SAN/1108-8

SOLAR THERMAL POWER SYSTEM, PHASE 1, CRDL ITEM 2 PILOT PLANT PRELIMINARY DESIGN REPORT

Volume 1. Executive Overview

By
Raymon W. Hallet, Jr.
Robert L. Gervais

October 1977
Date Published

Work Performed Under Contract No. EY-76-C-03-1108

McDonnell Douglas Astronautics Company
Huntington Beach, California

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CENTRAL RECEIVER
SOLAR THERMAL POWER SYSTEM
PHASE 1

CDRL ITEM 2
Pilot Plant
Preliminary Design Report

VOLUME I
Executive Overview

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PREFACE

This report is submitted by the McDonnell Douglas Astronautics Company to the Department of Energy under Contract EY-76-C-03-1108 as the final documentation of CDRL Item 2. This Preliminary Design Report summarizes the analyses, design, test, production, planning, and cost efforts performed between 1 July 1975 and 1 May 1977. The report is submitted in seven volumes, as follows:

- Volume I, Executive Overview
- Volume II, System Description and System Analysis
- Volume III, Book 1, Collector Subsystem
  - Book 2, Collector Subsystem
- Volume IV, Receiver Subsystem
- Volume V, Thermal Storage Subsystem
- Volume VI, Electrical Power Generation/Master Control Subsystems and Balance of Plant
- Volume VII, Book 1, Pilot Plant Cost and Commercial Plant Cost and Performance
  - Book 2, Pilot Plant Cost and Commercial Plant Cost and Performance

Specific efforts performed by the members of the MDAC team were as follows:

- McDonnell Douglas Astronautics Companv
  Commercial System Summary
  System Integration
  Collector Subsystem Analysis and Design
  Thermal Storage Subsystem Integration

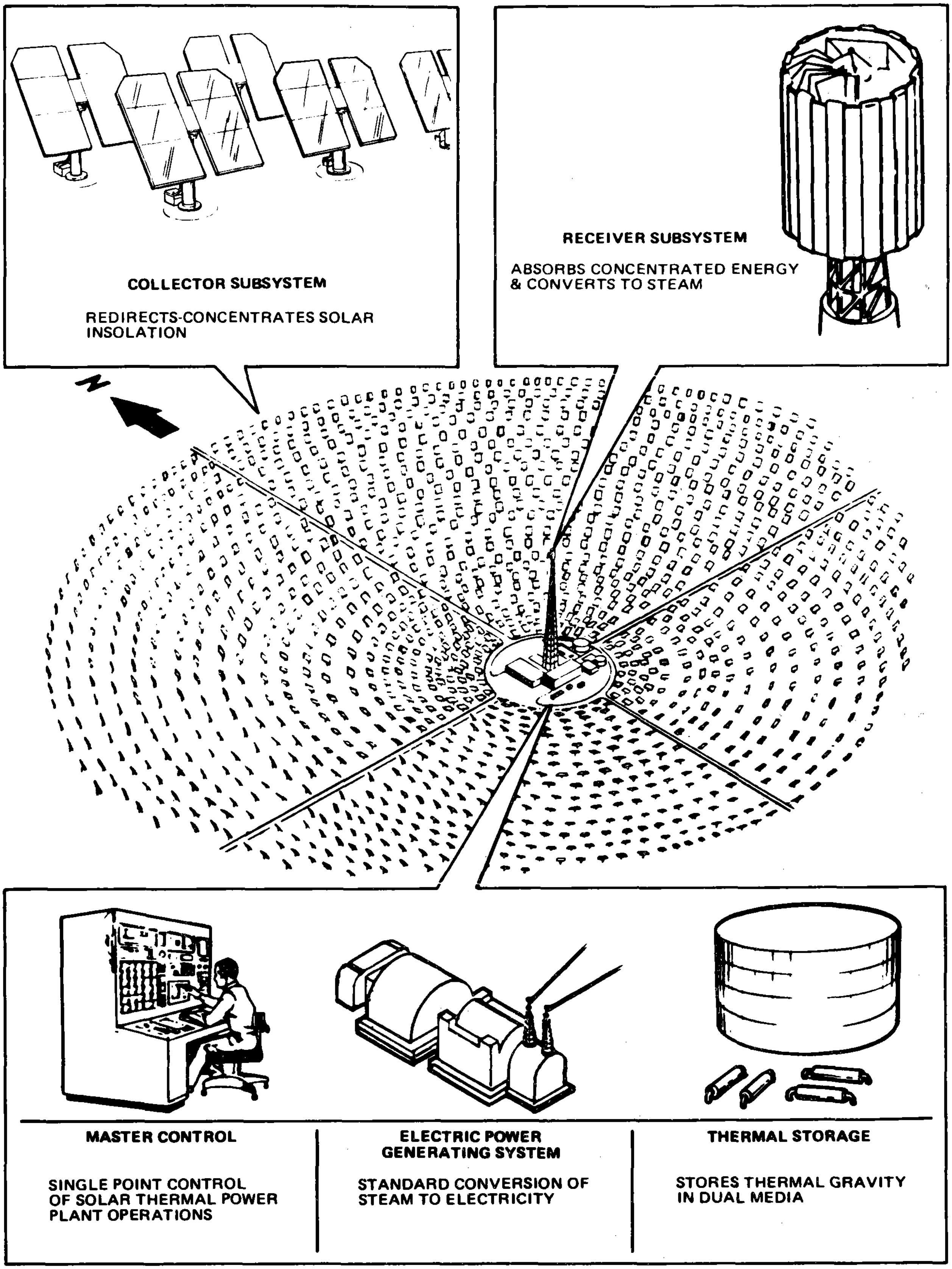
- Rocketdyne Division of Rockwell International
  Receiver Assembly Analysis and Design
  Thermal Storage Unit Analysis and Design

- Stearns-Roger, Inc.
  Tower and Riser/Downcomer Analysis and Design
  Electrical Power Generation Subsystem Analysis and Design

- University of Houston
  Collector Field Optimization

- Sheldahl, Inc.
  Heliostat Reflective Surface Development

- West Associates
  Utility Consultation on Pilot Plant and Commercial System Concepts


COLLECTOR SUBSYSTEM
REDIRECTS-CONCENTRATES SOLAR INSOLATION
RECEIVER SUBSYSTEM
ABSORBS CONCENTRATED ENERGY & CONVERTS TO STEAM
N
MASTER CONTROL
SINGLE POINT CONTROL OF SOLAR THERMAL POWER PLANT OPERATIONS
ELECTRIC POWER GENERATING SYSTEM
STANDARD CONVERSION OF STEAM TO ELECTRICITY
THERMAL STORAGE
STORES THERMAL GRAVITY IN DUAL MEDIA

PHASE 1 ACCOMPLISHMENTS

SUBSYSTEM RESEARCH EXPERIMENTS (SRE)

- Collector: Full-Size Heliostats Met All Performance Goals in Component, Environmental, Life, and Field Array Tests
- Receiver: Full-Size Pilot Plant Receiver Panel Test Met All Performance Goals
- Thermal Storage: Near Full-Scale Pilot Plant Tests Exceeded All Performance Goals

10-MWe PILOT PLANT

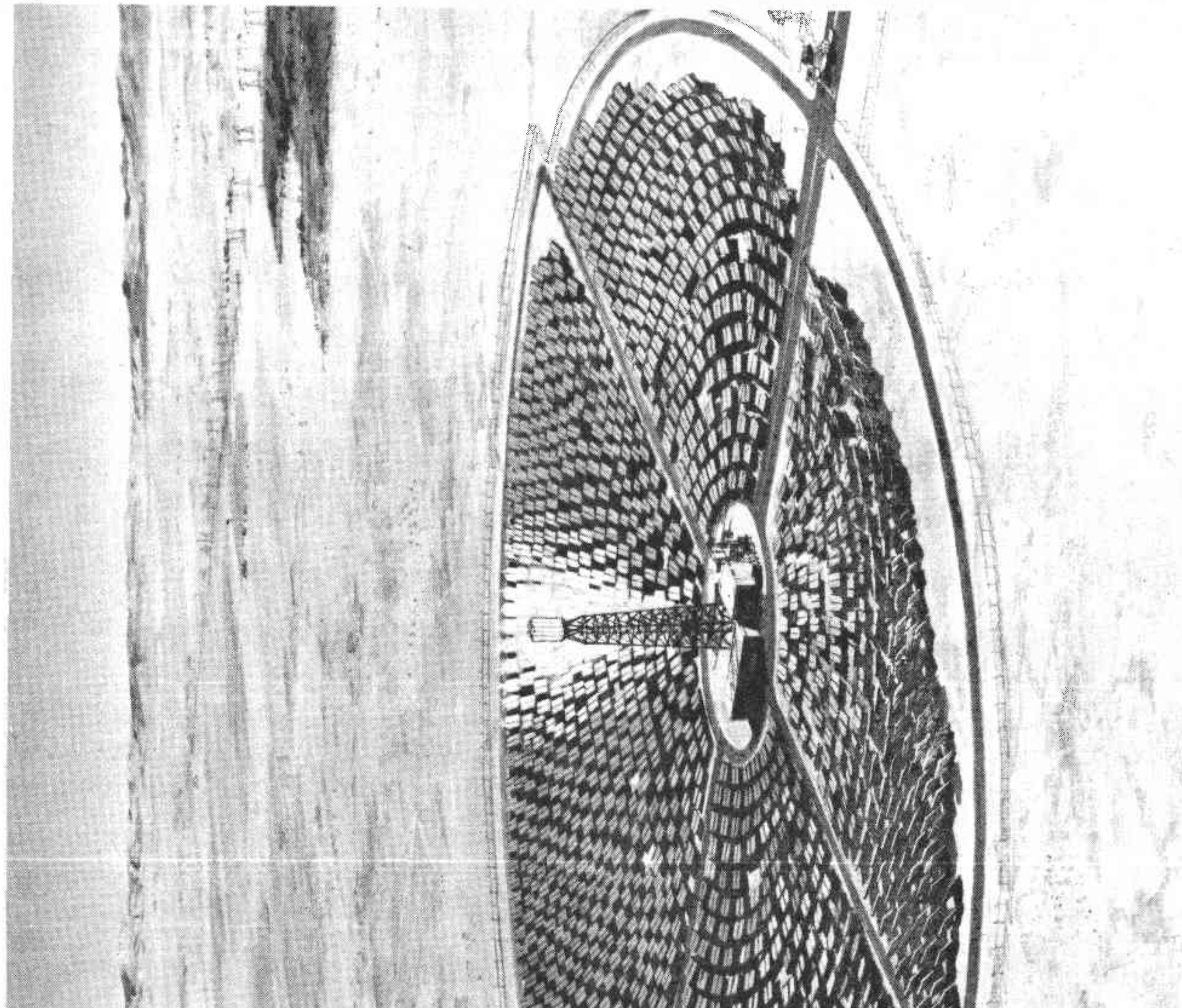
- Preliminary Design Completed from Commercial System Flowdown Requirements
- Reliability Data Base Established
- Collector, Receiver, Thermal Storage Performance Verified by SRE Tests
- Installation and Maintenance Procedures Defined
- Master Control Simulation Initiated

100-MWe COMMERCIAL

- Conceptual Design Completed
- Collector Performance Based on Full-Scale Tests in SRE
- High-Volume Heliostat Manufacturing Concept Defined
- Manufacturing and Installation Schedules Developed

COST PROJECTIONS

- Estimates for Pilot Plant and First Commercial Plant Completed
  - In-Depth Hardware Descriptions
  - Manufacturing Flows
  - Installation and Maintenance Plans
  - Reliability Assessment for Spares
- Projections for Nth Commercial Plant Completed
  - In-Depth Hardware Descriptions
  - Conceptual Design of High-Volume Heliostat Manufacturing Facility
  - Installation and Maintenance Plans
  - Reliability Assessment for Spares


R.L. ALLEN

CONTENTS

Section 1
INTRODUCTION

This summary introduces the McDonnell Douglas Astronautics Company (MDAC) Central Receiver System Preliminary Design and reports the results of the Subsystem Research Experiments (SRE) recently completed. This section describes the central receiver concept as proposed by the MDAC contractor team to implement the program in response to the Department of Energy's program phases. It also describes the preliminary design methodology of the Pilot Plant simulation of the projected Commercial Plant, indicating the program goals and methodology influencing the design. Section 2 describes the Pilot Plant preliminary design resulting from iterative analyses and SRE tests through this current phase of the program. Section 3 discusses the Commercial system projected by MDAC as the criteria for structuring development activities leading to operational utility service. Conclusions are presented in Section 4, together with comparisons of Pilot Plant and Commercial systems that highlight significant performance and design parameters.

During Phase 1, the basic objectives guiding MDAC activities were:

- Development of a competitive Commercial system to produce 100 MWe.
- Design of a Pilot Plant to provide the best representation of the technical performance of the Commercial system.
- Elimination of technical risk by subsystem and component test.
- Generation of a substantial data base for Pilot Plant and Commercial cost projection, including manufacturing, installation, and maintenance plans.

1.1 CENTRAL RECEIVER CONCEPT

This Phase 1 program has resulted in (1) the completion of the preliminary design of a central receiver 10-MWe Pilot Plant that simulates the projected

Commercial system, and (2) the completion of tests conducted on the collector, receiver, and thermal storage subsystems. The end design of the central receiver thus consists of qualified subsystems whose performance has been verified by design, analysis, and/or test.

The baseline central receiver concept defined by the MDAC team consists of the following features:

A. An external receiver mounted on a tower, and located in a 360-deg array of sun-tracking heliostats which comprise the collector subsystem.

B. Feedwater from the electrical power generation subsystem is pumped through a riser to the receiver, where the feedwater is converted to superheated steam in a single pass through the tubes of the receiver panels.

C. The steam from the receiver is routed through a downcomer to the ground and introduced to a turbine directly for expansion and generation of electricity, and/or to a thermal storage subsystem, where the steam is condensed in charging heat exchangers to heat a dual-medium oil and rock thermal storage unit (TSU).

D. Extended operation after daylight hours is facilitated by discharging the TSU to generate steam for feeding the admission port of the turbine.

E. Overall control of the system is provided by a master control unit, which handles the interactions between subsystems that take place during startup, shutdown, and transitions between operating modes. The master control equipment includes a computer and peripheral gear located in the power house control room. The system has been designed to allow a single operator the option of using the computer in an automatic mode, or of operating the system manually. Localized control is also provided by subsystem controllers, with the operator having the ability to change the localized controller set points.

F. The central receiver baseline concept is shown schematically in Figure 1-1.

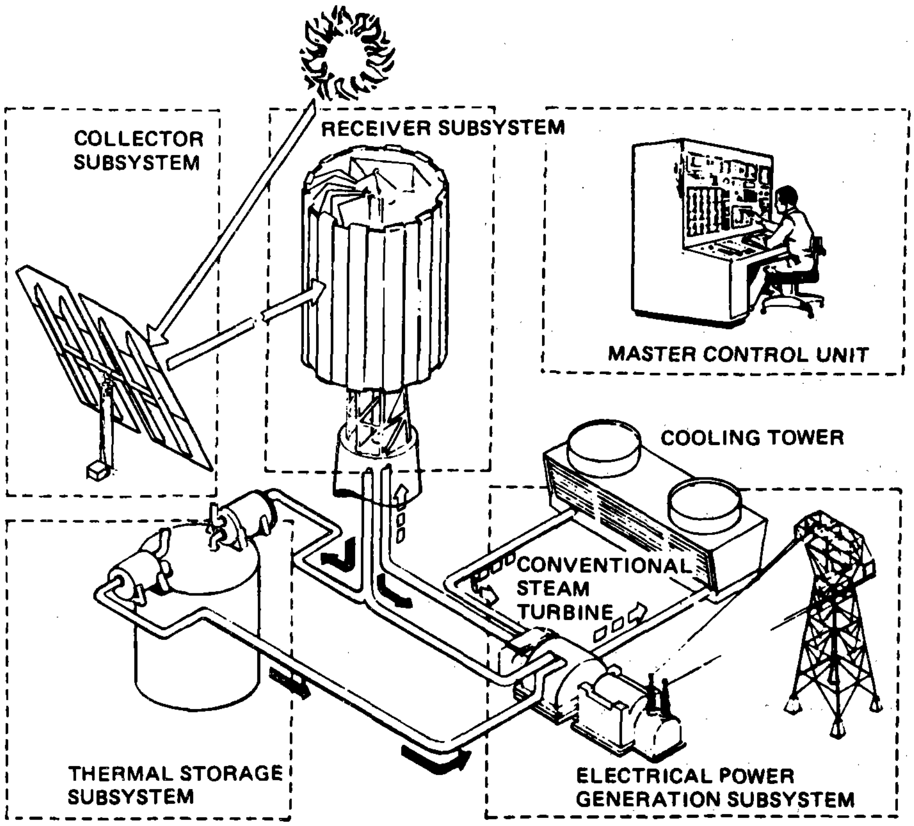


Figure 1-1. Central Receiver Baseline Concept

1.2 MDAC TEAM

To accomplish Phase 1 program objectives, MDAC recognized the need to provide the appropriate talent to accomplish the entire four-phase program as well as the initial phase. Thus, MDAC formed a contractor team that combines MDAC's own technical resources with those of other companies in an effective, complementing fashion. The other principal team members are:

- Rocketdyne Division of Rockwell International
- Stearns-Roger, Inc.
- University of Houston

The MDAC system integration role includes overall management, system design and integration, and the collector subsystem activity.

The other team member responsibilities include Rocketdyne's design, fabrication, and test activity for the receiver and thermal storage subsystems. The Pilot Plant receiver tower and riser/downcomer design, electrical power-generation subsystem design, and environmental impact data are the responsibility of Stearns-Roger, Inc. Collector field optimization was accomplished by the University of Houston. West Associates, a consortium of Western Utilities, assisted early in Phase 1 to establish Commercial system requirements, and to review progress on the Pilot Plant system design.

1.3 DEPARTMENT OF ENERGY PROGRAM PHASES

The Department of Energy central receiver power system effort consists of four phases which started in 1975 and will terminate in 1986 with the initiation of the first Commercial plant (Figure 1-2). MDAC is totally committed to a program whereby activities of each phase are designed to establish the building blocks for commercial implementation.

Phase 1, initiated in 1975, has resulted in a preliminary design of a 10-MWe Pilot Plant that best simulates a 100-MWe Commercial Plant, which was also conceptually designed during Phase 1. These activities, coupled with subsystem level tests performed during this phase, have provided the technical and operational data necessary to evaluate Commercial Plant technical feasibility, performance, schedules, and costs.

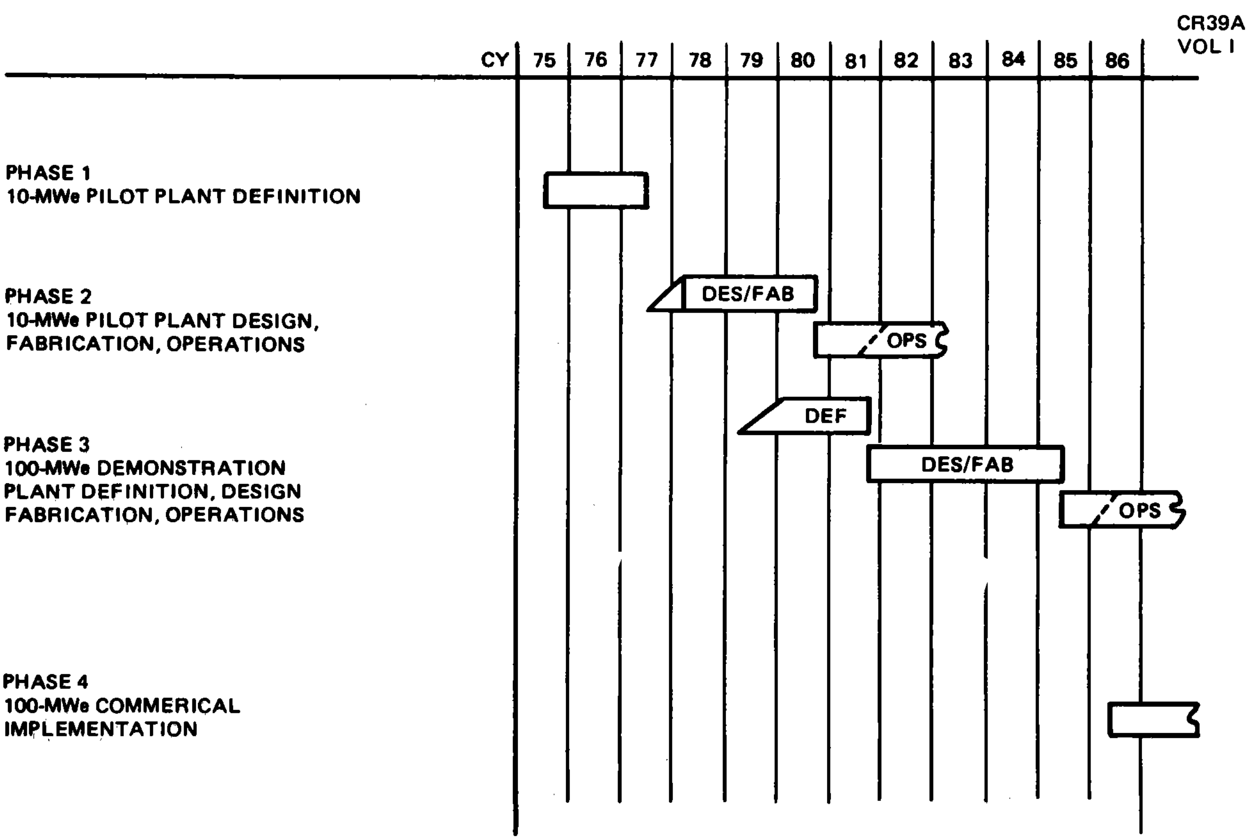


Figure 1-2. Central Receiver Development Program

Phase 2, which begins in 1977, encompasses the design, construction, and test of a 10-MWe Pilot Plant near Barstow, California. The objective of Phase 2 is to validate the technical feasibility of a central receiver solar thermal power plant that has significant Commercial potential and to obtain sufficient development, production, and operating data to verify the economic projection for operation of Commercial solar thermal power plants.

Phase 3, which results in a demonstration plant of 50 to 100 MWe becoming operational in mid-1985, has as its objective the operation of an economically competitive Commercial Plant.

Phase 4 is the introduction of a 100- to 300-MWe plant into operational utility service.

1.4 PRELIMINARY DESIGN METHODOLOGY OF 10-MWe PILOT PLANT

1.4.1 Program Goals

The program goals of Phase 1 were as follows:

A. Conceptual design of commercially feasible 100-MWe solar thermal power plant.

B. Preliminary design of accurate Pilot Plant representation of Commercial system.

C. Completion of subsystem testing to eliminate technical risk.

D. Development of an effective data base for cost projection of Pilot Plant and Commercial systems.

E. Establishment of detailed plans to develop credible schedules.

The major effort of the Phase 1 program has been to develop a preliminary design for a Pilot Plant system that is capable of providing technical verification of an anticipated, cost-effective, Commercial system design. Data acquired during the Pilot Plant operation will be used in confirming Commercial system cost projections as well as providing direction to major cost-reduction efforts.

A technically and operationally sound 100-MWe Commercial system design was defined. The Commercial system was consistent with Department of Energy design guidelines and restrictions, electrical utility requirements, and environmental requirements. Key system and intersystem trade studies were carried out to identify the most cost-effective design approach for the Commercial system. In all individual subsystems, technical performance was balanced against system optimization and elimination of technical risk. This systems engineering approach resulted in the lowest cost per kilowatt hour to generate electricity without introducing technical risk. The evaluation of each individual subsystem design was conducted in the context of cost and performance of the total balanced system.

1.4.2 Program Methodology

The overall program methodology that has served to guide the MDAC effort as well as a starting point for the subsystem design and test activities is shown in Figure 1-3.

Starting with a series of program inputs which include Department of Energy, utility, and self-imposed constraints, along with representative environmental conditions, an initial Commercial system definition was developed. From this definition, a series of verification requirements were established which combined with other Pilot Plant design objectives and guidelines to form a set of Pilot Plant design requirements.

Alternate approaches to Pilot Plant designs were considered which could also satisfy the defined requirements. This provided a baseline design for critical components with alternative designs available. Simultaneous to the Pilot Plant design effort, the Commercial system design was refined to provide continuous focus for the Pilot Plant design effort. Based on inputs from both the ongoing Pilot Plant design, results from the SRE and the revised Commercial system definition, a Pilot Plant analysis was conducted which included the selection criteria and culminated in the identification of the Pilot Plant design.

This methodology has resulted in qualified, cost-effective subsystems with high plant availability. The specific designs established in this manner are summarized in Sections 2 and 3 of this volume and are discussed in detail in Volumes II through VI of the Preliminary Design Report (PDR).

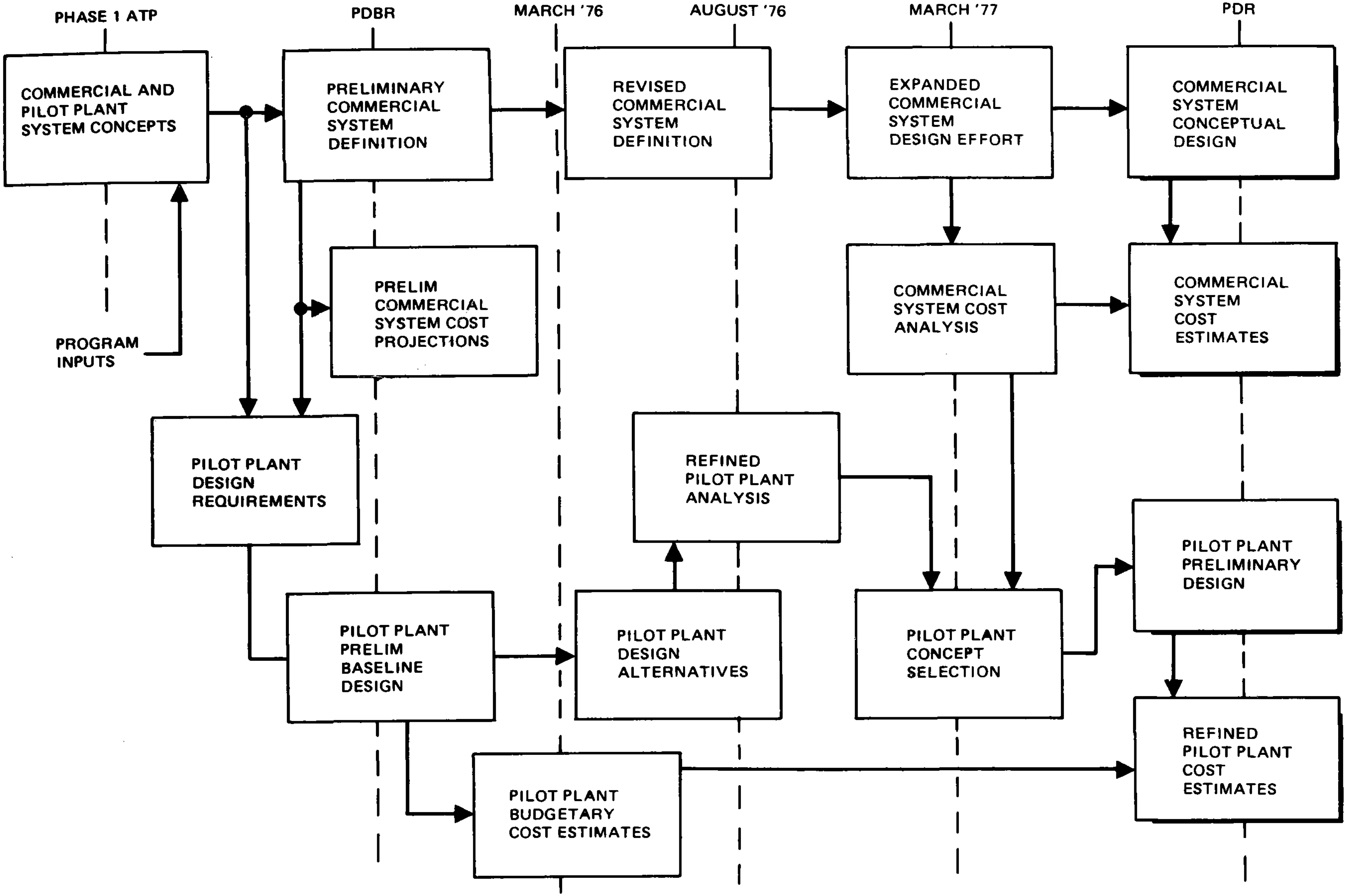


Figure 1-3. Phase 1 System Definition Network

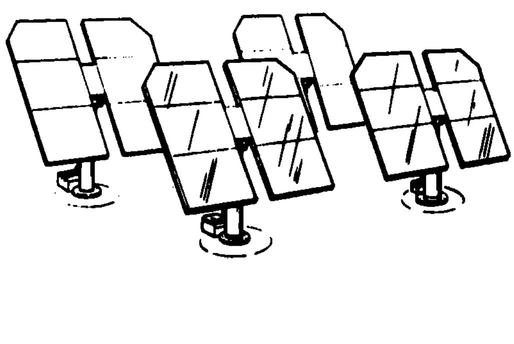
Section 2

PILOT PLANT SYSTEM

- Based on flowdown of Commercial system requirements.
- Subsystems qualified in Phase 1 by test.
- Simulates Commercial system performance.
- Validates Commercial system manufacturing processes.
- Test program confirms installation and maintenance procedures.

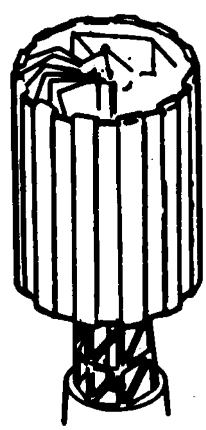
COLLECTOR

- Pilot Plant configuration identical to Commercial design.
- Compatible with all 10-MWe receiver aperture requirements.
- Reflective surface, flat panel construction.
- Second-surface mirrors eliminate technical risk and provide low cost.
- SRE tests confirmed component performance for basic and alternate subsystems.
- Face-down stowage provided for evaluation of Pilot Plant.



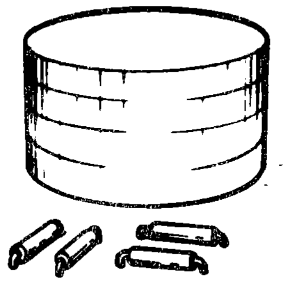
RECEIVER

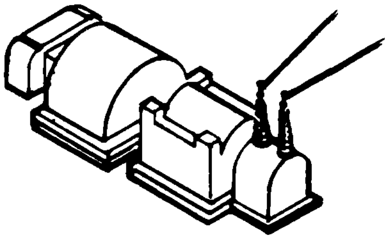
- Modular design provides rapid installation and ease of maintenance.
- Low weight increases seismic tolerance and reduces thermal leg.
- Single tower to minimize field piping and steam control complexity.
- Full-size Pilot Plant panel performance verified by test.



THERMAL STORAGE

- Design verified by test.
- Sensible heat provides low technical risk.
- Dual media (caloria and rock) is low cost.
- Thermocline provides constant temperature independent of residual stored energy.



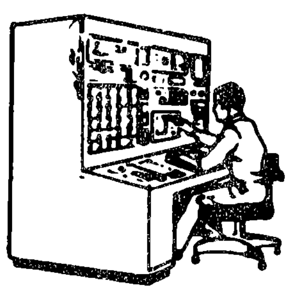


ELECTRICAL POWER GENERATION

- Equipment is commercially available.
- Compatible with steam conditions from receiver and thermal storage subsystems.

MASTER CONTROL

- Provides flexible reaction to variable solar insolation
- Computer control optimizes systems operation.
- Single operator manual capability.
- Software for computer control being verified in MDAC On Line Subsystem Facility (OLSF).



The purpose of the Pilot Plant is to provide technical verification of the projected Commercial system and an early indication of central receiver economics. The design activity for the Pilot Plant originated with a definition of the Commercial system from which system and subsystem level requirements were established. Program inputs from the Department of Energy established requirements were combined to form the bases of the initial Pilot Plant baseline design.

The subsystem designs which comprise the baseline Pilot Plant system were verified to the component level through an extensive SRE program. Data gathered were combined with the results of an ongoing system analysis effort to refine the original baseline Pilot Plant definition into the preliminary design presented in this report.

The Phase 2 Pilot Plant program will begin with qualified subsystems and components forming the bases for Pilot Plant verification of integrated system operation, overall system performance, and manufacturing, installation, and maintenance procedures. To confirm Commercial system projections, the manufacturing and installation processes for the Pilot Plant, particularly as they affect the collector field, will replicate those planned for the Commercial system. Thus, the overall Pilot Plant system design contains not only subsystem designs which are capable of a complete operational simulation of the Commercial system, but also includes plans for the confirmation of manufacturing and installation methods to ensure a cost-effective Commercial system.

2.1 REQUIREMENTS

A summary of the principal performance requirements for the Pilot Plant is presented in Table 2-1. With the exception of the value for solar multiple, which is a characteristic of the MDAC system, the requirements were all provided by the Department of Energy. The principal difference in the sizing condition between the Pilot Plant and Commercial system is that the Pilot Plant is sized for 2 PM on the worst cosine day (Winter solstice). The Commercial system, on the other hand, is sized for noon on the best field cosine day (equinox). The Pilot Plant is to be able to generate 10 MWe net directly at the design point or accumulate sufficient energy in thermal storage to be able to operate at 7 MWe net for 3 hr, while the Commercial plant is to

Table 2-1

PILOT PLANT SYSTEM REQUIREMENTS

Design Point Power Level (Net)	
• From Receiver	10 Mwe
(2 PM day of worst sun angle, 950 W/m^2 insolation level)	
• From Thermal Storage	7 MWe
Solar Multiple	1.1
Hours of Storage	3
System Startup Time	
• Hot	20 Minutes (or as fast as practical)
• Cold	6 Hours
Plant Availability (Exclusive of Sunshine)	90%
Operational Lifetime (With Normal Maintenance)	30 Years

generate 100 MWe and store enough energy for 6 hr operation at 70 MWe net. Additional requirements related to the design environment are identical to those specified for the Commercial system in Section 3.

2.2 SYSTEM DEFINITION

A summary description of the MDAC baseline Pilot Plant design is shown in Table 2-2, Figure 2-1, and Table 2-3. This design satisfies all requirements imposed by the Department of Energy and allocated by MDAC. The collector field layout summarized in Table 2-2 represents the radial stagger heliostat arrangement of the Commercial system. It is composed of 1,760 heliostats on 32 circular arcs with the inner 19 forming complete circles. To facilitate access, the continuous arcs are divided by quadrant roads. A summary of collector field sizing data is contained in the first part of Table 2-3.

The water/steam loop schematic, shown in Figure 2-1, depicts the major elements of the receiver, thermal storage, and balance of plant equipment. The receiver, which is schematically shown in the upper left of Figure 2-1, is composed of a set of 6 preheat panels followed by 18 parallel single-pass-

Table 2-2

COLLECTOR FIELD PHYSICAL CHARACTERISTICS

Field Arrangement	Radial Stagger/Circular Arcs
Number of Heliostats	1,760
Collector Field Area (Gross)	0.304×10^6 m^2 (75 Acres)
Glass Packing Density	
Maximum	45%
Minimum	13%
Average	23%
Central Exclusion Area	$10,387 m^2$ (2.6 Acres)
Tower Height	65m
Receiver Centerline Elevation	80m

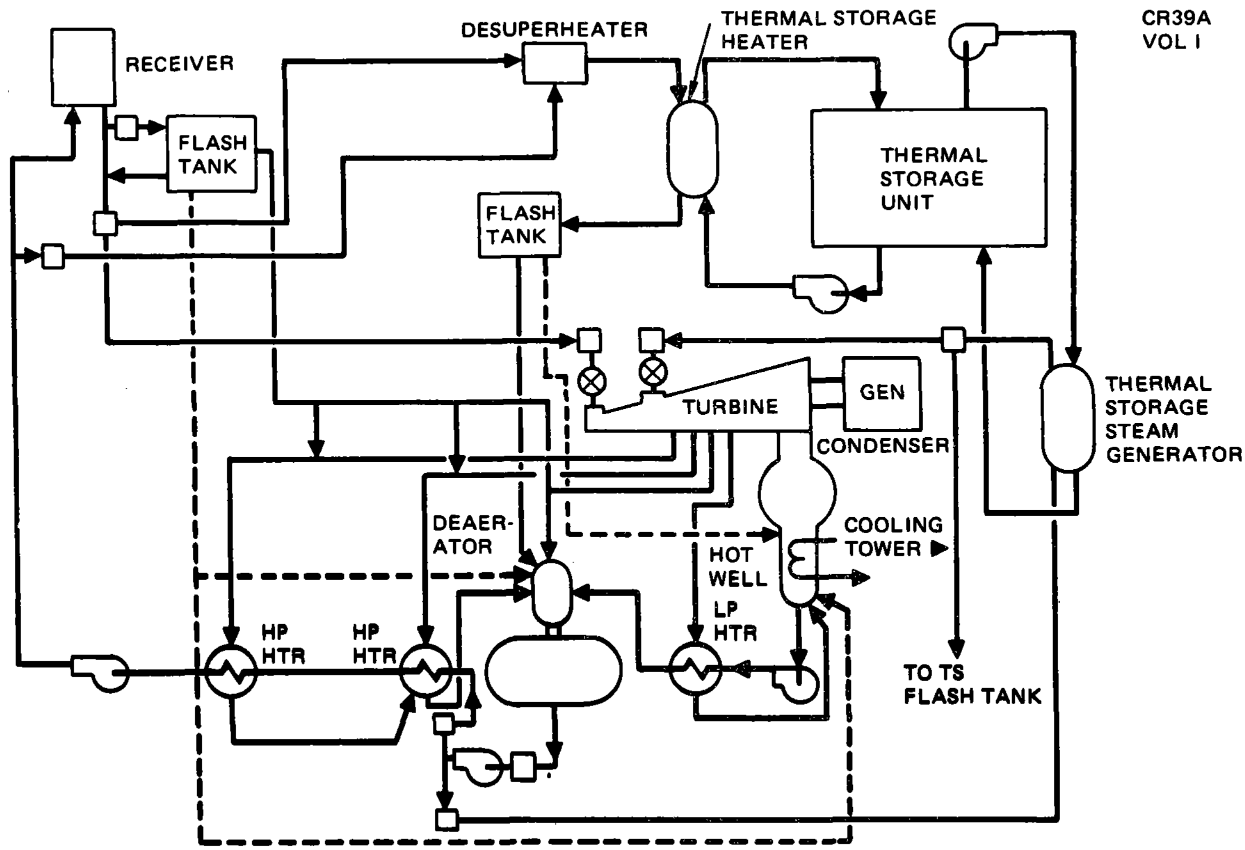


Figure 2-1. Simplified Pilot Plant System Schematic

to-superheat panels. During startup and shutdown, receiver outlet flow is diverted to the receiver flash tank to ensure that no water is passed to the rest of the system through the main steam downcomer. The thermal storage

Table 2-3

PILOT PLANT SYSTEM AND SUBSYSTEM LEVEL CHARACTERISTICS

Collector Field Size (Excluding Tower Exclusion)	0.29×10^6 m^2 (3.12×10^6 ft^2)
Number of Heliostats	1,760
Heliostat Arrangement	Radial Stagger (Continuous Arcs)
Receiver Centerline Elevation	80m (262 ft)
Receiver Size	
Diameter	7m (23 ft)
Height	12.5m (41 ft)
Receiver Steam Conditions	
Pressure	10.45 MPa (1,515 psia)
Temperature	
• Rated Steam	516°C (960°F)
• Derated Steam	349°C (660°F)
Thermal Storage Temperature Range	219°-302°C (425°-575°F)
Turbine Steam Conditions	
Throttle Steam	510°C (950°F) 10.1 MPa (1,465 psia)
Admission Steam	274°C (525°F) 2.65 MPa (385 psia)

subsystem shown in the upper right corner of the figure is composed of the thermal storage heater, which is used to charge the storage system by condensing receiver steam, a TSU containing the Caloria/rock mixture, and the steam generator used to generate turbine admission steam by extracting energy from the high-temperature side of the TSU. The turbine and balance of plant equipment shown at the bottom of the figure consists of a 12.5-MW automatic admission industrial turbine and four extraction heaters. The turbine can operate exclusively from receiver steam by using the first port or from thermal storage by using the downstream admission port. In addition, simultaneous operation from both steam sources is possible. In all cases, total receiver flow is limited by the maximum flow capability of the last stage. A summary of the pertinent design conditions for the receiver, thermal storage, and turbine are shown in the lower portion of Table 2-3.

2.2.1 Installation and Checkout

The installation and activation of the Pilot Plant have been reviewed in detail.

The installation of each subsystem is described in this volume and in its appropriate volume of the PDR. The completion of the construction activities on schedule and within cost, while protecting the environment, has been considered paramount in MDAC planning.

The construction activities will be coordinated through the construction manager to ensure schedule compliance and site construction cost control.

The successful completion of construction and installation activities will result from:

- Rigid scheduling and expediting equipment.
- Management of adequate labor supply.
- Control of material flow.
- Validation of plans and procedures during the detail design phase.

The construction activities and their interaction with subsystem manufacture, installation, and checkout is especially critical for a solar thermal power plant. This aspect has been considered and as an example the collector flow is presented in Figure 2-2.

2.2.2 Plant Availability

The availability of the MDAC Pilot Plant to generate electricity when solar insolation is available was determined by analyzing the failure characteristics of each component in the collector, receiver, and thermal storage subsystems and combining this with historical data for the electric power generation subsystem to obtain an estimate of the overall plant availability.

The failure rate or mean time between failures (MTBF) of each component in the collector, receiver, and thermal storage subsystems was determined from component historical data on similar components. The mean time to repair (MTTR) was obtained from actual field experience on the heliostats or by estimates. These were converted into component unavailable hours per year. The effect of a component failure on the system operation was con-

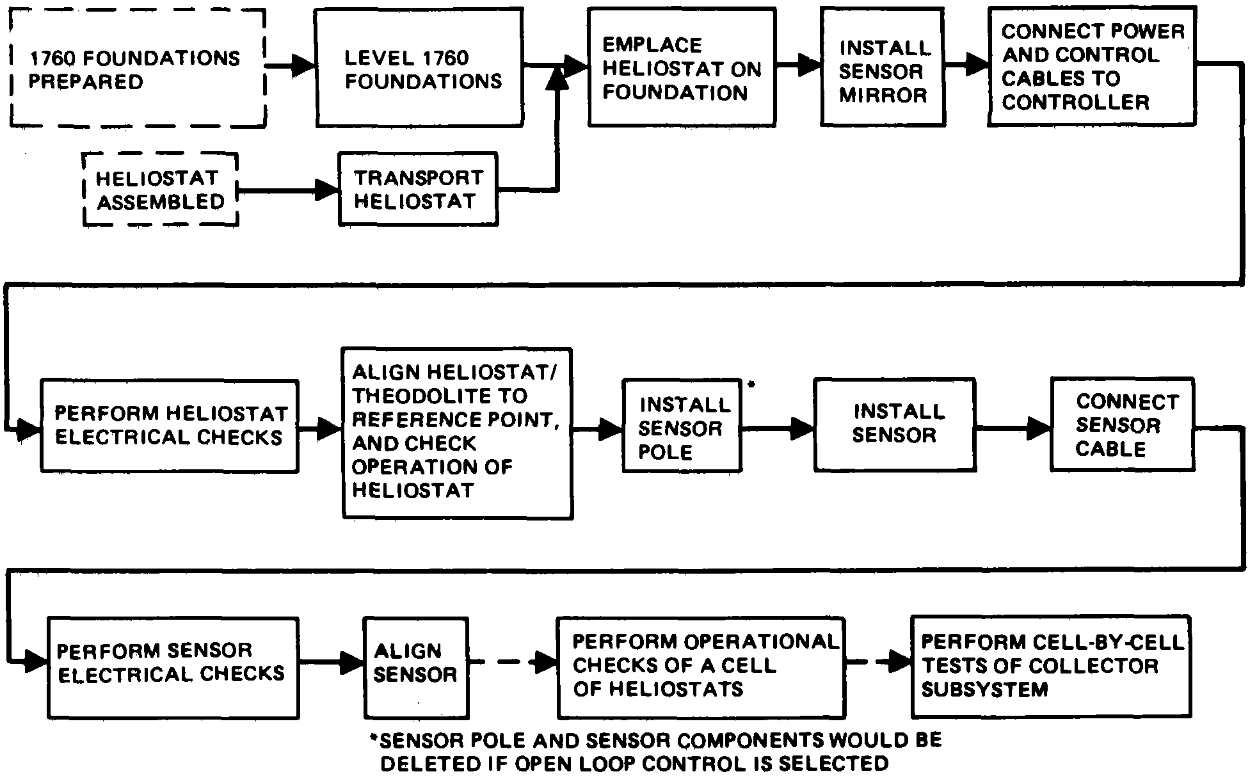


Figure 2-2. Heliostat Installation Sequence

sidered in applying these component unavailable hours to system unavailable hours. The system unavailable hours caused by component failures (forced outages) were then added to the required preventative maintenance time (planned outages) to obtain the overall system unavailable time and thus system availability. The estimate for the electric power generation subsystem was obtained by using historical data on fossil power plants of similar size (100 MW).

The results of the analysis give a power plant availability estimate of 89.8%. This compares with a goal of 90% and achievement of 88% on fossil power plants of similar size.

2.2.3 Maintenance

Scheduled maintenance identified for the receiver, collector, thermal storage, and electrical power generation subsystems is conventional and requires the expected walk-around inspections, lubrication, cleaning, painting, servicing, calibration, and proof-testing corresponding to that for similar industrial equipment. Cleaning of reflective surfaces in the collector subsystem is considered unusual only with respect to quantity and frequency requirements. This is illustrated in Figure 2-3. Scheduled maintenance functions for the Pilot Plant are essentially applicable to the Commercial Plant. It is anticipated that walk-around inspections to detect leaks and other mechanical and electrical anomalies and routine equipment servicing will be done by operating personnel. Correction of other than minor discrepancies will be reported and handled by assigned maintenance personnel, who will also perform the more extensive and time-consuming scheduled maintenance. A master schedule will distribute workloads evenly and optimize operating and maintenance crew requirements.

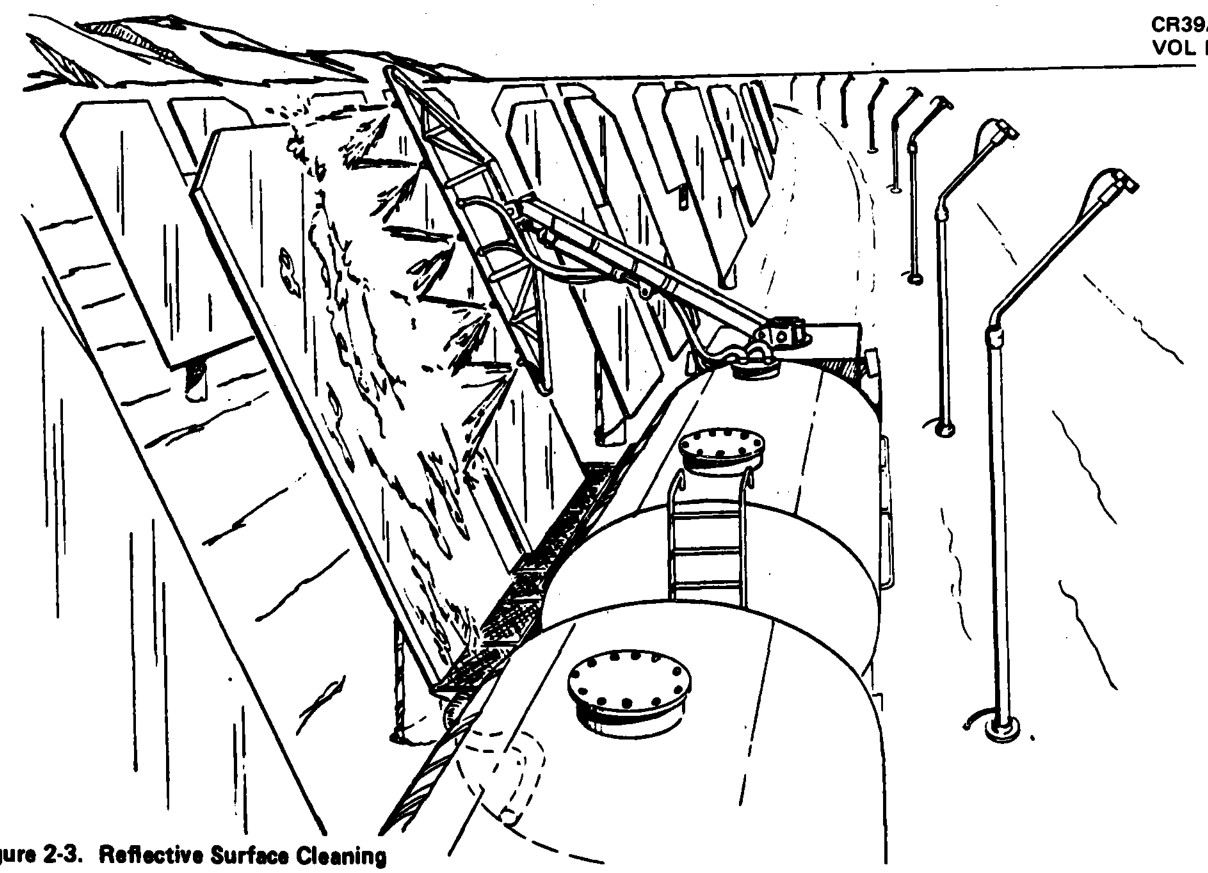


Figure 2-3. Reflective Surface Cleaning

With few exceptions, equipment failures do not result in subsystem outages that impact system availability requirements. Corrective maintenance can therefore be accomplished during operating or dormant periods to achieve a workload-leveling effect for the overall facility. Failures involving equipment and personnel safety will, of course, require immediate response.

In addition to visual indication of abnormal conditions, equipment functional failures are detected and displayed at the master control subsystem annunciation and monitor panels. Alarm conditions are indicated by annunciator light illumination. Readout of all instrumented parameters for each subsystem is available via gages, meters, and digital displays for operational control functions and maintenance activity. Depending on the nature of the fault indication, maintenance crews are immediately dispatched to investigate and correct the problem or the discrepancy is reported to the maintenance manager for scheduling of corrective action.

2.2.4 Safety

The Pilot Plant safety analysis performed in Phase 1 was conducted on a system basis, using the failure mode effects technique on each component. The analysis identified potential hazards, including the possible hazard to light aircraft from the heated air around the receiver and the concentrated solar energy produced by the heliostats.

An analysis of the thermal plume associated with the heating of the air near the receiver showed that there is no significant hazard from this source. Details of the analysis, as well as of other potential hazards such as the effect of concentrated solar beams on personnel or equipment, are in Volume II, Section 4.10.3.

No serious personnel or equipment hazard to the Pilot Plant or nearby people is anticipated.

2.3 PILOT PLANT COST PROJECTIONS

Cost projections for Pilot Plant were based upon detailed estimating methodology and are summarized below.

The manufacturing sequences for the Pilot Plant collector hardware were developed in depth and performance standards were then applied to each fabrication, assembly, installation, inspection, and test activity. Material estimates were provided by vendor sources. These data, together with the established labor hours, formed the bases for hardware costs. Engineering efforts for drawing release, system integration, and the 2-yr test program were directly estimated. Engineering estimates were verified by the financial community for the receiver and thermal storage subsystems. Detailed estimates based on actual experience for like activities were derived for the balance of the plant. Tasks and staffing were estimated for system engineering and integration activities. The total labor effort and material cost are summarized in Table 2-4.

The associated Pilot Plant schedule is shown in Figure 2-4.

2.4 MASTER CONTROL

The MDAC approach to master control uses the prevailing conventional power plant operating concepts and augments this concept with established computer-automated process control techniques. Inherent to this operational concept are three modes of control and monitoring, as follows:

- Fully manual mode using the prevailing manual techniques commonly incorporated into existing power-generation plants.
- Fully automatic mode using present-day computer process control technology to perform control and monitoring functions.
- Combination mode using the manual control supported with computer monitoring and alarm.

In the event of a complete power failure to master control MDAC uses an uninterruptible power source (UPS) to provide a sufficient electrical supply from lead-calcium batteries to manually operate the subsystem controls (i.e., collectors, turbine-generator, receiver, thermal storage), for a period of time adequate to make the plant safe. The system is located in series with the main power source in a manner whereby the main power continually charges the battery and master control power is drawn from the batteries. An automatic bypass switch is incorporated to assure continuous power if the UPS fails.

2.4.1 Requirements

The MDAC master control concept has been developed to satisfy the following development, demonstration, and operation functions:

- Monitoring and control of the collector subsystem.
- Balancing the steam and feedwater loop under variable collector heat input conditions.

Table 2-4

PILOT PLANT COSTS

Item	Total Cost* ($ Millions)
Operations and Maintenance	2.05
Test Program Technical Support	1.52
Spare Parts	0.64
Land and Land Rights	0.00
Yard Work	0.65
Turbine Building	1.19
Administration Building	0.43
Circulating and Service Water Pump House	0.01
Warehouse	0.54
Maintenance Building	0.06
Water Treatment Equipment Building	0.08
Sewage Treatment Building	0.00
Thermal Storage Structure	0.24
Control Building	0.00
Solar Plant Equipment	37.30
Turbine Plant Equipment	5.05
Electrical Plant Equipment	1.06
Plant Master Control	1.99
Miscellaneous Plant Equipment	3.23
Transmission Plant	0.00
Distributables	3.28
Indirects	12.57
Contingency	3.67
Total	75.56

*Estimates are in 1977 dollars.

- Allocating thermal storage heat to plant processes under variable heat input conditions and varying thermal storage capacity.
- Monitoring, logging, and reducing plant operations data for the day-to-day and long-term examination, comparisons, diagnosis, evaluation, and interpretation of subsystem operations.

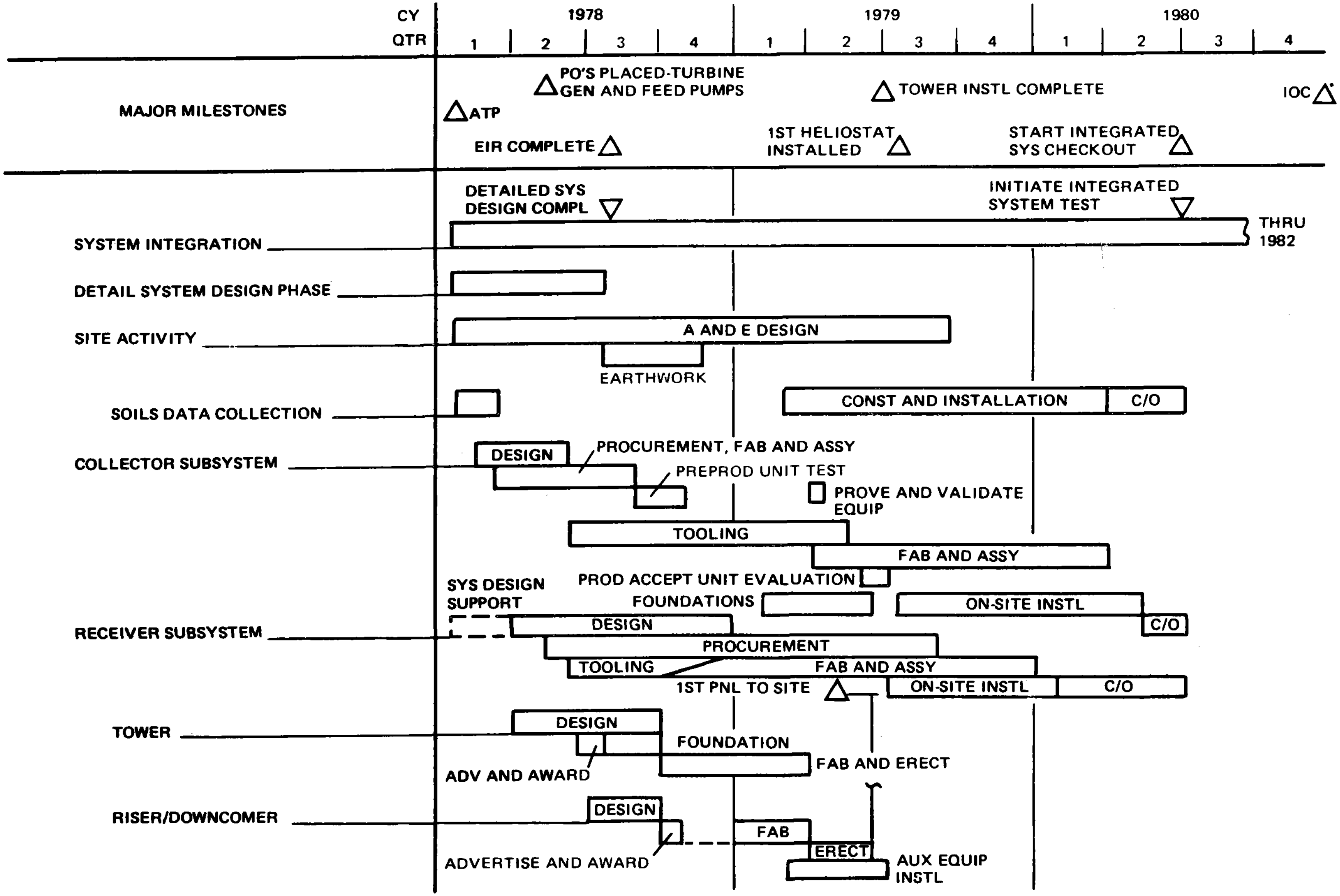


Figure 2-4. Master Program Phasing Schedule – Pilot Plant (Page 1 of 2)

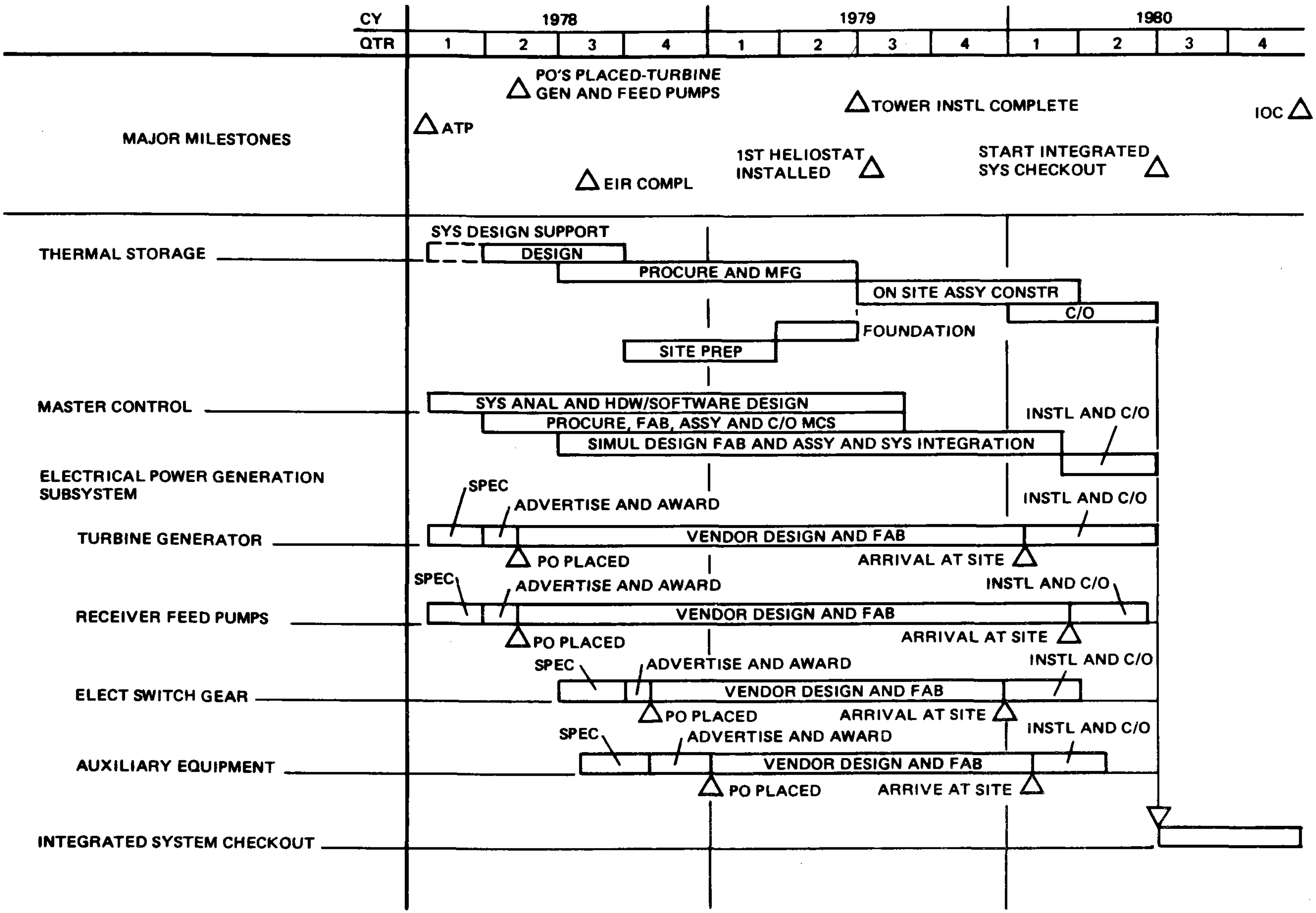


Figure 2-4. Master Program Phasing Schedule — Pilot Plant (Page 2 of 2)

- Implementing expedient changes to the subsystem control operations, procedures, and methods without disrupting the plant hardware configuration.

The solar power-generation plant differs from conventional plants in that the heat source is variable, thereby requiring continuous adjustments to maintain the proper temperature and pressure balances of the steam and feedwater system. Using master control in the automatic mode, variations from the balance are minimized. Balancing the variations is particularly important in order to initiate plant operation when sunlight is first available. In light of the fact that (1) the thermal storage is variable and limited to support steam and feedwater systems at start up, and (2) variations occur in receiver heat input because of fixed collector panel locations with respect to the receiver panels and the wide differences between winter and summer sunrises, strategy for getting the plant online in the shortest time possible is critical.

The computer system assures minimum deviations from the optimum path in plant startup. Master control flexibility provides the capability to implement effective controls to automatically correct receiver hot and cold spots, as well as correct position errors of the collector system based on receiver heat input. Using current meteorology data and continuously updated plant performance data, the computer can analyze and provide the plant operator with forecasts of collector position and heat input data along with optimized plant control parameters to use for the remaining solar day.

2.4.2 Description

Master control consists of the control and display hardware and the associated software necessary for coordination of all subsystem processes, either automatically or manually, under the direction of a single plant operator.

The MDAC concept of Pilot Plant master control is to provide a centralized operator control center with full manual controls as well as computer equipment to provide the flexibility for optimizing, expanding, and developing the Commercial Plant control performance criteria. Master control is also capable of being expanded and used for operating a Commercial Plant. The heart of the master control system is a commercially available minicomputer which communicates with each of the field controllers of the collector subsystem, the receiver subsystem, the thermal subsystem, and the electrical power-generation subsystem. The arrangement is shown schematically in Figure 2-5. A central control console provides for individual control and

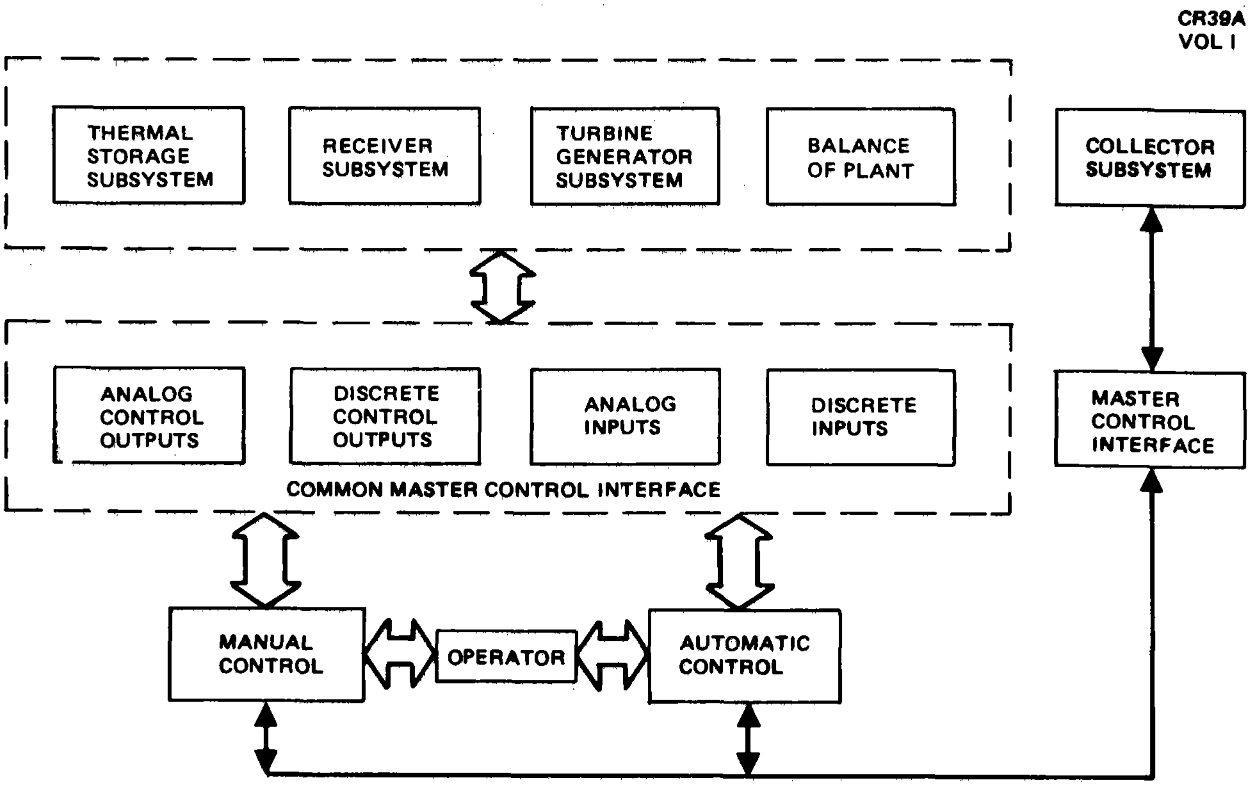


Figure 2-5. Master Control Element and Options

monitoring of the master control computer and each of the four subsystems. The plant operator may direct the master control computer to automatically coordinate the operation of all four subsystems, or place them under manual control. In addition, manual control of any one or more subsystems will facilitate plant development and system integration on a subsystem basis.

Master control was defined during Phase 1 and is being validated by simulation in the on-line simulation facility (OLSF) system at Huntington Beach. This hybrid analog-digital simulation of Pilot Plant will analyze total system behavior and subsystem interaction during transient operations. Software implementation will be established and confirmed in OLSF prior to actual system operation at the Pilot Plant site.

2.5 COLLECTOR SUBSYSTEM

2.5.1 Function

The function of the collector subsystem in the Central Receiver Solar Thermal Power System is to redirect and concentrate solar insolation on the receiver. This is accomplished by providing a working array of heliostats, which are sun-tracking mirrors with two-axis tracking capability. The energy absorbed by the receiver is used to convert preheated feedwater to superheated steam. The superheated steam is then directed to a conventional turbine and/or the thermal storage subsystem.

The collector subsystem developed by MDAC further provides the capability to orient the reflective surface such that the mirrors can be protected during inclement weather conditions. This provision offers the maximum degree of reflective surface protection presently considered to be within the state of the art for cost-effective heliostats.

2.5.2 Requirements

The principal collector subsystem requirements are as follows:

- The heliostat and its control system shall track the sun stably over the range of insolation from 300 W/m^2 to 1,100 W/m^2 and point the reflected beam toward the receiver with an accuracy of 1.7-mr standard deviation.
- The beam spread due to panel misalignment, surface waviness, and structural deflection shall result in a beam spread of 2.5-mr standard deviation for the operational ranges of wind up to 9 m/s temperature from 0° to $49^\circ C$.
- The heliostat and controls shall withstand a desert environment that includes high winds, rain, ice, snow, hail, high and low temperatures, and blowing dust without significant degradation for 30 yr.
- Critical components such as the drive unit and reflective surface shall fulfill a 30-yr service life.
- The collector subsystem must respond to master control orders for tracking, synthetic tracking, command positioning for maintenance, cleaning, stowage, etc., and to local manual control for maintenance and repair procedures.

2.5.3 Collector Subsystem Design Rationale

The heliostat employs flat, rectangular reflector panels. The panels are canted in the Pilot Plant design to provide a degree of focusing. The reflector is mounted on a central pedestal and employs rotary drives in an elevation/azimuth gimbal arrangement. The heliostat is arranged to provide for inverted or face-down stowage.

Closed-loop control employing a separately mounted beam sensor was selected for the Pilot Plant in Phase 1. An open-loop system is under evaluation and is expected to be recommended upon completion of testing later this year.

The principal rationale for the above selections are:

- Flat reflector surfaces reduce cost and technical risk.
- Foam-core panels provide rigidity and stability at low cost.
- Inverted stowage assures beam safety and reduces mirror soiling.
- Rotary drives supply accurate tracking at low cost throughout the required range of motion.
- Elevation/azimuth gimbals minimize survival wind loads (40 m/s winds).
- Closed-loop control was baselined as a verified, accurate control system at low cost.
- Open-loop control offers a probable further cost reduction.

A brief description of the collector subsystem preliminary design follows.

2.5.4 Collector Preliminary Design Description

The collector subsystem is separated on the component level into four categories: reflector, support pedestal foundation structure, drive unit, and heliostat controller. A sketch of the collector subsystem proposed is provided in Figure 2-6.

2.5.4.1 Reflector

The reflector consists of six panels having the configuration depicted on Figure 2-6. Each panel subassembly is made up of a second-surface silvered mirror, 3.24 mm (1/8 in.) thick of medium (0.55%) iron float glass adhesively bonded to a form core, which is in turn bonded to a thin galvanized steel back sheet. Each reflector subassembly panel yields an 2.16m x 2.9m in (85 in.

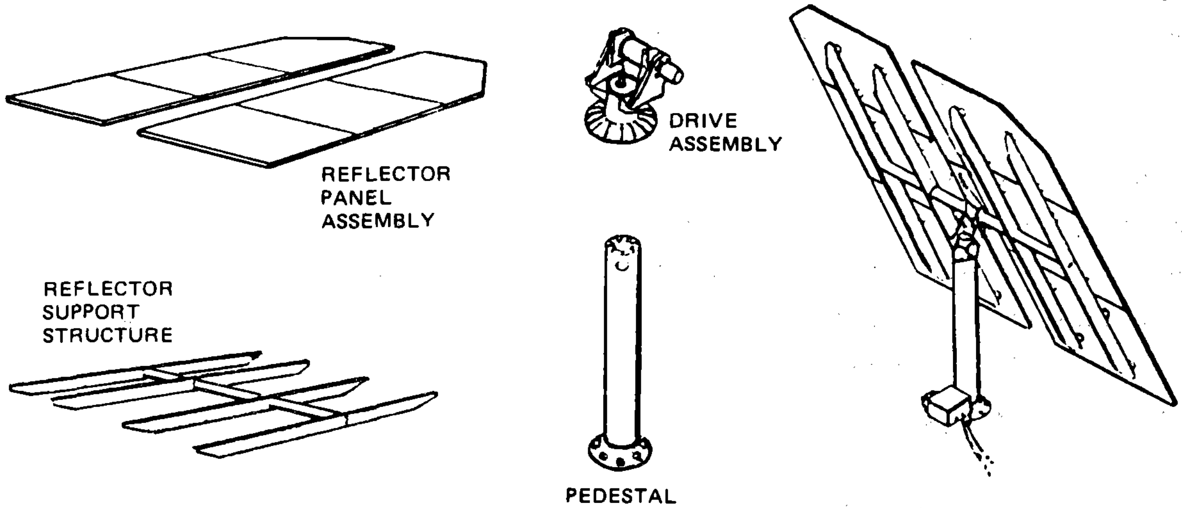


Figure 2-6. Heliostat Assembly

x 114 in.) overall dimension, thus providing for a total heliostat reflective surface area of $38 m^2$ ($408.3 ft^2$) including the tracking mirror. The mirror selected by MDAC will be of commercial grade quality as will be the foam core. Environmental protection of the reflector is provided by "treating" the panel edges with a polyurethane weatherseal compound. Attachment of each panel to the support structure is accomplished by four shallow circular steel cups bonded to the galvanized steel back sheet.

All of the reflector panels are identical in size except that the two "upper" panels have clipped corners. This feature is incorporated to maximize heliostat packing density and thus reduce land use requirements.

MDAC has also qualified a backup reflector using a laminated mirror as a substitute to the mirror/foam-core configuration. At present, we have not chosen this approach because of economic considerations.

2.5.4.2 Support Structure

The support structure consists of a main torque tube and four channel cross beams. As depicted in Figure 2-6, four cross beams provide the structural support for six reflector panels. The cross beams are spot-welded to the main torque tube, which is bolted to the heliostat drive unit. The main torque tube is attached to the drive unit by two fittings. Ring flanges attach the cross beams to the main torque tube. The slot formed between each panel group provides clearance for the pedestal when the reflector is rotated to the inverted or face-down stowage position.

2.5.4.3 Drive Unit

Control and positioning of each heliostat during normal sun-tracking, emergency slewing during high wind conditions, maintenance periods, and stowage is accomplished by the drive unit. Command signals to each heliostat drive unit are provided through the field controllers; they interface with the Pilot Plant master control.

The drive unit is primarily a speed reducer consisting of drive trains, motors, position feedback transducers, support bearings, and structural housing. The drive train incorporates a two-stage speed reducer coupled to a standard 240 VAC torque motor which will accommodate both the required normal sun-tracking speed and provide for reflector stowage in the appropriate time period dictated by environmental and structural considerations.

MDAC has, during the SRE Program Phase, qualified two different output and input stages for the drive unit, and, as such, will determine ultimate selection based upon further design and cost trade studies.

2.5.4.4 Heliostat Control

To maintain the proper heliostat-to-target (receiver) orientation during normal daylight operations, some form of heliostat control is required. Two methods are presently being considered by MDAC for the Pilot Plant program, i.e., "closed-loop" and "open-loop" control.

Closed-Loop Control

Closed-loop control is accomplished through the use of a sun sensor mounted on a separate pole between the heliostat and the receiver. The sun sensor is mounted such that the axis is oriented parallel to the line of sight to a predetermined aim point on the receiver. A portion of the reflected beam from the heliostat target mirror provides the required solar beam intensity to activate the photo-sensitive elements within the sun sensor. If the reflected beam is parallel to the sun sensor (proper heliostat orientation) a null signal is generated by the sensor and no command is given to the drive unit. If the reflected beam is not parallel to the sun sensor axis and within the sensor field of view, an error signal is generated, the controller processes the error signal and actuates the drive motors to null the error signal. Should the reflected beam extend beyond the sun sensor field-of-view (e.g., during passing closed cover or stowage), the heliostat will be controlled to gimbal axis positions determined by the master control.

The closed-loop control system approach has been demonstrated during the Phase 1 Subsystem Research Experiments Program.

Open-Loop Control

Open-loop control for heliostat positioning eliminates the need for a separate sun sensor and pole assembly. Rather than relying upon error signals generated through the sun sensor circuitry to the drive unit, an electronic device (shaft encoder) will be integrated into the drive unit controller that will measure drive shaft position. The heliostat position is compared to the "required" position determined by the field controller to generate error signals which will then be sent to the appropriate gimbal axis drive unit to reorient the heliostat.

Although MDAC has not, as yet, fully demonstrated the open-loop system, steps are being undertaken to validate this control system approach at present. Because of the substantial cost-saving potential, MDAC is strongly considering its adoption for heliostat control.

2.5.5 Design Verification

The objectives for the collector SRE were organized into specific tests designed to meet the verification requirements of Phase 1. The resulting tests are categorized into controls development structural tests, environmental tests, life tests, and subsystem-level array tests. A summary of the testing follows and detailed descriptions are in Volume III.

2.5.5.1 Controls Development Test

A controls development test was conducted to verify the field controller performance and stability, verify interfaces, and establish beam-pointing accuracy. The test, in addition to verifying the field controller and interfaces, established tracking performance of mr beam-pointing accuracy. This performance exceeds the nominal requirement of 1.7 mr.

2.5.5.2 Heliostat Structural Tests

Heliostat structural tests were conducted to verify heliostat strength, deflection, and fundamental vibration frequency. Complete heliostats of both the octagonal and inverted type were used. One segment or panel was given a finely distributed load. The remaining segments or panels were given concentrated loads simulating their contribution of total heliostats loading. The stress and deflection measurements were compared with predictions established from a finite element computer program (NASTRAN).

Deflection levels under the simulated operational loading of 11.6 m/s (26 mph) were within 10% of the predictions from the NASTRAN model. Measured strains under the survival wind load of 46.5 m/s (104 mph) for the octagonal heliostat and 44.7 m/s (100 mph) for the inverted heliostat were equal to or below NASTRAN predictions. Vibrational frequencies for pitch and yaw modes were within 5 to 10% of predictions based on the NASTRAN model. The closeness between the measurements and predictions verifies not only the heliostat design, but also the validity of the model for predicting the impact of potential future design improvements.

2.5.5.3 Environmental Tests

The drive unit, reflective surface, and controls sensors were subjected to environmental tests to verify their performance and survival during temperatures from -30°C (-22°F) to +60°C (140°F), rain to 5 cm (2 in.) per hour, icing from freezing rain, blowing dust, and hail impact up to 25 mm (1 in.). The drive unit was operated before, during, and after each test condition. Drive unit and controls sensors performance characteristics were monitored to detect any degradation of operating characteristics. No degradation of performance was observed in these tests. No indications of potentially damaging penetration of water or dust into the components was observed upon inspection. However, a buildup of ice on the linear actuator boot and around one potentiometer could be a problem if the drive unit is operated when severely iced.

The reflective surface was impacted with 19 mm (3/4 in.) and 25 mm (1 in.) spherical ice cubes at terminal velocity to determine whether hail impact will damage the reflector. Both first- and second-surface mirrors survived 19-mm hailstones without damage. However, some second-surface mirrors cracked when impacted near the corners by 25-mm hailstones. A passive protection against these larger hailstones may be required, depending on the plant site.

2.5.5.4 Life Tests

Life tests were conducted on the drive unit to simulate 30-yr lifetime operation. Post-test, backlash, compliance, efficiency, and tracking performance were compared to the pre-test values. After the equivalent 30 yr of operation, no significant changes in these key performance parameters resulted.

2.5.5.5 Array Tests

Beam quality tests were conducted at the Naval Weapons Center in China Lake to measure the flux distribution in the reflected beam. A digital image radiometer with an absolute calibration was used to acquire these data.

A prediction of total beam power was made; it accounted for the reflectivity of the heliostat, its orientation relative to the sun, absorption and scattering due to water vapor and aerosols between the heliostat and target, the A-D conversion of signals, and the low-intensity wings of the beam. The resultant measured beam power was within 3% of the analytical prediction.

The beam structure was also compared to predictions. This measurement both verified computer programs which predict receiver flux distributions and verified that the heliostat is properly aligned and within specified flatness tolerances.

Additional results from the heliostat array tests include the effect of environment and cleaning on mirror reflectivity, effects of environmental conditions on control, nontracking, and off-nominal operations, and data on installation operations and support concepts.

The above test program was successfully completed and the data obtained were used to support the preliminary design.

2.5.6 Conclusions

MDAC has conducted a series of environmental, life, and qualification tests which fully qualify the collector design. Because of these tests, it is envisioned that no significant testing will be required to build a fully satisfactory collector for a central receiver Pilot Plant.

Design data for the Pilot Plant preliminary design and detailed design have been obtained. These data include performance of the hardware and software and detailed data for evaluation of error budgets. The collector exceeds the performance and error requirements by a sufficient margin that the requirements can be relaxed in key areas to cause significant reductions in the collector costs at no loss to overall performance. An example of the above is a change to open-loop control.

2.5.7 Pilot Plant Manufacturing Plans

Production of the collector subsystem and ancillary hardware will be accomplished at MDAC-Huntington Beach and the MDAC facility at the Southern California Edison Coolwater Plant and with suppliers generally in the Los Angeles and Orange County industrial area. Wherever practical, the manufacturing processes and methods employed for the production of Pilot Plant hardware will be similar to that planned for the Commercial Plant. A brief review of the Pilot Plant manufacturing flow is depicted in Figure 2-7.

A series of operations are being planned to systematically develop and validate the production design, manufacturing, tools, processes, and procedures. The initial validation will occur through the manufacture of a "preproduction" heliostat using the final design drawings but without production tooling. This initial unit will form the basis to verify that the detail design drawings result in a finished product acceptable to MDAC. This will be followed by a second heliostat manufactured from the selected production tooling and processes. This unit may be considered as the final checkpoint before full-scale production begins.

To ensure an efficient and orderly integration of raw materials and components, buildup to the required production rate of 10 heliostats per day will occur over a period of approximately 2 mo. This approach will provide a

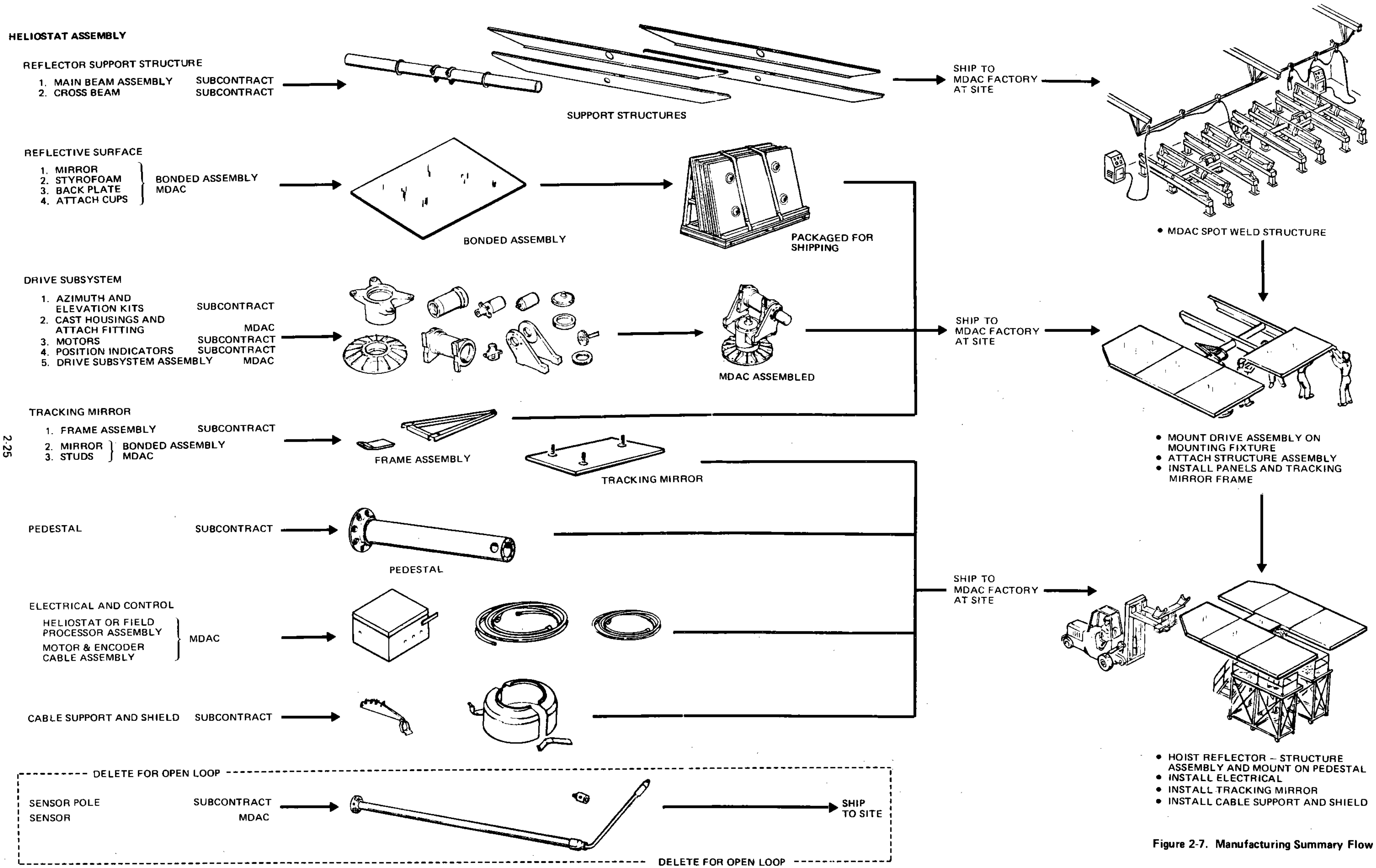


Figure 2-7. Manufacturing Summary Flow

reasonable time period during which the manufacturing and assembly personnel will be brought to a level of efficiency necessary to satisfy the production rate demands imposed by the program schedule.

MDAC is currently planning for the manufacture and assembly of critical hardware items such as the drive unit and reflective surface to be at the Huntington Beach facility. Subassembly of the structural elements as well as the final heliostat assembly will be performed on the SCE Coolwater Plant site in the MDAC assembly building. Upon completion of the heliostat assembly, it will be transported by forklift to the field for tiedown to the foundation. Transportation plans have been completed which outline the logistics from the acquisition of raw materials to the delivery of the completed heliostats at the foundations.

2.6 RECEIVER SUBSYSTEM

The receiver subsystem absorbs the solar insolation reflected from the collector subsystem, and converts water into superheated steam for delivery to either the turbine of the electrical power-generation subsystem or to the thermal storage subsystem. The receiver subsystem consists of the receiver unit, the tower on which the receiver unit is mounted above the collector field, and the supporting control and instrumentation equipment.

2.6.1 Requirements

The Pilot Plant receiver is required to accept water from the flow distribution system at 13.8 MPa (2,000 psia) and 250°C (401°F) and deliver superheated steam at rated conditions of 10.1 MPa (1,465 psia) and 510°C (950°F) to the turbine inlet of the electrical power-generation subsystem. Any rated steam generated in excess of turbine power requirements will be diverted to the thermal storage subsystem.

The receiver subsystem must also be capable of delivering steam at 10.45 MPa (1,515 psia) and 349°C (660°F) at the receiver outlet when it is required to divert the total receiver energy output into thermal storage.

The receiver must safely and efficiently absorb incident solar radiation at a maximum flux of 0.30 MW/m^2. In addition, the receiver must be able to accept, without damage, thermal gradients imposed by radiation transients from essentially zero to maximum flux in as little as 10 sec due to precipitation or the intermittent passage of clouds over the collector field.

As a forced flow steam generator, the receiver will be designed and certified to the requirements of Section 1 of the ASME Boiler and Pressure Vessel Code. Fatigue life verification will be made using the analyses techniques of Section VIII, Division 2 of the ASME code.

2.6.2 Rationale

The external receiver in a 360-deg configuration was selected in Phase 1. The description is summarized in subsequent paragraphs of this overview volume and in detail in Volume IV. The rationale for selection was:

- Lightweight reduces cost and increases seismic tolerance.
- Single pass to superheat eliminates steam drum, inherent weight, and operational lag.
- Single module for Commercial and Pilot Plant systems simplifies plant control and eliminates field piping.
- Modular construction provides low-cost assembly line production.
- Modular design allows rapid field installation and convenient maintenance with nocturnal panel removal and offsite repair.
- 360-deg configuration allows close proximity of heliostats, which results in lower heliostat tracking accuracy requirements and increases collector field interception factor.

2.6.3 Description

The Pilot Plant receiver design is a scaled-down version of the Commercial receiver. The fundamental concept of the MDAC receiver is its modular design. Thus, the basic receiver design performance characteristics are directly applicable to both Pilot Plant and Commercial Plant. Figure 2-8 shows the key features of the receiver.

The major hardware assemblies comprising the Pilot Plant receiver subsystem are the receiver unit, the tower on which the receiver unit is mounted above the collector field, and the supporting control and instrumentation equipment.

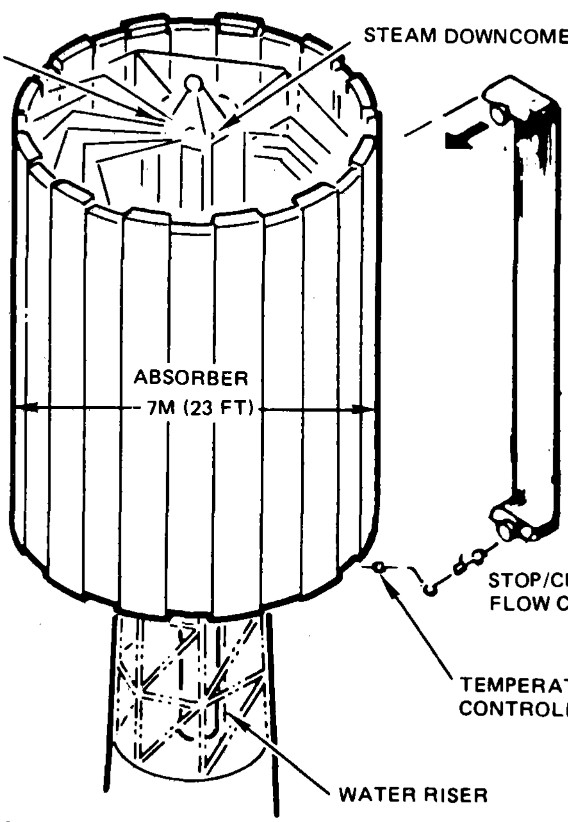


Figure 2-8. Pilot Plant Receiver

2.6.3.1 Receiver Unit

The receiver unit consists of six modular preheater panels and 18 identical boiler subpanels, flow control and instrumentation equipment, and the supporting structure.

All panel subassemblies are constructed of 70 tubes of high-strength, corrosion-resistant Incoloy 800 laid side-by-side and joined together thermally and structurally and made opaque to incident light by full-length longitudinal welds. Figure 2-9 displays a typical panel subassembly.

An Incoloy 800 water manifold at the lower end of the panel assembly functions to equally distribute water to all panel tubes. An Incoloy 800 steam manifold is also at the upper end of the panel subassembly to act as a collector manifold for the effluent steam from all tubes. To ensure leak integrity, all panel tubes are welded to both the water and steam manifolds. The surfaces of the tubes exposed to solar radiation are coated with Pyromark paint which has demonstrated an absorptivity of 95% over a wide range of wave-

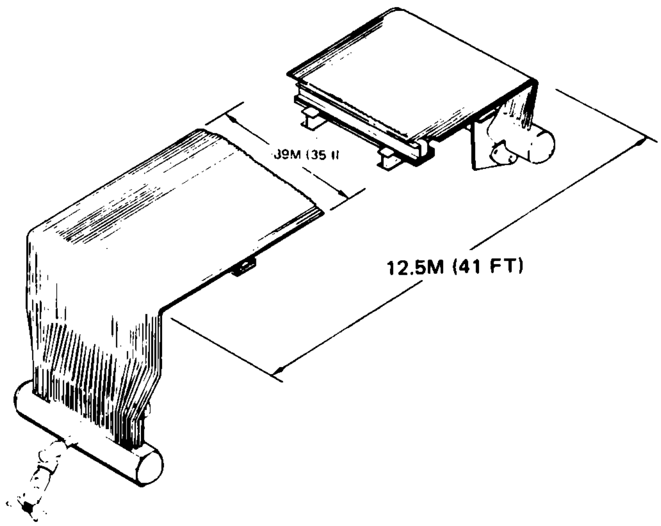


Figure 2-9. Pilot Plant Receiver Panel

lengths. Each panel is insulated on the backside to reduce thermal loss and protect the support structure and control components.

The individual tubular panel assemblies of the receiver unit are mounted on a central core steel support structure to form a single large and essentially circular (24-sided) cylinder 7m (23 ft) in diameter by 12.5m (41 ft) long. The heliostats surrounding the receiver tower direct their collected solar insolation onto the full 360-deg external surface of the receiver unit.

As the steam exits from each of the panel discharge manifolds, it passes through a cyclone water separator as a precautionary measure to ensure absolutely dry steam. The steam enters the downcomer collection manifold where it is mixed with the discharge flow from the other boiler panels and is finally carried away by the downcomer to the turbine of the electrical power-generation subsystem or the thermal storage subsystem or both as directed by master control.

2.6.3.2 Receiver Tower

The receiver tower is of steel construction and extends 65m (213 ft) above grade to the interface with the receiver unit steel support structure. This structure continues up through the receiver unit to an elevation of 84m (275 ft), where it is crowned with a service crane of 5-ton capacity. Mid-point of the receiver unit is 80m (262 ft).

The base of the tower is 12.2m (40 ft) square, tapering to 4.6m (12 ft) at the 65m elevation. The square concrete foundation is composed of a 0.61m (2 ft) thick mat which is 15.2m (50 ft) on a side and located 3.96m (13 ft) below finished grade. Concrete wall and pedestals extend 5.48m (18 ft) upward to meet the steel structure at an elevation of 1.52m (5 ft) above the grade. The receiver tower is shown in Figure 2-10.

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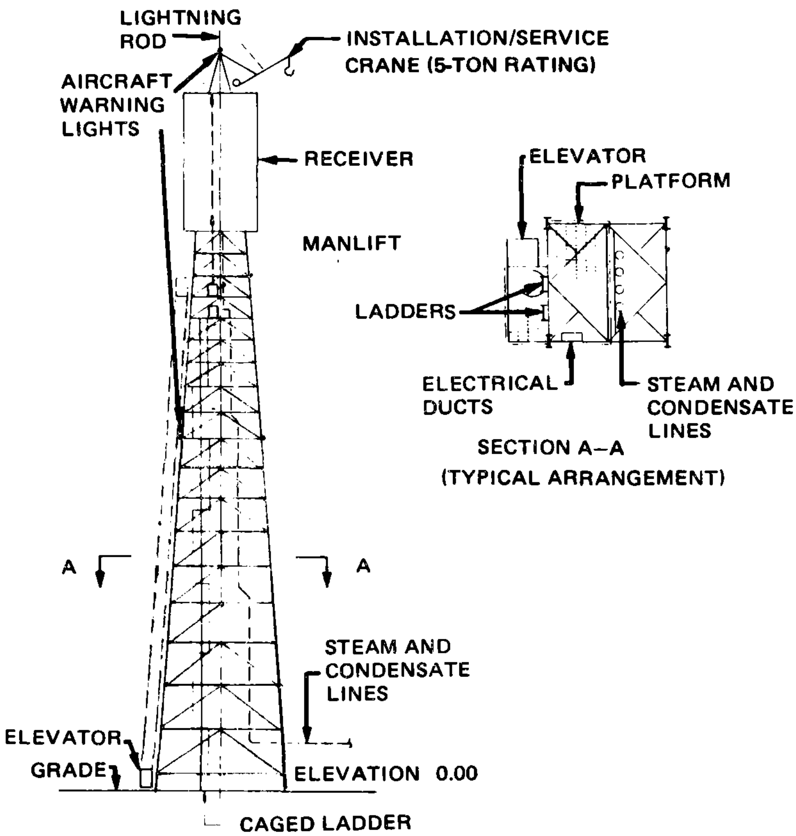

Figure 2-10. Pilot Plant Receiver, Tower, and Auxiliaries

2.6.3.3 Receiver Operation

Startup is initiated by introducing water from the water treatment equipment of the electrical power-generation subsystem and forcing it up the receiver tower riser by the receiver feed pumps and into the receiver inlet filter assembly at 13.8 MPa (2,000 psia) and 205°C (401°F). Leaving the filter assembly, the water enters a manifold which distributes the flow into the inlets of the three parallel sets of two panels in series located on the south side of the receiver and designated to function as preheaters. The water absorbs heat as it flows up through the first panel of each of the sets and then down the preheater through the second panel, where it joins the flow from the other preheaters in a ring manifold that supplies the remaining 18 panel assemblies designated as boiler panels. Passing through a modulating flow control valve located at the inlet to each boiler panel, the water again flows vertically upward, absorbing heat from the incident solar insolation at a level up to 0.3 MW/m^2 and leaving the upper end of the boiler panels as superheated steam. Individual boiler panel inlet valves provide the flow control necessary to maintain the selected outlet temperature of either 516^{o}C (960^{o}F) or 349^{o}C (660^{o}F) despite diurnal and seasonal variations in heat load at each panel. The control valves also control cloud-induced transients and regulate the startup and shutdown sequences. With this arrangement, active control of the water flow through the preheater panels is not required.

2.6.4 Test Verification

Proof of design concepts were accomplished through a series of Subsystem Research Experiments. These tests were designed to provide the feedback required to eliminate technical risks in the performance, control, stability, and mechanical integrity of the Pilot Plant receiver design.

Specifically, the parameters evaluated during Phase 1 testing were:

- Performance. Deliver specified steam conditions over the required range of input and output power.
- Cooling Capability. Withstand peak heat flux and heat loads, as well as gradients within a panel.
- Stability. Provide stable flow over the entire Pilot Plant power/flow spectrum.
- Life. Capable of operating over 30 yr (10,000 cycles).
- Structural. Withstand combined wind, seismic, pressure, and thermal loads.
- Clouds. Capable of accommodating passing cloud cover over the collector field.

The verification was accomplished through the following tests:

- Single tube test to establish initial flow stability and cooling capability.
- Narrow panel test to verify multitube stability, cooling, and fatigue characteristics over normal and emergency range of Pilot Plant operating conditions.

- Full-scale Pilot Plant panel assembly test over complete range of operating conditions to demonstrate performance, cooling, stability, and structural capability.
- Panel surface coating test under concentrated sunlight conditions.

Results of the tests were as follows:

- The fabrication methods and materials selected for the Pilot Plant receiver are compatible with the production of a boiler compatible with Section 1 of the ASME boiler code.
- Transportation and handling of the panel in both urban and business areas are practical and can be accomplished without specialized equipment.
- The devices which provide for thermal expansion of the panel function very satisfactorily.
- The panel can operate at maximum Pilot Plant heat fluxes with the tube temperatures well below the predicted values. Differential tube temperatures were such as to ensure a 30-yr panel life.
- During steady-state operation, flow is uniform from tube to tube and is stable, even under extreme variations in pressure, flow, or solar insolation.
- The panel can survive flow cessations for significant periods without excessive temperatures of damage.
- The panel control loop will automatically maintain steam outlet conditions within specified limits under anticipated transient conditions of pressure, flow, or insolation.
- The panel can reach steady-state temperature conditions in 7 to 12 min (depending on the heat flux) after a constant heat load is applied.
- Flow stability and uniformity were maintained in the full-scale panel without orifices.
- The receiver surface coating maintains high absorptance under extended cyclic and concentrated insolation.

2.6.5 Manufacturing and Installation Plan

The receiver unit consists of the insolation absorbers, feedwater and steam piping with all filters, instrumentation and control, flow control, safety relief and servicing valves, and the structural steel supporting structure.

A manufacturing flow diagram is shown in Figure 2-11. The flow used is identical to that used during SRE. The tubes are drawn and delivered in 100-ft straight lengths. The tubes are initially formed, trimmed, and welded into approximately 10 tube bundles. The 10 bundle ends are folded over and then welded into full-width panels. The end manifolds are installed and the tubes expanded and seal-welded in place. The remainder of the manifolds are welded into place and the assembly pressure-tested. The backup structure is added and a handling fixture is attached so the assembly can be raised to a position where it can be grit-blasted and painted. This fixture will also be used to stabilize the assembly during shipment and field installation.

The piping, pipe fittings, servicing valves, flow-control valves, safety relief valves, instrumentation, etc are delivered directly to the field site from suppliers. The pipe, fittings, valves, etc. are then integrated (welds inspected and X-rayed as required) into reasonable assemblies for raising and welding into place in the receiver. The welds in the receiver are inspected and X-rayed as required. Then the system is pressure-tested, leak-checked, and insulated.

The design will be accomplished in a manner that will permit fabrication of welded assemblies in the shop; these assemblies will generally be joined at the field site with high-strength bolts. Welding will be used at the field site only when it is more desirable or economical to do so. The fabricated assemblies will be trucked to the site. The crane used for the erection of the base tower will be used to erect assemblies. Crane capacity will determine the size and weight of shop-fabricated assemblies. Final painting will also be accomplished in the shop with only touchup after erection.

The absorbers, controls, instrumentation, etc are installed after fabrication of the supporting structure and the feedwater and steam systems are complete. The last picture in Figure 2-11 shows installation of the absorbers on

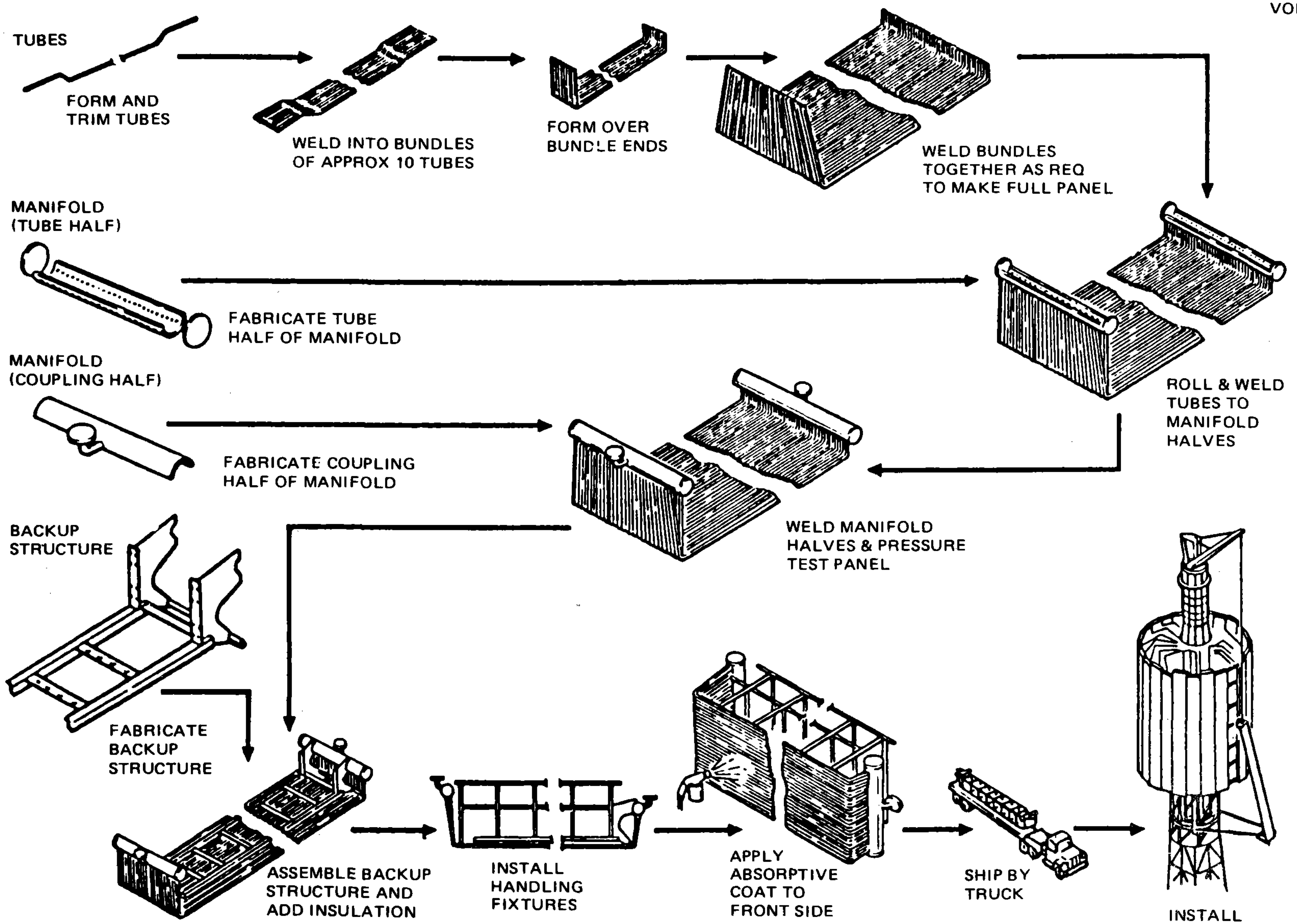

Figure 2-11. Fabrication Flow Diagram, Absorber Panel

to the receiver. The only attachments to be made are the bolted inlet and outlet flanges and bolts securing the absorber backup structure to the receiver structure.

All instrumentation and control electrical and pneumatics are hooked up after the absorbers are installed.

2.6.6 Conclusions

The MDAC-Rocketdyne receiver design team has conceived, designed, fabricated, and proven by test the solar design which best satisfies the specified solar Pilot and Commercial Plant criteria. The features of this design are summarized as follows:

- Simplified system with single receiver and shorter
  tower at 10 and 100 MWe.
- Development flexibility.
  Adaptable to optimum system design.
  Qualify full-scale Pilot Plant panel.
- Rapid thermal response.
- High seismic tolerance.
  Ease of manufacture.
  Simple, welded straight tube panels.
  Assembly line for identical panels.
- Ease of assembly.
  Modular panels.
- Ease of maintenance.
  Quick panel replacement.
  Short cooldown time.

These features result in:

- Competitive Pilot Plant cost.
- Lower Commercial Plant cost.
- Lower operational cost.
- Less complex plant control.

2.7 THERMAL STORAGE SUBSYSTEM

The thermal storage subsystem (TSS) buffers the electrical generating subsystem of the plant from short-term variations in insolation and extends the plant's generating capacity into periods with low or no insolation.

2.7.1 Requirements

The Pilot Plant TSS has the same general requirements as the Commercial Plant TSS and must buffer the electrical power-generating subsystem from excessive variations in insolation, and extend the plant's generating capacity into periods with low or no insolation.

The TSS is required to have an extractable storage capacity of at least 103.8 MWht, which is composed of 7.5 MWHt to provide a turbine hot start and 96.3 MWHt to permit the turbine-generator to supply 7 MWe net (7.8 MWe gross) for 3 hr following turbine startup. This extractable capacity is to be available following a full charge and a 20-hr hold period. The required charging rates are 1.5 MWt (rated steam operation) to 30 MWt (derated steam operation). The maximum allowable heat loss is 3% of extractable capacity in 24 hr, starting in a fully charged condition. Required discharge rates are 3.1 to 32.1 MWt. The subsystem is required also to provide night-time seal steam at a temperature of at least 135°C (275°F) and at a rate of 0.33 MWt for approximately 16 hr.

There are five fluid streams crossing the boundaries of the TSS, and each is a water or steam flow. A major requirement is to accept steam from the receiver at 343°/510°C (650°/950°F) and 10.1 MPa (1,465 psia), where the two sets of temperatures correspond to derated and rated steam operation, respectively. Another major requirement is to supply steam from the TSS steam generator for the turbine at 277°C (530°F) and 2.76 MPa (400 psia).

2.7.2 Rationale

The TSS selected during Phase 1 for Pilot Plant was a sensible heat storage system using dual media (liquid and solid) with the thermocline principal applied to provide a constant-temperature source independent of residual energy. The rationale for selection was:

- Sensible heat is low technical risk.
- Dual media (inexpensive rocks and hydrocarbon fluid) reduces cost.
- Thermocline principal (sharp thermal gradient) reduces storage volume and tank costs.

- Operation in single state reduces complexity.

2.7.3 Description

The Pilot Plant TSS employs sensible-heat storage using dual liquid and solid media for the heat storage in a single tank, with the thermocline principle applied to provide high-temperature, extractable energy independent of the total energy stored.

Figure 2-12 is a schematic diagram of the TSS, showing all major components, lines, and major control concepts. Process flow conditions are shown at various points in the subsystem. As shown in the figure, the subsystem can be considered in three major parts: (1) central thermal storage unit (TSU), (2) thermal charging loop, and (3) heat-extraction loop. In the charging loop, energy is removed from the receiver steam and stored in the TSU tank. A commercial heat-transfer fluid, Caloria HT43, is used to permit economical ambient pressure storage in the tank. The extraction loop uses the fluid to remove energy from the storage unit and produces steam for either turbine operation or equipment heating.

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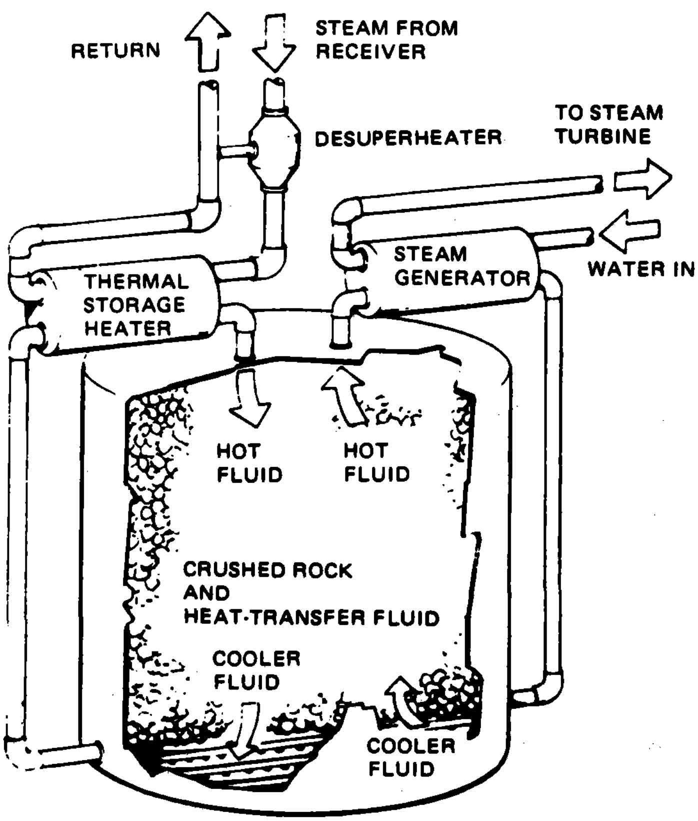


Figure 2-12. Thermal Storage Subsystem

2.7.3.1 Thermal Storage Unit

The TSU is a single cylindrical tank, axis vertical, installed above ground, with dimensions of 15.25m (50.0 ft) diameter by 13.4m (44.0 ft) high. The volume is 2,447m^3 (86,400 ft^3, 646,000 gal). It contains 4.53 x 10^6 kg (4,990 tons) of granite rock and course silica sand (approximately 2:1 rock and sand by volume) and 525,000 liters (139,000 gal) of Caloria HT43 heat-transfer fluid. The fluid temperature operating range is from 218° to 302°C (425° to 575°F). It is fabricated of ASTM A537-70 Class 2 structural steel by field-welded construction.

2.7.3.2 Ullage Maintenance Unit (UMU)

The UMU accomplishes storage and control of ullage gas with compressed gas storage at 1.38 MPa (200 psia). The unit also provides tank pressure control, venting, inert gas (nitrogen) control, volatile vapor recovery, and control.

2.7.3.3 Fluid Maintenance Unit

This hardware item features full-flow, continuous filtration with dual 80-mesh filters upstream of pump; periodic distillation with vacuum distillation unit is side-stream to remove polymerized materials; periodic fluid makeup capability is provided.

2.7.3.4 Desuperheater (DSH)

The DSH comprises a direct contact mixing chamber with water injected through multiple atomizing nozzles into superheated steam. It is a single unit with three nozzles.

2.7.3.5 Thermal Storage Heater

The heater is a two-stage (series) module. It features U-tube, baffled, counter/crossflow exchangers; two modules in parallel are used, with steam/water on the tube-side.

2.7.3.6 Steam Generator

Three-stage (series) modules are used, each with separate feedwater preheater, boiler, and superheater. The steam generator has two modules in parallel, with steam/water on shell side. Construction is of carbon steel.

Additional characteristics are as follows:

- Preheater is straight tube, floating head, counterflow exchanger.
- Boiler is horizontal U-tube kettle boiler.
- Superheater is horizontal U-tube, crossflow exchanger.

2.7.3.7 Fluid Charging Loop Pump

Two identical pumps are used in parallel. They are centrifugal, high-temperature type, with dual-speed electric motors.

2.7.3.8 Fluid-Extraction Loop Pump

Two identical pumps are used in parallel. They are centrifugal, high-temperature type with single-speed electric motors.

2.7.4 Test Verification

The SRE were conducted to provide data on system and components for design of the Pilot and Commercial Plants. The major test objectives were:

- Evaluate heat-transfer fluid thermal stability, compatibility, and surface fouling characteristics.
- Evaluate charging and extraction capabilities of a scaled TSU.
- Obtain performance of the TSU over all ranges of equivalent operating conditions in the Pilot Plant.
- Demonstrate stable operation for high, low, intermittent, and no insolation conditions.
- Demonstrate mode changeover and emergency operation.
- Evaluate the fluid under operational conditions.
- Determine the strain due to rock/wall interactions.

Characteristics of candidate heat-transfer fluids were evaluated in a series of fluid prequalification and life tests. These were conducted on three commercial fluids: Exxon Caloria HT43, Monsanto Therminol 55, and Monsanto Therminol 66. These tests further supported the choice of Caloria HT43, and demonstrated that it can fulfill the requirements of this solar power application. This fluid was found to have excellent stability and compatibility with rocks and materials of construction in tests up to 316°C (600°F) and for durations corresponding to about 4-yr equivalent in Pilot Plant operation. In addition, Caloria HT43 was found to develop no problems in fouling of heat-transfer surfaces in tests of nearly 4 yr in equivalent Pilot Plant operation.

Test objectives relating to the subsystem and operational characteristics resulted in a series of SRE subsystem tests. All test objectives were met or exceeded, culminating in a 3-mo test program completed in December 1976. A large variety of tests were conducted with thermal charging and discharging rates from 0.1 to 2 MWt and with hold periods up to 144 hr. The performance of the subsystem was excellent. Sharp, stable thermoclines were present, even during partial charging and discharging, with variable rates and under repeated cycling. The performance of the thermal storage unit was even better than expected during design for a unit of this size. The unit delivered over 5.1 MWHt of energy, which exceeded the design goal of a minimum of 4 MWHt.

Thermal Storage Subsystem SRE Results were as follows:

- The practicality and high performance of the dual-medium thermal storage concept have been demonstrated on a significantly large scale. Scale-up to the 10-MWe Pilot Plant can now be made with high confidence.
- The development and vertical movement of a sharp thermal gradient of thermocline in a dual-medium (liquid-solid) system is a predictable and reproducible phenomenon.
- Thermocline integrity and stability are high enough to provide high energy recovery performance for daily operation.
- Partial charging and extraction, and repeated cycling, do not significantly degrade the thermocline.
- Fluid flow and temperature uniformity are high across the TSU cross section. Flow channeling is insignificant in the SRE unit.
- Heat loss from the TSU is not severe. With larger units or improved insulation, little energy would be lost over typical hold periods of 1 to 8 hr.
- The use of low-cost, commercial river bed gravel provides adequate performance. Conventional filters incorporated in the charging circuit are adequate to rapidly remove, in situ, dust from the rock bed.

- For the test time accumulated, tank wall stresses were far below design values (i.e., passive load design), and there was no indication of high stresses induced from rock settling and packing. However, this may be a time-related effect and should be verified by continuing cyclic heating and cooling over a longer period of time.
- Initial removal of water from the bed occurs readily and controllably during initial bed heating. No special design features other than adequate vapor venting are necessary for water removal.

2.7.5 Manufacturing and Installation Plan

The manufacturing and installation plans for this subsystem are relatively simple in scope.

The heat exchangers will be fabricated by firms specializing in the production of commercial shell and tube exchangers with special consideration given to those firms having designs and standard components that most closely approximate the required units.

The TSU tank will be purchased from a fabricator specializing in on-site construction of API storage vessels. Special consideration will be given to those firms having complete off-site, prefabrication facilities.

The equipment items will be catalog equipment or supplier modifications of catalog equipment. Modifications will be described by specification permitting competitive bidding by all suppliers of similar equipment. Long-lead equipment items will be purchased separately. All other equipment will be purchased separately. All other equipment will be purchased by the mechanical contractor.

Construction will be separated into three discrete tasks, as follows:

A. Site preparation, followed by foundation construction.
B. Erection of the TSU; this is a discrete work task that will be performed as a continuation of the job prefabrication phase.
C. Remainder of the construction scope. This task will be given to a mechanical contractor who will subcontract controls, electrical, insulation, paint, and other separable specialty tasks.

The TSU will be field-erected as soon as shop fabrication and site foundations permit. Major items will be installed so that piping and installation of minor equipment items can begin.

The ullage maintenance unit will be field-fabricated as part of the system fabrication. No off-site work is required. Test and checkout of the ullage maintenance unit can be performed independent of the system.

The fluid maintenance unit will be installed as part of the system piping and requires no off-site fabrication or special handling. The filter vessels will be procured as equipment items. The distillation subsystem will be assembled on site as part of the mechanical installation. The heat exchangers, including the thermal storage heater, steam generator, and desuperheater will be installed on foundations by the mechanical contractor. These items are pacing items in the production plan because their installation is necessary before piping can be started.

2.7.6 Conclusions

The MDAC-Rocketdyne thermal storage subsystem design team has conceived, designed, fabricated, and proven by test the solar design which best satisfies the specified solar Pilot and Commercial Plant criteria. Some of the features of the subsystem are:

- Charging rates, 0.1 to 1.0 MW.
- Extraction rates, 0.15 to 2.0 MW.
- Charging hours, 85.
- Extraction hours, 25.
- Duty cycles simulated.
- Hot holds up to 100 hr.

2.8 ELECTRICAL POWER-GENERATION SUBSYSTEM

The electrical power-generation subsystem (EPGS) transforms steam from the receiver subsystem and/or thermal storage subsystem into electrical energy — the net output of the Central Receiver Solar Power Plant.

2.8.1 Description

The EPGS selected for the Pilot Plant consists of a nominal 12.5-MWe (gross) industrial turbine-generator set using wet cooling for heat rejection. The EPGS includes an in-line demineralizer and polisher for maintaining feedwater quality, a low-pressure feedwater heater, a deaerator for oxygen removal, and two high-pressure feedwater heaters for improved cycle efficiency. Brief discussions of the turbine and the selection of steam conditions follow.

2.8.1.1 Turbine

The turbine selected for the Pilot Plant is a tandem compound, single automatic admission, condensing unit of the same type intended for the Commercial system.

The turbine consists of high-pressure and low-pressure sections. The higher pressure steam (receiver steam) is supplied to the high-pressure turbine inlet valves, and the lower pressure steam (from thermal storage) is supplied through the automatic admission port ahead of the low-pressure section. The admission pressure is regulated by an electrohydraulic control system.

The type of turbine (automatic extraction or admission design) is widely used in various industrial installations, and it was selected over the conventional utility turbine for the EPGS because of its dual admission feature which lends itself to working with two steam sources of different pressure and temperature characteristics, such as we experience on this solar power plant.

From an operational standpoint, the single automatic admission turbine offers the following advantages over a conventional utility turbine:

- The changeover from receiver steam (high pressure) to thermal storage steam (low pressure) can be done instantaneously, from a turbine standpoint, without limiting the cyclic life of the turbine due to temperature transients.

- The turbine is capable of operating on both receiver steam and thermal storage steam simultaneously to generate the required load.

- The automatic admission feature will permit turbine startup on relatively low-pressure, low-temperature thermal storage steam, if required.

The Pilot Plant EPGS turbine-generator is sized to produce 11,200 kW electrical gross generation (10,000 kW net) when operating entirely from receiver steam at Winter solstice, 2 PM, which is the design point for the system. The turbine is also capable of producing 12,500 kW gross (11,100 kW net) during equinox noon, which corresponds to the maximum power collection time.

When operating entirely from storage steam, the turbine-generator will produce 7,800 kW gross (7,000 kW net) for 3 hr. The turbine back pressure for both the receiver steam and storage steam operating conditions is 8.46 kPa (2.5 in. HgA).

2.8.1.2 Turbine Inlet/Admission Steam Conditions

The turbine inlet steam conditions for both the Commercial Plant and Pilot Plant turbines are 10.1 MPa (1,465 psia) and 510°C (950°F). This selection was made for the following reasons:

- Compatibility with thermal storage charging requirements.
- Compatibility with admission steam conditions.
- Moisture limitations at the exhaust end of the turbine.

With respect to admission steam conditions, that is, steam from thermal storage, the requirements for the outlet steam conditions leaving the steam generator are determined by the temperature of the thermal storage fluid entering, namely 302°C (575°F). The temperature and pressure of the steam at the steam generator outlet are 277°C (530°F) and 2.76 MPa (400 psia), thus providing approximately 47.8°C (86°F) superheat in the steam being supplied to the turbine. For this temperature level, it is desirable, from a turbine standpoint, to keep the pressure as low as practical to increase the degrees of superheat and thus minimize the moisture content of the steam entering the last stage of the turbine.

2.8.2 Requirements

The basic performance and operating requirements for the Pilot Plant EPGS are as follows:

		Requirement Source
Gross Turbine Output		
Daytime (Design-Winter Solstice, 2 PM)	11.2 MW	MDAC
Nighttime	7.8 MW	MDAC
Net Turbine Output		
Daytime	10.0 MW	DoE/Sandia
Nighttime	7.0 MW	DoE/Sandia
Turbine Inlet Conditions		
Daytime (Receiver Steam)		
Pressure	10.1 MPa (1,465 psia)	MDAC
Temperature	510°C (950°F)	MDAC
Throttle Flow	12.93 kg/sec (102,440 lb/hr)	MDAC
Nighttime		
Pressure	2.65 MPa (385 psia)	MDAC
Temperature	274°C (525°F)	MDAC
Admission Flow	13.21 kg/sec (104,700 lb/hr)	MDAC
Turbine Exhaust Pressure		
Daytime	8.46 kPa (2.5 in. HgA)	MDAC
Nighttime	8.46 kPa (2.5 in. HgA)	MDAC
High Rejection		
Method	Wet Cooling	DoE/Sandia
Wet Bulb Temperature	23°C (73.4°F)	DoE/Sandia
Generator Output		
Generator Rating	16,000 kVA	MDAC
Power Factor	0.85	MDAC
Voltage	13,800V	MDAC
Frequency	60 Hertz	MDAC

		Requirement Source
Main Transformer		
Rating	12/16 MVA OA/FA	MDAC
Voltage	13.2/115 kV	MDAC
Feedwater Conditioning		
Dissolved Solids	20-50 ppb	MDAC
pH	9.5	MDAC

2.8.3 Conclusion

The output of the solar power generator plant is through a conventional steam-powered electric generator. Its operational performance is affected by the operation of the other subsystems and is required to be in the control chain for the system. Optimization of the central receiver system requires that each element in the system be linked with all other elements through the master control subsystem. The importance of these functional interfaces is depicted schematically in Figure 2-13.

2.9 PILOT PLANT OPERATIONAL TEST

MDAC has developed the initial concept for a Pilot Plant operational test. The test program will concentrate on validation of technical performance. The planning will incorporate systematic introduction of design refinements responsive to the Department of Energy, Sandia, and Southern California Edison use of the Pilot Plant for system demonstration. An artist's concept of the Pilot Plant construction phases are depicted on Figure 2-14.

The resulting operational test program is divided into three phases as follows:

- Phase A. Subsystem Installation and Test (12 mo)
- Phase B. Integrated System Tests (6 mo)
- Phase C. Operations Tests (24 mo)

The broad objectives of each stage are:

Phase A. Verify the proper installation and performance of each subsystem individually. No steam will be generated. Phase A will be completed when subsystem installation and performance (internal to each subsystem) have

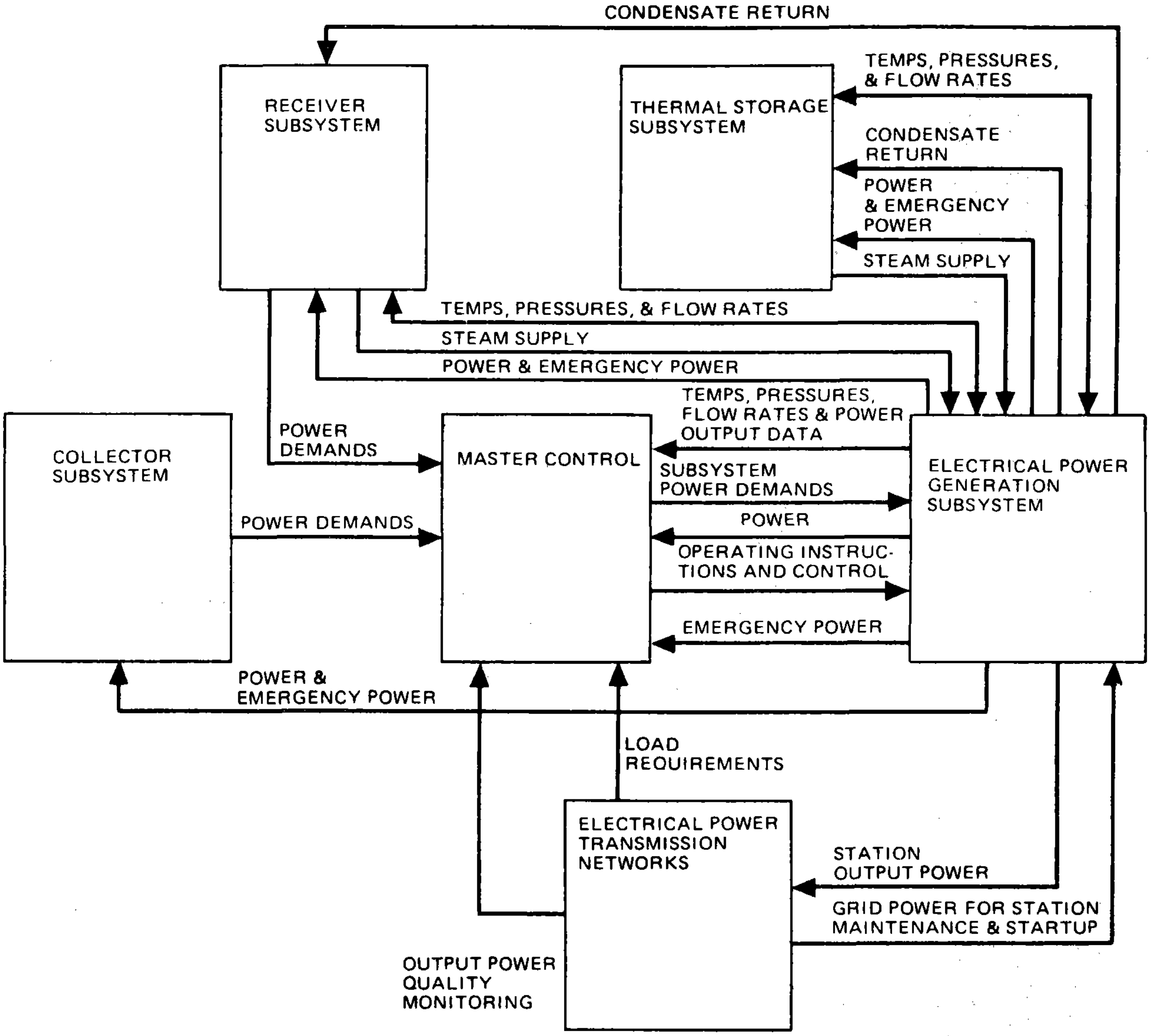


Figure 2-13. Functional Interfaces For EPGS and Other System Elements

been verified and all electrical and mechanical installations between subsystems completed.

Phase B. Verify the integrated performance of each system including all subsystem interfaces. Both steam and electricity will be generated during this phase but the electricity generated will only be for the purpose of demonstrating satisfactory subsystem performance, including all interfaces. Phase B will be successfully completed when all integrated subsystem performances have been verified.

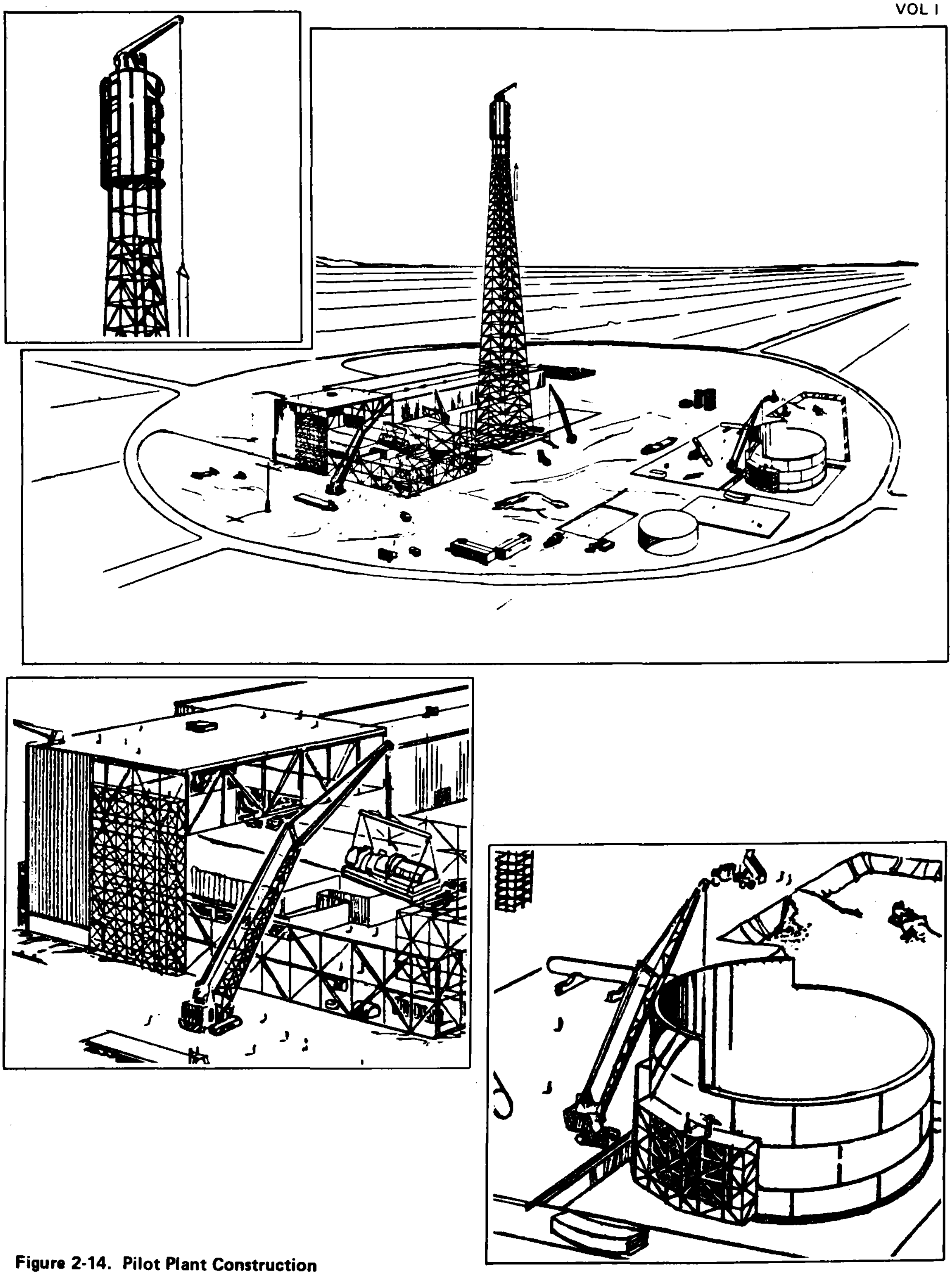


Figure 2-14. Pilot Plant Construction

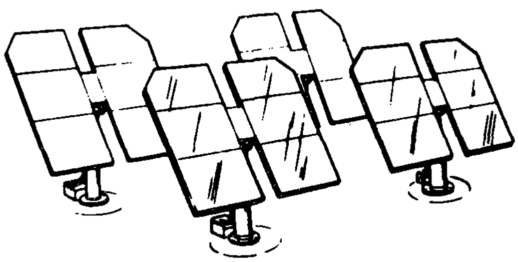
Phase C. Demonstrate the technical feasibility of a Commercial-sized solar thermal electric system and gather data to provide an indication of system economics. Both steam and electricity will be generated during this phase in all required system modes of operation — normal solar, low solar power, intermittent clouds, extended operation, thermal storage charging, and fully charged thermal storage. Phase C will be successfully completed when sufficient data have been collected and analyzed to (1) verify plant operation performance requirements under all required modes of operation, and (2) provide an indication of system economics.

Section 3
COMMERCIAL SYSTEM

- Lowest cost per unit of energy (mills/kW-hr).
- Design baseline for Pilot Plant preliminary design.
- Critical subsystem designs verified by SRE test.
- First Commercial cost projections based on detailed estimating methodology.
- Nth plant cost projection based on conceptual design of automated manufacturing facility.

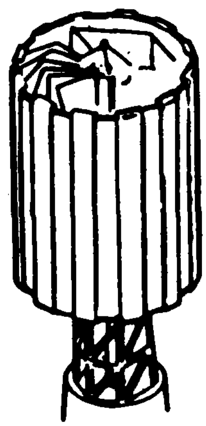
COLLECTOR

- Compatible with both cavity and external receivers.
- Constructed of flat panels minimizing risk and costs.
- Design verified by test.
- Identical to Pilot Plant and SRE.



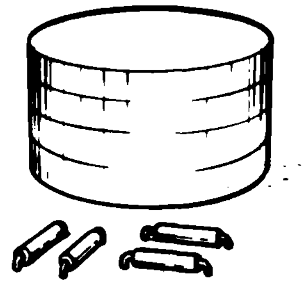
RECEIVER

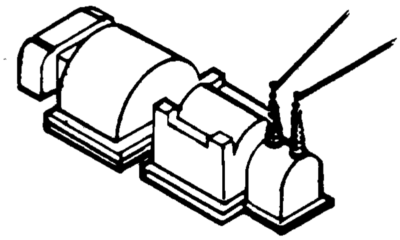
- Modular design for flexibility and producibility.
- Single tower.
- Low thermal mass.
- Minimum heat loss.
- Design verified by test.



THERMAL CONTROL

- Cost-effective, large-scale storage through use of Caloria and rock mixture.
- Steady-state source of turbine steam.
- Design verified by test.



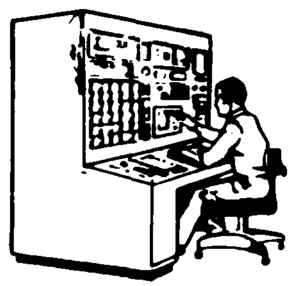


ELECTRICAL POWER GENERATION

- Commercially available.
- Compatible with steam conditions from thermal storage and receiver.

MASTER CONTROL

- Provides flexible reaction to variable solar insolation.
- Computer control available to optimize system operation.
- Single operator manual option.



The Commercial system definition was developed to provide a baseline for all Pilot Plant design and Subsystem Research Experiment (SRE) activities because Commercial use of solar thermal central station power plants is the primary program goal. In defining the Commercial system, priority was given to a configuration which can produce electricity at the lowest possible cost per unit of energy (mills/kW-hr) while satisfying the anticipated utility requirements.

The conclusions resulting from the Phase 1 study effort indicate that an external receiver with a 360-deg collector field is the most cost-effective approach to system design. The lower average collector field performance associated with a partial southern field layout and the higher heat losses associated with the external receiver are more than offset by the ability to use a single, shorter tower with lighter loads to support. The full 360-deg collector field allows a large number of heliostats to be placed close to the receiver. This is particularly important considering atmospheric attenuation factors and beam-dispersion effects from remote heliostats. The thermal responsiveness of the external receiver is compatible with the highly transient nature of the incident solar radiation. A multiple-panel single-pass-to-superheat approach was selected. The low thermal mass and the external nature of the panels permits rapid cooldown and ease of maintenance, which result in higher availability levels than that provided by a cavity-type receiver with a steam drum and relatively high thermal mass.

From the standpoint of receiver size, single- and multiple-module approaches were considered as alternatives for Commercial (100 MWe) system design. The results of a study comparing 1, 3, and 10 modules are shown in Figure 3-1. It is apparent from the tradeoffs that the single-module approach

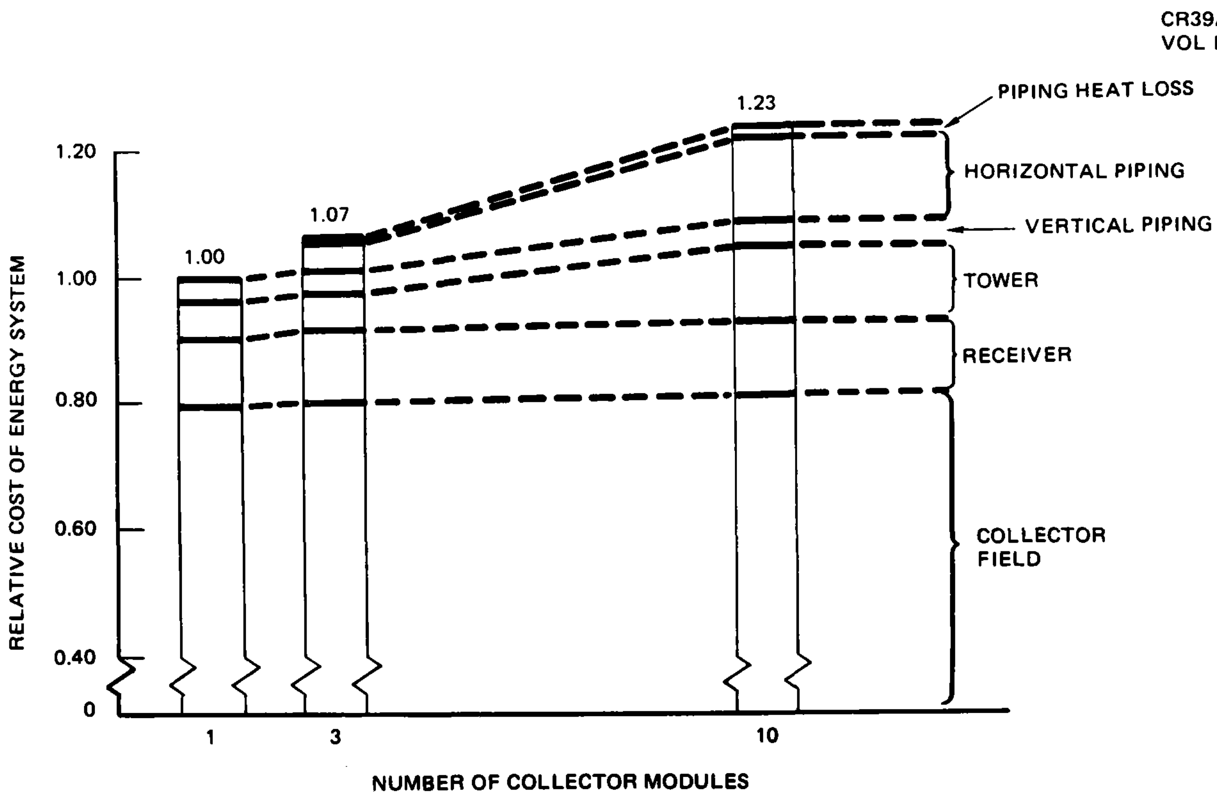


Figure 3-1. Impact of Multiple Modules on Cost (506 MW Peak Absorbed Power)

provides minimum costs for the system. The study was based on a total field size necessary to provide a 1.7 solar multiple. Implicit in the analysis are the assumptions of identical receiver performance in all cases (normally the smaller units would have a lower performance), geometrically identical collector fields, and negligible pressure drop in the interconnecting piping. The increase in relative cost as more smaller modules are assumed is due primarily to the addition of an extensive horizontal piping network, which is expensive and experiences heat loss over a 24-hr period, and an increase in tower costs associated with building many shorter towers as opposed to building a single larger tower. If the piping pressure drop effects were considered, the multiple-tower approaches would suffer additional penalties.

3.1 REQUIREMENTS

A series of generalized design guidelines have been established by the Department of Energy for the Commercial system to complement a specific set of performance requirements. The generalized guidelines require the use of conventional water-steam turbine equipment and exclude the use of a fossil-fueled boiler to supplement the collection of solar energy. This latter requirement necessitates the use of a thermal storage subsystem which is designed to buffer the transient input power to the system and to ensure an extended system generating capacity after sunset.

Specific Commercial system performance requirements are tabulated in Table 3-1. The 100-MWe net capacity requirement from receiver steam and the corresponding 70-MWe power level from the thermal storage represent Commercial-size modular capacity. The indicated values of solar multiple and hours of storage were developed by MDAC as a result of an economic trade study which treated collectible power, storage capacity, turbine power demand and spillage, for a stand-alone Commercial system. The hot-startup requirement, as indicated in the table, is intended to be as short as possible within the practical limits of available turbine equipment.

Since the operation of the system is closely coupled with the local environment, a summary of the major environmental and site-related requirements is presented in Table 3-2. For the most part, these requirements have been established from existing wind, ambient temperature, and seismic data.

Table 3-1

COMMERCIAL SYSTEM REQUIREMENTS

		Source
Design Point Power Level		
• From Receiver (Best sun angle at 950 W/m^2 insolation)	100 MWe Net	DoE
• From Thermal Storage	70 MWe Net	DoE
Solar Multiple = maximum power collected/design point power to turbine	1.7	MDAC
Hours of Storage	6	MDAC
System Startup Times		
• Hot	20 Minutes*	DoE
• Cold	6 Hours	DoE
Plant Availability (Exclusive of Sunshine)	90%	DoE
Operational Lifetime (With Normal Maintenance)	30 Years	DoE

*Minimize within practical limits.

Table 3-2

MAJOR ENVIRONMENTAL AND SITE-RELATED REQUIREMENTS

		Source
Temperature		
• Design Point	28°C (82.6°F) Dry Bulb 23°C (74°F) Wet Bulb	DoE DoE
• Survive	-30°C - +50°C (-20°F - +120°F)	DoE
Wind Condition		
• Maximum Operational with Gusts	16 m/s (36 mph)	MDAC
• Maximum Survival		
Sustained (Tower Only)	40 m/s (90 mph)	MDAC
With Gusts (Other Subsystems)	40 m/s (90 mph)	DoE
Seismological	Seismic Zone 3 NRC Reg Guide 1.60 Response Spectrum OBE - 0.165 hor "G" SSE - 0.333 hor "G"	DoE DoE MDAC
Soil Conditions	Barstow Data	DoE

3.2 SYSTEM CHARACTERISTICS

The principal characteristics of the overall system and major subsystems are summarized in Figure 3-2 and Table 3-3. In evolving this system design, a continual effort was made to develop a system which had the lowest cost of energy on an annual basis.

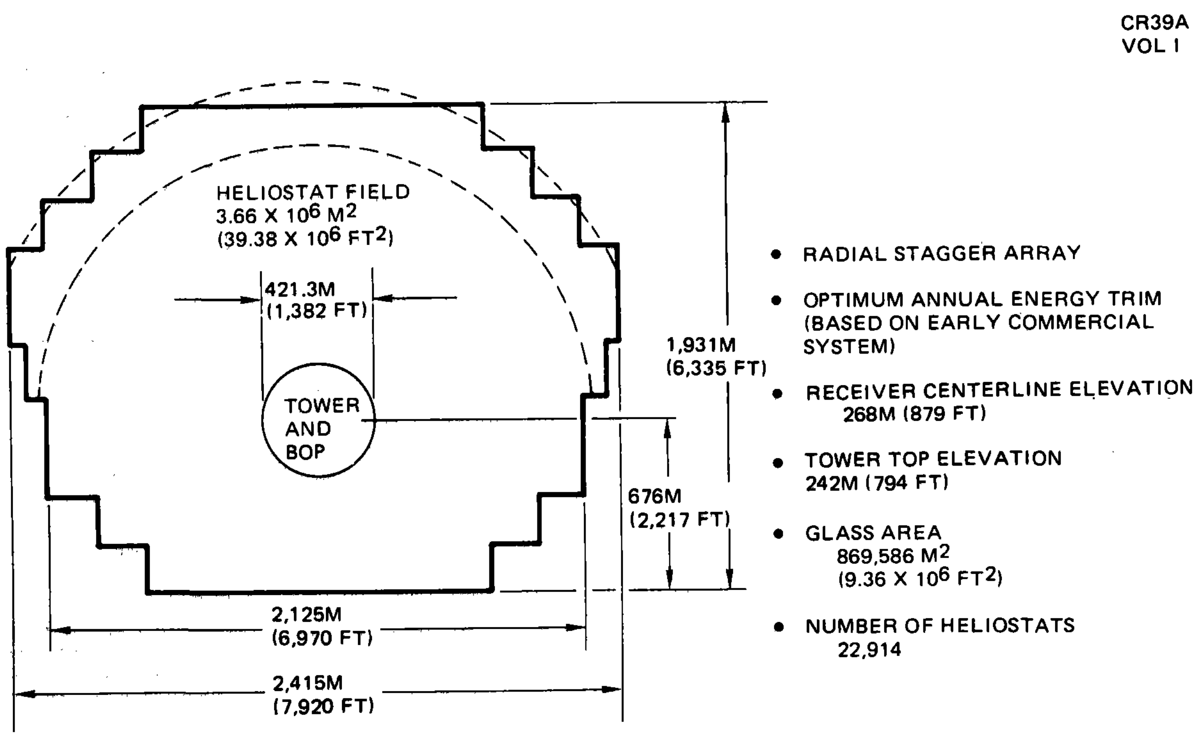


Figure 3-2. Commercial System Field Layout

The overall system design depicted in Figure 3-2 and summarized in Table 3-3 consists of a 100-MWe single tower module with an energy collection solar multiple of 1.7. The tower location and field shape were defined to maximize the annual energy collection per unit of investment. The heliostat field layout, which is in a radial stagger arrangement, has an average field coverage density of ~23%.

The heliostat is the sun-tracking element in the solar energy system and because of the required quantity, its cost is paramount to economical system

Table 3-3

COMMERCIAL SYSTEM CHARACTERISTICS

Module Size	
• Capacity	100 MWe
• Solar Multiple (equinox noon)	1.7
Receiver Configuration	External, Single-Pass-to-Superheat
Receiver Size	
• Diameter	17m (56 ft)
• Height	25.5m (84 ft)
Receiver Steam Conditions (Outlet)	
• Pressure	11.1 MPa (1,615 psia)
• Temperature	
Rated Steam	516°C (960°F)
Derated Steam	368°C (694°F)
Thermal Storage Media	Caloria HT-43 + Rock
Method of Storage	"Single" Tank (thermocline)
Thermal Storage Capacity	6 Hours
Thermal Storage Temperature Range	232-316°C (450-600°F)
Turbine Configuration	Tandem-Compound, Double-Flow, Automatic Admission, Industrial Turbine
Turbine Steam Conditions	
• Throttle Steam	510°C (950°F) 10.1 MPa (1,465 psia)
• Admission Steam	296°C (565°F) 2.52 MPa (365 psia)
Heat Rejection	Wet Cooling Towers

design. The ability to redirect solar insolation to the receiver is accomplished through a two-axis gimbal system. The MDAC design features the capability to orient the reflective surface such that the mirrors can be protected during inclement weather. MDAC recommends that the heliostat have open-loop control. Information from a shaft encoder (integrated into the drive unit controller to measure shaft position) is compared against the required position. Commands are sent to the appropriate gimbal axis drive unit to reorient the heliostat if required. This concept has been selected because it provides the required technical soundness coupled with high cost-saving potential necessary for Commercial Plant applications. The currently verified control system includes a closed-loop sensor as previously described in the Pilot Plant discussion.

The receiver is an externally heated single pass-to-superheat configuration designed to be compatible with the optimum collector field. The key features of the receiver are: (1) its low thermal mass, which enhances its responsiveness to both daily startup and the transient daily sunshine conditions, and (2) its low structural mass, which permits reasonable tower design even in seismically active areas. The two outlet steam conditions defined in Table 3-3 correspond to conditions where the receiver powers the turbine directly (rated steam) and when all receiver power flows to thermal storage (derated steam). The advantage of the two-steam condition approach is that the steam temperature can be maintained at as low a condition as possible while still satisfying the temperature requirements of the equipment it supplies. This results in minimizing receiver surface temperature and thereby reducing receiver heat loss.

The thermal storage subsystem, which employs a mixture of Caloria and rock in a single-tank thermocline storage mode, represents the most cost-effective approach to large-scale storage. The subsystem itself is capable of accepting excess receiver steam above that required for the turbine, producing a steady-state source of turbine steam while accepting highly transient input energy from the receiver, and developing a steam flow which can be used to supplement receiver flow through the turbine.

The turbine selected for the system is a commercially available automatic admission industrial turbine with the admission port being designed to be compatible with steam conditions available from thermal storage.

3.3 SYSTEM DESIGN EVOLUTION

The system design, as well as the conceptual definition of the various subsystems, emerged as a result of a series of cost and performance trade studies. These studies can be subdivided into two general categories: those related to optical energy transfer and those related to the water/steam loop.

The first of these categories include the collector/receiver configuration and collector field module size. The latter category treats the approach to thermal storage, the definition of the overall steam conditions, and overall water/steam loop complexity. Due to the highly interactive nature of the parameters involved in each of these categories, the trade studies are complex and not easily separable into discrete study packages.

For the purposes of this summary, the studies have been simplified into discrete study areas and are summarized in the following paragraphs.

3.3.1 Collector Field/Receiver Configuration and Module Size

The overall goal of this set of studies was to define the configuration and module size which leads to the lowest cost of energy on an annual basis. These studies treated all of the cost and performance aspects of the energy collection portion of the system which include the collector field, receiver, tower, and the water/steam piping.

From the collector field standpoint, critical performance issues include size and angular limitations imposed by the receiver, cosine effects, blocking and shadowing, and heliostat accuracy requirements.

The critical receiver parameters include size and weight, quantity, complexity, surface absorptivity, radiation/convection losses, availability, and thermal response. Tower considerations which are reflected almost exclusively in cost impacts include height, strength required for receiver support, and quantity.

Piping network parameters include run lengths, heat loss, and pressure drop. As a result of the quantity and complexity of these parameters, the evaluation of the system concept was conducted in a comprehensive rigorous manner considering all subsystem interactions.

3.3.2 Water/Steam Loop Design

The subsystems which combine to form the water/steam loop include the receiver, thermal storage, and electrical power generation. The overall goal in defining these subsystems is to minimize the cost per unit energy produced and to develop designs which are operationally compatible from a temperature, pressure, and flow rate standpoint.

The starting point for the design of these subsystems is the Department of Energy requirement to use existing steam turbine designs. The requirements imposed on the turbine are: (1) have an rating of at least 100 MWe, (2) have a non-reheat cycle, (3) be capable of rapid daily startup, and (4) be capable of separate or simultaneous operation from two steam sources (receiver and thermal storage). A survey of existing turbines capable of satisfying these conditions quickly narrowed to a 100-MWe industrial turbine manufactured by General Electric Co. The inlet steam temperature may be specified at any level between 482°-538°C (900° and $1,000^{\circ}$F), while the pressure may be specified somewhere in the range of 8.72-10.1 MPa (1,265-1,465 psia). From a cycle efficiency standpoint, which has significant leverage on sizing the rest of the system, it is desirable to operate at as high a pressure and temperature level as possible. This study has resulted in the selection of a pressure level of 10.1 MPa (1,465 psia) at the turbine inlet as the design point condition. To ensure that the bulk temperature levels in the receiver and piping network do not exceed 538°C ($1,000^{\circ}$F) on a steady basis, a design point turbine inlet temperature of 510°C (950°F) has been selected.

With the turbine inlet conditions established, the receiver and thermal storage subsystems were designed to be compatible to the greatest extent possible with these conditions. From the receiver standpoint, small variations in the design point pressure and temperature level produce only minor effects on receiver cost and performance. Therefore, the receiver can be designed to directly match the turbine inlet steam conditions (adding some temperature and pressure for piping losses).

Of the three subsystems which make up the water/steam loop, the design of the thermal storage subsystem plays a critical role in influencing system cost and performance. The critical issue which was investigated involves the trade between a moderate temperature (low-cost) and high-temperature (more expensive) storage approaches. This balances turbine cycle efficiency effects against the expense of the higher-temperature storage options.

The results of a trade study carried out to evaluate the design issue are shown in Figure 3-3. The horizontal bars on the figure are a measure of the cost of adding an increment of electrical energy and thereby combine all the critical cost and performance issues into a single evaluation parameter. The first case represents the baseline Caloria plus rock storage approach which employs the thermocline principle of stratified hot- and cold-temperature layers in a common storage tank. Also shown is the temperature level of the steam which can be produced by the storage media. The remaining cases shown are designed to produce steam of higher temperature by using multiple stages and Hitec as the high-temperature storage fluid. In viewing these results, it is seen that for all but Case 3, the incremental cost per unit energy increases because the increased cost associated with adding the high-temperature capability far outweighs the increased electrical output resulting from higher cycle efficiency. Only for the case (3) where both the Caloria and Hitec tanks are filled with rock material is it economically justified to adopt the high-temperature storage approach. Lack of experimental data pertaining to the operation of Hitec-rock systems in a thermocline mode prevented the adoption of the lowest cost per unit energy approach as the baseline design. However, continued experimental work should be carried out in that area by the Department of Energy to verify that the third approach does in fact provide minimum annual cost.

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CASE	THERMAL STORAGE STEAM TEMP (°C)	(°F)	COST OF ANNUAL ENERGY OUTPUT INCREMENT (¢/KWHe)
1. CALORIA/ROCK (BASELINE)	299	(570)	22
2. CALORIA/ROCK PLUS HITEC	400	(750)	26
3. CALORIA/ROCK PLUS HITEC/ROCK	400	(750)	14
4. ALL LIQUID (CALORIA, HITEC)	400	(750)	54
5. ALL HITEC/ROCK	400	(750)	68

Figure 3-3. Comparison of Thermal Storage Concepts

3.4 SYSTEM OPERATION AND CONTROL

To ensure the successful operation and control of the total Solar Thermal Power System, a master control subsystem has been included in the overall system design. The heart of the master control is a computerized control capable of assisting an operator in starting and running the system. It is felt that this capability will be necessary due to the unorthodox nature in which solar power plants will operate. Conventional plants maintain close control over their firing rate, which is one of their critical control parameters. The solar plant on the other hand must continually react to uncontrolled changes in input power. This reactive method of operation requires that a control capability exist which minimizes lag time. It is equally important that the system be brought up on a daily basis as rapidly as possible to maximize the energy production capability without compromising the lifetime of critical components. In addition, the master control and related computer capability will play a vital role in providing a predictive capability for the system which can be affected by a wide variety of environmental factors.

3.5 COST PROJECTIONS

The cost projections for Commercial plants were developed from the system design and subsystem hardware configuration developed as the baseline for Phase 1 activities. All elements of the system are compatible with conventional manufacturing processes. A first Commercial cost was developed by a detailed estimating methodology. The master planning schedule for first Commercial implementation is shown in Figure 3-4.

An Nth plant cost projection was developed and the automated manufacturing equipment and facilities required to achieve Nth production rates and volumes were defined. The conceptual design of the collector manufacturing facility is summarized in Section 3.6 and described in more detail in Volume III, Book 2.

3.6 MANUFACTURING

3.6.1 General

Of the components of the thermal power system, the heliostats present the greatest opportunity for cost reduction through the application of mass production methods. The other elements, such as the receiver and master

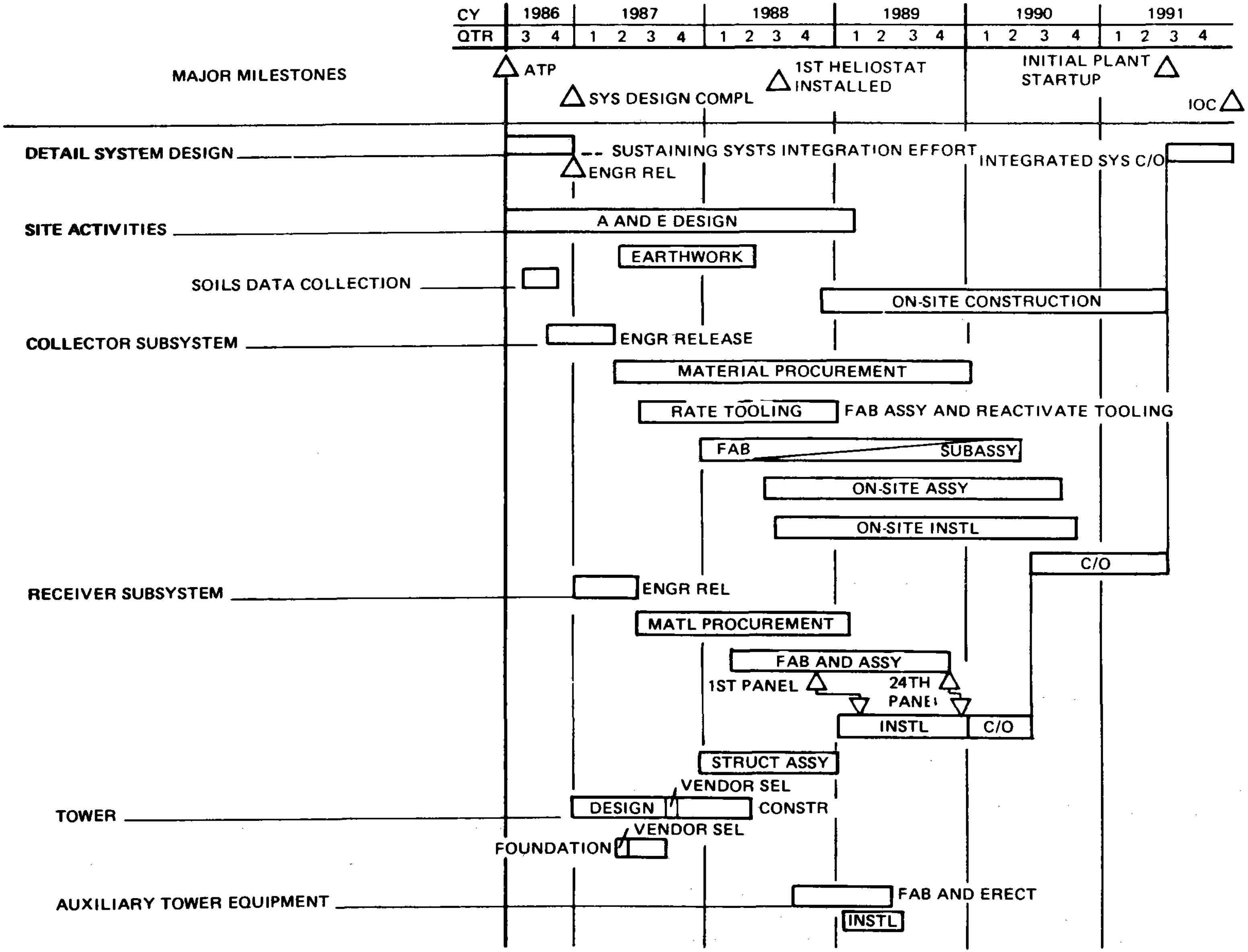

Figure 3-4. Master Program Phasing Schedule — First Commercial Plant (Page 1 of 2)

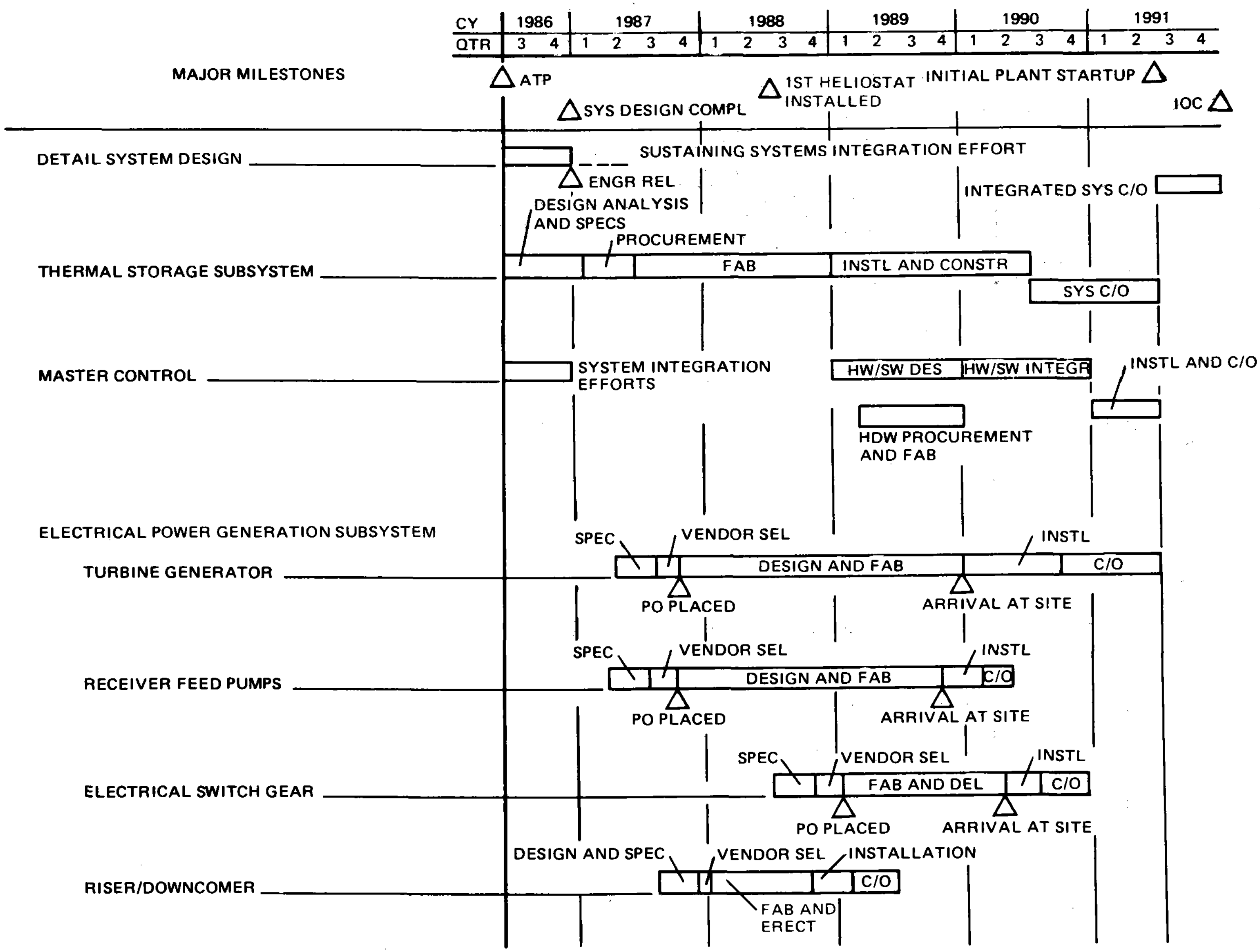

Figure 3-4. Master Program Phasing Schedule – First Commercial Plant (Page 2 of 2)

control, require a relatively lesser quantity of hardware and will not require the high-rate production planning described for heliostats in this volume. The production requirement for heliostats is forecast to total millions of units by the last decade of this century. This will require a manufacturing plan capable of meeting production needs resulting from growing Commercial plant requirements.

3.6.2 Approach

The MDAC manufacturing plant and site plant concepts described in the following pages were the result of a study designed to minimize production costs, achieve high product consistency, and provide sufficient manufacturing flexibility to accommodate design changes and rate variations. The design of the hardware has specifically been approached with high production in mind. For example, the cross-beams of the reflector substructure are designed for roll-forming, a technique which can be progressively automated until a continuous-process line is achieved. The approach taken to design the manufacturing plant and the site plant to meet the discussed requirements involved the following:

- Analysis of current design for producibility.
- Defining and analyzing the flow of all manufacturing operations required to produce a finished heliostat assembly ready for installation.
- Evaluation of alternative manufacturing methods.
- Selection and optimization of manufacturing and material-handling equipment required to meet yearly forecast rates.
- Development of equipment lists and facility area requirements.
- Development of optimum plant layout.

3.6.3 Conceptual Design, Fabrication, and Installation of Commercial Manufacturing Plant

The manufacturing plant shown in Figure 3-5 and the layout shown in Figure 3-6 are for a steady-state capacity of 60,000 heliostat per year. The manufacturing plant concept provides the capability to expand an initial 15,000-unit annual output to the steady-state output. At 60,000-unit capacity there is sufficient time to build additional baseline plants or an improved facility depending on market factors.

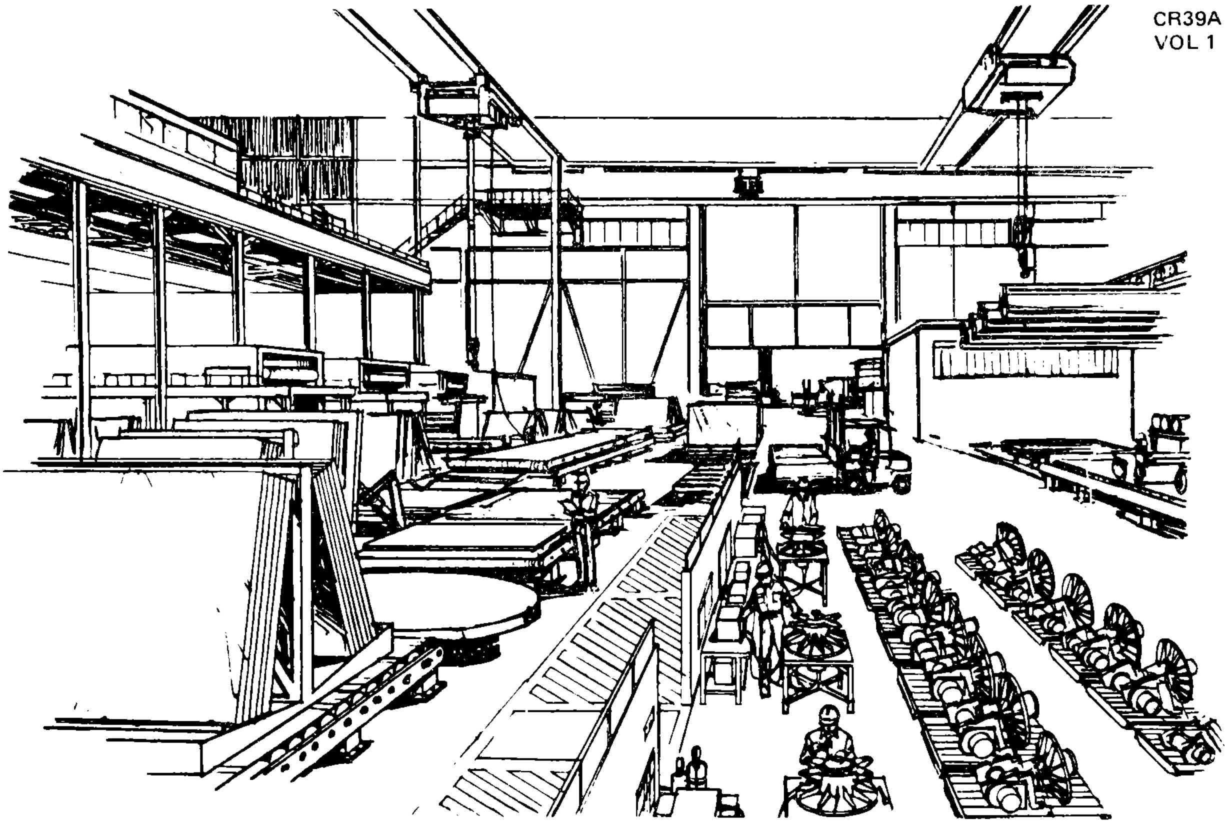

Figure 3-5. Collector Commercial Production Facility

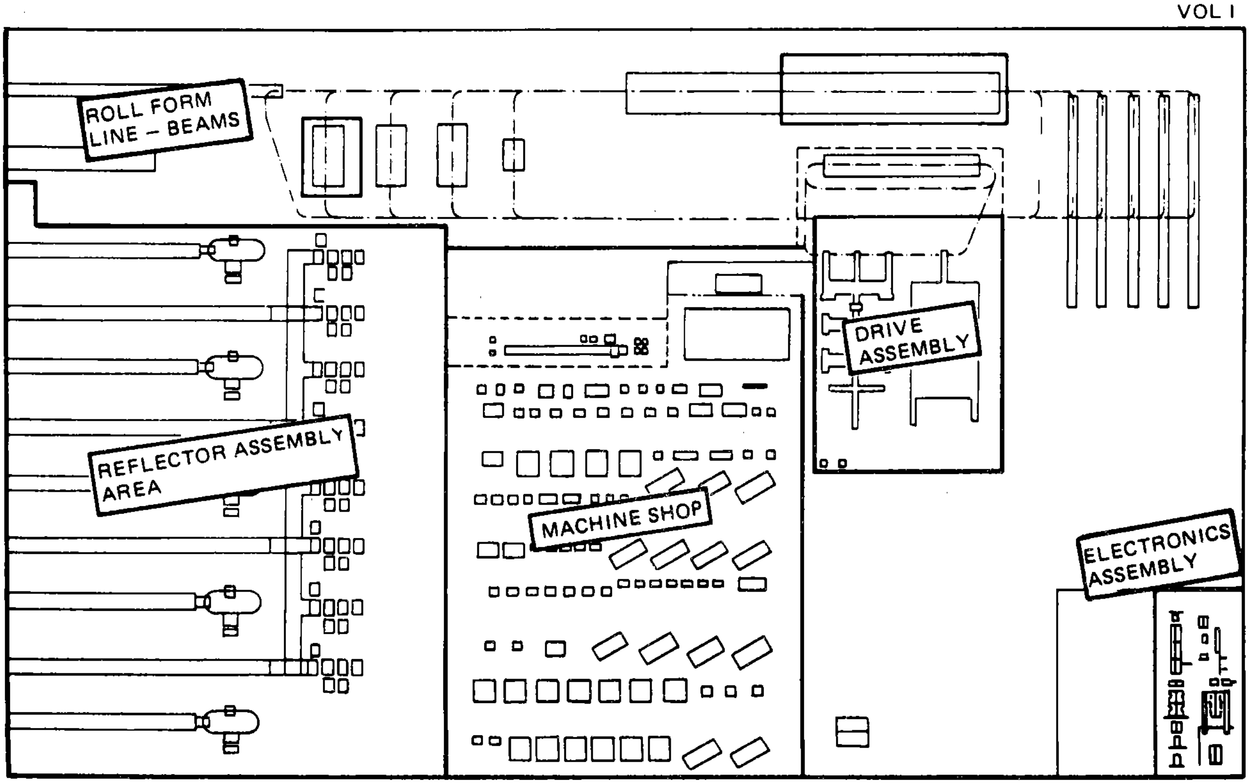

Figure 3-6. Nth Commercial Manufacturing Plant Layout (450,000 Sq Ft)

The plant dimensions are 900 ft by 500 ft, providing 450,000 ft^2 of manufacturing and storage space. Eight separate sections are contained within the area.

3.6.3.1 Support Component Fabricating Area
This section of the plant contains process lines for the fabrication of beams, torque tubes, and pedestals. Each process line produces a complete element assembly with minimal labor.

3.6.3.2 Finishing Process Line
This section includes the finishing process line for support components and a separate finishing unit for drive and miscellaneous components. All of the items produced in the support component fabricating area go through the finishing process line and emerge as cleaned, painted, and ready to assemble.

3.6.3.3 Support Component Assembly and Shipping Area
A monorail conveyor permits each component to be assembled, used, and loaded for shipment directly underneath one of the spurs of this conveying system, minimizing the need for material handling. For the pedestal and similar components, the monorail spurs extend to the shipping dock so that finished parts can be loaded directly onto the shipping vehicle.

3.6.3.4 Reflective Assembly Area
At the top of this area is the panel backsheet fabrication line. This line processes galvanized sheet metal in coil form into individual backsheets measuring 114 in. x 85 in. These sheets are stored in-process or supplied to the foam-sheet bonding tables at the right side of the reflective surface assembly area.

The foam cores will be provided by suppliers and stored along the right-hand side of this section. These cores and the backsheets will then be laminated on eight work tables and cured through four compression conveyors as they are transported toward the left side of the reflective array assembly area. The second-surface mirrors are received from the mirror supplier on the left edge of this area and with minimal handling by automatic equipment are transported from the receiving area to 15 work tables where each mirror is mechanically removed from its container and rotated to a horizontal position on the work table. No manual contact with the mirror is necessary. On the table, the mirror back is prepared, the foam core-steel backsheet mated to it, and this three-part sandwich panel is moved to five compression conveyors running counter to those mentioned above for the foam-backsheet subpanels.

At the output end of the compression conveyors, the reflective panels will be picked up on monorails while operators apply edge-sealing compound. After drying, these panels will be placed directly onto their shipping frames, covered, and transported to their finished goods storage area or the truck dock for immediate shipment. The storage area and dock are located in the lower right portion of the section.

3.6.3.5 Component Machining Area

The machining area is subdivided into five bays. Each bay has been designed to process from one to nine components of the heliostat, depending on the complexity of the machining, machine load, and similarity of machining operations. Part of the two bays closest to the top portion of the machine shop process the elements that support the support component fabricating area, and all bays are used to machine components that support the drive assembly area immediately to the right of the machine shop.

3.6.3.6 Drive Assembly Area

This area includes nine-operation, multiple-station assembly conveyor lines for fully assembling the drive components. Since the time necessary to complete each of these operations varies, the numbers of stations devoted to each activity vary proportionately.

3.6.3.7 Electrical Assembly and Test Area

This area is to be used for the assembly and testing of all of the wiring harnesses, electrical boxes and equipment associated with the heliostat. In addition, there is one final assembly line for harnesses, P/C boards and boxes, an environmental testing chamber, and functional and continuity testing areas. The area also contains space for packaging and storage for raw and finished goods.

3.6.3.8 Storage and Rework Area

Area is provided for:

- Raw materials storage for drive units.
- Finished goods storage for drive units.
- Finished goods storage for structure support components.
- Rework areas.

3.6.4 Conceptual Design of Site Assembly Plants

The manufacturing plant is designed with a capacity to simultaneously supply a minimum of four site assembly plants. The components shipped from the manufacturing plant have been designed for transport to the site plants on currently available vehicles within present standard transportation regulations.

The site plant is shown in Figure 3-7. Each site plant measures 240 ft x 320 ft to provide a total area of 76,800 ft^2. The nominal assembly capacity of each site plant is 60 heliostat units per day. Site plants are located adjacent to the installation site to reduce the final transport requirements for fully assembled heliostats.

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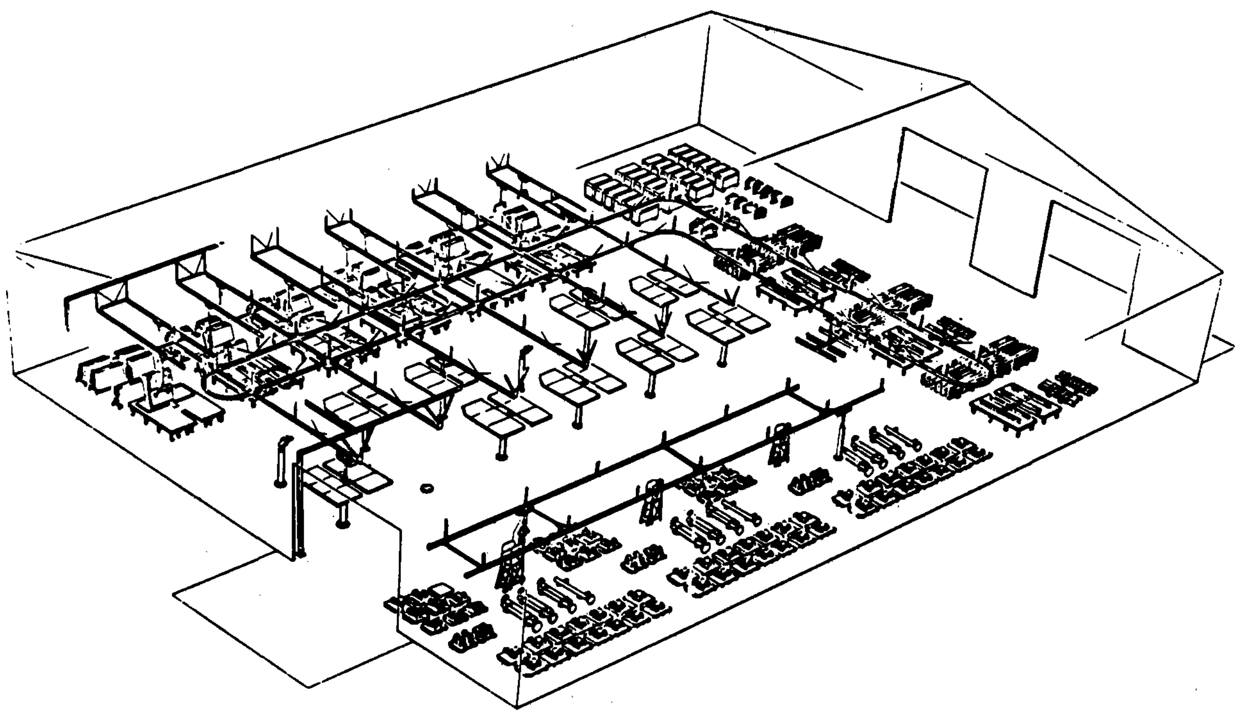

Figure 3-7. Commercial Site Plant

Four basic assembly operations take place in the site plant:

- Assembly of the crossbeams to the torque tube.
- Assembly of the crossbeams and torque tube to the reflective panels.
- Assembly of the drive units and wiring harnesses to the pedestal.
- Assembly of the reflective array and supports to the drive and pedestal.

Three work tables are provided for the assembly of crossbeams and torque tubes. After welding, the assembly will be hoisted from a table on a monorail and either stored in the overhead or moved to the reflective array assembly work table. The array assembly area contains six work tables. Operators remove the reflective panels from shipping "A" frames at stations adjacent to the tables and, using mechanical aids, lay them on the work surface in predetermined positions. One of the torque tube beam assemblies is then positioned over the work surface and panels, and the two structures are mated and locked together. This subassembly is then left to cure for a predetermined period while the crew assembles other arrays.

Simultaneously, three other crews are assembling drive assemblies to pedestals at stations displayed at the lower portion of the layout. The last work station within the site plant is shown in the central portion of the layout. Three additional crews at the six stations perform the final steps in the heliostat assembly process: joining of the reflector array to the pedestal/drive assembly. None of the activities in the site plant requires special fabricating or assembly equipment.

3.6.5 Fabricating Techniques

The equipment and techniques used to manufacture and assemble the components of a heliostat are conventional and currently available.

The bonding processes for the reflective panels have been designed to require minimal handling of the mirror glass prior to assembly as well as after assembly. The process involves mechanical removal of a mirror pane from its shipping container and immediate translation of the pane to a horizontal work surface. By combining the pane pickup mechanism with an articulating work surface, all manual contact has been eliminated and the number of transfers is reduced to one. All of the mechanisms involved in the mirror-handling process exist today. Combining these mechanisms in the sizes required for heliostat glass handling does not require the development of new techniques or equipment.

After mating the foam-steel (bonded in a prior process) and glass members of a reflective panel, the bonding agent will be cured in an operation similar to industrial tape manufacturing. The sandwich will be compressed between two flat, supported, elastometric belts operating at slow speeds in a controlled environment. The process minimizes the number of bonding stations and the volume of space that must be environmentally controlled.

3.6.6 Cost-Saving Techniques

The design of the Commercial plant considered the following concepts for achieving low production costs:

- Integration of the manufacturing processes to the most practical extent.
- Use of continuous, rather than batch or job-shop processes.
- Use of automatic machines, tools, and fixtures wherever practical.
- Reduction of waste and assurance of quality by minimizing manual handling.
- Maximizing manufacturing plant usage and minimizing installation site activities.

In the MDAC plant operations, all of the components are completely fabricated and assembled in-plant. The only production requirements thereafter are:

- Transportation to the pedestal position at the site.
- Assembly to the concrete pad leveling bolts.
- Plug-in connection of the controllers and power source.
- Alignment.

Section 4
CONCLUSIONS

Tables 4-1 and 4-2 provide comparisons of key Pilot Plant and Commercial Plant parameters. Table 4-1 contains a comparison of performance. Table 4-2 compares the designs.

The Phase 1 study conclusions are as follows:

- The MDAC single-tower external receiver concept is a low technical risk, cost-effective approach.
- The MDAC Pilot Plant is an accurate representation of the Commercial system.
- Subsystem Research Experiments have minimized technical and schedule risk to Pilot Plant.
- Extensive MDAC Phase 1 planning has established an effective data base for cost projections of Pilot Plant and Commercial systems.

Table 4-1
PERFORMANCE COMPARISON

	Pilot Plant	Commercial
Design Point Power Level (Net Power)		
• From Receiver	10 MWe	100 MWe
• From Thermal Storage	7 MWe	7 MWe
Solar Multiple	1.1	1.7
Hours of Storage	3	6
System Startup Times		
• Hot	20 Minutes	20 Minutes
• Cold	6 Hours	6 Hours
Plant Availability (Exclusive of Sunshine)	90%	90%
Operational Lifetime (With Normal Maintenance)	30 Years	30 Years

Table 4-2

SYSTEM DESIGN COMPARISON

	Pilot Plant	Commercial
Collector Field Size (Excluding Tower Exclusion)	3.04×10^5 m^2 (32.7×10^5 ft^2)	3.66×10^6 m^2 (39.38×10^6 ft^2)
Number of Heliostats	1,760	22,914
Heliostat Arrangement	Radial Stagger	Radial Stagger
Receiver Centerline Elevation	80m (262 ft)	268m (879 ft)
Receiver Size		
• Diameter	7m (23 ft)	17m (56 ft)
• Height	12.5m (41 ft)	25.5m (84 ft)
Receiver Steam Conditions (Outlet)		
• Pressure	10.45 MPa (1,515 psia)	11.1 MPa (1,615 psia)
• Temperature		
Rated Steam	516°C (960°F)	516°C (960°F)
Derated Steam	349°C (660°F)	368°C (694°F)
Thermal Storage Temperature Range	219°-302°C (425°-575°F)	232°-316°C (450°-600°F)
Turbine Inlet Conditions	510°C (950°F)	510°C (950°F)
• Throttle Steam	10.1 MPa (1,465 psia)	10.1 MPa (1,465 psia)
• Admission Steam	274°C (525°F) 2.65 MPa (385 psia)	296°C (565°F) 2.52 MPa (365 psia)

*U.S. GOVERNMENT PRINTING OFFICE: 1978-740-306/9353. Region 4.