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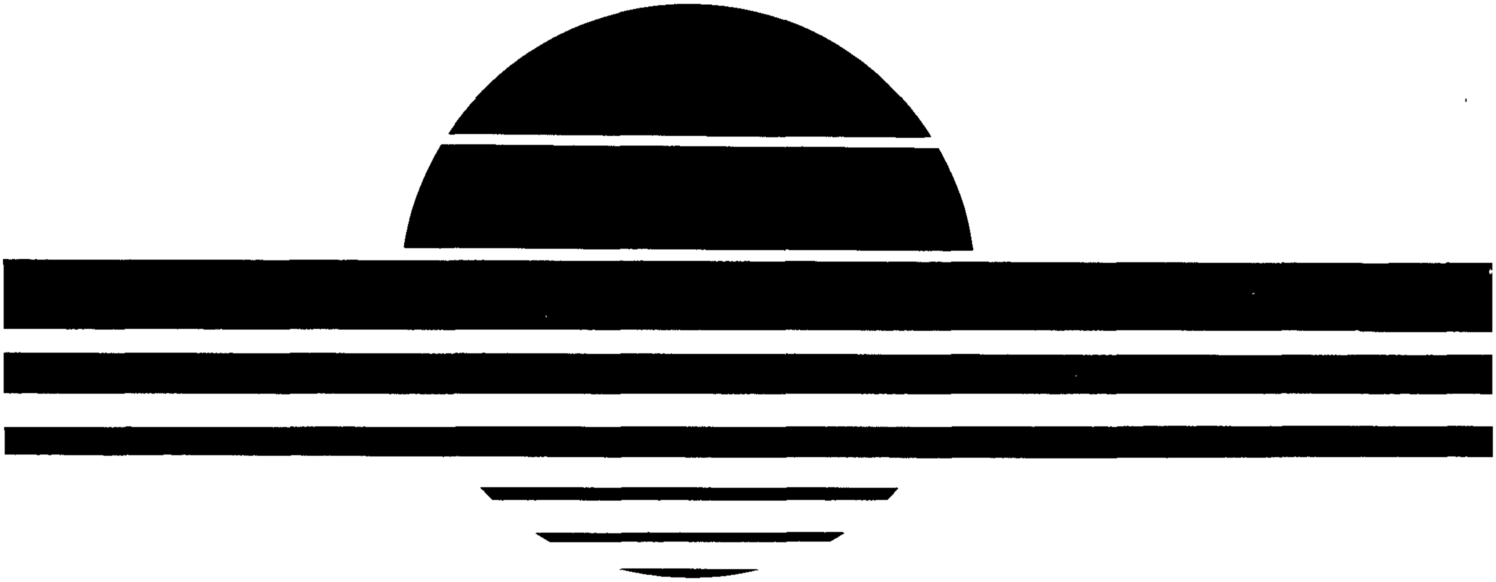
CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM, PHASE 1: PRELIMINARY DESIGN REPORT

Volume 1. Executive Overview

April 1977

Work Performed Under Contract No. EY-77-C-03-1110

Martin Marietta Corporation
Denver, Colorado



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FOREWARD

This document is Volume I of the seven-volume Central Receiver Solar Thermal Power System Pilot Plant Preliminary Design Report. The complete report consists of the following volumes.

I. Executive Overview
II. System Description and System Analysis
III. Collector Subsystem
IV. Receiver Subsystem
V. Thermal Storage Subsystem
VI. Electrical Power Generation/Master Control Subsystems and Balance of Plant
VII. Pilot Plant Cost and Commercial Plant Cost and Performance

The work described herein was performed during the period of July 1975 through April 1977 by the Martin Marietta Corporation (Denver, Colorado) in accordance with ERDA Contract EY 76-C-03-1110 under the technical direction of Sandia Laboratories (Livermore, California).

Four organizations, each with major subsystem responsibilities, combined forces to perform the preliminary design and subsystem research experiments. The team is led by Martin Marietta Aerospace of Denver, Colorado, who is the integrator for the overall effort and collector subsystem designer. Bechtel Corporation, San Francisco, California, is responsible for the electrical power generation subsystem and the architect-engineer tasks; Foster Wheeler Energy Corporation, Livingston, New Jersey, is responsible for the receiver subsystem; and the engineering experiment station of the Georgia Institute of Technology is responsible for the thermal storage subsystem.

The prime contract was under the overall direction of George Kaplan, ERDA Division of Solar Energy. Robert Hughey of the ERDA, San Francisco field office was the contract administrator. Sandia Laboratories technical direction was provided by Clifford Selvage, Alan Skinrood and William Moore.

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ABBREVIATIONS AND ACRONYMS

A	Ampere
BTU	British Thermal Unit
^oC	Degrees Celsius
CS	Collector Subsystem
CRT	Cathode Ray Tube
DHS	Data Handling System
EPGS	Electrical Power Generation Subsystem
ERDA	Energy Research and Development Administration
^oF	Degrees Fahrenheit
fps	Feet Per Second
ft	Feet
FW	Feedwater
g, kg	Gram, Kilogram
gal	Gallon
hr	Hour
ID	Identification
I/F	Interface
in	Inch
j	Joule
K	Kelvin
KVA	Kilovolt-Ampere
KV	Kilovolt
l	Liter
lbs	Pounds
m, mm	Meter, Millimeter
MCS	Master Control System
min	Minutes
MMC	Martin Marietta Corporation
mph	Miles Per Hour
Pa, kPa	Pascal, Kilopascal
PCS	Plant Control System
psf	Pound Per Square Foot
psia	Pound Per Square Inch-Absolute
psig	Pound Per Square Inch-Gage
rad	Radian
RAM	Random Access Memory
RH	Relative Humidity
ROM	Read Only Memory
RS	Receiver Subsystem
s	Second
SRE	Subsystem Research Experiment
STTF	Solar Thermal Test Facility
TSS	Thermal Storage Subsystem
TTY	Teletype
W_e, kW_e, MW_e	Watt, Kilowatt, Megawatt-Electrical
W_t, kW_t, MW_t	Watt, Kilowatt, Megawatt-Thermal

I. INTRODUCTION

Feasibility of a Central Receiver Solar Thermal Power System having significant commercial potential has been established by analysis and by test of solar collector, receiver steam generator, and molten salt - oil thermal storage experimental subsystems.

Phase I of the Central Receiver Solar Thermal Power System (CRSTPS) program was initiated under Contract No. EY-76-C-03-1110 from the San Francisco Operations Office of the Energy Research dnd Development Administration (ERDA) June 15, 1975. The program, authorized by the Division of Solar Energy, ERDA, Washington, D. C. is the two year initial phase of the Central Receiver Solar Thermal Power Development and Demonstration program which includes the construction and operation of a 10 MWe pilot plant by 1980 and a commercial demonstration plant by 1985.

A team of organizations with complementary capabilities was formed to perform the CRSTPS Phase I, Preliminary Design Phase. Martin Marietta Corporation was the team leader, responsible for program management, system integration of the CRSTPS commercial and pilot plant designs, the collector subsystem design, and the collector research experiment.

Foster Wheeler Energy Corporation performed the design of the receiver steam generators for the full scale solar plants, and the design, fabrication, and erection of the 5 MWth receiver for the the subsystem research experiment.

Georgia Institute of Technology was responsible for the thermal storage subsystem designs and the thermal storage research experiment.

Bechtel Corporation had design responsibility for the Electric Power Generation Subsystems and the Architect and Engineering features of the plants.

Basic features of the Martin Marietta team's solar power plant concept, shown in Figure I.A-1, have been established to achieve a practical utility scale solar plant with the highest performance consistent with the triple goals of (1) minimized capital and operating costs, (2) safe, flexible, reliable and long life application features, and (3) timely development of solar power technology.

The CRSTPS plant is made up of five major subsystems, the collector, receiver, and thermal storage, which are unique to the solar application, and the electrical power generation and plant control, which are currently commercial. Energy flow through the plant starts with the solar energy intercepted by the heliostats of the collector subsystem. The solar energy is reflected in concentrated beams to the receiver. Within the receiver subsystem the solar energy is converted to thermal energy in the form of superheated steam and is transmitted to the thermal storage and electrical

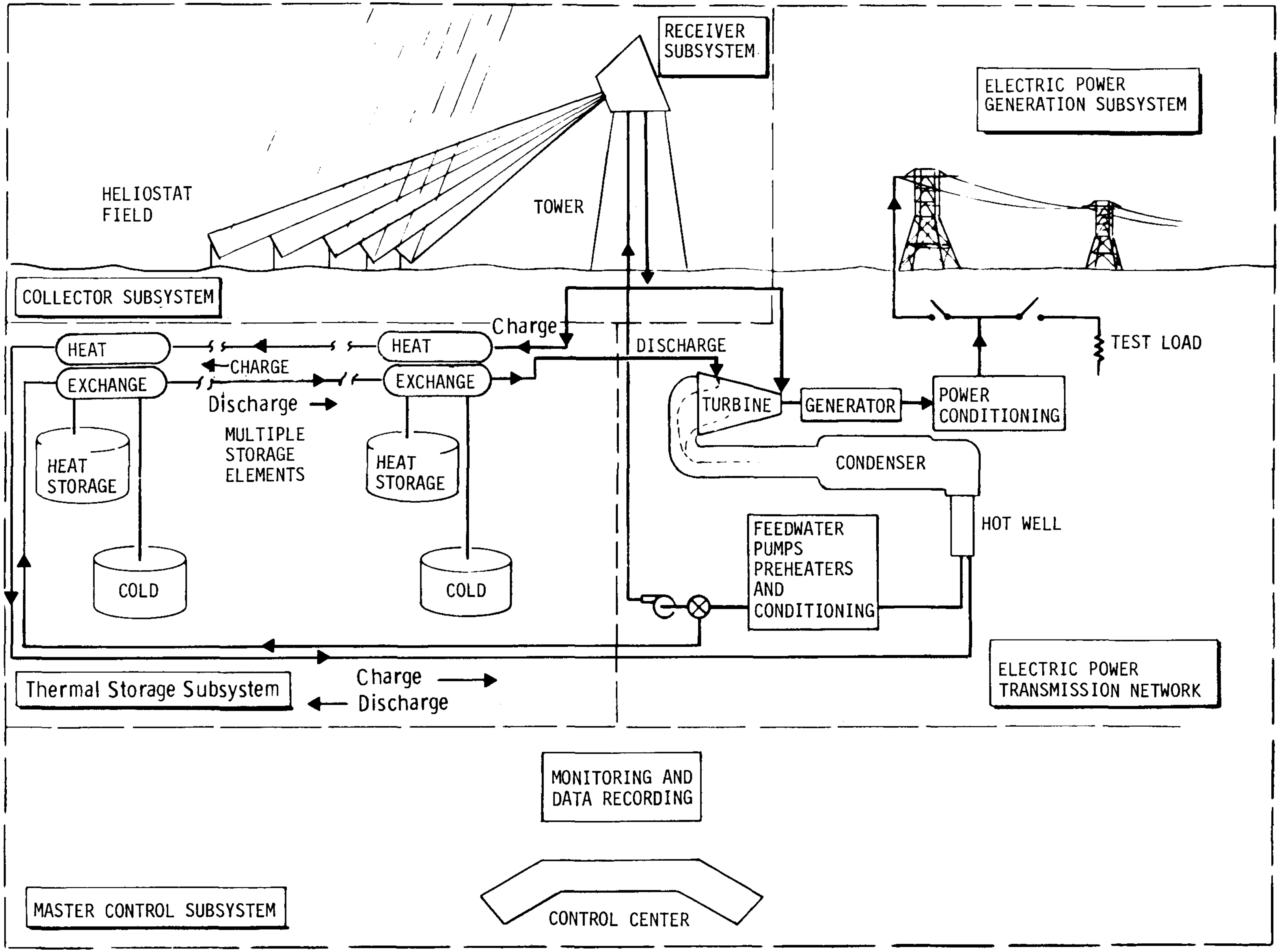


Figure I.A-1 Overview Schematic, Martin Marietta Team Central Receiver Solar Thermal Power System power generation subsystems. Conversion of thermal energy from either the receiver or the storage system to electricity takes place in the turbine and generator of the electrical power generation subsystem. Energy flow in the thermal storage subsystem is from steam to sensible heat in the storage fluids during charging and from the sensible heat of the fluids to steam during discharge.

Phase I, the preliminary design of the CRSTPS, was broadly divided into three major activities. The first major task was the baseline design definition for the commercial plant and the pilot plant which would best serve as the development vehicle for the commercial plant. The baseline designs were accomplished during the first five months of the program and were documented in the "Preliminary Design Baseline Report" (PDBR), December 1975.

Figure I.A-2 is an artist's concept of the "Preliminary Baseline Design" 10 MWe CRSTPS pilot plant, illustrating major visible features of the PDBR design. The tower mounted cavity receiver, the north side location of the field of focusing heliostats, the two stage sensible heat storage subsystem, the open air turbine building and the administration building are shown in a non-specific semi-arid site.

The second major activity of the Phase I program was the parallel design, fabrication and testing of the subsystem research experiments to demonstrate feasibility of the solar unique subsystems. The collector subsystem research experiment consisted of four full size heliostats, controls, and energy measurement instrumentation installed in a valley on the Martin Marietta plant site near Denver, Colorado. The receiver subsystem research experiment consisted of a 5 MWt cavity receiver, controls, support equipment and instrumentation erected by Foster Wheeler at the IR Test Facility of Sandia Laboratories in Albuquerque. The thermal storage subsystem research experiment consisted of a 1.6 MWt -hr operational subsystem capable of charge and discharge rates of 2 MWt installed by Georgia Institute of Technology on the property of the Georgia Power Co. at Newman, Georgia. Steam at the quality needed for charging the experiment and feedwater of the purity needed for the discharging steam generation were provided from the power plant. The subsystem research experiment activities spanned a period of fifteen months from December 1975 to March 1977.

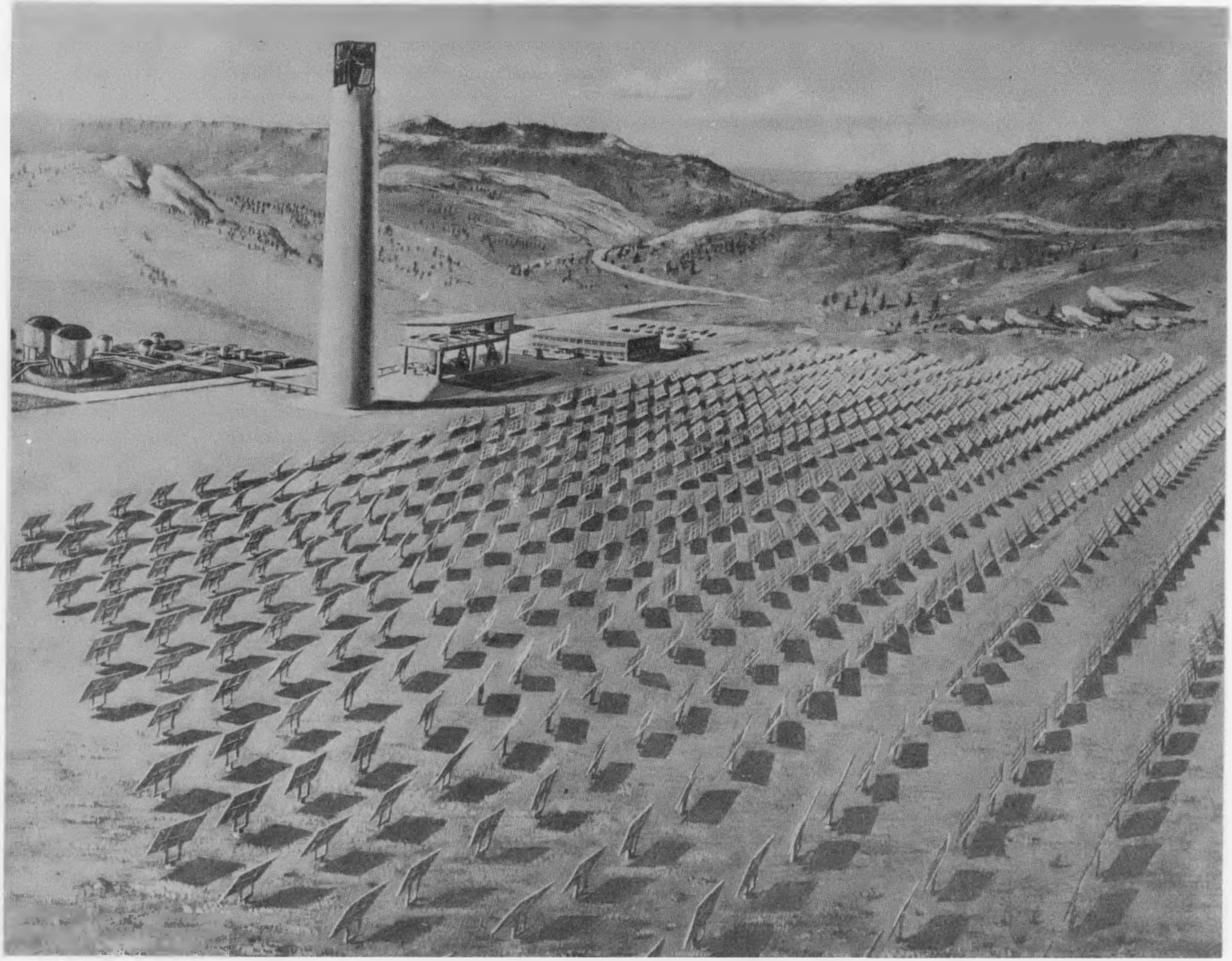


Figure I.A-2 Preliminary Baseline Design, 10 MW_e CRSTPS Pilot Plant

The third major activity was the "Preliminary Design" finalization which culminates in the issuance of this report. The bulk of this activity occurred in the final six months of the basic program and overlapped with the later stages of the subsystem research experiment testing. Figure I.A-3 is the rendering of the "Preliminary Design" 10 MWe CRSTPS resulting from the design finalization activity. Many of the evolutionary modifications to the design which occurred in the course of the program are visible in the rendering and are evident when it is compared with the PDBR configuration of Figure I.A-2. These include (1) the shortened tower, (2) the enclosure of the receiver within the tower, (3) use of a sheathed steel rather than concrete tower, (4) relocation of the thermal storage subsystem, (5) reduced tankage of the thermal storage subsystem, (6) use of spherical tanks for the oil storage stage, (7) integration of the Electric Power Generation and Administration buildings, and (8) depiction of the plant at its selected site on the Southern California Edison site at Barstow, California. Many other important evolutionary modifications, not evident to the eye in a rendering, were also incorporated during the finalization period. Key among these were (1) collector layout optimization, (2) heliostat size increase to $41.0m^2$, (3) heliostat number decrease to 1554 per module, (4) use of open loop computer controlled tracking for heliostats, (5) incorporation of dual mode (simultaneous charge discharge) operational capability for thermal storage, and (6) revision of the operating state points in the receiver, thermal storage, and turbine equipment.

The basic technical approach to the design of the CRSTPS commercial and pilot plants at the outset of the program was based on the results of the conceptual level system and design analyses performed during 1974 under the National Science Foundation supported "Solar Power System and Component Research Program (Grant No. AER 75-07570) and work performed in support of the Phase I proposal. All basic features were re-examined and optimized analytically in the preliminary baseline design, the first segment of the program.

The finalization design period included a further re-examination of the basic features to the preliminary design level of depth made possible by the expanded knowledge generated in the subsystem research experiments, the Phase I CRSTPS program analyses, and the ongoing parallel solar power program. These parallel programs included the 1 MWe Bench Model Cavity Receiver (ERDA SAN EY 76-C 03 1068) which fabricated and tested a 1 MWt cavity steam generator with both IR and solar energy and the 5 MWt Solar Thermal Test Facility Heliostat program (Sandia 03 3852) which designed, built,

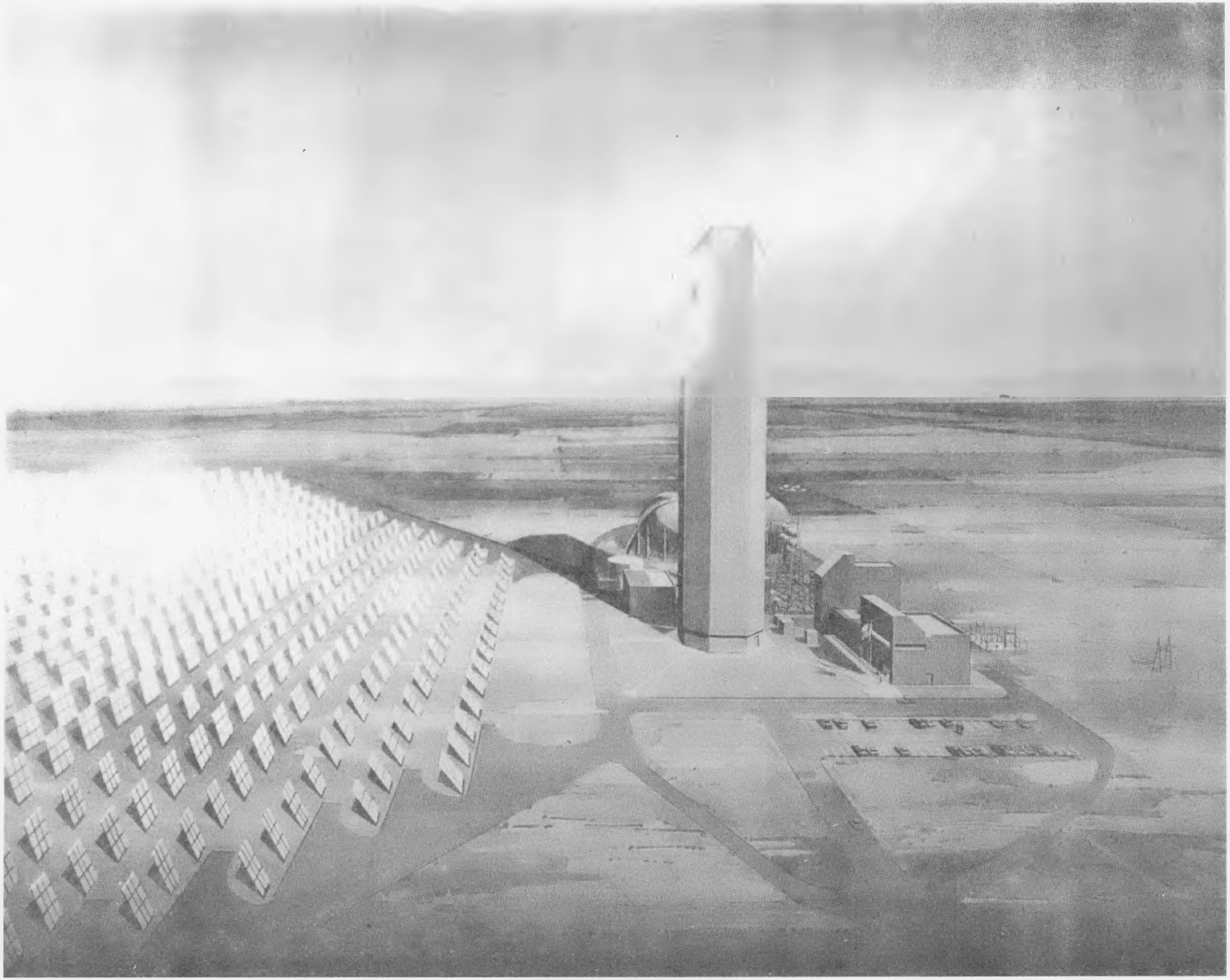


Figure I.A-3 Rendering of Preliminary Design 10 MW_e CRSTPS Pilot Plant and tested computer controlled heliostats and a computer controlled focus and alignment system. Two hundred twenty two heliostats are being installed at the Solar Thermal Test Facility in this program.

Each feature of the design was evaluated for the degree of its positive or negative implications over the broad range of selection considerations, as summarized in Table I.A-1 and was incorporated only after being judged substantially beneficial. By system and subsystem the table lists the key features and a brief summary comment for each of the evaluation criteria. Columns for (1) technical performance, (2) state-of-the-art, (3) safety, (4) practical utility application aspects, (5) economic optimization, (6) timely development for the pilot and commercial plants, (7) long life capability, and (8) environmental impact, are followed by a column listing the primary selection drivers. The configurations of the CRSTPS plants are balanced designs reflecting clear influences of each of the reference criteria. While the primary design drivers are emphasized, it will be noted that strong support from the remaining categories is the rule for the design features finally selected. A substantial negative evaluation in any category was grounds for rejection of candidate alternative features.

The modular collector-receiver strongly contributes to the high performance goal of the commercial plant by providing maximized optical performance, thermal conversion efficiency, system reliability, and operational flexibility. With the modules of the collector subsystems the north field collector of focused heliostats transmitting focused sunlight over moderate slant ranges maximizes optical performance. For the commercial plant module, 1554 concentrating heliostats, each having an area of $41m^2$ ($441 ft^2$) are computer controlled to reflect their energy to the focal zone of the receiver 90m (295 ft.) above the ground plane on which the heliostats are mounted.

For the pilot plant a collector field containing only 1325 heliostats will meet all of specified requirements. However, this size field will provide only limited operational time at 10 MWe and will provide no significant capability to charge the thermal storage while operating at 10 MWe. The commercial size field of 1554 heliostats has two significant advantages for the pilot plant. First, it better simulates an operational plant (10 MWe operation is raised from 4 to 7.5 hours on the design day, and the capability to charge storage while generating 10 MWe is increased from 0.2 to 1.3 hours). Secondly it will

Table I.A-1 Selection Considerations for Major CRSTPS Design Features

KEY FEATURES OF CRSTPS PRELIMINARY DESIGN	TECHNICAL PERFORMANCE 1	TECHNICAL STATE-OF-ART 2	SAFETY 3	PRACTICAL UTILITY APPLICATION ASPECT 4	ECONOMIC OPTIMIZATION 5	TIMELY DEVELOPMENT, PILOT 1980, COMMERCIAL 1985 6	THIRTY-YEAR LIFE CAPABILITY 7	ENVIRONMENTAL IMPACT 8	PRIMARY SELECTION DRIVER(S)
1. SYSTEM									
Modularized Collector Near 50 MW_{th} Size	Near Optimum	Future Development	Not Impacted	Maximum Reliability, Versatility	Within 1 of Optimum	Vital to Commercial Plant 1985	Not Impacted	Minimizes Affected Air Space Envelope	1, 4, 6
150 MW_e Size Commercial Plant	High, Not Keyed to Plant Size	Turbo Machinery Available	Not Impacted	Common Utility Plant Size	Optimum	Compatible with Commercial Plant 1985	Not Impacted	Land Use Keyed to Plant Size	2, 5
1554-Heliostat Pilot Plant vs 1325-Heliostat Plant	High with Either Module	Not Impacted	Not Impacted	Simulates Operating Modes and Application	4-5 More Expensive Pilot Plant	More Fully Develops Receiver	Not Impacted	No Impact	4, 6
2. RECEIVER SUBSYSTEM									
Cavity Configuration, Aperture Diameter/Depth ≈ 1.5	Mandatory for Receiver, Effectivity = 0.92-0.94	Long History and Recent 1 MW_t Receiver Confirmation	Removes Major Optical Hazard from Reflection	Not Impacted	Optimum Due to System Size Minimization	Minimum Risk, 1 MW_t and 5 MW_t in Being	Not Impacted	Removes Major Optical Hazard	1, 2, 3, 8
Natural Circulation	Self-Compensating for Flux Variation	Widespread Use; Utility, Industrial, Naval Boilers	High, Function Not Keyed to Support Equipment	Well Understood and Accepted, Simple Controls	Optimum Due to Minimized Support Equipment and Controls	Minimum Risk, Current Practice	Demonstrated	No Effect	2, 3, 6
Conventional Boiler and Superheater Flux Levels	Attainable with Current Design Practice	Widespread Use	High, Readily Adaptable to ASME Code	Provides Highly Flexible Operation	Not Impacted	Minimum Risk, Current Practice	Demonstrated	No Effect	3, 4, 7
10687 kPa (1550 psig) Operating Pressure	Exceeds Minimum Requirement for EPGS and TSS	Well Within State of Art	Demonstrated Widely	Minimum Impact 5-10 minutes/Day Availability	Optimum, Higher Pressure Allowed, Smaller Piping	Current Practice	Demonstrated	No Effect	5
90 m (295 ft) Cladded Steel Tower	Net 3 Penalty	Well Within State of Art	Slight Reduction in Optical Hazard	Not Impacted	Optimum	Available Now	Not Impacted	Slightly Decreased Air Space Envelope	5
3. COLLECTOR SUBSYSTEM									
North Side Heliostat Field Feometry	Optimum Use of Reflector Area	SRE Confirmed Optics and Projected Performance	Confines Zone of Optical Hazard	Minimum Plant Capacity Variation during Year	Optimum, Keyed to Optimum Performance	Assured	Not Impacted	Confines Zone of Hazardous Air Space	1
Glass Mirrors	Highest Performance Now and Potentially	Only Consistently Successful Solar Reflectors	Not Impacted	Minimum Maintenance	Optimum, Highly Automated Industry in Being	Highest Performance with Process Modification	Only Type to Ever Be Used More Than 20 Years	No Effect	1, 5, 7

Table I.A-1 (concl)

KEY FEATURES OF CRSTPS PRELIMINARY DESIGN	TECHNICAL PERFORMANCE 1	TECHNICAL STATE-OF-ART 2	SAFETY 3	PRACTICAL UTILITY APPLICATION ASPECT 4	ECONOMIC OPTIMIZATION 5	TIMELY DEVELOPMENT, PILOT 1980, COMMERCIAL 1985 6	THIRTY-YEAR LIFE CAPABILITY 7	ENVIRONMENTAL IMPACT 8	PRIMARY SELECTION DRIVER(S)
Steel Heliostat Structure	Readily Meets Requirements	Long History, SRE and STTF Confirmation	Readily Meets Requirements	Minimum Maintenance	Key Factor in Plant Capitalization	Assured	Demonstrated	No Effect	1, 3, 7
Focusing Heliostat	Vital to Minimum Cavity Size	New for CRSTPS, Demonstrated SRE and STTF	Confines Zone of Optical Hazard	Not Impacted	Optimum Due to Performance Benefit	Assured	Not Impacted	Confines Zone of Optical Hazard	1, 5
Open-Loop Computer-Controlled Tracking	Readily Meets Requirements	Demonstrated at STTF	Optimum, Enables Accurate Stow-to-Track Control	Maximum Flexibility of Control	Optimum	Assured	Periodic Maintenance Required	Not Impacted	4, 5
Face-Down Stowage	Reduces Structure for High Winds	Demonstrated SRE at STTF	Vital to Aerial Safety during Shutdown	Minimizes Cleaning Cycle	Optimum Due to Structure and Cleaning	Not Impacted	Not Impacted	Eliminates Hazard during Shutdown	1, 3, 4, 8
Gear Drives for Azimuth and Elevation	Achieve Drive Function with Minimum Power	Widespread Use	High	Highly Reliable, Minimum Maintenance	Key Factor in Plant Capital Cost	Assured	Demonstrated	No Effect	1, 4, 7
Caisson Foundation	Small Impact on Total Tracking Error	Widespread Use	Not Impacted	Simplifies Installation	Optimum	Available Now	Not Impacted	Minimizes Ground Disturbance	5, 8
Laser Focus and Alignment	Readily Meets Requirements	Demonstrated at STTF	Enhanced, Allows Night Focus/Alignment	Benefits Installation and Maintenance	Optimum	Assured	Not Impacted	No Effect, Laser Power at Safe Level	1, 5
4. THERMAL STORAGE SUBSYSTEM Sensible Heat	Readily Meets Requirements	Only Option Ready for Application	Demonstrated Industrial Safety	Demonstrated Operational	Uses Low-Cost Commercial Materials	Assured	Periodic Makeup Required	Tankage Keeps Impact to Aesthetics	2, 4
2-Stage Oil, Salt Configuration	Highest Effective Utility Scale Storage	Commercial Materials, SRE Confirmed System Feasibility	Readily Meets ASME and Industry Codes	High Reliability, Broad Operational Flexibility	Optimum	Assured	On-Line (Oil) Maintenance Equipment Required	Requires Earthen Dike Spillage Control	1, 5
Dual-Mode Charging and Discharging Capability	Enables Optimized Charge and Discharge Exchangers	Expanded Version of SRE Reversible System	Slightly Enhanced by Independent Loops	Best Operational Flexibility, No Built-In Time Lapse	Optimum	Assured	Not Impacted	No Effect	4, 5
5. ELECTRIC POWER GENERATION SUBSYSTEM Dual Admission, 9308 kPa (1350 psi) 783K (950°F) Turbine	Highest Performance over Wide Range of Loads and Steam Conditions	Commercial Design	Demonstrated	Most Effective Equipment Meeting Broad Operating Requirements	Optimum at Commercial Size	Available Now	Attainable with Daily Cycling	No Effect	2, 4, 7

demonstrate the receiver performance and functional parameters at full scale for the commercial module. For these reasons the 1554 heliostat collector was incorporated into the preliminary design heliostat.

In the receiver subsystem maximized thermal energy conversion performance in the steam generator is keyed to the use of a cavity receiver having a minimum aperture size. The cavity is designed for maximum performance with flux levels, materials, and natural circulation steam generation consistent with commercial powers, industrial, and naval boiler practices.

Choice of sensible heat storage from the broad range of thermal storage technology options was based on its state-of-the-art readiness for incorporation into near term plants. Use of two stages, utilizing molten salt and hydrocarbon oil, both of which are in wide commercial use as heat transfer fluids, enables maximized turbine performance on steam generated from the stored energy, as superheat temperature of 700°K (800°F) is attainable.

Selection of a dual admission turbine in the moderate pressure range centered around the requirement for daily cyclic operation and utilizing a single machine to operate from either or both steam conditions present in the plant, receiver steam at 9308 kPa (1350 psig)/783°K (950°F) or storage steam at 2758 kPa (400 psig) 700°K (800°F). The superior partial load heat rate performance of the admission type turbine is of particular benefit to the solar plant operational flexibility.

Timely development is assured by the virtual elimination of a scaling difference between the commercial and pilot plants in the solar subsystems, thereby eliminating a development stage between the pilot and commercial size plants.

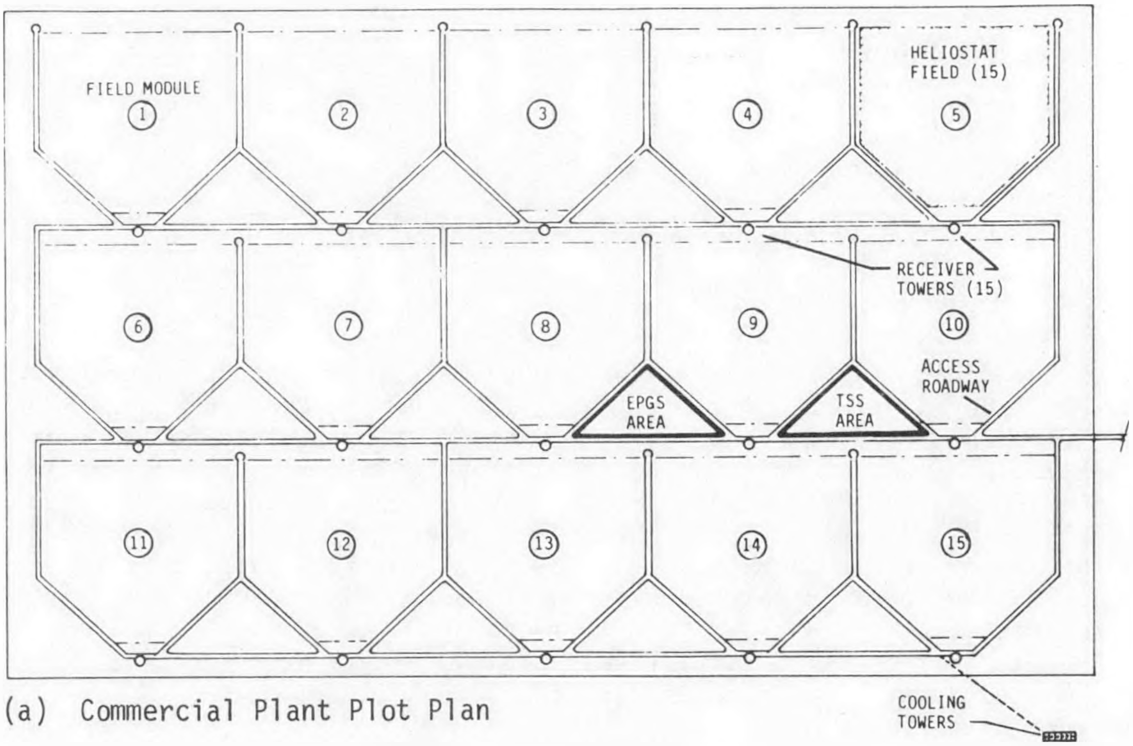
II. COMMERCIAL PLANT

The Martin Marietta team commercial "CRSTPS" design is an efficient plant of versatile design having broad operational flexibility, low technical risk, strong commercial potential, and minimum development cycle time.

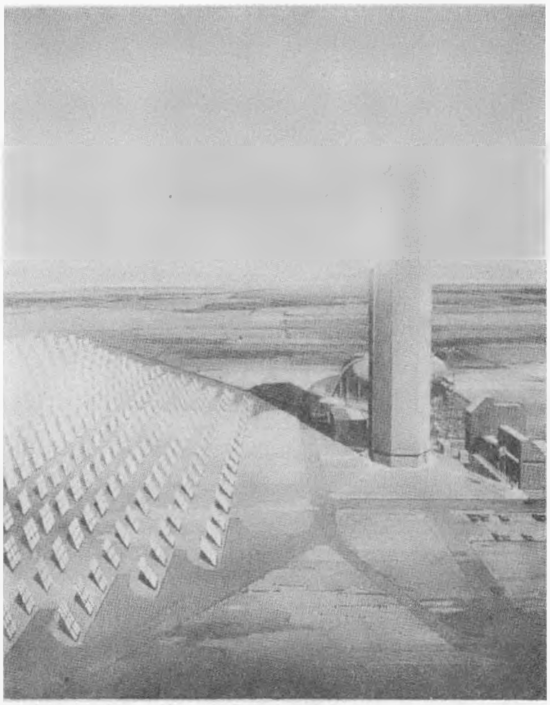
Two conceptual configurations of the commercial size central receiver solar thermal power plant were established during the program. The first, generated at the outset of the program, was rated at 100 MWe operating from direct solar and 70 MWe operating from storage, with the storage capacity being 6 hours. The second configuration established during the preliminary design effort reflected the increased knowledge base generated during the first year of the program and revised guidlines established by ERDA. The updated commercial plant configuration is rated at 150 MWe solar and 105 MWe storage with the storage capacity being 3 hours and is the configuration recommended for commercial intermediate load applications.

A. SYSTEM DESCRIPTION

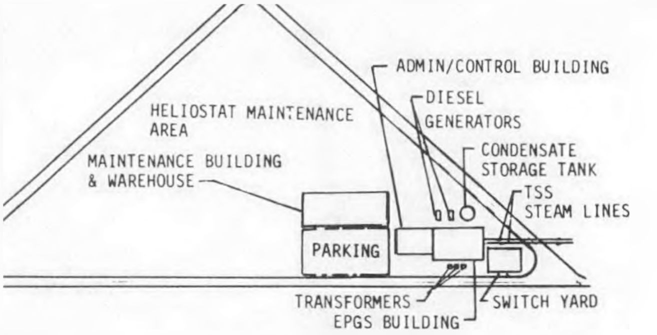
General features of the CRSTPS commercial plant are shown in Figure II.A-1. Dominating the layout and setting the land use requirement of 6.06×10^6 m^2 (6.52×10^7 ft^2 = 1498 acres = 2.34 sq. miles) are the fifteen solar collector subsystem modules with 1554 heliostats each. Two of the open triangular plots in the central zone of the layout are used for the thermal storage subsystem (TSS) and for the electric power generation subsystem (EPGS). Insets in the Figure show the layouts of the TSS and EPGS and an artist's rendering of the pilot plant module which is typical of the commercial plant in the configuration of the collector and receiver subsystems. Table II.A-1 lists values of major parameters of the commercial plant design. Modular design of the collector-receiver module provides versatility of design and flexibility in operational deployment in that site variations and sizing variations over broad limits can be accommodated by this basic design. The modular design also provides the shortest development path to the commercial plant in that collector and receiver subsystems are full scale in the pilot plant. Key also to attaining early the development, high reliability, moderate cost, and credible costing, required for commercial acceptance are the low risk features of the design, notably the cavity receiver steam generator, the focused heliostats, use of sensible heat storage and use of a non re-heat dual admission turbine.



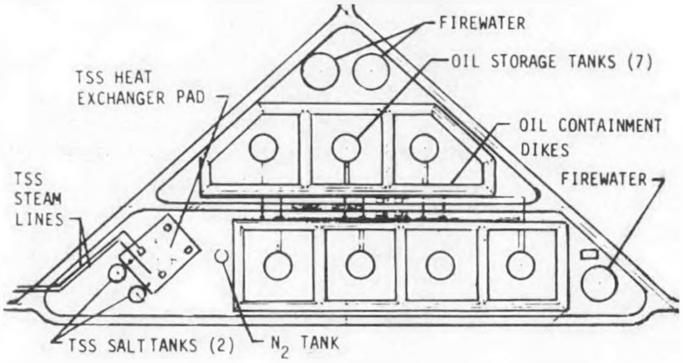
(a) Commercial Plant Plot Plan



(b) Collector Module



(c) Electric Power Generation Plant



(d) Thermal Storage Subsystem

Figure II.A-1 Martin Marietta Team Commercial Central Receiver Solar Thermal Power Plant Configuration

Table II.A-1
Major Parameters of Commercial CRSTPS Plant

Rated Output, Receiver Steam	150 MW$_e$
Rated Output, Storage Steam	105 MW$_e$
No. Collector Modules	15
No. Heliostats	23,310
Mirror Area	9.5×10^5 m^2 (10.28×10^6 ft^2)
Land Use	3,393 x 1.894 m (11,133 x 6,214 ft)
Receiver Type	North Facing, Horizontal Cavity
No. Receivers	15
Maximum Receiver Input (Each)	52.3 MW$_t$
Maximum Receiver Steam (Each)	49.6 MW$_t$
Receiver Steam Conditions	10,783 kPa (1550 psig) 789 K (960°F)
Storage Type	Two Stage Sensible Heat Salt & Oil
No. Tanks	7
Volume of Tankage	291,750 m^3 (10.07×10^6 ft^3)
Storage Steam Conditions	2,855 kPa (400 psig) 700 K (800°F)
Turbine Heat Rate - Receiver Steam (Gross)	9,655 kJ/kW-hr (9151 Btu/kW-hr)
Turbine Heat Rate - Storage Steam (Gross)	11,585 kJ/kW-hr (10,980 Btu/kW-hr)

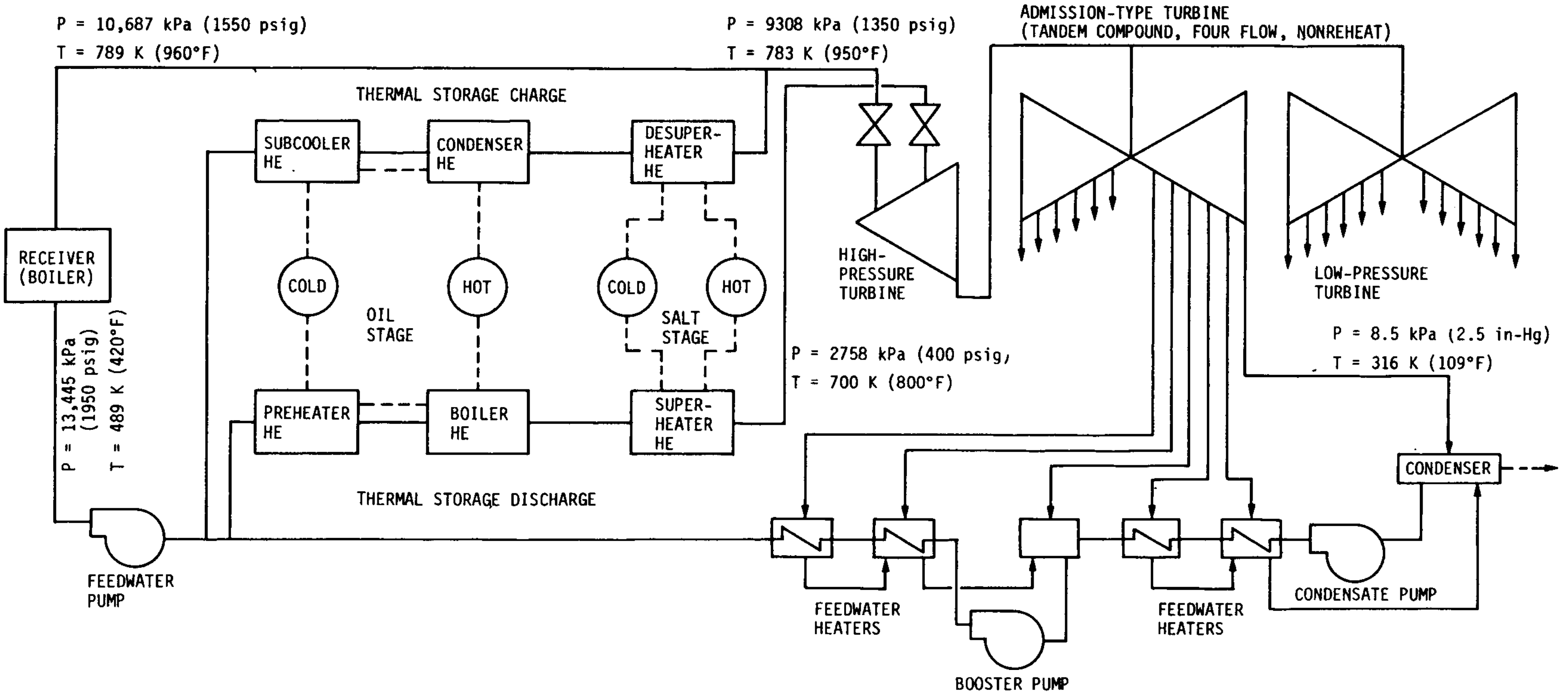
The commercial plant design represents an optimization of performance within the frame work of optimum economics. These two goals have been consistent in power generation technology and have been generally consistent in this program. A specific exception occurred in the collector subsystem geometry where the optimum height tower for technical performance was 137.2m (450 ft) and the optimum height for best economics was 90m (295 ft). In this case best economics was favored, impacting the performance only 3 percent. The commercial plant has an end to end efficiency of 25.1 percent while operating on receiver steam, based on the 150 MWe power delivered to the transmission line divided by the potential solar energy intercepted by the full area of the mirrors in the system, 570 MWt. This is a specific power generation of 238 W/m^2 (for state-of-the-art and competitive perspective, the SKYLAB photovoltaic solar array generated 93.2 W/m^2 in equivalent terrestrial sunlight).

This high level of performance was obtained by optimization of the system as well as the subsystems. Design features within the collector subsystem for instance are responsible for major aspects of the receiver subsystem's performance.

Operational features between subsystems specifically the receiver and EPGS have also been maintained particularly in the area of design factors which impact temperature rise rates, since an incompatibility results in a shorter operating day.

The block diagram of the major elements of the commercial plant energy conversion system and the subsystem interface steam condition state points are shown in Figure II.A-2. The solid line flow path is for operation of the EPGS on receiver steam. The charge and discharge modes of storage are shown dashed. Key elements firmed up in the design finalization included selection of a specific tandem compound four flow non-reheat turbine, use of a parallel mode (charging and discharging) storage system, and revision of the system operating state points to accommodate the optimum piping loss/cost configuration.

The receiver pressure has been increased to 10687 kPa (1550 psig) which is near, but still below, the bounding limit for natural circulation boiling under the system solar flux level. This was done to accommodate optimized field piping pressure drops and to maximize turbine inlet pressure with its attendant efficiency gain. Piping losses of the balanced field are 1329 kPa (200 psi). The main turbine steam inlet pressure is 9308 kPa (1350 psig). The pressure of steam from storage has



MAIN STREAM	ADMISSION STREAM
160 MW_e (GROSS)	117 MW_e (GROSS)
HEAT RATE = 9655 KJ/kW-hr (9151 Btu/kW-hr)	HEAT RATE = 11741 KJ/kW-hr (11128 Btu/kW-hr)

Figure II.A-2 Commercial Plant Schematic been decreased to 2758 kPa (400 psig) to minimize the storage system size.

Operational versatility of the CRSTPS is illustrated by the range of steady state operating modes shown in Figure II.A-3, available to meet the diverse requirements of the daily insolation cycle and the utility load demand:

Mode 1: Operation of the EPGS on receiver steam would be normally selected at the start of the day, the end of the day, and periods when thermal storage is fully charged.

Mode 2: Dual operation of the EPGS and the TSS in the charging mode would be normal in the central part of good solar days and is by far the most used mode.

Mode 3: Dual mode steam generation would normally be used during the final hour of the solar day and is a transition mode between solar and storage operation.

Mode 4: Dual mode charging and discharging of the thermal storage subsystem would be used in periods when the solar steam generation is highly variable due to cloud interruptions and is an optional transition mode between solar and storage operation.

Mode 5: Storage charging without operation of the EPGS is available as an operator option.

Mode 6: Storage discharge would be the normal after sundown mode and is an available option any time storage is sufficiently charged.

Output during modes 1 and 2 can reach 150 MWe while output during the storage modes, 3, 4, and 6, is limited to 105 MWe.

Seasonal variations in the daily power profile of the commercial CRSTPS plant are shown in terms of the thermal energy available at the turbine/TSS in Figure II.A-4. Seasonal peak output occurs in winter and is 1.6 percent higher than equinox and 9.7 percent above summer. Seasonal daily energy however, peaks in the summer and is 6.9 percent above equinox and 30.2 percent above winter. The third performance indicator, thermal storage energy, peaks at the equinoxes, being 19.6 percent above winter and 34 percent higher than summer (based on the full period of rated EPGS operation being maintained). Rated performance, 150 MWe, is attainable for 6.8 hours on a winter day and 8.5 hours on both equinox and summer days.

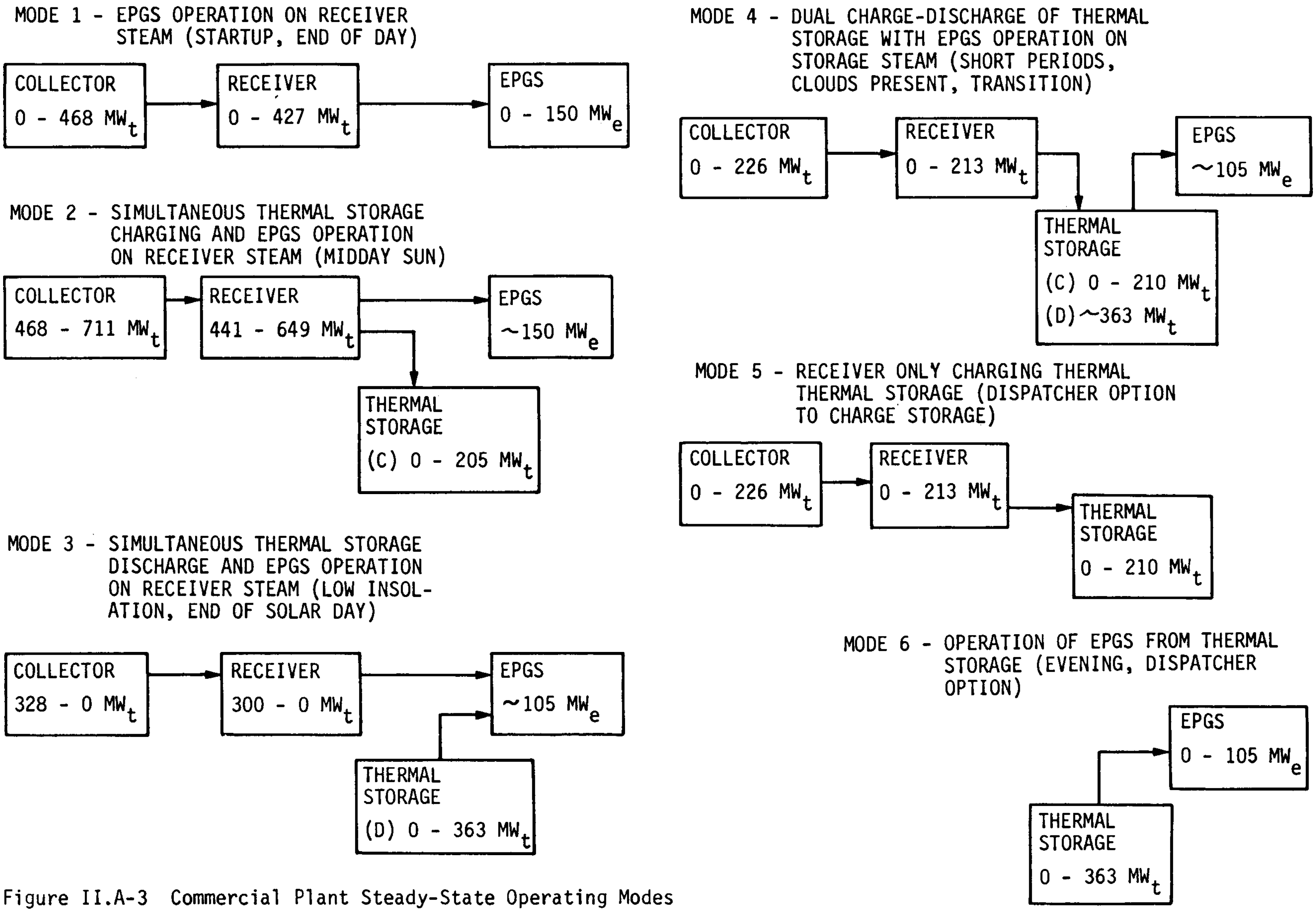
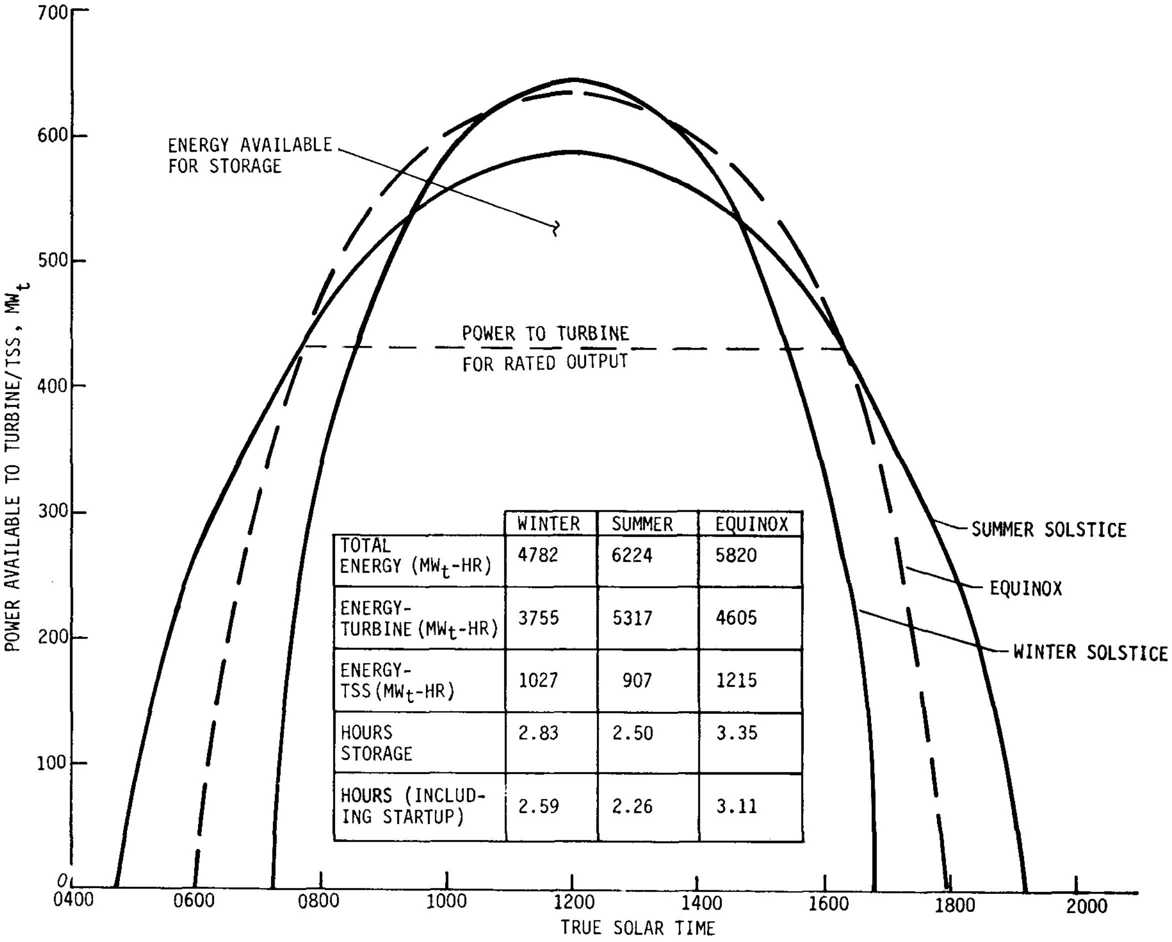


Figure II.A-3 Commercial Plant Steady-State Operating Modes



	WINTER	SUMMER	EQUINOX
TOTAL ENERGY (MW_t-HR)	4782	6224	5820
ENERGY-TURBINE (MW_t-HR)	3755	5317	4605
ENERGY-TSS (MW_t-HR)	1027	907	1215
HOURS STORAGE	2.83	2.50	3.35
HOURS (INCLUDING STARTUP)	2.59	2.26	3.11

Figure II.A-4 15-Module Commercial Plant Power Profile

Annual energy for the commercial plant (based on the 1963 Inyokern profile) is 5.78 x 10^5 MWe-hrs (626 kWe-hr/m^2 of collector), of which 88.4 percent is generated on receiver steam and 11.6 percent on storage steam.

Top level requirements for the commercial CRSTPS design are listed in Table II.A-2. The minimum rating value specified by ERDA has been raised as a Martin Marietta derived requirement to 150 MWe based on economic analysis and the desirability of using the largest suitable turbine-generator equipment currently available without new tooling. All requirements in the list are satisfied by the design.

B. COMMERCIAL PLANT PERFORMANCE

Overall performance of the solar plant, the electrical power delivered to the network referenced to the potential sunlight intercepted, controls the sizing of the plant to meet its total requirements. The stair step method of presentation and energy/power accounting shown in Figure II.B-1 for operation on receiver steam and in Figure II.B-2 for storage operation has been used throughout the program for system level design control. The minimum number of heliostats required to meet the "Solar Multiple = 1" definition is derived from the peak of the day and year performance profile of Figure II.B-1 to be 15336. The minimum number of heliostats required to supply sufficient energy to storage for three hours operation on retrieved energy is derived from the average operation in the 6.8 hour peak hours of the year's best day, Figure II.B-2, to be 6790. The full complement of heliostats in the plant was established at 23310, 1184 more than the sum of the two minimums. These added units expand the time for rated operation from the "momentary" design point to 6.8 hours for a winter day and 8.5 hours for equinox and summer days.

The individual subsystem performance contributions to the whole are evident in the stair step. The first energy loss steps, (a) heliostat utilization, (b) tower shadow, (c) effective cosine, (d) reflectivity, (e) atmospheric absorption, (f) tracking error, (g) optical error, and (h) tower sway, yield a collector subsystem performance of 0.764 for the design point. The next five steps (i) radiation loss from the receiver, (j) convection loss from the receiver, (k) insulation loss from the receiver, (l) riser loss, and (m) downcomer loss, yield a receiver subsystem efficiency of 0.928. The final two steps, (n) turbine/generator gross efficiency, and (o) auxiliary loads combine for an EPGS efficiency of 0.354. End to end plant efficiency on receiver steam is 0.251.

TABLE II.A-2 SYSTEM LEVEL COMMERCIAL CRSTPS REQUIREMENTS

1. Rating:

   100 MWe Peak Net or Cost Effective Peak Net Greater Than 100 MWe on Receiver Steam at Design Point Environment*

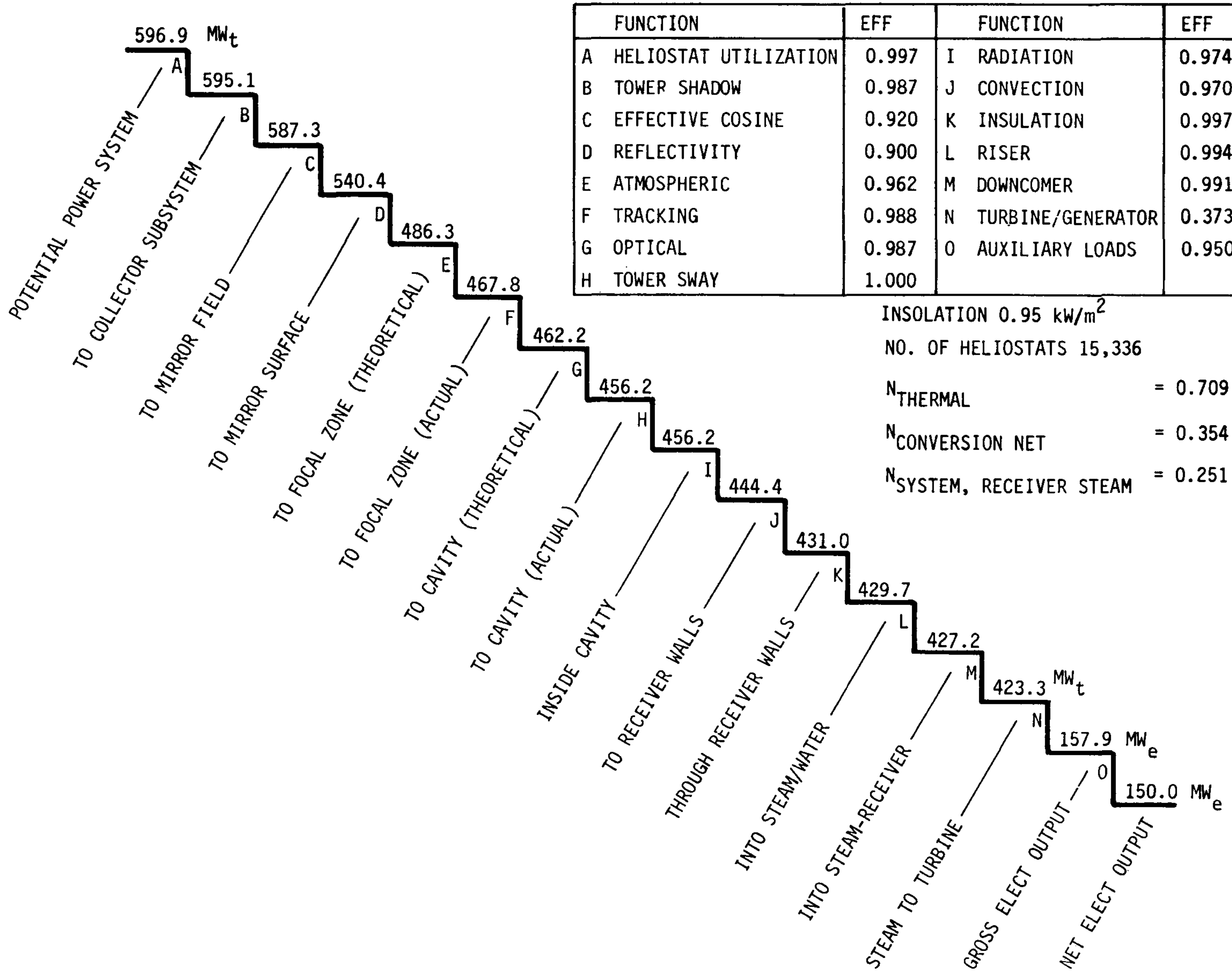
2. Design Point

   a. Site: Inyokern, California*
   b. Insulation: 950 W/M^2 Direct Normal*
   c. Sun Angle: Best Geometry for Thermal Energy Collection (Best Cosine)*
   d. Wind Speed: 3.5 m/sec (8 mph) at height of 10 meters*
   e. Wet Bulb Temp: 23°C (74°F)*
   f. Dry Bulb Temp: 28°C (82.6°F)*
   g. Cooling Method: Wet*

3. Operating Points

   a. Peak Electrical Power - 150 MWe**
   b. Auxiliary Loads - In addition to auxiliary loads associated with electric power generation subsystem the plant shall be capable of carrying the auxiliary load required for thermal storage charging while carrying peak power.*
   c. Thermal Storage - 70 percent of peak (105 MWe**) for 3 hours and capacity for start up and shut down from storage.*

   * ERDA Requirements
   ** MMC Derived



	FUNCTION	EFF		FUNCTION	EFF
A	HELIOSTAT UTILIZATION	0.997	I	RADIATION	0.974
B	TOWER SHADOW	0.987	J	CONVECTION	0.970
C	EFFECTIVE COSINE	0.920	K	INSULATION	0.997
D	REFLECTIVITY	0.900	L	RISER	0.994
E	ATMOSPHERIC	0.962	M	DOWNCOMER	0.991
F	TRACKING	0.988	N	TURBINE/GENERATOR	0.3730
G	OPTICAL	0.987	O	AUXILIARY LOADS	0.950
H	TOWER SWAY	1.000			

INSOLATION 0.95 kW/m^2

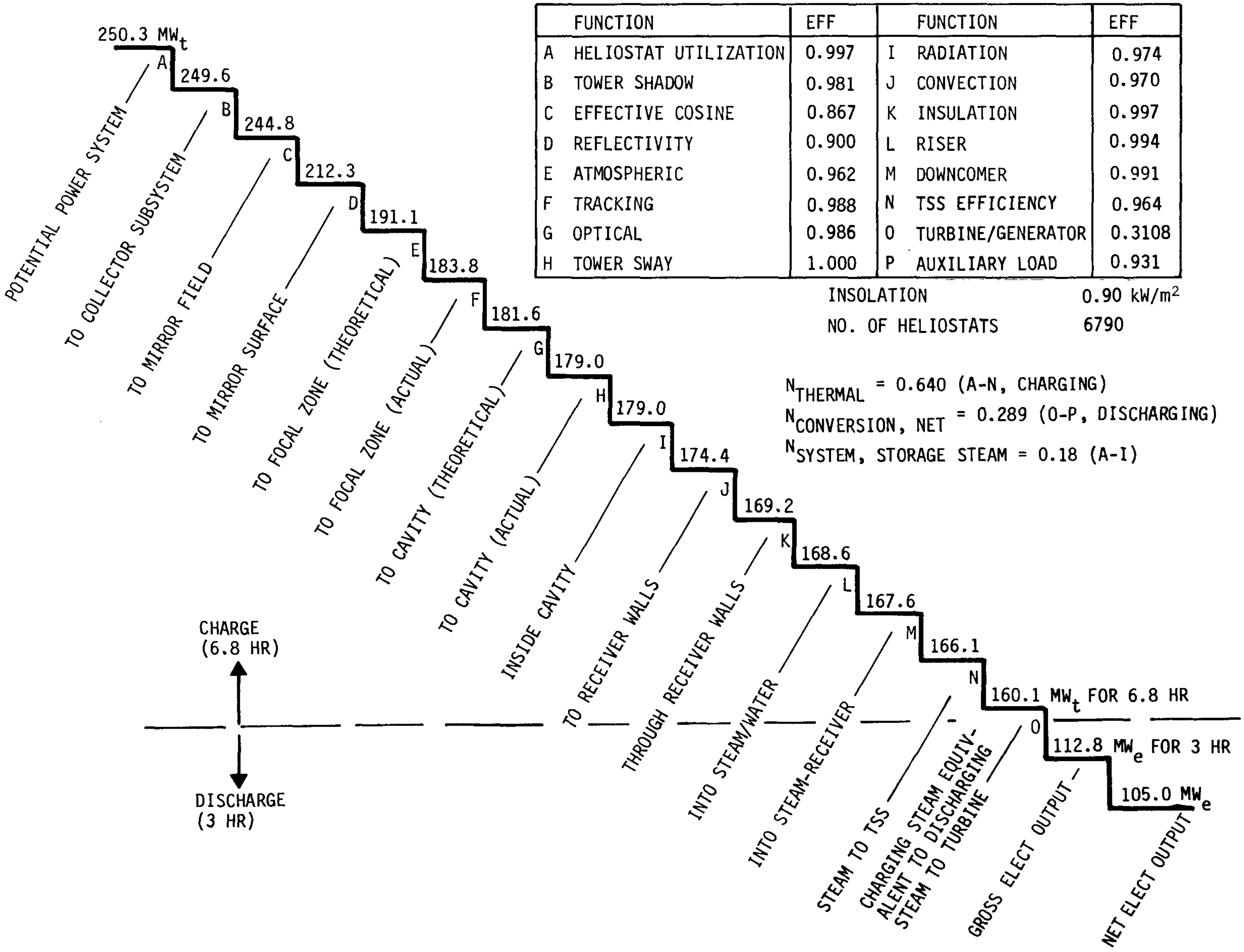
NO. OF HELIOSTATS 15,336

$N_{THERMAL}$ = 0.709 (A-M)

$N_{CONVERSION\ NET}$ = 0.354 (N-O)

$N_{SYSTEM,\ RECEIVER\ STEAM}$ = 0.251 (A-O)

Figure II.B-1 Commercial Plant Design Point Energy Balance
150 MW$_e$ SM = 1.0



	FUNCTION	EFF		FUNCTION	EFF
A	HELIOSTAT UTILIZATION	0.997	I	RADIATION	0.974
B	TOWER SHADOW	0.981	J	CONVECTION	0.970
C	EFFECTIVE COSINE	0.867	K	INSULATION	0.997
D	REFLECTIVITY	0.900	L	RISER	0.994
E	ATMOSPHERIC	0.962	M	DOWNCOMER	0.991
F	TRACKING	0.988	N	TSS EFFICIENCY	0.964
G	OPTICAL	0.986	O	TURBINE/GENERATOR	0.3108
H	TOWER SWAY	1.000	P	AUXILIARY LOAD	0.931

INSOLATION	0.90 kW/m^2
NO. OF HELIOSTATS	6790

$N_{THERMAL}$ = 0.640 (A-N, CHARGING)

$N_{CONVERSION,\ NET}$ = 0.289 (O-P, DISCHARGING)

$N_{SYSTEM,\ STORAGE\ STEAM}$ = 0.18 (A-I)

Figure II.B-2 Commercial Plant Energy Balance for Charging and Discharging

Assessable thermal storage efficiency is a combination of the effects from the TSS and the reduced EPGS efficiency while operating on storage steam. Effective storage efficiency is 0.964 (energy retrieved/charging energy supplied) multiplied by 0.817 (increased heat rate and auxiliaries fraction effect) for a net efficiency of 0.787.

C. TECHNICAL DISCUSSION OF COMMERCIAL CRSTPS-RATIONALE FOR KEY FEATURE SELECTION

In acknowledgement of the parallelism of minimum plant cost and maximum performance, the baseline design activity was strongly driven toward defining the highest possible performance plant within the constraints of the application's imposed and inherent requirements. During the later preliminary design activity, which had a broader data base for reference, some features were modified to better accommodate an optimum economic design. These decisions were always weighted with the caution that the technical data were more "solid" than the economic data due to the early state of solar power industrial art.

Early technical choices selected for strong technical reasons included the cavity receiver, focusing heliostats, north side collector geometry, modular collectors, sensible heat storage, and two stage storage. Choice of a moderate pressure single stage turbine cycle was constrained by the daily cycling nature of the application and the piping complications which largely negated the benefits potentially attainable from better performing re-heat turbines.

Technical compromises at the system level which were driven by economics included reducing the receiver aperture height from 137m (450 ft) to 90m (295 ft) and reducing the pressure of storage generated steam from 4240 kPa (600 psig) to 2855 kPa (400 psig) to benefit the storage subsystem size.

CAVITY RECEIVER STEAM GENERATOR

The cavity configuration was chosen for the receiver steam generator due to its excellent energy absorption and retention properties. Attainment of these properties is related to the "cavity depth/aperture diameter" ratio. For a ratio near 1.5, the absorption approaches black body, the radiation loss is below 3 percent, convection loss is near 3 percent and the defucusing of the collector beam within the cavity produces flux levels used in current commercial steam generators.

Adherence to design practice of commercial conventional steam generators has been maintained throughout the program. Of the three basic types of steam generators, (1) natural circulation, (2) forced circulation, and (3) once through, natural circulation was selected. This is because it is simple, easily adapted to the given cavity configuration, and particularly suited to the 50 MWt receiver module because of its long history of reliable operation in utility, industrial, and marine boilers of comparable capacity operating at similar pressure and temperature conditions.

Conventional materials, carbon steel in the boiler and stainless steel in the superheater, adequately fulfill the design requirements. Commercially available controls having identical functions with those in currently built power plants are used.

FOCUSING HELIOSTATS

Use of focusing heliostats is keyed to the receiver design. The feature was introduced into the collector subsystem because of its substantial benefit to the energy capture and retention performance of the receiver. As stated earlier, it permits a single design configuration, the "L/D = 1.5 cavity," to optimize performance and operate at normal steam generator flux levels. Without focusing heliostats, commercial design flux levels and high receiver performance independently drive toward drastically different receiver design configurations. To attain commercial flux levels with non-focused heliostats virtually opens the cavity, reducing receiver performance by more than 20 percent. To hold high performance of the cavity with non-focused heliostats doubles the linear dimensions of the cavity, quadrupling the heat exchange surfaces.

Factory pre-focusing of the facets for the focused heliostat is planned. One of the heliostats of the subsystem research experiment was an experiment with this fabrication concept. Final focusing of the heliostat (co-aiming the facets) is accomplished in the field with a laser alignment system patterned heavily after the one built for the 5 MWt Solar Thermal Test Facility.

NORTH FIELD COLLECTOR GEOMETRY

The north side collector geometry was selected to maximize the area utilization of the collector. To provide the required equal angles of incidence and reflection, the heliostat's basic geometric function is to bisect the angle between the incoming sunlight and the reflected beam to the receiver. Design of a collector which minimizes this angle minimizes the angle between the heliostat normal and the sunlight, therby maximizing heliostat area efficiency.

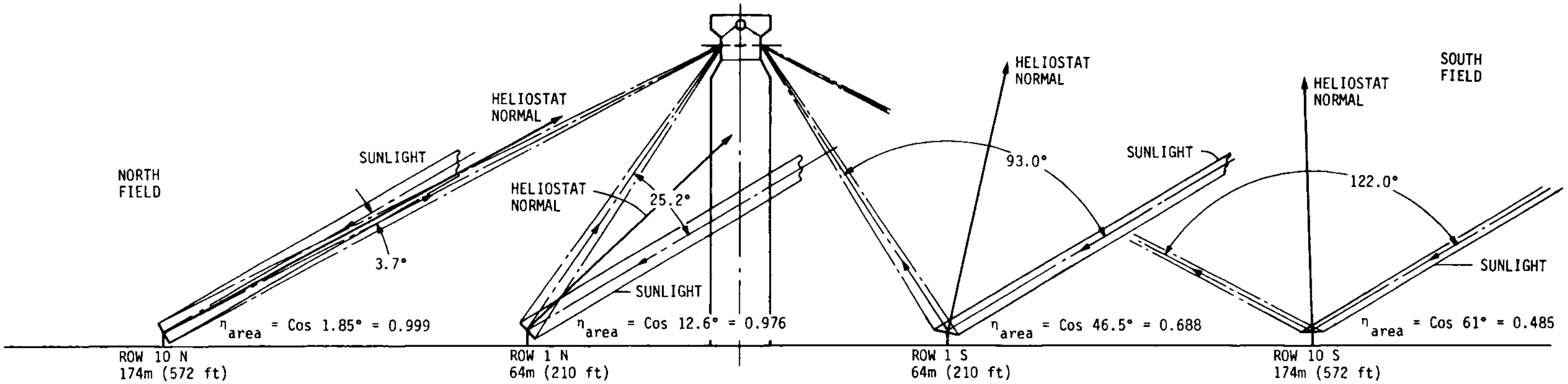
Figure II.C-1 illustrates the basic effect which favors heliostats located in the north field over those at corresponding positions in the south field. The geometric patterns for noon on the solstices and equinox are shown for the centerline heliostat at row 1 and row 10 both north and south of the tower. For the north field heliostats the angle between the incoming solar beam and reflected focused beam is consistently a small acute angle generally yielding a half angle cosine (incident and reflected beams to the heliostat normal) greater than 0.9. For south field heliostats the major angle (solar to reflected) is consistently larger and grows progressively as the position of the heliostat moves away from the tower. The south field angles frequently become obtuse with resultant half angles greater than 45^{o} reducing the area effectiveness cosine below 0.7.

An early design goal of the central receiver was to achieve competitive performance with on-axis tracking collectors. Due to focal zone and support structure shadowing, the best of these systems attained an area utilization factor of 0.88. For this reason the goal of the central receiver was to achieve a comparable area efficiency (effective cosine of the angle of heliostat normal to the sun) throughout the bulk of the operating day and year. This goal was only approachable with the north field collector geometry which did yield the desired performance for the September to March half of the year and was only mildly compromised it in the other half. A reduction in this performance parameter of three percent was accepted late in the program, the net result of the tower height reduction design modification and the offsetting effects of the field layout using 41m^2 heliostats.

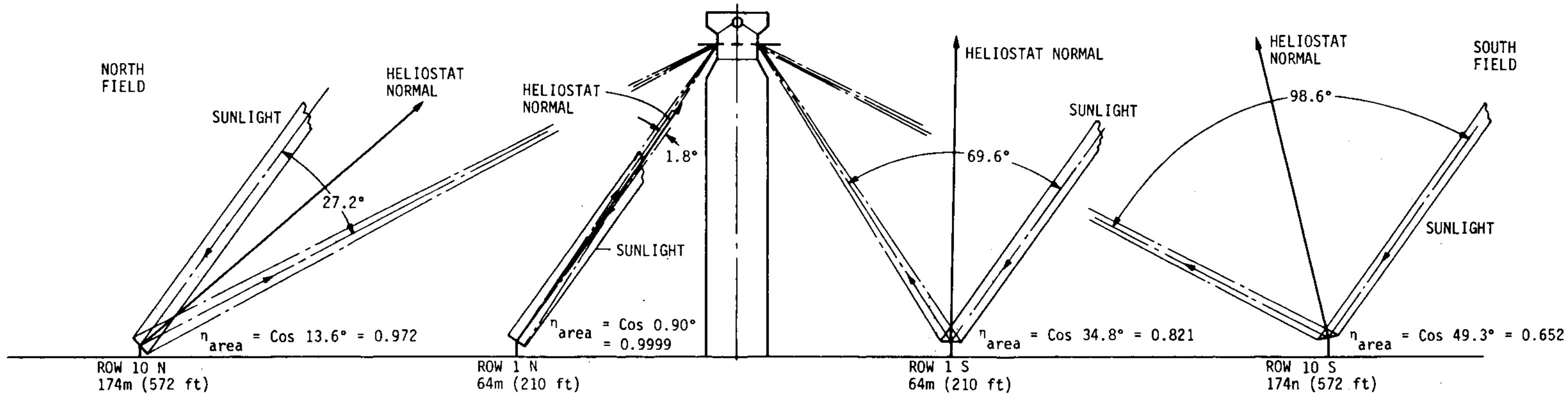
Data for the two positions shown and for corresponding positions 20 and 30 rows north and south are listed in Table II.C-1. The increasing advantage of the north field positions with module size is illustrated. The north field margin is greater in the winter with low sun angles, 1.42:1 (Row 1) to 2.75:1 (Row 30), and narrows in the summer, 1.07:1 (Row 1) to 1.19:1 (Row 30). Annual variation in the area efficiency is substantially smaller for the north field. For the north field the advantage of the best cosine of the year over the worst cosine of the year ranges between factors of 1.02 and 1.18, while for the corresponding south field it ranges between factors of 1.34 and 1.95.

Table II.C-1 Area Efficiency Comparison for Corresponding North and South Field Heliostats, 90 m (295 ft) Tower

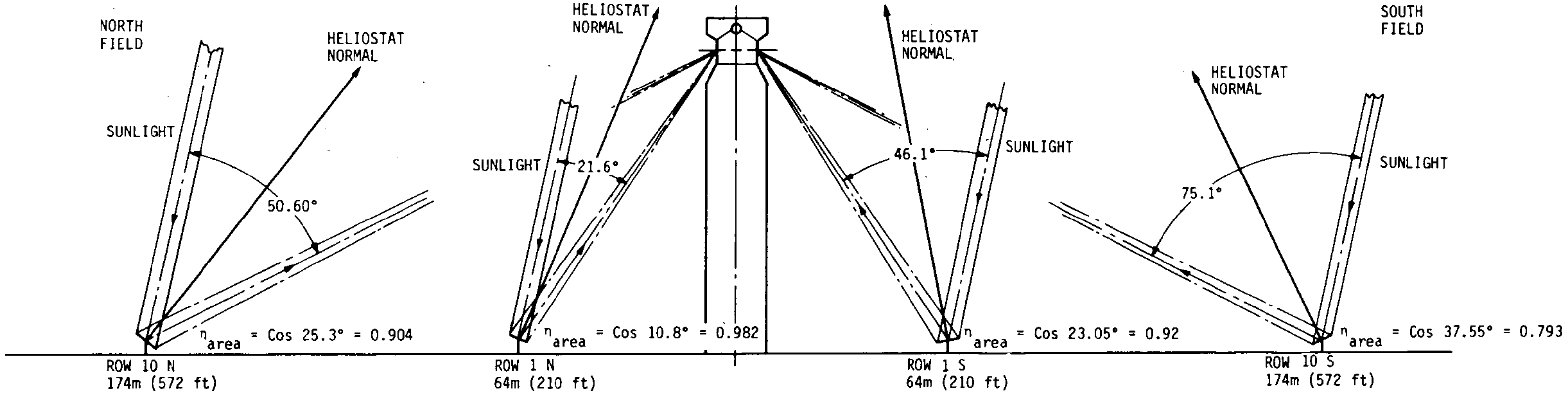
Position in Collector Module	Time of Year	Noon Geometric Area Efficiency (Cosine)		North/South Area Efficiency Ratio
		North Field	South Field	
Row 1, Position 1 64 m (210 ft)	Winter	0.976	0.688	1.42
	Equinox	0.999	0.821	1.22
	Summer	0.982	0.920	1.07
Row 10, Position 1 174 m (572 ft)	Winter	0.999	0.485	2.06
	Equinox	0.972	0.652	1.49
	Summer	0.904	0.793	1.14
Row 20, Position 1 326 m (1069 ft)	Winter	0.990	0.390	2.54
	Equinox	0.942	0.569	1.66
	Summer	0.854	0.724	1.18
Row 30, Position 1 448 m (1469 ft)	Winter	0.985	0.358	2.75
	Equinox	0.930	0.540	1.72
	Summer	0.835	0.700	1.19



(a) Noon, Winter Solstice



(b) Noon, Equinox



(c) Noon, Summer

Figure II.C-1 Reflection Angle/Area Efficiency Comparison Corresponding North and South Heliostat Positions

The results are relatively insensitive to lattitude. While the example shown was for Inyokern lattitude, 35.68; it is generally applicable for the southwestern U.S. The basic north side geometry advantage has been consistently verified in analysis of module designs with full surrounding layout, and tower south of center surrounding layout and the north side collector layout integrated for the complete year on an hourly increment. East and west fields yield an intermediate performance between the north and south.

SENSIBLE HEAT STORAGE

Sensible heat storage was selected from the broad range of storage technology options due to the depth of experience available on which to base a design for near term plants. The heat exchange properties and heat capacity properties for the selected fluids are available from the heat transfer technology and remote steam generation applications used in specialized industries for many years. The selection of two stages for the heat storage system enabled attainment of a high effective storage efficiency by enabling the turbine to operate at a maximum performance level for the low pressure steam.

ECONOMIC SCALING INFLUENCES OF PLANT SIZE

The commercial plant design is completely flexible over the 100-300 MWe range in increments keyed to a single module size without cost impact on the subsystems. To establish the commercial plant size an economic trade-off was performed from 100 to 300 MWe. Factors contributing to the overall economics of scale of the commercial plant include elements of cost which are sensitive and insensitive to scale in both capital equipment and operating costs. In capital equipment for example the collector-receiver costs are direct linear functions of scale (or constant $/KW) while electric power generation equipment cost benefits from increased scale and piping costs suffer from increased scale. Operating costs associated with plant operation benefit from scale while maintenance costs of the collector field do not.

The 150 MWe plant sizing is based on a trade-off of the scale sensitive factors. Conversion of operating costs to equivalent initial capital costs is made to enable comparison on the same baseline, dollars per kilowatt capital cost. (This conversion was made on the basis of a capital equipment purchase which would have the same cost as the operating cost over 30 years. The operating cost is divided by 2.914 to obtain the equivalent capital cost, based on a 9 percent interest rate on the capital investments).

Figure II.C-2 shows the combined effect of the major scaling influences, the turbine generator's declining cost with scale, the piping's rising cost with scale, and the operating manpower's declining cost with scale, the curve being very flat in the 100-150 MWe range followed by a break upward above 150 MWe. Table II.C-2 lists the full values as well as the relative values plotted.

The 150 MWe was selected for the commercial plant size on the basis of the foregoing combined influences study, the recognition that fixed plant facilities, not yet considered, will also benefit from larger scale, and that a 150 MWe turbine generator can be assembled from existing hardware.

COLLECTOR MODULE SIZE

Selection of a collector module size for the commercial plant near that required for the pilot plant has a technical and economic basis as well as being the most timely development path to commercialization. The technical merits of the current module size are related to keeping the slant range of the focused energy within practical limits when referenced to the resulting image size and increasing atmospheric absorption from larger modules. Economic considerations favoring the use of smaller modules and a larger number of shorter towers center around the cost of towers being an exponential function of the height with an exponent in the 2.1-3 range.

Effects of increasing the collector module size by a factor of two and a factor of four were examined in the design finalization to evaluate the degree to which later design and cost data had influenced the size selection made in the baseline design. Figure II.C-3 shows the three "commercial configurations" used in the trade-off. The reference plant was increased to 16 modules to enable equal size plants with the double and quadruple size modules being evaluated. Land area requirements for all three plants are very close, differing by only 1.5 percent from the largest to the smallest.

The scale sensitive variable factors in the collector and receiver subsystems were established as the receivers, towers, piping, and quantity of heliostats. Figure II.C-4 and Table II.C-3 show the trade-off data, the differential costs being shown on the plot, and the total and differential costs being listed in the table. Receiver and piping costs favor the larger module size while heliostat and tower costs favor the smaller module. The combined curve shows a low point for the double size module, 2.2 million dollars lower in capital cost than the plant with the smallest module.

Table II.C-2 Major Commercial Plant Sizing Cost Influences

	100 MW_e Plant Size		150 MW_e Plant Size		200 MW_e Plant Size		300 MW_e Plant Size	
	Total	Relative	Total	Relative	Total	Relative	Total	Relative
Turbine Cost $/kW	95	5	92.5	2.5	90	Base	90	Base
Piping Cost $/kW	101	Base	109	8	121	20	158	57
Operating Manpower Equivalent Cost $/kW Capital	94.4	21.3	89.1	16.0	83.7	10.6	73.1	Base
Subtotal Scale Sensitive Costs	290.4	26.3	290.6	26.5	294.7	30.6	321.1	57

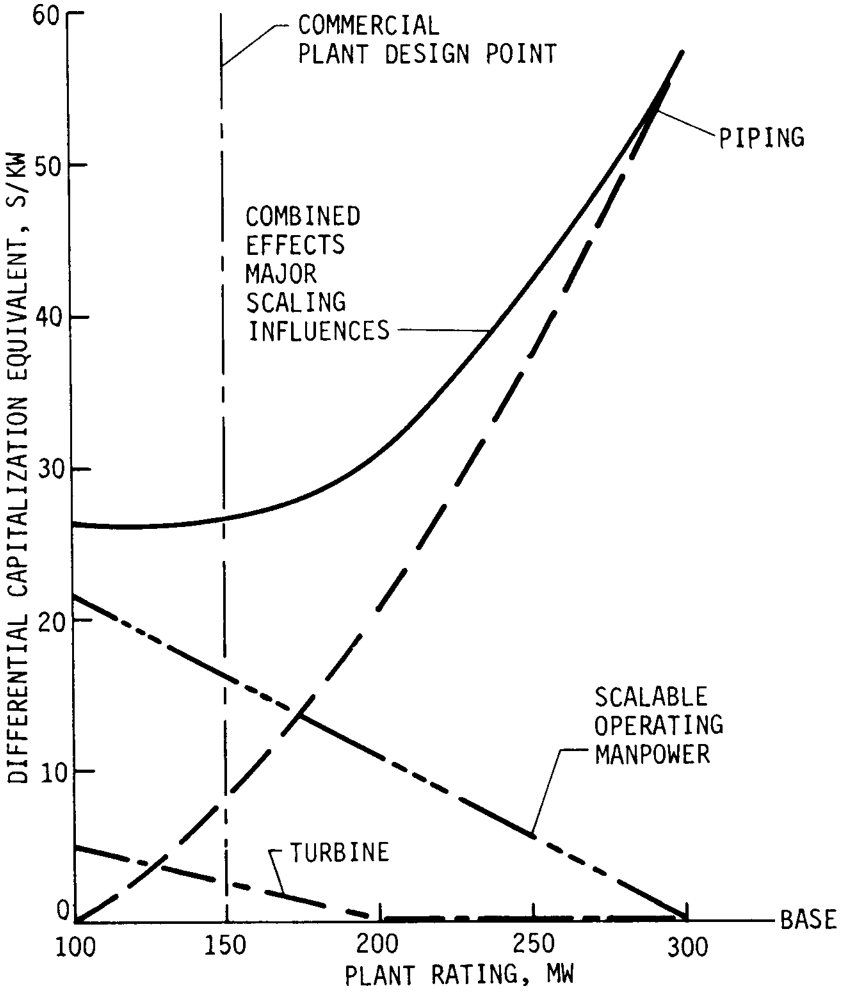
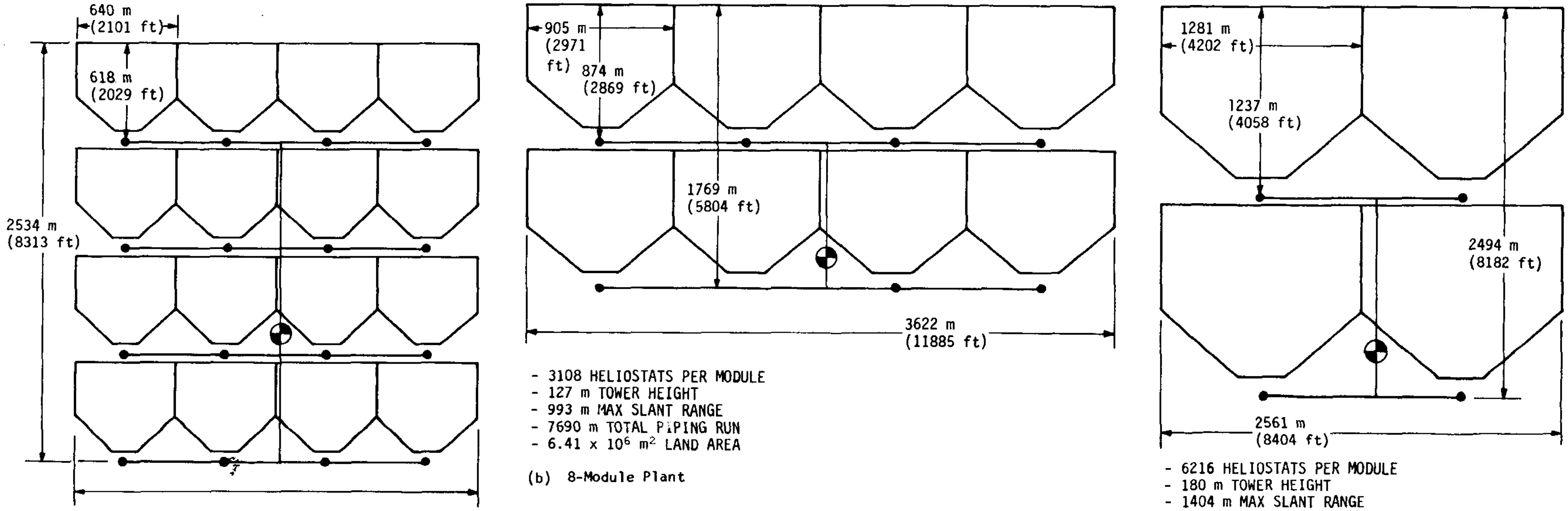


Figure II.C-2 Primary Economic Scaling Influences - Commercial Plant



- 1554 HELIOSTATS/MODULE
- 90 m TOWER HEIGHT
- 707 m MAX SLANT RANGE
- 11240 m TOTAL PIPING RUN
- 6.49 x 10^6 m^2 LAND AREA

(a) 16-Module Plant

- 3108 HELIOSTATS PER MODULE
- 127 m TOWER HEIGHT
- 993 m MAX SLANT RANGE
- 7690 m TOTAL PIPING RUN
- 6.41 x 10^6 m^2 LAND AREA

(b) 8-Module Plant

- 6216 HELIOSTATS PER MODULE
- 180 m TOWER HEIGHT
- 1404 m MAX SLANT RANGE
- 4520 m TOTAL PIPING RUN
- 6.39 x 10^6 m^2 LAND AREA

(c) 4-Module Plant

Figure II.C-3 Commercial Plant Configurations for Module Size Tradeoff

Table II.C-3 Module Size Parametric Data Summary

	10 MW_e + Storage 16 Modules 1554 Heliostats		20 MW_e + Storage 8 Modules 3108 Heliostats		40 MW_e + Storage 4 Modules 6216 Heliostats	
	Total	Relative	Total	Relative	Total	Relative
Heliostats Cost (Atmospheric Attenuation Impact Using 4K per Heliostat)	99.46M	Base	101.32M	1.86M	104.43M	4.97M
Receiver Cost	48.48M	11.74	42.20M	5.46M	36.74M	Base
Tower Costs	38.88M	Base	42.32M	3.44M	53.16M	14.28M
Piping	17.10M	2.70	15.88M	1.48M	14.40M	Base
Total Solar Systems	203.9M	14.44	201.7	12.24	208.7	19.25

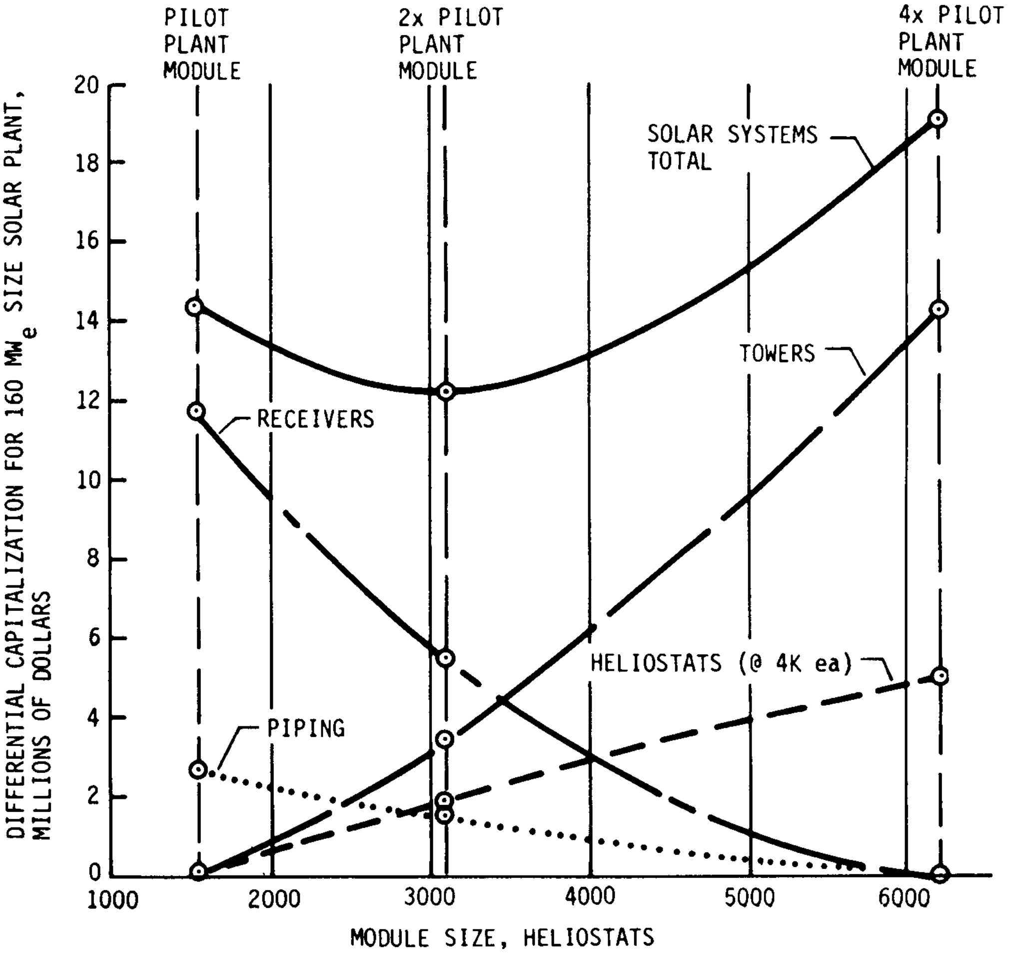


Figure II.C-4 Module Size Tradeoff Factors

As previously stated in the design selection considerations (Table I.A-1), the three primary drivers on module size were performance, the utility application aspects (maximum reliability and versatility), and the timely development consideration. The 1 percent negative economic impact was not considered sufficiently important to override the primary drivers.

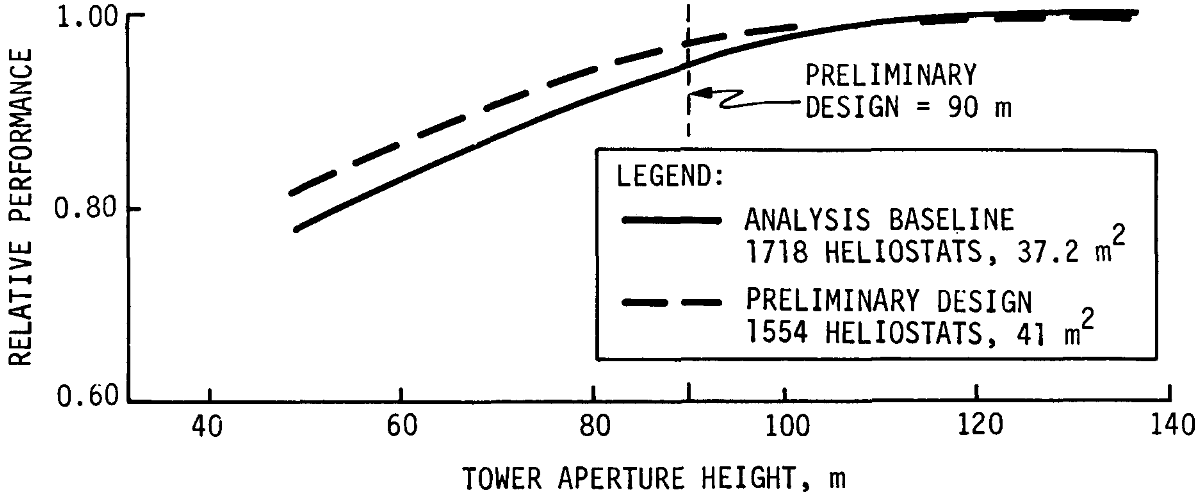
TOWER HEIGHT SELECTION - TECHNICAL AND ECONOMIC INFLUENCES

The tower height vs collector performance characteristic curve, the solid curve of Figure II.C-5(a), was derived for a flat north field collector based on total annual energy collected, early in the program. The curve is relatively flat at the taller tower end, peaking at 137.2m (450 ft). An economic trade-off during design finalization yielded the cost characteristic curves for variable priced heliostats shown as solid lines in Figure II.C-5(b). The clear indication of economic benefits resulting from a tower height reduction to the 90m (295 ft) level was accepted at the expense of a six percent performance penalty. Subsequent design modification of the heliostat area and heliostat module layout partially offset the performance penalty as indicated by the dashed curve of Figure II.C-5 (a). This in turn produced a modified economic characteristic, as shown for $4000 per unit heliostats as the dashed curve of Figure II.C-5 (b), indicating that further tower shortening will be desirable when the heliostat cost goal is met. For the preliminary design the receiver aperture height has been selected at 90m (295 ft).

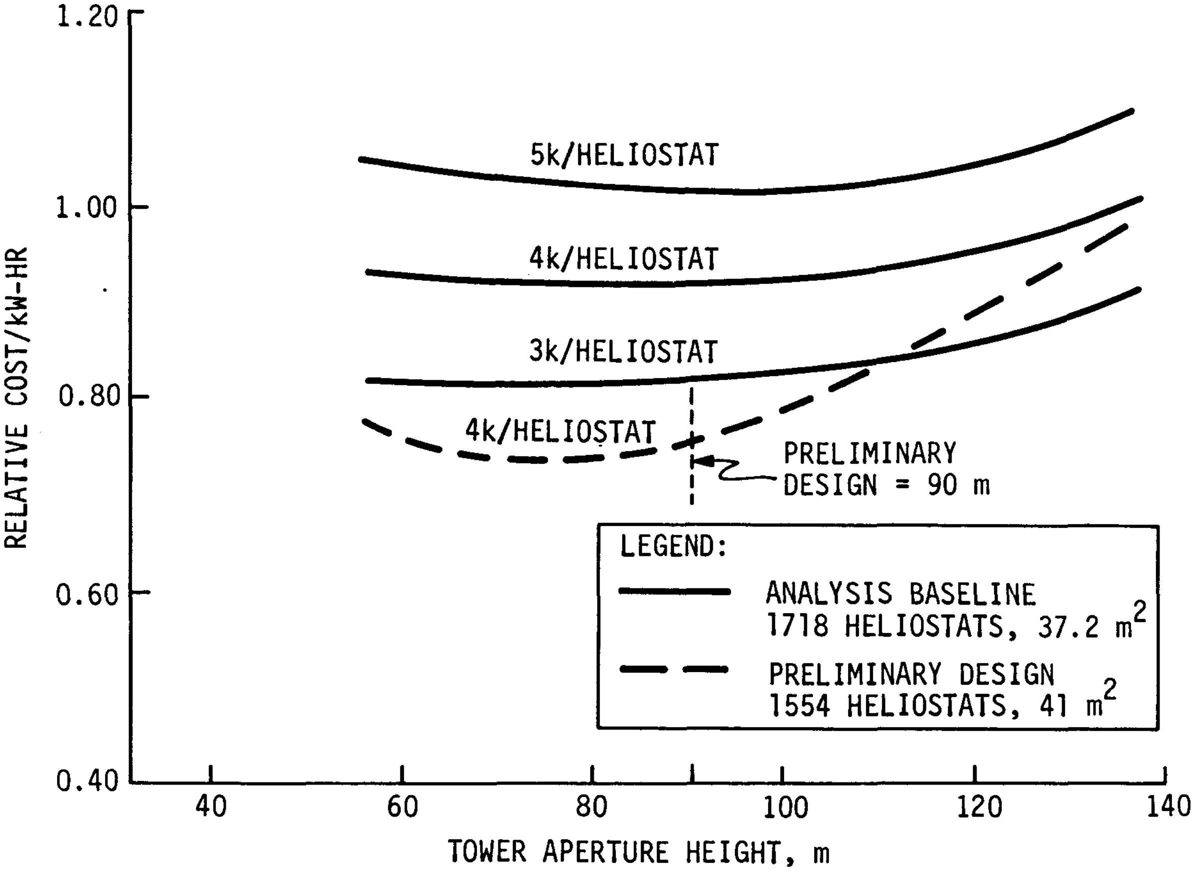
SAFETY CONSIDERATIONS

In common with current utility power plants the solar power plant includes a set of safety hazards which must be neutralized in the design, fabrication and operational phases. Those problems in the electrical power generation system associated with the handling and conversion to power of high pressure high temperature steam and the control and distribution of high voltage electricity will be treated as in current power plants.

The major solar unique hazards include concentrated sunlight from the collector and the storage of large volumes of hot fluids in the thermal storage system. Figure II.C-6 illustrates the concentrated sunlight flare effect from individual heliostats and the concentrated beam size at the focal plane (the receiver aperture).



(a) Relative Module Performance



(b) Relative Module Cost per Kilowatt-Hour

Figure II.C-5 Tower Height Tradeoff Data

To avoid structural damage and personnel injury from the concentrated reflected solar energy, the selected control system will provide full time beam control from stowage to target and return. Beams will only move to and from the receiver in a specific corridor. This corridor will avoid all unprotected structures and occupied areas. Fail safe features in each heliostat control logic provides the capability for each heliostat to command movement to a safe beam position and stow maneuver upon loss of the master computer control signal.

Elevated beam hazards to aircraft are avoided by controlling the zone where beam overlapping can occur to within the plant boundaries at elevation less than the tower height. Such a walk-the-wire control was developed for the heliostat field of the 5 MWt Solar Thermal Test Facility at Sandia, Albuquerque, New Mexico.

By application of fail safe controls, tank separation, and ASME code control of component design and manufacture, the hazards in the thermal storage subsystem have been reduced to common industrial hazards and do not represent a significant personnel hazard.

Reliability

Reliability has been a major consideration throughout the design of the commercial plant. The use of proven designs and materials are used in all subsystems and coupled with simplicity of design, controls, and operation, provide added reliability at the system and subsystem level. Inherent redundancy of the modular concept provides added reliability for reduced down time as well as facilitating maintenance requirements.

System Reliability - The modular concept of the commercial plant includes 15 collector-receiver modules. These modules are independent entities operating in parallel redundancy and providing the flexibility to operate with or without selected modules as required. In addition, the commercial plant reliability will be further enhanced by building and demonstrating a pilot plant that is one full scale module of the commercial plant.

Collector Subsystem Reliability - In addition to the collector subsystem being divided into the 15 modules, each module consists of 1554 heliostats. The design of the collector-receiver module is such that operation is insensitive to loss of individual heliostats or groups of heliostats within a module.

(a) Sun Flashes from SRE Heliostats

(b) Combined Images of Four SRE Heliostats

Figure II.C-6 Concentrated Sunlight Photographs Highlight Unique Safety Hazard of CRSIPS

Receiver Subsystem Reliability - In addition to the receiver subsystem consisting of 15 parallel redundant receiver modules, individual receiver design incorporates the high reliability of the natural circulation design concept. The three element feedwater regulator coupled with the natural circulation provides dependable, reliable and stable operation over large swings in solar insolation. These features coupled with the simple single point aim strategy, required for the collector to receiver interface enhances the reliability of each module. Added reliability is provided by the use of standard, proven boiler construction techniques and materials.

Thermal Storage Subsystem Reliability - The thermal storage subsystem design concept uses sensible heat for storage of the thermal energy. Both storage materials, the hydrocarbon oil and the molten salt, have been used commercially for many years as thermal transport materials and are well understood. Conventional heat exchangers are used in their normal applications. Redundant full flow pumps are provided unless replaceable on an overnight basis.

Electrical Power Generation, Balance of Plant Reliability - The reliability provided by the non-solar portion of the plant is provided to a large extent by utilizing state-of-the-art proven hardware. A turbine at the recommended commercial plant size can be built from existing components requiring no new design or engineering. The component applications have recognized the cyclic requirements of the solar plant and life expendancy has been a primary consideration. Also a component redundancy philosophy has been followed to facilitate continued operation and ease of component isolation and replacement.

Emergency Operation

In addition to the normal steady state modes of operation and the transient and transition modes, there are also emergency conditions that the plant design must be capable of handling. Each subsystem is designed to react to out of limit fault conditions and provide for a safe shutdown. The safe shutdown of a particular subsystem may or may not effect another subsystem. Depending on the mode of operation and status of the plant, a shutdown of the total plant could result.

The emergency condition resulting from the loss of the utility grid in combination with fault conditions that trip out the EPGS is the most significant and requires additional equipment be incorporated in the design. In the event of loss of power to the auxiliary electrical equipment in the power plant, harm to personnel and/or damage to equipment could occur unless backup power sources are provided. Two sources of backup power are provided to preclude this danger. A standby diesel generator is provided to prevent either harm to personnel or damage to equipment if power is lost. In addition, an emergency battery is provided to preclude harm to personnel during the startup period of the diesel generator or if there is a malfunction in the diesel generator.

Environmental Impact

An attractive aspect of harnessing the sun's energy to produce power commercially is the potential to do so without compromising our environment. The design of the Central Receiver Power Generation concept described herein has been influenced by a recognition of this goal. Our design constitutes a practical approach to minimizing environmental impacts and still maintaining consistency with the major cost and operational performance parameter goals.

The collector subsystem includes the more dominant features of the solar plant with respect to environmental factors. The deployment of 23,310 individual heliostats in ordered matrices on the land surface is a basic design requirement of the concept. A 150 MWe commercial plant requires over 6 million m^2 (1500 acres) for this function, constituting 72% of the total plant area. This amount of land area, along with the extensions necessary for access roadways and security fencing, must be committed to the plant site; no common use potential is apparent.

The total disrupted ground surface area required for installations (roadways, foundations, trenching, etc.) has been held to approximately 17% of the total heliostat field area by the decision to use low pressure tires on construction and maintenance vehicles in lieu of extensive heliostat row paving. Water quality of the area will be preserved by our mirror washing approach which utilizes demineralized water without chemical cleaning agents.

The heliostat field area microclimate will be modified by the shading of the ground surface by the heliostats. This can exceed 30% of the ground area during morning and afternoon hours in summer. This, and water dispersed from mirror washing operations, could have minor effects on local biology. Species not normally residing or growing in the area may be attracted to the cooler, shaded area, or to the slight irrigation effects of mirror wash water. This impact could be considered beneficial depending upon site location.

It is expected that occasional stowing/unstowing of heliostats will be required under sunlight conditions. The reflected sunlight, sweeping regions off the tower structure, could create distracting flashes visible for long distances from the plant site. This feature may be objectionable to those in visual range of the phenomenenon and could constitute a close range hazard under certain conditions. Adverse effects will be avoided by positive control of mirror movement operations to minimize or eliminate objectional paths, by providing opaque fencing for the near ground level regions, and by procedural control of on-site personnel during mirror stowing operations.

The receiver is environmentally quite comparable to its boiler counterpart in a fossil fuel plant, with the notable absence of combustion product pollutants. The design and operation requires no new or unproven technology and should present no more accident potential than contemporary boilers. Flux levels at and near the aperture during operation would be damaging to intruding birds in flight, but experience at a comparable solar furnace facility in France indicates that birds sense the solar beam and avoid it.

The receiver tower is another basic design requirement of the Central Receiver Solar Power Plant concept. Elevated positions for the receivers are required to efficiently collect the reflected thermal flux from large numbers of heliostats. Although the towers are the most prominent visual features of the plant to a ground observer, our proposed design includes external surface geometry, finish and color that contribute to an aesthetically non-intrusive appearance when viewed against natural background surroundings. Our modular concept has enabled us to optimize tower height at only 113 m (370 ft), the height requirement to enclose a receiver with an aperture height of 90m (295 ft), which further reduces visual prominence, bringing the height well within that of stacks associated with contemporary fossil fuel power and industrial plants.

Our thermal storage subsystem design presents no significant threats to the environment. Although the thermal storage concept represents new technology at the subsystem level, all elements of our subsystem design, including the storage media, involve materials and processes that are well proven in industrial applications. Neither of the storage media (salt or oil) present any special toxicity problems or require special handling. Nitrogen ullage blankets, design and construction to applicable codes, and containment basins for accidental spills all contribute to avoid accidents or to limit consequences should they occur.

Environmental influencing factors summarized here, and presented in more detail for the pilot plant in an appendix to Volume II, are considered easily acceptable when compared with alternative power generating concepts. No significant pollution, biological or meteorological effects are indigenous to the concept. Unavoidable factors of significance all pertain to land preemption, to aesthetic perceptions (the existence and appearance of power generating installations on land areas that might otherwise remain pristine in nature), and to consequential socio-economic influences attendant with plant construction and operation.

Mitigation of the dominant feature - commitment of relatively large land areas for heliostat fields - hinges on a rational approach to plant site selection. A selection process is indicated, whereby those areas that are acceptable on technical basis are further screened to avoid projected conflicts with more valued land utilization.

Advantages of Martin Marietta Team Commercial Conceptual Design

The Phase I Central Receiver Solar Thermal Power System Program integrated team effort has produced a Commercial Conceptual Design having substantial advantages over competing concepts both within and outside of the Central Receiver concept.

A constant goal and guideline throughout the program has been the optimization of performance within the framework of optimum economics. The design presented has an end to end efficiency of 25.1 percent while operating on receiver steam, based on the power delivered to the transmission line divided by the potential solar energy intercepted by the full area of the mirrors in the system. This is a specific power generation of 238 W/m^2, 2.5 times higher than the competing solar photovoltaic technology as embodied in the multi kilowatt SKYLAB array.

Modular design of the collector-receiver module provides versatility of design in that site variations and sizing variations over broad limits can be accommodated by the basic design. The modular design provides the shortest development path to the commercial plant in that all solar subsystems are full scale by the pilot plant stage. Key to attaining early development, operational flexibility, moderate cost and commercial acceptance are the low risk features of the design, notably the cavity receiver steam generator, the focused heliostats, use of sensible heat storage and use of a single stage expansion turbine.

III. 10 MWe CRSTPS PILOT PLANT

The "preliminary design" pilot plant is an optimum configuration development vehicle for the central receiver concept, which brings full scale solar equipment on line in an attractive, low risk, development application at the earliest possible time.

A. SYSTEM DESCRIPTION

Physical Configuration: The pilot plant is one module of the commercial plant described in the preceding section, providing one-for-one scaling in the most critical areas. Basic features and plant arrangement are shown in the artist rendering of Figure III.A-1.

The collector subsystem for the pilot plant/commercial module contains 1554 heliostats focused into the cavity receiver mounted on a tower with the aperture height centered at 90 meters (295 ft). The physical and geometric relationships of the collector and receiver subsystems are identical with those of the commercial plant module. All performance characteristics of the collector and receiver subsystems are also identical with the commercial plant, including the heat flux and distributions, steam temperature pressures and flowrates for all operating modes. Controls are the same as the commercial plans.

The thermal storage subsystem is functionally and operationally the same as for the commercial plant but sized to accommodate the single collector/receiver pilot plant module. Important scaling criteria are maintained, including heat transfer rates, storage media fluid temperature, heat exchanger coefficients, and steam temperatures and pressures into the turbine admission point.

The electrical power generation subsystem used for the pilot plant includes an admission turbine, as does the commercial plant, and has all of the operational and control modes of the commercial plant. The pilot plant turbine size has been scaled down from the utility size turbine in the commercial plant to an available industrial size.

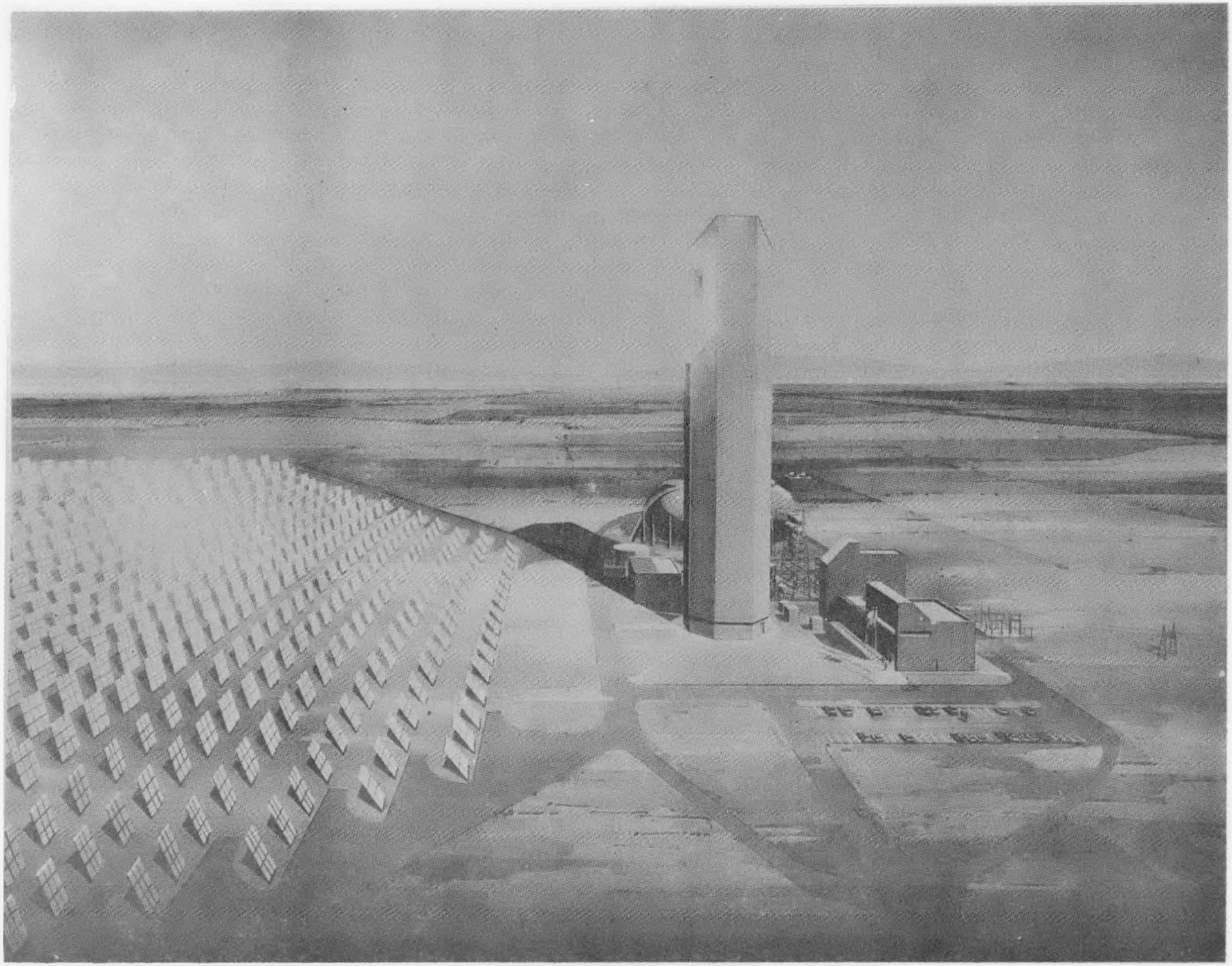


Figure III.A-1 Rendering of Preliminary Design 10 MW_e CRSTPS Pilot Plant

The pilot plant program has been developed to minimize developmental risks. This starts with the use of standard commercial concepts and includes the development of research experiments that are total subsystem demonstrations. These experiments demonstrate the total operation and controls for the pilot plant subsystems. The pilot plant design will demonstrate the high performance projections of the solar peculiar systems while providing simultaneous thermal storage operation with the generation of 10 MWe net electrical output. Additionally, while meeting all requirements, the pilot plant provides low risk scalability to the commercial plant.

Major pilot plant parameters are listed in Table III.A-1 together with the values of the same parameters of the commercial plant. Identical items which will be demonstrated at full scale in the pilot plant include the module size, heliostat size, collector geometry, tower, receiver, operating cycle on receiver and storage, and storage materials. Differences between the pilot plant and the commercial plant parameters are elements sized to their respective ratings, 10 MWe and 150 MWe, and items keyed to their respective design point seasons (the same receiver meets the 40.5 MWth summer design requirement of the pilot plant and the 46.2 MWth winter design requirement of the commercial plant).

A plan view of the pilot plant is shown in the plot plan of Figure III.A-2. The forty-four rows of heliostats are located symmetrically about a north/south line, north of the tower. Paved turning zones border the collector field on the east and west sides. The combination EPGS/Control/Administration building is in the southwest corner of the plant site at the tower base. Thermal storage heat exchangers are located in the southeast section of the plant site and the thermal storage tanks are located at the far east end of the plant site.

Collector Subsystem

Layout of the heliostats within the collector field is controlled by shading and blocking optimization. The preliminary design layout, shown in Figure III.A-3(a) was established in the final design phase and is the design solution generated to offset the increased blocking which accompanied the tower height reduction. The blocking problem was alleviated, but the packing density of positions was decreased. The enlargement of the heliostat mirror area from 37.2 m^2 (400 ft^2) to 41 m^2 (441 ft^2) enabled preservation of the total reflective surface area while using only 1554 heliostats in the module. The dashed line through

Table III.A-1 Key Pilot Plant Parameters and Correlation with Commercial Plant

Parameters	Pilot	Commercial Correlation
Design Point System Performance Main Steam	10 MW_e	150 MW_e
Design Point System Performance Admission Steam	7 MW_e	105 MW_e
Collector Subsystem	1 Module of 1554 Heliostats	15 Modules of 1554 Heliostats Each*
Heliostat Size	41.0 m^2 (441 ft^2)	41.0 m^2 (441 ft^2)*
Collector Layout	Heliostats North of Tower	Heliostats North of Tower*
Receiver Aperture Height	90 m	90 m*
Receiver	Cavity, Zero Tilt	Cavity, Zero Tilt*
Maximum Receiver Output	52.3 MW_t	52.3 MW_t*
Receiver Design Point	40.5 MW_t (Summer)	46.2 MW_t (Winter)
Receiver Steam	789°K/10687 kPa (960°/1550 psig)	789°K/10687 kPa* (960°F/1550 psig)*
Turbine Main Steam	783°K/9308 kPa (950°F/1350 psig)	783°K/9308 kPa* (950°F/1350 psig)*
Turbine Storage Steam	700°K/2758 kPA (800°F/400 psig)	700°K/2758 kPa* (800°F/400 psig)*
Collector Annual Reflected Energy	2204 kW_t-hr/m^2	2204 kW_t-hr/m^2 *
Storage Media	HITEC Caloria HT43	HITEC* Caloria HT43*
Storage Capacity	91 MW_t-hr	1185 MW_t-hr
Gross Heat Rate Main Steam	11183 kJ/kW-hr (10600 Btu/kW-hr	9655 kJ/kW-hr (9151 Btu/kW-hr)
Gross Heat Rate Admission Steam	13821 kJ/kW-hr (13100 Btu/kW-hr)	11585 kJ/kW-hr (10980 Btu/kW-hr)
Land Use	517992 m^2 (5.575 x 10^6 ft^2) (128 acres)	6.426 x 10^6 m^2 (6.918 x 10^7 ft^2) (1588 acres)

*Common between commercial and pilot plants.

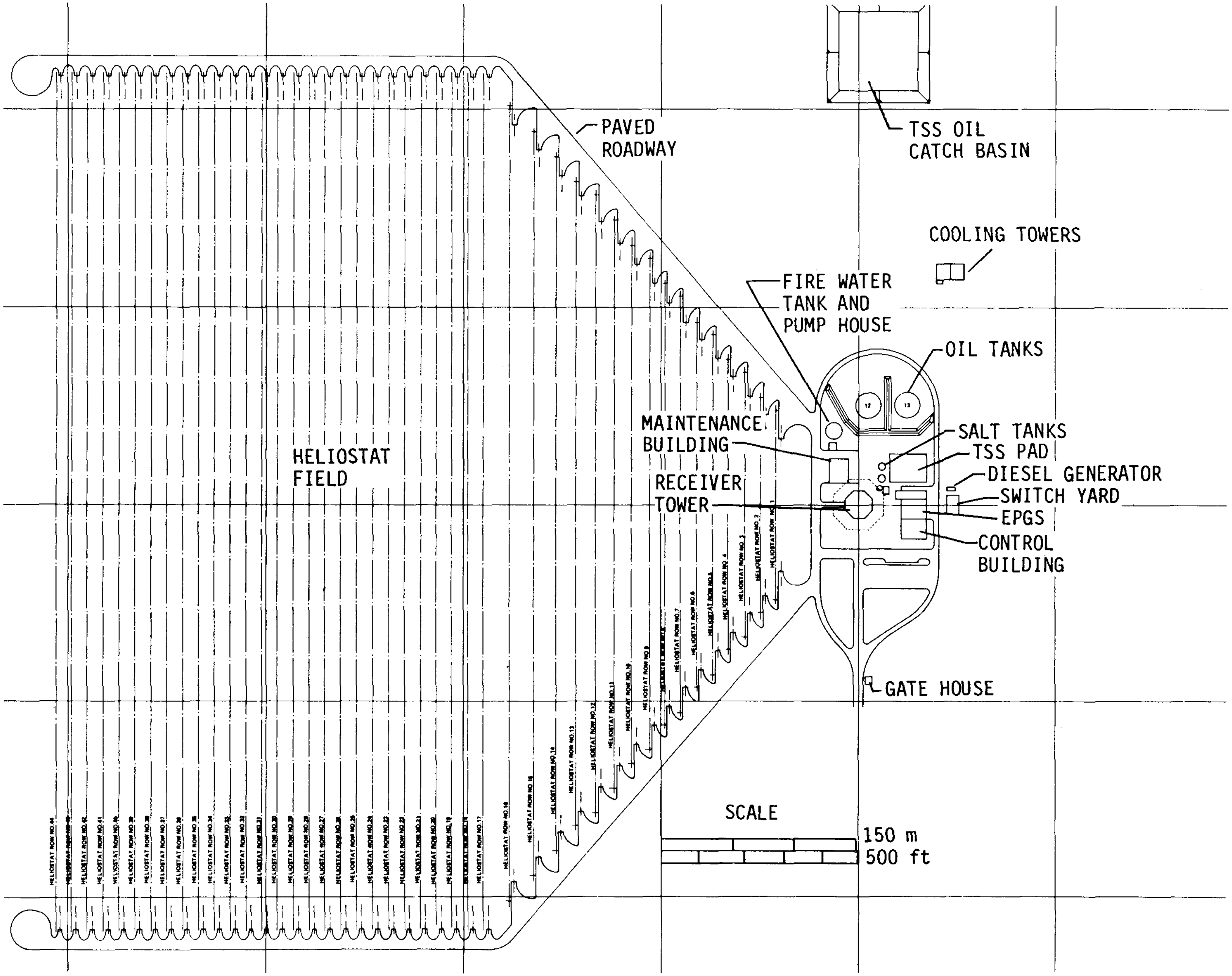


Figure III.A-2 Pilot Plant Plot Plan

the module indicates the northern boundary if only the 1325 heliostats required to generate 10 MWe are used for the pilot plant.

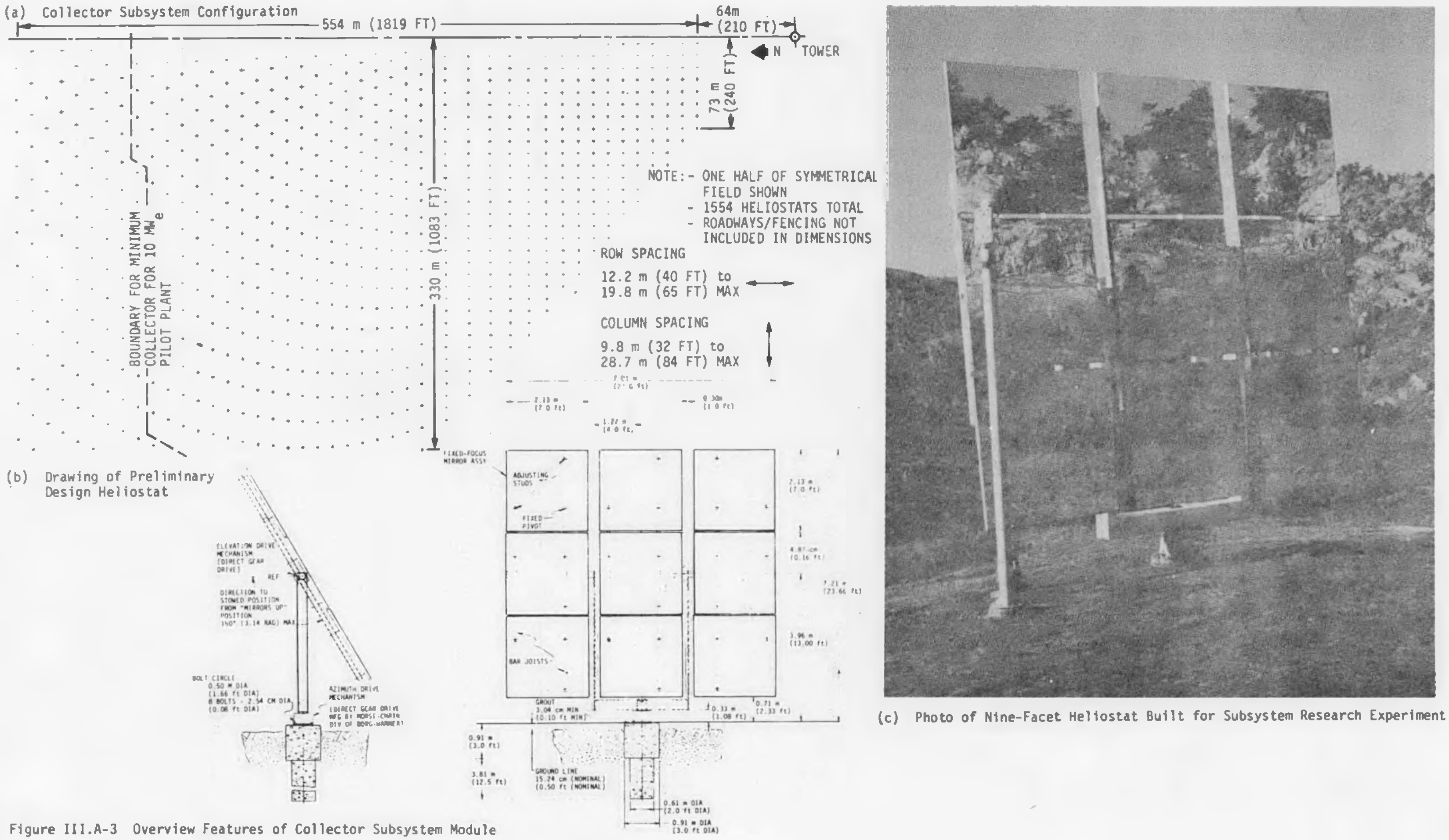
The general configuration of the preliminary design heliostat is shown in view (b) of Figure III.A-3. In appearance it is similar to the subsystem research experiment heliostat shown in the photo of view (c). Nine pre-focused facets, 2.13 x 2.13 m (84 x 84 in), are mounted on a rack structure which is supported by and driven about its central horizontal shaft. A yoke structure supports the rack and is itself driven about its vertical centerline by a two stage worm-spur gear drive. Gearing is identical in the elevation drive, mounted integrally with the mirror support rack. **The** azimuth drive interfaces with a caisson foundation, the best economic foundation resulting from the program. Honeycomb construction is used for the pre-focused facet back structure. A sandwich of steel face sheets and aluminum core is fabricated with the desired curvature, and the mirror is then bonded onto the concave side.

Open loop control has been selected for the heliostat rather than the closed loop control used in the subsystem research experiment. The successful application of this technique for the 222 Solar Thermal Test Facility heliostats, being installed, enabled comparison of the two control techniques on similar heliostats at the hardware stage. Economic factors and design maturity favor the open loop control. The STTF heliostats track well within the specified ± 1.5 mr (5.1 arc-min). Operation under control of the Master Control Computer via communication with the Heliostat Array Computer such as is planned for the CRSTPS plants has been successfully checked out with the first heliostats installed at the STTF.

Operational and performance testing of the subsystem research experiment heliostats has confirmed the optical performance projections for the full scale collector's focusing heliostats. Thermal power transmitted optically from the 37.2 m^2 (400 ft^2) heliostats has exceeded 30 KW in terrestrial sunlight (0.80 KW/m^2) at the 342 m (1124 ft) range.

Receiver Subsystem

The receiver subsystem provides the necessary function within the CRSTPS of converting the optically concentrated solar energy into high temperature-pressure steam and transmitting it to the electric power generation system. Major elements of the subsystem


(a) Collector Subsystem Configuration

(b) Drawing of Preliminary Design Heliostat

(c) Photo of Nine-Facet Heliostat Built for Subsystem Research Experiment

Figure III.A-3 Overview Features of Collector Subsystem Module include the tower, receiver steam generator, riser/downcomer/horizontal piping, controls and instrumentation. As shown in Figure III.A-4 view (a) the tower is a steel structure, octagonal in cross section, which supports and encloses the receiver. The tower structure is modified in the focal zone area to allow a clear path for the collected sunlight to reach the receiver aperture.

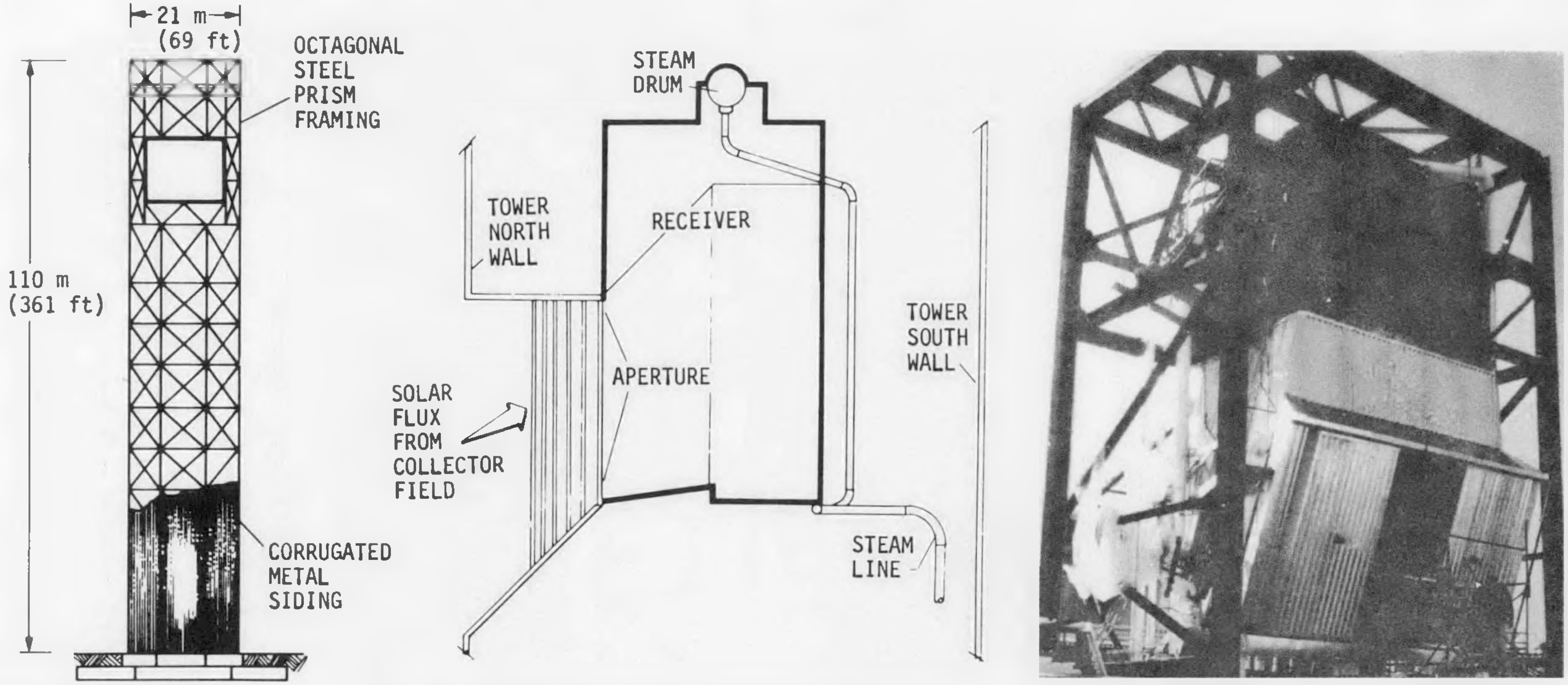
Positioning of the receiver in the tower is shown in view (b) of Figure III.A-4. The steam drum, the heaviest element of the receiver, is located near the centerline of the receiver and on the centerline of the tower enabling very uniform loading of the tower structure.

A photo of the 5 MWth receiver, built and tested in the subsystem research experiment phase of the current program, is shown in view (c) of Figure III.A-4. This unit was erected at Sandia Laboratories Radiant Heat Facility in Albuquerque by Foster Wheeler Energy Corporation. The support equipment module and the control console needed for the receiver operation were built by Martin Marietta. The infra-red lamp array, condenser and water treatment equipment were supplied by Sandia. The SRE testing included (1) low pressure cleaning and check-out runs, (2) high pressure and high temperature performance test runs, (3) hot start, cold start, and cloud interruption cycling sequences, and (4) partial load performance runs. Total test time of 112.5 hours covered 19 operational cycles of which 6 attained rated pressure, 9140 kPa (1325 psig), and rated temperature, 789 k (960°F).

Thermal Storage Subsystem

The pilot plant thermal storage subsystem is functionally and operationally identical to the commercial plant. The important scaling parameters have been retained including the heat exchanger coefficients, storage media temperatures and steam conditions.

An overview of the thermal storage subsystem is shown in Figure III.A-5. View (a) is the top level schematic showing the major components of the system, the high temperature storage and flow loops, the low temperature storage tankage and flow loops, the charging mode heat exchangers and the discharging mode heat exchangers. View (b) shows the layout arrangement of the equipment planned for the Pilot Plant and view (c) shows the TSS subsystem research experiment in operation.



(a) Receiver Tower Configuration

(b) Arrangement of Receiver in Tower

(c) 5 MW_e Receiver Built for Subsystem Research Experiment

Figure IIIA-4 Overview Features of Receiver Subsystem

The thermal storage subsystem consists of two stages, both of which are used for either extracting heat from the steam generated in the receiver (charge) or for generating steam from the feedwater returned from the electrical power generation subsystem (discharge). The energy extracted from the steam is stored as sensible heat in either HITEC, a molten salt, or a hydrocarbon oil, depending on the storage temperature. HITEC is used for high temperature storage, and the hydrocarbon oil for the lower temperature storage. The energy is stored in insulated tanks for later use to generate superheated steam for the generation of electrical power.

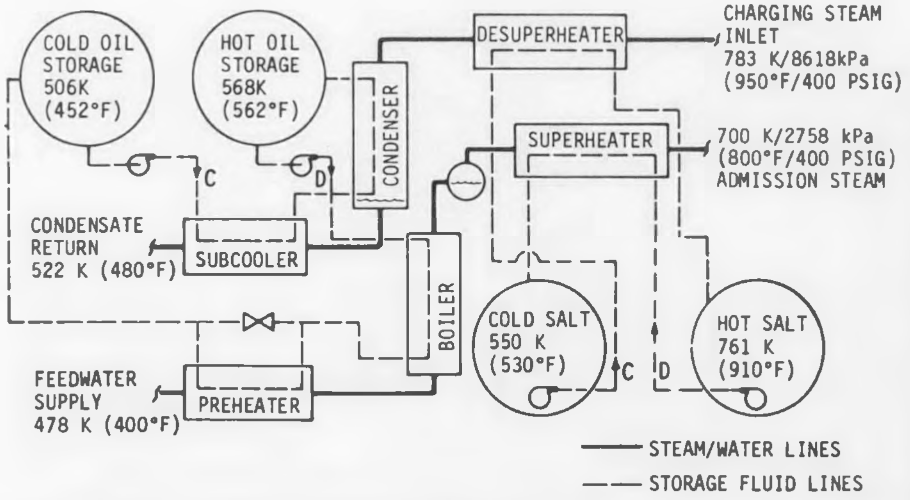
Most of the superheat is removed in the first stage and stored as sensible heat in the HITEC. In the second stage, the latent heat is removed in a condensing heat exchanger and stored as sensible heat in the hydrocarbon oil. The water exiting the condenser is slightly subcooled and is further subcooled in the last heat exchanger. During discharge the flow direction and process is reversed from that of charge. Feedwater is preheated and boiled in the second stage using the heat stored in the hydrocarbon oil. Superheat is added to the steam in the first stage, using the heat stored in the HITEC.

The subsystem research experiment, a complete subsystem scaled down to a 1.6 MWth-hr capacity and 2 MWth Charge/Discharge rate was built by Georgia Institute of Technology on the Newnan, Georgia power plant property of the Georgia Power Company.

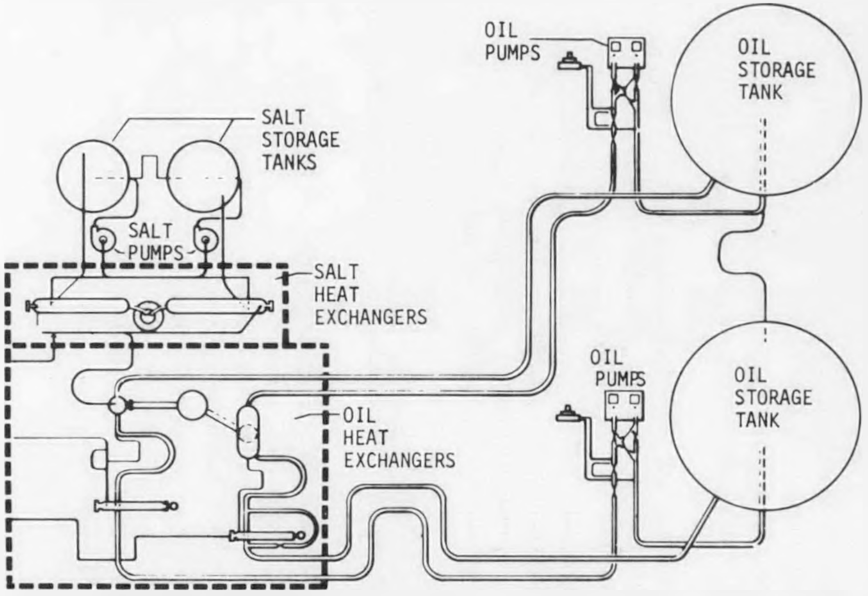
Testing of the thermal storage SRE included 15 complete charge-discharge cycles, twelve constant rate performance test runs and three transient operation experiments. The design charge rate of 2 MWt was met or exceeded in 13 cycles, reaching a maximum of 3.38 MWt. The design discharge rate of 2 MWt was attained during two cycles late in the program, reaching a maximum of 2.59 MWt (a throttling pressure drop of two control valves at the silencer restricted early discharge runs to approximately 1.5 MWt). The design capacity of 1.6 MWt-hr was also exceeded, reaching 2.12 MWt-hr.

Electric Power Generation Subsystem

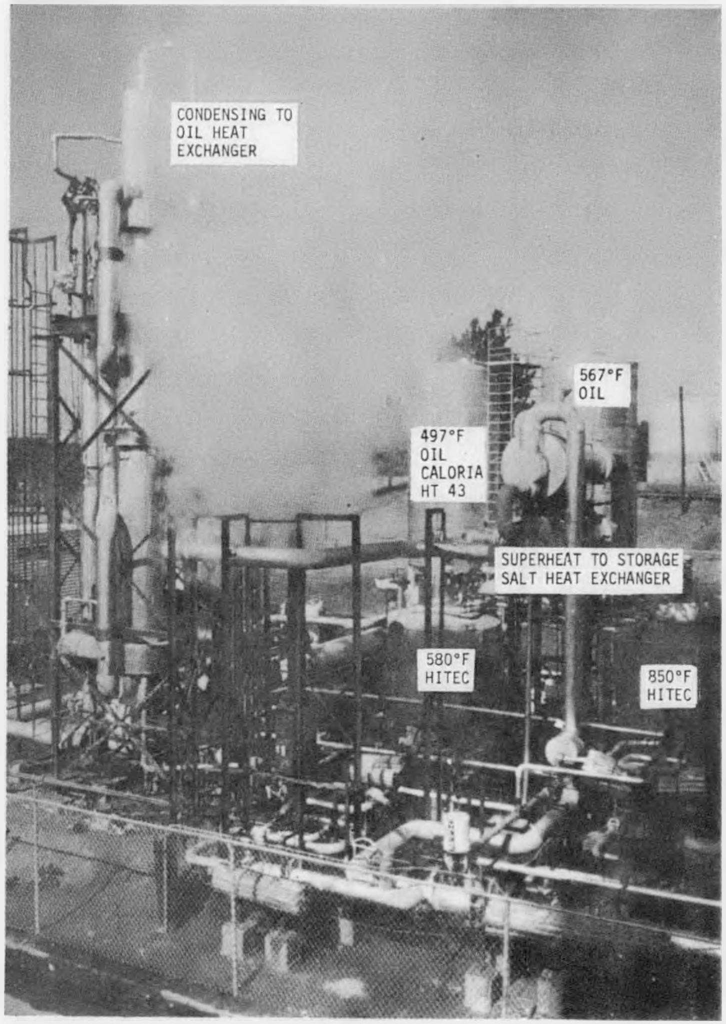
The pilot plant electrical power generation subsystem is capable of all the operational modes of the commercial plant, therefore permitting complete simulation of commercial plant operational modes. The change from dry to wet cooling in both the pilot and commercial plants provides increased efficiency of plant performance.



(a) Dual Charge/Discharge Schematic



(b) Thermal Storage Subsystem - Plan View of Components



(c) Thermal Storage Research Experiment in Operation at Georgia Power Co, Newnan GA

Figure IIIA-5 Overview Features of Thermal Storage Subsystem

The turbine in the electrical power generation subsystem is a dual admission machine that accepts high pressure and temperature main steam from the receiver subsystem and lower pressure and temperature admission steam from the thermal storage subsystem at a separate admission point in the turbine. The selected turbine can produce in excess of the design point power requirements for both the main steam and the admission steam. The selected concept of a dual admission turbine is compatible with the cyclic operation of a solar power plant and is also scalable to larger power plant.

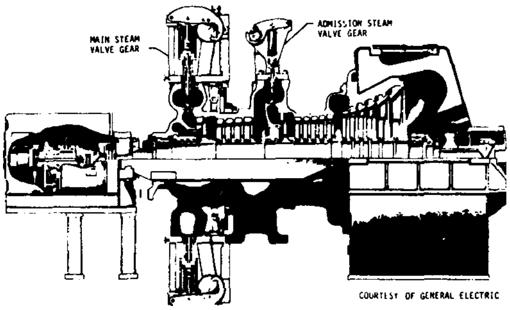
Views (a) and (b) of Figure III.A-6 show the equipment arrangement planned for the pilot plant EPGS building. The turbine floor is not enclosed. View (c) shows a cross section of a dual admission turbine of similar size and construction to the pilot plant turbine.

Pilot Plant Operation

The schematic for the pilot plant working fluid network is shown in Figure III.A-7. Subsystems included in the network are the receiver (upper left) electrical power generation (upper right) and the thermal storage (lower left).

The system provides for generation of electrical power from the receiver alone, from the thermal storage alone, or from both the receiver and the thermal storage operating together. In addition, the receiver can charge thermal storage alone, or can charge thermal storage while providing steam for the generation of electrical power.

The boiler and superheat sections shown, line the cavity walls of the receiver and accept the solar energy. The steam drum receives feedwater from the EPGS and/or the TSS via the high pressure boiler feedwater pump. The feedwater that enters the steam drum is distributed to the boiler section by gravity feed. The steam is separated in the steam drum and sent to the superheater to provide 789 K (960°F), 10687 K Pa (1550 psig) steam. This superheated steam is delivered down the tower for generation of electrical power, for conversion and storage in the thermal storage subsystem, or both. As required, feedwater coming up the tower is diverted and sent to the attemperator for temperature control of the superheated steam. The receiver provides the necessary controls for regulation of feedwater flow, attemperator flow, and signals to the plant control subsystem for control of the heliostats, as required for meeting operational limits and out of limit conditions.



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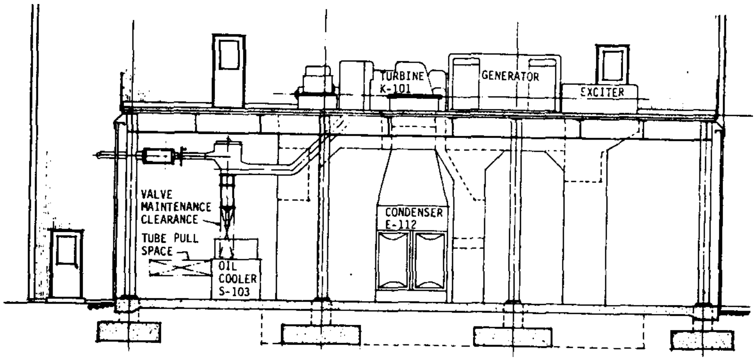
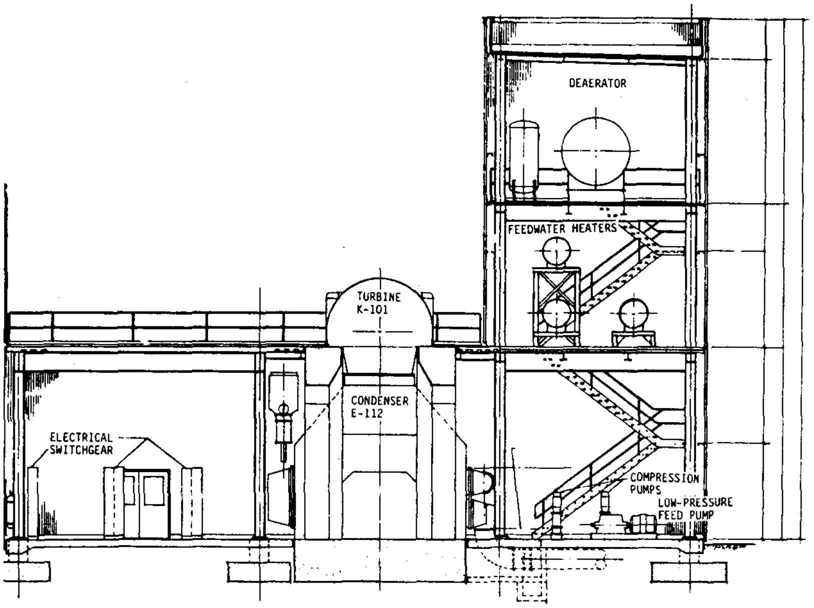
(c) Cross Section of Pilot Plant Configuration Turbine



(b) Side View Cutaway of Turbine Generator Plant Building



(a) Cross Section of Turbine Generator Plant Building - End View

Figure III.A-6 Overview Features of Electric Power Generation Subsystem

For periods when the receiver is not operating shutoff valves seal the receiver and insulated doors cover the cavity aperture to minimize the rate of cool-down.

The electrical power generation subsystem consists of conventional power plant components. The turbine is an admission type machine which accepts 783 K (950°F), 9308 kPa (1350 psig) steam from the receiver, 700 K (800°F), 2758 kPa (400 psig) admission steam from thermal storage. The subsystem contains four stage feedwater heating using uncontrolled extraction from the turbine. The turbine accepts superheated steam from the receiver via the main steam throttle valve and/or lower temperature and pressure steam from thermal storage via the admission throttle valve for conversion into electrical power. Steam leaving the turbine is condensed in the water cooled condenser. The resultant condensate is pumped through the full flow demineralizer and the feedwater heaters, pumped to high pressure, and returned to the receiver and/or thermal storage subsystems, depending on the mode of operation.

Independent charging and discharging flow loops have been incorporated into the Thermal Storage Subsystem Design. This results in maximum operational flexibility, and eliminates the need for a switchover time lapse between charging and discharging operations. Charging and discharging modes are normally run at different times, but the dual mode operation to enable smooth transition or operation during a period of intermittent cloud cover is an available operator option.

When the subsystem is being charged (energy extracted from the steam), the steam coming from the receiver is diverted at the base of the tower to the thermal storage subsystem. The control valve insures that pressure at the turbine is not reduced below operating conditions due to thermal storage charging.

In the desuperheater heat exchanger most of the superheat is removed from the steam and is stored as sensible heat in the molten salt. During this charge mode, the flow of salt is controlled by the steam exit temperature from the heat exchanger. The exit from this first stage is sent to a spray attemperator to assure that the temperature of the superheated steam entering the condenser will not cause the oil to overheat.

In the second stage of the TSS, the steam enters a condensing heat exchanger where the latent heat is removed and stored as sensible heat in a hydrocarbon oil. The steam pressure in the condensing heat exchanger controls the rate of flow of oil which, in turn,

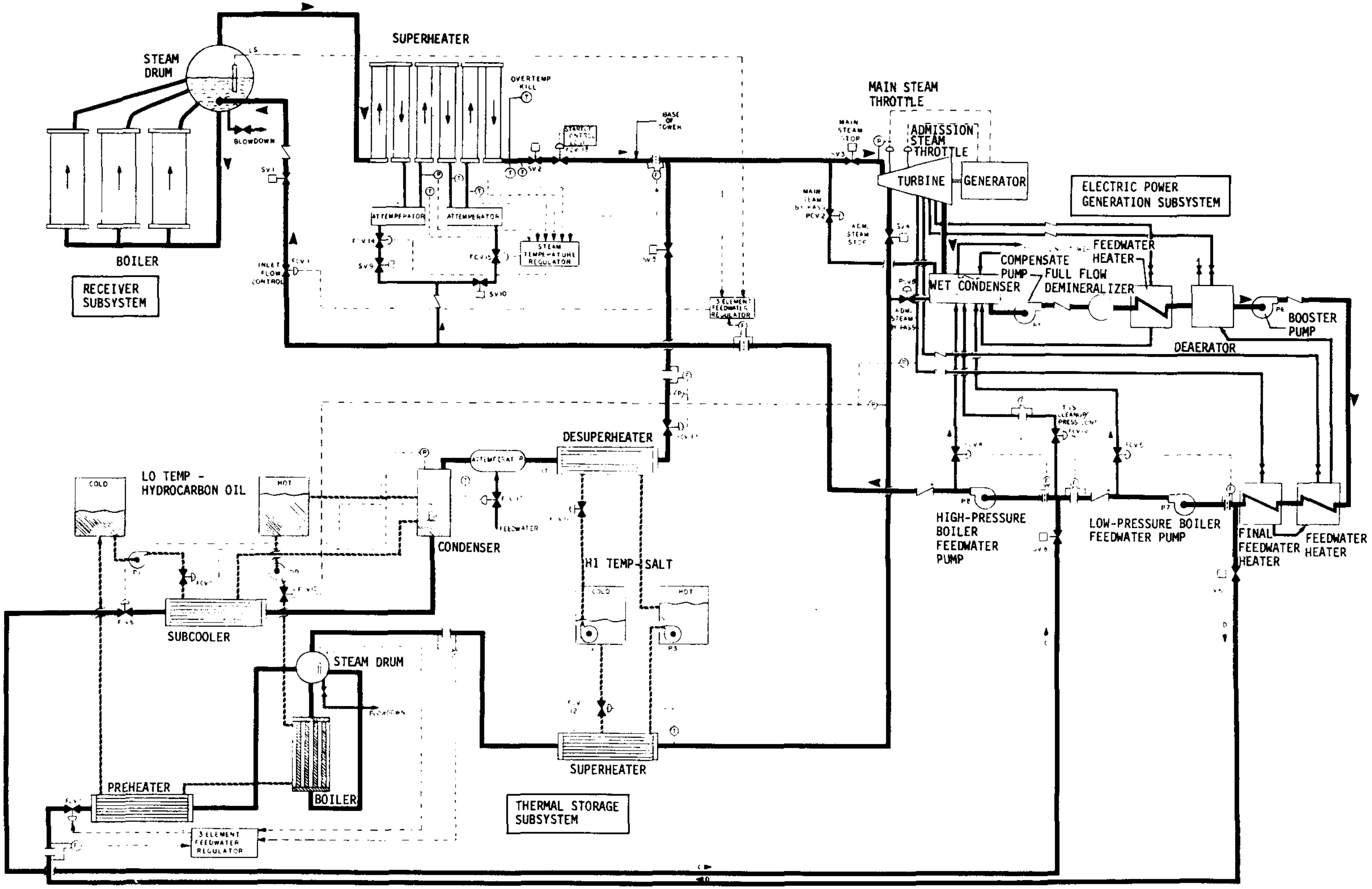


Figure III.A-7 Central Receiver Solar Thermal Power System Schematic controls the rate of condensation. The water exiting the condenser is slightly subcooled and is further subcooled in the subcooler heat exchanger. Condensate flow is controlled as a function of liquid level in the condenser. The exit water from the subcooler heat exchanger is provided as feedwater to the suction of the high pressure boiler feedwater pump for return to the receiver steam drum via the tower.

When the subsystem is being discharged (producing superheated steam for the generation of electrical power) feedwater is provided from the low pressure boiler feedwater pump to the preheater heat exchanger. The feedwater enters the heat exchanger and is preheated prior to entering the boiler heat exchanger.

The flow of oil from the hot tanks (which can be compared to the firing rate of a boiler) is controlled by the pressure of the superheated steam leaving the thermal storage subsystem. The flow of feedwater into the thermal storage subsystem is controlled by a three element feedwater regulator similar to those used in conventional boilers. The steam is separated and enters the next heat exchanger for superheating.

The flow of salt from the hot tank to the cold tank is controlled by the exit temperature of the superheated steam. This superheated steam is sent to the admission steam point on the turbine. Both the charge and discharge functions described above can be performed simultaneously.

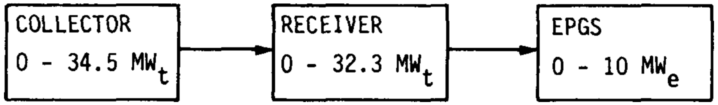
The pilot plant is capable of operating in all of the modes of the commercial plant. Block diagrams of the steady state modes are shown in Figure III.A-8.

Mode 1: Operation of the EPGS on receiver steam would be normally selected at the start of the day, the end of the day, and periods when thermal storage is fully charged.

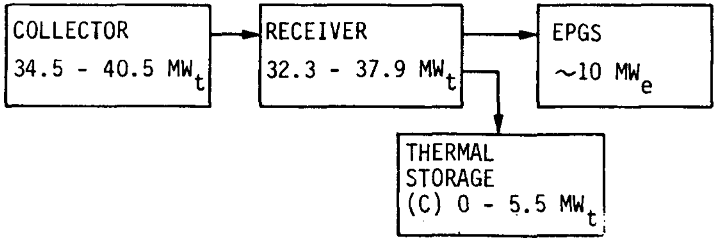
Mode 2: Dual operation of the EPGS and the TSS in the charging mode would be normal in the central part of good solar days and is by far the most used mode.

Mode 3: Dual mode steam generation would normally be used during the final hour of the solar day and is a transition mode between solar and storage operation.

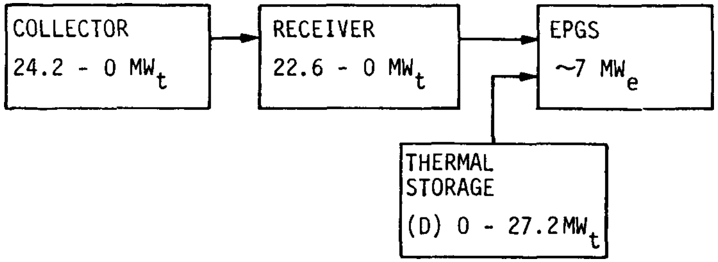
MODE 1 - EPGS OPERATION ON RECEIVER STEAM (STARTUP, END OF DAY)



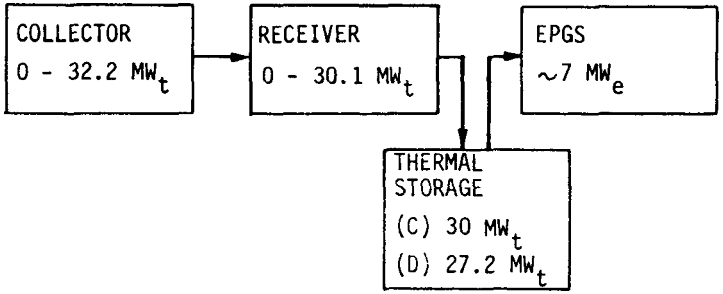
MODE 2 - SIMULTANEOUS THERMAL STORAGE CHARGING AND EPGS OPERATION ON RECEIVER STEAM (MIDDAY SUN)



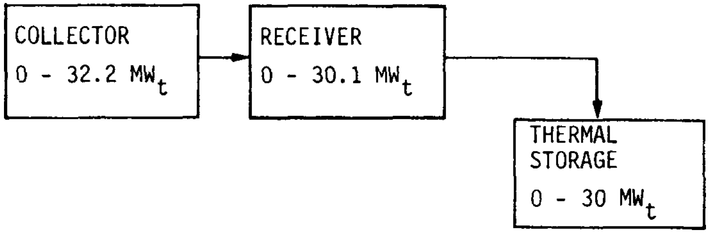
MODE 3 - SIMULTANEOUS THERMAL STORAGE DISCHARGE AND EPGS OPERATION ON RECEIVER STEAM (LOW INSOLATION, END OF SOLAR DAY)



MODE 4 - DUAL CHARGE-DISCHARGE OF THERMAL STORAGE WITH EPGS OPERATION ON STORAGE STEAM (SHORT PERIODS, CLOUDS PRESENT, TRANSITION)



MODE 5 - RECEIVER ONLY CHARGING THERMAL STORAGE (DISPATCHER OPTION TO CHARGE STORAGE)



MODE 6 - OPERATION OF EPGS FROM THERMAL STORAGE (EVENING, DISPATCHER OPTION)

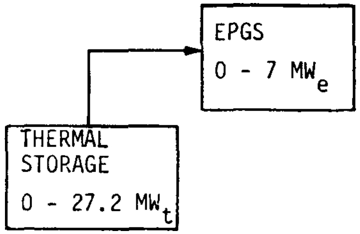


Figure III.A-8 Pilot Plant Steady-State Operating Modes

Mode 4: Dual mode charging and discharging of the thermal storage subsystem would be used in periods when the solar steam generation is highly variable due to cloud interruptions and is an optional transition mode between solar and storage operation.

Mode 5: Storage charging without operation of the EPGS is available as an operator option.

Mode 6: Storage discharge would be the normal after sundown mode and is an available option any time storage is sufficiently charged.

Output during modes 1 and 2 can reach 10 MWe while output during the storage modes, 3, 4, and 6, is limited to 7 MWe. Mode 5 has no electrical output.

Sizing of the pilot plant collector the same as the commercial plant module results in exceeding the 10 MWe design point requirement specified for the pilot plant. Figure III.A-9 shows a comparison of the thermal output of the collector/receiver subsystems on the design day for the preliminary design pilot plant and for a reduced size plant matching the minimum requirement. The commercial module collector contains 1554 heliostats of the $41m^2$ ($441\ ft^2$) size while the minimum size pilot plant would contain only 1325 similar heliostats.

Key operational differences between the two pilot plant sizes involve the rate and energy available for storage while operating at rated output and the potential operating hours at rating during a day. Energy sufficient for 1.3 hours storage operation is available with the commercial module size, while only enough for 0.2 hours is available from the minimum plant when full rated turbine output is used. Operating time at rating is increased from four hours with the smaller plant to 7.5 hours with the larger plant on the design point day. From the standpoint of achieving a most practical plant at the pilot plant stage of development, these differences substantiate selection of the larger size for the preliminary design.

Pilot Plant Requirements

Top level requirements for the CRSTPS pilot plant are listed in Table III.A-2. All requirements listed are satisfied in the design.

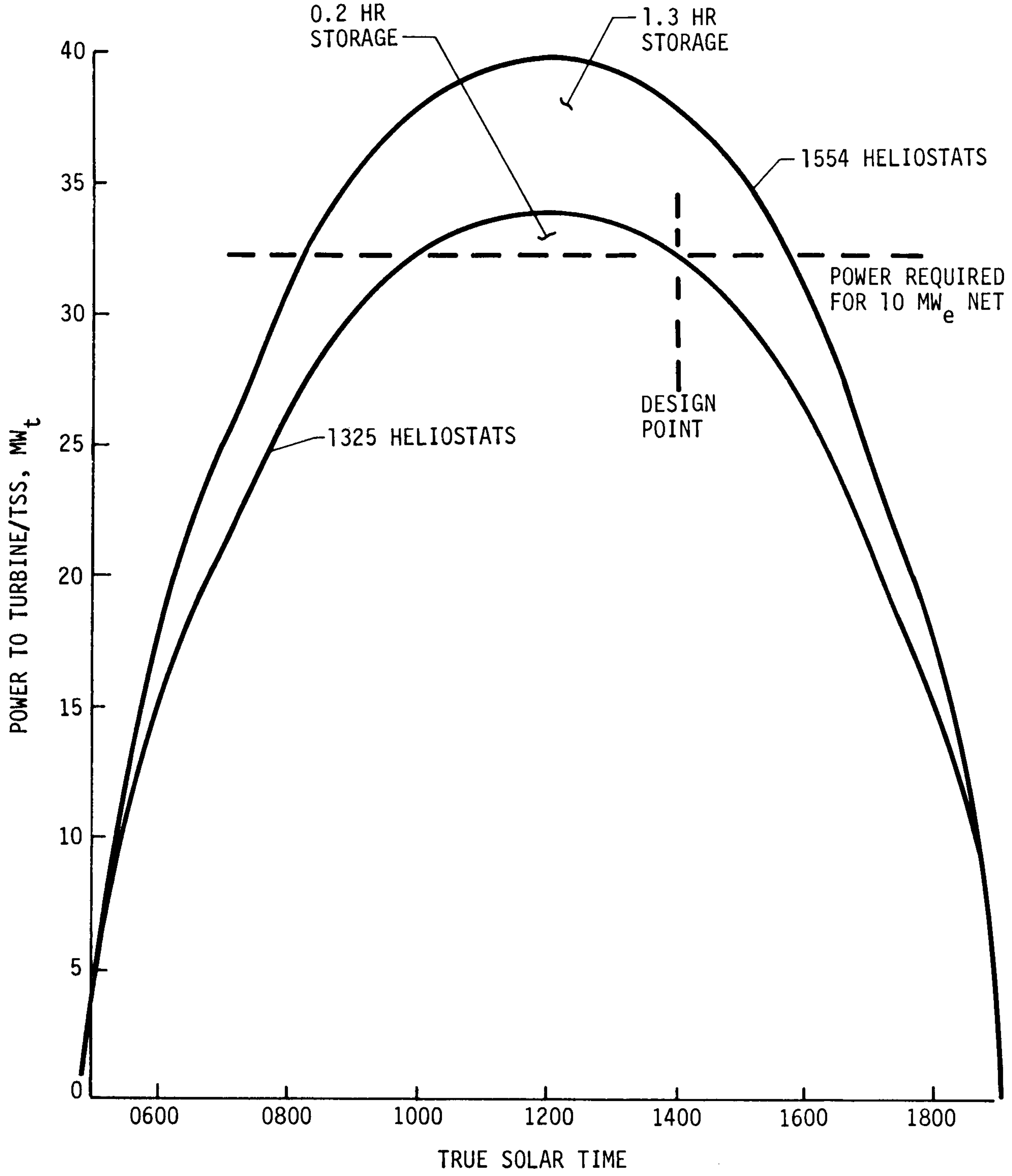


Figure IIIA-9 Pilot Plant Power Profile, Summer, 1554 vs 1325 Heliostats

Table III.A-2 - PILOT PLANT REQUIREMENTS

1. Net Power Output

   * 10,000 KWe on Receiver Generated Steam

   * 7,000 KWe on Storage Generated Steam for 3 hours after 20 hour hold.

2. Design Point

   * Site: Inyokern, California

   * Rated Operation Environment:
   2:00 P.M. day of least favorable cosine with 0.95 KW/m^2 insolation.
   Wet Cooling for EPGS
   Wet Bulb Temperature: 23°C (74°F)
   Dry Bulb Temperature: 28°C (82.6°F)
   Wind Speed: 3 m/sec (8 mph) 10 ft. above ground varying with height to 0.15 power.

3. Survival Environment

   * Maximum Wind Speed: 40 m/sec (90 mph) stowed 24 m/sec (50 mph) gusts operating

   * Seismic: 0.25 g vertical and horizontal ground accelerations.

   * Lightning: Minimum damage protection.

   * Temperature: -30°C (-20°F) to 50°C (120°F) while operating.

4. Life Capability

   * 30 year operational lifetime

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* ERDA Requirements

B. PILOT PLANT DESIGN POINT PERFORMANCE

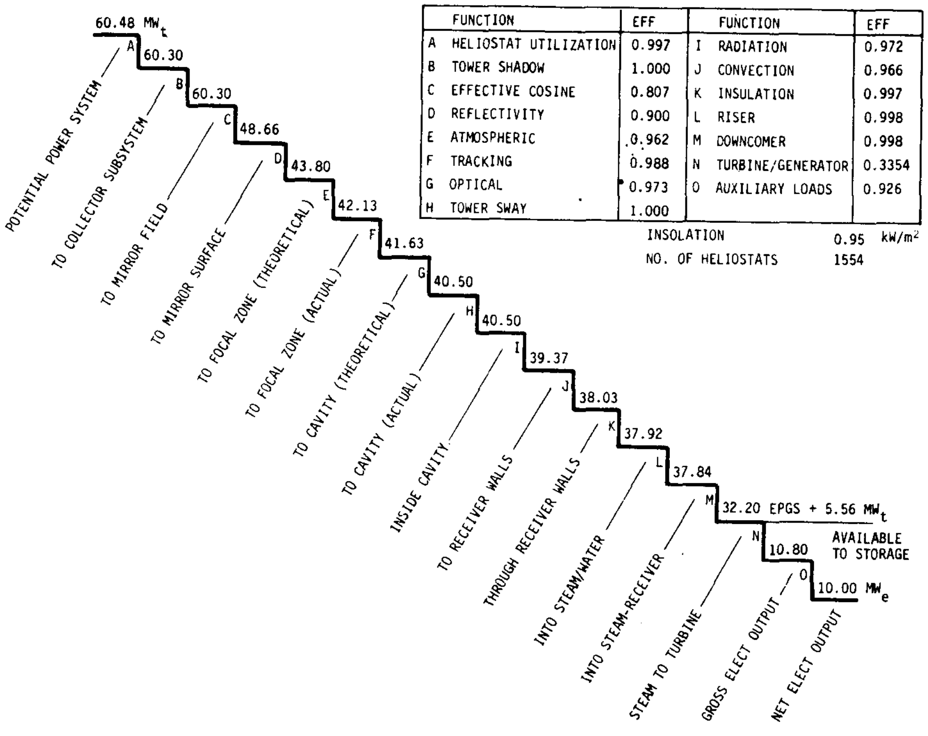
The Pilot Plant Preliminary Design includes a full commercial plant module containing 1554 heliostats. This commercial plant module, along with the pilot plant thermal storage and electrical power generation subsystems, makes up a pilot plant which exceeds the minimum pilot plant performance requirements in that it is capable of producing 10 MWe net electrical power at the design point while simultaneously charging thermal storage.

Design Point Performance Profiles

The ERDA defined pilot plant design point is 2:00 P.M. on the day of least favorable collector cosine (summer solstice for the MMC concept) at Inyokern, California. The environmental conditions at the design point are defined as an insolation of 0.95 KW/m^2, wet bulb temperature of 23°C (73°F), dry bulb temperature of 29.4°C (85°F) and a wind velocity of 3 m/sec (8 mph). The Pilot Plant Design Point Performance, using the full 1554 heliostat commercial plant modules, is illustrated in the Pilot Plant Performance Profile (stair-step) shown in Figure III.B-1. The profile depicts the power flow through the pilot plant from potentially collectable incident solar radiation through the net electrical output power and the thermal power available for storage. It identifies and quantifies all the losses involved in the conversion of solar input power into usable electric power for the pilot plant. This Pilot Plant Performance Profile shows a potential solar input power of 60.48 MWt is converted to the required 10 MWe of net electrical power while providing an additional capability of supplying 5.56 MWt for charging thermal storage. The letters on the performance profile are keyed to the inset table which shows the system efficiency between the two locations.

A second performance profile is shown in Figure III.B-2. This profile shows the minimum number of heliostats required to meet the ERDA design point requirement of producing 10 MWe net electrical output. Using the same efficiency factors shown in Figure III.B-1, and the 10 MWe output requirement, the required potential power to the system was calculated. This required input power of 51.57 KWt, together with the design point insolation and heliostat mirror area, results in a minimum heliostat requirement of 1325.

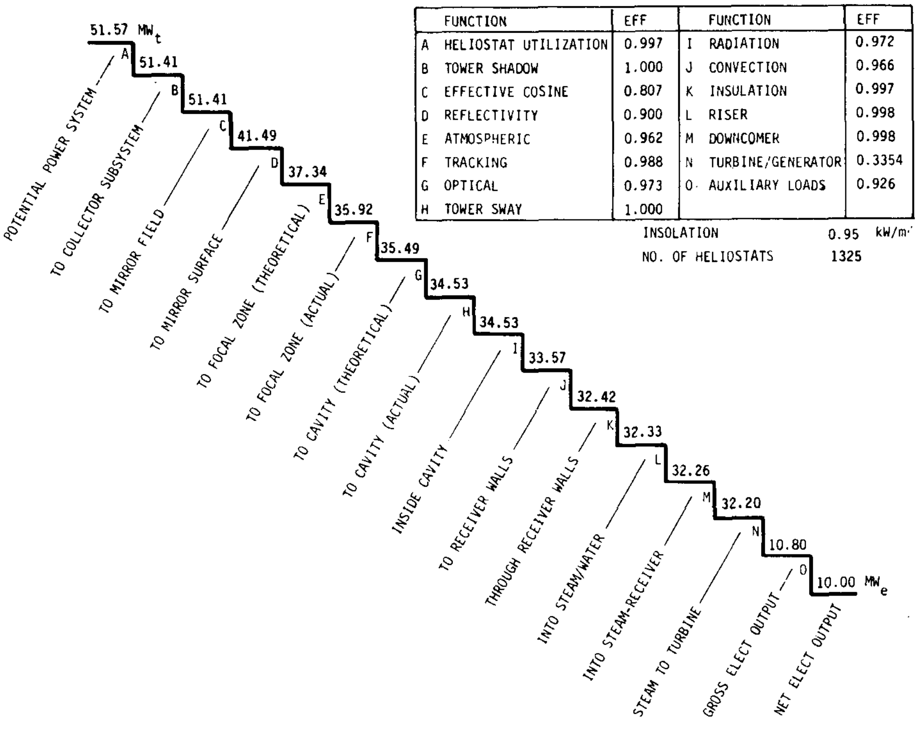
Efficiency of the pilot plant collector, the combination of (a) heliostat utilization (0.997), (b) tower shadow (1.00),



	FUNCTION	EFF		FUNCTION	EFF
A	HELIOSTAT UTILIZATION	0.997	I	RADIATION	0.972
B	TOWER SHADOW	1.000	J	CONVECTION	0.966
C	EFFECTIVE COSINE	0.807	K	INSULATION	0.997
D	REFLECTIVITY	0.900	L	RISER	0.998
E	ATMOSPHERIC	0.962	M	DOWNCOMER	0.998
F	TRACKING	0.988	N	TURBINE/GENERATOR	0.3354
G	OPTICAL	0.973	O	AUXILIARY LOADS	0.926
H	TOWER SWAY	1.000			

INSOLATION	0.95	kW/m²
NO. OF HELIOSTATS	1554	

Figure III.B-1 Pilot Plant Design Point Stairstep



	FUNCTION	EFF		FUNCTION	EFF
A	HELIOSTAT UTILIZATION	0.997	I	RADIATION	0.972
B	TOWER SHADOW	1.000	J	CONVECTION	0.966
C	EFFECTIVE COSINE	0.807	K	INSULATION	0.997
D	REFLECTIVITY	0.900	L	RISER	0.998
E	ATMOSPHERIC	0.962	M	DOWNCOMER	0.998
F	TRACKING	0.988	N	TURBINE/GENERATOR	0.3354
G	OPTICAL	0.973	O	AUXILIARY LOADS	0.926
H	TOWER SWAY	1.000			

INSOLATION	0.95	kW/m²
NO. OF HELIOSTATS	1325	

Figure III.B-2 Minimum Heliostats Pilot Plant Design Point Stairstep

(c) effective cosine (0.807), (d) reflectivity (0.90), (e) atmospheric absorption effect (0.962), (f) tracking error spillage effect (0.988), (g) optical error spillage effect (0.973) and (h) tower sway (1.00) is 0.670. This is 87.6 percent of the value for the commercial plant. The two values represent the extreme conditions for the year, since the design point for the commercial plant is winter solstice (best geometry) and for the pilot plant is summer solstice (worst geometry).

Efficiency of the pilot plant receiver, the combination of (i) radiation loss efficiency (0.972), (j) convection loss efficiency (0.966), (k) insulation loss efficiency (0.997), (l) riser loss efficiency (0.998), and (m) downcomer loss efficiency (0.998) is 0.934. This is slightly higher than the 0.923 for the commercial plant due to the lower flow at the pilot plant design point and correspondingly higher riser and downcomer efficiencies.

The pilot plant electric power generation efficiency, the combination of (n) turbine/generator efficiency (0.3354) and (o) auxiliary load efficiency (0.926) is 0.311, lower than the 0.354 of the commercial plant due to the relatively small size of the turbine. End to end efficiency of the pilot plant at design point is 0.194 as compared to 0.251 for the commercial plant.

Annual Performance

Output of the pilot plant in the central hours of the day varies only 11 percent during the year as illustrated by Figure III.B-3, a plot of the 2 P.M. output capabilities for the commercial module size pilot plant and the minimum size pilot plant. This small variation is the result of the north side collector configuration.

Annual energy performance for the pilot plant based on the insolation for Inyokern, California, 1963 was obtained for (a) the potential plant input (203,410 MWt-hr = 3195 KWt-hr/m^2), (b) the collector system reflected energy (139930 MWt-hr = 2198 KWt-hr/m^2), (c) the steam at the base of the tower (117,920 MWt-hr = 1852 KWt-hr/m^2), and the plant electrical output (35,916 MWe-hr - 564 KWe-hr/m^2). The integrated energy patterns are shown on a monthly basis in Figure III.B-4.

Figure IIIB-3

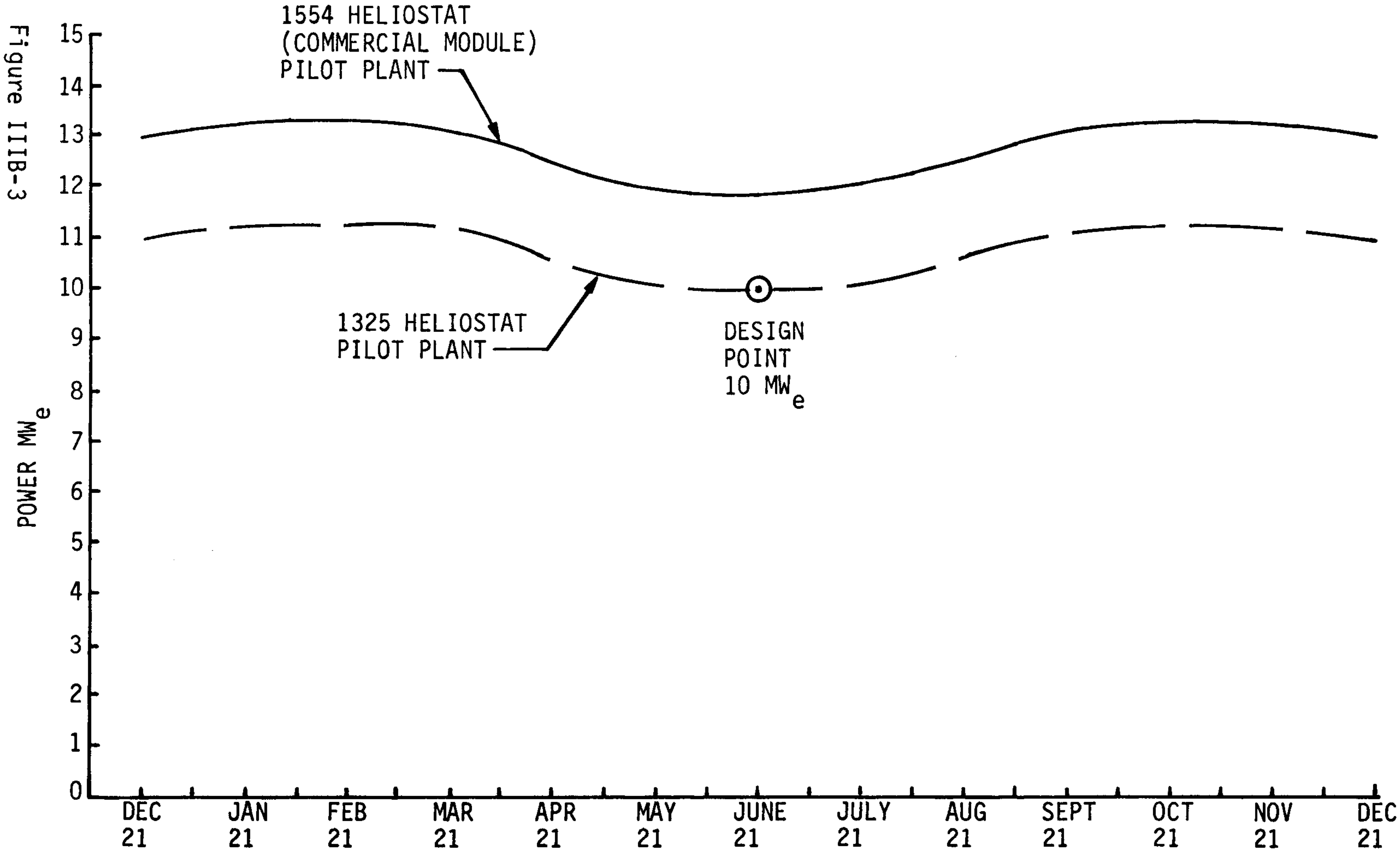


Figure III.B-3 Annual Variation in Pilot Plant Output at 2 pm

YEARLY TOTALS	TOTAL ENERGY	ENERGY PER M^2 OF MIRROR
POTENTIAL ENERGY TO SYSTEM	203,410 MW_t-HR	3195 kW_t-HR/m^2
REFLECTED ENERGY	139,930 MW_t-HR	2198 kW_t-HR/m^2
RECEIVER OUTPUT	117,920 MW_t-HR	1852 kW_t-HR/m^2
NET ELECTRICAL OUTPUT	35,916 MW_e-HR	564 kW_e-HR/m^2

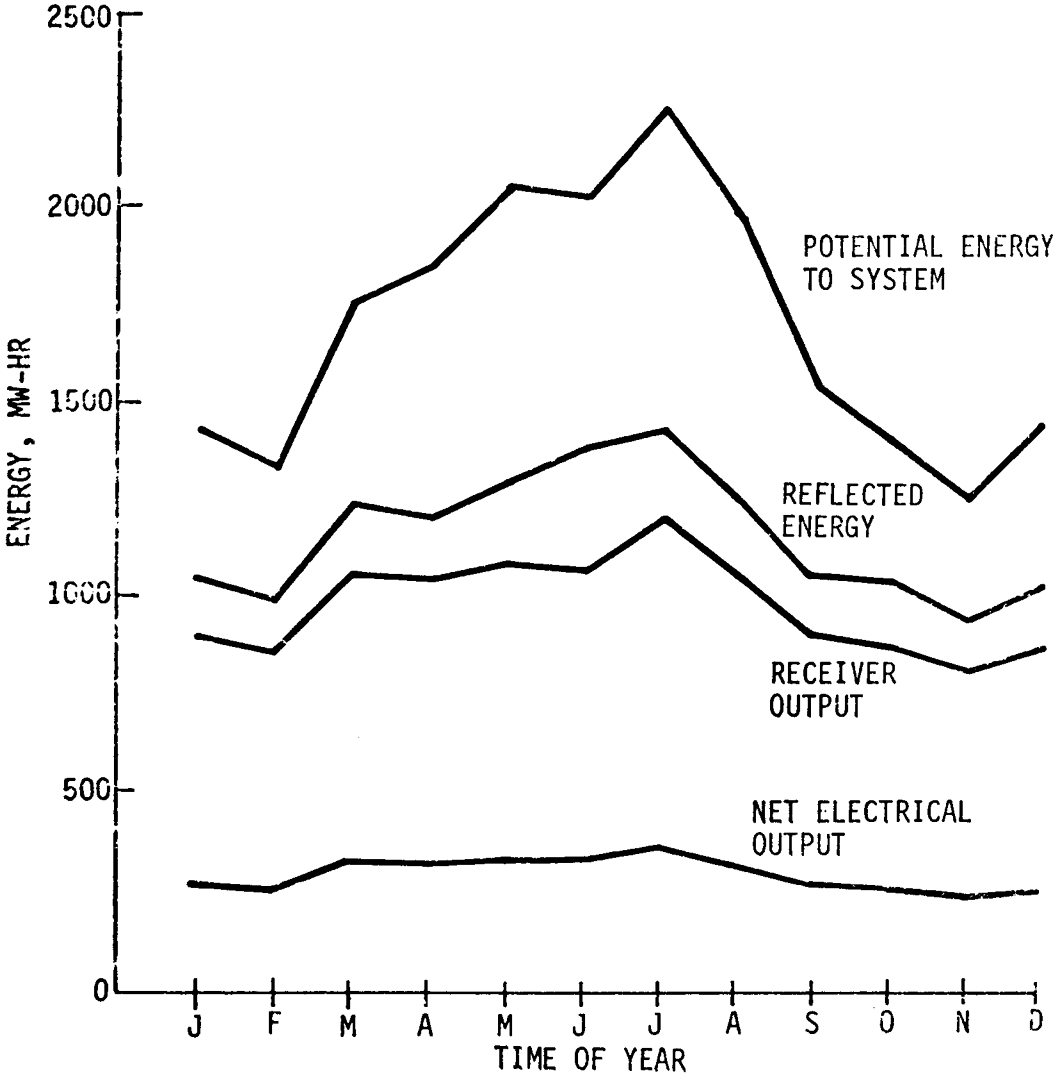


Figure III.B-4 Pilot Plant Annual Energy

C. TECHNICAL DISCUSSION

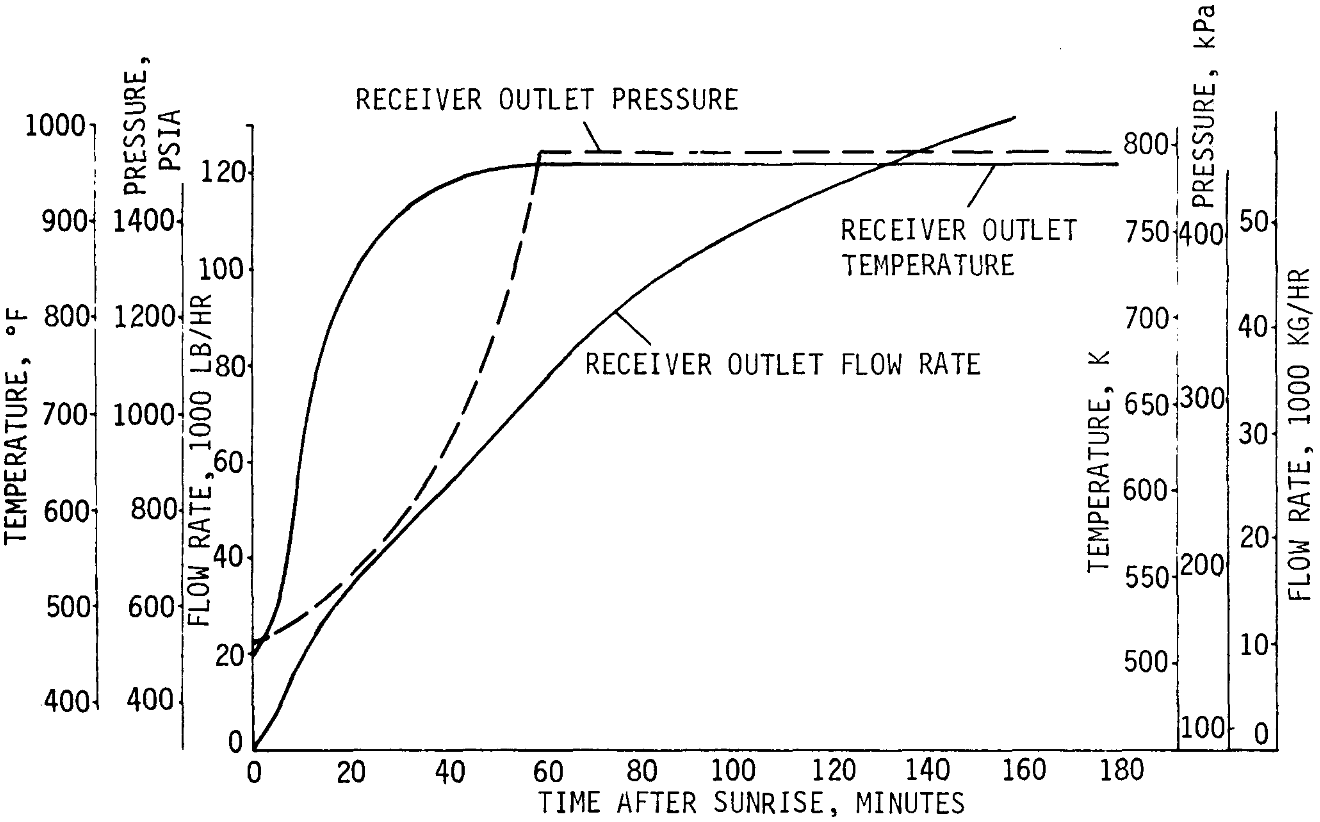
Rationale Setting Pilot Plant Configuration

Design features of the pilot plant have been established to match the commercial plant, technically throughout and physically to the maximum extend feasible to assure that the pilot plant program adequately develops the technology needed for a commercial demonstration. The rationale for the basic plant features, the cavity receiver natural circulation steam generator, the north side collector of 1554 focusing heliostats, use of two stage sensible heat thermal storage, and use of a moderate pressure non-reheat dual admission turbine was discussed on Section II.C. The pilot plant preliminary design uses the receiver and collector at full commercial plant scale. The storage system and turbine operate at identical state point conditions with the commercial plant but are physically scaled to the 10 MWe plant size requirements. Control functions and attainable modes of operation are identical for the two plants. Finalization of the turbine operating pressure at 9303 kPa (1350 psig) and the receiver output pressure at 10687 kPa (1550 psig) balanced the influences of economics, technology and available turbine configurations suitable for the daily cycling application. The highest pressure in the boiler section of the receiver at maximum flow is near the maximum allowable for natural circulation with the solar flux environment in the receiver and sets the pressure ceiling on the system. Significant pressure drops occur in the superheater, to achieve high heat transfer performance, and in the piping to achieve optimum economics. The turbine pressure is near the maximum for the single wall turbines which can respond to the cycling requirements.

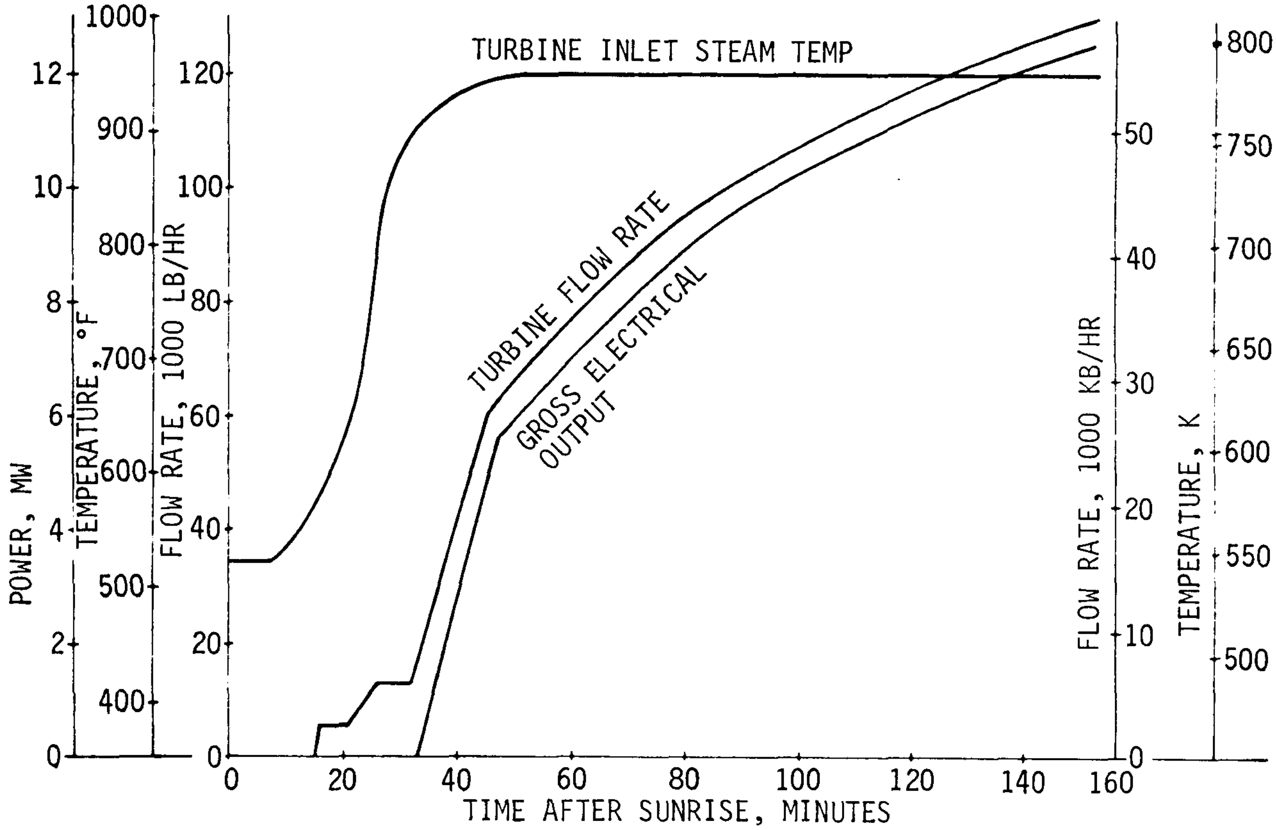
Transient Operation

Inherent in the solar thermal power application is the requirement for fast response transient operation to follow the sun at dawn and to respond to transient insolation resulting from cloud interruptions. The bulk of the dawn start-ups will be "hot starts following overnight shutdowns" with the receiver and turbine response patterns shown in Figure III.C-1. The "start-up" period during which constraint on the utilization of available solar energy is imposed by the equipment, either the receiver or turbine lasts 45 minutes after which time all available solar energy is converted and utilized. Full pressure is not reached until 60 minutes, but is not required for "full solar utilization".

Recovery from cloud transients is keyed to the receiver since the turbine would normally be operating on storage steam and varies



(a) Morning Startup, Receiver



(b) Morning Startup, EPGS

Figure III.C-1 Morning Start Up Transients After Overnight Shutdown with the duration of the cloud interruption between 5 and 40 minutes.

Verification of the ability of the receiver to operate in transient modes as analyzed has been obtained from the 1 MWt IR and solar tests, and the 5 MWt SRE receiver IR test. Figure III.C-2 shows the drum and superheated steam temperature trace for the 1 MWt Receiver Test of July 28, 1976 at Odeillo, France. The morning start-up reached full pressure in 47 minutes and full superheat temperature in 84 minutes. Without the 15 minute temperature oscillation just prior to attaining full rated conditions, which was induced by experimental caution to avoid overshoot using manual controls, full conditions would have been reached in 69 minutes. Recoveries from cloud interruptions of 11 and 60 minutes were 5 and 23 minutes respectively.

Morning start-up and cloud transient tests were performed on the 5 MWth SRE receiver at the Sandia laboratories radiant heat facility in Albuquerque. The input power, drum pressure, superheater tube temperature and superheated steam temperature profiles are shown in Figure III.C-3. Rated superheat temperature was obtained at 55 minutes on the start-up run and at 30 minutes after the simulated cloud interruption.

D. 10 MWe CRSTPS PILOT PLANT PROGRAM PLAN

The objective of the Phase II CRSTPS program is the detail design, fabrication, build, and checkout testing of a 10 MWe pilot plant by the end of 1980. This is a formidable task from the planning, scheduling, and construction standpoints. It requires the parallel performance of five major subsystem programs and the smooth integration of their results technically and physically if costly time delays are to be avoided. The top level schedule for Phase II is shown in Figure III.D-1, covering the following seven major work breakdown areas.

1. Solar Integration, December 1977 - September 1980
2. Collector Subsystem, January 1978 - March 1980
3. Receiver Subsystem, December 1977 - May 1980
4. Thermal Storage Subsystem, February 1978 - July 1980
5. Electrical Power Generation Subsystem, September 1977 - August 1980
6. Plant Control Subsystem, January 1978 - February 1980
7. Plant Start-up and Checkout, June 1980 - November 1980

Critical path status is reasonably balanced between the collector, receiver, and electric power generation subsystems. The earliest element of the plan is the advance procurement activity for the

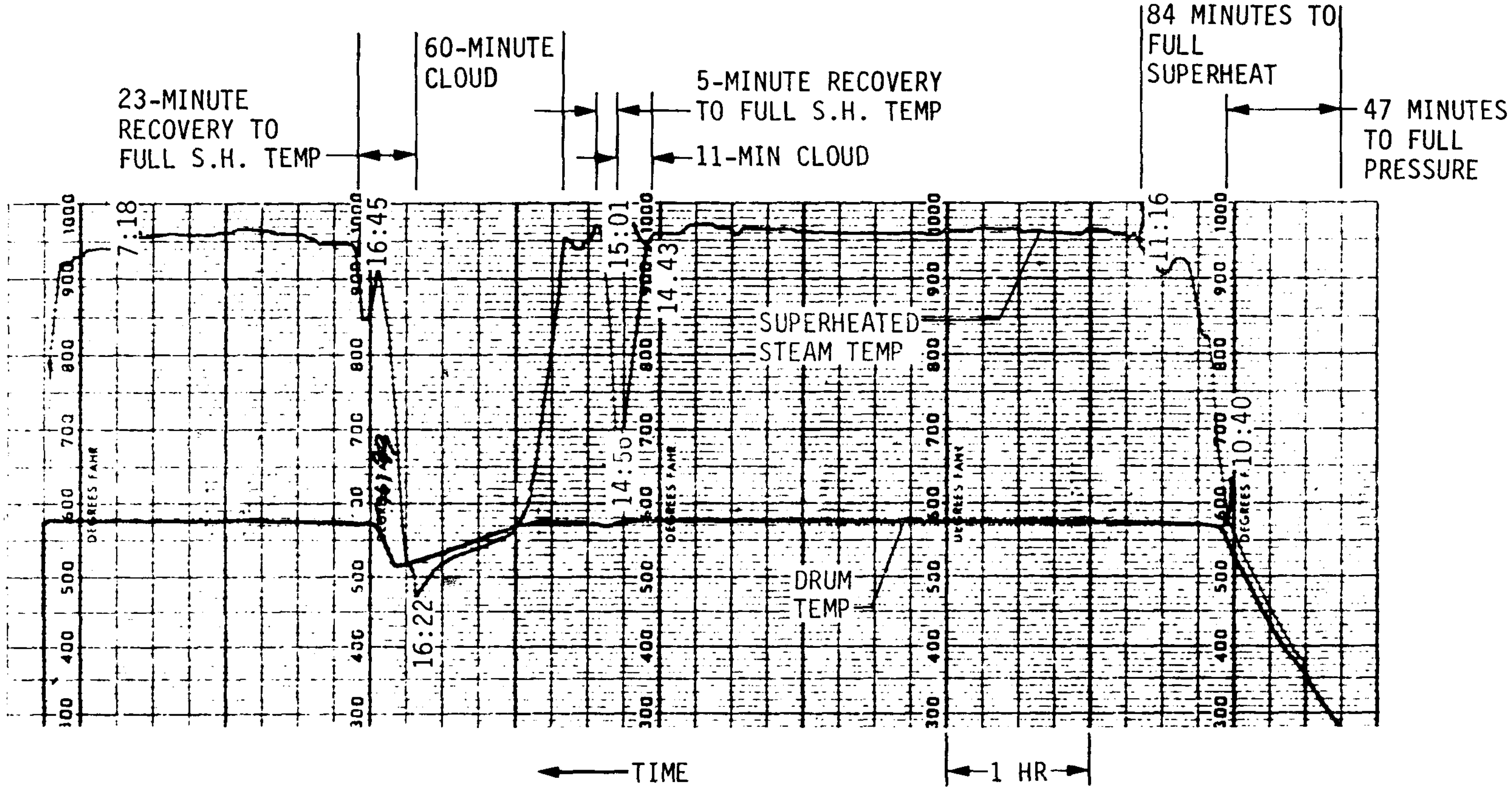
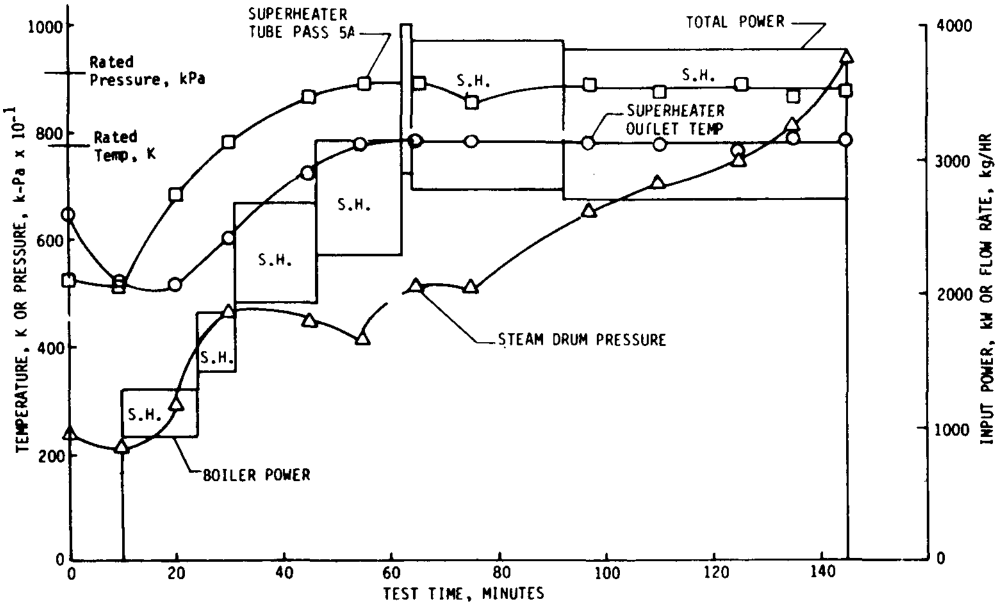
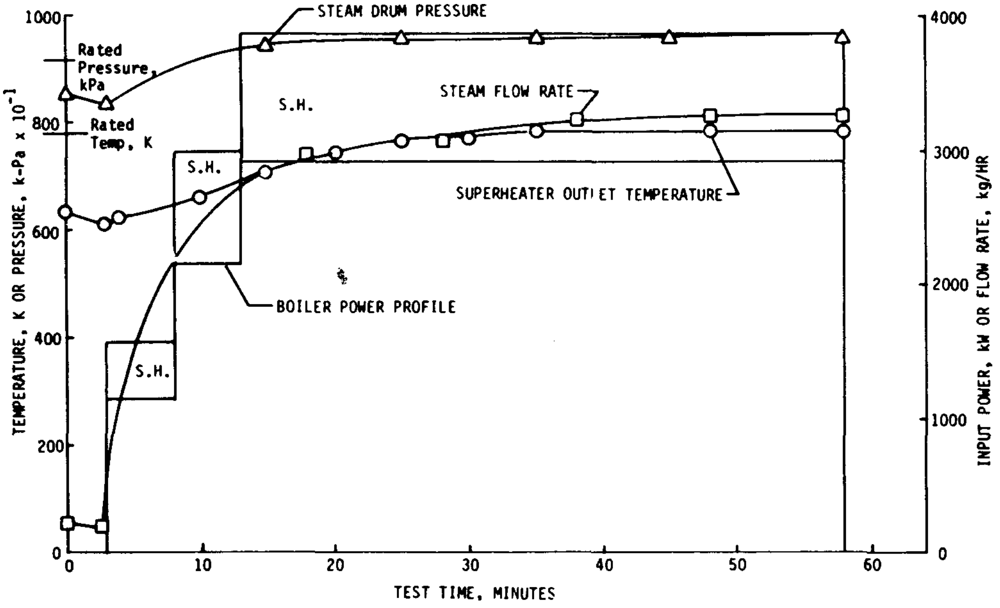


Figure III.C-2 Startup and Cloud Transient Temperature Data - 1 MW_t Receiver 28 July 1976, Odeillo, France



(a) Hot Restart Test - 5 MW_t Receiver - 2/23/77 -
I.R. Facility, Sandia Laboratories, Albuquerque



(b) Cloud Passage Test - 5 MW_t Receiver - 2/22/77
I.R. Facility, Sandia Laboratories, Albuquerque

Figure III.C-3 Startup and Cloud Transient Test Profiles - 5 MW_t SRE Receiver

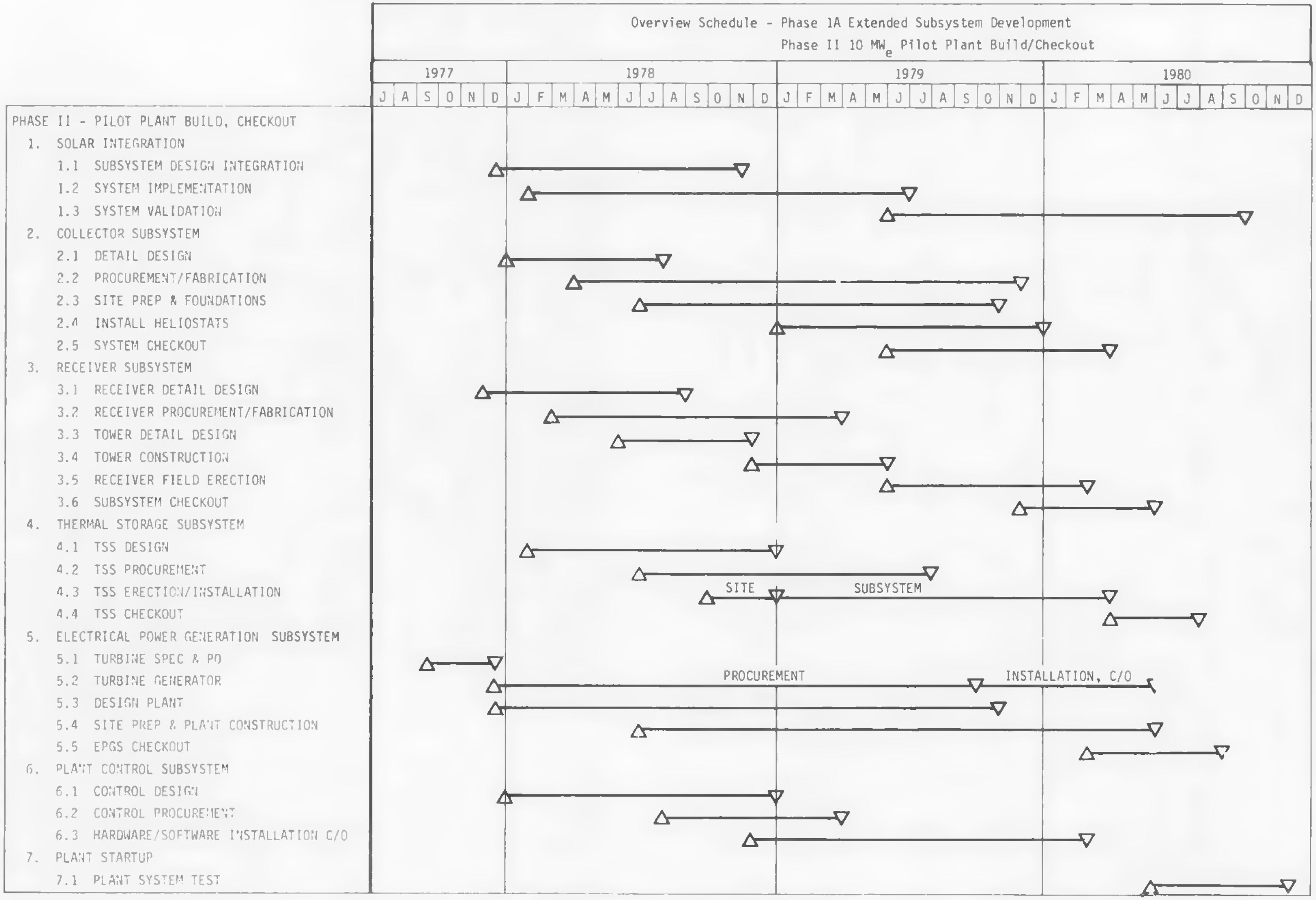


Figure III.D-1

Central Receiver Solar Thermal Power Development Schedule   Phase 2 Pilot Plant Build & Checkout turbine of the EPGS, planned for the second half of this year. The inter subsystem dependence of the collector subsystem on the receiver subsystem is keyed to the tower construction being complete by May 1979. This milestone paces both the receiver erection and the collector subsystem checkout program which includes focus, alignment and functional test at the component level using the tower mounted focus and alignment system.

The program planning is based on implementing the preliminary design established in Phase I. The "preliminary design", accordance with the Phase I, program structure and objectives, represents the best technology at this time. It includes updated features from the experience of the SRE experiments, the 1 MWt Receiver Program, the Solar Thermal Test Facility Heliostat program, and Phase I design Finalization analyses. To insure minimum technical risk and avoid potential delays in the implementation of the selected design it is vital that the technology development started in Phase I be continued during the first year of Phase II to bring the design to qualification status.

Program costing for the 10 MWe, pilot plant, the final activity of the currently authorized Phase I program is based on the program period of performance and schedule of Figure III.D-1.

Cost Analysis

Three cost analysis efforts are included in the Phase I CRSTPS program, preliminary and finalized costing of the pilot plant and a costing of the commercial plant. The preliminary costing for the pilot plant was done following the conceptual baseline design period and submitted, 8 March 1976. The results of the other two analyses will be submitted following the preliminary design in June 1977.

IV. COLLECTOR SUBSYSTEM

The collector subsystem for CRSTPS commercial and pilot plants is an optimum performance configuration embodying north side geometry and focusing, durable heliostats based on technology developed by the SRE and STTF programs.

A. COMMERCIAL PLANT COLLECTOR

The solar energy collector subsystem for the 150 MWe CRSTPS plant consists of fifteen (15) operationally independent fields of heliostats as shown in the plant layout of Figure IV A-1. Each collector module reflects the energy intercepted by 1554 heliostats and concentrates it through the aperture of the tower mounted cavity steam generator located at the center of the south border. The commercial plant collector contains 23310 heliostats and dominates the land use requirements for the plant, requiring a site 3673 m (12050 ft.) wide by 2240 m (7,350 ft.) deep (inside perimeter fence).

Positioning of the heliostats in each module is the same and is shown on Figure IV A-2. Row spacing and spacing in the rows is in accordance a pattern developed to minimize shading and blocking losses. Rows 1-9 are controlled by the shading of the incoming sunlight while rows 27-44 are controlled by blocking of the reflected beam by nearby heliostats. Rows 10 to 16 are a transition zone where the row spacing is controlled by blocking and the positions in the row are maintained in the high density configuration of rows 1-9.

The basic heliostat configuration evolves from the nine facet prefocused heliostat constructed for the SRE shown in Figure IV.A-3. Principal components of the heliostat include the nine prefocused mirror modules, 2.13 m x 2.13 m (7 ft. x 7 ft.) in size, the rack structure on which the modules are mounted, the yoke structure on which the rack is mounted, the elevation drive, the azimuth drive, the heliostat control electronics, and the foundation. Closed loop control is used for the heliostat tracking based on the system developed for the heliostat of the ERDA/Sandia Solar Thermal Test Facility.

The heliostat design for the commercial plant will be an evolutionary update of the "preliminary design" heliostat of the pilot plant. It will incorporate improvements from the phase II development and parallel heliostat technology development programs just as the pilot plant heliostat design drew from the experience of the SRE and STTF programs.

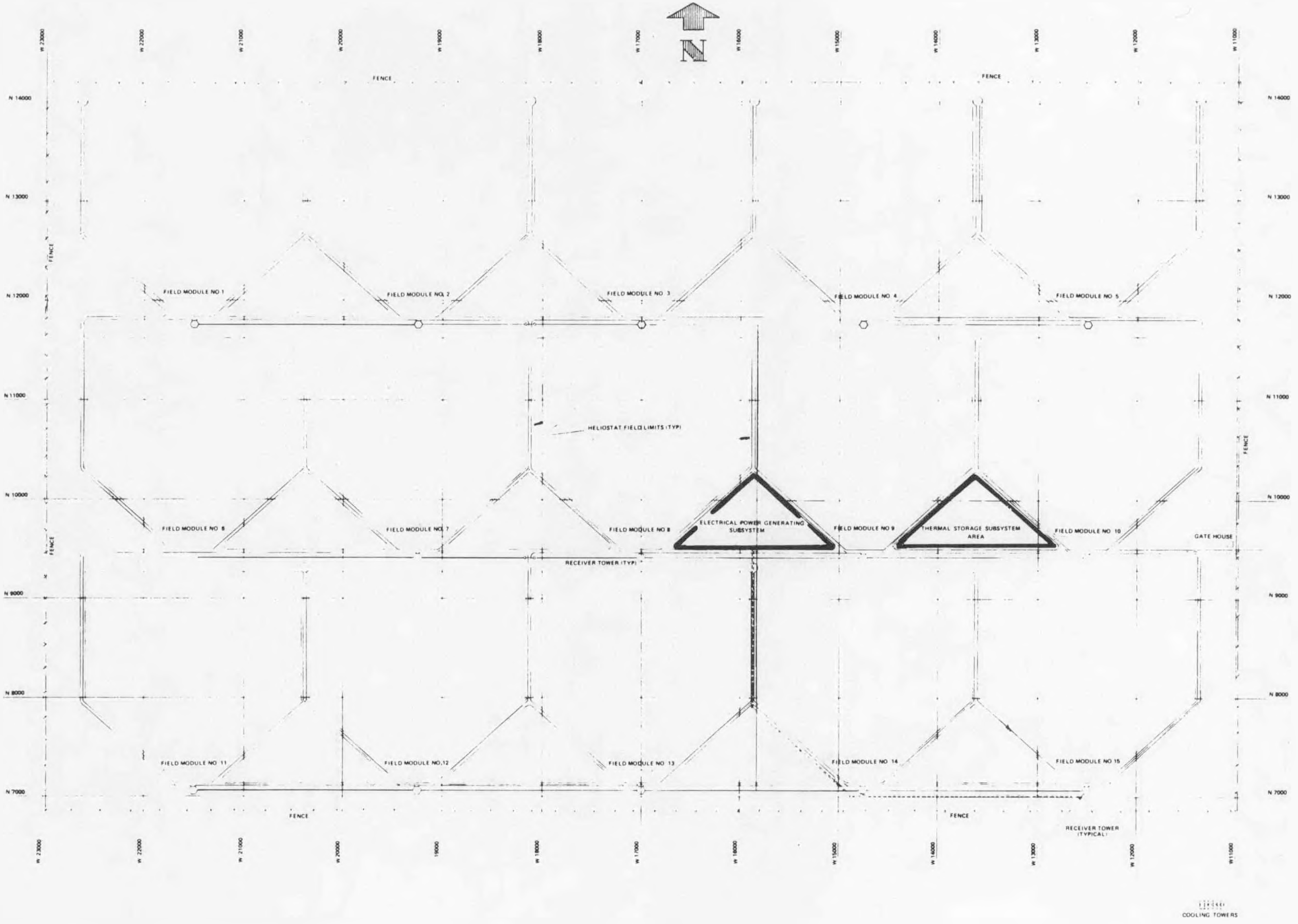
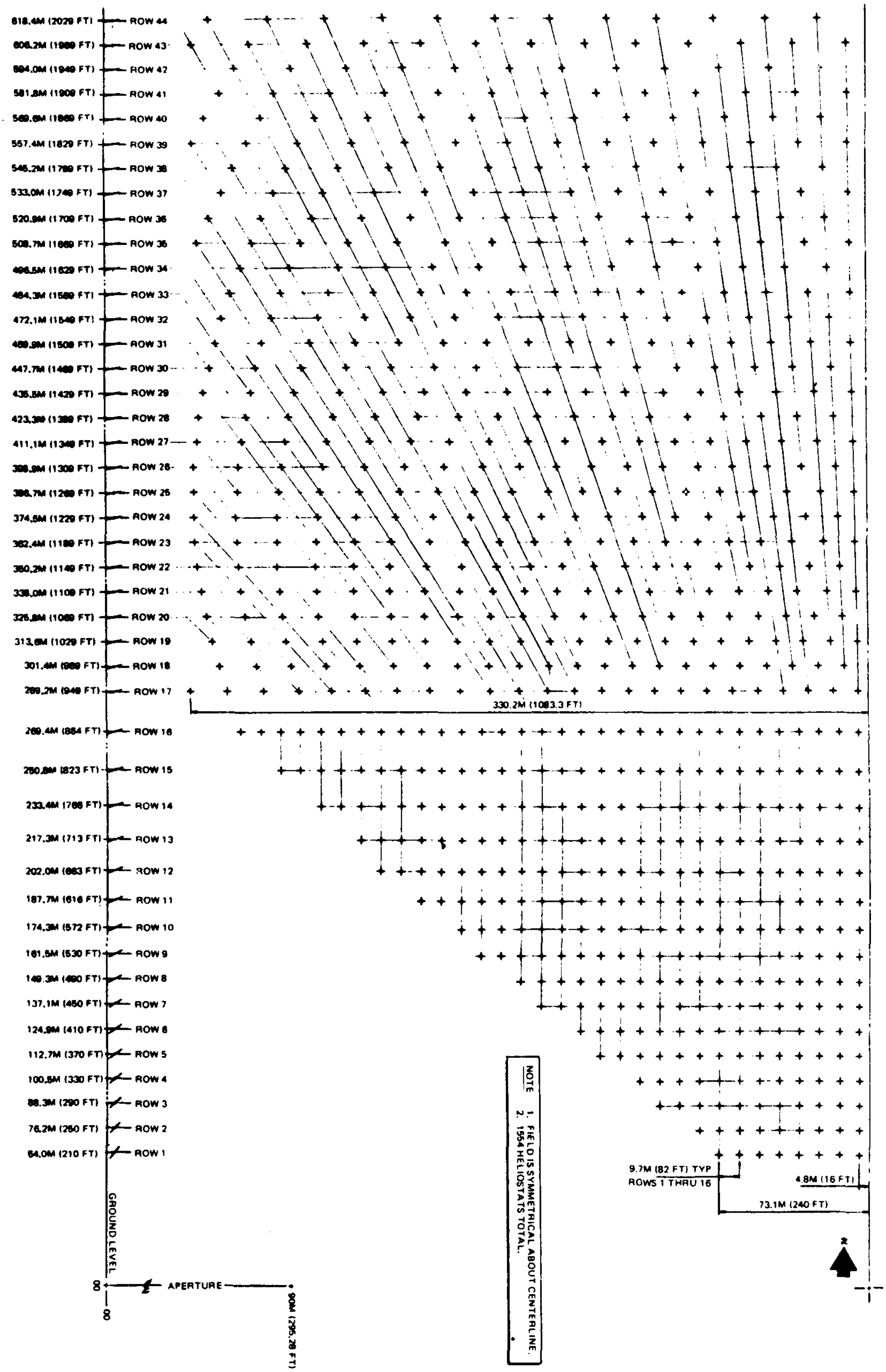
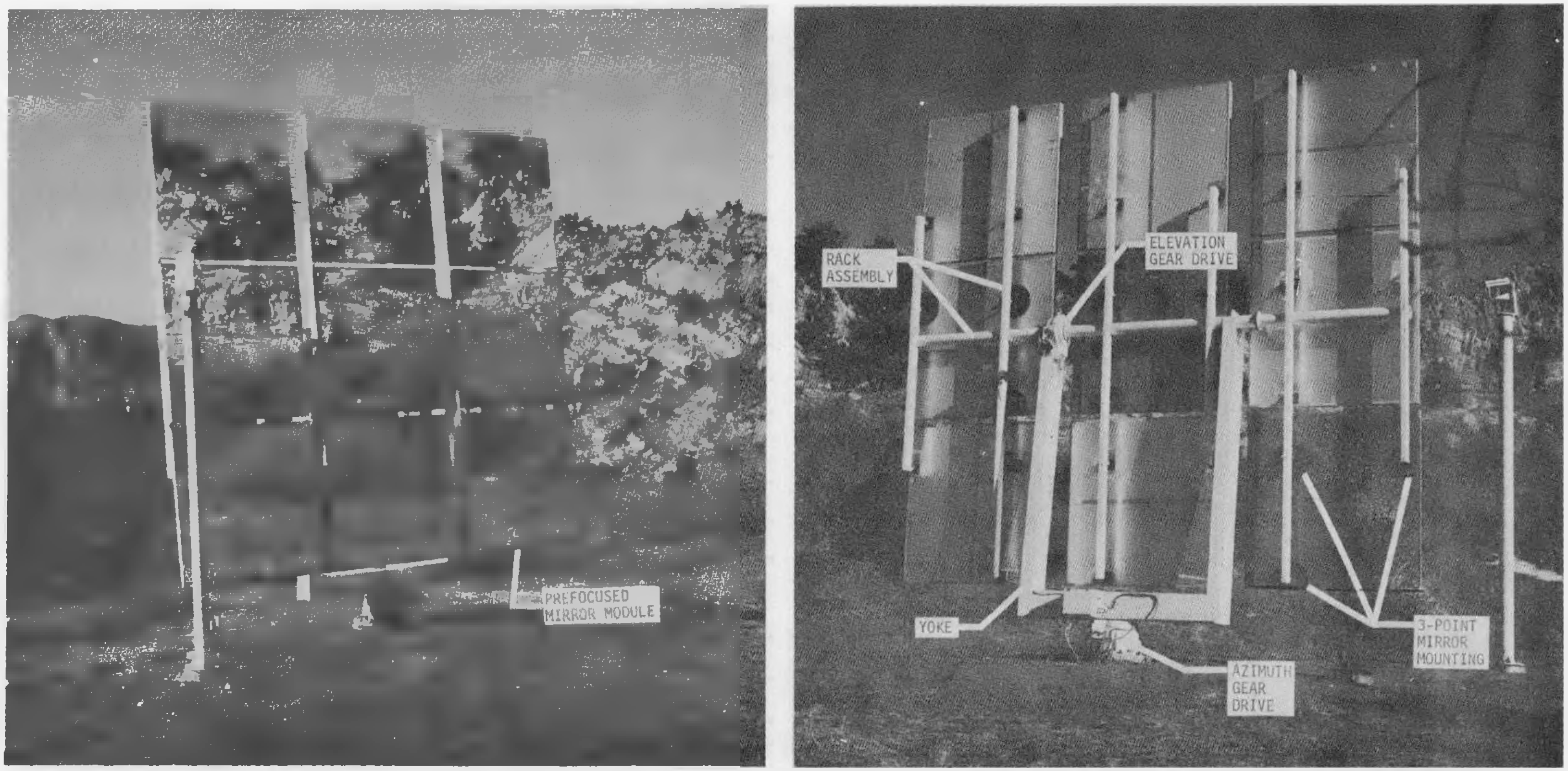


Figure IV.A-1 Commercial Plant Collector Layout



NOTE 1. FIELD IS SYMMETRICAL ABOUT CENTERLINE.
2. 1554 HELIOSTATS TOTAL.

Figure IV.A-2 Central Receiver Commercial Module Field Layout



(a) Front View

(b) Rear View

Figure IV.A-3 Nine-Facet, Fixed-Focus Heliostat

B. PILOT PLANT COLLECTOR

The collector subsystem for the pilot plant is a single module of the commercial plant collector. As stated earlier the fully packed module of 1554 heliostats is recommended even though a smaller collector would meet the design point requirements of the pilot plant. The smaller collector however would not be as attractive from the viewpoint of the pilot plant application scalability and operational versatility. Performance of the collector subsystem, the optical performance of the solar plant, varies only moderately with the annual apparent solar position variation as illustrated by the subsystem "stair steps" of Figure IV.B-1. Performance profiles for the collector at 2 PM in summer and winter are shown. Optical efficiency varies between 67 and 72.5 percent driven mainly by the effective cosine.

A feel for the hourly variation in the subsystem performance can be obtained from the effective cosine variation. Figure IV.B-2 lists the effective cosines for the pilot plant collector for the 21st day of each month on an hourly basis. For the central four hours of all days it is above 0.8. Tailing off of the cosine during the ends of the day to the 0.5 level is typical.

C. COLLECTOR SUBSYSTEM RESEARCH EXPERIMENT

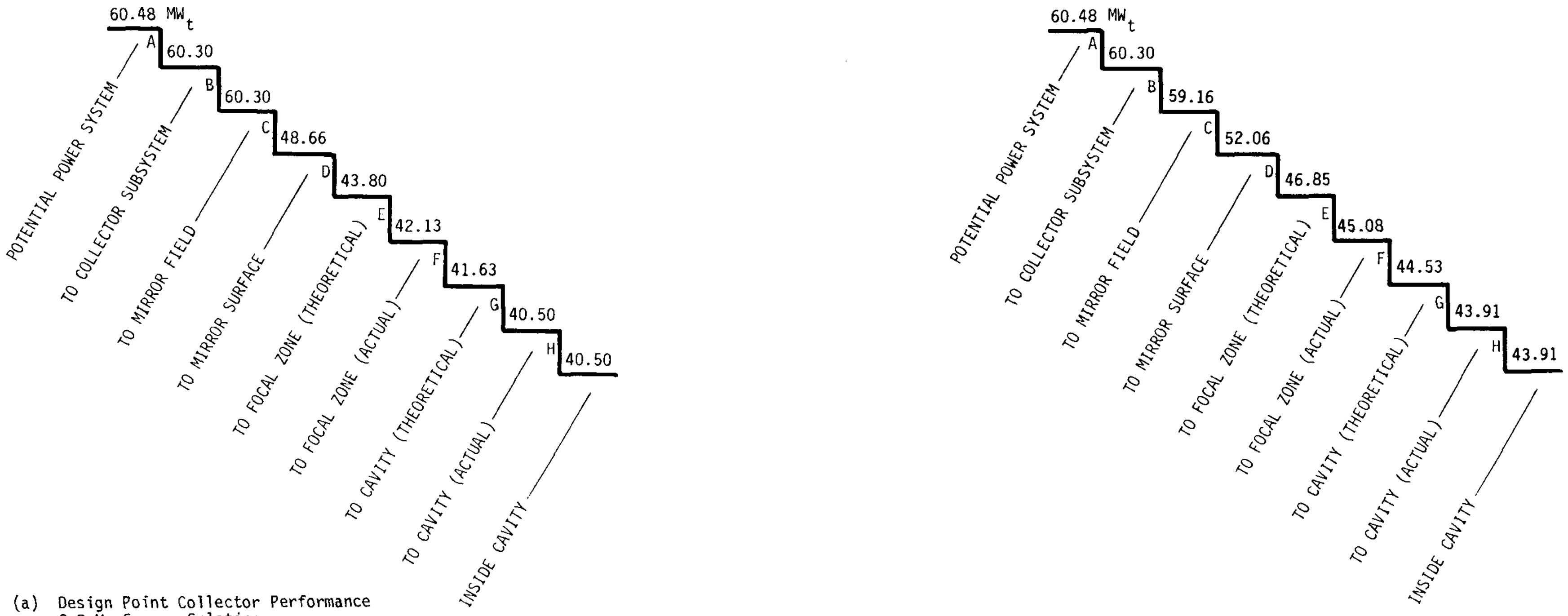
The collector subsystem research experiment was designed to demonstrate and evaluate as many of the features of a collector at full scale as possible. Within the program scope constraint limiting the number of SRE heliostats to four, an experiment to accomplish (1) full scale focusing heliostat construction, (2) full range optical transmission, (3) full scale field control, and (4) full scale prefocused facet manufacture was formulated. The geometry of the experiment closely simulated that of sample locations in the collector field both in plan view location and elevation (due to the natural terrain elevation difference between the target equipment and the heliostats). Monitoring and control equipment of the facility provided means to measure total energy and beam quality during solar tests of the heliostats. Heliostats built for the SRE were of two types, 25 facet units with variable focus mirror facets and nine facet units with prefocused facets. As shown in Figure IV.C-1, three of the 25 facet units were built and installed at slant ranges of 271 M (888 ft.), 342 M (1124 ft.) and 506 M (1659 ft.). Two of these mirrors used the highest reflectivity float glass mirrors obtainable commercially at this time, 0.83, and were of laminated construction to enable use of a minimum thickness of glass, 2.5 MM (0.098 in.) for the mirror lamination. One heliostat used low iron sheet glass in order to evaluate its potential. The single nine facet heliostat used 6.4 MM (0.25 in.) glass with 0.72 reflectivity of necessity,

INSOLATION 0.95 kW/m²
NO. OF HELIOSTATS 1554

FUNCTION	EFF
A HELIOSTAT UTILIZATION	0.997
B TOWER SHADOW	1.000
C EFFECTIVE COSINE	0.807
D REFLECTIVITY	0.900
E ATMOSPHERIC	0.962
F TRACKING	0.988
G OPTICAL	0.973
H TOWER SWAY	1.000
COLLECTOR SUBSYSTEM	0.670

INSOLATION 0.95 kW/m²
NO. OF HELIOSTATS 1554

FUNCTION	EFF
A HELIOSTAT UTILIZATION	0.997
B TOWER SHADOW	0.981
C EFFECTIVE COSINE	0.880
D REFLECTIVITY	0.900
E ATMOSPHERIC	0.962
F TRACKING	0.988
G OPTICAL	0.986
H TOWER SWAY	1.000
COLLECTOR SUBSYSTEM	0.725



(a) Design Point Collector Performance
2 P.M. Summer Solstice

(b) 2 P.M. Winter Solstice Collector Performance

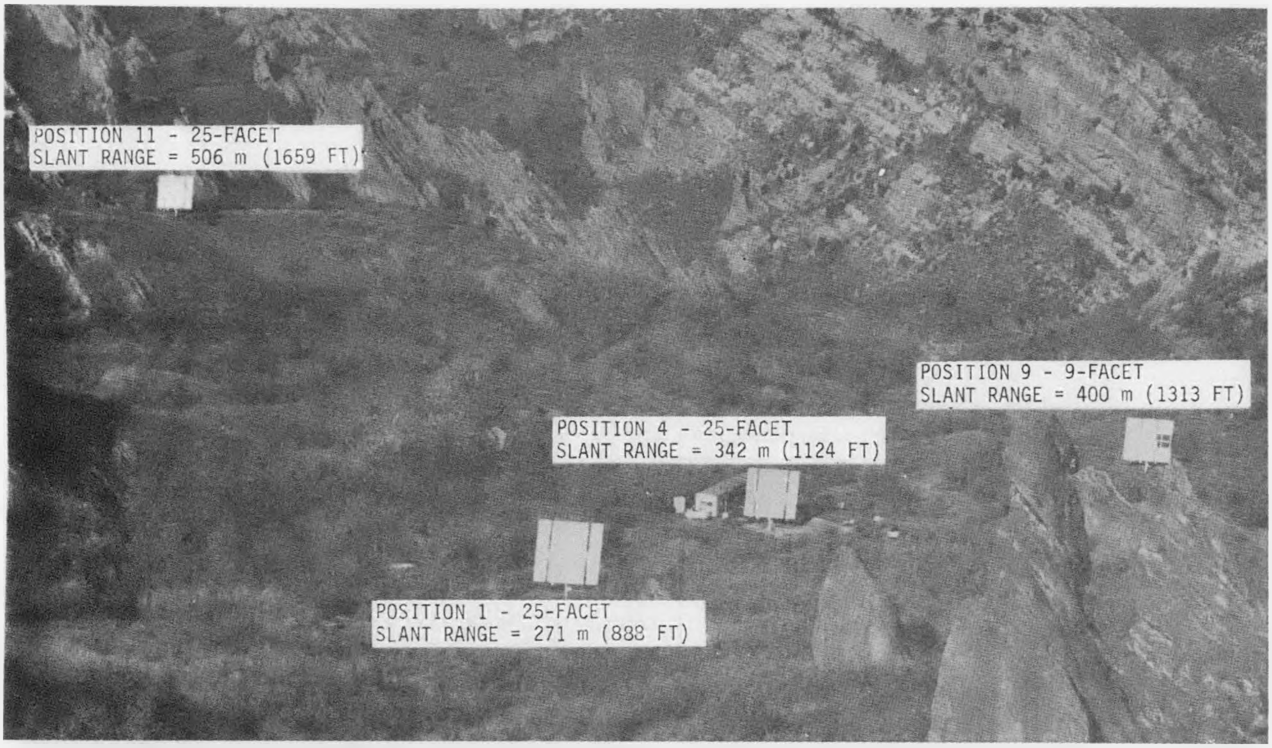
Figure IV.B-1 Collector Subsystem Performance Stair Step Summer and Winter

COLLECTOR FIELD EFFECTIVE COSINE

	TIME OF DAY														
MONTH/DAY	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900
JAN 21				0.708	0.827	0.896	0.921	0.928	0.921	0.896	0.827	0.708			
FEB 21			0.614	0.785	0.861	0.893	0.913	0.920	0.913	0.893	0.861	0.785	0.614		
MAR 21			0.600	0.760	0.834	0.873	0.894	0.902	0.894	0.873	0.834	0.760	0.600		
APR 21		0.371	0.579	0.729	0.802	0.844	0.867	0.875	0.867	0.844	0.802	0.729	0.579	0.371	
MAY 21		0.502	0.602	0.714	0.781	0.819	0.842	0.850	0.842	0.819	0.781	0.714	0.602	0.503	
JUNE 21	0.475	0.524	0.611	0.708	0.771	0.807	0.830	0.838	0.830	0.807	0.771	0.708	0.611	0.524	0.475
JULY 21		0.510	0.605	0.712	0.778	0.816	0.838	0.847	0.838	0.816	0.778	0.712	0.605	0.510	
AUG 21		0.404	0.583	0.726	0.799	0.840	0.863	0.871	0.863	0.840	0.799	0.726	0.583	0.404	
SEPT 21			0.539	0.755	0.829	0.869	0.890	0.898	0.890	0.869	0.829	0.755	0.539		
OCT 21			0.616	0.786	0.859	0.891	0.911	0.919	0.911	0.891	0.859	0.786	0.617		
NOV 21				0.717	0.835	0.899	0.921	0.928	0.921	0.899	0.835	0.717			
DEC 21				0.665	0.783	0.880	0.910	0.920	0.910	0.880	0.783	0.665			

TOWER HEIGHT = 90 m
FLAT FIELD OF 1554 HELIOSTATS

Figure IVB-2 Collector Module Effective Cosine (Combined Cosine, Shading, Blocking Area Efficiency Factors)



(a) Four Heliostats in Operation

(b) Flares from Four Operating Heliostats Photographed from Base of Calorimeter

Figure IV.C-1 Collector Research Experiment Heliostats since handling for thinner mirrors in the desired size has not been developed commercially. It was prefocused for a focal length of 400 M (1313 ft.).

The four heliostats were tested individually and operated together as illustrated in view (b) of Figure IV.C-1.

Two key features of the SRE heliostat design, the closed loop tracking control sensor and the face down stowage position are illustrated in Figure IV.C-2. The closed loop control was chosen for the experiment based on its selection for the "Preliminary Baseline Design" (September 1975) pilot plant for its potentially higher accuracy and its state-of-the-art readiness. Face down stowage satisfied safety, minimum wind profile, and minimum rate of dirt deposition objectives.

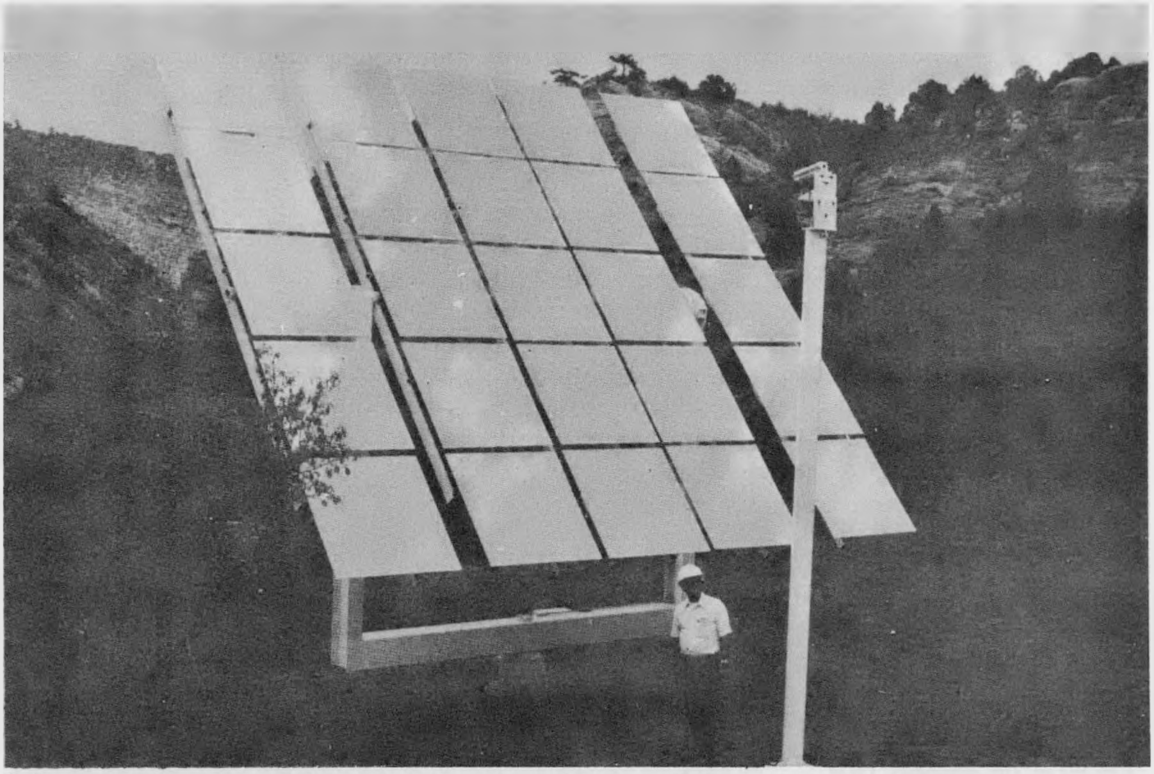
Elements of the full scale heliostat field control built for the SRE are shown in the four views of Figure IV.C-3. The control subsystem consists of an executive control computer, heliostat control electronics, and a feedback optical sensor as shown. The executive control using the PDP11-03 computer had sufficient capacity to control the full scale heliostat field. It controls start up, shut down, manually inserted commands and emergency conditions, but turns over tracking control to the fine track closed loop sensor.

Due to the open loop development performed for the STTF heliostats, the state-of-the-art margin advantage of closed loop disappeared. The economic and plant flexibility benefits offered by open loop control over rode the small accuracy advantage benefit offered by closed loop control.

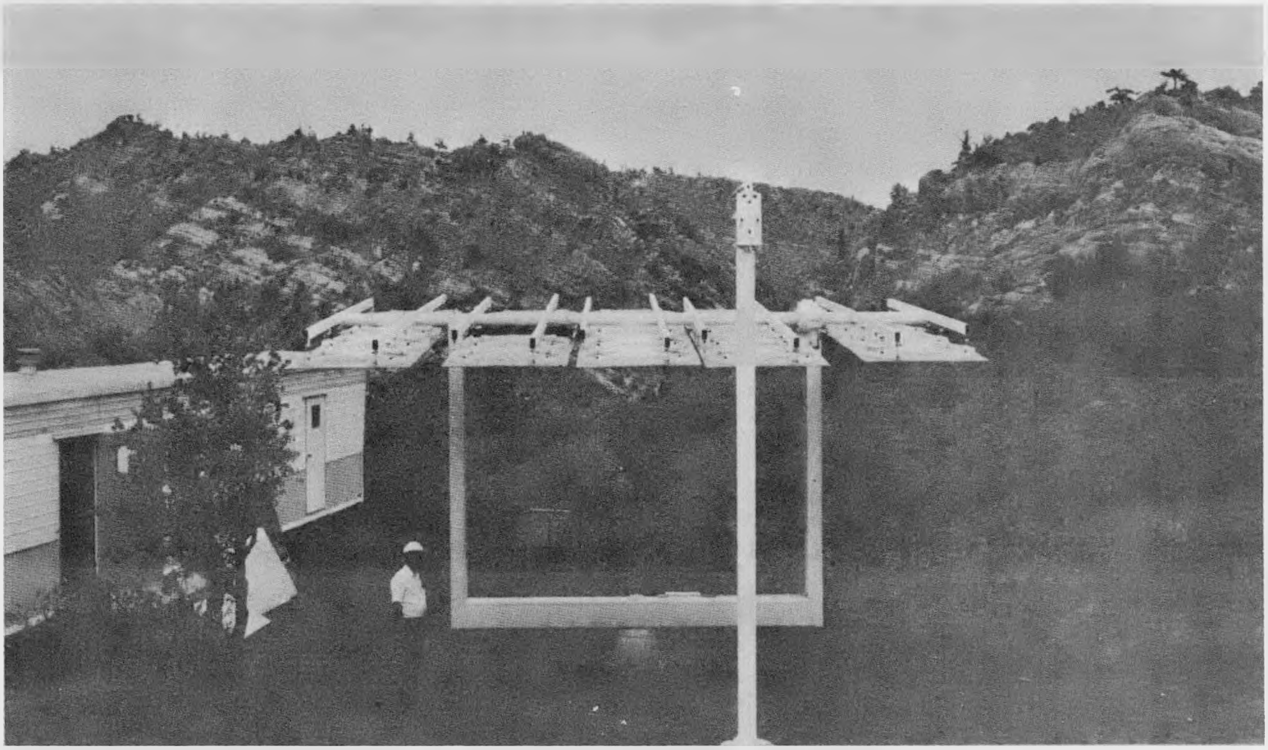
The forerunner of the "Preliminary Design" heliostat in overall configuration is the nine facet fixed focused heliostat shown in Figure IV.C-4 view (a), (picture was taken with only eight facets in place and clearly shows the elevation axis drive installation). Image quality was obtained visually during focusing alignment by photographing the image on the optical target on the doors of the calorimeter.

These tests indicated that the fabrication technique would yield images within the 12 to 13 milliradian range (a growth from the theoretical sun's image of 9.3 mr due to manufacturing tolerances).

Quantitative data on the solar energy collection-concentration performance of the heliostats was obtained with the water cooled calorimeter and the radiometer installations shown in Figure IV.C-5. Total energy collected in the water together with an energy balance to ascertain the energy flow to and from the environment were combined to obtain the total energy data.

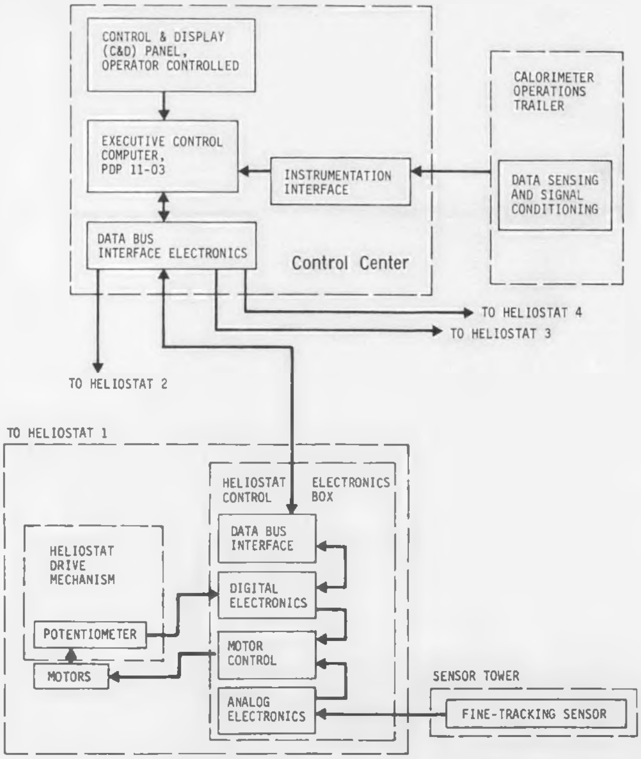


(a) Position 4 Heliostat Operating Under "Closed Loop" Control



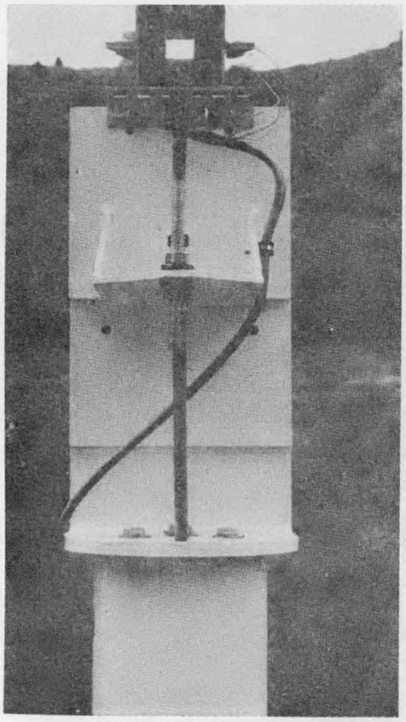
(b) Position 4 Heliostat in Face-Down Stowage Position

Figure IVC-2 Twenty-Five Facet Heliostat - Position 4, Slant Range 343m (1124 ft)

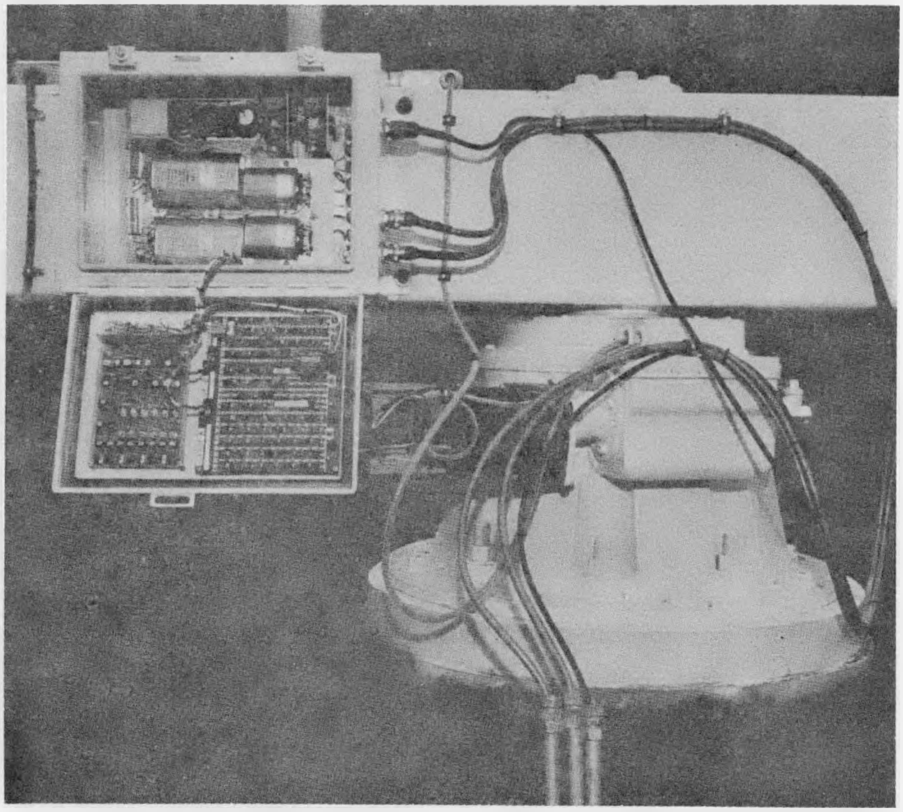


(a) Functional Schematic of Heliostat SRE Control System

(b) Control Subsystem for Heliostat Subsystem Research Experiment

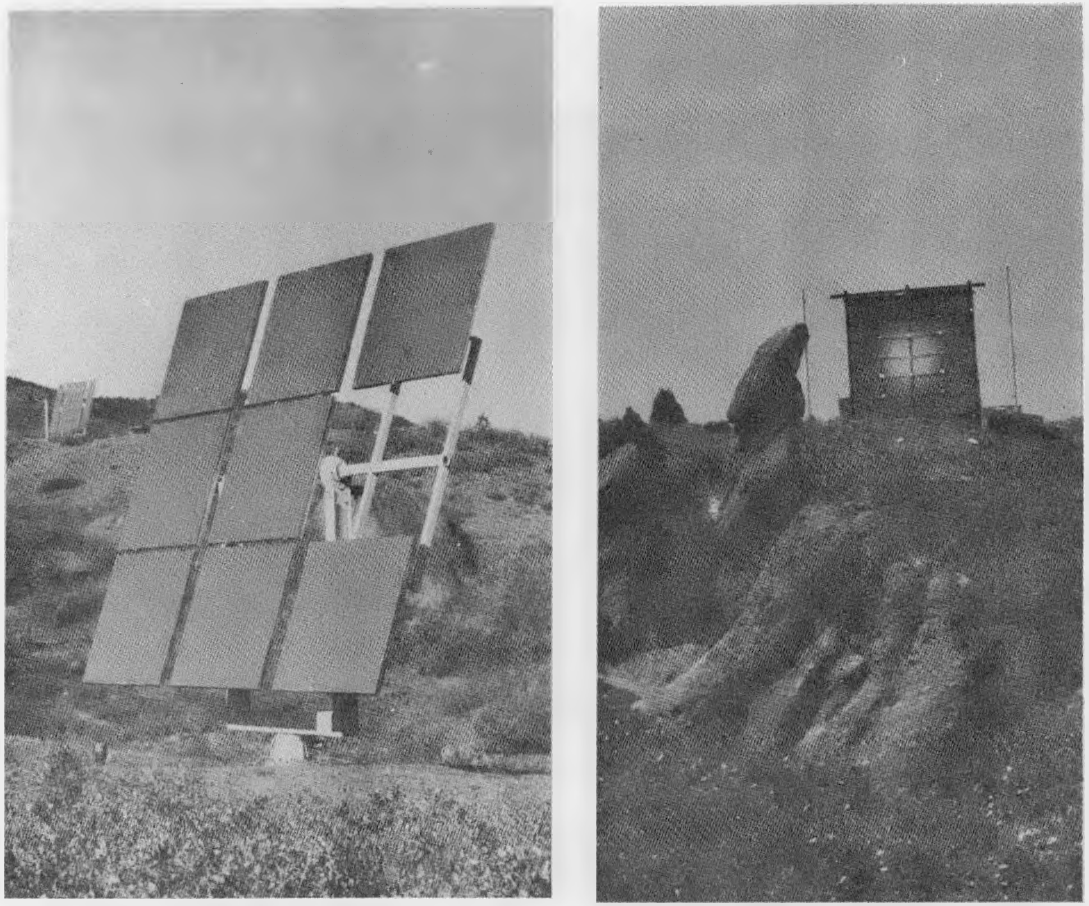


(c) Tower-Mounted Sensor for First Subsystem Research Experiment



(d) Heliostat Drive and Electronic Package

Figure IV.C-3 Control/Electronics for Heliostat SRE



(a) SRE Nine-Mirror Heliostat

(b) Image Quality Testing of Prototye Fixed-Focus Mirror

Test

Samples: Prototype, 1st SRE
Size: 2.0x2.0 m (80x80 in.)
Mirror: 6 mm, Float, Back-Surface Silver
Slant Range: 400.2 m (1313 ft)

Test Results

Measured Image Quality

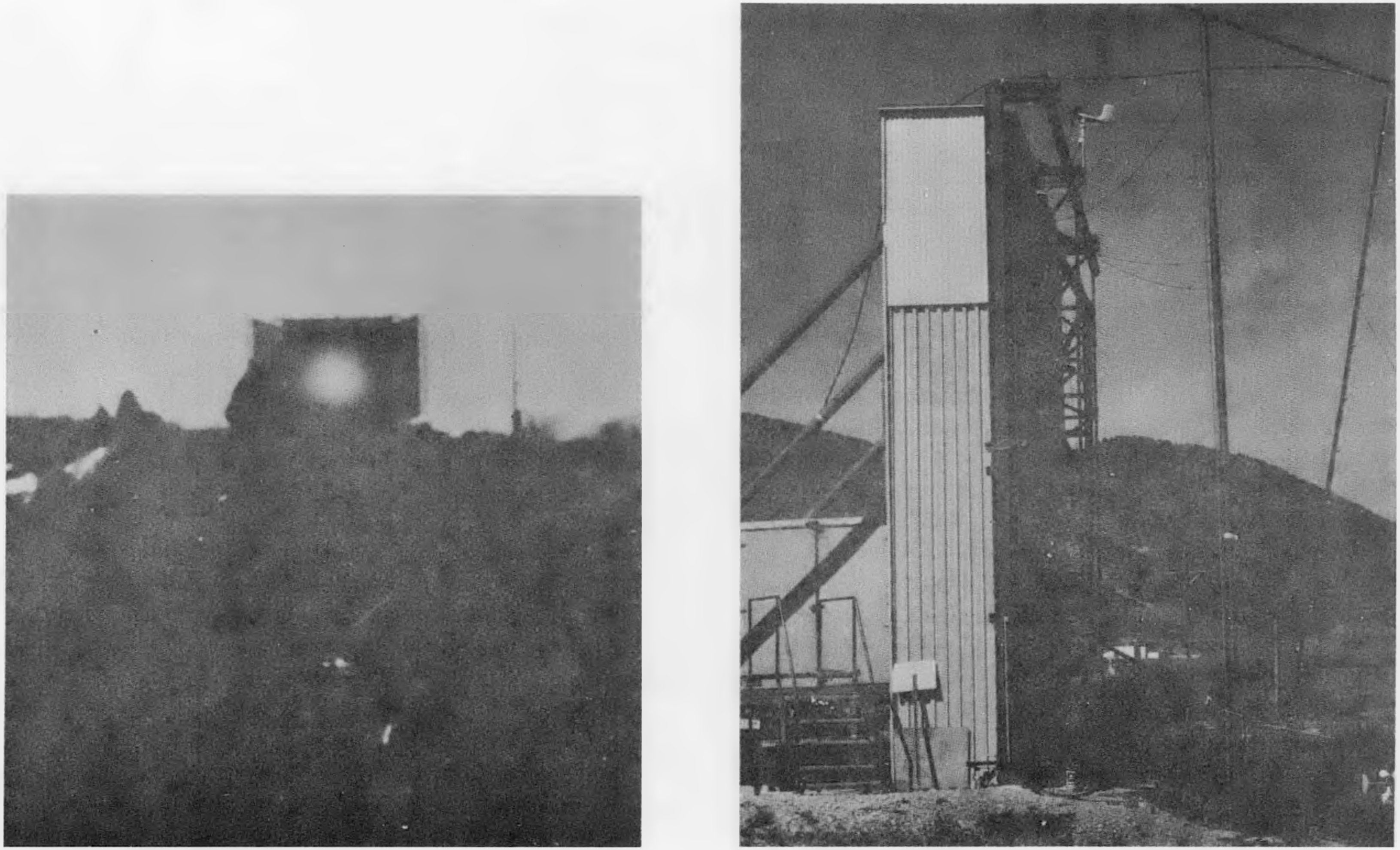
Mirror	Major Dia, m (ft)	Minor Dia, m (ft)
Proto	17	12
SRE 1	16	12

Calculated Image Quality

Theoretical Sun Dia:	3.72 m (12.2 ft)
$d_s = 0.012\ R_s$	4.80 m (15.8 ft)

(c) Results of Fixed-Focus Mirror Testing

Figure IV.C-4 Nine-Facet, Fixed-Focus Heliostat Configuration (General Features of Preliminary Design Heliostat)



(a) Calorimeter - Doors Open, Image from Four Heliostats

(b) Calorimeter - Doors Closed, Radiometer Rake with 13 Mounts

Figure IV.C-5 Collector Subsystem Research Experiment - Calorimeter and Radiometer Equipment

Beam quality and flux patterns were obtained by traverses of the solar beam across the radiometer rake. The focal patterns of the heliostats varied substantially as would be expected due to the nearly 2:1 variation in slant ranges (with a corresponding 4:1 effect on peak flux) as shown in Figure IV.C-6. The mirror performance factors of the float glass heliostats closely matched the reflectivity observed in the pyrheliometer reflectivity test rig. The sheet glass value was low, probably due to the ripple scattering.

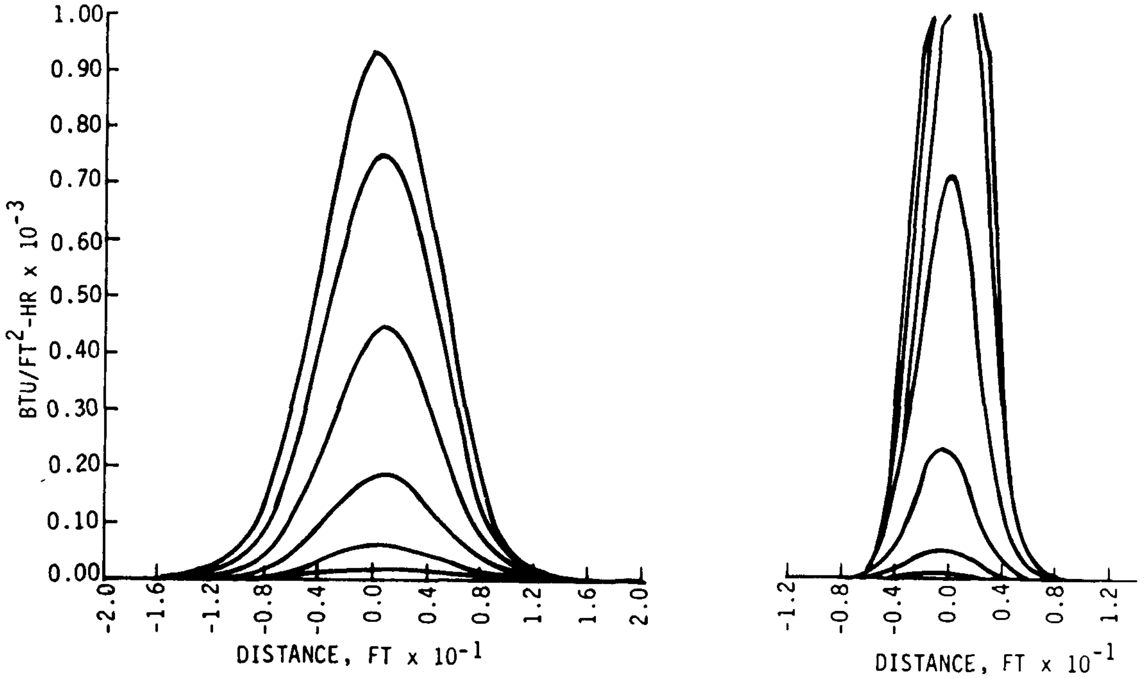
D. PRELIMINARY DESIGN COLLECTOR

Features updated into the Preliminary Design include (1) revision of the module layout to 1554 heliostat positions, (2) increasing the reflective area on each heliostat 10.2 percent, (3) use of low iron glass mirrors, (4) revision in the prefocused facet back structure, (5) open loop fine tracking control, (6) use of microprocessor electronics in the heliostat and (7) use of caisson foundations. Front and side elevations of the heliostat are shown in Figure IV.D-1 and a blow up of the revised prefocused facet construction is shown in Figure IV.D-2.

The 1554 heliostat position layout was driven by the performance penalty minimization it allowed, associated with the reduction in receiver aperture height from 137.2 M (450 ft) to 90 M (295 ft). The increase of unit heliostat area 10.2 percent was also coupled to this change in that it permitted retention of the total collector area even though the number of heliostats had been reduced. Structural beef-up to accommodate the larger structure is centered in the rack structure, permitting the basic SRE yoke design to be preserved.

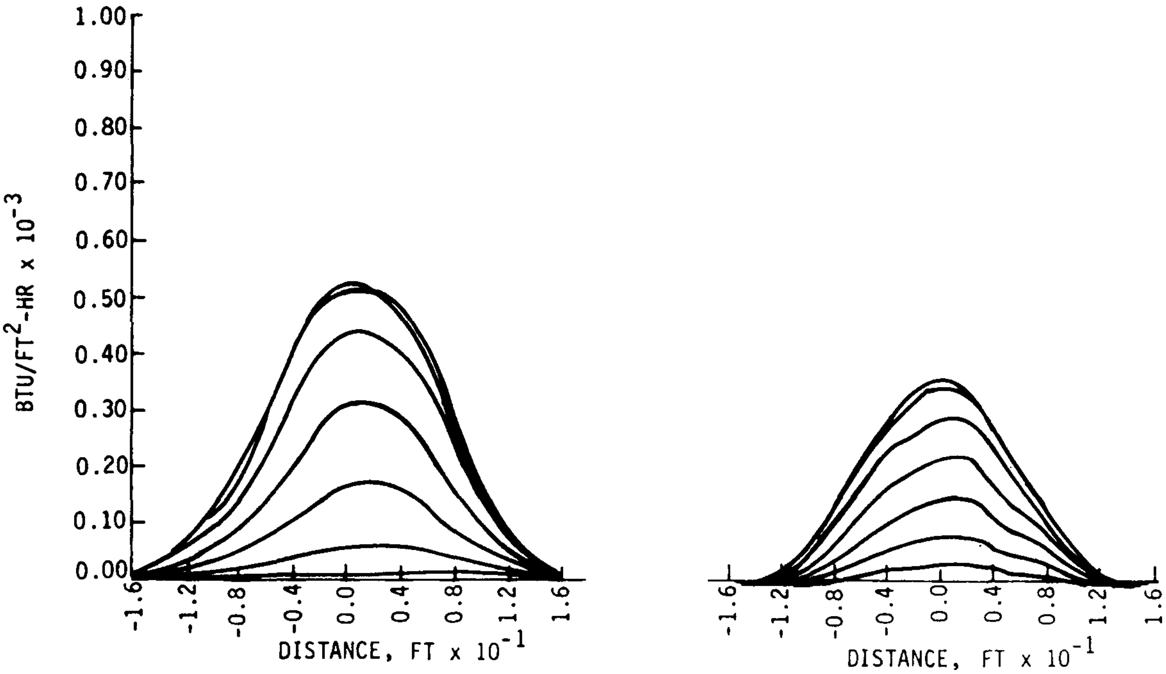
Low iron float glass is key to attaining the projected optical performance. Low iron sheet glass was initially installed in the SRE based on its 0.91 reflectivity measured in the test rig. However, the ripple effect inherent in the process made the mirrors unsuitable for closed loop tracking, the ripples forcing the tracker to readjust for their angular change from the base mirror. The associated light scattering lowered the performance below acceptable limits. The expectation that low iron float will be available is supported by recent experimental batch runs made by Pittsburgh Plate Glass.

The prefocused facet structure design revision was made to accomplish a more stable optical curvature than the method developed for the SRE. Enhanced stability from moisture penetration is obtained by changing from paper core to aluminum core honeycomb. Enhanced stability from temperature changes has been obtained by forming the honeycomb sandwich independent of the mirror and assembling the mirror into it.



(a) Heliostat 4, 1/8-in. Float Glass, MPF = 0.828 Slant Range 343 m (1124 ft), 30.3 kW_t

(b) Heliostat 1, Sheet Glass, MPF = 0.820 Slant Range 271 m (888 ft), 24.4 kW_t



(c) Heliostat 9, ¼-in. Thick Float Glass, MPF = 0.700 Slant Range 400 m (1313 ft), 25.1 kW_t

(d) Heliostat 11, 1/8-in. Float Glass, MPF = 0.747 Slant Range 506 m (1659 ft), 23.9 kW_t

Figure IV.C-6 Radiometer Profiles from SRE Heliostats

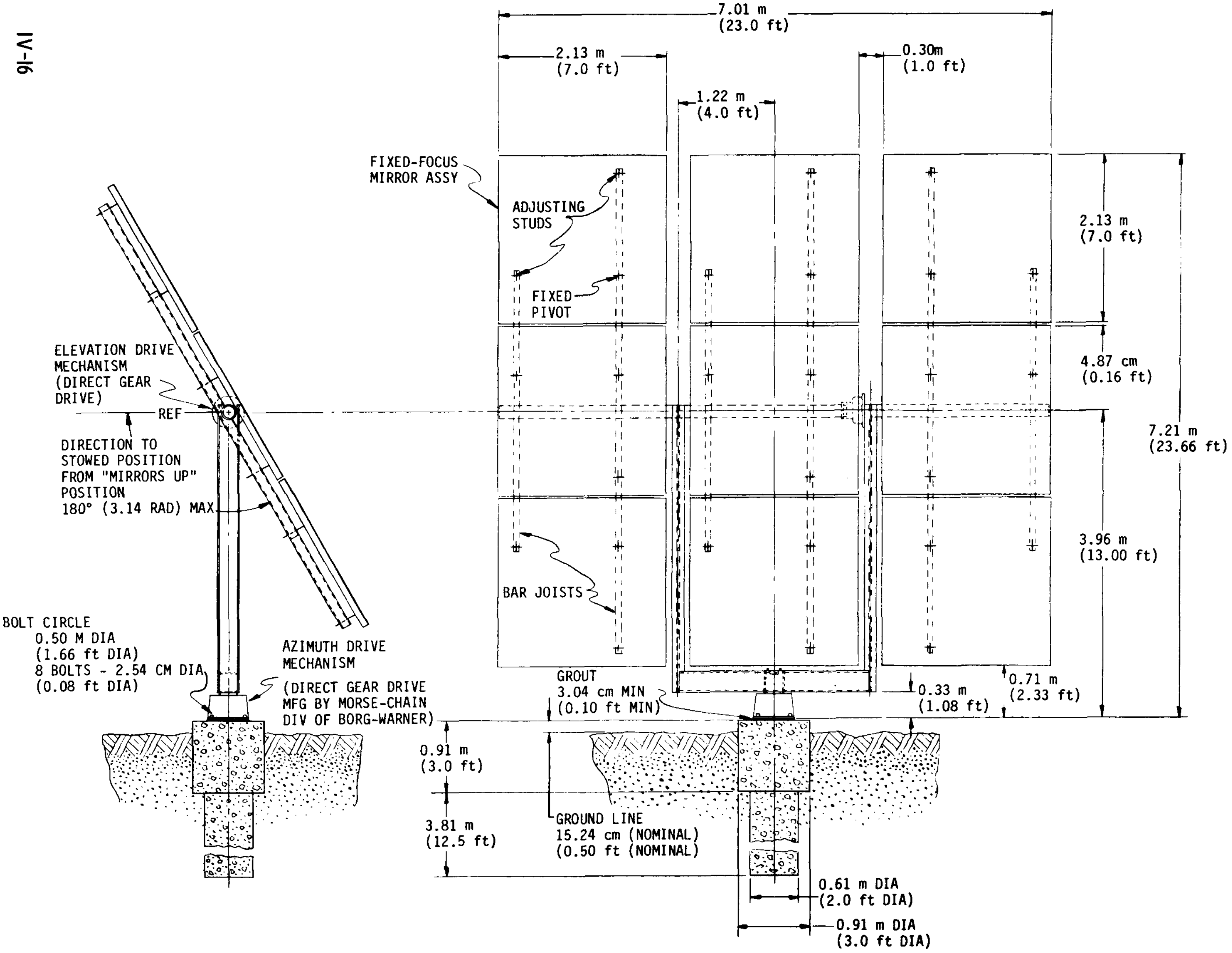


Figure IV.D-1 Baseline Design for 10 MWe Pilot Plant Heliostat

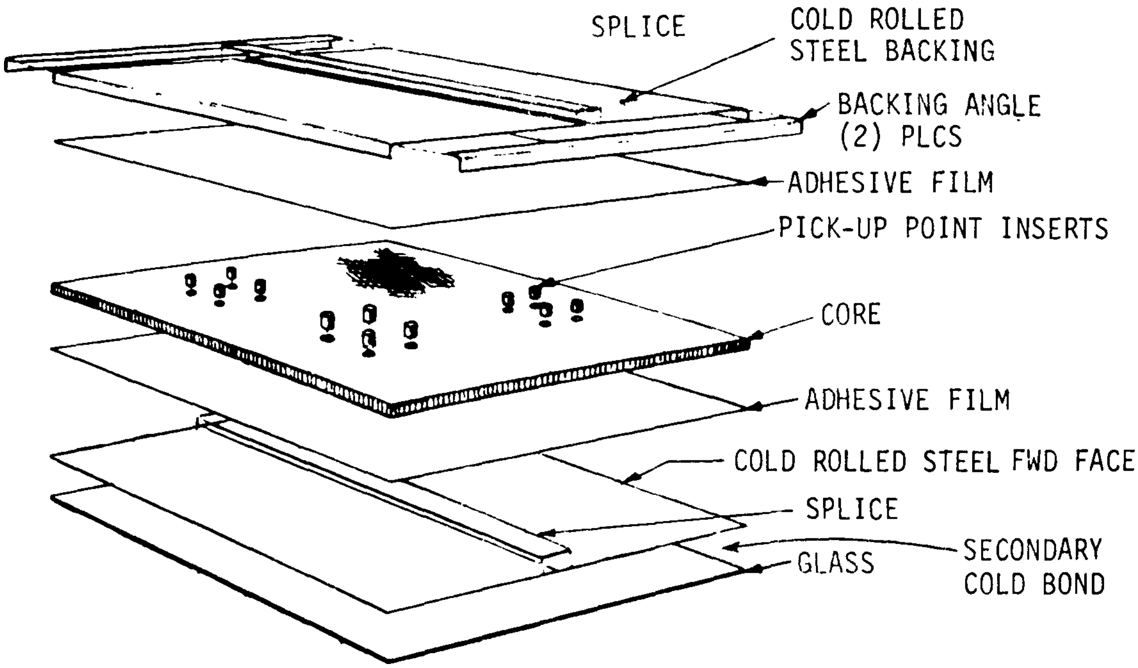


Figure IV.D-2 Baseline Honeycomb Substrate Mirror Assembly

The change to open loop control and simplification of the heliostat control electronics by use of a microprocessor are based on the experience with these elements in the heliostats and "focus and alignment" equipment built for the STTF in Albuquerque. The open loop control has been brought to operational status in that program. A forerunner of the microprocessor heliostat control electronics was used in the focus and alignment electronics very satisfactorily.

The caisson foundation is the most cost effective of the options evaluated even though a stability specification under wind loads had to be opened up 0.3 mr (1 arc-min).

The Preliminary Design Collector embodies the preliminary baseline concept built and tested in the SRE plus key updated features from all current programs which enhance its suitability for the pilot plant.

V. RECEIVER SUBSYSTEM

The CRSTPS receiver steam generator embodys an optimum performance cavity configuration, utilizes natural circulation for maximum reliability and minimum risk, and is designed in accordance with applicable ASME code provisions, most recently proven satisfactory in the 1 MWt and 5 MWt cavity receivers.

The commercial-plant receiver subsystem consists of 15 identical tower-mounted steam-generating receivers. Each receiver is designed to accept energy from a concentrating solar-collector field consisting of 1554 heliostats, each with 41 m^2 (441 ft^2) of reflective surface area. The steam output of each receiver module feeds a common manifold system from which either the Electrical Power Generation System (EPGS) or the Thermal Storage Subsystem (TSS) or both can be served. The plant can operate quite efficiently with one or more receivers inoperative.

A yearly average of 97.7 percent of the energy projected to the receiver is captured by the aperture and enters the cavity. The minimum proportion captured (95 percent) occurs in the early morning on the summary solstice, and the maximum (99 percent) occurs at noon on the winter solstice. At the commercial plant design point, 94.6 percent of the energy entering the cavity exits the receiver as superheated steam. The losses consist of radiation through the aperture (2.5 percent), convection through the aperture (2.7 percent), and conduction through cavity walls (0.2 percent). The absolute value of these losses are nearly constant over the whole range of energy input level; only the radiation component varies with energy input.

The working fluid used in the pilot-plant receiver is water delivered in the form of superheated steam at 9136 kPa (1325 psig) and 789 K (960^{o}F) to either the EPGS or the TSS. The steam-generating concept selected uses a natural-circulation boiler. The three major elements of the receiver are:

- The boiler tubes which generate saturated steam from feedwater,
- The steam drum which separates the steam/water mixture from the boiler tubes,
- The superheater which raises the temperature and energy content of the steam to the specified exit condition.

The three major elements are linked together by a system of feeders, risers, headers, and downcomers, which provide the necessary internal fluid flow paths.

The main reason the natural-circulation type of boiler was selected was because it is a well-proven, highly reliable concept that has been successfully used in many different applications over a period of many years. It is deemed to be entirely compatible with the CRSTPS operating requirements.

A. COMMERCIAL PLANT RECEIVER

The commercial/pilot-plant receiver is natural-circulation, side-opening-cavity receiver supported by an enclosed and roofed structural-steel tower. It has a number of features that contribute to low cost, low risk, and safe operation and maintenance. The side-opening cavity, which is equipped with an aperture door, has a high-energy absorption efficiency and low thermal losses, both while in operation and overnight when the cavity door is closed. The exterior surfaces of the receiver are easily protected from stray solar flux by a shield mounted on the tower. There are no structural supports to be protected. The side-opening cavity also permits use for a single focal point for the collector subsystem.

Natural circulation has a history of high reliability in fossil-fueled boilers. Using it eliminates capital and maintenance costs, reliability considerations, and power consumption associated with a forced-circulation pump. The boiler tubes are relatively large in diameter and no small orifices, prone to plugging, are needed to control flow distribution. Flow circuitry and valving are inherently uncomplicated. The receiver is relatively tolerant to impure feedwater because of its large tubes and sizeable water inventory. It is also immune to loss of feedwater pumps for periods in excess of those required for safe shutdown due to the large water inventory within. The circulation is inherently self-compensating for energy input variations. Heat-transfer characteristics in boiler and superheater are well known by the designer. Conventional, reliable, low-cost systems are used for feedwater and steam temperature control.

The receiver is similar in design to a fossil-fueled steam generator, and it would be designed, manufactured, and constructed using conventional, well-established materials, processes, and techniques. The vertical cavity walls, ample platforms and access doors, and aperture door make it convenient and safe to maintain and repair.

The receiver has been designed to meet ASME Boiler Code Section I, applicable criteria of Section VIII, Division 2, and Code Case 1592 of Section III. Conventional materials are used throughout. In the boiler and superheater, the exact tube sizes and materials of the commercial receiver were used in the 5 MWt SRE receiver.

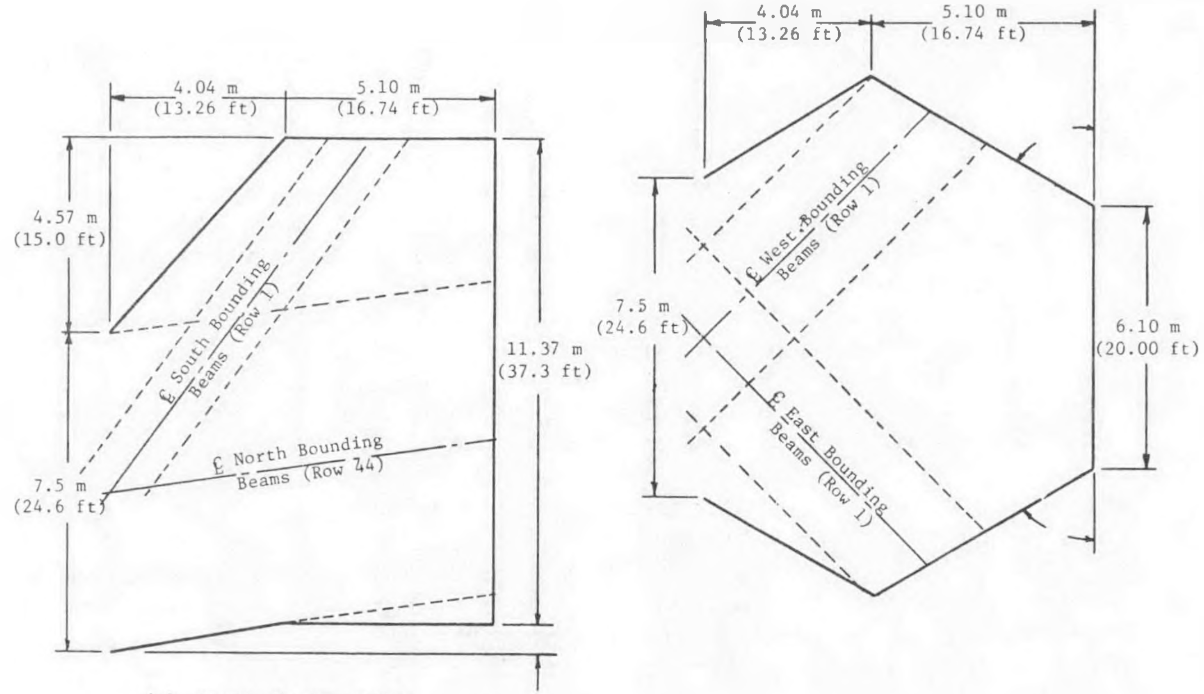
The receiver subsystem includes the tower, the receiver steam generator enclosed within it, the riser/downcomer piping and the steam generator controls. Figure V.A-1 shows the receiver subsystem rendering, the basic steel arrangement in the tower, and the position within the tower of the receiver.

The basic cavity shape and the relationship of bounding solar beams from the collector subsystem are shown in view (a) of Figure V.A-2. The implementation of this shape in the final design is evident from the side elevation and horizontal sections of the receiver assembly shown in view (b) of Figure V.A-2. The vertical rear walls for the heater exchange surface were a beneficial by-product of the tower shortening decision. The position of the aperture doors in the open position, above and below the aperture are evident in the sectional elevation. The receiver exterior front and side elevations are shown in Figure V.A-3. It is generally a box like envelope except for the shallow pocket for the lower aperture door. The positioning of the drum near the center of gravity improves both the piping design and the load distribution.

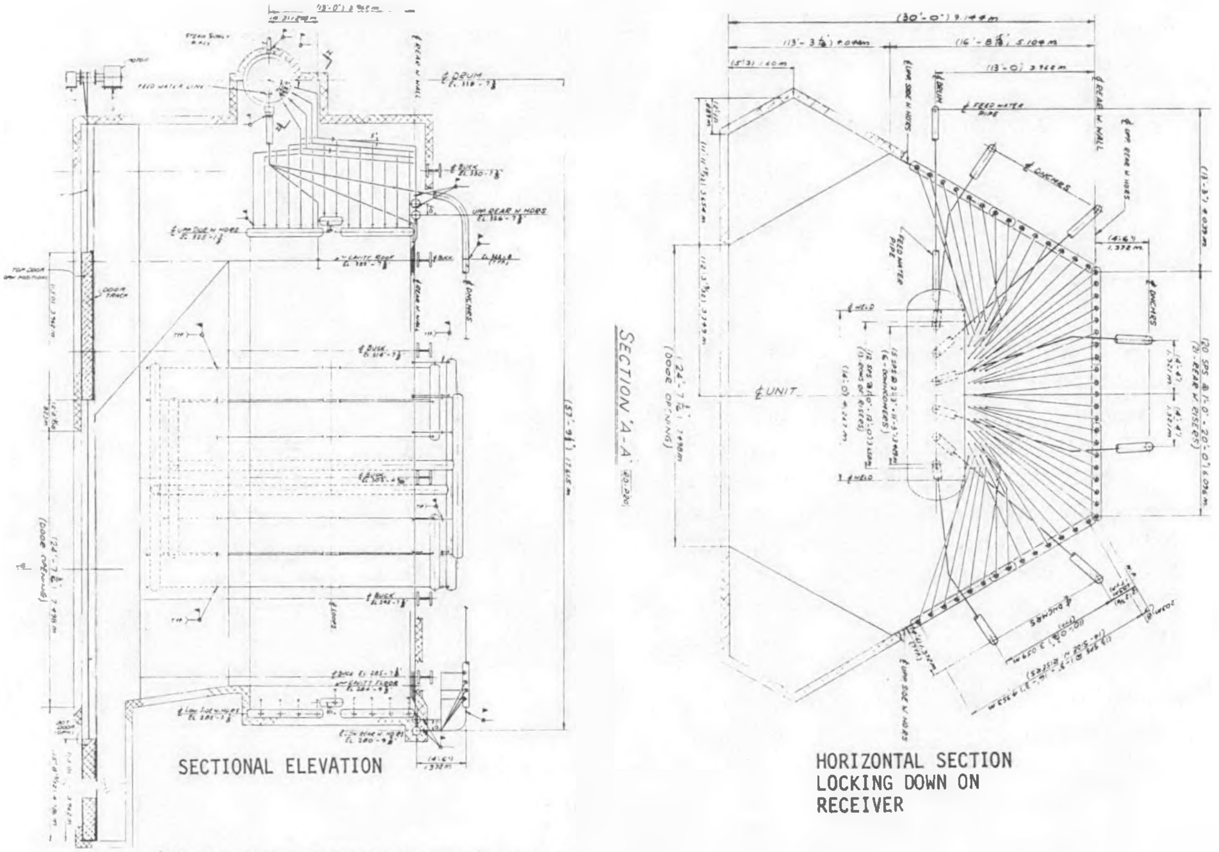
As stated earlier, the commercial receiver design is identical to the pilot plant receiver.

B. PILOT PLANT RECEIVER

Each receiver is a natural-circulation steam generator designed to generate superheated steam at a pressure of 10,687 kPa (1550 psig), a temperature of 789 K (960^{o}F), at a flow rate up to 75,300 Kg/h (160,000 lb/h). Each steam generator is arranged in a cavity configuration into which concentrated solar energy is directed. A flow schematic of one module is shown in Figure V.B-1. Water flows from the steam drum through external downcomer pipes and branching feeders to the lower headers of the boiler, where the flow is divided among the various upflow circuits in the waterwalls (boiler tubes). As the water flows upward through the tubes, a portion of it is converted into steam by the absorbed heat. The resultant mixture of water and steam leaving the tubes is collected in the upper side and rear-wall headers and carried to the steam centrifugal separators which separate the steam from the water. The water, after mixing with incoming feedwater in the drum, enters the



(a) Cavity Configuration

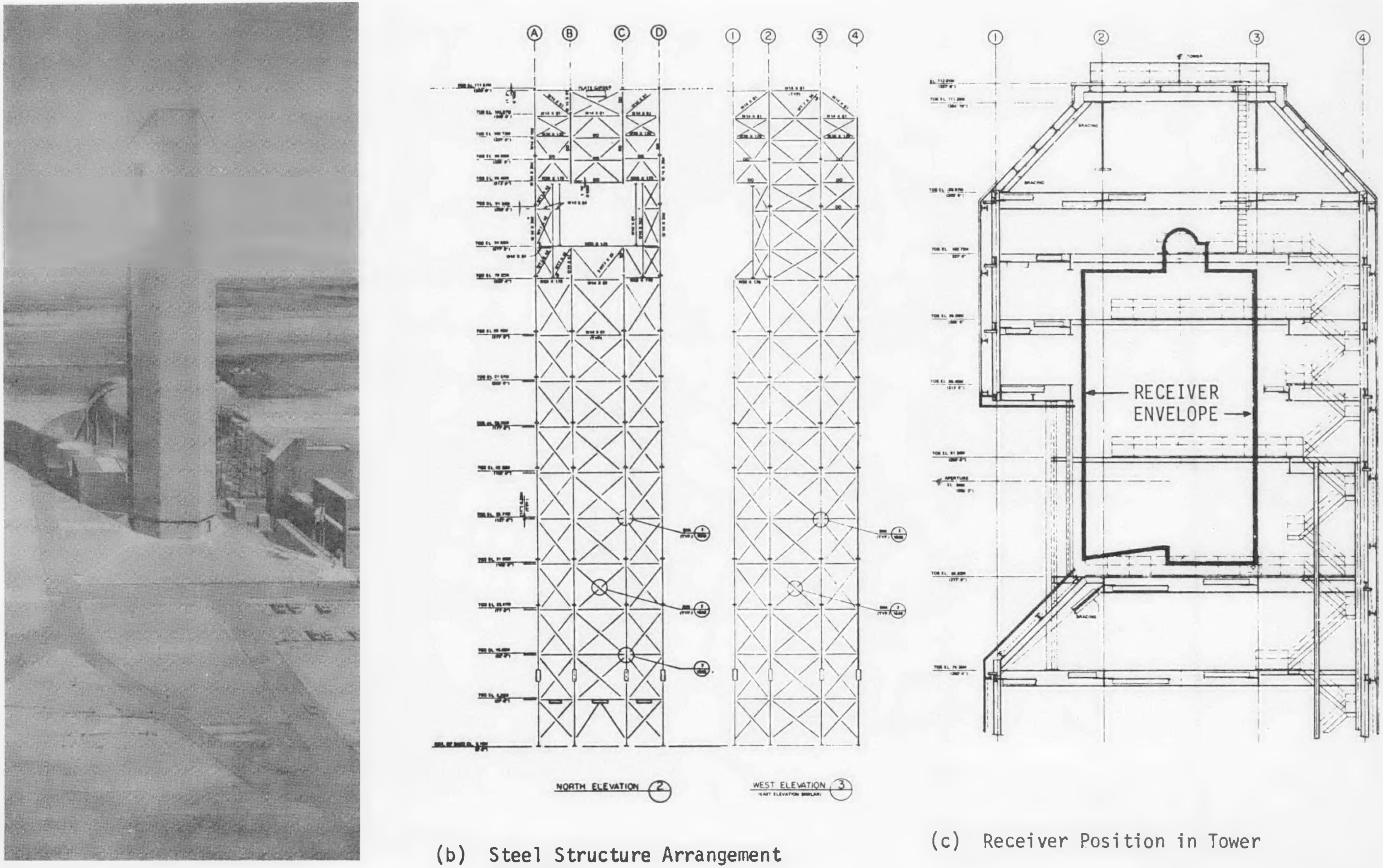


SECTIONAL ELEVATION

HORIZONTAL SECTION
LOCKING DOWN ON
RECEIVER

(b) Receiver Assembly Design Features

Figure V.A-2
Commercial/Pilot-Plant Receiver Cavity
Configuration and Overall Design Features

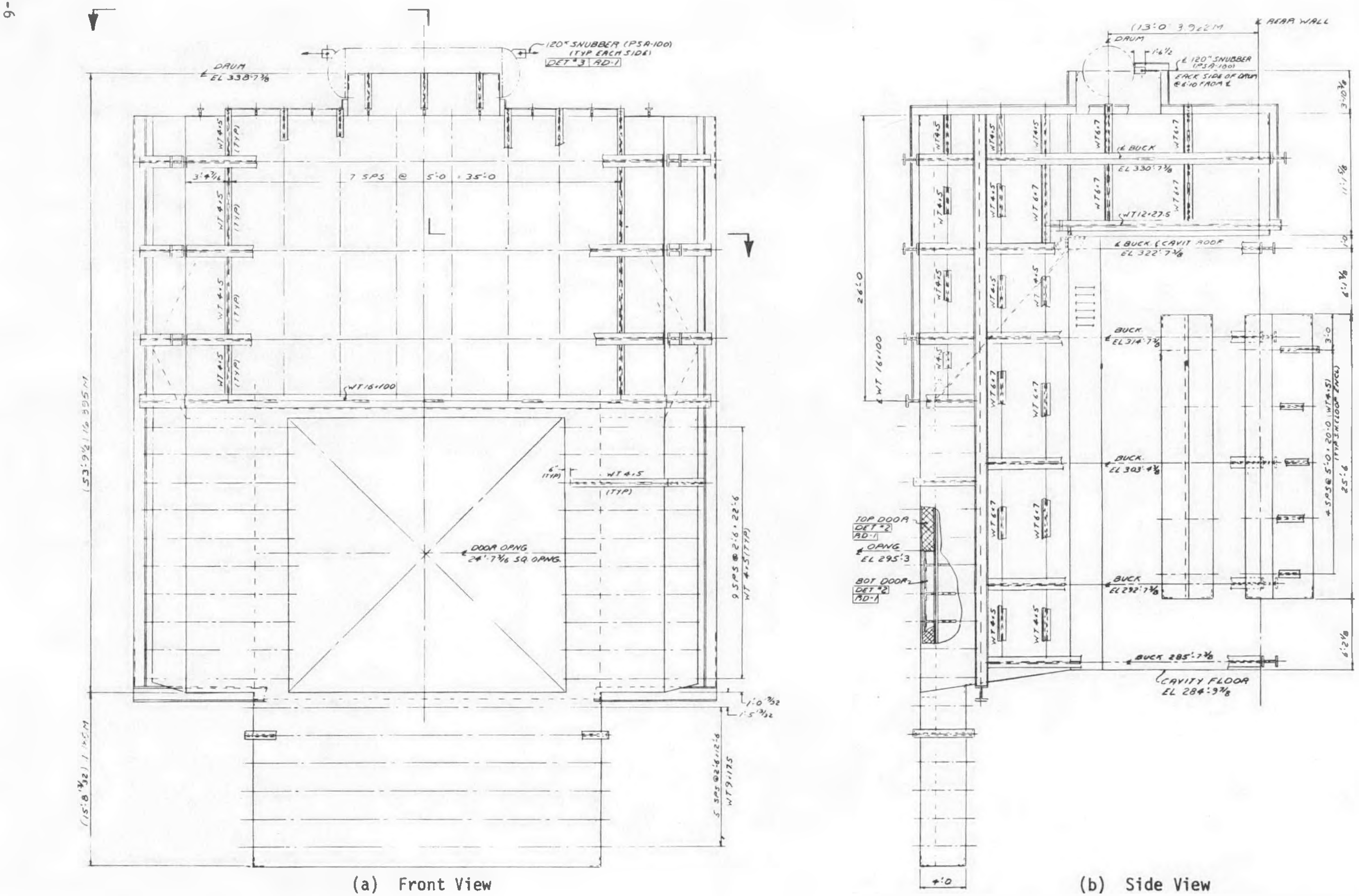


(a) Rendering of Receiver Enclosed in Tower

(b) Steel Structure Arrangement of Tower

(c) Receiver Position in Tower

Figure V.A-1 Receiver Subsystem Installation - Commercial/Pilot Plants



(a) Front View

(b) Side View

Figure VA-3 Exterior Configuration of Receiver

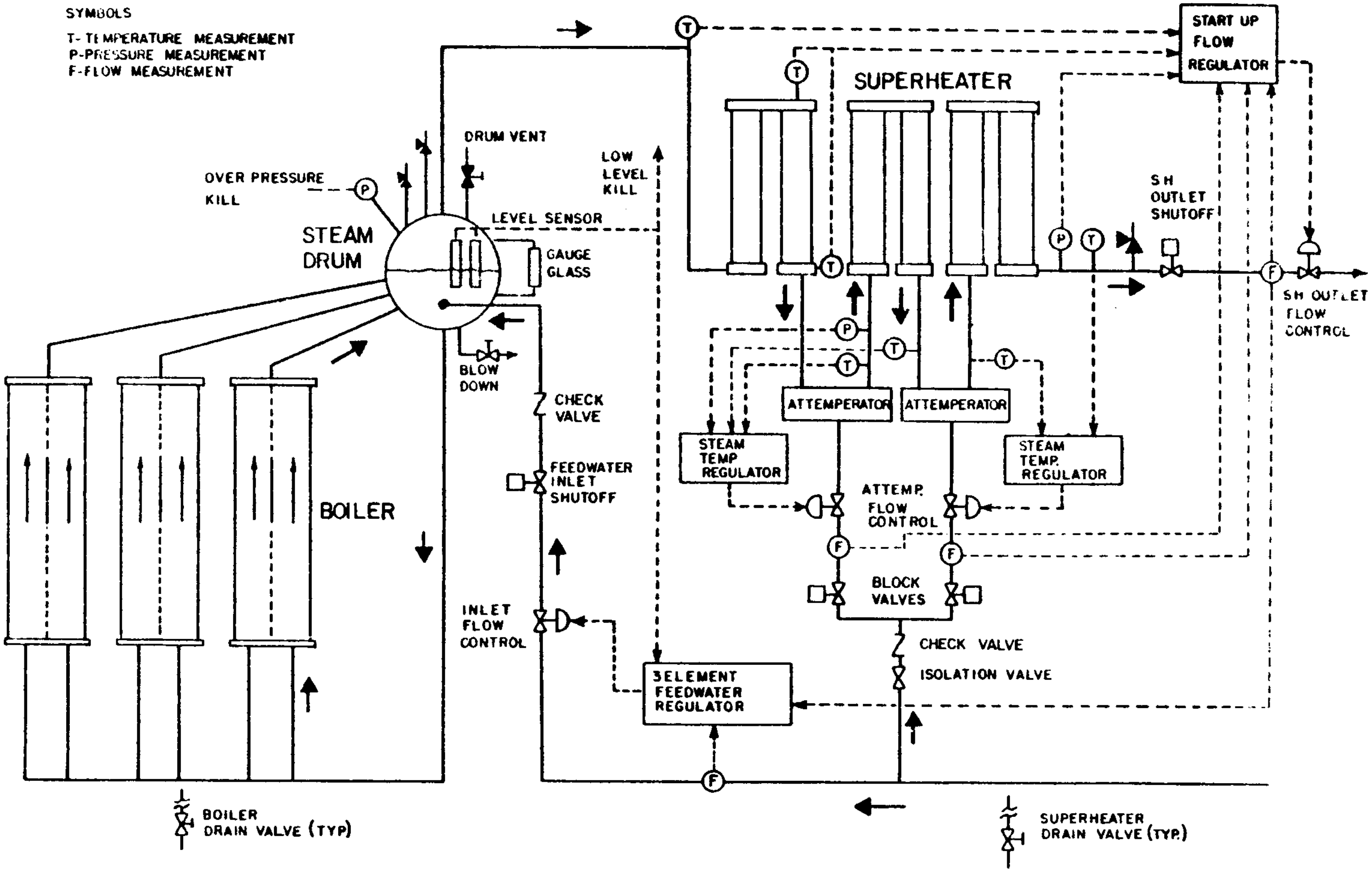


Figure V.B-1 Schematic of Commercial/Pilot-Plant Receiver downcomers for another trip around the circuit while the steam passes through chevron-type driers (mist eliminators) for removal of any entrained water droplets. From the drum, the dry, saturated steam flows through a number of pipes to the six-pass superheater, where it is heated to its specified outlet temperature.

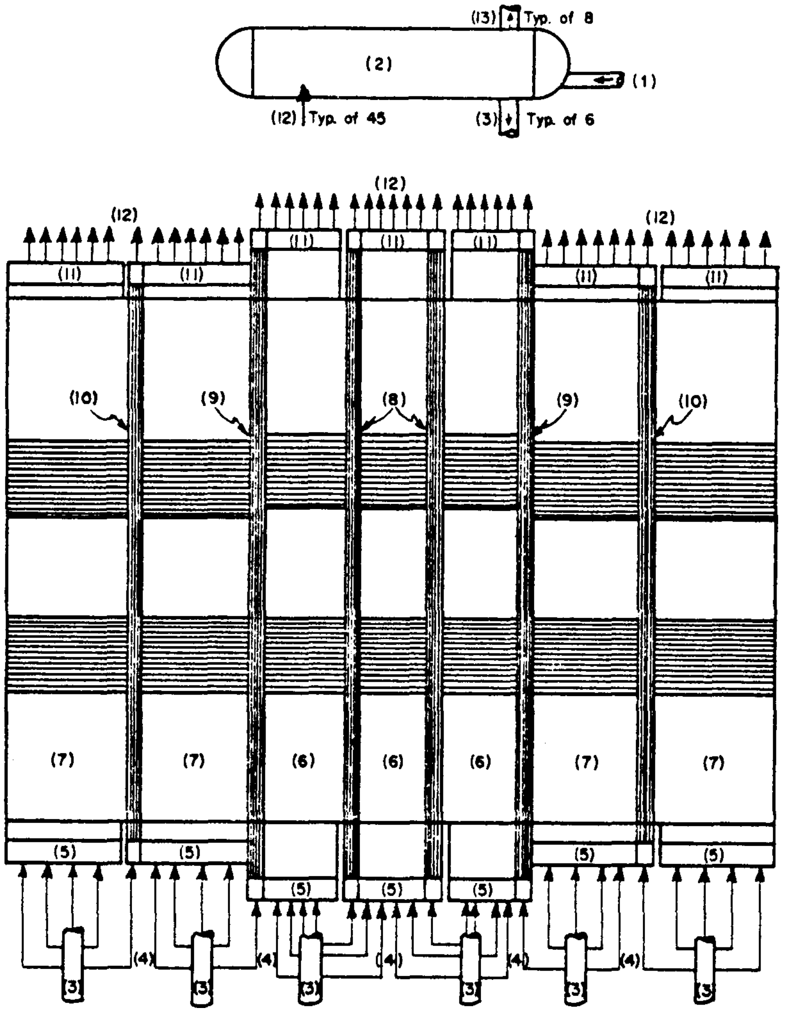
Feedwater flow to the receiver is controlled by a conventional three-element feedwater regulator that matches feedwater flow to steam flow, with a trimming override in response to drum water level.

Superheated steam temperature is controlled by attemperators in which feedwater is sprayed into the superheated steam and evaporated, thus lowering the steam temperature. Two attemperators are used--one between the second and third passes and another between the fourth and fifth passes. Attemperation is required during start-up not only to control steam temperature, but also to prevent excessively high tube temperatures in the superheater. During normal operation, it is required since the fraction of the total solar flux incident on the superheater varies with the time of day and season of the year.

Sensors are provided to activate alarms so that the operators can defocus the heliostats in the event of high superheater-outlet steam temperature, high steam-drum pressure, or low water level in the steam drum. A flow-control valve in the superheater outlet line is used during start-up to control flow through the superheater as pressure is being raised so that the superheater tubes are adequately cooled while pressure increases at an optimum rate.

Each lower boiler header and superheater header is equipped with a drain valve. The superheater drain valves are all remotely operated from the plant control room, since they must be opened and closed during start-up. The receiver is completely drainable. One superheater-outlet safety valve and two drum safety valves are provided as required by ASME Code.

The arrangement of the heat exchange walls is illustrated in Figure V.B-2. All walls of the cavity are vertical. The rear wall and a large portion of both side walls are covered with 38.1-mm (1-1/2 in.) O.D. carbon steel boiler tubes on 44.5-mm (1-3/4 in.) centers, using Monowall^{TM} construction in which the tubes are jointed together along their length by continuous-weld integral fins to form flat panels. This construction was adopted because it is structurally rigid, can be handled in shipment and during erection with relative ease, and is impenetrable to solar flux.



LEGEND

(1) Feedpipe
(2) Drum
(3) Downcomers
(4) Feeders
(5) Lower Headers
(6) Rear Walls
(7) Side Walls

(8) Rear Wall Screens
(9) Corner Screens
(10) Side Wall Screens
(11) Upper Headers
(12) Risers
(13) SH Supply Lines.

Figure V.B-2 Boiler Circuitry of the Commercial/Pilot-Plant Receiver

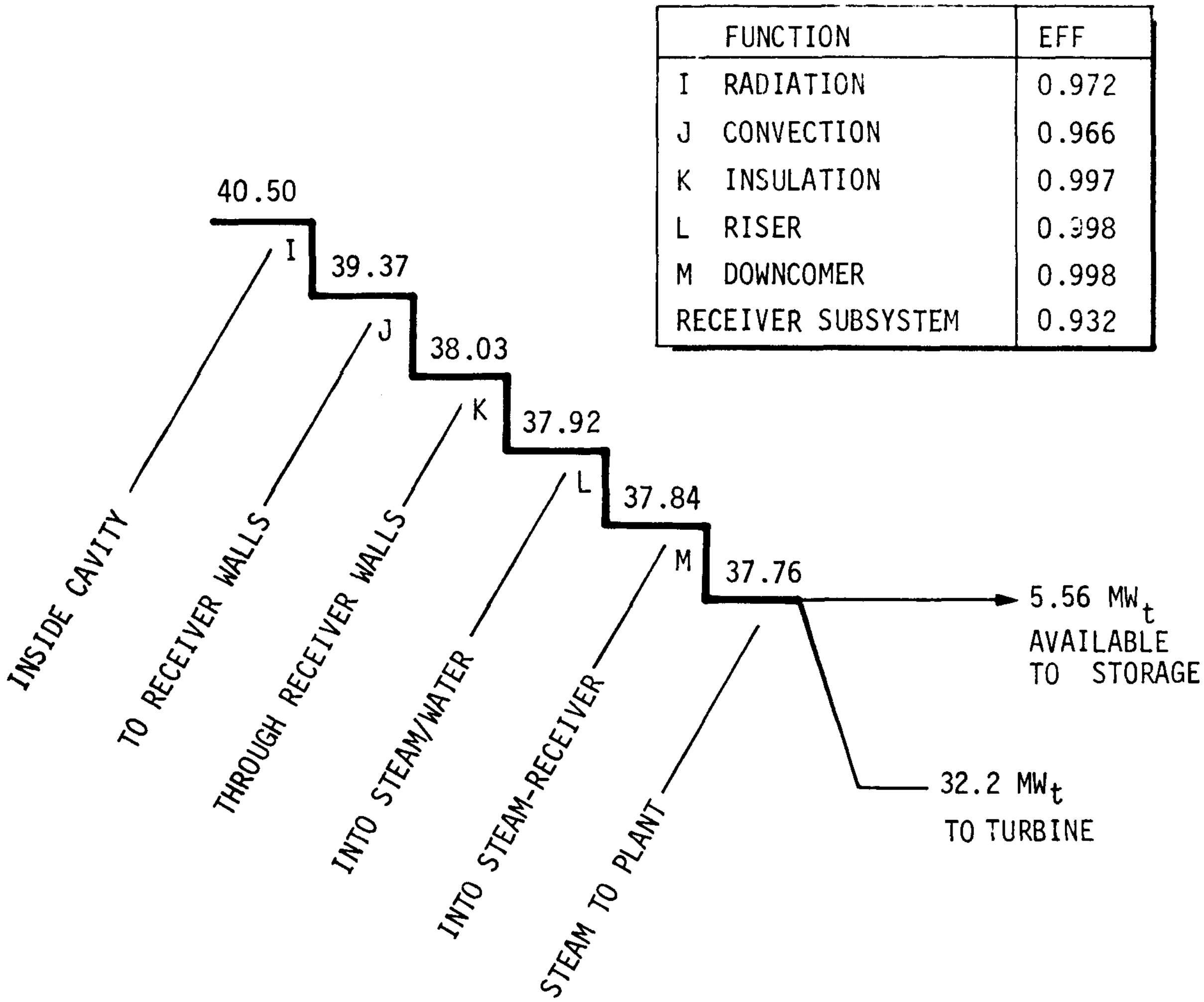
The superheater consists of six passes in series, two passes on each of the side walls and two on the rear walls. Each pass is made from a number of parallel 25.4-mm (1-in.) O.D. austenitic stainless steel tubes arranged side by side on 28.6-mm (1-1/8 in.) centers to form one or more platens. These tube platens are placed in front of the waterwall panels (on the cavity side) as shown.

The heat-flux pattern requires that the passes on all three walls be approximately aligned horizontally at two elevations. All passes are divided into two subpasses each, and steam flow is split into one upper and one lower subpass. This reduces the vertical heat-flux variation in each pass and therefore, effects a more uniform flow distribution and steam temperature rise among the tubes. All superheaters and transfer lines between passes are located behind the waterwall panels. Superheater tubes penetrate through openings in the waterwall panels at the inlet and outlet of each pass and at intervals along each pass where expansion loops and intermediate supports are located.

The aperture was sized to accommodate two divergent considerations. The opening must be large enough to capture most of the reflected energy from all heliostats. However, increasing the aperture size also increases thermal losses from the cavity by radiation and convection. Therefore, the optimum aperture size is that which allows the most energy to enter the cavity and yet minimize direct radiation and convection losses from the cavity. The 7.498-m (24.60 ft) square aperture selected from the pilot-plant receiver captures an annual average of 97.7 percent of the energy projected from the heliostat field and loses about 6 percent by radiation and convection from the cavity. A stair step breakdown of the receiver subsystem performance profile for the design point is shown in Figure V.B-3. The end to end subsystem efficiency of 0.932 includes the effects of radiation, convection, insulation, riser, and downcomer thermal losses.

Start-Up Transients

A comparison of start-up and shutdown transients shows that the latter is much easier than the former for the receiver system to accommodate. During a shutdown transient, when the incident heat flux to the receiver is cut off, heat exchange is between the boiler, superheater, and cavity interior surfaces and from the receiver exterior surfaces to its surroundings. The closed cavity door and insulated wall minimize heat loss from the receiver. Heat soaks back into the boiler section at a moderate rate, and any slight over-pressure caused by this heat flow in the initial



FUNCTION	EFF
I RADIATION	0.972
J CONVECTION	0.966
K INSULATION	0.997
L RISER	0.998
M DOWNCOMER	0.998
RECEIVER SUBSYSTEM	0.932

Figure V.B-3 Receiver Subsystem Stairstep - Pilot Plant period of the transient can be vented either through the superheater or directly from the steam drum. The superheater section, when experiencing gradual decreases in temperature level and front-to-back wall temperature gradients, is subjected to a stress condition no more severe than that encountered during steady-state operation. Therefore analytical studies and testing were concentrated on start-up transients.

Key receiver transient operation modes evaluated included:

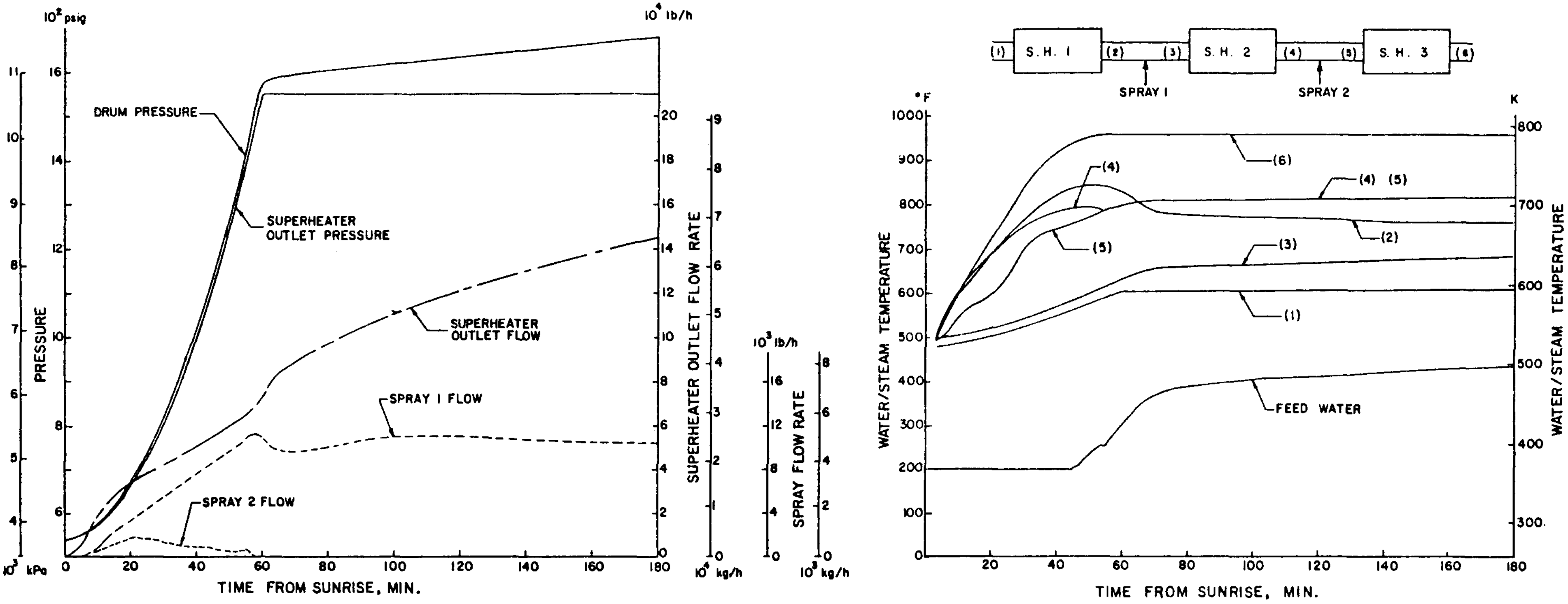
- Hot start-up after overnight shutdown
- Restart after cloud passage
- Cold start-up from ambient condition.

Hot start-up is a diurnal morning start-up of the receiver after overnight shutdown. Since the receiver cavity insulation is designed to limit the drop in saturation temperature of 83K (150^{o}F) during a 12-hour shutdown period, the receiver can be re-started each morning from a relatively hot standby state. To utilize all available insolation during the start-up period, it is desirable to bring up the receiver with the full solar energy input anticipated for any day of the year or, simply phrased, "start up with the sun." This method minimizes the control functions required for the collector subsystem but incurs more operational restraints on the receiver subsystem. Among all the parameters affecting a hot start-up transient, the most important and governing parameter is the rate of drum pressure increase.

Design temperature and pressure profiles for the hot start-up are shown in Figure V.B-4. Full rated temperature is reached earliest, 50 minutes after starting. Full pressure of the outlet steam is reached in 60 minutes. The steam flow which is a function of the insolation of the day continues to climb and imposes a gradual build-up of the pressure in the drum until peak operation is reached.

C. SUBSYSTEM RESEARCH EXPERIMENT

Receiver development has reached the 1 MW$_t$ level in the parallel "1 MW$_t$ Bench Model Cavity Receiver Steam Generator" program (ERDA San EY-76-C-03-1068) program. Testing sequences powered by both Infrared (IR) and solar energy were completed substantiating the design approach. The receiver for the subsystem research experiment was scaled up by a factor of 5 to the 5 MW$_t$ size, the agreed



(a) Pressures and Flow Rates

(b) Feedwater and Steam Temperatures

Figure V.B-4 Hot Start Up Temperature and Pressure Profiles for Commercial/Pilot-Plant Receiver on intermediate size needed prior to the pilot plant. The program was scoped around IR testing of necessity since the Solar Thermal Test Facility would not be available during Phase I. Sandia Laboratories radiant heat facility, site of the 1 MW_t receiver IR tests was an optimum site for the tests based on the prior experience, facility capacity, and proximity to the future solar test site. Photos of the SRE receiver installation are shown in Figure V.C-1.

The objectives of the test were to confirm thermal/hydraulic performance, structural design, and operation of controls and to simulate pilot plant operating transients, steady-state operation at design point and reduced loads, and steady-state operation at peak heat flux. The need for simulating the pilot plant receiver operating conditions resulted in the following basic requirements for the subsystem receiver experiment:

1. Delivery of steam at the same pressure and temperature as the PDBR pilot plant receiver.

2. A structural arrangement similar to that of the pilot plant receiver in critical zones.

3. Use of the same materials of construction

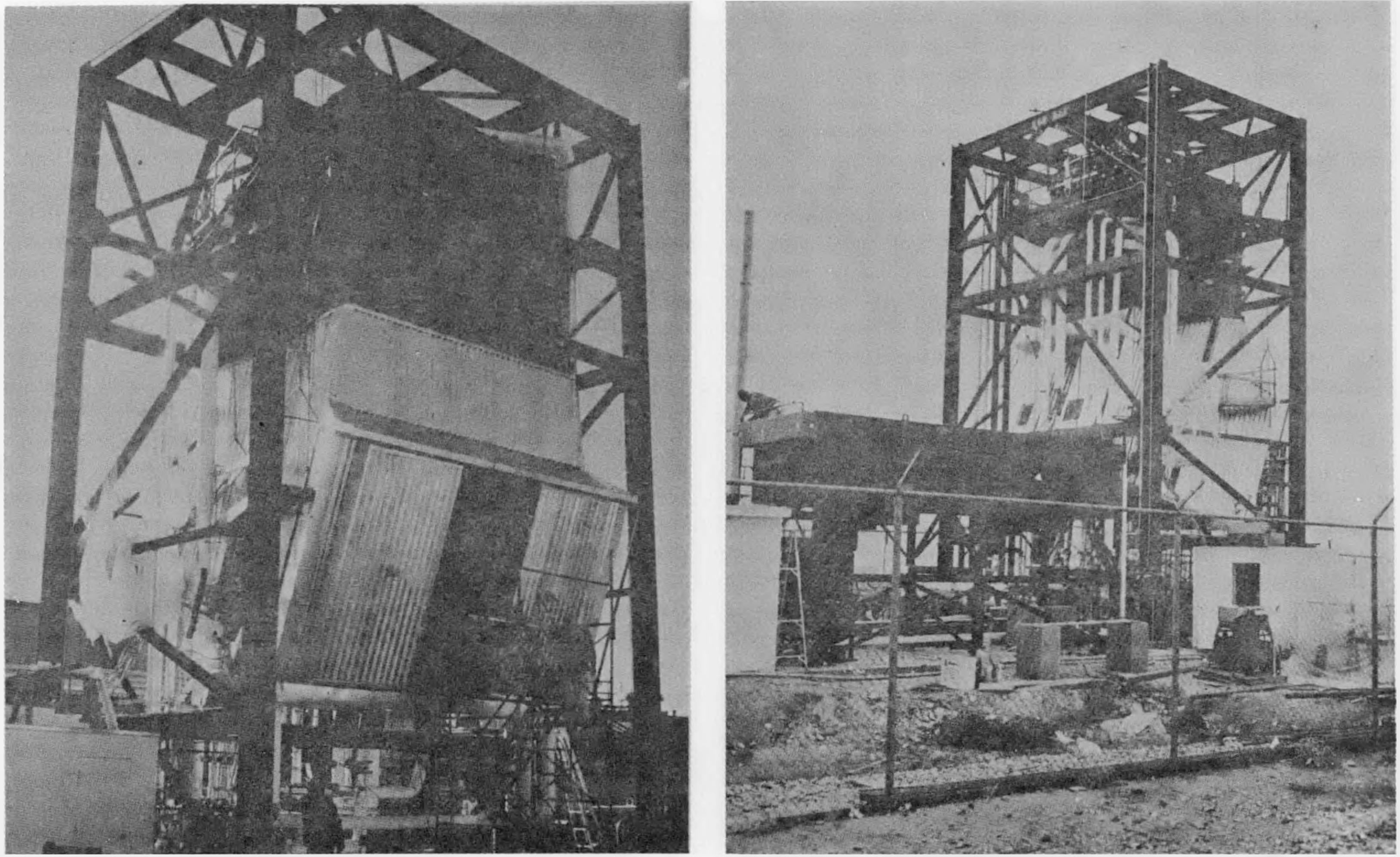
4. The distribution of absorbed heat flux with the same pattern over the heating surfaces as the preliminary design commercial and pilot plant receiver.

5. An experimental receiver subjected to start-up and other transients typical of those predicted for the pilot plant.

Schematically the SRE receiver is the same as the pilot plant (ref. V.B-1) except that the superheater has 16 passes instead of 6 and only a single attemperator. The SRE receiver is geometrically and structurally similar to the PDR pilot plant receiver in most respects. The superheater and boiler tubes are the same diameter as in the pilot plant receiver. Some exceptions are:

1. The length of the drum has been shortened in proportion to steaming capacity, while the drum diameter is the same.

2. There are 16 passes, rather than 6, in the superheater.



(a) Front View Showing Aperture Position and Doors

(b) Rear View Showing Drum Position, Downcomers, and Structure for Support on STTF Tower

Figure V.C-1 Subsystem Research Experiment Receiver Installed at Sandia Laboratories Radiant Heat Facility Albuquerque, New Mexico

Thermal/Hydraulic Design

The procedures used in the thermal/hydraulic design of the SRE receiver were the same as for the pilot plant receiver. The rated heat-flux condition was used as the basis for calculating the steady-state tube-wall and steam bulk temperatures. The superheater pressure drop, not including attemperators, was calculated as 896 kPa (130 psi) at the rated steam flow of 6559 kg/h (14,460 lb/h) and 1482 kPa (215 psi) at the maximum steam flow of 8760 kg/h (19,312 lb/h). Circulation characteristics of the SRE and pilot plant boilers were different because of the scaling criteria. The exit steam qualities predicted for the SRE receiver were lower than for the pilot plant receiver. Therefore, biasing of heat-flux distribution to obtain zones of high heat flux during receiver tests was required so that the extreme steam quality vs heat-flux-intensity condition expected for the pilot plant receiver could be simulated and tested in the SRE receiver. The outer panel of the left-hand-side boiler wall was chosen and designed for the purpose of this biased heat-flux test.

Field Erection

The receiver was erected at the Sandia Laboratories-Albuquerque test site by local craft labor under the supervision of a Foster-Wheeler Energy Corporation erection superintendent.

Foundations for the experimental receiver were poured in mid-June 1976, and the supporting steel for the receiver was erected on these foundations during the first week of July. The steam drum arrived at the site on July 19 and was immediately raised into position and secured. The waterwalls were then lifted into position after black radiation-absorbing paint had been applied to their heating surfaces. After erection of the waterwalls, the superheater panels (painted black on both sides along their heated length) were put in position in front of the waterwalls. Risers, feeders, and downcomers were then installed. When all pressure parts (drum, waterwalls, superheater panels, downcomers, feeders, risers, and superheater transfer lines) were in place, work began on the enclosure). After welding of the pressure parts was completed, the unit was ready for hydrostatic testing, which was performed on November 2. The remaining work consisted of completing the enclosure, installing insulation on the enclosure and exposed piping, and applying aluminum sheathing and lagging over the insulation. The boiler section of the receiver was given an alkaline wash and acid cleaning on November 17 and 18. Test instrumentation was installed as construction proceeded.

The receiver was constructed in conformance with the applicable sections of the ASME Boiler and Pressure Vessel Code as witnessed and certified by the National Board of Boiler and Pressure Vessel Inspectors.

Test Result Summary

The SRE receiver was subjected to a total of 19 test cycles, comprising over 112 hours of test time, and was brought to full temperature and pressure conditions on 6 of these tests. All the major test objectives were successfully demonstrated, including:

1. Demonstrated the proper thermal-hydraulic characteristics; all system-flow, circulation, and pressure-drop characteristics were confirmed during transient and steady-state operating modes.

2. Verified the structural design integrity; no major structural malfunction or failure occurred. The minor anomalies that did appear were all caused by improper installation.

3. Demonstrated the system operational controls capability; the receiver closed-loop control system performed satisfactorily throughout the hot-restart, cold-start, cloud-passage, and steady-state tests, including those at reduced power levels.

Table V.C-1 presents a tabulation of the radiant-heat tests performed and the significant operating parameters. Because of power-supply limitations, the maximum electrical input power was 4.35 MW. However, this power level was adequate to establish receiver operating characteristics and to provide a sufficient data sample to project the pressure loss and temperature differentials for full-power conditions. In addition, the pilot-plant and commercial receiver design and operating concepts have been successfully confirmed.

It is concluded that the radiant-heat testing demonstrated the capability of the SRE receiver to progress to solar testing, where full flux levels and rated output will be obtained.

Table V.C-1 SRE Test Condition Summary

Run No.	Date	Test Description	Duration, min.	Superheater Pressure, kPa (psig)	Outlet Temperature, K (°F)	Conditions Steam Flow Rate, Kg/h (lb/h)	Input Power, kW	Comments
---	2/01	Boiler Cleaning	140	103 (15)	389 (240)	136 (300)	420	IR cable overheating
---	2/02	Boiler Cleaning	470	690 (100)	442 (336)	375 (826)	842	IR cable overheating
---	2/03	Boiler Cleaning	750	690 (100)	442 (336)	363 (800)	760	
1	2/04	Trial Run - 690 kPa (100 psig)	210	103 (15)	389 (240)	136 (300)	420	
2	2/07	Trial Run - 3448 kPa (500 psig)	780	3448 (500)	569 (564)	1940 (4275)	1878	SCR overheating
3	2/10	Trial Run - 8964 kPa (1300 psig)	375	5034 (730)	557 (543)	726 (1600)	1148	Boiler tube leak
4A	2/14	Low-Temperature & Pressure Run	450	3965 (575)	647 (705)	1815 (4000)	2074	Attemperator control problem
4B	2/15	Low-Temperature & Pressure Run	420	3034 (440)	644 (700)	1815 (4000)	1981	IR cable overheating
5A	2/17	High-Temperature & Pressure Run	450	6895 (1000)	711 (820)	1815 (4000)	2052	Superheater thermowell plug leak
5B	2/18	High-Temperature & Pressure Run	540	9136 (1325)	715 (828)	2178 (4800)	2772	Gasket blowout
5C	2/19	High-Temperature & Pressure Run	785	2136 (1325)	789 (960)	3221 (7100)	3600	TCV control problems
6	2/21	Cold Start No. 1	440	9136 (1325)	790 (962)	3675 (8100)	4351	
7A	2/22	50% Power Run	60	9136 (1325)	773 (932)	2813 (6200)	3317	
7B	2/22	25% Power Run	20	9236 (1325)	716 (830)	910 (2005)	1741	
8	2/22	Cloud Passage No. 1	76	9136 (1325)	789 (960)	3267 (7200)	4050	
9	2/22	Cold Start No. 2	420	9136 (1325)	785 (954)	3176 (7000)	4000	
10A	2/23	Hot Restart No. 1	142	9136 (1325)	779 (943)	2677 (5900)	4000	Frozen FCV-1 valve control
10B	2/23	Hot Restart No. 2	53	8274 (1200)	758 (905)	2405 (5300)	3800	Pump relief valve leak
11	2/23	Cold Start No. 3	168	1048 (152)	615 (647)	1452 (3200)	2154	Surge-damaged power supplies

SUMMARY: Total Test Time: 112.5 hours
Total Test Cycles: 19
Total Cycles to Full Temperature and Pressure: 6

VI. THERMAL STORAGE SUBSYSTEM

The CRSTPS thermal storage concept utilizes sensible heat of commercial heat transport materials in an optimum economic, high performance two stage salt and oil configuration capable of dual mode charging and discharging operation.

The Thermal Storage Subsystem stores thermal energy in two stages operating at different temperature levels. The higher temperature stage stores steam's superheat energy as sensible heat in a heat transfer salt medium and the lower temperature stage stores the steam's latent heat energy and condensate sensible heat in a hydrocarbon oil storage medium. The system is designed to accept thermal energy in the form of superheated steam from the Receiver Subsystem, store the energy for a period of time up to 20 hours, then supply the stored energy to the Electric Power Generation Subsystem in the form of superheated steam for operation of a turbine.

A. Commercial Plant Thermal Storage Subsystem

The general site arrangement for the Commercial Plant is shown in Figure VI.A-1. The Thermal Storage Subsystem site is a triangular area between two heliostat fields. The major hardware components are:

1. Seven spherical, insulated oil storage tanks, 23.2 m (76 ft) in diameter,
2. Two spherical, insulated salt storage tanks, 15.8 m (52 ft) in diameter, and
3. Heat exchangers and other process equipment, dikes, roads, and water tanks for a fire protection system.
4. Controls for normal and fail-safe operation.

The Commercial Plant storage system is required to accept superheated steam that has been generated in the receiver, extract heat from this steam and store the heat for later use. This process is referred to as charging. Figure VI.A-2(a) shows a schematic of the 150 MWe Commercial Plant storage system charging loop. The superheated steam is introduced into a counter flow heat exchanger where it is used to raise the temperature of heat transfer salt received from a "cold" storage tank. The hot salt is then pumped

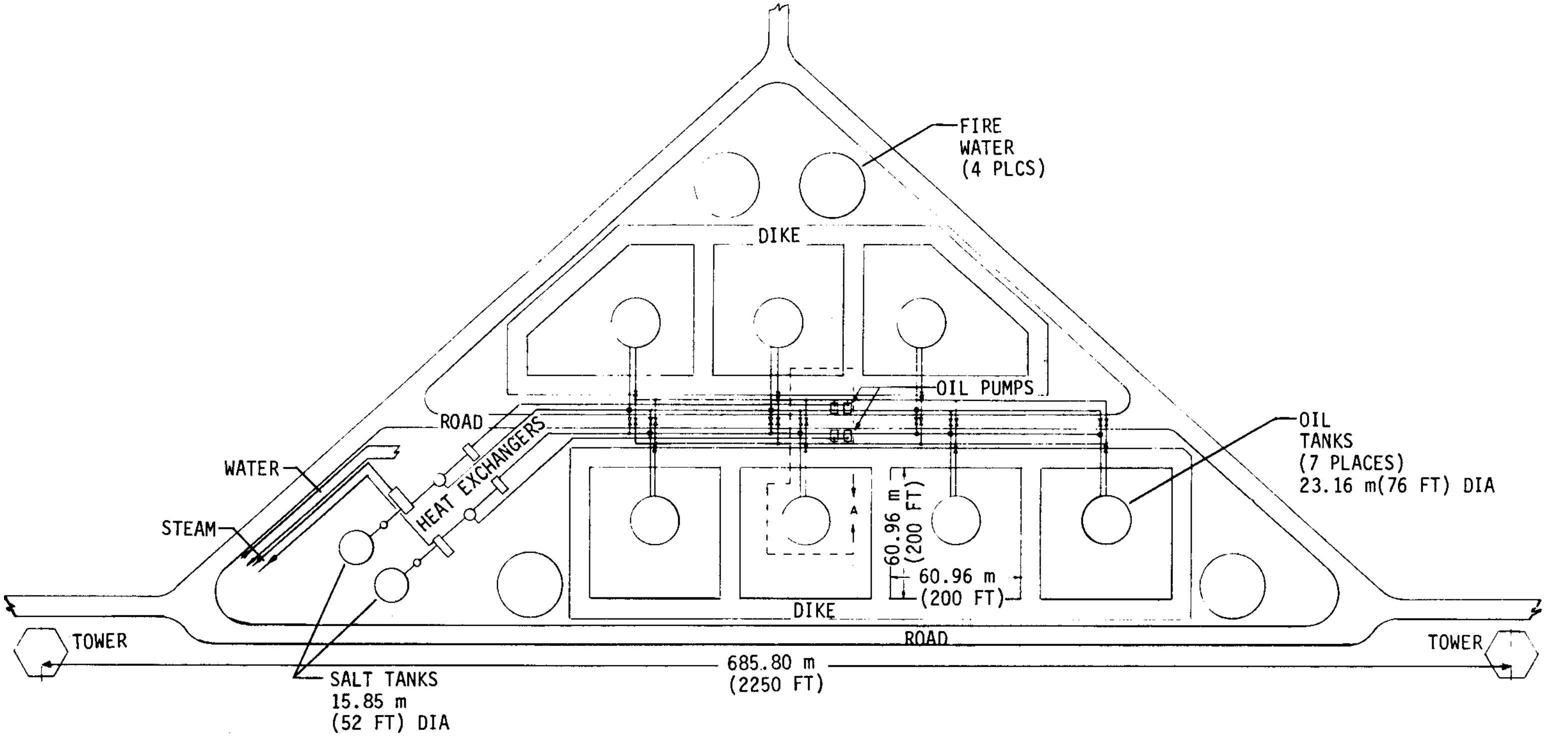
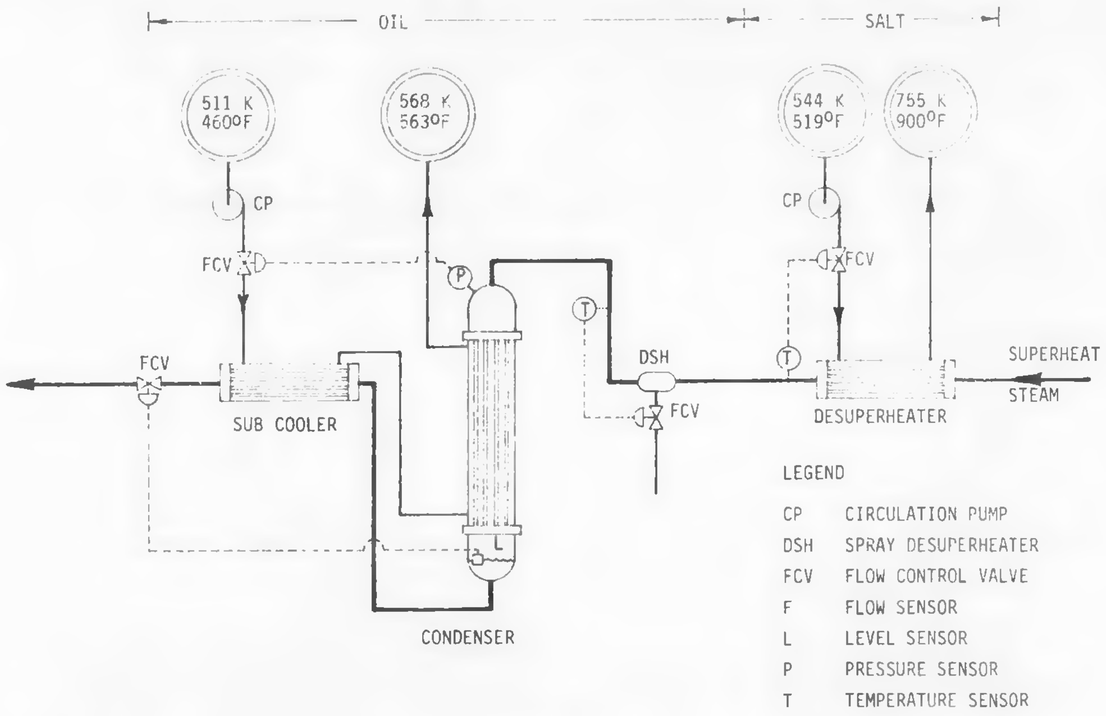
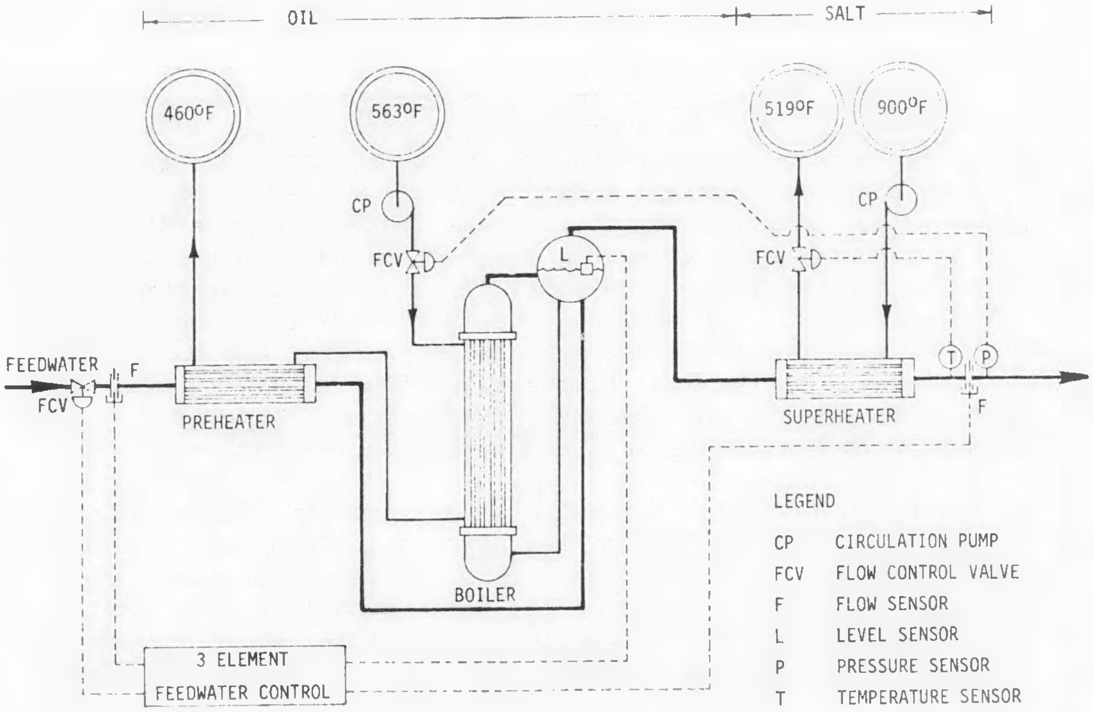


Figure VI.A-1 Commercial Plant Thermal Storage Subsystem Plot Plan



(a) Simplified Commercial Plant Charging Schematic.



(b) Simplified Commercial Plant Discharging Schematic.

Figure VI.A-2 Schematics of Thermal Storage System Charge and Discharge Operations to an insulated "hot" storage tank where it is stored for later use.

The steam leaving the salt heat exchanger is still slightly superheated. This steam enters a condenser where it is condensed by a hydrocarbon fluid (oil). The hot oil leaving the condenser is pumped to an insulated hot oil storage tank where it is stored for future use. The water that is leaving the condenser now enters a subcooler that subcools the water so that it can be pumped back into the receiver feedwater system.

The storage system must be capable of providing the turbine with superheated steam for the generation of electrical power. Figure VI.A-2b is a schematic of the commercial plant storage system with the discharge flow system emphasized. Feedwater is received from the EPGS. The feedwater then goes into the boiler where it is converted into steam. The heat for the boiling and the preheating comes from the oil that had been previously heated and stored in the insulated hot oil tank during charge. The oil that has given up its heat in the process of preheating and boiling the feedwater is pumped to the insulated "cold" storage tank where it is stored for the next charge cycle.

Saturated steam then leaves the boiler and enters a counter flow heat exchanger where it is superheated. The heat source for the superheating comes from the hot molten salt that had been stored during the previous charge cycle. The cold salt, after it has given up its heat to the steam, is pumped back to the insulated "cold" tank where it is stored for the next charge cycle. The bounding temperatures between the incoming charging steam and the exiting discharging steam shown in Figure VI.A-3 form the operating envelope within which the storage fluids must operate. The design goal of keeping the temperature "deltas" in the two modes of operation balanced in evident. In the low temperature stage the oil temperature curve runs diagonally through the operating envelope with a "pinch point" at the hot end on charging and cold end on discharging. In the high temperature stage the salt curve more nearly bisects the envelope which has a much broader temperature swing due to the nature of the superheating operation.

As stated in Table IA.-1 the design drivers for the two (2) stage oil-salt thermal storage configuration selection were performance and economics. The two stages achieved the performance, while the oil-salt combination achieved the best economics. The economics considerations has two components, the initial capital cost, and the make up or maintenance cost over the lifetime of the plant.

HITEC salt was selected for the high temperature stage due to its long history of steam generation heat transport and ability to

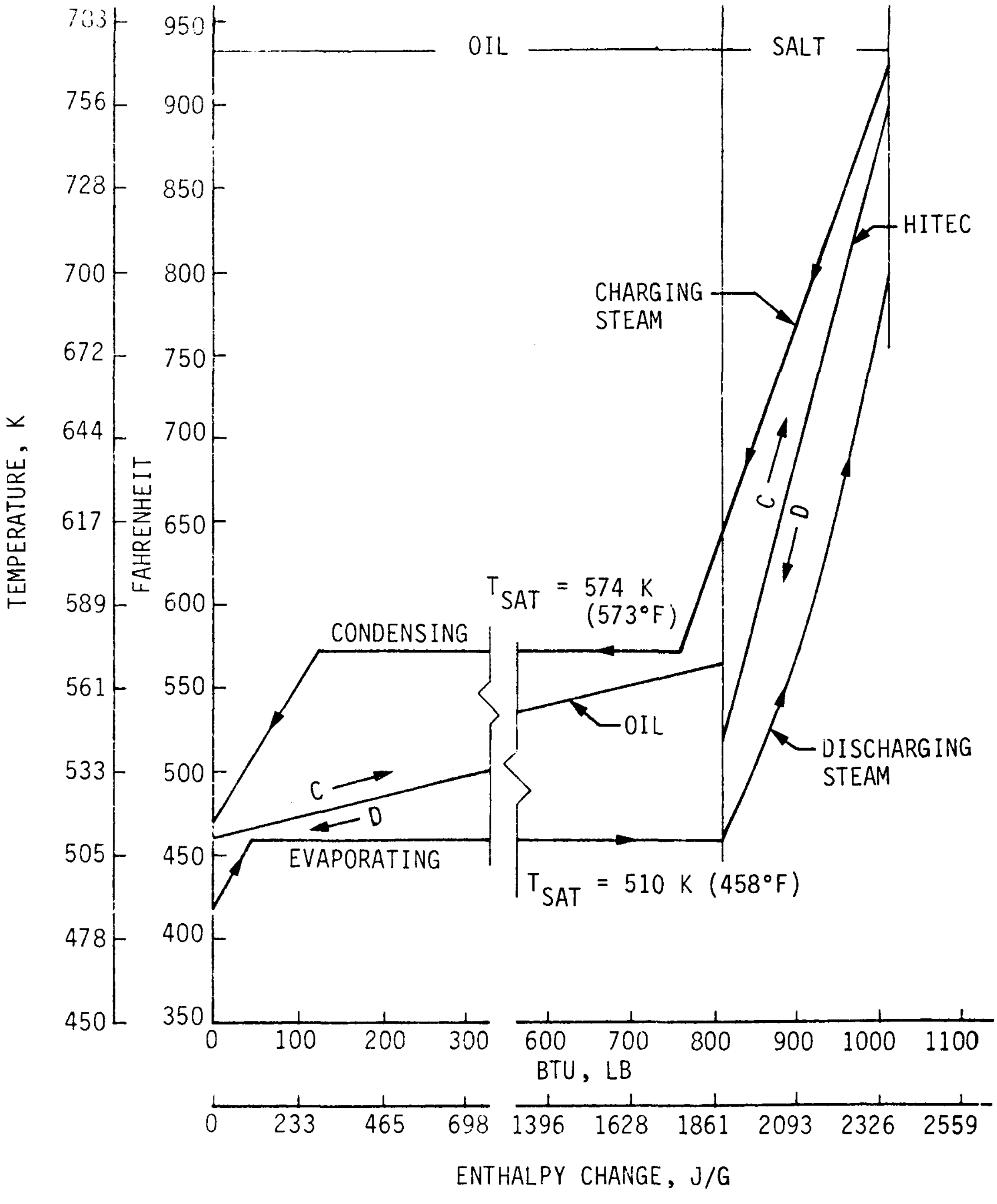


Figure VI.A-3 Commercial Plant Temperature Enthalpy Diagram.

operate in the required temperature range with very low decomposition. Nitrogen blanketing of the tanks has been introduced to assure the low decomposition.

Candidate fluids for the low temperature stage included hydrocarbon oils and HITEC salt. The oil decomposition rates of Figure IV.A-4 for the family of available oils illustrates the broad differences in performance attainable commercially. The inexpensive hydrocarbon oils Therminol 55 and Caloria HT 43, at \$264/M^3 (\$1.00/gallon) are the only ones less expensive than the salt. However, to keep the decomposition under control, side stream processing equipment has been added to the design, enabling the oil make-up to be held to 12 percent per year. This narrows the economic advantage of the oil over the salt and continued study of an all salt alternative configuration in the detail design phase is warranted.

Dual Mode operation, the ability to run the charge and discharge modes independently has been incorporated into the design, benefitting both economics, plant operational flexibility, and transient operation.

B. PILOT PLANT THERMAL STORAGE SUBSYSTEM

The Pilot Plant Thermal Storage System is a scaled down version of the Commercial Plant design. It incorporates the same low risk approach using the well understood sensible heat concept and commercially available industrial components.

Plant Layout

Figure IV.B-1 shows the general arrangement of equipment and piping for the Pilot Plant Thermal Storage Subsystem and their location with respect to the EPGS building and the receiver tower. Figure VI.B-2, is the detail schematic of the pilot plant thermal storage subsystem with the equipment used during the charge mode highlighted. The oil storage tanks are spherical, 17.7m (58 ft) in diameter, and are located 34 (113 ft) from the cylindrical salt tanks which are 5.8 m (19 ft) in diameter. The oil pumps are "full capacity" redundant for both the CHARGE and DISCHARGE circuits and are located near the respective oil tank and behind 1.83 m (6 ft) high dikes separating the oil tanks and pumps from the balance of the system. The side stream processor is located near the hot oil tank.

Salt is pumped using vertical shaft "cantilever" type pumps operating in small sump tanks located adjacent to the main salt storage tanks. All salt pipes and valves are steam traced with tubing elements operating between a trace steam supply pipe and a condensate return pipe as shown in detail "E" of this figure.

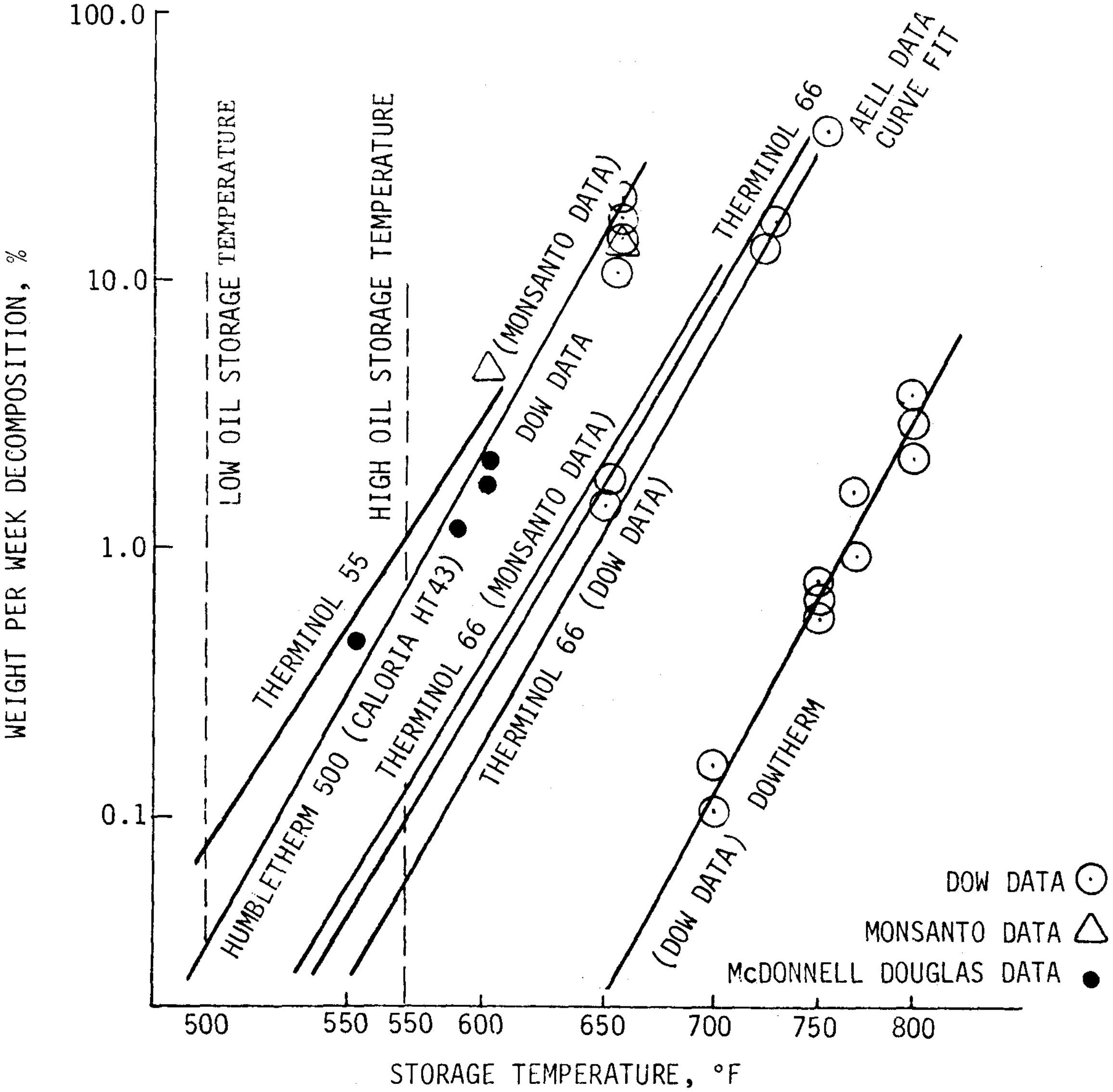


Figure VI.A-4 Oil Decomposition Rate Versus Temperature

This trace system is required to provide plant start-up and operational capability on the salt circuit.

The desuperheater and superheater are located at an elevation sufficient to insure draingage of condensate to the boiler and condenser, and to provide the capability to drain the salt back into the storage tanks, as shown in the pilot plant TSS elevation view of Figure VI.B-3. Heat exchangers are provided with rupture discs and safety catch tanks to contain the oil or salt in case of a steam tube rupture internal to the heat exchanger.

Gaseous nitrogen for tank ullage pressure and steam system purging is provided by a centrally located liquid nitrogen tank. The piping is configured to provide the necessary flexibility for the thermal expansion design requirements. Key features of the tanks and their installation are shown in Figure VI.B-4.

Performance of the thermal storage subsystem in terms of recovered energy during discharge divided by the energy input during charge is a function of plant size. Stair step performance profiles for the commercial plant thermal storage subsystem, efficiency = 0.963 and the pilot plant TSS, efficiency = 0.907, are shown in Figure VI.B-5. Of the three factors impacting the TSS performance, (1) the charge system loss, (2) the hold time loss, and (3) the discharge system loss, the most significant for both plants is the chage system loss.

C. THERMAL STORAGE RESEARCH EXPERIMENT

The principle objectives of the Thermal Storage Subsystem Research Experiment were to:

1. Build a small operating model of a thermal storage subsystem based on the conceptual design for the proposed storage subsystem for the commercial plant and the pilot plant,
2. Operate the scaled down system under steady state and transient conditions in order to demonstrate the feasibility of the storage concept,
3. Develop a better understanding of the requirements imposed on thermal storage in an electric power generating plant environment,
4. Gain experience in handling the proposed storage media,
5. Use the knowledge acquired from operating the Thermal Storage Subsystem Research Experiment to refine the preliminary design of the pilot plant and commercial plant Thermal Storage Subsystems.

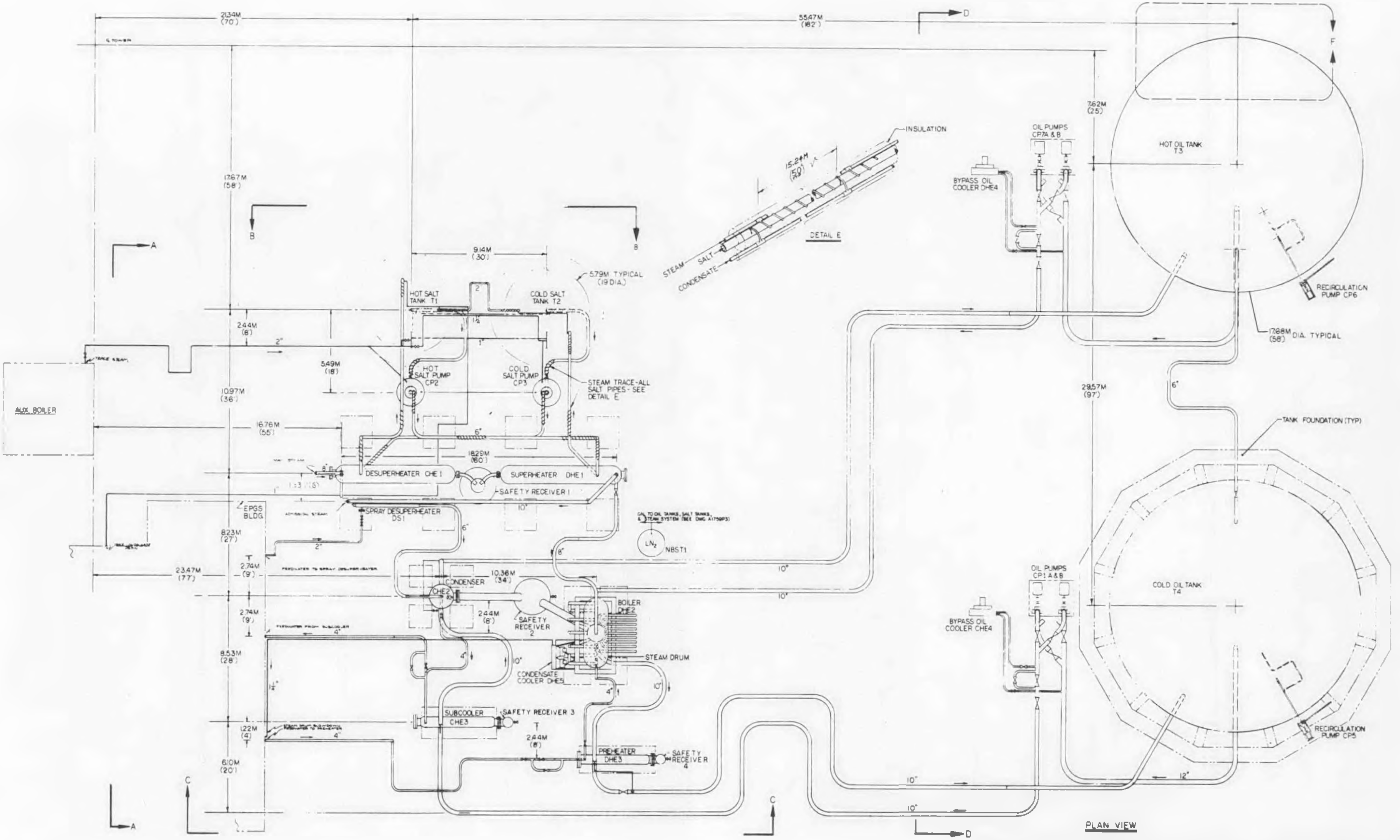
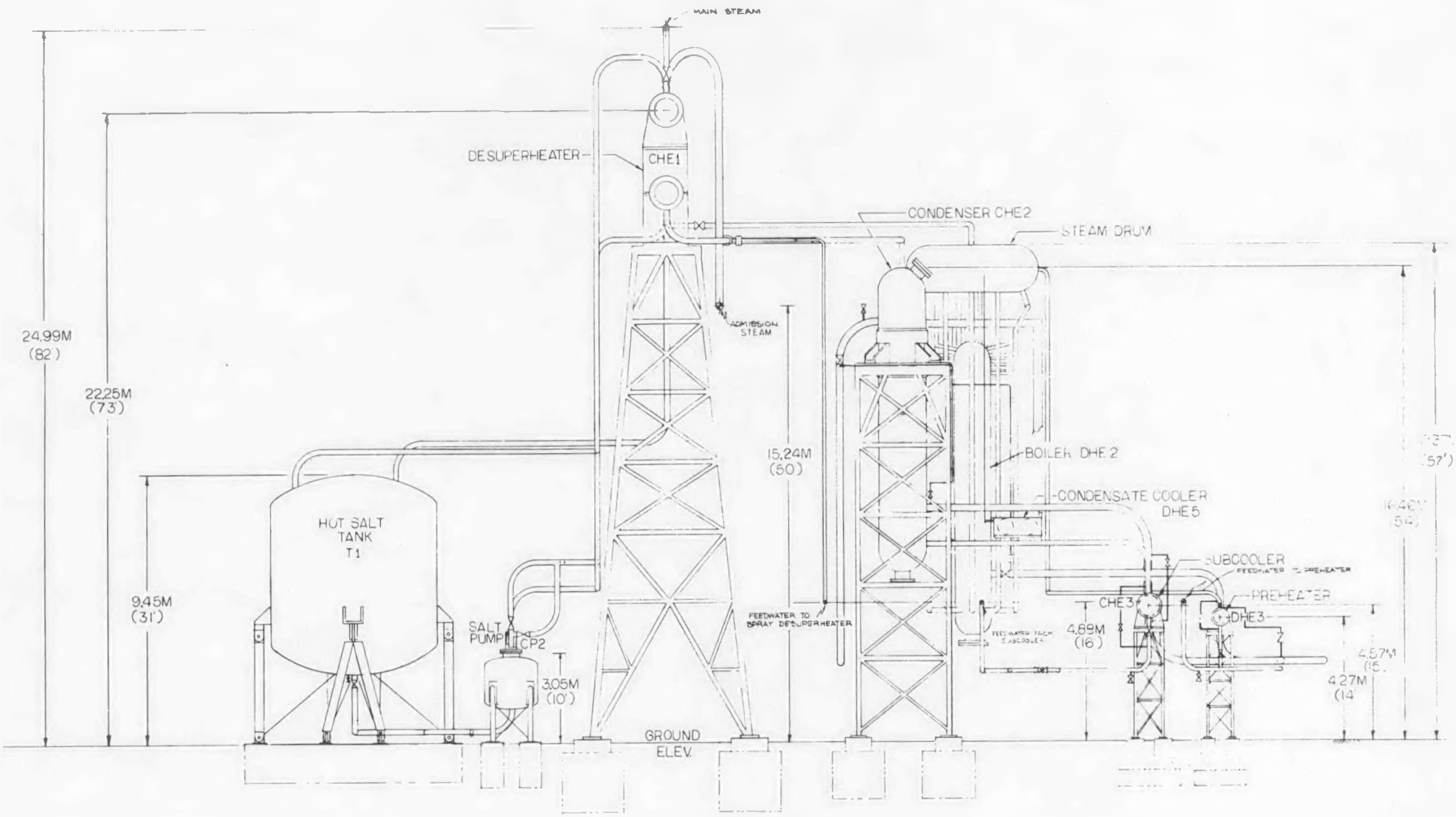


Figure VI.B-1 Pilot Plant Thermal Storage Subsystem Layout



VIEW A-A

Figure VI.B-3 Pilot Plant Elevation View Showing Heat Exchangers

LEGEND

BDV	BLOW DOWN VALVE	NCV	NITROGEN CHECK VALVE
BPFCV	BYPASS FLOW CONTROL VALVE	OCV	OIL CHECK VALVE
BV	BLEED VALVE	OFV	OIL FILL VALVE
CHE	CHARGE HEAT EXCHANGER	PR	PRESSURE REGULATOR
CP	CIRCULATION PUMP	PRD	PRESSURE RUPTURE DISC
DHE	DISCHARGE HEAT EXCHANGER	PS	PRESSURE SENSOR
DS	DESUPERHEATER	RV	RELIEF VALVE
DV	DRAIN VALVE	SFN	SALT FILL NOZZLE
FCV	FLOW CONTROL VALVE	SP	SIDESTREAM PROCESSOR
FRS	FLOW RATE SENSOR	SR	SAFETY RECEIVER
IV	ISOLATION VALVE	ST	STEAM TRAP
LCV	LEVEL CONTROL VALVE	T	TANK
LF	LINE FILTER	TEFWC	THREE ELEMENT FEEDWATER CONTROL
LLS	LIQUID LEVEL SENSOR	TS	TEMPERATURE SENSOR
NBST	NITROGEN BLANKET STORAGE TANK	VRV	VACUUM RELIEF VALVE

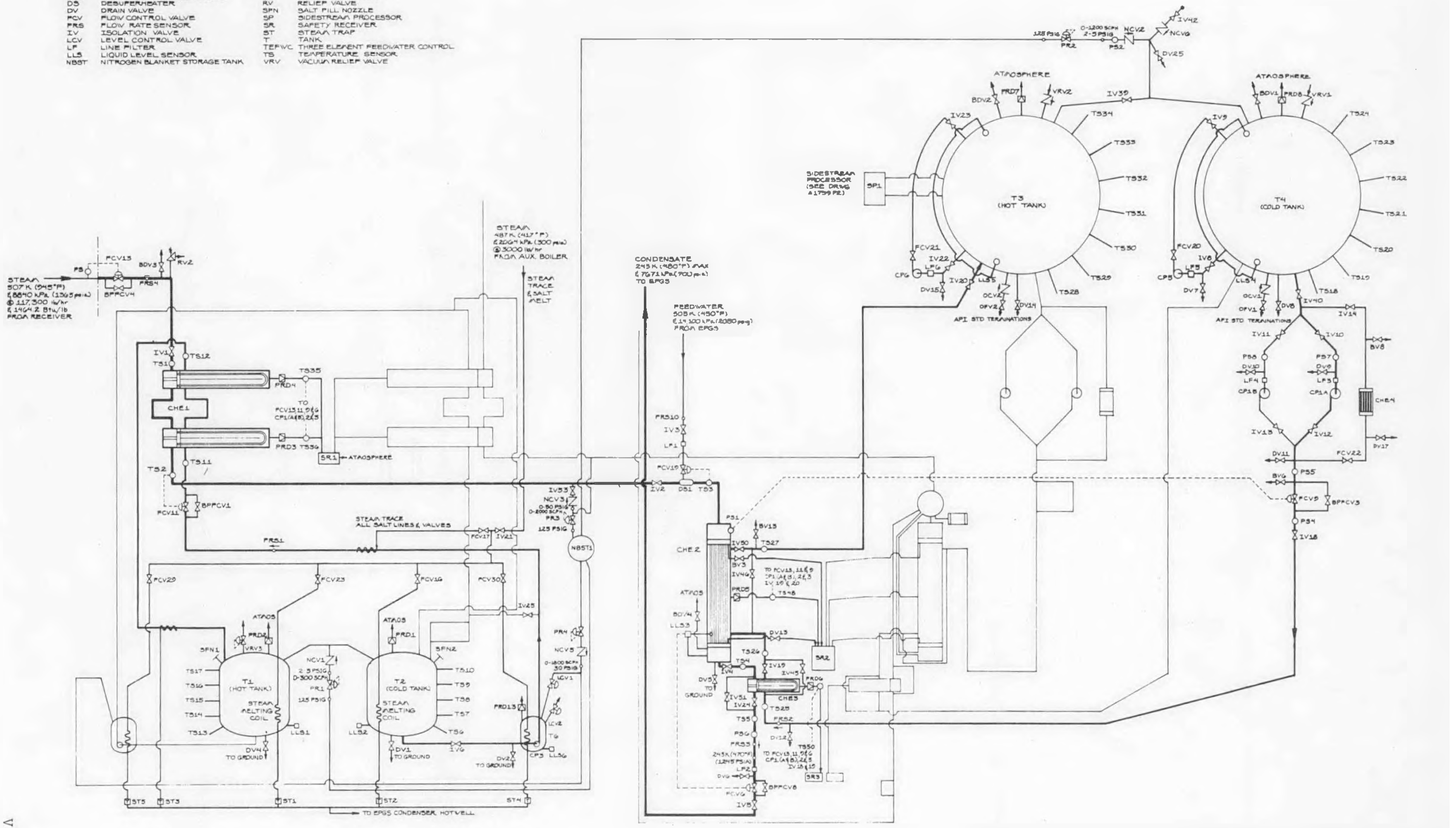


Figure VI.B-2 Pilot Plant Charge Mode Detail Schematic

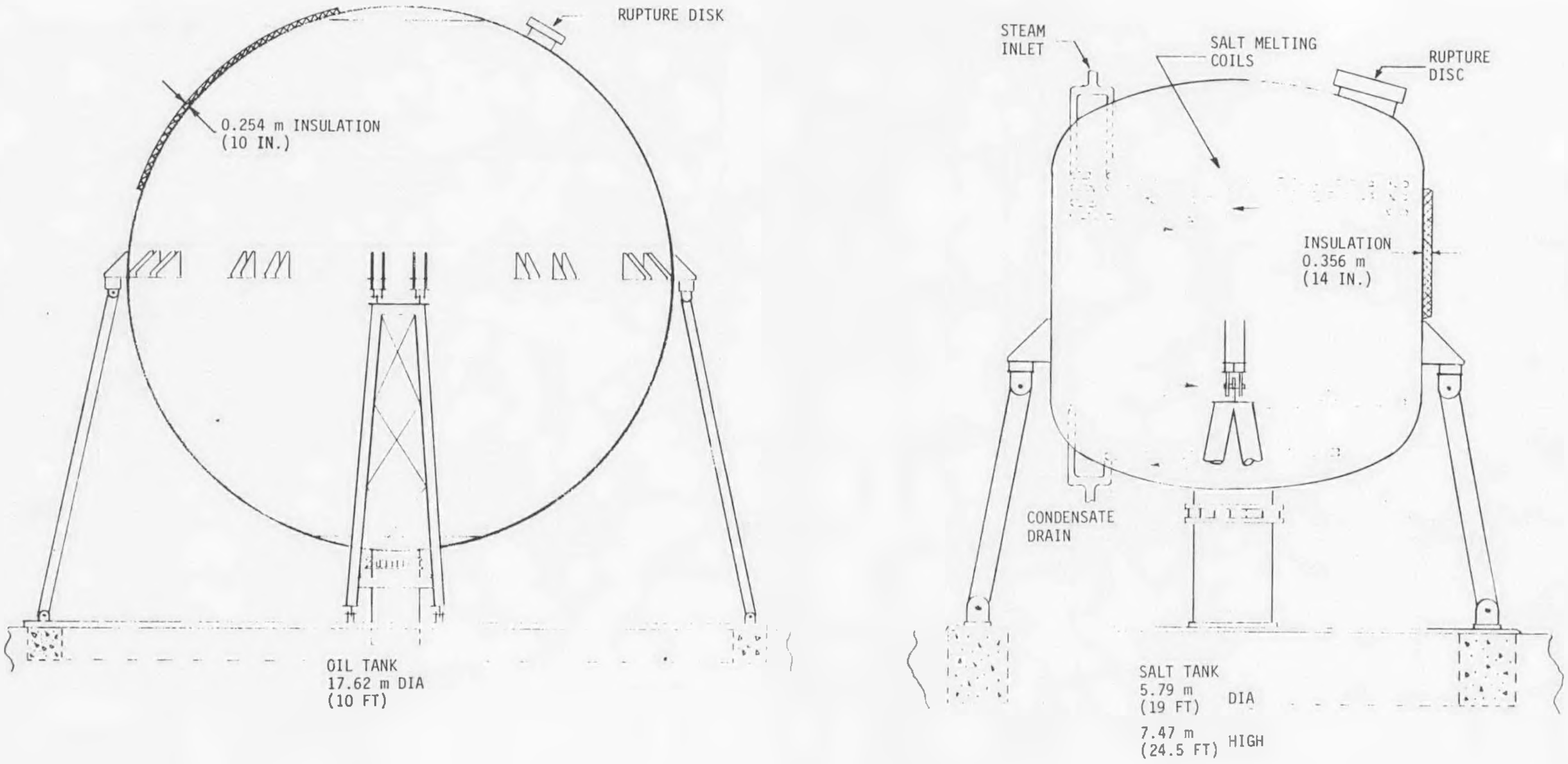
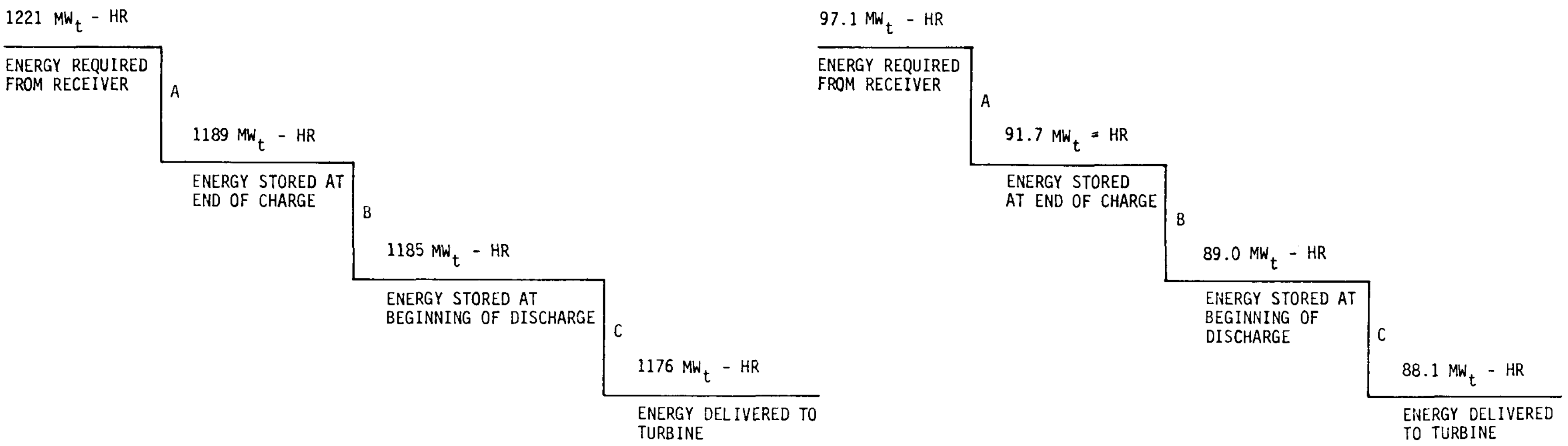


Figure VI.B-4 Pilot Plant Storage Tanks Elevation View



FUNCTION	EFF
A = CHARGE SYSTEM DIURNAL HEAT LOSS	0.974
B = HOLD LOSS (3 HOURS ASSUMED)	0.997
C = DISCHARGE SYSTEM DIURNAL HEAT LOSS	0.992
THERMAL STORAGE SUBSYSTEM	0.963

(A) Commercial Plant Thermal Storage Subsystem

FUNCTION	EFF
A = CHARGE SYSTEM DIURNAL HEAT LOSS	0.944
B = HOLD LOSS (20 HOURS ASSUMED)	0.971
C = DISCHARGE SYSTEM DIURNAL HEAT LOSS	0.990
THERMAL STORAGE SUBSYSTEM	0.907

(B) Pilot Plant Thermal Storage Subsystem

Figure VI.B-5 Thermal Storage Subsystem Stair Step Performance Profiles

All of these objectives were satisfied during the Research Experiment program. This Research Experiment was a complete storage system which contained all of the major components of the proposed pilot plant and commercial plant thermal storage subsystems, and performed all of the operations that will be required of storage in the pilot and commercial plants. Because all of the elements of the storage system have been designed, built and successfully operated, their performance in the pilot and commercial plants can be realistically evaluated and predicted.

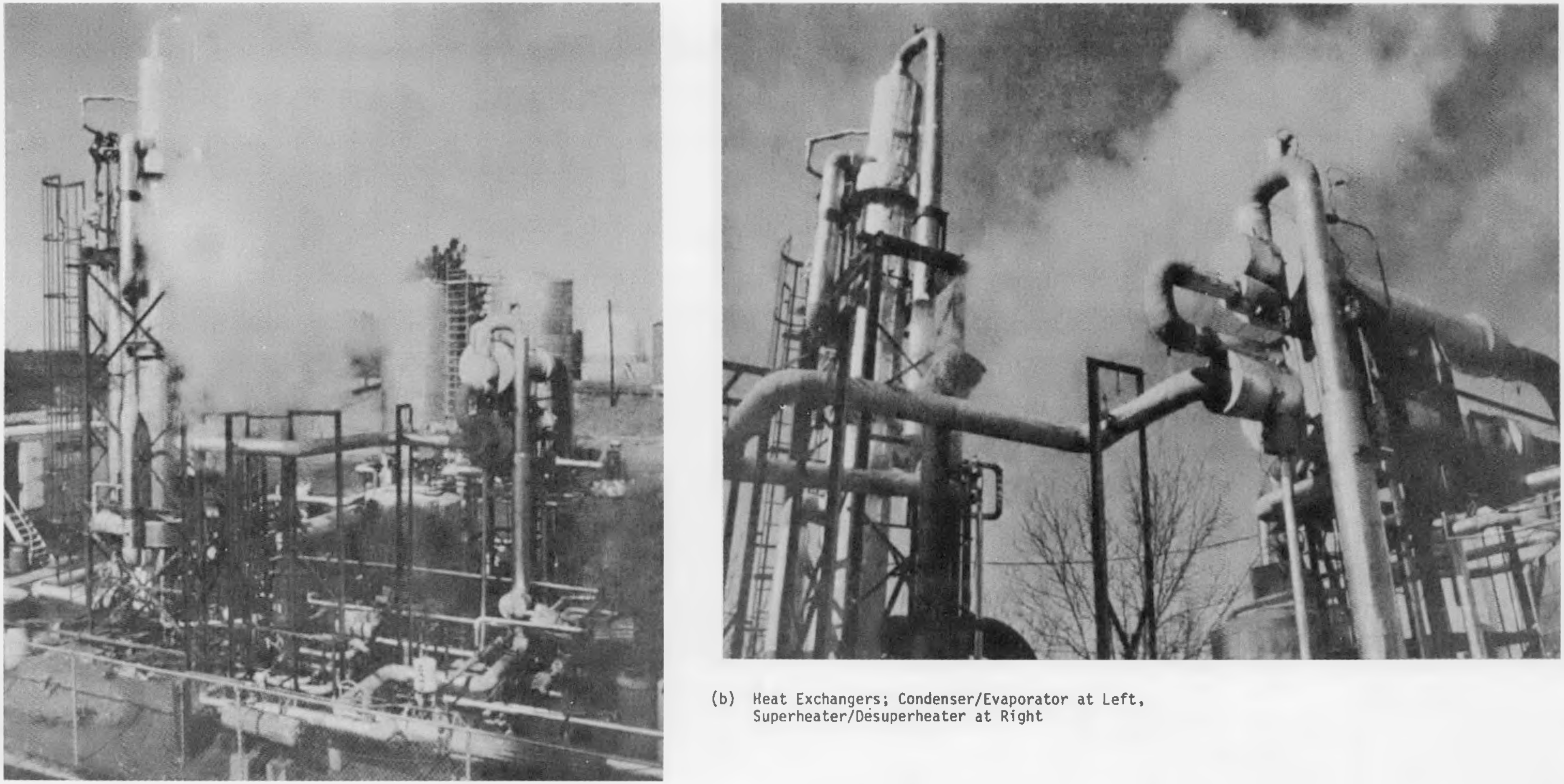
Figure VI.C-1 shows the overall installation of the experiment installed by Georgia Institute of Technology at the Newnan, Georgia plant of the Georgia Power Compnay in view (a). At the time of the photo, the experiment was in a discharging mode, generating steam from the heated storage fluids. View (b) shows the two major heat exchangers during the same operation. Steam is discharging from the silencer of the experiment.

In accordance with the design established in the "preliminary baseline" design phase of the program, the TSS of the subsystem research experiment WAS REVERSIBLE. In the high temperature stage a single heat exchanger provided both superheating and de-superheating. In the low temperature stage the same unit was both a boiler and a condenser. Turn around time associated with reversing was approximately 25 minutes. As stated earlier the reversible feature is not planned for the larger plants, being replaced with the dual mode equipment.

In the SRE tests, the two stage concept of thermal storage was validated. The storage system was stable and predictable in its operation throughout the entire test program. The thermal capacity of the research experiment was larger than the 1.6 MW_t-hr that was specified at the beginning of the program. The addition capacity was due to the performance of the condenser-evaporator heat exchanger, which consistently produced a larger temperature change in the oil than the minimum design value. The most thermal energy stored in a single charging operation was 2.83 MWhr-t and the least was 2.23 MWhr-t. The maximum amount of thermal energy discharged from storage during a single complete discharge was 2.12 MWhr-t and the minimum was 1.24 MWhr-t.

Table VI.C-1 lists the 31 test runs, describing the operational mode or sequence, the steam flows and the thermal equivalents of the steam flows.

The amount of heat stored in, and extracted from storage during the tests was calculated. For charge tests, the heat put into the salt and oil was calculated by using the steady state temperatures and flow rates from the heat balance and the length



(a) Installation Overview

(b) Heat Exchangers; Condenser/Evaporator at Left, Superheater/Desuperheater at Right

Figure VI.C-1 Thermal Storage Subsystem Research Experiment Installation at Georgia Power Co, Newnan, Georgia, during Discharge Steam Generator Test Cycle.

Table VI.C-1 Log of Thermal Storage Subsystem Research Experiment Demonstration Tests

Test No.	Test Description	Steam Flow Rate				Rate of Heat Transfer Charge/Discharge	
		Charge		Discharge			
		kg/hr	(lb/hr)	kg/hr	(lb/hr)	kW	kW
1	Initial Charge of Complete System at Full Rate	2953	6510			2622	
2	Initial Discharge of Complete System at Full Rate			2858	6300		1302
3	Charge of System at Constant Rate	2722	6000			2084	
4	Discharge of System at Constant Rate			1996	4400		1395
5	Charge of System at Constant Rate	2989	6590			3215	
6	Discharge of System at Constant Rate			2295	5060		965
7	Charge of System at Constant Rate	3402	7500			2637	
8	Discharge of System at Constant Rate			1832	4040		1209
9	Charge of System at Constant Rate	3130	6900			2328	
10	Discharge of System at Constant Rate			2236	4930		2130
11	Charge of System at Constant Rate	953	2100			2199	
12	Recharge of System at Constant Rate	1878	4140			--	
13	Discharge of System at Constant Rate			2019	4450		1506
14	Charge of System at Constant Rate	3221	7100			2792	
15	Discharge of System at Constant Rate			2932	6465		1444
16	Charge of System at Constant Rate	3243	7150			2239	
17	Discharge of System at Constant Rate			2817	6210		1948
18	Charge of System at Constant Rate	2740	6040			3385	
19	Discharge of System at Constant Rate			2132	4700		952
20	Charge of System at Constant Rate	3266	7200			2859	
21	Discharge of System at Constant Rate			2900	6570		1542
22	Charge of System at Constant Rate	2794	6160			3064	
23	Discharge of System at Constant Rate			3084	6800		1660
24	Transient Charge of System	980 to 3266	2160 to 7200			1078 to 1191	
25	Transient Discharge of System						1825
26	Charge of System at Constant Rate	3452	7610			2768	
27	Discharge of System at Constant Rate			2449	5400		1585
28	Charge of System at Constant Rate	3493	7700			2429	
29	Transient Discharge of System			695 to 1538	1532 to 3390		890 to 1028
30	Transient Charge of System	881 to 2023	1942 to 4460			668 to 1469	
31	Discharge of System at Constant Rate			4273	9420		2590

of time each fluid was pumped at that rate. For discharge tests, the heat taken out of the salt and oil and put into steam was again calculated from the heat balance steady state properties and flow rates, and the time each fluid was pumped. During charging test number 9, the total amount of thermal energy stored was 2.369 MWhr-t (8,086,000 BTU) with 0.430 MWhr-t (1,468,000 BTU) going into the salt and 1.939 MWhr-t (6,618,200 BTU) going into the oil. During the following discharge, test number 10, a total of 2.120 MWhr-t (7,234,000 BTU) was recovered from storage with 1.855 MWhr-t (6,332,500 BTU) coming from the oil and 0.265 MWhr-t (901,500 BTU) coming from the salt. The ratio of the total heat extracted from storage to the total heat put into storage was 0.895.

The sequence of demonstration tests that were conducted at the Research Experiment site included operations that were equivalent to all of the functions (steady state and transient) required of the Thermal Storage Subsystem in the Pilot and the Commercial Plants. The experience gained in the test program therefore permits a realistic evaluation of the operating procedures and the Research Experiment system components: tanks, heat exchanger, pumps, controls. This experience is reflected in the Pilot and Commercial Plant designs.

VII. ELECTRIC POWER GENERATION SUBSYSTEM

The CRSTPS electric power generation subsystem designs are centered around commercially available turbine-generators having the highest performance consistent with long life operation in the solar power application. The dual admission turbine is uniquely suited, being capable of operating from receiver or storage steam.

A. COMMERCIAL CRSTPS ELECTRICAL POWER GENERATION SUBSYSTEM

Electrical Power Generation Subsystem (EPGS) for the commercial plant consists of a single turbine/generator set, feedwater pumping and conditioning equipment, condenser, wet cooling towers, steam and water piping, and the necessary valves, control elements and auxiliary equipment for subsystem operation. Figure VII.A-1 shows the triangular area within the plant plot plan where most of these components are located, and the general arrangement of installations in this area. Six cooling tower units are shown in the southeast corner of the plot plan, consistent with generally westerly or northwesterly prevailing wind conditions. The location of the cooling towers and the location of the EPGS triangle may require changes to optimize the site arrangement for other prevailing wind conditions. It is required to place the cooling towers downwind of the heliostat fields to minimize deposition of fallout water droplets from the cooling tower plumes, and to locate the towers to avoid significant shadowing of heliostats by cold weather (visible) plume conditions, and absorption of incoming insolation.

The turbine/generator set is located on an open air deck, supported by an isolated, concrete pedestal foundation/support structure. Ancillary equipment, including five (5) feedwater heaters, is installed in a multi-level enclosed structure adjacent to the turbine deck. Another adjacent building contains the central control equipment.

EPGS Turbine

The turbine selected for the commercial plant application is a General Electric admission type unit, rated at 160 MWe output, and commercially available with minor modifications to the basic design. The 160 MWe standard size closely matches that required to supply 150 MWe plus the plant auxiliary loads.

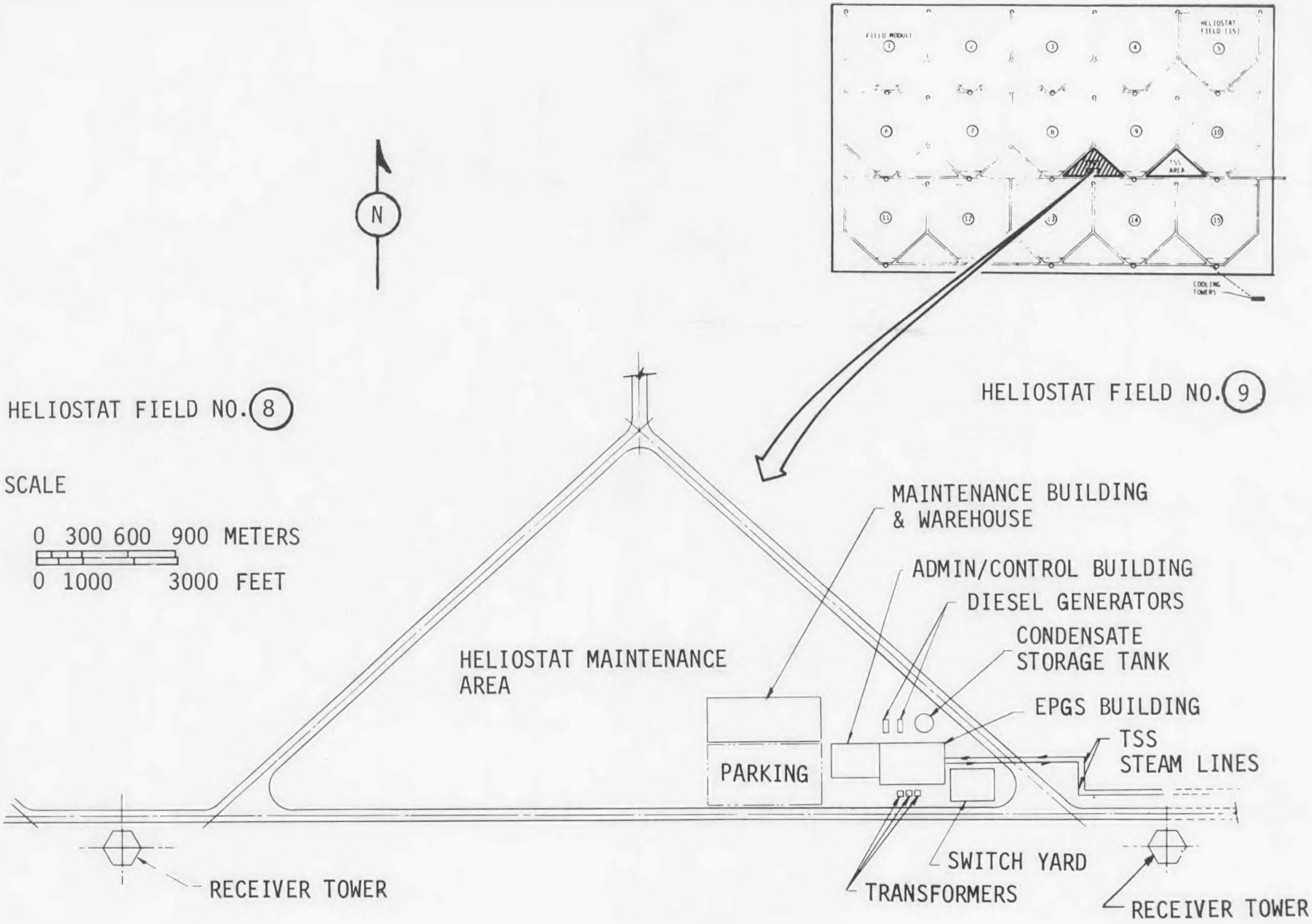


Figure VII.A-1 Electrical Power Generation System

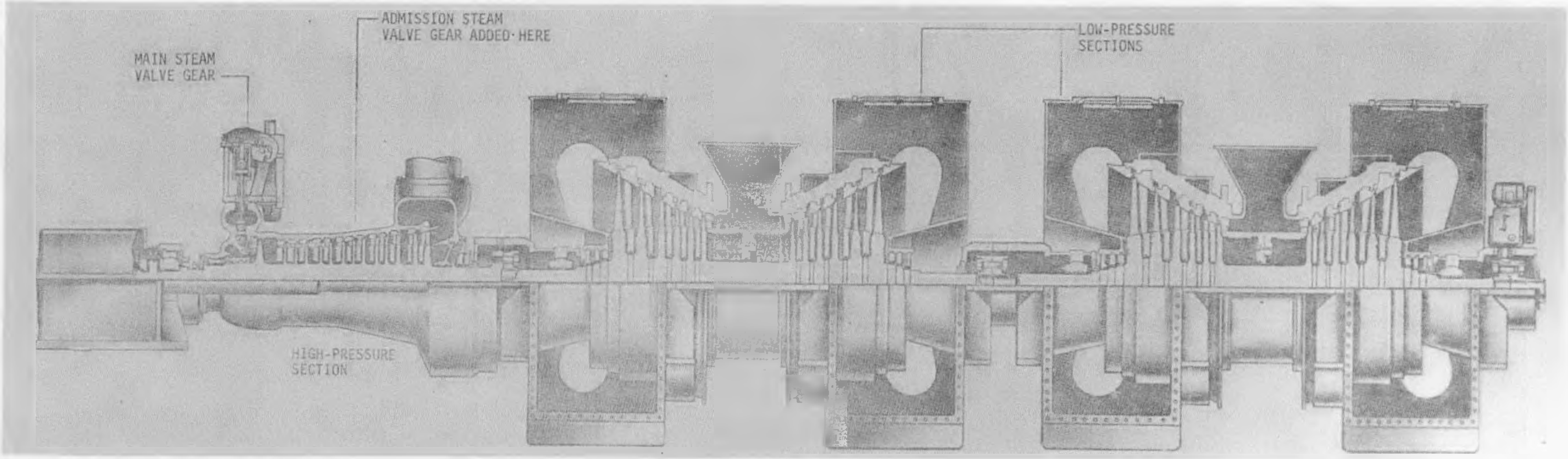
Figure VII.A-2 shows a cross section of a typical unit of this size and type. It is technically described as an automatic extraction, non-reheat, tandem compound, four flow unit. The single flow, high pressure section on the left is in tandem with two parallel, double flow, low pressure sections on the right. The general area where internal admission valve gear will be added to the high pressure section is indicated in the figure. This admission port improves operating efficiency at reduced loads when operating on thermal storage steam. Under these lower temperature/pressure conditions, steam is admitted several stages downstream of the main stream admission point. Extraction nozzles will be provided downstream of the admission valve gear in the turbine casing to supply steam for use in feedwater heating and conditioning.

B. PILOT PLANT ELECTRICAL POWER GENERATION SUBSYSTEM (EPGS) DESCRIPTION

EPGS General Arrangement

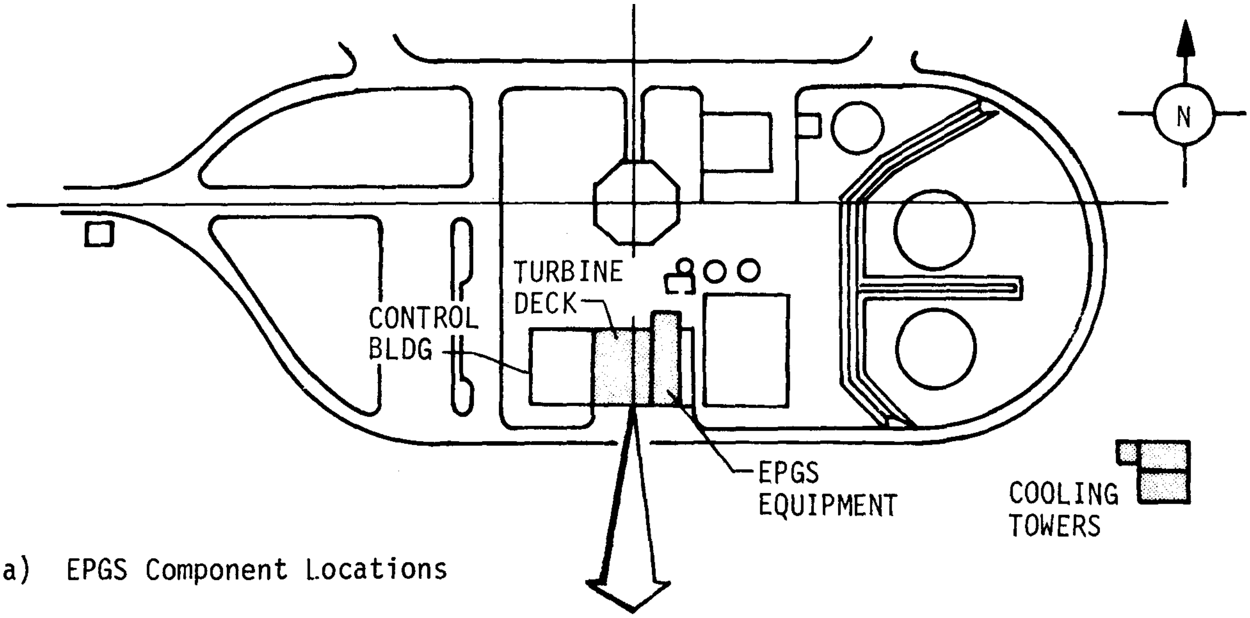
The EPGS for the pilot plant includes the turbine-generator set, feedwater pumping and conditioning equipment, condenser, wet cooling tower, steam and water piping, and the necessary valves and control elements for subsystem operation. Figure VII.B-1(a) shows the general locations of the EPGS major components. An elevation detail of the EPGS building is shown in view (b). The turbine-generator set is located on an open air deck, supported by an isolated, pedestal, concrete foundation/support structure. Ancillary equipment, including feedwater pumps and four (4) feedwater heaters, is installed in an adjacent, three-level building, east of the turbine deck. External siding, where used, is 18 ga. corrugated steel with a pre-finished protective surface.

Cooling water for the condenser is piped to and from a two unit wet (evaporative) cooling tower, located approximately 180 m (600 ft.) east of the condenser. The location of the cooling tower was chosen in conjunction with Barstow, California wind data to place it downwind of the heliostat field for the large majority of the time. Water droplet fallout from the cooling tower plume onto the mirror surfaces is thus avoided during prevailing wind conditions by cooling tower positioning. Fallout deposition during unusual wind conditions is minimized by cooling tower design (to reduce water droplets in the plume), and by the 168 m (550 ft.) separation distance to the nearest heliostat. The cooling tower location is also acceptable when considering the adverse shadowing effects on heliostats during cold weather conditions, when a visible plume could significantly attenuate insolation.

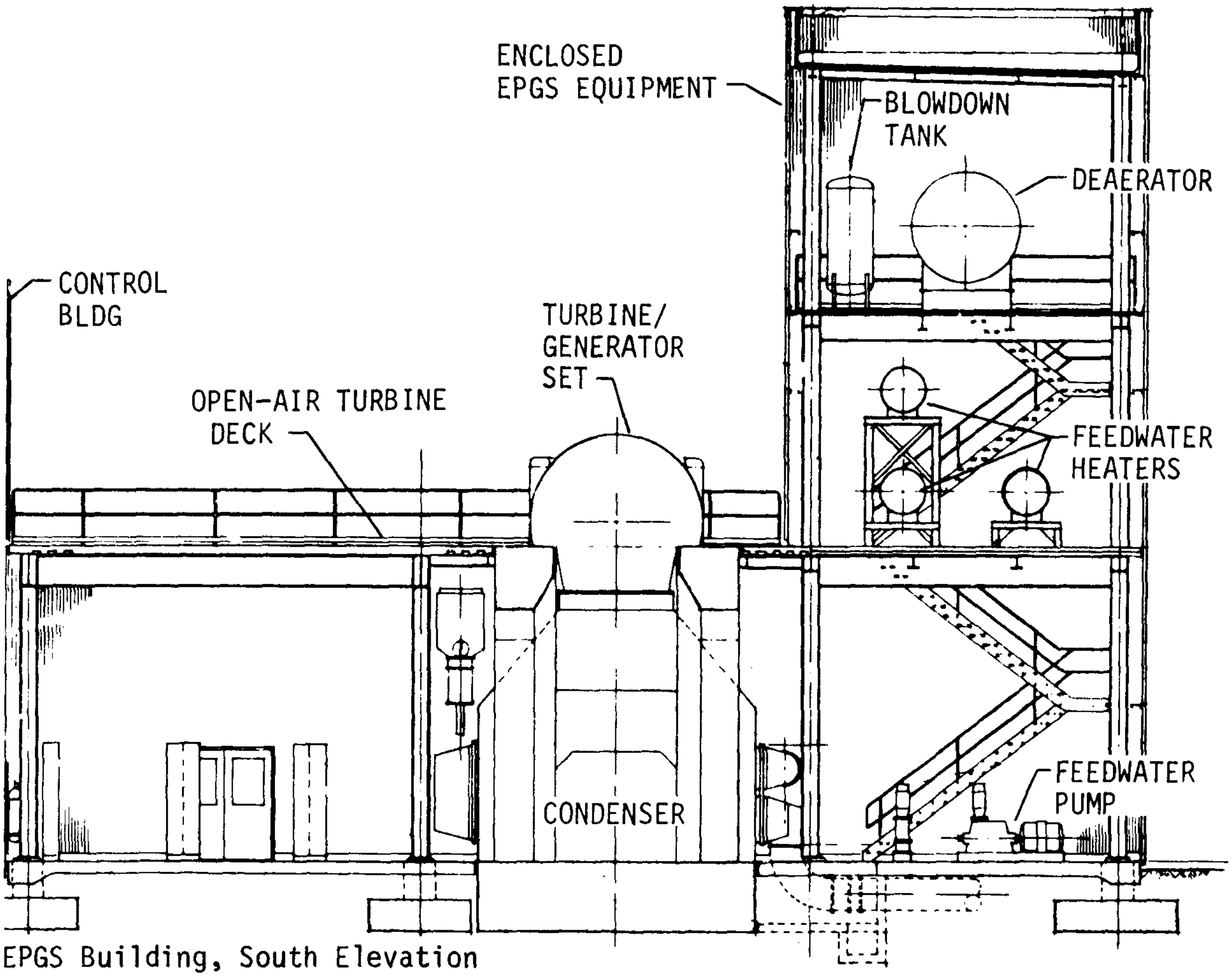


Courtesy of General Electric Co.

Figure VII.A-2 Typical 160MW$_e$ Turbine



(a) EPGS Component Locations



(b) EPGS Building, South Elevation

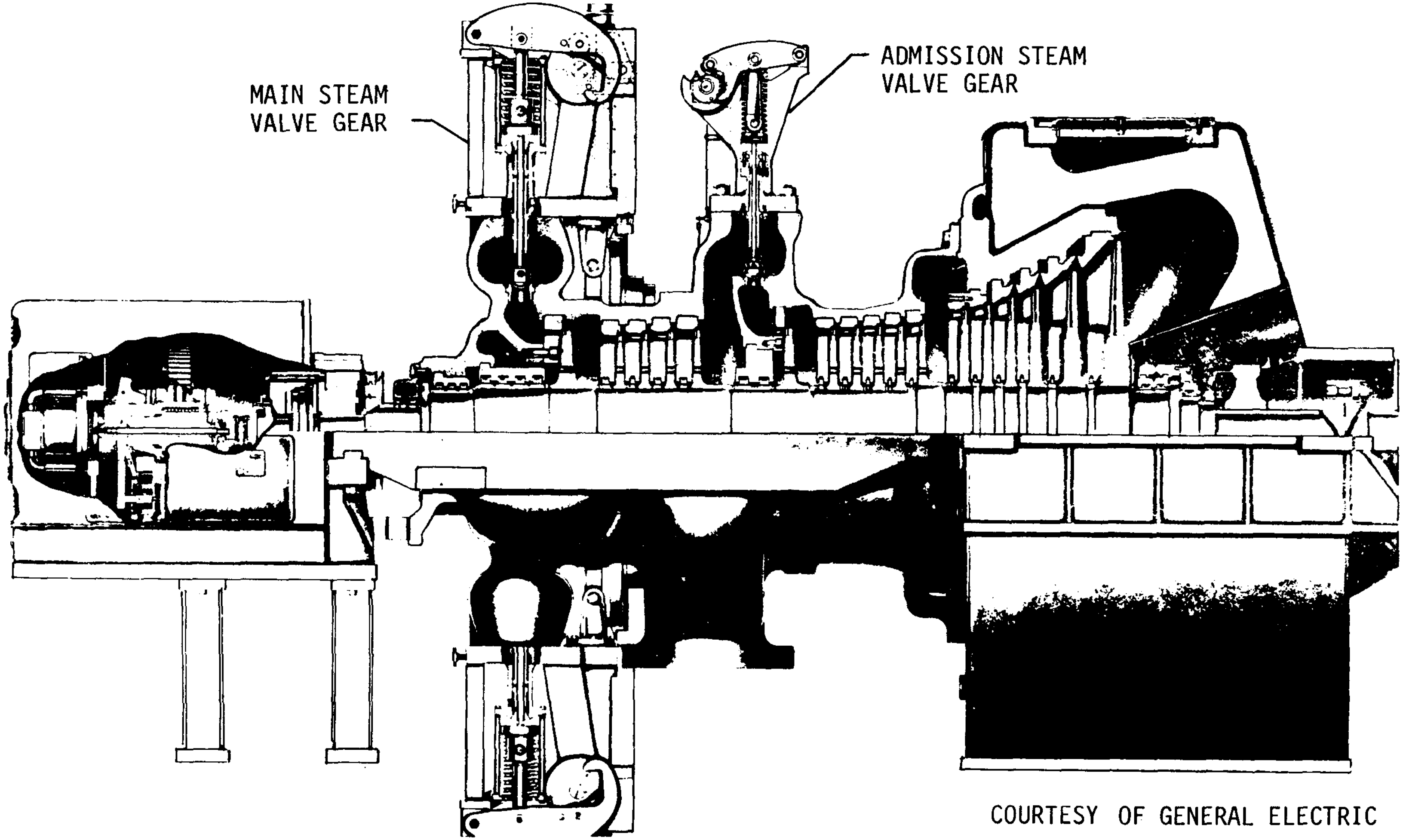
Figure VII.B-1 Pilot Plant EPGS Arrangement

2. EPGS Turbine

The turbine selected for the Pilot Plant application is a General Electric admission type unit, rated at 12.5 MWe output, and commercially available with only minor modifications required to the basic design. Figure VII.B-2 shows a cross section of a typical unit of this size and type. It is a single flow, non-reheat configuration with an electrohydraulic control system operating partial arc control valves at both the main and admission steam inlets.

The 12.5 MWe standard size closely matches that required to supply the specified 10 MWe net, plus the plant auxiliary loads. The admission port improves operating efficiency at reduced loads from thermal storage steam. Under these lower temperature/pressure conditions, steam is admitted four stages downstream of the main steam admission point.

Four conventional uncontrolled extraction points will be provided downstream of the admission valve gear in the turbine casing for use in feedwater heating and conditioning.



COURTESY OF GENERAL ELECTRIC

Figure VII.B-2 12.5 MW Pilot Plant Turbine

VIII. MASTER CONTROL SUBSYSTEM

The CRSTPS master control concept has been configured to utilize hands-on control of hard wired logic subsystem controls in accordance with advice received from utility personnel.

As in a conventional power plant, operation of the solar thermal pilot plant will be carried out by the control operators. The operators are assisted in this important function by the pilot plant master control system (MCS). The MCS is modeled after a typical control system in a fossil fuel power plant, and design of the controls is strongly influenced by several discussions with power plant control operators. The MCS is a system which is simple, is user oriented, and is a system which employs state of the art hardwired control logic. The master control system is comprised of the subsystems controls, the plant control system element, and the data handling system. The rationale for the general design of the master control system stems from the character of the pilot plant itself and its operating characteristics. By industry standards, the plant is small (10 MWe), and elaborate controls are not required.

A. MASTER CONTROL SYSTEM FEATURES

The MCS enables the control operators to safely control plant operations. Features of this master control system are:

> Controls are maximized within subsystems, and subsystem control is essentially autonomous.
>
> The MCS has emergency control capability to respond immediately to subsystem alarm conditions (subsystem control elements), and to initiate a response to system level alarm conditions.
>
> The MCS provides a capability to coordinate system level operations by control through subsystem control elements, and the plant control subsystem.
>
> Integrated pilot plant operations are accomplished by manually implementing written procedures which define operational profiles and sequences for steady state mode control and for transition between modes.

Subsystem Controls

To the maximum extent possible, plant control capabilities reside within the subsystem controls, and these controls are integrated by a system level control element designated the plant control system (PCS). Subsystem controls perform the majority of the plant control functions inasmuch as these controls have been designed to maintain stable operations over the wide range of conditions expected during a plant's daily operational cycle. The receiver subsystem (RS), thermal storage subsystem (TSS), and electrical power generation subsystem (EPGS) controls are all implemented with conventional hardwired logic and controllers. The heliostats are controlled by a minicomputer, and that control represents the only computer controlled element of the pilot plant. Because of the critical nature of heliostat control, the collector subsystem control minicomputer is backed up by the data handling system (DHS) minicomputer.

Plant Control System (PCS)

The PCS coordinates the subsystem controls and provides a system level emergency response capability to the operators. Specifically, the PCS is a plant control element whose major functions are to:

Implement certain system level emergency actions automatically and provide control operators with the capability to manually command certain system level emergency actions;

Display subsystem alarm status;

Provide control operators with the capability to enable or disable certain major subsystem functions during operational sequencing;

Provide control operators with the capability to establish plant control configurations --

Configure emergency action logic,

Set data acquisition rates,

Display plant mode or mode transition status

Physically the plant control system element is similar to a subsystem's controls but simpler in appearance and functions. The PCS is housed in an electronics rack, the panels of which contain displays of plant alarm status and displays of the current mode in which the plant is operating (or the modes between which the plant is transitioning). The panel also contains a sequencing section with switches which enable or disable appropriate subsystem functions. Perhaps the most important PCS panel contains the system level emergency action controls.

MCS Definition

Figure VIII.A-1 is a simplified schematic showing major control elements of the pilot plant and defining the MCS as those elements within the heavy dashed lines. In this figure, "boxes" represent functional elements of the plant; for example, "TSS" represents the entire thermal storage field hardware, and "TSS control" represents the TSS control logic.

The MCS encompasses all subsystem control elements, the PCS as well as the data handling and data logging functions. It should be emphasized that the data handling system has been designed to be completely independent of the controls. That is, if the DHS were removed, the plant control activities would continue analtered.

The Control Room Philosophy

The basic philosophy underlying the master control system design is that absolute control of the plant is in the hands of the control operators. To understand how this philosophy is implemented, consider the control room environment and specifically the control console layout. Reference is made to the set of subsystems' controls and PCS as the control console, and the design considers each segment of the console to be a more-or-less free standing rack of controls; the racks are assembled side by side to form the console. The CS segment will consist of a video (CRT) display with keyboard and a teletypewriter nearby. The RS, PCS, EPGS, and TSS console segments follow, in that order, with the PCS and EPGS control segments being contiguous and centrally located, a reflection of their criticality in the plant operation. Each of the subsystem control segments will contain displays and control devices to accomplish essentially autonomous operation of that subsystem to the degree the subsystem can be so operated. The PCS segment will provide system level displays and control capability to the operators.

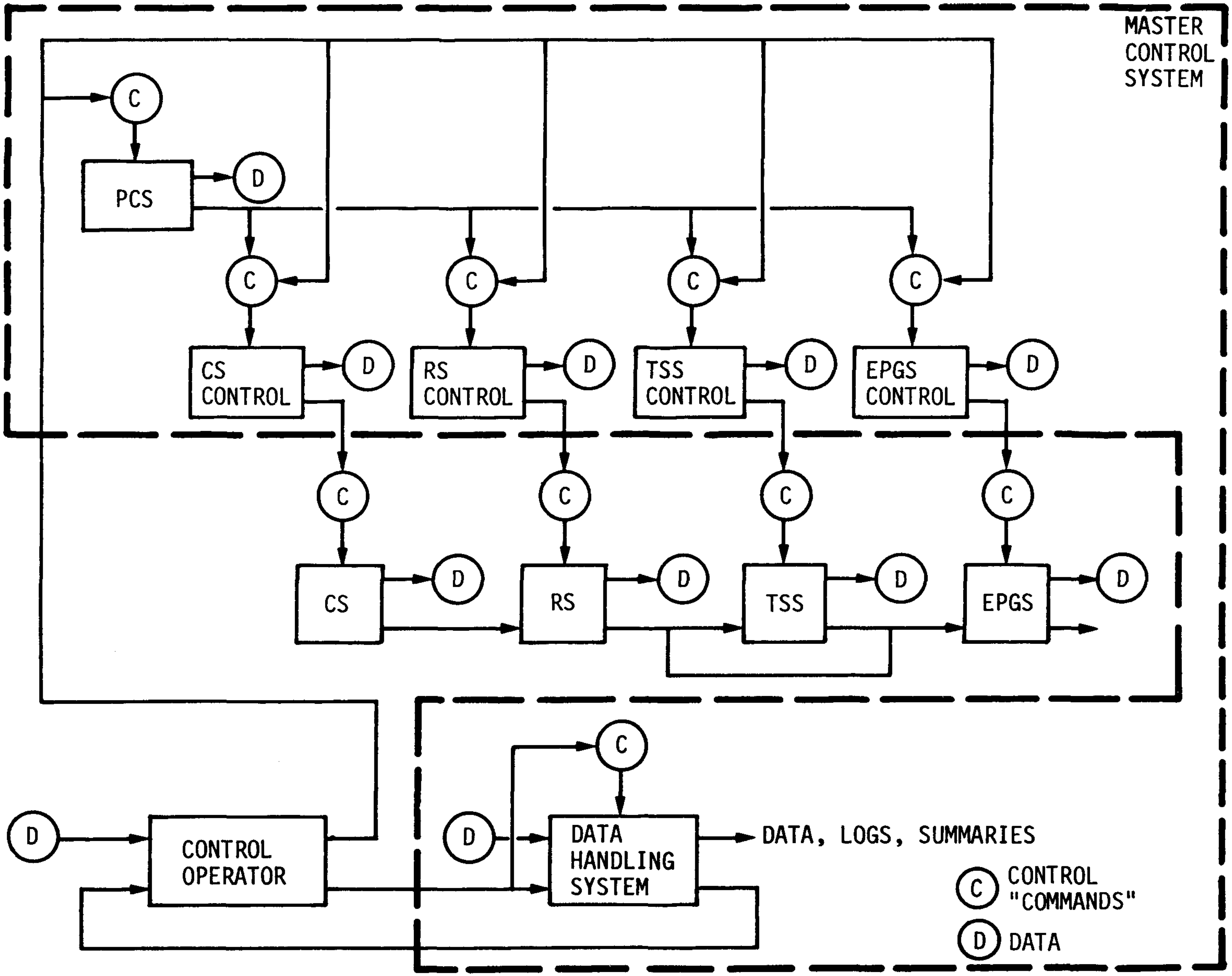


Figure VIII.A-1 Pilot Plant Schematic Defining Master Control System

Operational Cycles, Modes and Mode Transitions

Aside from the energy source for a solar plant, the predominate characteristic which distinguishes a solar power plant from a conventional power plant is the solar plant's diurnal operational cycle as contrasted to the more or less constant operation of a conventional plant. The solar plant goes through a daily set of operations:

- startup
- normal operations (including)
  - charge mode

Maintenance will be accomplished in parallel or after plant shutdown. A normal operational cycle involves getting the plant into one of several "steady state" modes and causing the plant to change from one mode to another. As an example consider Figure VIII.A-2 which schematically depicts the power output from a single daily operational cycle. The "C", "R", "T", and "E" represent the collector, receiver, thermal storage and electrical power generation subsystems respectively. To accomplish the power output the plant will be configured in different steady state modes during the cycle.

These characteristics of steady state mode control, and transitions between modes are fundamental to the plants' control design. In fact the total capability of the plant can be defined in terms of six steady state modes and transitions between these modes. Figure VIII.A-3 lists the eight modes, seven of which are active modes representing various configurations in which the plant can be operated, and Mode VIII which is the passive overnight mode. The master control system is capable of controlling the plant in any of the modes and accomplishing transitions between them. It is anticipated, however, that for normal operations, only a few of the eight modes will be used.

Data Handling

A major portion of the pilot plant's data handling will be implemented using a minicomputer with disc mass storage capabilities. This approach recognizes the capabilities of digital computer systems to handle efficiently moderate to large quantities of data generated by the solar thermal pilot plant in a cost effective manner. In addition to using the digital computer, some of the plant's data display and "logging" will be accomplished using the strip chart or other pen recorders.

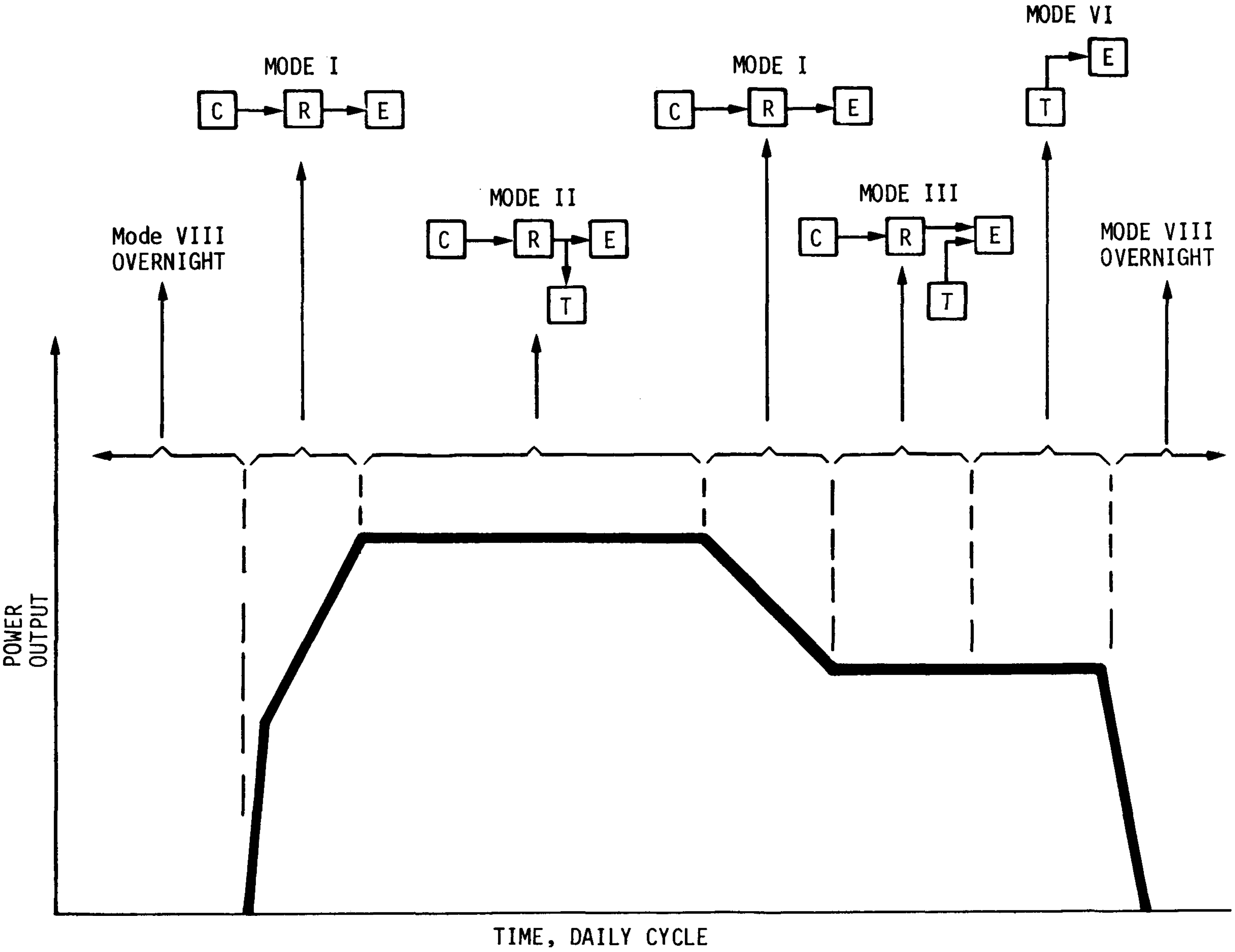


Figure VIII.A-2 Schematic Representation of Operational Modes During a Daily Cycle

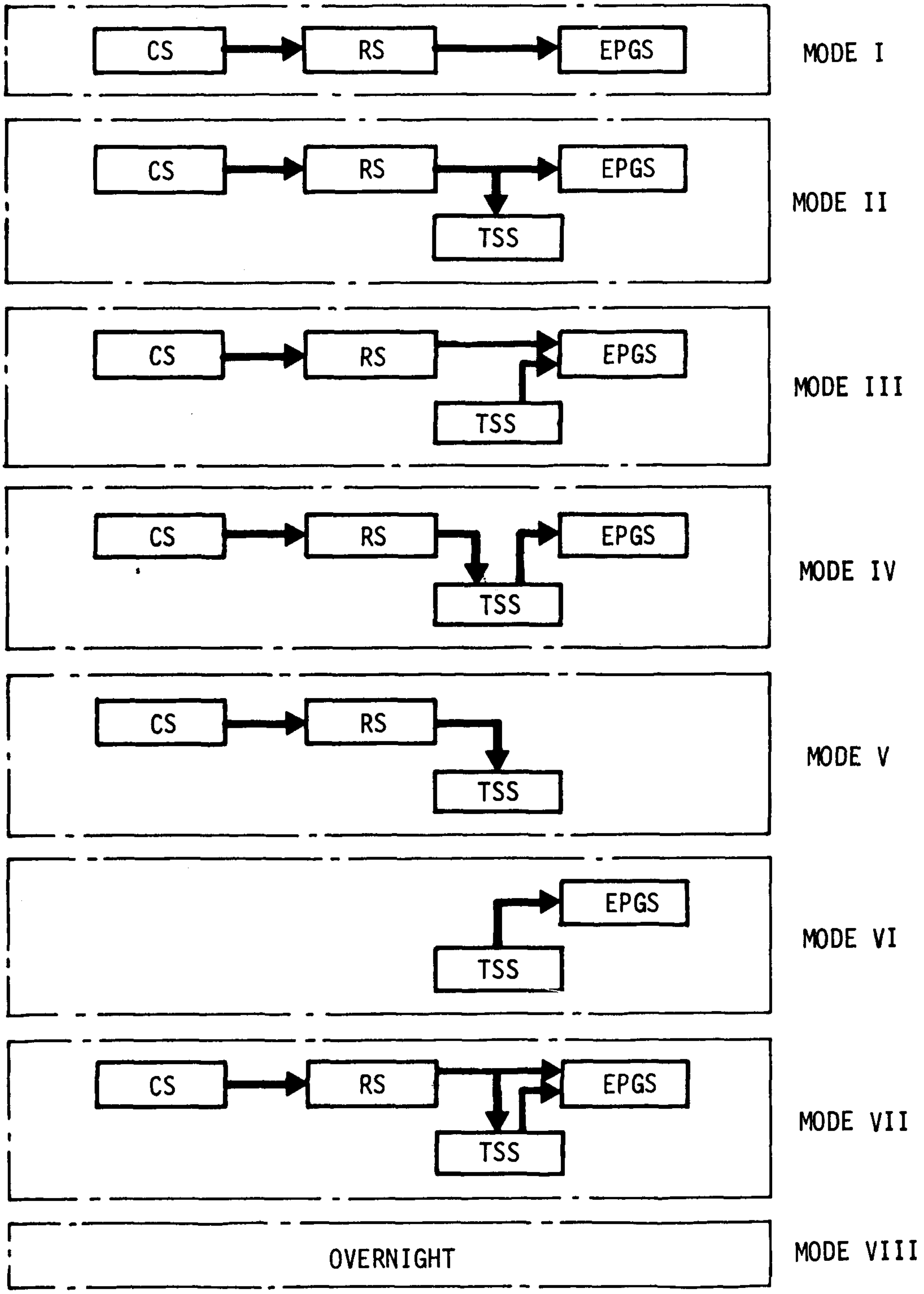


Figure VIII.A-3 Pilot Plant Steady-State Modes

The data handling system computer functions as the redundant back-up to the CS control computer, and this concept is seen most clearly when a CS control computer anomaly is detected. The data handling activities are suspended while the collector subsystem control software is loaded on the redundant computer by the control operator, and heliostat control is continued from the back-up machine. The plant's automatic data logging capability is diminished until the CS control computer capability has been restored.

In summary, the preliminary design Master Control Subsystem performs two basic functions as follows.

> <u>Controls</u> - It provides the capability for the control operators to safely control the entire plant operations in all modes and mode transitions and to detect, alarm, and respond to emergency conditions;
>
> <u>Data Handling</u> - It acquires, processes, stores and retrieves, and outputs data for all plant elements. Data processing includes production of logs, summaries, performance calculations, and archieval data.

IX. SUMMARY/CONCLUSIONS

During the course of the Phase I CRSTPS program the Martin Marietta-Foster Wheeler-Bechtel-Georgia Tech team (1) established baseline commercial and pilot plant designs for the intermediate solar power application, (2) designed, fabricated, and tested complete solar subsystem research experiments supporting that design, and (3) finalized the "Preliminary Design Central Receiver Solar Power System" making use of technology developed in this program and the parallel 1 MW_t Receiver and STTF heliostat programs. This preliminary design fulfills the program objectives to the limit of available technology. It is an adequate basis for subsystem concept selection and an adequate basis for preparation of requirements specifications for subsystems. However, it should be noted it is not the basis for a subsystem build to print specification and does not replace the detail design activity planned for the initial segment of Phase II.

Basic features have been established to achieve a practical utility scale solar plant with the highest performance consistent with the triple goals of (1) minimized capital and operating costs, (2) safe, flexible, reliable and long life application features, and (3) timely development of solar power technology.

Each feature of the design was evaluated for the degree of its positive or negative implications over the broad range of selection considerations, and incorporated only after being judged substantially beneficial.

Design decision drivers for all selected features came from considerations regarding (1) technical performance, (2) state-of-the-art, (3) safety, (4) practical utility application aspects, (5) economic optimization, (6) timely development for the pilot and commercial plants, (7) long life capability, and (8) environmental impact.

A summary of the primary selection influences for the fundamental features of the design is shown in Table IX.A-1, a digest of the total decision matrix of Table I.A-1. We believe all features listed are vital to the attainment of the highest quality pilot and demonstration plants needed to advance the technology and commercialization of Solar Thermal Power

The commercial "CRSTPS" design is an efficient plant of versatile design having broad operational flexibility, low technical risk, strong commercial potential, and minimum development cycle time. The modularized concept provides complete plant sizing flexibility over the range of 100-300 MWe with minimum impact and is highly adaptable to specific site requirements.

The pilot plant is an optimum configuration development vehicle for the central receiver concept, which brings full scale solar equipment on line in an attractive, low risk development application at the earliest possible time.

The collector subsystem is an optimum performance configuration embodying north side geometry and focusing, durable (glass mirrors, steel structure, gear drives), computer controlled heliostats based on SRE and STTF design fabrication and experience.

The Receiver Steam Generator embodys an optimum performance cavity configuration, utilizes natural circulation for maximum reliability and minimum risk, and is designed in accordance with applicable ASME code provisions most recently proven satisfactory in the 1 MW_t and 5 MW_t cavity receivers. A tower height of 90 m (295 ft) has been selected as it optimizes the collector/receiver module economics.

The thermal storage concept utilizes sensible heat of commercial heat transport materials in an optimum economic, high performance 2 stage salt and oil configuration capable of dual mode charging and discharging operation. Practicality of this system from an operational standpoint and its high performance potential were amply demonstrated by the subsystem research experiment.

The electric power generation system design is centered around commercially available turbine-generators having the highest performance consistent with long life operation in the solar power application. The dual admission turbine is uniquely suited, being capable of operating from receiver or storage stream.

The master control concept has been configured to utilize hands on control of hard wired logic subsystem controls in accordance with advice of utility personnel.

KEY FEATURES OF CRSTPS PRELIMINARY DESIGN	TECHNICAL PERFORMANCE 1	TECHNICAL STATE-OF-ART 2	SAFETY 3	PRACTICAL UTILITY APPLICATION ASPECT 4	ECONOMIC OPTIMIZATION 5	TIMELY DEVELOPMENT, PILOT 1980, COMMERCIAL 1985 6	THIRTY-YEAR LIFE CAPABILITY 7	ENVIRONMENTAL IMPACT 8	PRIMARY SELECTION DRIVER(S)
1. SYSTEM Modularized Collector Near 50 MW_{th} Size	Optimum			Maximum Reliability, Versatility		Vital to Commercial Plant 1985			1, 4, 6
150 MW_e Size Commercial Plant		Turbo Machinery Available			Optimum				2, 5
1554-Heliostat Pilot Plant vs 1325-Heliostat Plant				Simulates Operating Modes and Application		More Fully Develops Receiver			4, 6
2. RECEIVER SUBSYSTEM Cavity Configuration, Aperture Diameter/Depth ≈1.5	Mandatory for Receiver, Effectivity = 0.92-0.94	Long History and Recent 1 MW_t Confirmation	Removes Major Optical Hazard from Reflection					Removes Major Optical Hazard	1, 2, 3, 8
Natural Circulation		Widespread Use; Utility, Industrial, Naval Boilers	High, Function Not Keyed to Support Equipment			Minimum Risk, Current Practice			2, 3, 6
Conventional Boiler and Superheater Flux Levels			High, Readily Adaptable to ASME Code	Provides Highly Flexible Operation			Demonstrated		3, 4, 7
10687 kPa (1550 psig) Operating Pressure					Optimum, Higher Pressure Allowed, Smaller Piping				5
90 m (295 ft) Cladded Steel Tower					Optimum				5
3. COLLECTOR SUBSYSTEM North Side Heliostat Field Feometry	Optimum Use of Reflector Area								1
Glass Mirrors	Highest Performance Now and Potentially				Optimum, Highly Automated Industry in Being		Only Type to Ever Be Used More Than 20 Years		1, 5, 7
Steel Heliostat Structure	Readily Meets Requirements		Readily Meets Requirements				Demonstrated		1, 3, 7
Focusing Heliostat	Vital to Minimum Cavity Size				Optimum Due to Performance Benefit				1, 5
Face-Down Stowage	Reduces Structure for High Winds		Vital to Aerial Safety during Shutdown	Minimizes Cleaning Cycle				Eliminates Hazard during Shutdown	1, 3, 4, 8
Gear Drives for Azimuth and Elevation	Achieve Drive Function with Minimum Power			Highly Reliable, Minimum Maintenance			Demonstrated		1, 4, 7
Caisson Foundation					Optimum			Minimizes Ground Disturbance	5, 8
Laser Focus and Alignment	Readily Meets Requirements				Optimum				1, 5
4. THERMAL STORAGE SUBSYSTEM Sensible Heat		Only Option Ready for Application		Demonstrated Operational					2, 4
2-Stage Oil, Salt Configuration	Highest Effective Utility Scale Storage				Optimum				1, 5
Dual-Mode Charging and Discharging Capability				Best Operational Flexibility, No Built-In Time Lapse	Optimum				4, 5
5. ELECTRIC POWER GENERATION SUBSYSTEM Dual Admission, 9308 kPa (1350 psi) 783K (950°F) Turbine		Commercial Design		Most Effective Equipment Meeting Broad Operating Requirements			Attainable with Daily Cycling		2, 4, 7

Figure IX. A-1 Summary of Design Feature Drivers

This Phase I program has substantially accelerated solar power technology, but must be regarded in the perspective of being a great start. Continued intensive development is vital during the succeeding phases to successful accomplishment of the pilot and demonstration plant goals.

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