)	31.6	207.2
Charge Efficiency	0.838	0.838
Thermocline Utilization Efficiency-MS (including 20 hours of hold)	0.774	0.774
Feedwater Temperature, °C	205	190.5
Feedwater Flow, kg/h	49,025	411,135

THERMAL STORAGE CONTROL/RESPONSE

The storage subsystem has been designed to respond to a discharge demand instantaneously limited only by valve and actuator response times. Thermal lags are minimized by periodically cycling the oil and Hitec discharge auxiliary pumps to maintain boiler pressure and line heat losses. To manage all of the necessary control functions 13 analog controllers are specified with set point controllers. These set points can be manually positioned or automatically positioned through a direct digital control interface with plant master control. On the charge side controllers are used to maintain the steam at the proper temperature for heat transfer with the transfer fluids and for maintaining liquid inventory. On the discharge side controllers are used to supply steam at the proper pressure and temperature, to maintain the proper energy balance and to maintain liquid inventory.



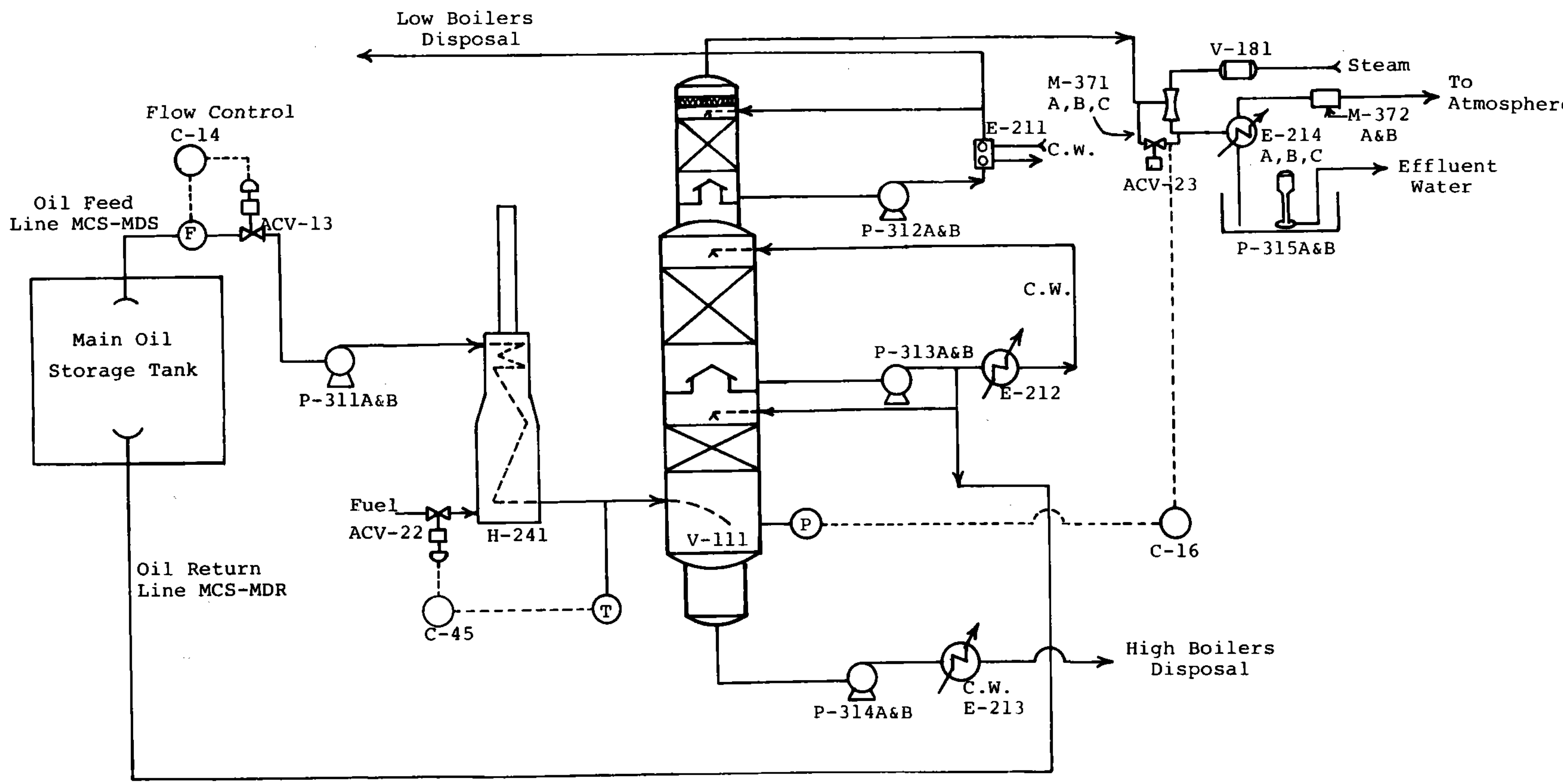
THERMAL STORAGE CONTROL SYSTM

THERMAL STORAGE MAINTENANCE UNITS

In order to keep the Caloria HT-43 hydrocarbon in a continuously useable form reprocessing must be done. Oil is withdrawn from the storage and heated in a charge heater. The charge enters the vacuum distillation tower and flash separation of the HT-43 with both the low boiling and high boiling fractions take place. The product is withdrawn and is returned to storage. The high boilers are removed from the bottom of the column and the low boilers are withdrawn from the top. Ancillary equipment provides the proper fluid conditioning.

The ullage maintenance unit consists of liquid nitrogen storage and a two-stage ambient air vaporizer. Gaseous nitrogen is supplied to both the Hitec and Oil Storage Tankage. The unit maximum rate was determined by the main storage discharge cycle conditions.

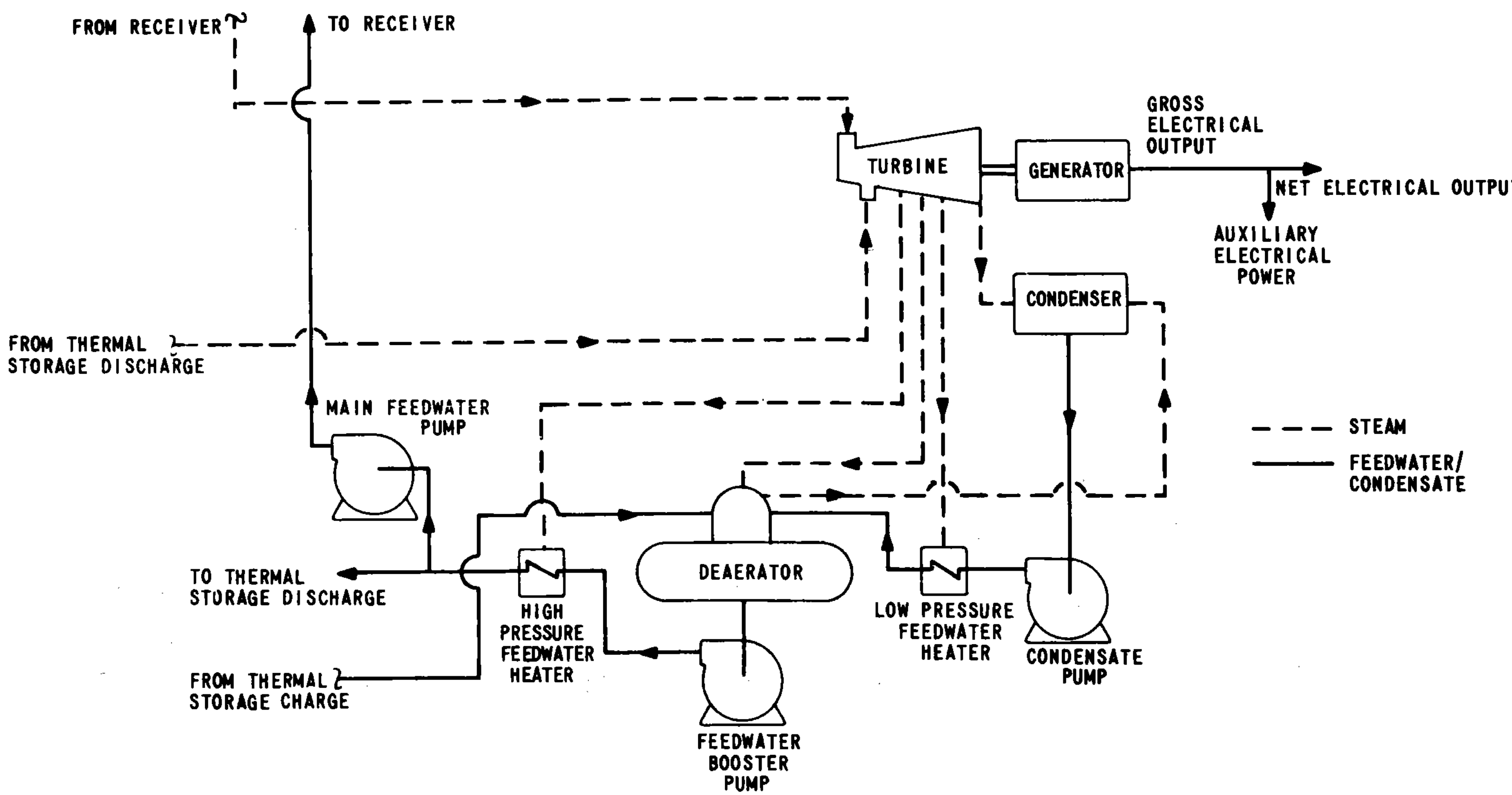
Both maintenance units are modular for the pilot and commercial plants.



OIL MAINTENANCE FLOW DIAGRAM

ELECTRICAL POWER GENERATION SUBSYSTEM

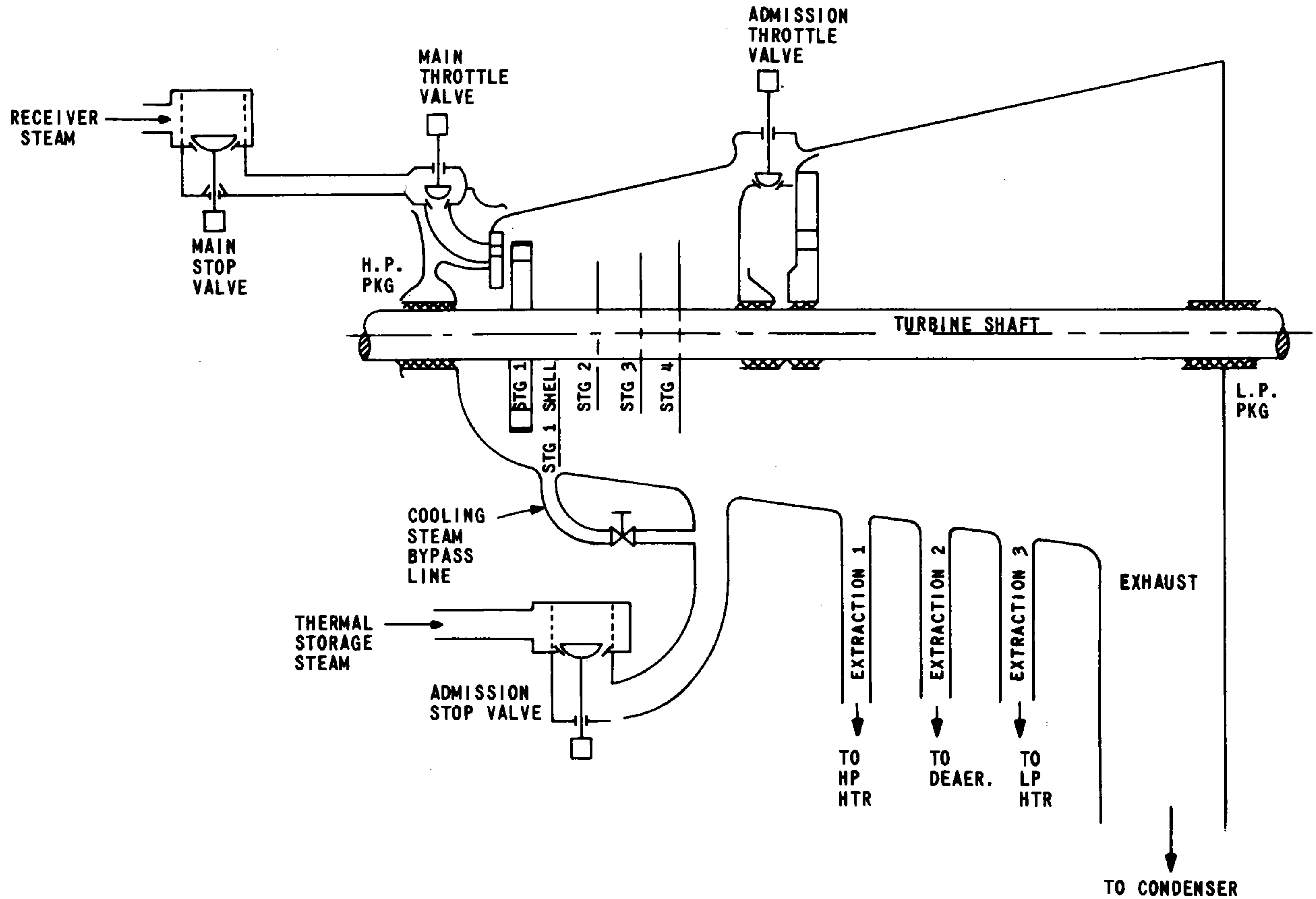
The Pilot Plant electrical power generation subsystem generates electrical power for satisfying the auxiliary power requirements of the plant as well as supplying power to the electric grid. The turbine accepts steam from the receiver through the throttle port or steam from the storage subsystem through the admission port. The condensed turbine exhaust steam is pressure and temperature conditioned to supply feedwater to the receiver, storage charge, and storage discharge flow circuits. A wet cooled condenser is employed. Six (6) operating modes are possible. These modes allow for a combination of steam sources and turbine/generator operation with various receiver, storage charge, storage discharge, and storage holding conditions.



PILOT PLANT ELECTRICAL POWER GENERATOR SUBSYSTEM

TURBINE

The electrical power generation subsystem employs a General Electric turbine generator set. The turbine is a 3600 rpm, non-reheat, condensing, bottom exhaust, single shell automatic admission type turbine. Three extraction parts for regenerative feedwater heating are located between the automatic admission port and the turbine exhaust. The turbine is directly connected to a rotating field, synchronous, totally enclosed, air cooled generator. Turbine characteristics permit instantaneous switchover from operation with receiver steam to operation with storage steam. Steam states at the admission ports allow for steam temperature matching.

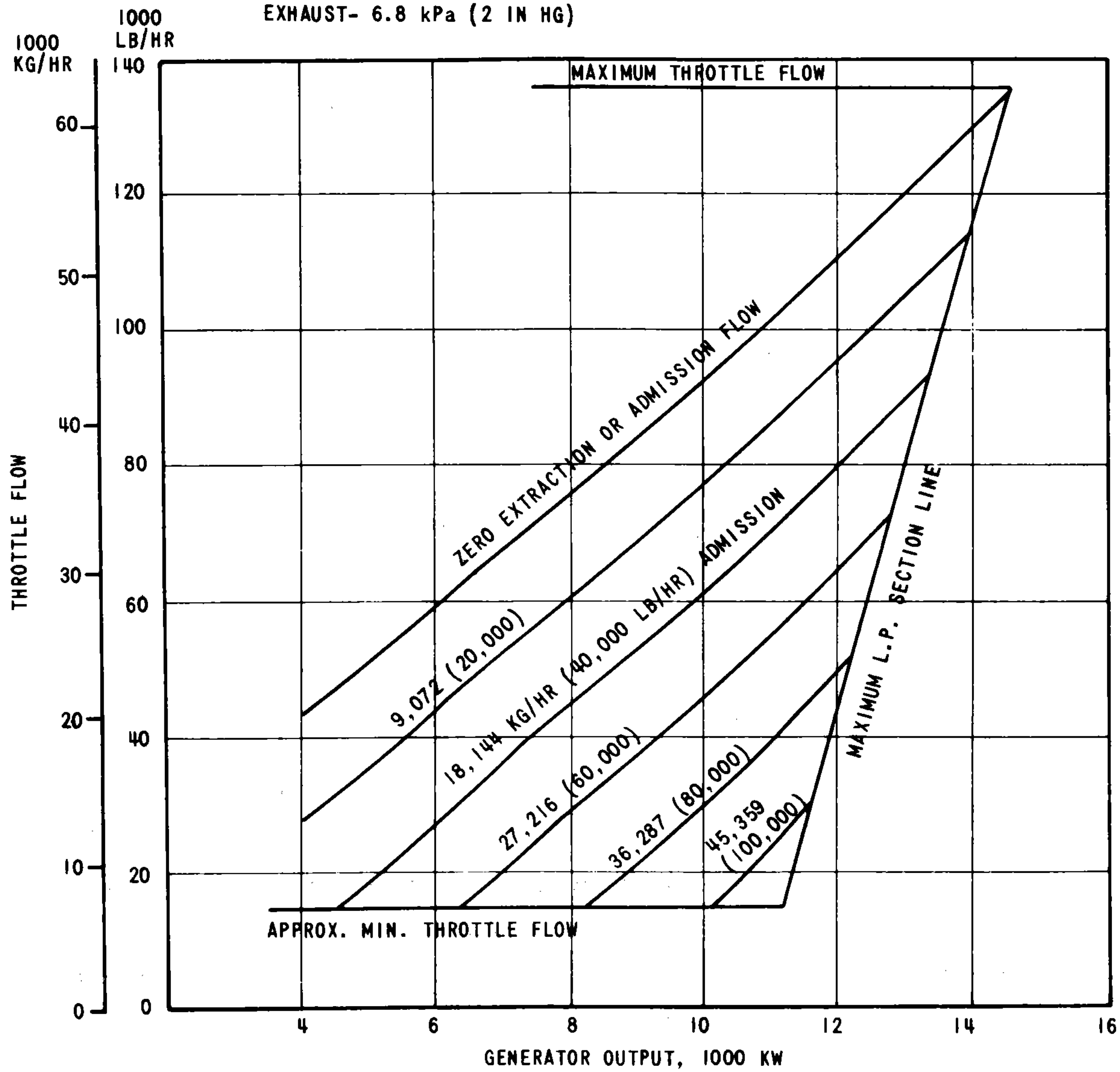


PILOT PLANT TURBINE

ELECTRICAL POWER CONVERSION SUBSYSTEM PERFORMANCE REQUIREMENTS

The Pilot Plant will generate 10 MW net busbar electricity at 2 pm on winter solstice using superheated steam supplied from receiver subsystem. It will also generate 7 MW net busbar electricity for three hours using superheater steam supplied from the thermal storage subsystem and 7 MW net busbar electricity using steam from receiver and thermal storage subsystems simultaneously. Furthermore, it will operate safely and reliably at the maximum steam flow generated by the receiver subsystem.

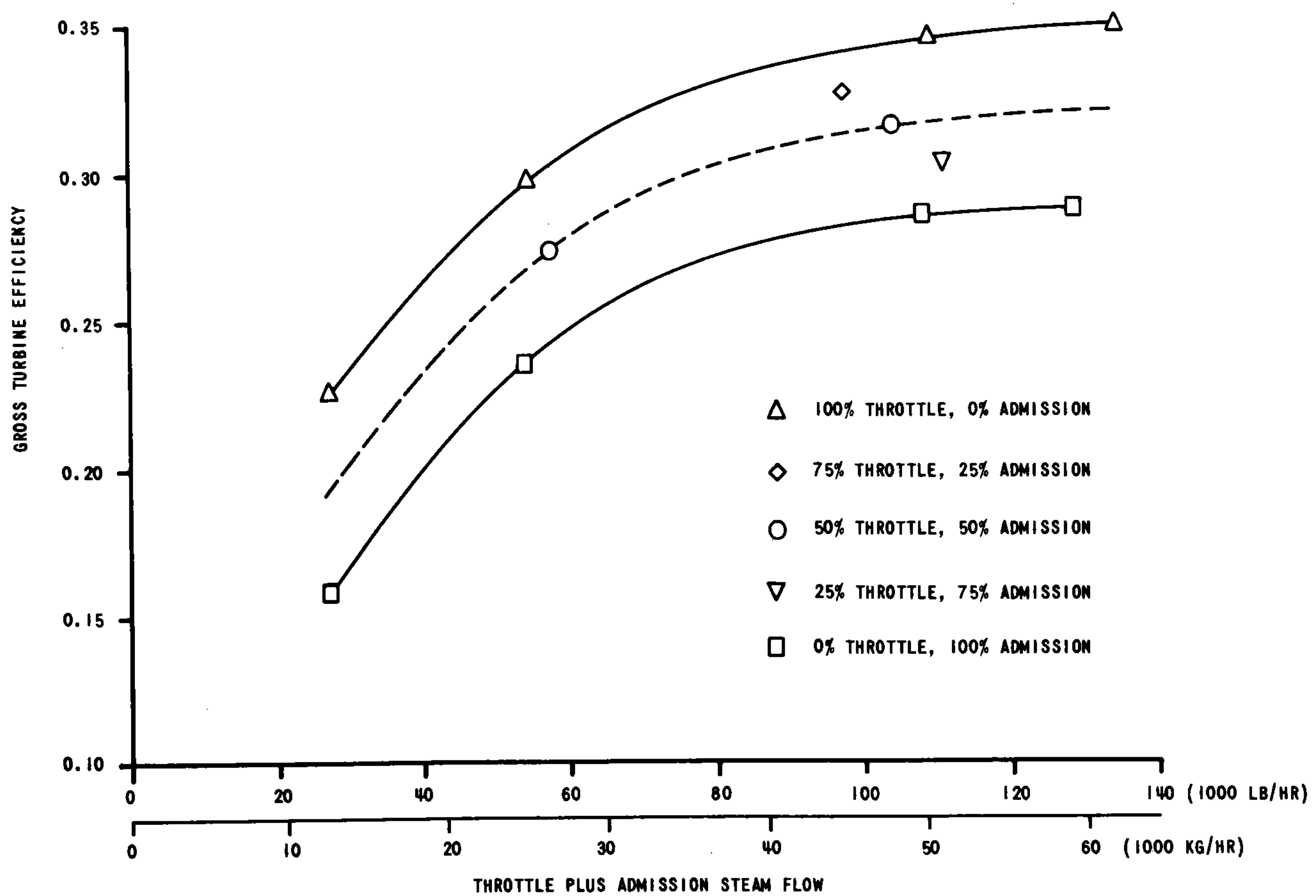
THROTTLE - 10101 kPa (1465 PSIA), 510°C (950°F)
ADMISSION - 3275 kPa (475 PSIA), 388°C (730°F)
EXHAUST- 6.8 kPa (2 IN HG)



PILOT PLANT GENERATOR OUTPUT

TURBINE EFFICIENCY

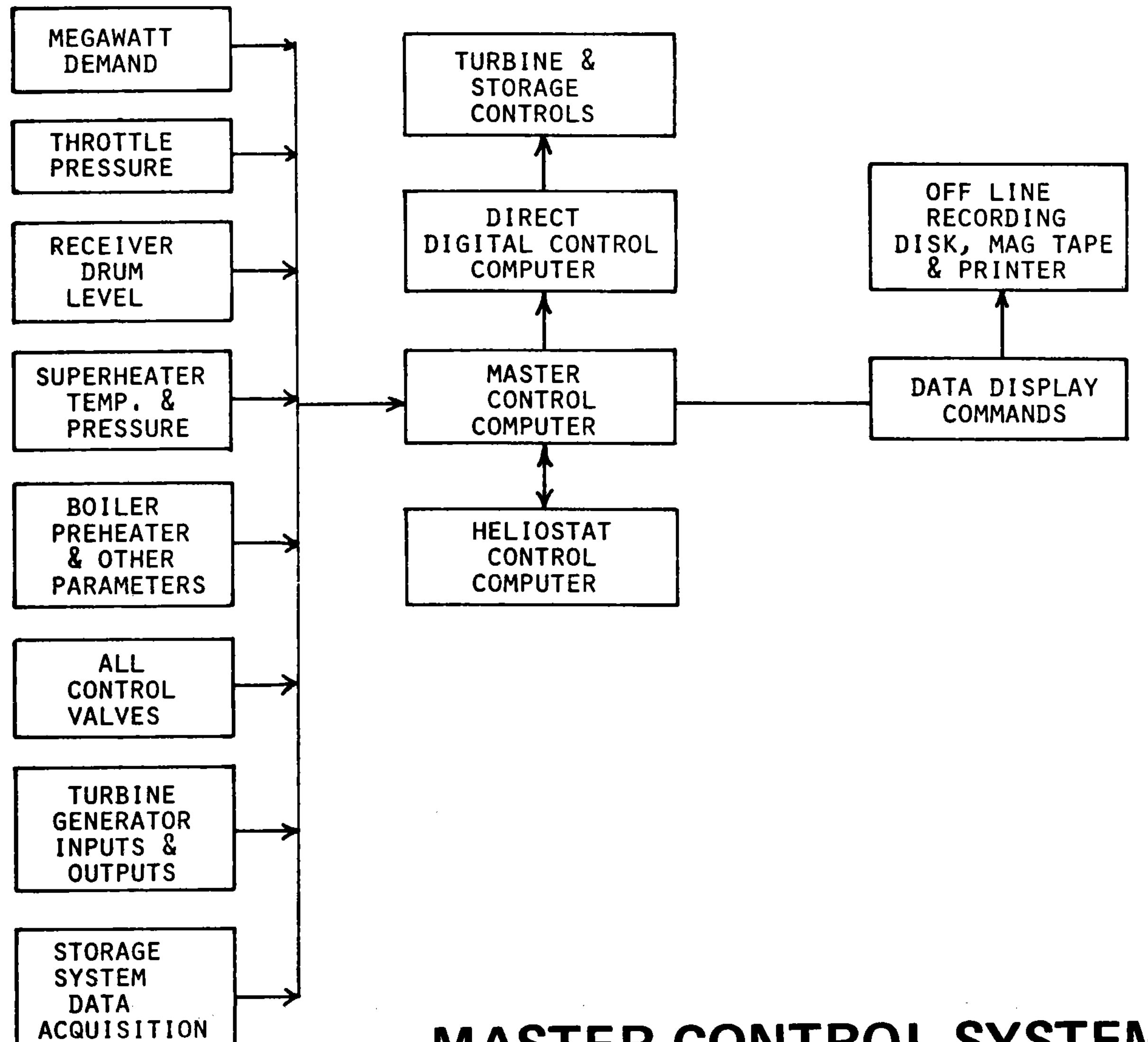
The General Electric automatic admission turbine offers high performance in a variety of plant modes. It is this high performance along with flexibility of operational modes that makes the Pilot Plant a valuable test bed for commercialization of solar power.



TURBINE EFFICIENCY

PLANT CONTROL

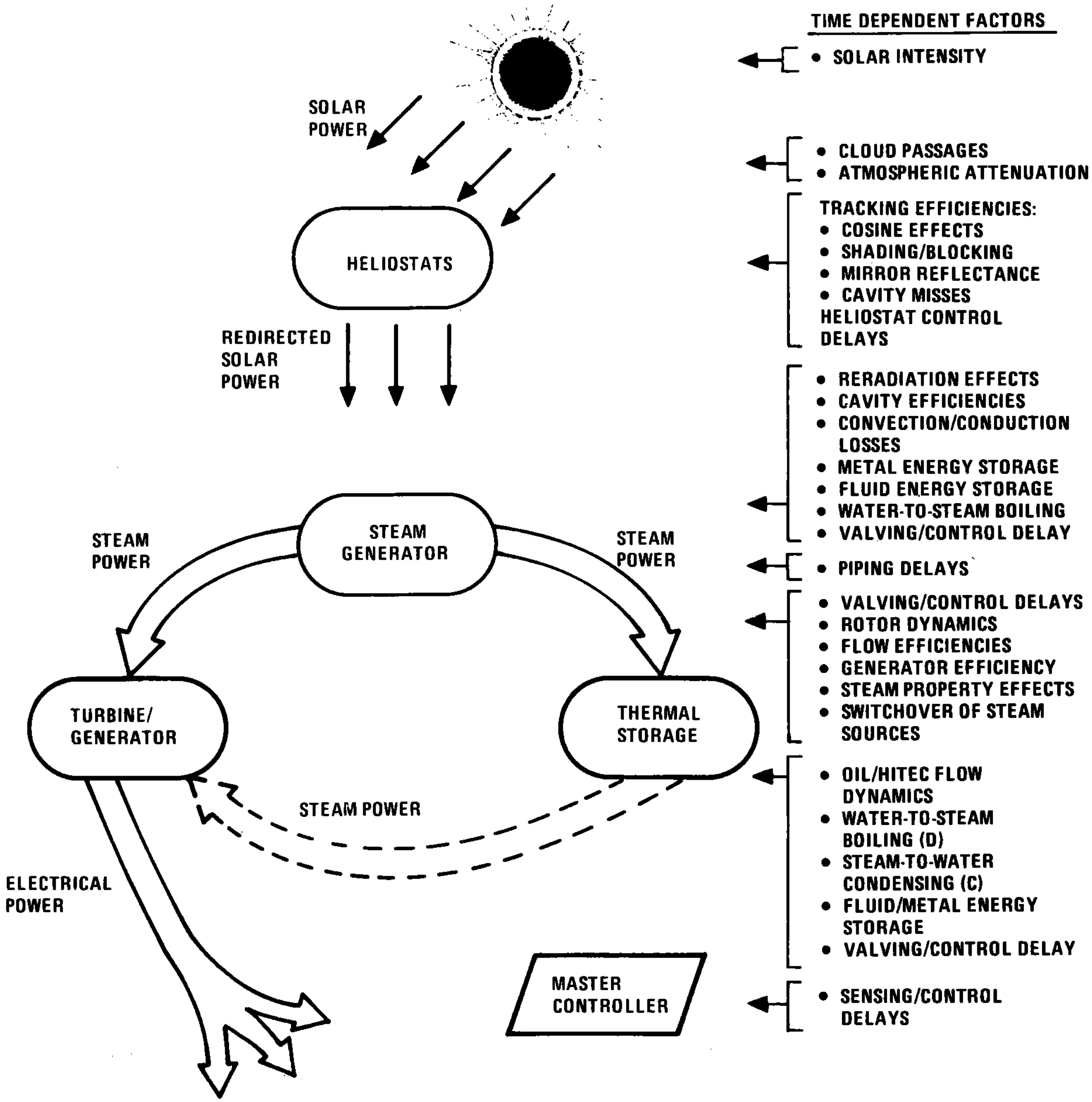
The coordinated master control is the highest level in the control hierarchy. Its function is to develop demand signals to "storage in", "storage out" and turbine governor controls based on the demand and any unbalance between steam generation and use. In operation, the system senses a deviation of generated megawatts from megawatt demand and commands the turbine governor to increase or decrease the load as required. If solar steam is generated at rates in excess of turbine requirements, an increase in turbine load demand uses the generated steam that would normally go into storage. If turbine load demand exceeds the solar steam generation rate, the system stops flow to storage and "holds down" the turbine until the resulting megawatt error causes the "storage out" to make up the difference from storage.



MASTER CONTROL SYSTEM

PILOT PLANT DYNAMIC ANALYSIS

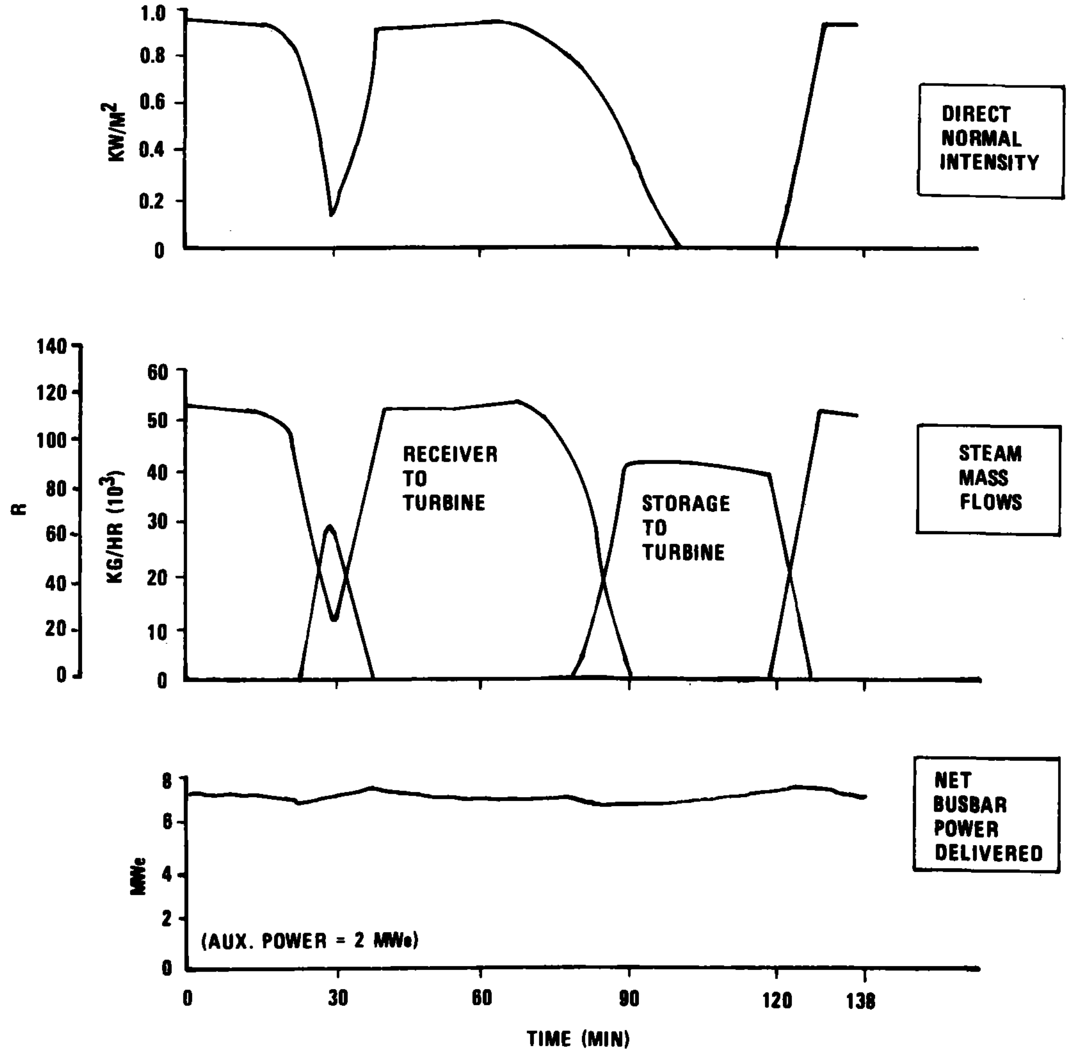
A detailed mathematical model of the pilot plant was developed to investigate the effect of transient conditions such as the diurnal variation of insolation, cloud passages, load demand changes and equipment failure.



PILOT PLANT DYNAMIC ANALYSIS

STABILITY TO TRANSIENT LOSS OF INSOLATION

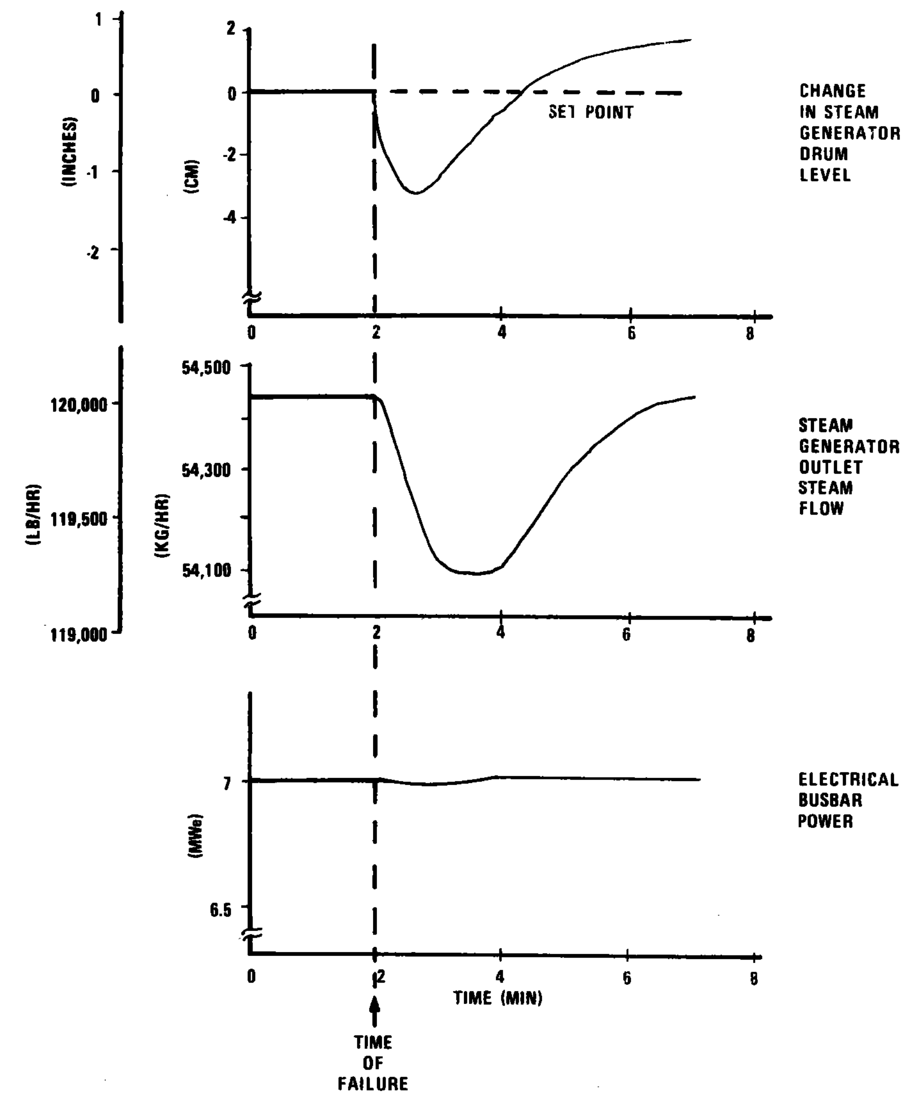
The simulation was exercised for several kinds of cloud passage situations that resulted in partial or total loss of insolation on the heliostat field at varying wind speeds. The response capability of the storage subsystem was critical in ensuring continued stable output.



STABILITY TO TRANSIENT LOSS OF INSULATION

EQUIPMENT FAILURE

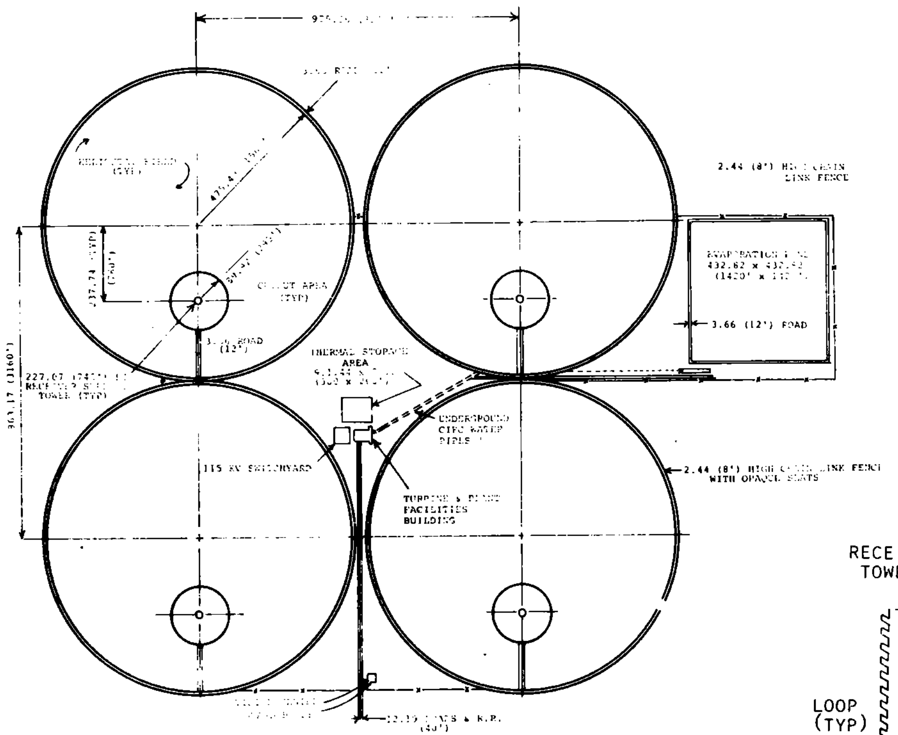
The effect of critical equipment failure, such as the recirculating pumps was investigated during the simulation. Again, the response of the storage subsystem stabilized conditions and prevented loss of output.



EQUIPMENT FAILURE

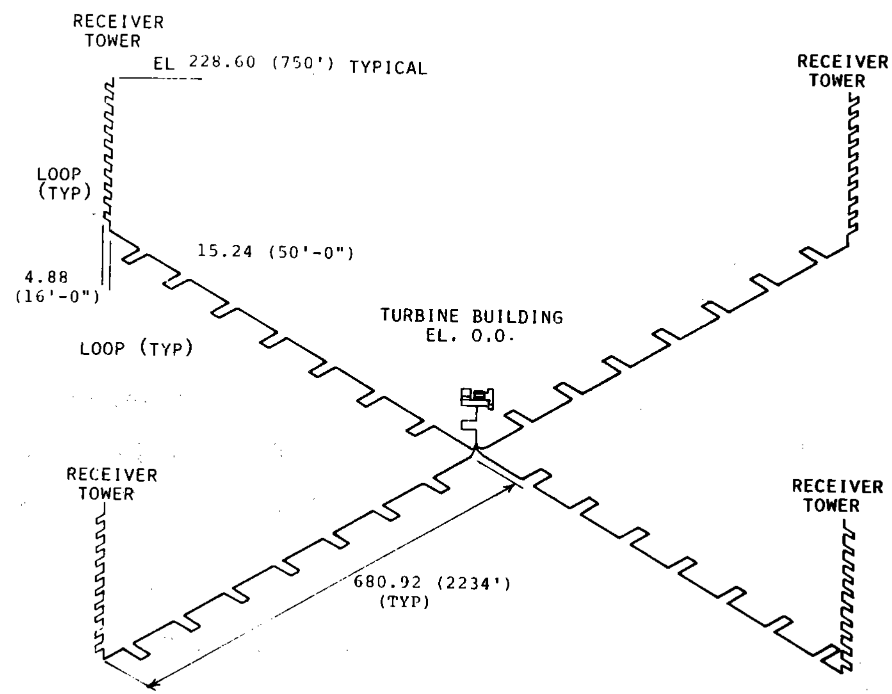
FIRST COMMERCIAL PLANT CONFIGURATION

The design of the first commercial plant features four receiver and collector fields. Each field and receiver produces one fourth the thermal power required for the plant to generate 100 MW(e) net. A central station complex is located at the centroid of the four receiver towers to minimize piping run lengths. The central station contains the 120 MW(e) nameplate turbine generator and balance of plant. The cooling tower and evaporation pond are located downwind with prevailing wind from the collector fields.



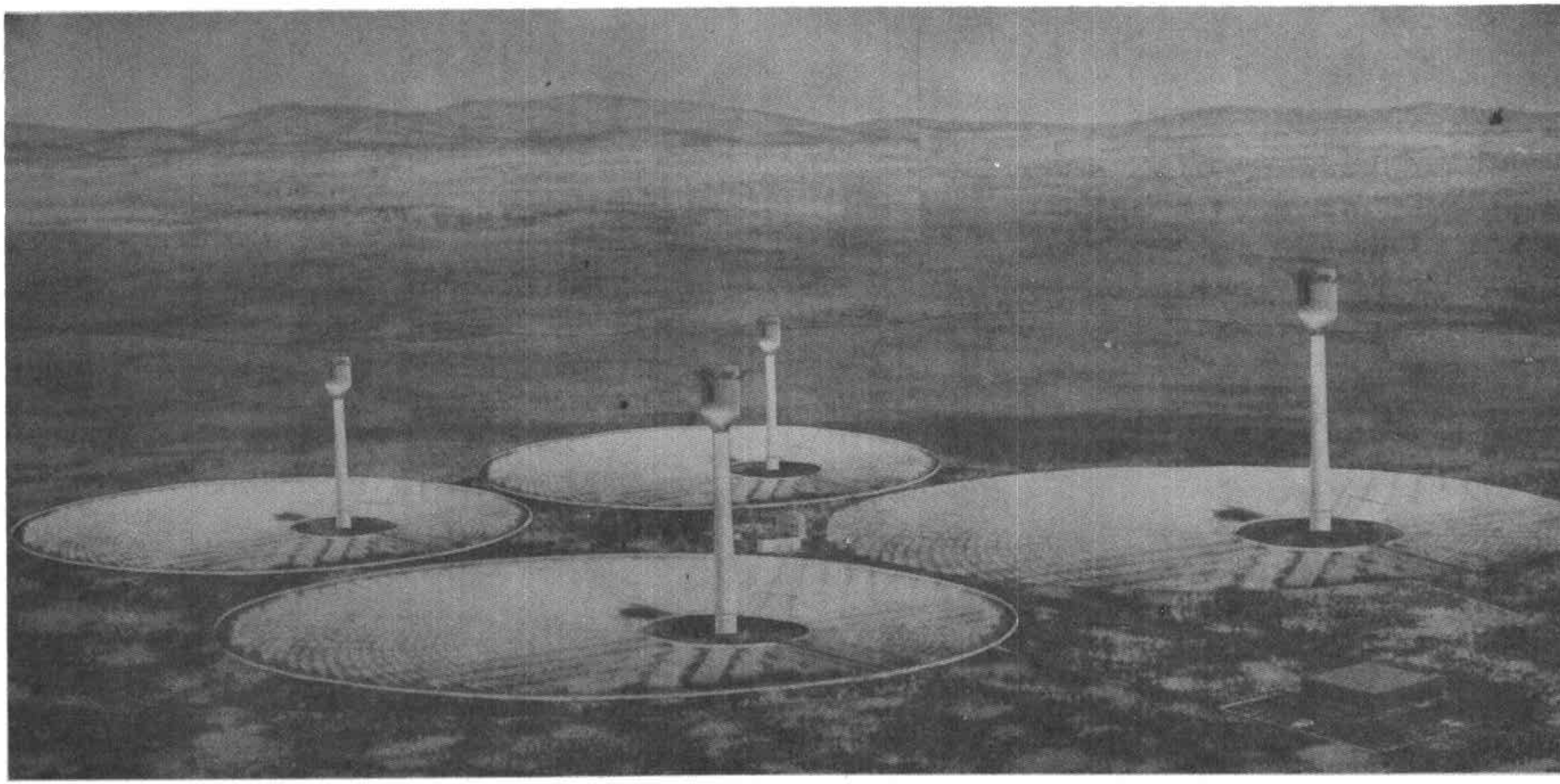
COMMERCIAL PLANT SITE PLAN

100 MW(e) MAIN STEAM LINES



PILOT AND COMMERCIAL BASELINES

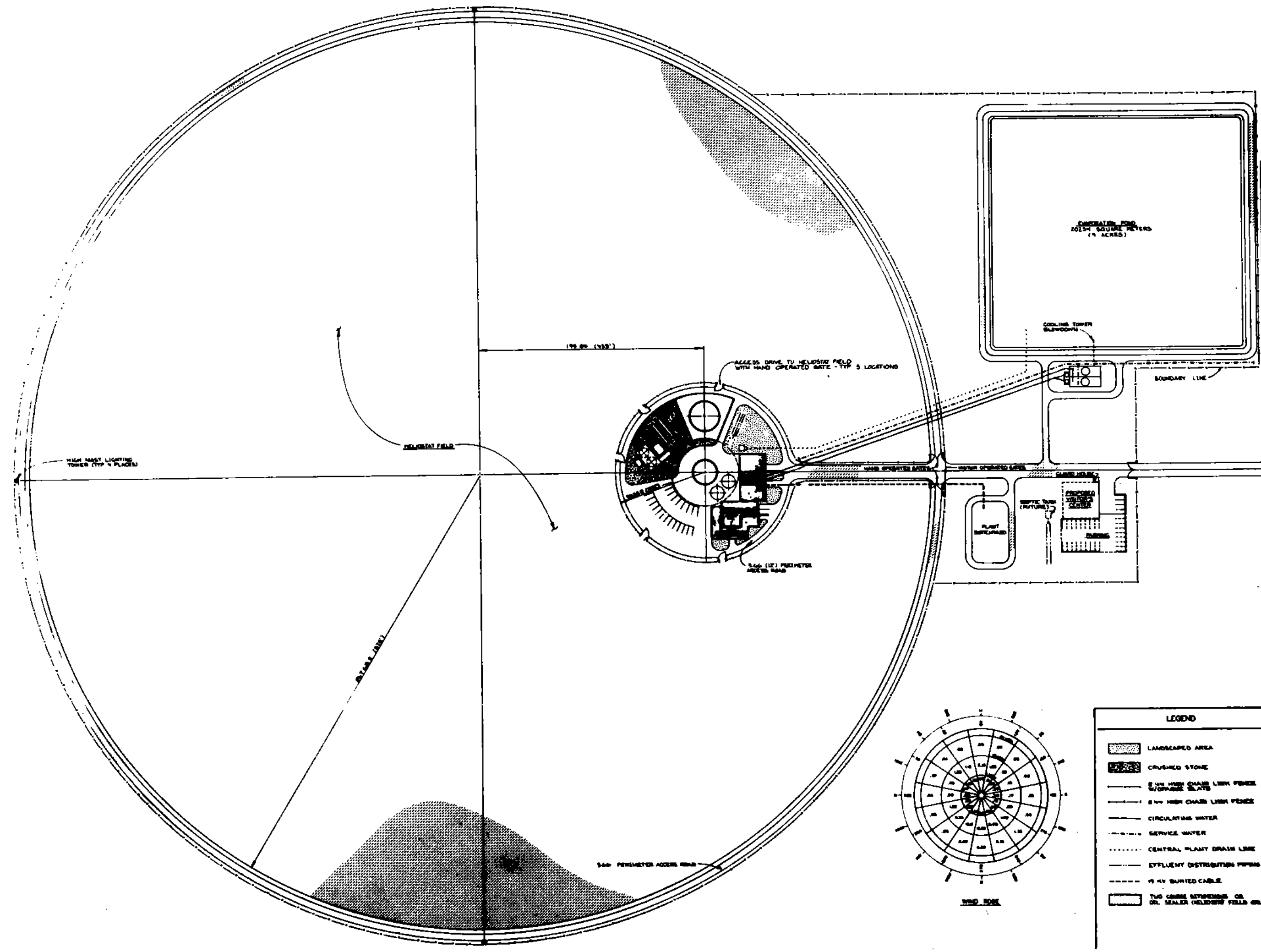
The direct scaling between the Pilot and Commercial Plants is a result of industrial/government planning which took place well before the Phase I program was initiated. It ensures that successful Pilot Plant demonstration guarantees a successful Commercial plant.



COMMERCIAL PLANT CONCEPTUAL DESIGN

PILOT PLANT SITE PLAN

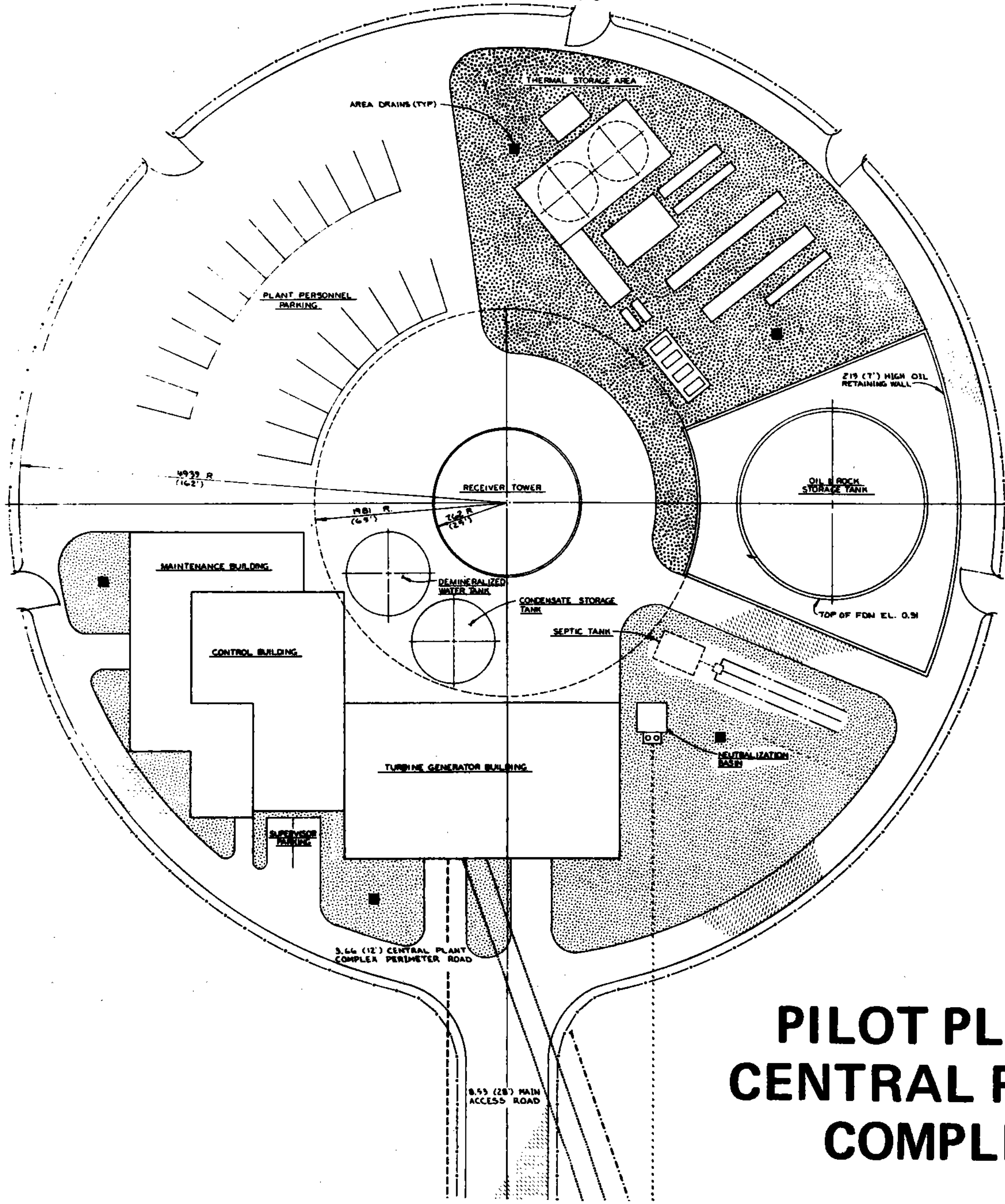
The Site Plan at Barstow, California features the heliostat field with the central tower complex surrounded by security fencing. The entrance from the south features a visitors center and plant security. The cooling tower is located down wind. An evaporation pond completes the site elements.



PILOT PLANT SITE PLAN

PILOT PLANT CENTRAL COMPLEX

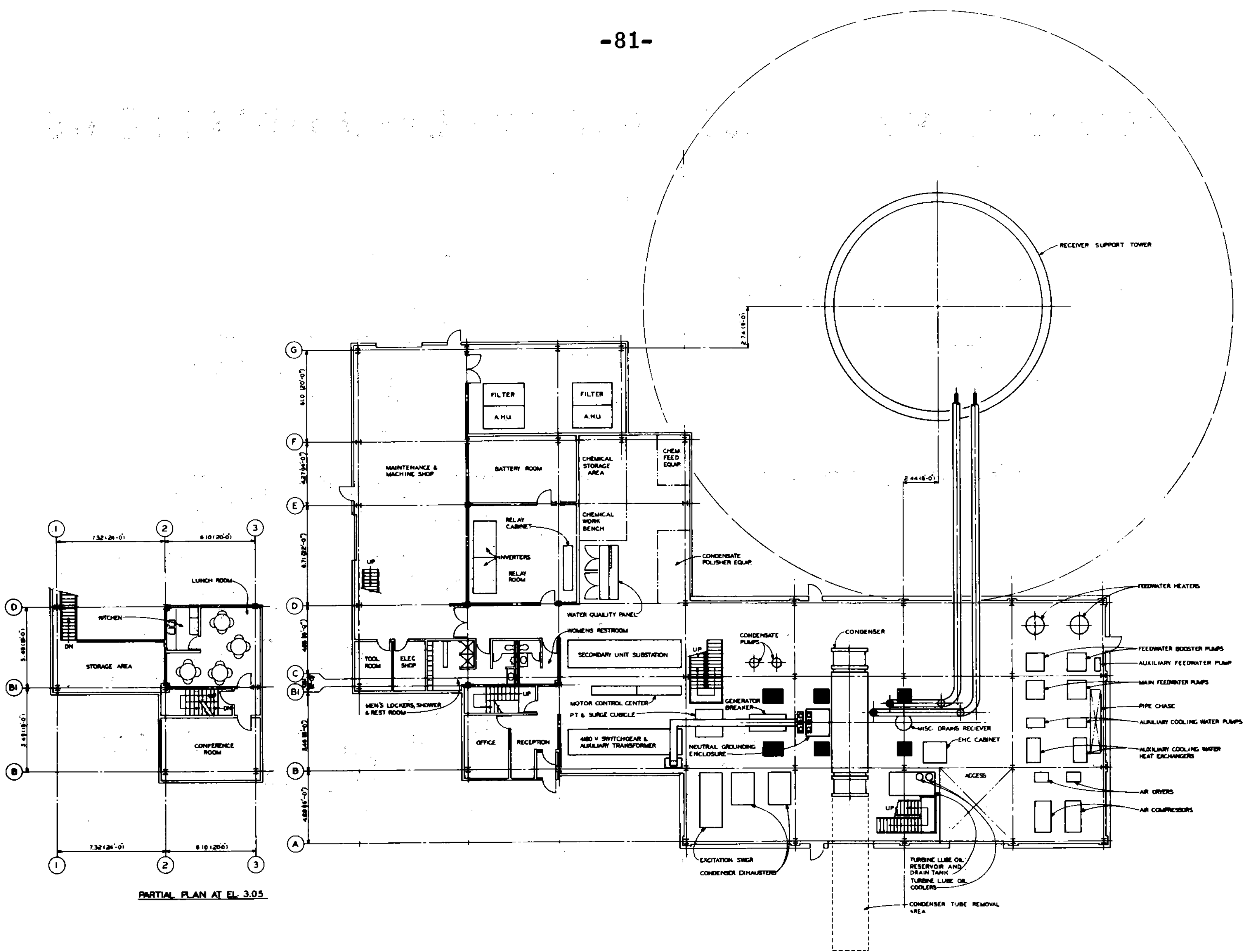
The central area surrounding the tower is used for the turbine and central station elements, the thermal storage complex, and access roads to the heliostat field and plant personnel parking.



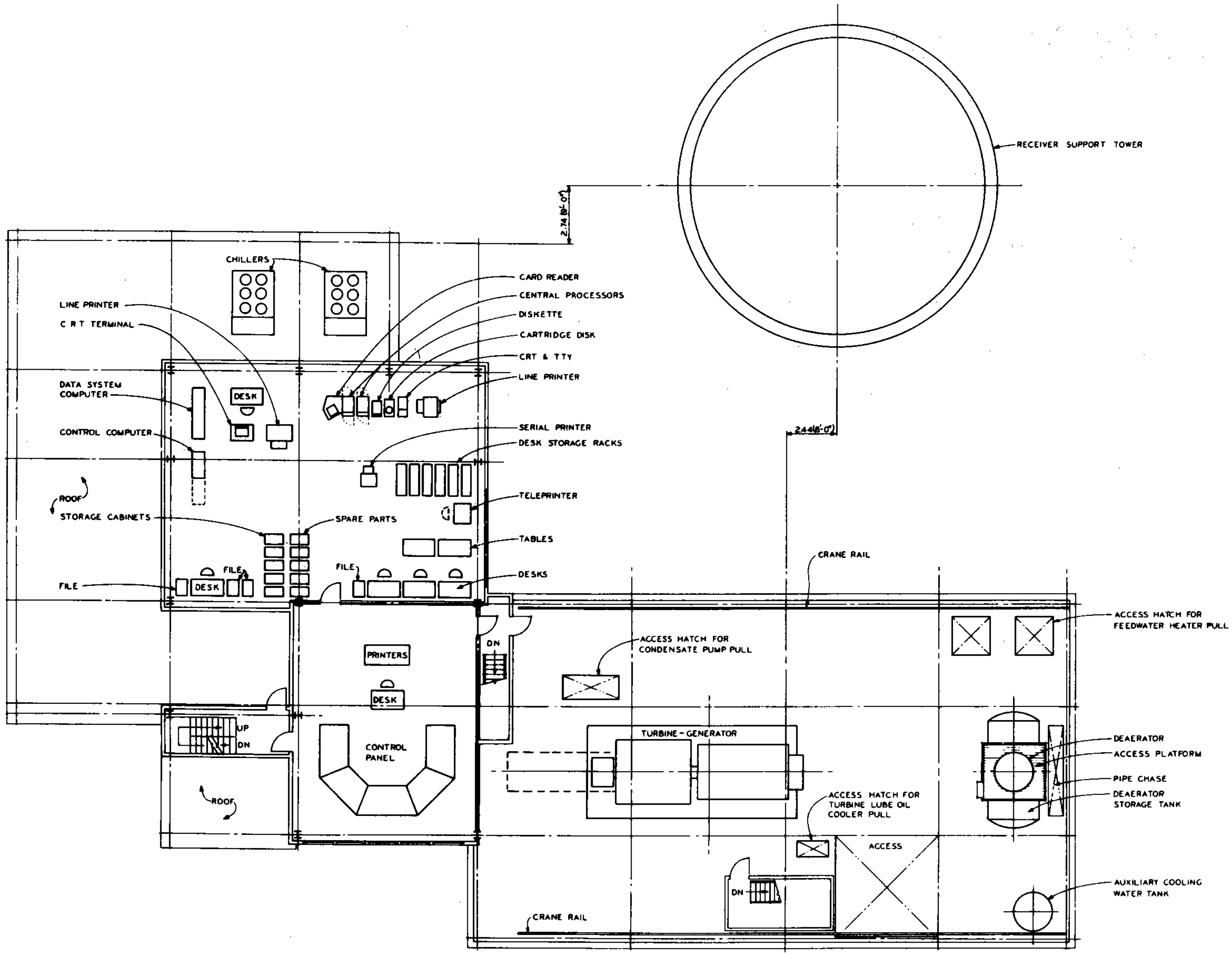
PILOT PLANT CENTRAL PLANT COMPLEX

PILOT PLANT STATION PLAN

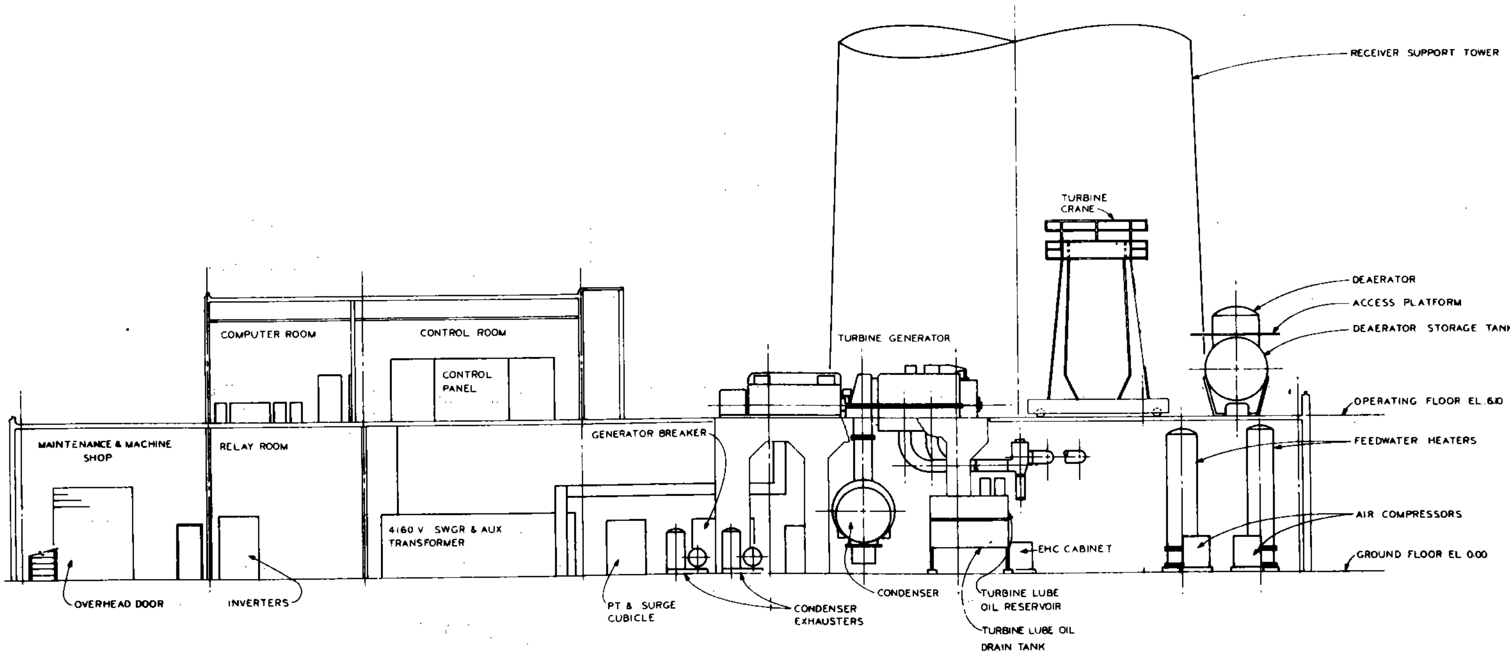
The central station features an open turbine designed for outdoor operation to take advantage of the near ideal Barstow weather conditions and a compact set of offices, central room, machine shop area and chemical analysis and battery rooms. The turbine support function, feedwater heaters, condenser, and pumps are located on the ground floor.



PILOT PLANT CENTRAL STATION — GROUND FLOOR



PILOT PLANT CENTRAL STATION – TURBINE FLOOR



PILOT PLANT CENTRAL STATION — ELEVATION

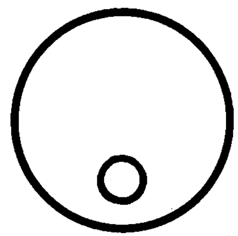
COLLECTOR CHARACTERISTICS

The vital statistics of the collector design are compared for both pilot and commercial scale designs. Careful attention to scaling from one to the other was present throughout the program.

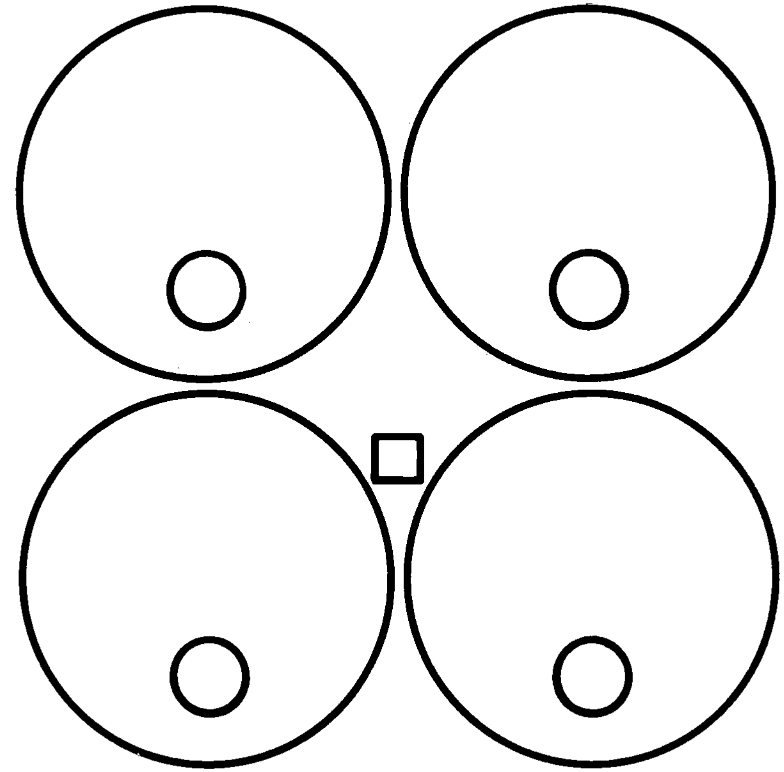
Tracking Accuracy
- -- 1 mr, 1 optics
- - 2 mr, 1 /axis

Reflectivity 0.9 clean
Heliostat Area $40m^2$

PILOT PLANT



FIRST COMMERCIAL PLANT



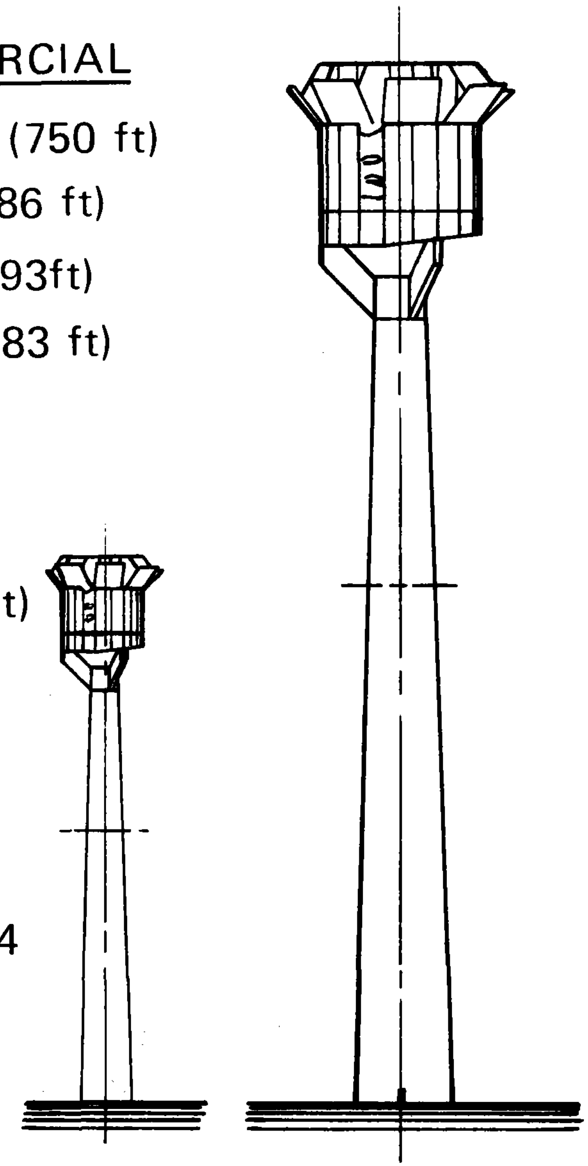
	PILOT PLANT	FIRST COMMERCIAL PLANT
FIELD OD	535m	951m/FIELD
FIELD ID	101m	180m/FIELD
GROUND COVER	29% Avg	Same
SOLAR MULTIPLE	1.23	1.7
HELIOSTAT QUANTITY	1598	5055/FIELD, 20,220 Total
NET ANNUAL ENERGY	2.14×10^4 MWhr(e)	28.9×10^4 MWhr(e)

COLLECTOR CHARACTERISTICS

RECEIVER CHARACTERISTICS

The vital statistics of the receiver design are compared for both pilot and commercial scale designs. Careful attention to scaling from one to the other was present throughout the program.

PARAMETER	PILOT PLANT	FIRST COMMERCIAL
TOWER HEIGHT	126.5m (415 ft)	228.6m (750 ft)
CAVITY DIAMETER	14.9m (49ft)	26.1m (86 ft)
CAVITY HEIGHT (Major)	16.6m (54 ft)	28.3m (93ft)
(Minor)	14.6m (48 ft)	25.3m (83 ft)
ANNULUS APERTURE AREA	218 m^2	651m^2
PEAK ABSORBED POWER	43 mw (t)	510 mw(t)
PEAK INCIDENT WALL FLUX	300 kw/m^2	same
RCVR PEAK/AVE EFFICIENCY	87.2/84.1	87.5/84.4



RECEIVER CHARACTERISTICS

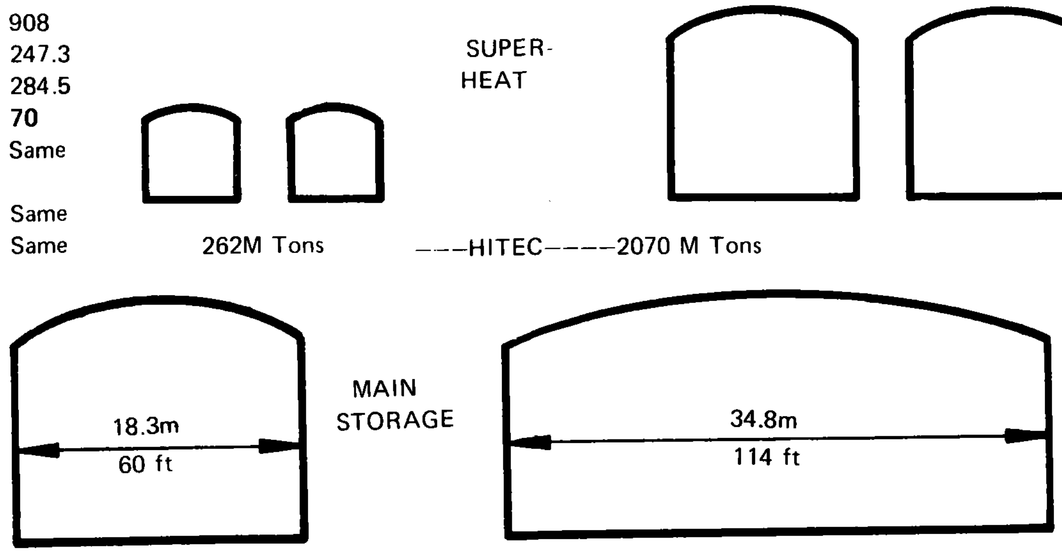
THERMAL STORAGE AND EPGS CHARACTERISTICS

The vital statistics of the Thermal Storage and Electric Power Generation Subsystem designs are compared for both Pilot and Commercial scale designs. Careful attention to scaling from one to the other was present throughout the program.

PERFORMANCE	PP	FC
CAPACITY, MWhr(t)	115	908
MAX Input rate, MW	37.7	247.3
Max Out put rate, MW	31.6	284.5
Max Electrical Net Out put, MWe	7	70
Duration, hours	3	Same
Hold time prior to discharge, hrs	20	Same
Loss rate	24%/100 hrs	Same

PILOT PLANT

FIRST COMMERCIAL



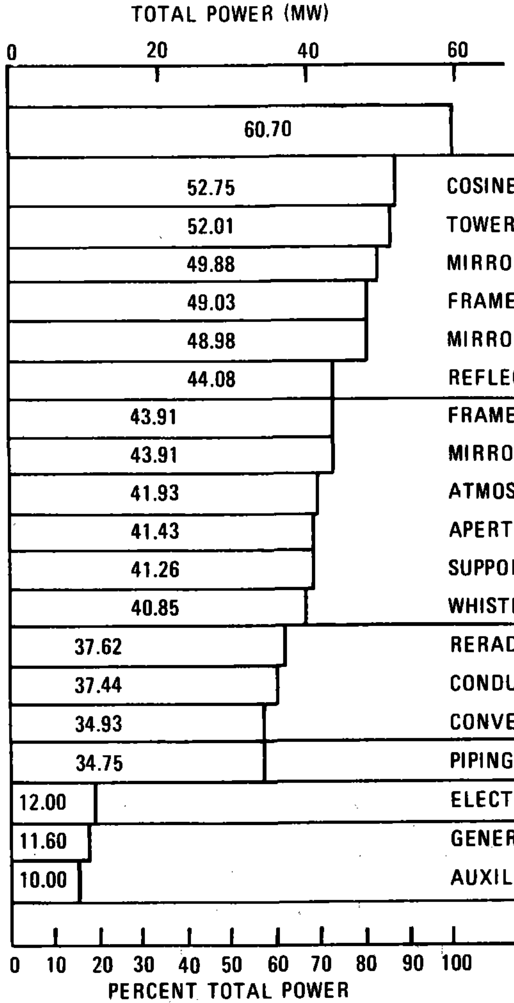
5783 m tons---Gramite---50,259 m tons
696,875 liters---Caloria---5,498,091 liters

PARAMETER	PILOT PLANT	FIRST COMMERCIAL
Turbine Type	Automatic Admission	Same
Name Plate Capacity	15 MWe	121 MWe
Cycle Conditions		
-Throttle	**10.2 MPa/510°C (2450 PSI/950°F)**	Same
-Admission	**3.2 MPa/388°C (460 PSI/730°F)**	Same
Number of Extractions	3	5
Heat Rejection Type	Wet Cooling	Same
Net Plant Efficiency		
–Receiver Design Point	34.5%	38.5%
-Storage Design Point	28.5%	31.8%

THERMAL STORAGE AND EPGS CHARACTERISTICS

PILOT PLAN PERFORMANCE - DESIGN POINT 12/21 - 2 PM

The Pilot Plant has been designed for optimal economic performance by carefully balancing each of the loss mechanisms so as to minimize bus bar energy cost. On December 21 the sun is at its lowest in the southern sky of any time throughout the year. At 2 PM of that day the plant is capable of producing exactly 10 MWe. At all other times of the year (between 10 AM and 2 PM) the plant can make in excess of 10 MWe and the power can be made available to either the grid or to thermal storage.

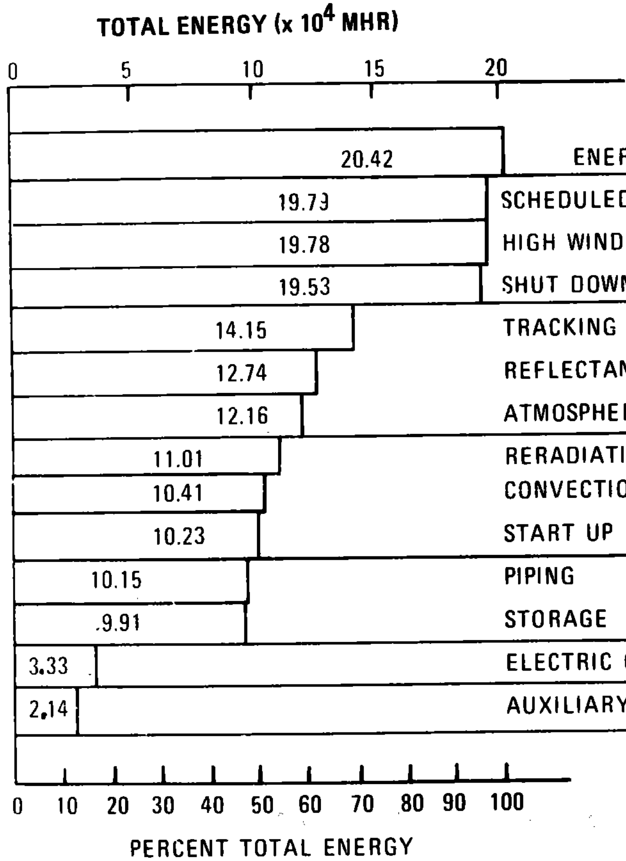


TOTAL POWER (MW)	POWER LOSS	% LOSS OF AVAILABLE POWER	AVAILABLE POWER SOLAR INPUT (DNI & MIRROR AREA)	% TOTAL AVAILABLE POWER
60.70				100
52.75	COSINE	13.1		
52.01	TOWER SHADOW	1.4		
49.88	MIRROR SHADOW	4.1		
49.03	FRAME SHADOW	1.7		
48.98	MIRROR FACET EDGE	0.1		
44.08	REFLECTANCE	10.0	REDIRECTED	72.6
43.91	FRAME BLOCK	0.4		
43.91	MIRROR BLOCK	0.0		
41.93	ATMOSPHERIC ATTENUATION	4.5		
41.43	APERTURE MISSES	1.2		
41.26	SUPPORT STRUCTURE HITS	0.4		
40.85	WHISTLE THROUGHS	1.0	CAVITY INPUT	67.3
37.62	RERADIATION	7.9		
37.44	CONDUCTION	0.5		
34.93	CONVECTION	6.7	ABSORBED	57.6
34.75	PIPING	0.5	TURBINE INPUT	57.3
12.00	ELECTRIC CONVERSION	15.5	GROSS ELECTRICAL OUTPUT	19.8
11.60	GENERATOR	3.3		
10.00	AUXILIARY	13.8	NET ELECTRICAL OUTPUT	16.5

PILOT PLANT PERFORMANCE – DESIGN POINT 12/21 2 P.M.

PILOT PLANT PERFORMANCE - NET ANNUAL ENERGY

The pilot plant design calls for producing 10 NW net electric power on December 21 at 2 PM. Most of the major design tradeoffs however have centered upon maximizing the annual energy production while keeping the capital cost low. These production estimates are obtained by detailed Monte Carlo trace simulation of the plant operation over the entire year.



ENERGY LOSS	% LOSS OF AVAILABLE ENERGY	AVAILABLE ENERGY SOLAR INPUT (DNI & MIRROR AREA)	% TOTAL AVAILABLE ENERGY 100
SCHEDULED MAINTENANCE	3.1		
HIGH WIND TRACKING	0.1		
SHUT DOWN	1.3	USABLE	95.6
TRACKING	27.5		
REFLECTANCE	10.0		
ATMOSPHERIC ATTENUATION	4.5	CAVITY INPUT	59.6
RERADIATION AND CONDUCTION	9.5		
CONVECTION	5.4		
START UP	1.7	ABSORBED	50.1
PIPING	0.8		
STORAGE	2.4	TURBINE INPUT	48.5
ELECTRIC CONVERSION	66.4	GROSS ELECTRICAL OUTPUT	16.3
AUXILIARY	35.8	NET ELECTRICAL OUTPUT	10.5

PILOT PLANT PERFORMANCE NET ANNUAL ENERGY

COLLECTOR/RECEIVER FEATURES AND BENEFITS

Every effort has been made to ensure that the Pilot Plant provides high performance at low risk, and with reasonable cost.

COLLECTOR/RECEIVER FEATURES AND BENEFITS

COLLECTOR SUBSYSTEM FEATURES

- LOW PROFILE/WIDE STANCE/WIND RESISTANT
- MINIMAL FOUNDATION REQUIREMENTS
- USES ONLY STANDARD COMMERCIAL COMPONENTS
- MODULAR DESIGN PROVIDES EASY FIELD ASSEMBLY
- DEMONSTRATED ENVIRONMENTAL PERFORMANCE
- SIMPLE COMMAND AND CONTROL AND POWER DISTRIBUTION
- SIMPLE ELECTRONIC ALIGNMENT APPROACH
- FIELD DESIGN MINIMIZES SHADOWING/BLOCKING
- 360° FIELD YIELDS SUPERHEATER THERMAL AVERAGING AND HIGH TRACKING EFFICIENCY

COLLECTOR DESIGN BENEFITS

- NO PHASE II RISK BECAUSE IT HAS BEEN VALIDATED BY BOTH ANALYSIS AND BY TEST
- ACHIEVES HIGH PERFORMANCE AT MODERATE COST WITH EXCELLENT LOW COST POTENTIAL

RECEIVER SUBSYSTEM FEATURES

- TOWER UTILIZES PROVEN DESIGN/CONSTRUCTION METHODS
  - SLIP FORM POURED CONCRETE
  - APERTURE OPTIMALLY MATCHED WITH HELIOSTAT FIELD
- STEAM GENERATOR DESIGN USES
  - STANDARD ASME CODE PRACTICE
  - FORCED CIRCULATION DRUM SEPARATION
  - HIGH TURNDOWN RATIO
  - LOW PEAK FLUXES
  - SUPERHEATER THERMAL AVERAGING
  - STANDARD MEMBRANE WALL BOILER
  - SPRAY DOWN STEAM CONTROL
  - CLOUD TRANSIENT BALANCE CONTROL

RECEIVER DESIGN BENEFITS

- LOW PHASE II RISK BECAUSE:
  - MINIMAL CONFIGURATION CHANGE FROM SRE TO PILOT PLANT
  - INDEPENDENT BOILER/SUPERHEATER CONTROL MINIMIZES STARTUP PROBLEMS
  - THE DESIGN METHODOLOGY HAS BEEN VALIDATED BY SRE TEST
  - THE SRE RESULTS INDICATE HIGHLY RELIABLE OPERATION
- HIGH PERFORMANCE OPTIMALLY MATCHED WITH HELIOSTAT FIELD ECONOMICS

THERMAL STORAGE/EPGS FEATURES AND BENEFITS

Every effort has been made to ensure that the pilot plant provides high performance at low risk, and with acceptable cost.

THERMAL STORAGE DESIGN FEATURES

- SUPERHEAT FOR EXPANSION LINE MATCHING
- COST OPTIMAL ADMISSION PORT PRESSURE
- UTILIZES "BEST" FEATURES OF ALTERNATIVE DESIGNS
  - HITEC HOT & COLD TANKS
  - OIL & ROCK MAIN STORAGE
- STEAM GENERATION TIME CONSTANT LESS THAN RECEIVER–TURBINE T/C

STORAGE DESIGN BENEFITS

- LOW PHASE II RISK BECAUSE:
  - TURBINE UPSET MINIMIZED
  - DESIGN UTILIZES PROVEN TECHNOLOGY
  - CLOUD OUTAGE ALEVIATED BY FAST ACTING CONTROL
- LOWER CAPITAL AND BUSBAR COST

EPGS FEATURES

- DUAL PRESSURE ADMISSION TURBINE
- SIMULTANEOUS STEAM SOURCE TRANSFER/ OPERATION
- HIGH CYCLE EFFICIENCY
- AMERICAN MADE TURBINE/COMMERCIALLY AVAILABLE
- DDC MASTER CONTROL

EPGS DESIGN BENEFITS

- LOW PHASE II RISK BECAUSE:
  - PROVEN TECHNOLOGY
  - CAREFULL ATTENTION TO DETAIL
  - CONTROL SIMPLICITY
- LOW CAPITAL AND BUSBAR COST

THERMAL STORAGE/EPGS FEATURES AND BENEFITS

SYSTEM INTEGRATION

The key factor in obtaining high performance at minimum cost is to properly integrate parameters effecting these elements. The facing page is but a few of the elements which were extensively analyzed during the Phase I design.

SYSTEM INTEGRATION FEATURES

PARAMETER	VARIABLE
COLLECTOR–RECEIVER ISSUES	
GROUND COVER	SHADOW/BLOCKING LOSSES
TOWER HEIGHT	COSINE LOSSES
FLUX DENSITY	HEAT TRANSFER/TUBE STRESS
APERTURE SIZE	RERAD/CONVECTION/SPILLAGE
CLOUD COVER	FOCUS/SPRAY CONTROL
STARTUP	BOILER/SUPERHEATER SEPARATION
SUN POSITION	SUPERHEATER CONFIGURATION
RECEIVER–TURBINE ISSUES	
DIURNAL VARIATION	THROTTLE CYCLE SELECTION
STORAGE–TURBINE/STORAGE–RECEIVER ISSUES	
DIURNAL VARIATION	ADMISSION CYCLE SELECTION
CLOUD OUTAGES	MASTER AND STORAGE CONTROL
SEALING REQUIREMENTS	CAPACITY
BUSBAR & CAPITAL COSTS	ALL SPECIFICATIONS
CAPACITY	I/O RATES
OPERATIONAL STRATEGY	
OVERALL	
MAINTENANCE	
SAFETY	
SCALING	

SYSTEM INTEGRATION

FINDINGS AND RECOMMENDATIONS

The technical feasibility of the Central Receiver concept has been established and there are no unusual requirements associated with the design. Our recommendation is that the detailed design and construction of the world's first solar electric plant begin immediately.

SUMMARY OF PHASE I FINDINGS

- PRELIMINARY DESIGN FEASIBILITY ESTABLISHED
- NO UNUSUAL TECHNOLOGY REQUIRED
- PLANT ECONOMICS HIGHLY DEPENDENT ON ULTIMATE HELIOSTAT AND STORAGE COSTS
- PHASE II OBJECTIVES CAN BE ACCOMPLISHED AT LOW RISK AND MODERATE COST

FINDINGS AND RECOMMENDATIONS

RECOMMENDATIONS

- PROCEED IMMEDIATELY TO PHASE II
- ESTABLISH WELL FUNDED, FLEXIBLE, ON-GOING HELIOSTAT DEVELOPMENT PROGRAM AIMED AT LOW COST
- ESTABLISH WELL FUNDED, FLEXIBLE, ON-GOING THERMAL STORAGE DEVELOPMENT PROGRAM AIMED AT LOW COST
- PROCEED WITH SUNLIGHT RECEIVER TESTS
- PROCEED WITH LATENT HEAT STORAGE TESTS
- PROVIDE FOR ADDITIONAL SRE TESTS AS RECOMMENDED BY ALL CONTRACTORS