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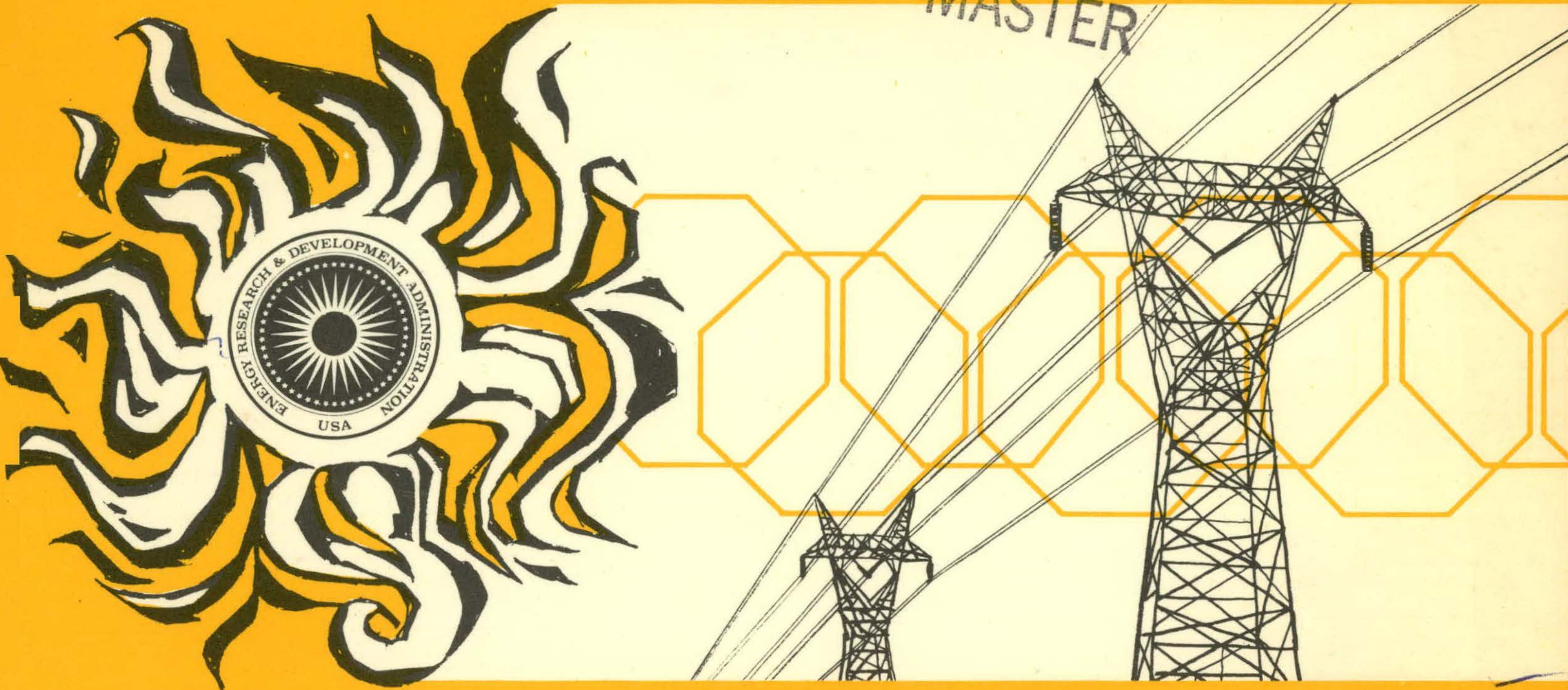

CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM PHASE 1

CDRL ITEM 10
First Quarterly Technical Progress Report

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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Date Published - January 1976

Prepared for the U.S. Energy Research and
Development Administration
Under Contract No. E(04-3)-1108

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $5.45; Microfiche $2.25

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PREFACE

This report is submitted to the Energy Research and Development Administration under Contract E(04-3)-1108 as the First Quarterly Technical Progress Report, in accordance with the requirements of CDRL Item 10. It summarizes the analysis and design efforts performed on the Phase 1, Central Receiver Solar Thermal Power System Program by the MDAC team between 1 July 1975 and 31 December 1975.

This report was prepared for distribution by ERDA to the technical public under Standard Category UC-62, as contained in Document TID-4500.

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

- McDonnell Douglas Astronautics Company
  - 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

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CONTENTS

ABSTRACT

Results of analysis and design efforts by McDonnell Douglas Astronautics Company (MDAC), Rocketdyne, Stearns-Roger, Inc., Sheldahl, Inc. and the University of Houston between 1 July 1975 and 31 December 1975 on ERDA Contract No. E(04-3)-1108 are summarized. This is the first quarterly technical progress report published on the Phase 1 Central Receiver Solar Thermal Power System contract.

The current definition of a 10-MWe pilot plant preliminary design baseline is presented, as well as a summary of a 100-MWe commercial plant baseline. The subsystems described for the plants include the collector, receiver, thermal storage, and electrical power generation. A master control concept employing a centralized computer is also described.

The subsystem research experiment activities for the collector, receiver, and thermal storage subsystems are presented, including a summary of SRE test requirements, overall test scheduling, and status through the conceptual design review phase of the SRE effort.

Section 1
INTRODUCTION

The status of technical progress on the Phase 1 Central Receiver Solar Thermal Power System contract during the period between 1 July 1975 and 31 December 1975 is summarized in the following sections of this document. This is the first of seven technical progress reports that will be published during Phase 1, with the reporting frequency being quarterly for subsequent issues. A discussion of the program approach and program status follows.

1.1 PROGRAM APPROACH

The objectives of the Central Receiver Solar Thermal Power System Phase 1 contract are to develop a preliminary design of a central receiver pilot plant concept and to define and carry out a series of test programs to verify the critical subsystems contained in the design. The methodology used to accomplish this program is presented in Figure 1-1. Starting with a series of program inputs which include ERDA, utility, and self-imposed constraints along with representative environmental conditions, a preliminary design baseline phase was implemented. In order to provide proper focus to this activity, a commercial plant and related commercial system requirements were initially defined from which the pilot plant preliminary baseline definition and subsystem research experiment requirements could be derived. With the establishment of the preliminary baseline design, program activity continues toward the subsystem research experiment and preliminary design phases. The content of this first quarterly report will focus on the results from the preliminary design baseline phase and initial activities being carried out in preparation for the subsystem research experiments.

1.2 PROGRAM STATUS

The summary schedule of Phase 1 program activities is shown in Figure 1-2. All tasks are being performed on schedule through December 1975, and no major problems are anticipated on program progress during the next reporting period. The initial preliminary design baseline for the pilot plant was

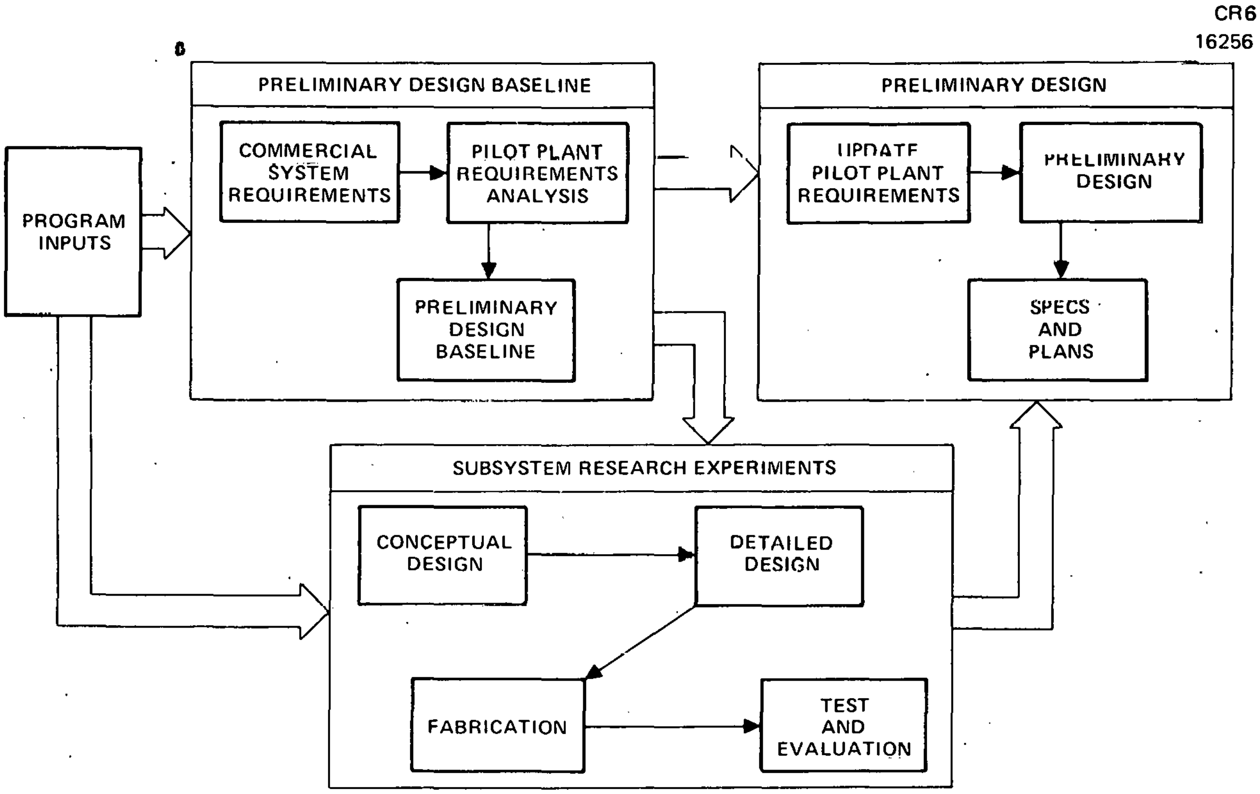

Figure 1-1. Central Receiver, Phase 1, Program Network

defined and documented as of 1 September 1975, with additional work being accomplished during September. An addendum to the preliminary design baseline report draft was submitted on 1 October 1975, and an oral preliminary design baseline review was presented to ERDA, Sandia, and Aerospace on 14 October. Conceptual design draft reports for the collector, receiver, and thermal storage subsystem research experiments (SRE's) were also submitted during the week of 15 October, and oral conceptual design reviews were presented to ERDA, Sandia, and Aerospace on 15 and 16 October. These report drafts have been approved for publication, and the final reports will be distributed during January 1976.

The WBS SC010 activity shown on the schedule for the preliminary design baseline encompasses the following tasks:

WBS SC110 Integration and Assembly
SC210 Collector Subsystem
SC310 Receiver Subsystem
SC410 Thermal Storage Subsystem
SC510 Electrical Power Generation Subsystem

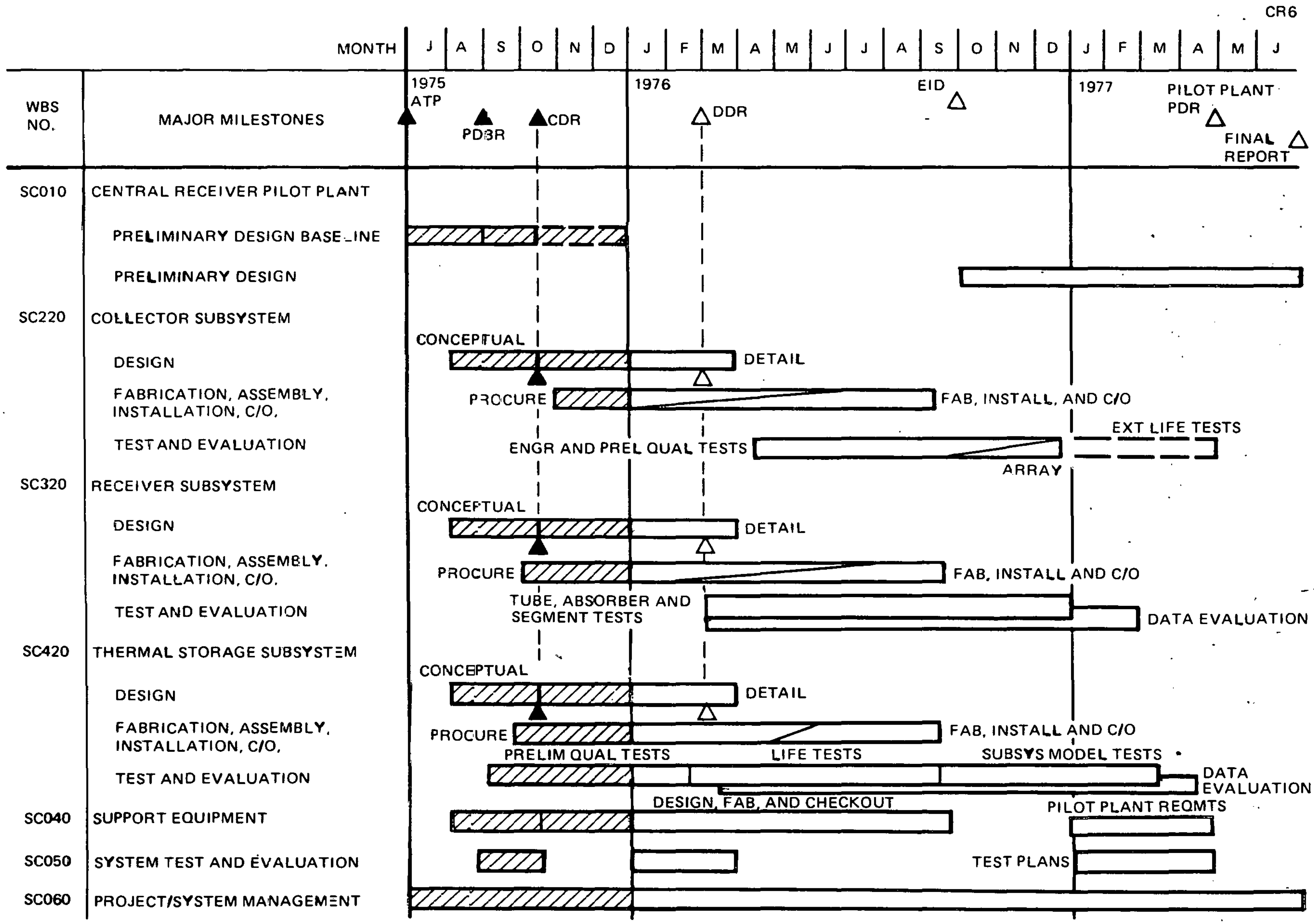

Figure 1-2. Summary Master Program Schedule

The subsystem research experiment activities depicted as WBS Items SC220, SC320, and SC420 on the schedule include the conceptual design (221, 321, 421) and detail design (222, 322, 422) tasks, with the conceptual design effort being the principal SRE activity reported on in this document.

Section 2
COMMERCIAL/PILOT PLANT SYSTEM

2.1 COMMERCIAL SYSTEM REQUIREMENTS SUMMARY

The commercial system shall be capable of operating in the peaking to intermediate load range utilizing water/steam as its principal working fluid. The system also shall be compatible with diurnal and seasonal solar flux variations and be capable of operation for a period of 6 hours after sunset at 70 percent of rated capacity with the aid of a thermal storage device. Due to the limited water availability anticipated for most favorable solar insolation sites, dry cooling equipment will be utilized exclusively for heat rejection. The system shall be designed for a 30-year operational life with normal maintenance, which is compatible with normal utility practices, and have a system availability of 90 percent exclusive of sunshine. The commercial plant shall also be economically competitive with alternate energy sources.

2.2 BASELINE COMMERCIAL SYSTEM

Based on these requirements and guidelines, a definition of a commercial system has been developed as a result of both cost and performance considerations. The major elements of this system are depicted in Figure 2-1. The collector subsystem consists of a large number of single-pedestal-mounted heliostats with first-surface, acrylic-coated mirrors. Each reflector element is composed of eight trapezoidal segments which are attached to a central hub and can be canted to provide some degree of heliostat focusing. The segments are designed to facilitate manufacturing, transportation, and handling while minimizing cost.

The receiver subsystem includes the receiver unit, which serves the function of a conventional plant boiler, the supporting tower, and the riser and downcomer equipment. The receiver unit is an externally heated cylindrical configuration composed of 24 independently controlled single pass-to-superheat panels. The single pass-to-superheat concept was selected due to its responsive nature in a potentially transient heat flux environment. The receiver

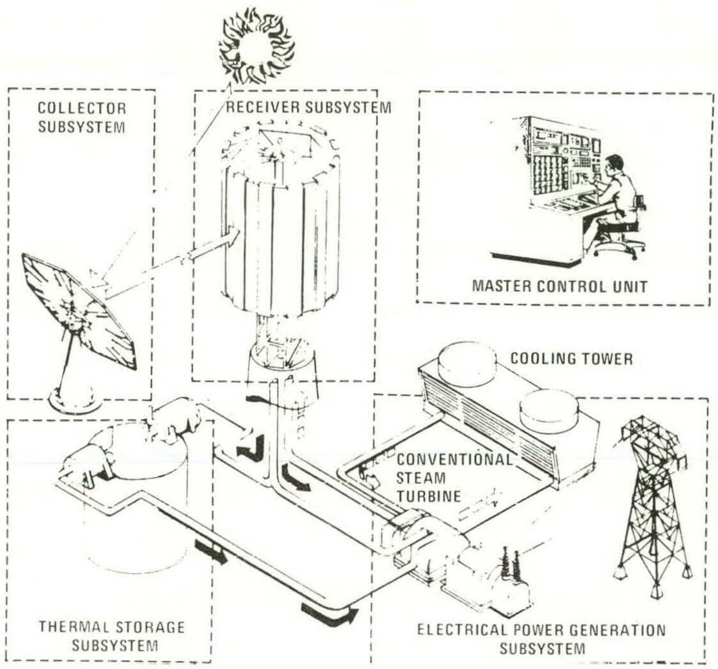

Figure 2-1. Central Receiver Baseline Concept

tower is a 305 m (1,000 ft) concrete structure which provides support for the receiver and riser/downcomer and is capable of surviving the local seismic and environmental conditions.

The thermal storage subsystem is designed to provide the necessary steam for extended turbine-generator operation while also being capable of absorbing thermal transients caused by rapid variations in solar insolation. This latter function protects the turbine from potentially damaging variations in steam conditions. Due to the material-intensive nature and technical risk associated with most thermal storage concepts, considerable effort has been made to define a concept which is low cost and has a low technical risk while providing satisfactory system performance. The resulting design utilizes a sensible heat concept in which a high temperature heat transfer fluid is used to charge and discharge the thermal storage unit while the thermal energy is stored under thermocline conditions in a tank filled with crushed granite and thermal storage fluid. The use of low cost crushed granite as a heat storage media in the thermal storage tank displaces approximately 75 percent of the much more expensive fluid volume which would otherwise be required. The thermal storage subsystem is designed to permit charging only, discharging only, or the simultaneous operation of both functions. This approach permits the greatest system flexibility possible.

The electrical power generation subsystem utilizes conventional 100-MWe turbine generator equipment and employs dry cooling for heat rejection. Due to the multistage nature of the turbine, receiver steam can be introduced directly into the high pressure stage while steam produced from the thermal storage subsystem can be introduced into an intermediate pressure stage. The turbine inlet conditions corresponding to receiver steam operation are 510°C (950°F), 12.4 MN/m^2 (1,800 psia) while those related to operation exclusively from thermal storage steam are 294°C (550°F), 3.5 MN/m^2 (500 psia).

The master control, which consists of the control and display hardware and the associated software, provides integrated control for all plant subsystems. In addition to establishing the plant operating mode and controlling the transitions between modes, the master control will provide a supporting role by processing maintenance data, predicting plant performance, and processing and compiling system data for reporting purposes.

2.3 PILOT PLANT BASELINE DEFINITION

The expressed goal of the pilot plant is to prove technical feasibility of the commercial system and to give an indication of system economics. Therefore, the pilot plant must demonstrate and verify the integrated operation and control of all of the elements of the commercial system in a scalable fashion. In addition to satisfying the goals and requirements established for the commercial system (Subsection 2.1), the pilot plant must possess a system test and a power producing mode. The pilot plant shall be sized to produce 10 MW of net electrical power at 2 p.m. on winter solstice with a 30°C (85°F) ambient temperature and to produce 7 MW of net electrical power for a period of up to 6 hours from thermal storage.

The preliminary baseline pilot plant system, which serves as the focal point for this Phase 1 activity, is a selectively scaled down version of the commercial system discussed in Subsection 2.2. A comparison of the key parameters of the two systems is shown in Figure 2-2. As seen in the illustration, the temperatures and pressures associated with the pilot plant are less than for the commercial system due to two factors. First, a design conservatism has been introduced into the pilot plant to minimize early program risk. Second, the turbines available in the 10-MWe range are lower pressure units than the 100-MWe turbines commonly used by the utilities. The heliostats utilized in the pilot plant are identical to their commercial system counterpart since they represent the major cost elements of the system. Heliostat items remaining to be verified in going to a commercial system relate exclusively to questions of producibility.

2.4 PILOT PLANT OPERATING MODES

The operation and control of the pilot plant can be reduced to a series of steady state or psuedosteady state operating modes and the required

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CHARACTERISTIC	COMMERCIAL (100-MWe MODULE)	PILOT PLANT
FIELD DIMENSIONS	5,650 X 6,220 FT (1,723 X 1,896 M)	1,728 X 1,728 FT (527 X 527 M)
NUMBER OF HELIOSTATS	29,300	2,350
HELIOSTAT SIZE	20 FT (6.1 M)	20 FT (6.1 M)
TOWER HEIGHT	1,000 FT (305 M)	312 FT (95 M)
RECEIVER TEMPERATURE (PEAK)	950°F (510°C)	890°F (475°C)
THERMAL STORAGE TEMPERATURE	600°F (316°C)	575°F (302°C)
TURBINE INLET TEMPERATURE	950°F (510°C)	890°F (475°C)
TURBINE THROTTLE PRESSURE	1,800 PSIA (12.4 MN/M^2)	1,450 PSIA (10.0 MN/M^2)
NET PLANT EFFICIENCY		
DIRECT (RECEIVER STEAM)	33%	28.9%
THERMAL STORAGE STEAM	27%	23.0%

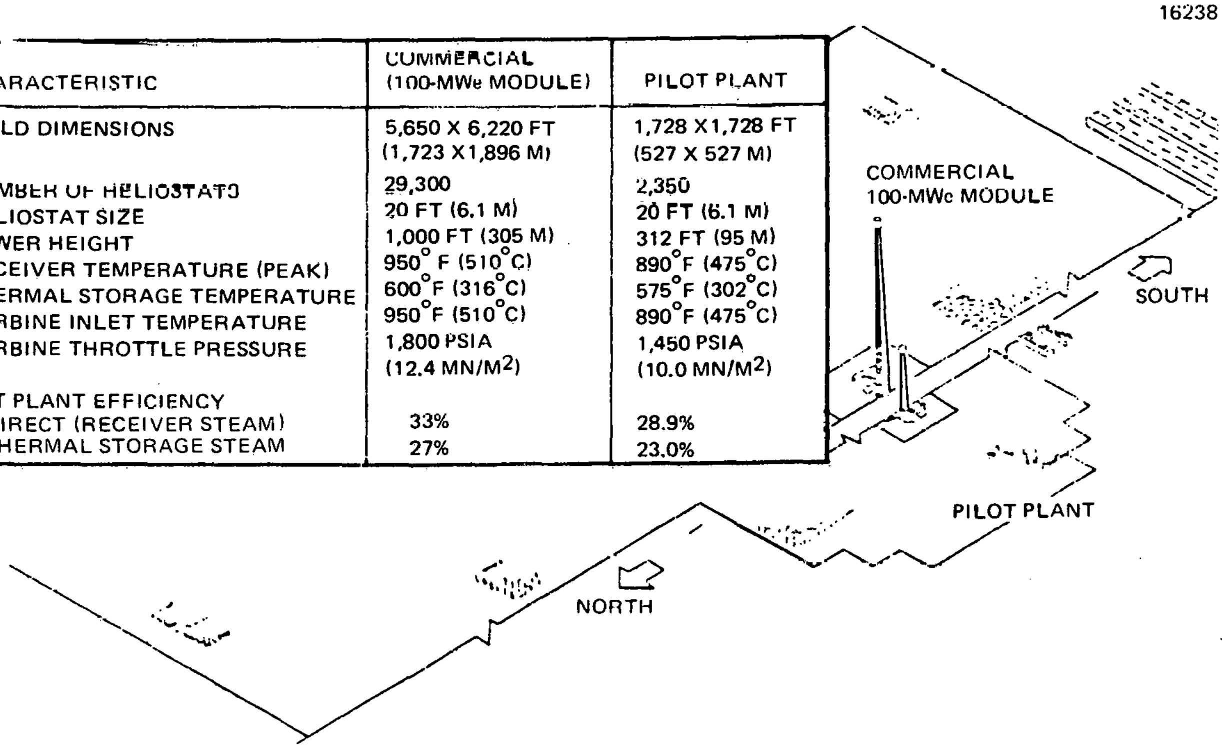

Figure 2-2. Commercial/Pilot-Plant System Characteristics

transitions between these modes. The six basic modes, excluding shutdown and standby states, include (1) normal solar, (2) low solar power, (3) operation with intermittent clouds, (4) extended operation, (5) thermal storage charging, and (6) fully charged thermal storage. The normal solar and extended operation modes are shown schematically in Figures 2-3 and 2-4. The basic pilot plant schematic is identical to that anticipated for the commercial system with the exception of the turbine and number of feedwater heaters.

2.4.1 Normal Solar Operation

The period of normal solar operation occurs at any time when excess receiver steam is available over that which is required for the desired electrical output. During this mode, which is illustrated in Figure 2-3, surplus receiver steam is shunt fed through the desuperheater and into the thermal storage charging heat exchanger. Condensate from this heat exchanger passes through a drain tank level control valve and is flashed in the flash tank. Condensate from the flash tank is fed directly to the deaerator while flash vapor is available for feedwater heating and displaces steam which would otherwise be extracted from the turbine.

The remainder of the steam that is not diverted to thermal storage enters the turbine, flowing first through the throttle valve, which regulates receiver pressure. As indicated, three extraction ports are available for feedwater heating while the turbine flow passes through the condenser and into the hotwell.

Condensate which accumulates in the condenser hotwell passes through the demineralizer where proper water quality is maintained. Feedwater heating and deaeration are accomplished with the three heaters (Figure 2-3) with required energy being provided from steam extracted from the turbine. The design feedwater and receiver steam conditions are indicated. During this mode, it is anticipated that the turbine will have a heat rate of 10,710 Btu/kwh at an ambient temperature of 37°C (100°F) with a 19°C (35°F) condenser approach temperature.

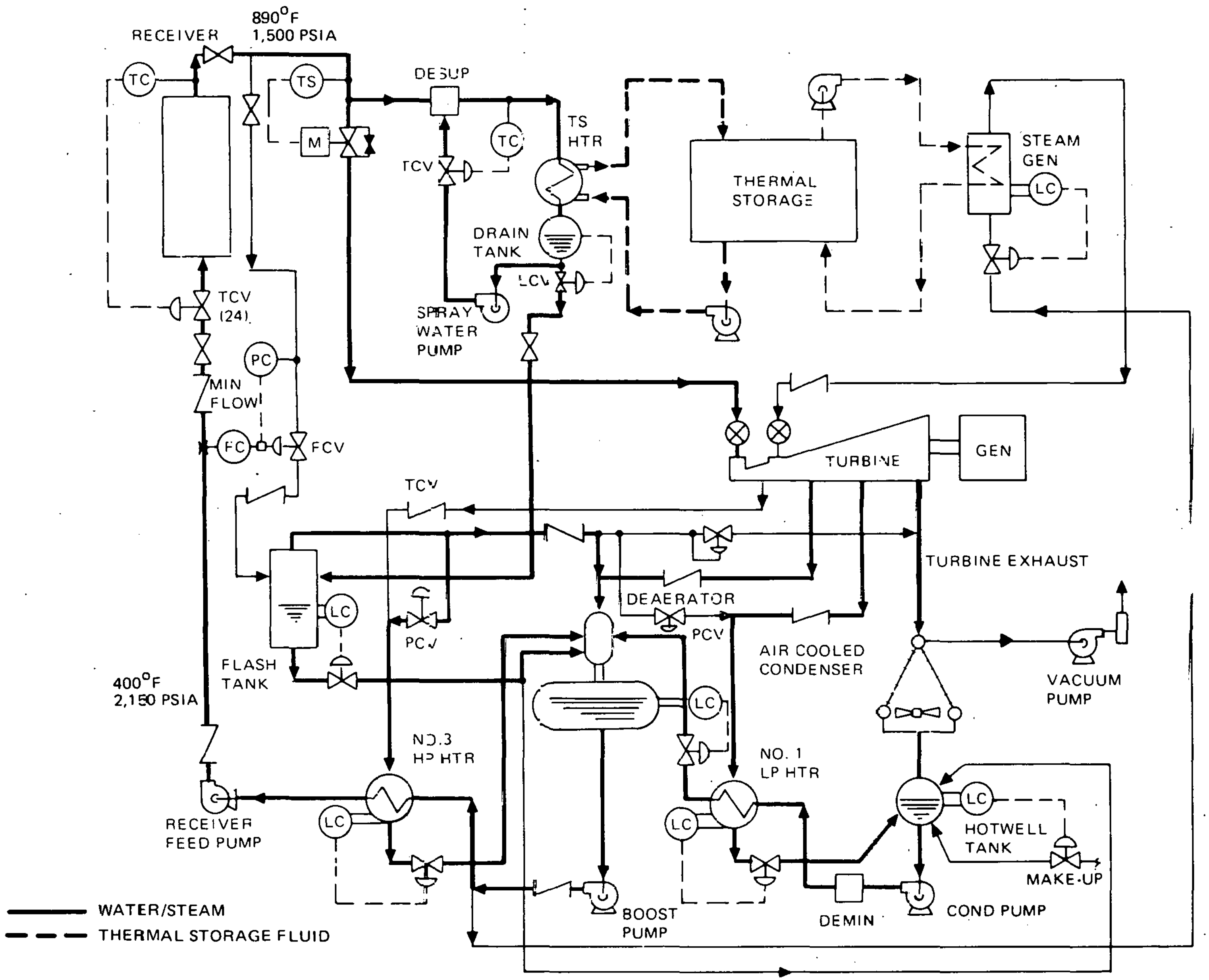

Figure 2-3. Normal Solar Operation

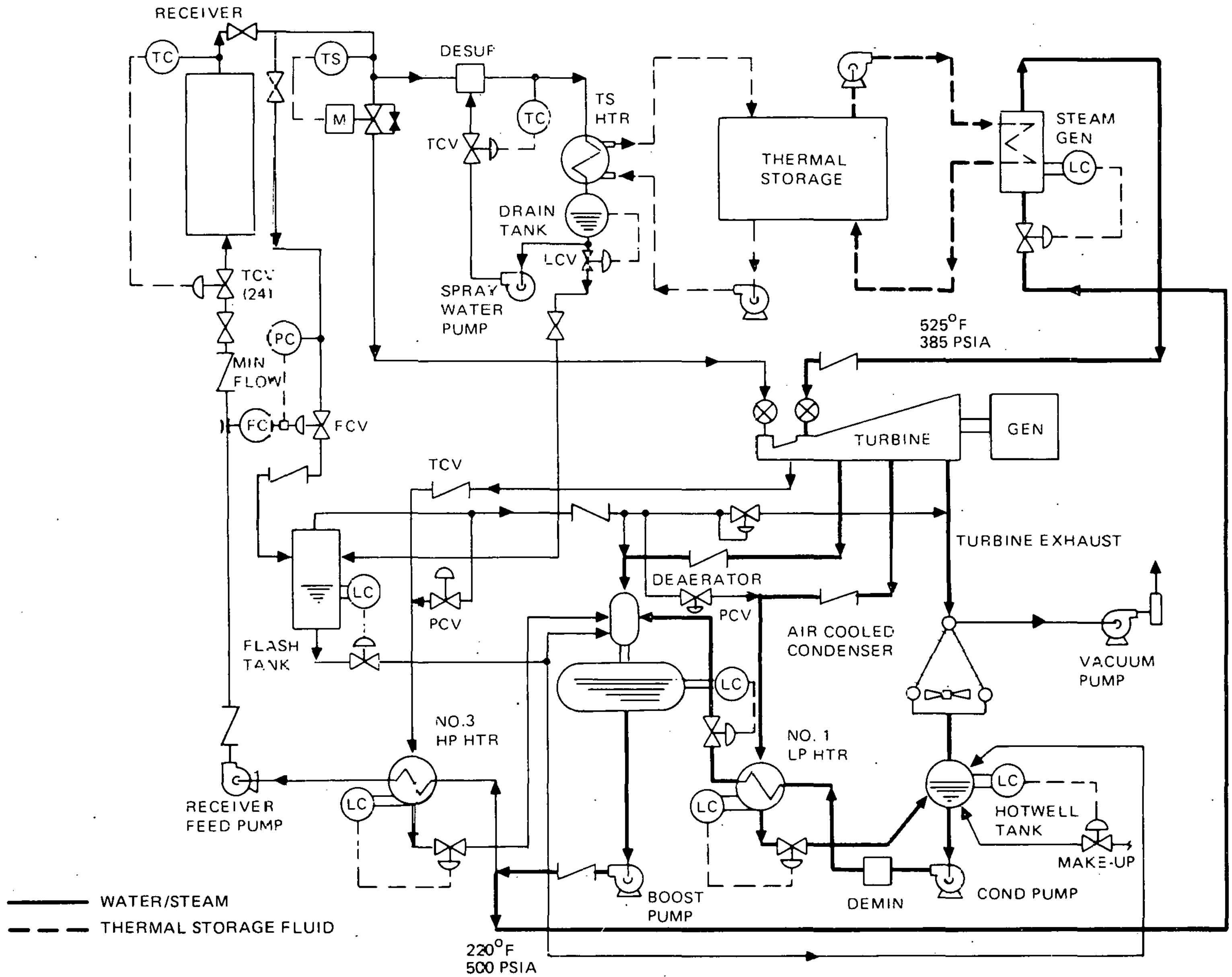

Figure 2-4. Extended Plant Operation

2.4.2 Low Solar Power Operation

During periods when the quantity of available receiver steam is less than that required to maintain the desired electrical output due to a reduction in insolation (either normal diurnal or haze induced), the bypass steam flow to thermal storage is eliminated while all available steam is diverted to the turbine at design pressure and temperature. Turbine operation is supplemented by simultaneously introducing steam generated by the thermal storage steam generator into the secondary turbine admission port with the extent of the secondary admission depending upon the availability of receiver steam, the electrical demand, and the extraction rates. Steam exhausting from the turbine subsequently passes through the condenser, demineralizer, and the first two feedwater heaters. Upon leaving the second feedwater heater, the condensate flow is split, with the majority passing through the third heater and on to the receiver feed pump. The second branch of the condensate loop leaving the second feedwater heater passes through the steam generator where stored thermal energy is used to produce steam for supplemental turbine operation. This mode introduces a great deal of flexibility into the system and serves as a natural transition between the normal solar and extended or intermittent cloud operational modes.

2.4.3 Operation With Intermittent Clouds

During periods when excessive transients in solar insolation are anticipated due to the passage of opaque clouds, the system shall operate in the intermittent cloud mode, in which the turbinc is powered completely from thermal storage steam. During this mode of operation, all receiver generated steam will be directed to the thermal storage charging heat exchanger, which will be designed to accept the potential transients in inlet steam. Since the turbine is not directly powered by receiver steam during this mode, it is not necessary to maintain rated receiver outlet steam temperature [447°C (890°F)]. As a result, the outlet steam condition of the receiver is controlled to 343°C (650°F) which completely eliminates the need to utilize the desuperheating function in this mode. Condensate from the thermal storage charging heat exchanger then passes to the flash tank where a mixture of water and steam are produced as a result of the reduction in pressure. The condensate portion passes to the deaerator while the vapor is available for feedwater heating. During periods when sufficient flash steam is available (i.e., sufficient pressure), the flash steam will replace the turbine extraction steam for feedwater heating by closing the appropriate check valves on the extraction lines. The merit of this approach is that available steam from the flash tank which would be lost in the condenser is used for feedwater heating, thereby permitting a greater turbine flow to be maintained resulting in a higher electrical output capability and improved system efficiency.

The system condensate which reaches the hotwell subsequently passes through the demineralizer and the first two feedwater heaters. At this point, the flow is split in such a manner to provide required flow to the receiver to absorb the net thermal power at the receiver while maintaining flow to the steam generator at sufficient flow to maintain the derated turbine output at 7 MWe net. Therefore, depending on the flow path of the flash steam and condensate, all or a portion of the feedwater equipment (condenser hotwell through deaerator heater) must be sized to be compatible with the peak-required receiver flow and the flow to the steam generator required to produce 7 MWe net output power, simultaneously. In addition, the thermal storage charging loop must be sized to accommodate the maximum receiver flow condition.

2.4.4 Extended Plant Operation

During periods when insufficient solar insolation is available as a result of normal diurnal variation or cloud obstruction and energy is available in the thermal storage unit, extended plant operation can be accomplished in the manner indicated in Figure 2-4. In this mode of operation, derated steam [274°C (525°F), 2.70 MN/m^2 (385 psia)] is produced in the steam generator by extracting energy from the thermal storage fluid. The steam then enters the turbine through the secondary admission port at a sufficient flowrate to maintain an output of 7 MWe net power output including normal extraction for feedwater heating. The exhaust steam from the turbine passes through the condenser and hotwell, and then proceeds to the demineralizer, the low pressure heater, and the deaerator heater. The condensate is then recirculated through the thermal storage steam generator. During this mode, it is anticipated that the turbine will have a heat rate of 13,480 Btu/kwh and the steam generator will have a design capacity of 30.4 MWth.

2.4.5 Charging of Thermal Storage

During periods when it is desired to charge thermal storage exclusively, the pilot plant will be operated in a manner in which the turbine is not activated and receiver outlet steam temperature is reduced. During this mode, all of the feedwater heating requirements for deaeration must be accomplished with flashed steam developed in the flash tank. Flash steam not consumed in the feedwater heating operation passes to the condenser, where it is condensed and collected in the hotwell along with any flash tank condensate which was not passed to the deaerator.

Since the turbine is not activated during this mode, the system is capable of accepting severe transients in solar insolation. Such a mode could continue until a near fully charged condition was realized in the thermal storage unit.

2.4.6 Fully Charged Thermal Storage

During periods of system operation when the thermal storage subsystem is incapable of accepting thermal energy, either as a result of being fully charged or due to a malfunction in the charging equipment, an operational mode identified as "fully charged thermal storage" can be initiated. During this period, the energy collected is adjusted, if necessary, through partial heliostat field shutdown, to be compatible with the maximum turbine capacity. Since the turbine for the pilot plant is sized to accept full summer noon flow, this mode would be rarely, if ever, needed for the pilot plant. For a commercial system on the other hand, the turbine would be designed to accept only a portion of the peak summer noon flow of collected thermal energy and, thus, such a mode of operation would be required. For this reason, it is included as a basic mode to be demonstrated during pilot plant operation. It is seen that this mode represents the threshold between normal solar and low solar power operation in that rated receiver steam is utilized while neither the thermal storage charging nor the discharging function is required.

2.5 COLLECTOR FIELD LAYOUT

In arriving at the heliostat layout for the central receiver concept, a cell-by-cell optimization procedure was employed. In this procedure, a square collector field is subdivided into an 11 by 11 array which defines the 121 computational cells employed in the analysis. Within each cell, an iterative procedure is executed in which glass area is added and subtracted until the point of maximum annual energy per unit of investment is determined. Cost factors contained in this analysis include the heliostats, land, and wiring in addition to a portion of the nonheliostat part of the system costs which is applied to an individual cell on the basis of that cell's contribution to the total annual energy collected by the system. Performance factors include blocking and shadowing, image foreshortening due to cosine effects, receiver interception fractions, and angular dependency of receiver absorptivity. Since it is the goal of the pilot plant to verify the commercial system, this analysis is carried out based on commercial system cost estimates, thereby permitting the simulation of a commercial field layout. By contrast, if anticipated pilot plant costs were used, i.e., higher heliostat costs owing to lower production levels, a strong tendency toward low shading/blocking geometries, a taller tower, and deletion of the more remote heliostats would occur.

With the completion of this analysis for each of the 121 computational cells, a comparative evaluation can be made between each of the computational cells. Those with poorer performance can be deleted from the field. The resulting collector field arrangement is shown in Figure 2-5. The square grid represents the 11 by 11 computational matrix while the shaded portion of the field represents deleted regions due to cost and performance considerations. Some minor adjustments have been made to improve the circumferential heat flux distribution on the receiver with only a minor impact on annual performance. The heliostat spacing within each cell is presented in Table 2-1. An upper limit on spacing ratio of 0.88 has been imposed to ensure sufficient heliostat clearance. The tower location which is to the south of center was determined on the basis of annual energy collected.

2.6 COLLECTOR/RECEIVER INTERFACE

In order to properly design the elements of the steam/feedwater loop, and in particular the receiver, it is necessary to thoroughly specify the nature of the collector/receiver interface from an energy flow standpoint. The nature of this interface is, of course, highly dependent on the heliostat field layout just discussed.

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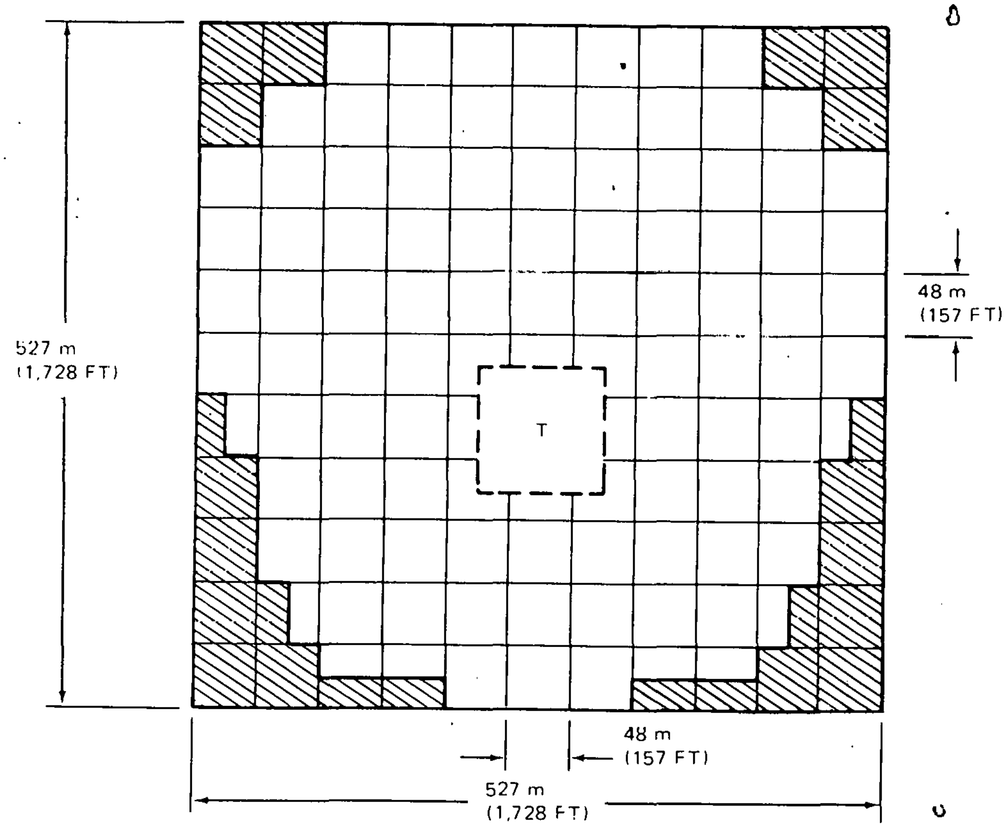

Figure 2-5. Pilot Plant Collector Field Layout

The total energy incident on the receiver surface is shown in a nondimensional sense in Figure 2-6 as a function of time of day and year. Each of the lines corresponds to the 21st day of the appropriate month (i. e., summer solstice - 21 June, equinox - 21 April or 21 September, winter solstice - 21 December). A line of 15 degree sun elevation angle also is plotted which represents the average limit of effective energy collection. Below this level, energy collection startup and shutdown activities are being carried out. From this curve, the time duration and magnitude of energy collection can be determined directly. The maximum summer noon collection capability (incident on the receiver) corresponds to 55.8 MW of thermal power for the pilot plant system. It should be noted that the heliostat layout selected for this system produces thermal power curves which coalesce into a single curve on the summer side of equinox as noon is approached. Therefore, during a significant portion of the year, the system energy collection capability will reach its maximum potential at noon. This has resulted in the sizing of turbine-generator, piping, and storage equipment to be compatible with this maximum capability.

Table 2-1

HELIOSTAT SPACING RATIOS (H_{SR})

$$H_{SR} = \frac{\text{HELIOSTAT DIAMETER}}{\text{CENTER-TO-CENTER SPACING}}$$

N

	.410	.440	.520	.380	.390	.360	.390	.380	.520	.440	.410	
	.530	.560	.590	.520	.480	.460	.480	.520	.590	.560	.530	
	.590	.590	.640	.560	.590	.570	.590	.560	.640	.590	.590	
	.650	.670	.680	.650	.670	.670	.670	.650	.680	.670	.650	
W	.530	.570	.590	.680	.700	.710	.700	.680	.590	.570	.530	E
	.530	.590	.600	.670	.710	.680	.710	.670	.600	.590	.530	
	.520	.650	.670	.680	.640	T	.640	.680	.670	.650	.520	
	.500	.500	.650	.680	.740	.700	.740	.680	.650	.500	.500	
	.520	.500	.590	.630	.670	.740	.670	.630	.590	.500	.520	
	.500	.500	.500	.590	.600	.680	.600	.590	.500	.500	.500	
	.500	.500	.510	.580	.580	.590	.580	.580	.510	.500	.500	

S

(A) NORTH-SOUTH SPACING RATIO (CELL BY CELL)

N

	.340	.440	.590	.880	.880	.790	.880	.880	.590	.440	.340	
	.390	.460	.590	.880	.880	.880	.880	.880	.590	.460	.390	
	.380	.590	.620	.880	.880	.880	.880	.880	.620	.590	.380	
	.370	.480	.610	.880	.880	.880	.880	.880	.610	.480	.370	
W	.520	.660	.670	.880	.880	.880	.880	.880	.670	.660	.520	E
	.350	.430	.700	.880	.880	.770	.880	.880	.700	.430	.350	
	.290	.440	.610	.790	.880	T	.880	.790	.610	.440	.290	
	.320	.500	.610	.770	.880	.880	.880	.770	.610	.500	.320	
	.370	.590	.680	.720	.790	.830	.790	.720	.680	.590	.370	
	.590	.680	.740	.710	.750	.790	.750	.710	.740	.680	.590	
	.700	.720	.780	.760	.760	.850	.760	.760	.780	.720	.700	

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(B) EAST-WEST SPACING RATIO (CELL BY CELL)

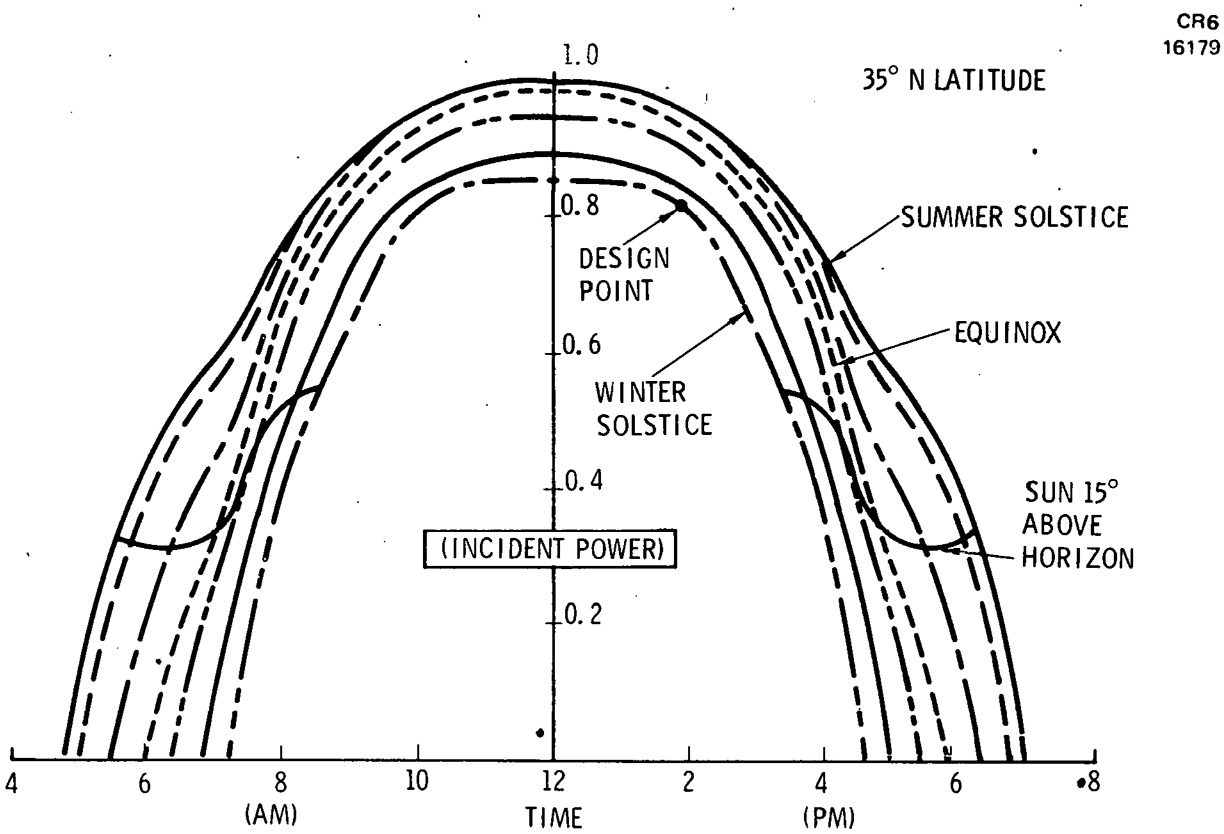

Figure 2-6. Relative Receiver Thermal Power

The heat flux variation on the northernmost receiver tube at equinox noon, which represents the worst-case for the north side of the receiver, is shown in Figure 2-7. The curves shown correspond to 2-, 3-, and 5-point heliostat vertical aim strategies. In order to maximize the size of the receiver tubes, it is necessary to maximize the total power along an individual tube while minimizing the peak heat flux. As seen, this can best be accomplished with the 5-aim point strategy. In addition, from a design conservatism standpoint, it is desirable to use a reduced peak heat flux from the 0.6 MW/m^2 value assumed for a commercial receiver. Therefore, the 5-aim point strategy was selected as the baseline concept. The apparent end spillage can be eliminated by a selective aim approach in which the more remote heliostats are used to illuminate the midportions of the receiver while close in heliostats direct energy to the top and bottom extremes of the receiver.

The flow control characteristics required for receiver operation can be determined from maximum panel thermal power, turndown range, and circumferential heat flux data. A summary of these data is presented in Figure 2-8

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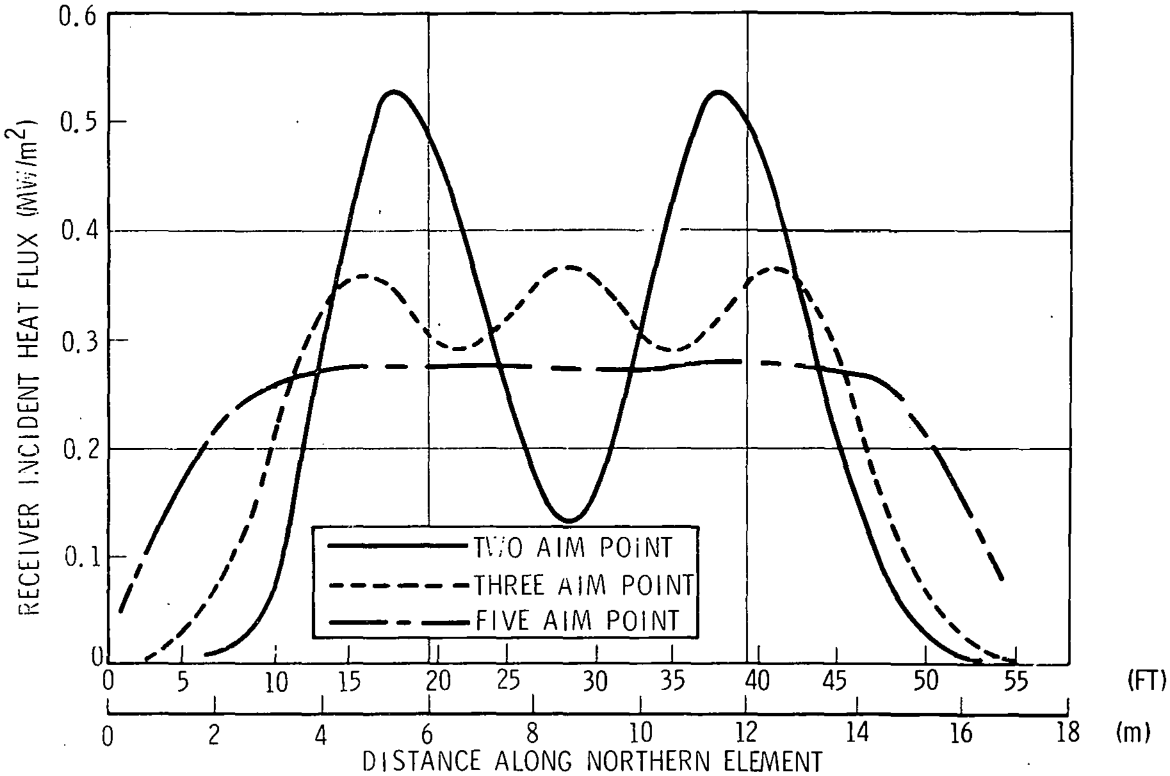

Figure 2-7. Pilot Plant Receiver Heat Fluxes

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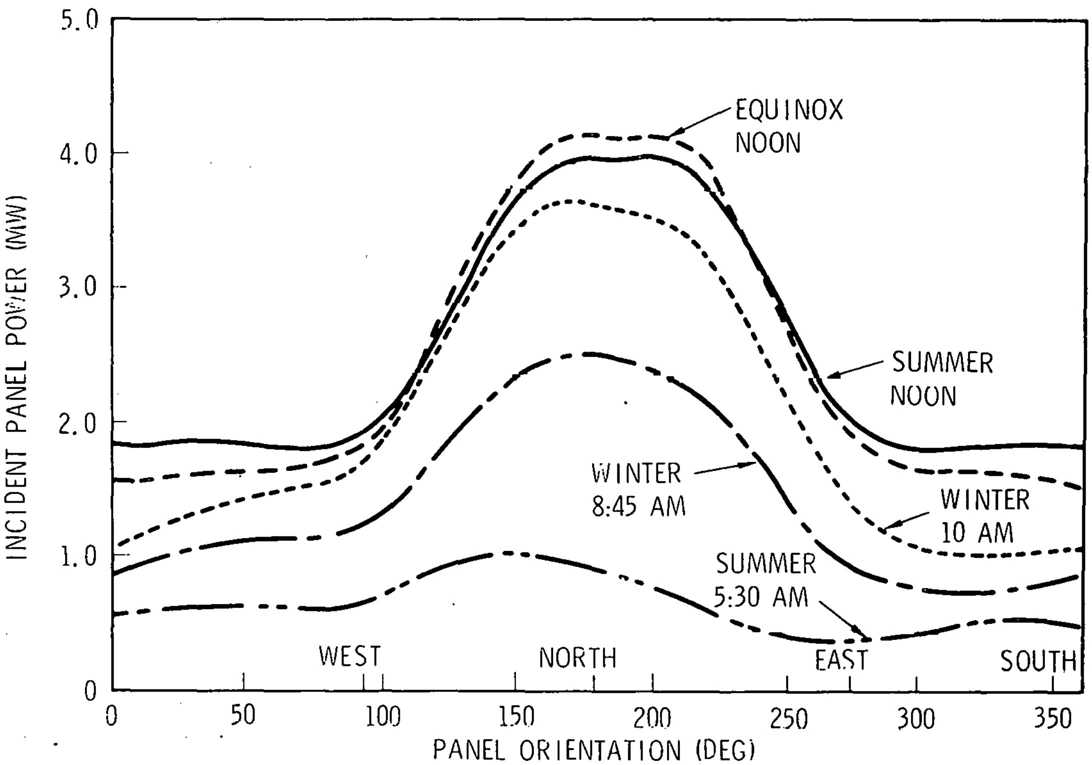

Figure 2-8. Pilot Plant Receiver Thermal Power

for an unwrapped cylindrical receiver. As noted, the worst panel thermal power condition occurs at equinox noon on the north side. The maximum circumferential variation occurs for the winter 10 a.m. profile as indicated. The variation between curves is indicative of the required turndown ratio.

2.7 MASTER CONTROL

The master control consists of the control and display hardware and the associated software necessary for the overall control and integration of the pilot plant. This overall control includes only those functions involved in startup, operating mode changes, system status determination, shutdown, and emergency safing.

Master control allows for three basic operating modes: (1) automatic, (2) manual, and (3) on-line. In the automatic mode, the pilot plant system is under the control of application software in the central computer. The operator is provided with the capability to monitor the status of the pilot plant and intervene in the execution of the application software. In the manual mode, the operator has the ability to control the system by overriding the application software via discrete hardwire controls and displays. The on-line mode allows the operator to prepare and modify the application and support software through the alphanumeric displays and their associated keyboards.

In addition to the basic operating modes, the master control computing capability will be used in a support role to process maintenance data, predict plant performance, process and compile data for reporting plant operations, compile and assemble application software, and assemble system software. The data to be processed for maintenance and report generation will be gathered during plant operation, stored, and processed off-line when the plant is shut down. The program to predict plant performance will use real time data such as thermal storage charge conditions, steam conditions, and current weather predictions as inputs to an off-line program, i.e., a mathematical model of the pilot plant, which will run concurrently with the real time control operation. As planned now, this program would be run in a redundant computer as this program could be destroyed if the redundant computer was required to come on-line. Compilation and assembly would be accomplished only during shutdown conditions.

In the automatic mode, computer-generated commands of the type shown in Figure 2-9 are transferred to the signal interface equipment where they are converted to electrical signals compatible with control elements the commands must drive. System data points or responses are converted to digital format in the signal interface equipment and transferred to the computer for evaluation by computer software. Computer-generated commands for the collector field, turbine-generator, and receiver are transferred digitally via data buses. Responses to these commands are digitized by the control element and transferred via the same digital data buses to the computer. Concurrent with the control via the application program, the computer will be gathering data to update the operator displays, and processing and storing data to be used later for preparation of plant status reports or for predicting plant performance.

In the manual mode, the control will be via hardwire operator control and display panels. At this time this is not defined as a normal operating mode. It would be used for emergency operations, maintenance, or special one-of-a-kind operations. In the manual control mode, the computer can be used to display, store, or process data.

The on-line mode was added to provide flexibility at the control room to work around parameters that are causing the applications software to hold the operation. An example would be to change an out-of-tolerance limit if it was determined that the instrumentation was faulty, and not the process. This capability should only be used by experienced and competent operators.

The basic architecture shown in Figure 2-10 incorporates computerized automation since some of the required control functions cannot be accomplished effectively with dedicated hardware or manually by operators. Examples are calculation of the sun acquisition and synthetic track commands, the communications with 94 field controllers, the evaluation of the status of 2,350 heliostats, and the response time and large number of parameters required for receiver control. A critical ingredient to the architecture now becomes its availability; therefore, redundancy was included in the basic architecture. The critical redundancy implementation is the switch over to a backup computer. The baseline architecture is for standby redundancy. As conceived for this baseline, this switch over will occur in about a second, not microseconds, which

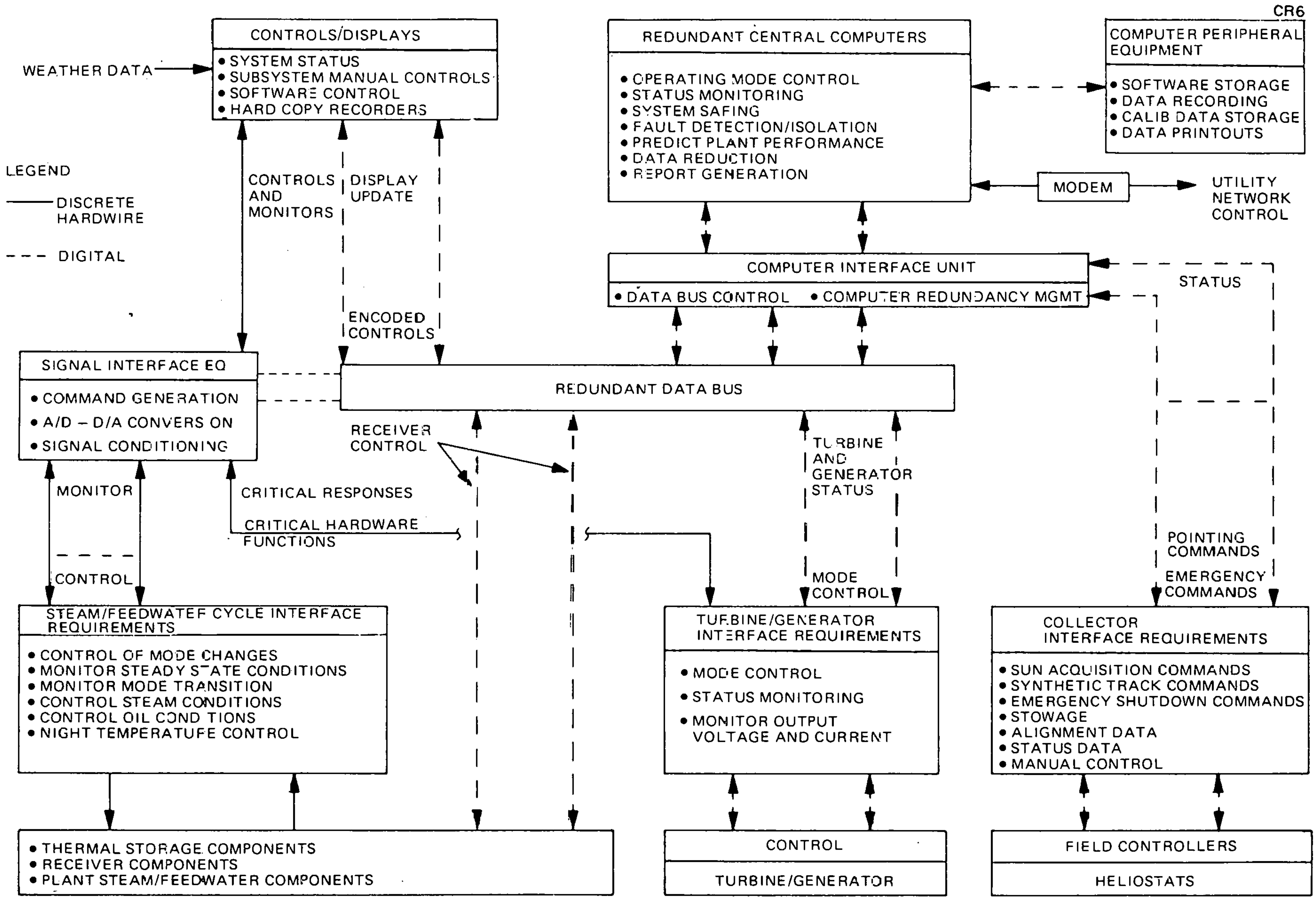

Figure 2-9. Pilot Plant Master Control Information Flow

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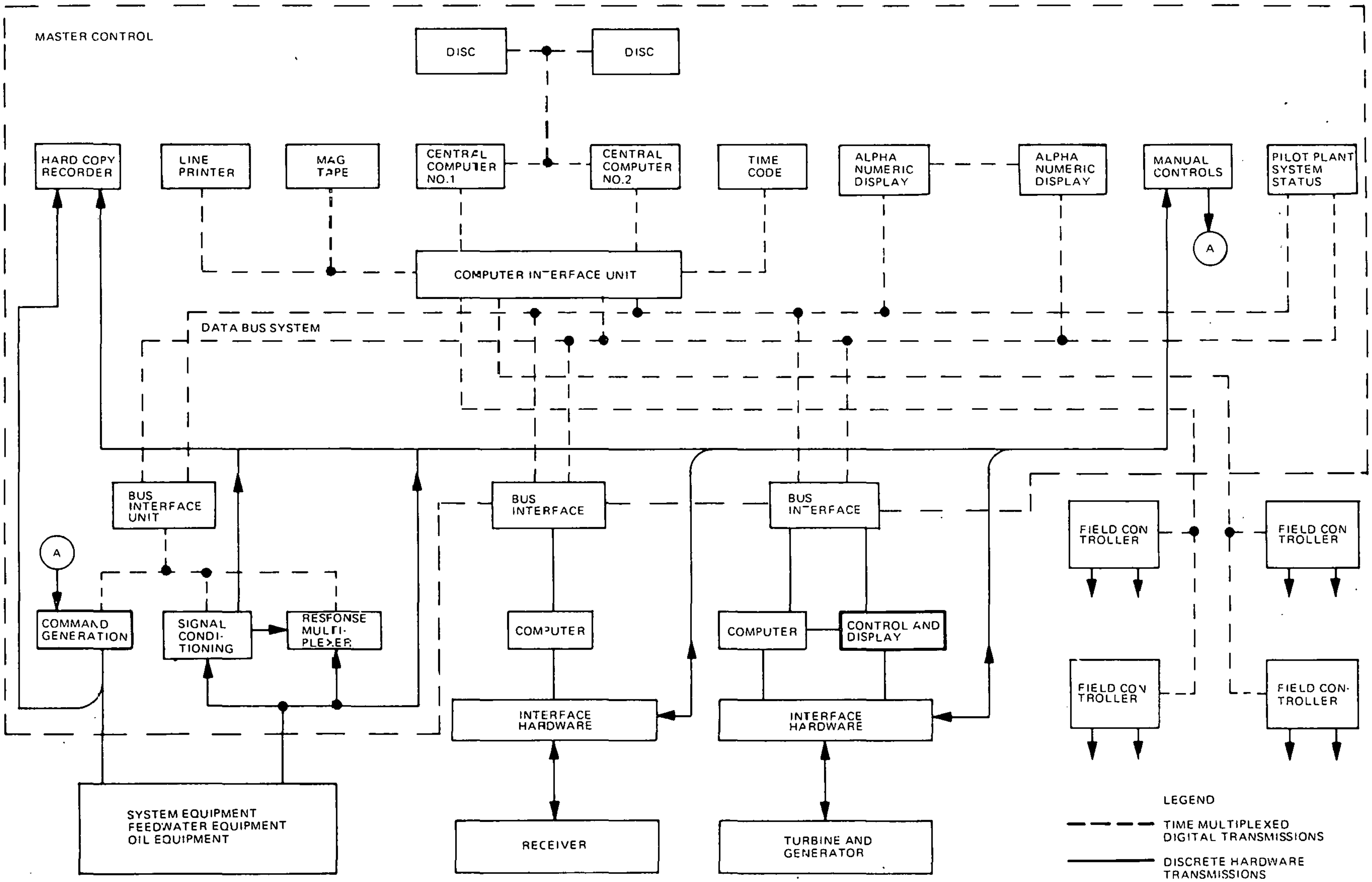

Figure 2-10. Pilot Plant Master Control Architecture

will relieve the standby computer of the necessity to synchronize execution with the on-line computer. Thus, when the on-line computer malfunctions, the backup computer will execute a startup program which will gather information concerning the present status of the pilot plant and begin control from this point. The critical data required are the receiver conditions and the steam conditions to the turbine. Detection of the computer malfunctions will be accomplished with a combination of hardware and software techniques.

Section 3
ELECTRICAL POWER GENERATION SUBSYSTEM

3.1 REQUIREMENTS SUMMARY

The electrical power generation subsystem includes all equipment necessary to fulfill the requirement of converting superheated steam into an electrical output which is compatible with the local electrical grid. In addition, the subsystem must provide feedwater at the proper conditions (thermodynamic and water quality) for satisfactory system operation. The principle subsystem elements, which were schematically identified in Figure 2-3, are the turbine-generator unit, including the extraction feedwater heaters, and the heat rejection equipment.

In specifying the equipment to be used, it is desirable to select and utilize off-the-shelf components to minimize system development problems and maximize the use of existing technology while, simultaneously, minimizing the impacts on the energy collection and steam generation portions of the system. One of the critical issues affecting these components is that conventional off-the-shelf equipment is utilized in a highly nonconventional manner. From a turbine standpoint, the operation required represents a unique application in that it will experience a daily startup and shutdown cycle in addition to a situation where steam conditions can change from the high temperature and pressure state associated with receiver steam to the lower temperature and pressure state associated with thermal storage steam.

The specific requirements of this subsystem are to produce 10 MW of net electrical power at 2 p.m. on winter solstice at a 30°C (85°F) ambient temperature and to produce 7 MW net electrical power from thermal storage. During plant operation, it also will be necessary to supply sufficient additional electrical power to accommodate the plant parasitic loads. In an effort to maximize system output, a 20 minute hot turbine startup has been established as a target goal with a corresponding cold startup requirement of 6 hours.

Additional goals are a subsystem availability, exclusive of sunshine, in excess of 97 percent, a 30-year operational lifetime with normal maintenance, and the capability to maintain feedwater with a pH of 9.5 and dissolved solids in the range of 20 to 50 ppb. In addition, due to anticipated scarcity in available water, all heat rejection shall be accomplished with dry cooling equipment.

3.2 TURBINE-GENERATOR

The turbine-generator unit selected for the pilot plant includes a tandem-compound, single-flow, single automatic admission condensing industrial turbine with a nominal rating of 15,000 kw (gross) when exhausting at a back pressure of 5 in. Hg absolute. The generator portion is a nominal 15,000 kw, 17,650 kva, air-cooled unit with an output of 13,200-volts at a frequency of 60-cycles. The capacity of this equipment was selected to accommodate the full summer noon energy flow which can exceed the winter design point energy collection capability by 25 percent.

The turbine was selected on the basis of operational responsiveness and the ability to operate from two independent steam sources either separately or simultaneously. A cutaway view of this baseline turbine is shown in Figure 3-1. In addition to the main high pressure admission port at the left end of the turbine, which is used for receiver steam, an intermediate automatic admission port is available which can be used to accept steam produced from thermal storage. Simultaneous operation can be accomplished properly matching the mix-steam pressure and enthalpy from two steam sources. The anticipated turbine heat rate associated with operation from receiver steam only is 10,220 Btu/kwh at a 2.75 in. Hg back pressure. The corresponding heat rate for operation from thermal storage steam is 13,480 Btu/kwh.

Due to the goal for rapid daily system startup, the transient operational limits of the turbine are of critical importance. The recommended temperature ramp rate versus temperature change is shown in Figure 3-2, where the temperature change is measured using a first stage inner-shell thermocouple. The values on the curves are the life expenditure in percent per cycle. For an assumed 30 year design lifetime (10,000 cycles), the operating curve labeled 0.01 would

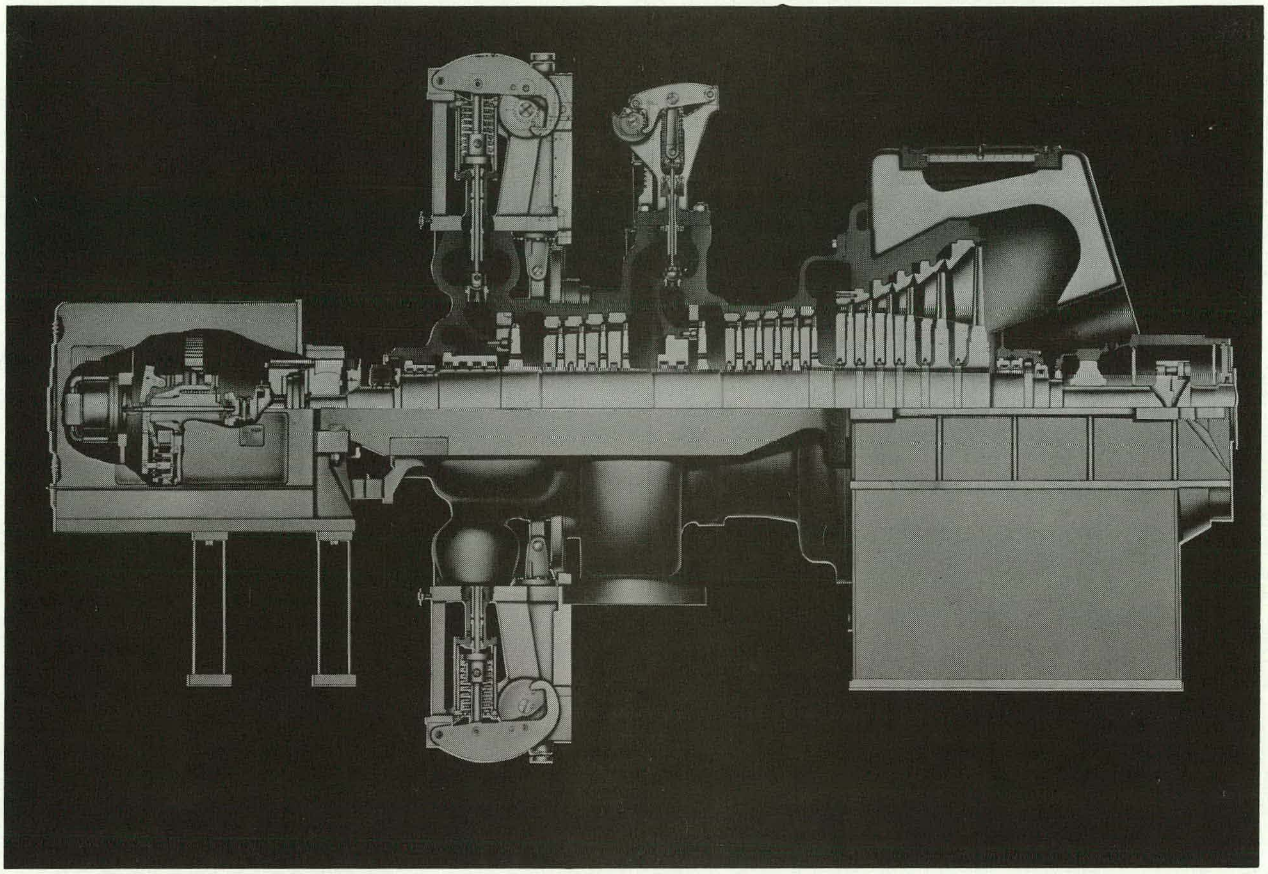

Figure 3-1. 10-MW Industrial Turbine

be appropriate. For a specified change in turbine temperature, this curve fixes the temperature ramp rate in order to maintain the planned life expectancy. The steam inlet temperature for this turbine can lead the metal temperature by 28 to 56°C (50 to 100°F). Figure 3-2 also shows that instantaneous temperature changes of 83°C (150°F) and ramp rates of 236°C (425°F) per hour and less will not have any adverse effects on turbine life.

The type of start (defined as cold, warm, or hot) will depend on the average temperature of the shell metal and will establish the rotor acceleration rate after startup as well as the loading rate and time required to bring the turbine to rated speed. The average metal temperature can be established by actual thermocouple readings or by the duration of the previous shutdown as follows:

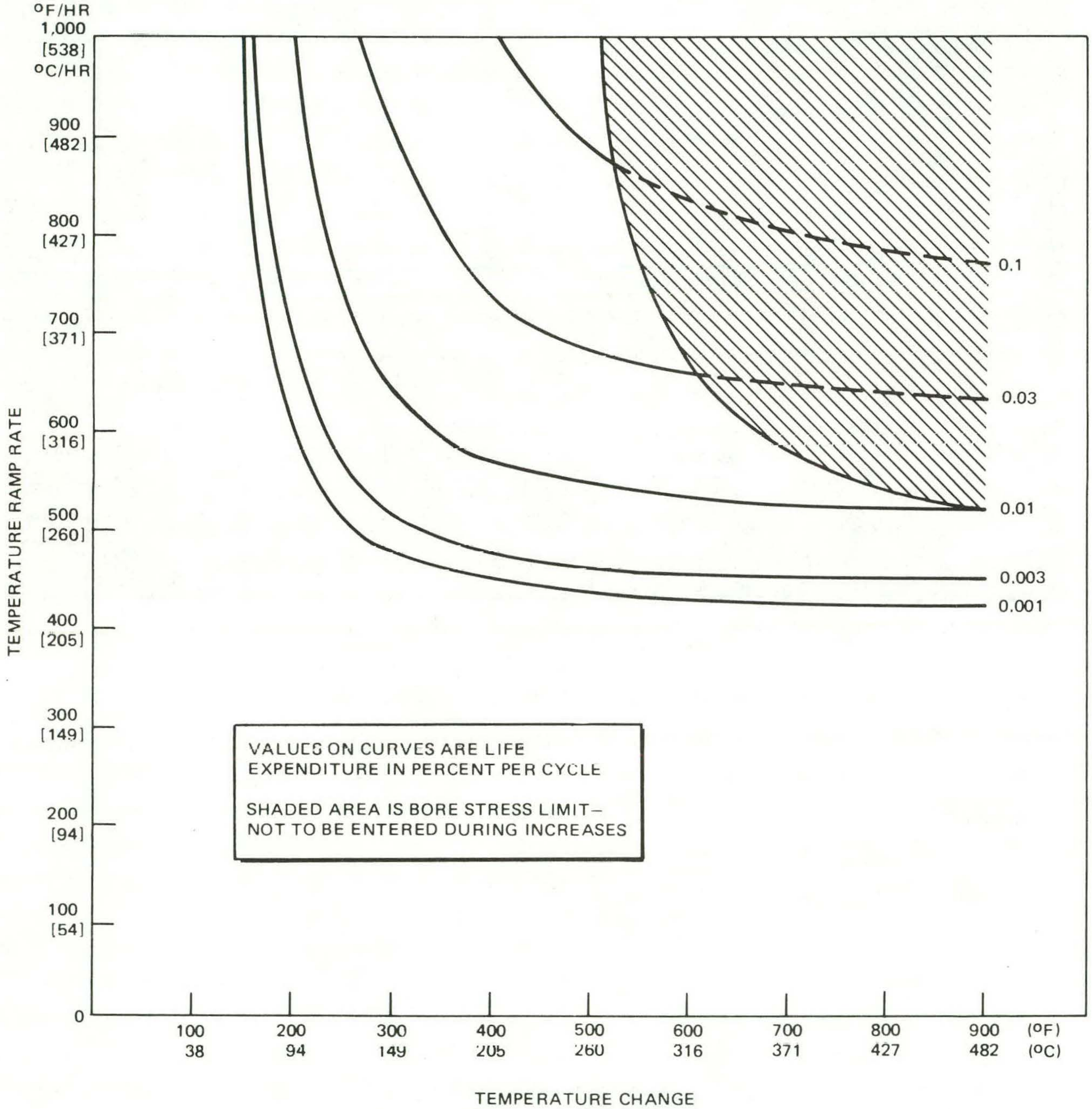

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Figure 3-2. Recommended Temperature Ramp Rate Versus Temperature Change Using First Stage Inner Shell Thermocouple

Duration of Previous Shutdown	Type of Start
Longer than 72 hours	Cold — average metal temperature -18° to 149°C (0° to 300°F)
12 to 72 hours	Warm — average metal temperature 149° to 371°C (301° to 700°F)
Less than 12 hours	Hot — average metal temperature 372° to 538°C (701° to 1,000°F)

With the appropriate startup condition identified, the acceleration rates for the turbine may be defined from Table 3-1.

Current information on pilot plant operation indicates that the daily morning start would fall in the range defined as a warm start due primarily to the use of 274°C (525°F) thermal storage steam the previous evening, and the expectation that the average metal temperatures will fall in the 149° to 371°C (301° to 700°F) range. For such a start, the turbine would take a minimum of 17 minutes. After reaching synchronous speed, it is recommended that an initial load of 3 to 5 percent of unit rating be applied. Following this initial loading phase, the unit load can be increased at 0.5 percent per minute for a cold start, 1.5 percent per minute for a warm start, and 3 percent per minute for a hot start. For a warm start, this corresponds to a time of approximately 63 to 65 minutes to reach nameplate rating after the unit has been initially loaded. The total time required from the turbine roll to full load is, therefore, approximately 80 to 82 minutes.

3.3 FEEDWATER HEATERS

Three feedwater heaters are proposed for the pilot plant; one low pressure heater, one high pressure heater, and one deaerating heater. The low and high pressure heaters are of the U-tube type with integral drain coolers. The denerating heater is of the spray-tray type with internal vent condenser. The deaerator will be mounted on a horizontal deaerator storage tank which will be sized for ten minutes minimum storage at full load.

Table 3-1

SPEED-TIME PROFILE FOR STARTUP ACCELERATION

	Final Speed (RPM)	Acceleration Rate (RPM/Minute)	Minimum Hold Time at Speed (Minutes)
Cold Start			
	1,000	250	10
	3,550	250	None
	3,600	As required	None
Warm Start			
	1,000	500	10
	3,550	500	None
	3,600	As required	None
Hot Start			
	1,000	500	5
	3,550	500	None
	3,600	As required	None

The construction materials for the baseline pilot plant feedwater heaters are:

Component	Material
Low-Pressure Heater	
Shell	Carbon steel
Tubes	Stainless steel
High-Pressure Heater	
Shell	Carbon steel
Tubes	Carbon steel
Deaerator	
Shell	Carbon steel
Trays	Stainless steel
Vent condenser	Stainless steel

Because of daily startup and shutdown of the pilot plant, it is necessary to provide steam blanketing on the shell side of the high pressure heater and deaerator in order to prevent oxygen from entering the heaters during the shutdown period to minimize corrosion. A low-pressure, electric-fired auxiliary steam boiler is furnished on the pilot plant for this purpose, in addition to providing steam for the turbine seal steam system during the shutdown periods. Steam developed from thermal storage could be used to perform this function if available; however, the auxiliary boiler will be necessary during times when thermal storage is not operable.

3.4 HEAT REJECTION

Due to anticipated limitations in water availability at most potential system sites, dry cooling has been included into the pilot plant baseline system definition as the method of heat rejection. The two systems currently available are shown conceptually in Figure 3-3. The first dry cooling concept, a direct condensing system manufactured by GEA in Bachum, Germany, sends the turbine exhaust steam directly to the air condenser which may be roof- or tower-mounted. The steam enters the top of the air condenser and is

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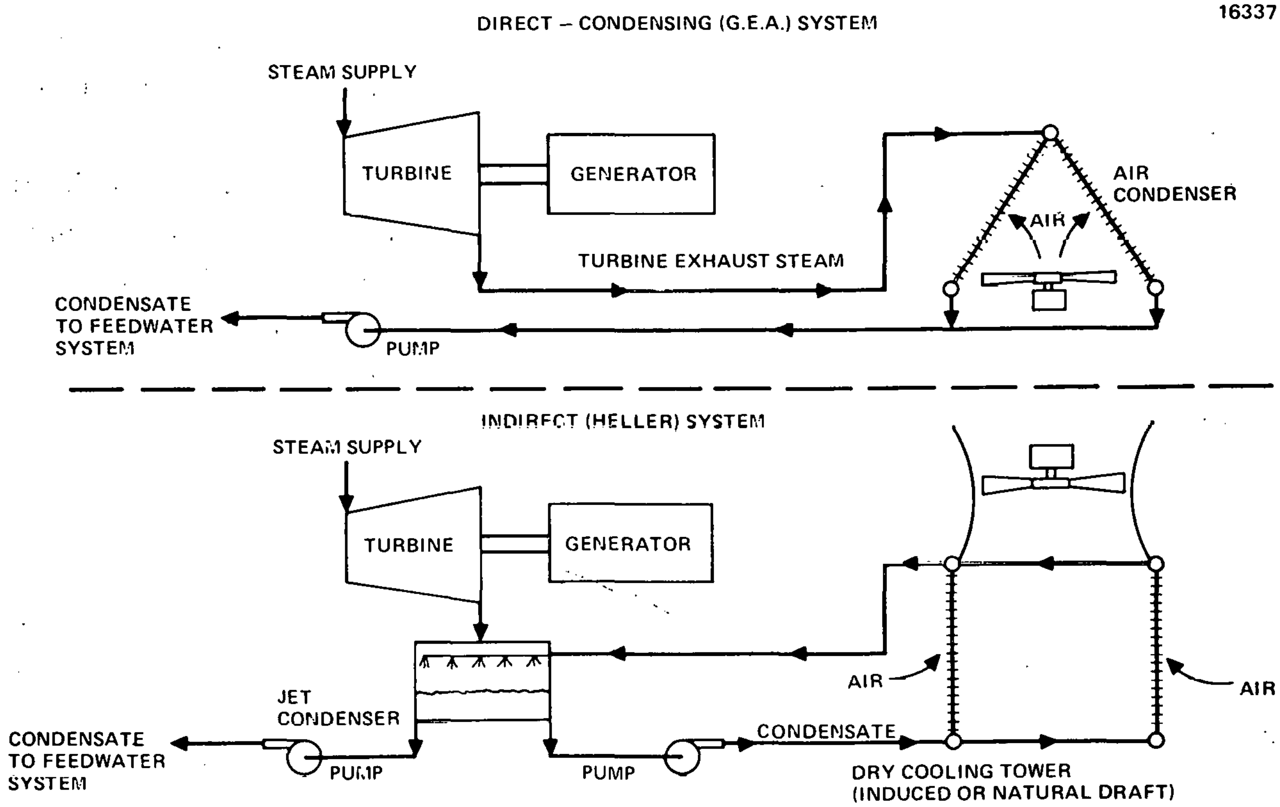

Figure 3-3. Dry-Cooling Concepts

condensed by air forced over fin-tube surfaces by the cooling fans. Gravity flow causes the condensate to collect in the collection headers and flow to the condenser hotwell where condensate pumps reintroduce the water to the feedwater loop. The principal advantage of this concept is that the steam is condensed directly without any intermediate heat exchange process. The limitation on this concept is that, for large systems, the turbine exhaust line to the condenser may become very large and excessive pressure drops may occur in the line, which can result in elevated turbine back pressures. This concept is the only dry cooling system currently used by a utility in the United States. The single installation was designed and constructed by Stearns-Roger, Incorporated for the Black Hills Power and Light Company near Gillette, WY. Due to the limitations described above, this concept is practical for smaller systems of capacities less than 300 MWe.

The second dry cooling concept illustrated in Figure 3-3 is the indirect or Heller system which is available from an English manufacturer. This concept utilizes direct contact condensing at the turbine exhaust. The hot condensate in turn is pumped to the cooling tower where either a natural or induced draft is used to provide the desired air circulation for heat rejection. The advantage of this system occurs in large capacity units where the steam flow of the direct system is replaced by pumped circulation of condensate to the cooling tower.

The baseline configuration for the pilot plant system corresponds to the direct condensing concept manufactured by GEA. It consists of steel fin-tube sections for condensing and air removal which are located above six 150/38 hp, 2-speed, electric motor-driven fans. An elevation drawing of the cooling equipment mounted on top of the turbine building is shown in Figure 3-4, along with the turbine exhaust steam duct.

The critical parameters affecting the cost and performance of the heat rejection equipment are the design condensing pressure and the design ambient air temperature. For this pilot plant design, high ambient air temperatures can be expected due to the liklihood of the system being placed in a high insolation desert location. For current sizing purposes, pending the actual site selection, a 5-in Hg. turbine back pressure was selected [57°C(134°F) condenser temperature] along with 38°C(100°F) design point ambient air temperature.

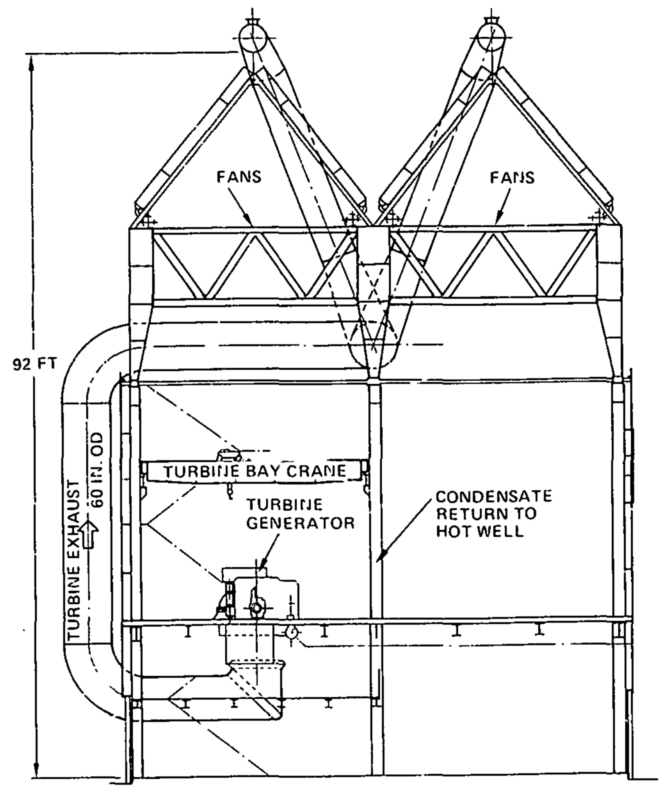

Figure 3-4. Air-Cooled Condenser Installation

The 57°C (134°F) condenser temperature is 3°C (6°F) below the maximum condensate temperature limit imposed by the resins in the water demineralizing equipment. These conditions were determined as a result of cost and performance trade studies carried out using Edwards Air Force Base and Inyokern, CA data. Once the specific pilot plant site is selected, a reassessment of the assumed design point conditions can be made.

3.5 AUXILIARY POWER

As part of the system sizing activity, parasitic power loads were estimated for the system for a variety of operating and nonoperating conditions. A condensed version of this estimate is presented in Table 3-2. The items indicated represent the major power draw elements within the system. The miscellaneous entries represent the aggregate of approximately 30 power consuming units. During the summer noon period, when excess thermal energy is diverted to thermal storage, the estimated power required for the thermal storage charging pumps is 200 kva. The emergency power is

Table 3-2

PILOT PLANT AUXILIARY POWER REQUIREMENTS

	Daytime (Receiver Operation) 10 MW (net) KVA	Evening (Therm Stor) 7 MW (net) KVA	Night (Standby) KVA	Emergency Power AC KVA
Receiver feed pump	395	-	-	-
Booster pump	85	92	-	-
Hotwell pump	20	20	-	-
Air-cooled condenser fans	800	225	-	-
Heliostats (incl field controllers)	144	-	-	212
Thermal storage charging pump	-	-	-	-
Thermal storage extraction pump	-	200	-	-
Miscellaneous	355	315	481.6	208.5
Total	1,899	852	481.6	420.5

provided for emergency shutdown of the collector field in addition to other critical services upon loss of commercial power. A 500-KW diesel-generator unit will provide the emergency power supply.

None emergency auxiliary power will be supplied by two 13,200/480 v, 1,000/ 1,288 kva oil insulated transformers. These transformers will be designed for operation at rated kva under ambient conditions associated with the pilot plant site. The transformers do not provide redundant capacity, but will permit very limited overload operation on one transformer. If greater reliability is desired, a spare transformer is an economic alternative instead of going to larger transformers which can increase substantially the switchgear costs.

Section 4
RECEIVER SUBSYSTEM

4.1 REQUIREMENTS SUMMARY

The primary mission of the receiver subsystem is to efficiently utilize incident solar radiation from the collector field to create and deliver steam to the electrical generation or thermal storage subsystems. The major hardware assemblies comprising the subsystem are the receiver assembly, the tower, and the riser/downcomer.

Nominally, the receiver subsystem will be required to receive water from the flow distribution system at 13.8 MN/m^2 (2,000 psia) and 204°C (400°F) and deliver superheated steam at rated conditions of 10 MN/m^2 (1,500 psia) and 477°C (890°F) to the electrical 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 receiving water at 13.8 MN/m^2 (2,000 psia) and 104°C (220°F) and delivering steam at 10 MN/m^2 (1,500 psia) and 343°C (650°F) when it is required to charge the total receiver energy output into thermal storage.

The receiver must safely and efficiently absorb incident solar radiation at a maximum flux of 0.3 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 ten seconds due to precipitation or the intermittent passage of clouds over the collector field.

The overriding need for efficient capture and utilization of solar insolation requires a high solar absorptance value on the external surface of the receiver which is not less than 0.9. This value must exist regardless of degradation due to weathering, abrasion, etc., as may be expected in a desert environment. Additionally, the surface must be easily refurbished.

As a forced flow steam generator, the receiver will be designed and certified to the requirements of Section I of the ASME Boiler and Pressure Vessel Code. Design verification will be made utilizing the more sophisticated analysis techniques of Section VIII, Division 2.

The receiver subsystem design shall also minimize complexity and cost, and maximize ease of fabrication and maintenance within the limitations permitted by performance requirements.

4.2 RECEIVER ASSEMBLY DESCRIPTION

The receiver assembly is comprised of 24 individual panels, flow control subassembly, the instrumentation subassembly, and supporting structure.

Each panel subassembly includes a tube bundle, manifolds, backup structure, and insulation. The function of the panel subassembly is to efficiently utilize incident thermal energy to convert ingested water into superheated steam and to protect the structure from radiation.

The flow control subassembly includes the control computers, controllers, orifices, valves, filters, and plumbing whose function is to direct and control the flow of water to the various parts of the receiver. This subassembly also provides for cleaning of the receiver by filtering, flushing, and purging.

The instrumentation subassembly includes the sensors and signal conditioning equipment. This subassembly determines the condition of the receiver and utilizes the data to inform the plant operators, master control, and the flow control subassembly.

The structural assembly provides support for the other subassemblies with respect to gravity, wind, and seismic forces. These loads are transmitted by the structural assembly to the tower unit.

Figure 4-1 depicts the pilot plant receiver as it would appear on top of the tower.

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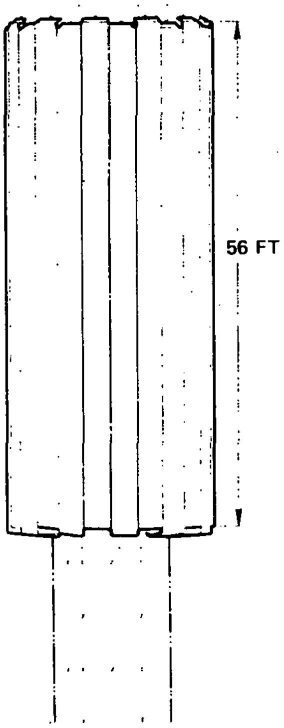


RECEIVER UNIT ASSEMBLY	
DIA	7.0M (23 FT)
HEIGHT	24.4M (80 FT)
NO. OF ABSORBER PANELS	24
ABSORBER PANEL	
HEIGHT	17.1M (56 FT)
WIDTH	1M (3.3 FT)
WEIGHT	1,816 KG (4,000 LB)
NO. OF TUBES	70
TUBE OD	1.27 CM (0.5 IN)
TUBE ID	0.68 CM (0.269 IN)
TUBE MATERIAL	INCOLOY 800
SOLAR SURFACE COATING	S-31

Figure 4-1. Receiver Configuration

4.3 PANEL SUBASSEMBLIES

Each panel subassembly includes a tube bundle, inlet and outlet manifolds, backup structure and insulation as described below.

4.3.1 Tube Bundles

The tube bundle consists of 70 tubes. Each tube is 1.27 cm (0.500 in.) OD by 18.5m (726 in.) long. The length includes a 1.1m (45 in.) length folded over at the bottom to protect the water manifold and lower steel structure from radiation and a 0.3m (12 in.) length folded over on top to protect the steam manifold from insolation. The tubes are fabricated from Incoloy 800 seamless tubing.

The surfaces of the tubes exposed to solar radiation are coated with S-31 paint which has demonstrated an absorptivity of 93 percent over a wide range of wavelengths. The coating is resistant to weathering and will be tested for long-term compatibility with high intensity solar radiation during the subscale research experiments. The tubes are welded together to affect mechanical and thermal integrity.

The nominal incident heat flux profile utilizes a 5-point heliostat aim strategy. With this strategy, most of the incident heat flux is at a constant value of 0.26 MW/m^2 (0.16 Btu/in^2-sec).

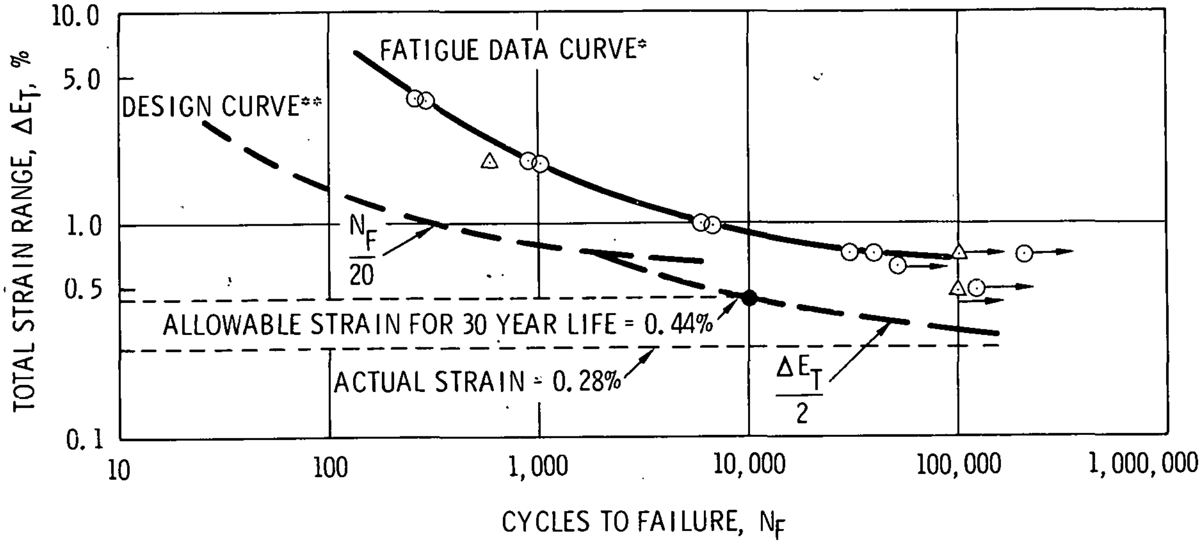
The thermal analysis for the panel tubes utilized a computerized one-dimensional heat transfer model and this flux profile to study axial temperature variations, and a two-dimensional computer model to study the cross-sectional temperature distribution. The heat transfer coefficients generated in the one-dimensional program were used in the two-dimensional model in order to study the tubes in detail. Incident heat fluxes were modified to account for reflection, radiation, and convection losses.

Experimental data from Company-sponsored test programs were used to check the calculated heat transfer coefficients. The coefficients in both the water and the steam phases agreed analytically and experimentally.

The one-dimensional computer program performed heat balance calculations at stations along the tube. Using calculated heat transfer coefficients, these balances allowed determination of tube wall temperatures. Heat loads were used to determine the fluid enthalpy and temperature rise for the next station. In addition, pressure drops were determined.

Life analyses also were performed for the receiver panel tubes. Limitations were established on the temperatures and temperature gradients, based on low cycle fatigue life. Maximum hot surface and minimum cold wall temperatures were determined for a given wall temperature differential, in order to prevent a low cycle fatigue failure.

The stress analysis resulted in a graph, Figure 4-2, with various temperature parameters. The life cycle data indicated that a value of effective strain, E_{eff}, of 0.44 percent would provide a cycle life of 10,000 cycles (daily cycling for 30 years). Actual strain in the panel tubes was calculated to be only 0.28 percent.



*J. B. CONWAY, "FATIGUE STUDIES OF INCOLOY 800", GENERAL ELECTRIC, REPORT GEMP-732, DEC. 1969
** ASME CODE REQUIREMENT (SECTION 3, APPENDIX I)

Figure 4-2. Incoloy-800 Fatigue Data and Design Curve

In addition to the effects of temperature gradients in a single tube, the effects of heat flux gradients across a panel tend to add to the effective strain. An analysis of tube life capability was conducted for the panel with the most extreme gradient. The analysis resulted in a predicted life of $>1 \times 10^6$ cycles.

4.3.2 Manifolds

The Incoloy 800 water manifold is located at the lower end of the panel assembly and functions to equally distribute water to all panel tubes. The water manifold is a bolted assembly which permits field installation of individual tube flow control orifices. This allows a minimum number of panels to be stocked as spares since any panel can be used in any receiver position by installing the appropriate orifices.

The Incoloy 800 steam manifold is located at the upper end of the panel subassembly and acts as a collector manifold for the effluent steam from all tubes. To ensure leak integrity, all panel tubes are welded to the steam manifold.

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4.3.3 Backup Structure

The function of the panel backup structure is to maintain the panel shape and hold it to the tower structure in proper location while allowing for thermal growth and providing support for wind and seismic loads.

Each panel is independently mounted on the tower as shown in Figure 4-3. The panel is attached rigidly to the tower at the upper end where the tube bundle is folded approximately 90 degrees from the vertical.

Two fixed T-beams on the tower engage sliding blocks at several axial stations on the panel to provide for downward axial expansion. Each pair of sliding blocks (at a given axial station) is fastened to a channel having a hat-shaped cross section. Clips welded to the tubes slide on the above-mentioned channels (hat bands) to permit lateral expansion of the panel.

In addition to providing panel support, the transverse hat band will be used to mount the thermal insulation on the back of the panels and behind the gaps between panels.

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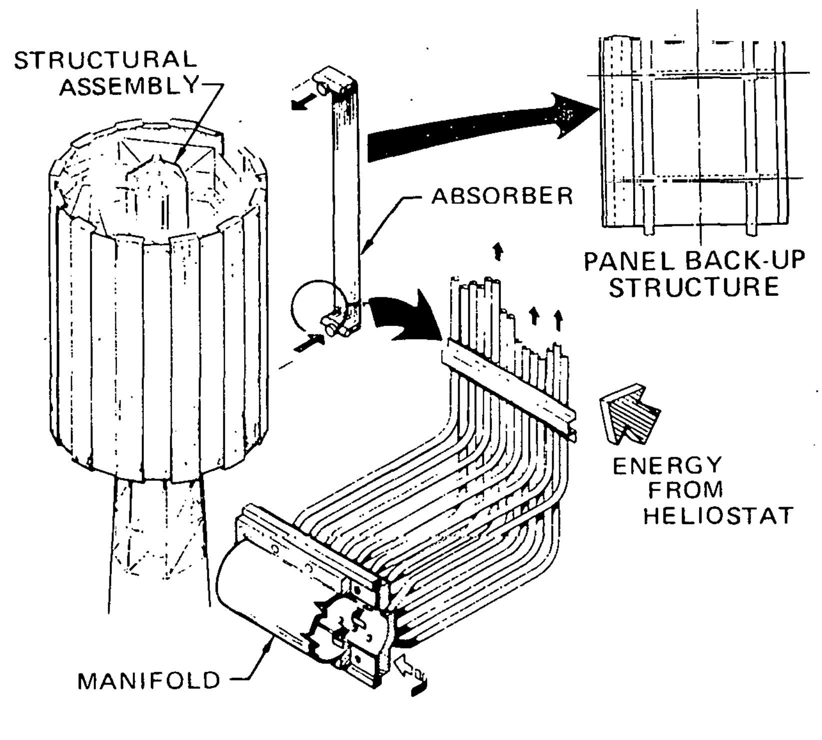

Figure 4-3. Receiver Subsystem

4.3.4 Insulation

Insulation is required between the adjacent panels to protect the structure from incident radiation. Blown, closed-cell fiberglass was selected for this application. Insulation is also required behind the panel to reduce heat losses from the back side of the tubes.

4.3.5 Panel Installation

Installation of a panel in the receiver will be essentially identical for both the pilot plant and the commercial receiver. The only attachments which need to be broken and remade for a removal and installation are the bolted inlet and outlet flanges and the bolts securing the panel backup structure to the main receiver structure. The simplicity of the procedure provides a reasonable confidence that a panel can be changed during the nighttime down period with a zero impact on plant outage.

4.4 FLOW CONTROL SUBASSEMBLY

The basic requirements for the flow control subassembly are to provide specified receiver steam outlet conditions, to protect the receiver during emergencies, and to provide filtration, flush, and purging functions as required. Receiver inlet and exit pressures and inlet temperatures are regulated by other plant subsystems.

Provisions for two different types of flow control are made in the receiver; (1) individual tube orifices and (2) panel flow control valves. The individual tube orifices provide a pressure drop at the entrance to each tube to enhance flow stability in the tubes under low flow conditions. These orifices also assist the flow control valves in distributing the flow about the receiver to match the circumferential variations in heat loads. The flow control valves (Figure 4-4) provide the control necessary to maintain constant outlet temperature 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.

4.4.1 Typical Startup and Shutdown

At the beginning of the day, prior to focusing solar energy from the heliostats on the receiver, master control will send a signal to the receiver which

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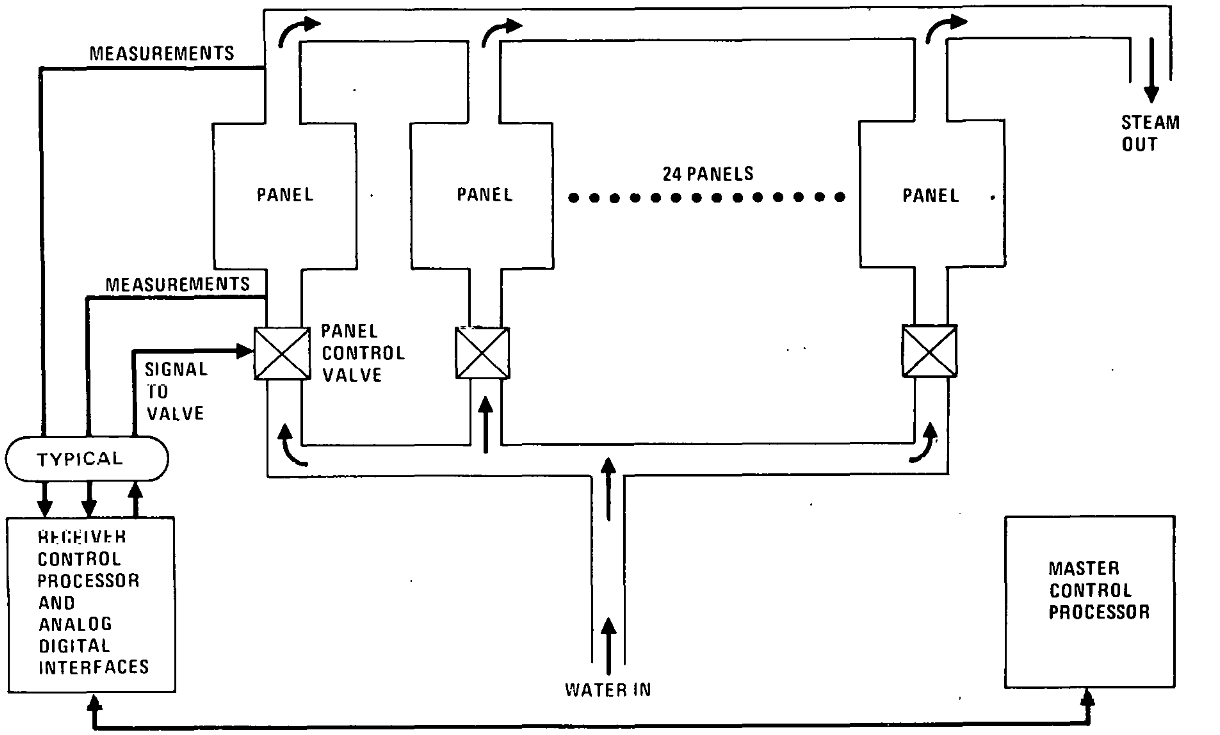

Figure 4-4. Receiver Control Schematic

initiates receiver checkout. This checkout includes checking the sensors, checking the computer, verifying control valve functionality, water inlet pressure and flow conditions, and pneumatic pressure level. These checks will be performed internally within the receiver computer logic. Should any of the checks fail, an indication of the failure will be sent to master control. When the checks have been successfully completed, an acknowledging signal will be sent to master control. At this point, the heliostats will be focused on the receiver generating a heat flux transient which will culminate in a quasi-steady-state value of approximately 1/4 the maximum heat load. During this transient, the receiver will maintain a water flowrate at a value sufficiently high to ensure flow stability (Point A to Point B in Figure 4-5). At the end of the transient, the receiver will be generating slightly superheated steam to be transferred to the thermal storage system. As the heat load continues to increase, the water flowrate will be increased to maintain the slightly superheated steam condition (Point B to Point C). When the incident heat reaches approximately 50 percent of maximum value, a point is

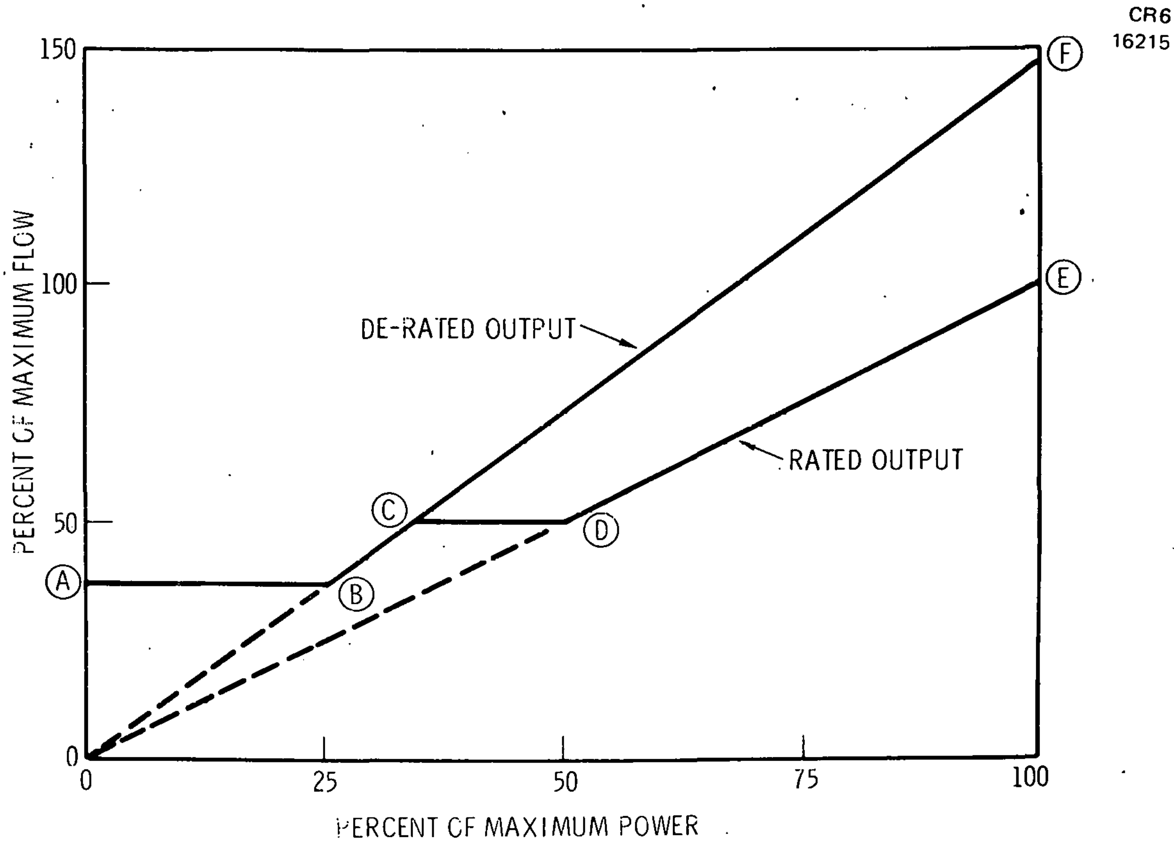

Figure 4-5. Receiver Power Flowrate

reached where, by maintaining the flow constant at this value (Point C to Point D), rated superheated steam will be generated. The controller will then function to maintain this steam temperature as the heat load varies during the day between 50 and 100 percent of the rated maximum heat load (Point D to Point E).

The shutdown procedure is somewhat similar with the controller following the heat load along the portion DE of the curve to supply rated temperature steam; maintaining constant flow while the heat load decreases from D to C maintaining constant temperature along the slightly superheated line CB; then maintaining constant flow for the remainder of the shutdown procedure.

4.4.2 Cloud Transients

During periods of heavy cloud transients, the receiver will be commanded to supply slightly superheated steam to the thermal storage system. As a cloud passes over the heliostat field, the control system will attempt to maintain this steam outlet condition by following the thermal input down the line FB in Figure 4-5. If the heat loads decay below 25 percent (AB), the control system will maintain the minimal control valve position in order to assure stability. Thus, the output of the receiver will vary from subcooled liquid to slightly superheated steam during the cloud cover transient condition. A signal from master control is required by the receiver to effect the cloud cover mode of operation.

4.4.3 Emergency Controls

In the event of an emergency, as indicated by a low flowrate, a low inlet pressure, or a high steam temperature, the function of the receiver is to protect itself. If the emergency condition is sufficiently severe, a signal will be sent to master control to defocus the heliostat field. In addition, the control valve in the effected area will be signaled to the full open position to provide maximum cooling capability. Pertinent data will be transmitted for display so that the operator can verify the emergency condition.

Component redundancy, backup power, and filtration are being provided in the system design to eliminate loss of water flow to the receiver as a credible failure. Nevertheless, an analysis was made assuming a sudden loss of coolant water to determine the time within which emergency protective systems would be required to function to protect the receiver from damage. Since defocusing of the heliostats from the receiver is probably the slowest of the possible protective actions, the analysis investigated the impact of the high heat flux during the time lag of the mirror control system. The emergency slew rate of the heliostat field was found sufficient to protect the receiver even in the event of a complete and instantaneous loss of water.

For the case where the mirrors are not slewed [constant heat flux incident of 0.262 MW/m^2 (0.16 Btu/in^2-sec)], the tubing will reach radiative equilibrium [1,205°C (2,200°F)] in approximately 400 sec (0.1 hr); however, catastrophic failure will not occur for 0.7 hr. Evaluation of the predicted values of temperature together with the creep properties of the material indicate that distortion damage due to creep will be negligible if tube pressure is vented, and relatively small if slew is initiated within minutes after feedwater flow is lost even if pressure is maintained.

It should be noted that the present receiver panel design includes a remote controlled vent valve which could be activated in any emergency sequence if desired.

The overall outlet temperature of each panel will be sensed to provide the nominal control function. Temperatures in each of the four quadrants of every panel will be sensed to indicate the need for emergency procedures. These quadrant sensors will provide indications of excessive overall temperature, or excessive temperature differentials from one side of the panel to the other, resulting from plugging or abnormal thermal input gradients.

In order to detect single tube failures, a fusible conductor wire will be bonded across the backs of the tubes of a panel with a dielectric material. The material for the fusible wire will be selected so that the wire will melt and indicate a loss of continuity at a temperature of approximately 620°C (1,150°F). Loss of continuity will be the signal for initiation of emergency procedures.

4.5 INSTRUMENTATION SUBASSEMBLY

The basic instrumentation requirement is to sense those parameters required for receiver control and evaluation of safe operation. The instrumentation signals must be available for control, recording, or display.

The output of the various sensors will be used for control, display, and recording purposes. For control and detection of emergency conditions, a sampling rate in the order of one sample per second is advisable. All parameters will be recorded on magnetic tape for historical and diagnostic purposes. It is recommended that display of all parameters for any three panels be simultaneously available on command from the operator.

4.6 TOWER ASSEMBLY

The receiver tower assembly is required to provide safe support to the receiver [wet weight of 103,000 kg (225,000 lb)] and riser/downcomer [wet weight of 24,000 kg (52,800 lb)] during the 30-year system design lifetime while permitting minimum tower top sway during all periods of system operation [less than 0.3 m (1 ft) deflection at the 95 m (312 ft) level]. In addition, the tower assembly must be designed to be compatible with all codes and regulations while providing access and installation/maintenance support equipment as required for installation, inspection, maintenance, or repair activities associated with the receiver and riser/downcomer.

In selecting a baseline configuration, a comparative analysis was carried out between a free-standing steel and jump-formed concrete configuration. Using postulated wind and seismic data, the analysis indicated that the free-standing steel concept is superior from a cost and performance standpoint. The seismic criterion used for this design was the AEC Regulatory Guide 1.60 normalized to 0.165g for the operating basis earthquake and 0.33g for the safe shutdown earthquake. For stronger earthquake conditions, the steel tower would prove to be more superior due to its greater ability to flex with the ground motion.

The baseline steel tower which is shown in Figure 4-6 consists of square cross section, cantilever K-braced frames which are supported on a square

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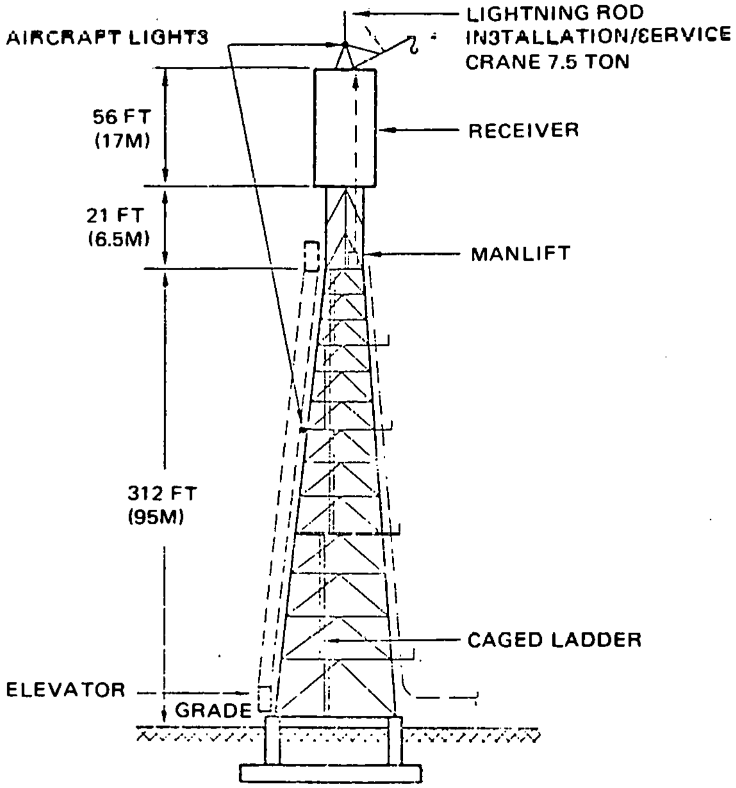

Figure 4-6. Steel Receiver Tower

concrete footing. The width of the tower at the top is 6.1 m (20 ft) while the base dimension is 15.24 m (50 ft). The square concrete foundation has a 0.91 m (3 ft) thick mat which is 19.8 m (65 ft) on a side and located 3.05 m (10 ft) below finished grade for both the fixed and flexible base cases. Concrete walls and pedestals extend 5.48 m (18 ft) upwards from the foundation to meet the steel structure at an elevation 1.52 m (5 ft) above the grade. The estimated tower cost is approximately $915,000.

Figure 4-6 also shows the required auxiliary equipment. This includes a service elevator of the rack-and-pinion type for equipment and personnel transport, with a parallel caged ladder for emergency use, access platforms, aircraft lighting, an installation/service crane, as well as other miscellaneous equipment.

4.7 RISER/DOWNCOMER ASSEMBLY

The riser/downcomer must be capable of transporting superheated steam from the tower top receiver to the ground based turbine and thermal storage subsystem while returning the preheated feedwater to the receiver. The design conditions for each are as follows:

A. Downcomer Design Conditions

Summer Noon-Normal Operation	Summer Noon-Intermittent Clouds
10.4 MN/m^2 (1,500 psia)	10.4 MN/m^2 (1,500 psia)
477°C (890°F)	343.3°C (650°F)
17.9 kg/sec (142,000 lb/hr)	23.1 kg/sec (183,000 lb/hr)

B. Riser Design Conditions

Summer Noon-Normal Operation	Summer Noon-Intermittent Clouds
13.8 MN/m^2 (2,000 psia)	13.8 MN/m^2 (2,000 psia)
204°C (400°F)	204°C (400°F)
17.9 kg/sec (142,000 lb/hr)	23.1 kg/sec (183,000 lb/hr)

The baseline concept mounts the pipes on the outside of the tower with a 180-degree wrap at the base of the tower to accommodate thermal expansion (the interface with the tower top receiver is assumed fixed). Pipe supports include variable spring, constant support, and rigid type supports as required to facilitate expansion. Rigid pipe guides also will be used for seismic and wind restraints as required.

The pipe size and materials selected for the pilot plant baseline design are as follows:

Item	Riser	Downcomer
Nominal pipe size	10.16 cm (4 in.)	14.70 cm (6 in.)
Nominal wall thickness	1.11 cm (0.438 in.)	1.43 cm (0.562 in.)
Material	ASTM A106B Carbon Steel	ASTM A355 P11 1-1/4 CR - 1/2 MO
Maximum allowable working pressure (ANSI B31.1)	19.0 MN/m^2 (2,755 psia) at $<343°C$ (650°F)	14.7 MN/m^2 (2,083 psia) at 482°C (900°F)
Maximum flow rate	23.1 kg/sec (183,000 lb/hr)	23.1 kg/sec (183,000 lb/hr)
Velocity at maximum flow rate	4.0 mps (13.1 fps)	31.3 mps (102.5 fps)

4.8 SUBSYSTEM RESEARCH EXPERIMENTS

The receiver subsystem research experiments (SRE) are designed to eliminate any risks inherent in the performance, control, stability, and mechanical integrity of the pilot plant receiver. The conceptual designs of the receiver subystem research experiments and hardware were completed on schedule and accepted by ERDA as the basis for the detail SRE design which is now underway.

The receiver subsystem research experiments are designed to verify the following specific capabilities of the pilot plant receiver design:

A. Performance — Deliver rated steam over required range of power, and variations thereof.

B. Cooling Capability — Withstand peak heat flux and heat loads, as well as gradients within a panel.

C. Stability — Provide stable flow over entire range of power/flow spectrum.

D. Life – Be capable of operating over 30 years (10,000 cycles).

E. Structural – Withstand combined wind and seismic loads.

F. Fouling – Provide capability of maintaining cooling surfaces and restrictions designed into systems corrosion/erosion free when supplied with nominal power plant water.

G. Clouds – Be capable of reacting to passing cloud cover over collector field with no degradation of subsystem.

4.8.1 <u>SRE Test Plan</u>

The receiver SRE includes test of subassemblies as well as tests of a complete segment of a full scale pilot plant receiver. The lower level tests include tests of single and multiple tube configurations to provide thermal, hydrodynamic, structural, and life data. A summary of the SRE test requirements is provided in Table 4-1.

4.8.1.1 Single Tube Tests

A single tube will be tested in vertical orientation over the ranges of anticipated pilot plant operating conditions using a radiant heat input. Various inlet orifices will be used to determine a lower limit on orificing requirements for stability. Preliminary assessment of absorber integrity and efficiency will be obtained. Abnormal operating conditions also will be explored.

Objectives of the single tube tests are (1) facility checkout, (2) preliminary demonstration of thermal performance, (3) preliminary demonstration of safe tube operation under nominal conditions, (4) preliminary assessment of emergency operating conditions, and (5) demonstration of flow stability in a single tube.

4.8.1.2 Narrow Panel Test

A panel consisting of three to five tubes will be oriented vertically and tested in a manner similar to the single tube tests. This test, by including inter-tube stability characteristics, will better define orificing and control valve requirements. Further definition of absorber integrity and performance will be obtained including the effects of flow reduction in a single tube. Verification of vertical expansion capability, the adequacy of the panel restraint

Table 4-1

RECEIVER TEST REQUIREMENTS

Design Considerations	SRE Test Requirements
Performance Cooling capability Stability Fatigue life Structural Fouling Clouds	Test single tube to establish initial flow stability and cooling capability. Test narrow panel to verify multitube stability, cooling, fouling resistance, and fatigue characteristics over normal and emergency range of pilot plant operating conditions. Test complete pilot plant panel assembly over complete range of operating conditions to demonstrate performance cooling, stability, and structural capability. Test panel surface coating under concentrated sunlight conditions.

(to warping), and the tube-to-tube weld integrity will be obtained. The basics of panel fabrication method and transportation will be demonstrated.

The objectives of the narrow panel test are (1) to demonstrate thermal performance of the absorber, (2) to verify safe operation and wall temperatures consistent with 30-year life under pilot plant operating conditions, (3) to demonstrate flow stability in a multiple tube panel, (4) to provide a preliminary demonstration of fabrication techniques, (5) to verify the adequacy of the backup structure with respect to restraint and thermal expansion capability, and (6) to evaluate emergency shutdown procedures.

4.8.1.3 Absorber Surface Test

A tube will be exposed to high-intensity solar radiation for extended periods of time while being cooled to nominal operating temperature. This test will be preceded and followed by measurements of absorptivity of the tube surface and will provide a demonstration of exposure capability.

The objective of the absorptivity surface test is to determine the effect of high-intensity solar insolation on panel surface absorptivity.

4.8.1.4 Receiver Segment Test

Steady-state and transients tests will be conducted on a receiver panel which is functionally identical to a panel of the pilot plant receiver. The test receiver will include the absorber, flow control components, and structural backup subassembly.

Objectives of the receiver segment test are (1) to demonstrate pilot plant absorber fabricability, weight, and transportability; (2) to verify pilot plant receiver performance including compatibility with thermal storage and electrical power generating subsystem interfaces, operation at safe wall temperature with design pressure drop, and efficient transfer of incident thermal energy to produce steam; (3) to verify control and stability of a pilot plant segment including steady-state stability and accuracy, stability and accuracy during start and shutdown sequences, stability and safety during cloud cover transients, component dynamic characteristics, and response to standard control signals; and (4) to verify thermal stress and expansion provisions.

4.8.2 Overall Schedule

The overall schedule for the subsystem research experiments is shown in Figure 4-7. The single-tube tests are scheduled to be in progress prior to the detailed design review (DDR) so that information derived from these tests can be incorporated into the design and fabrication of the receiver panel. Fabrication of the five-tube panel will have been initiated one month prior to DDR for the pilot plant panel so that experiences gained on it can be incorporated into the design of the pilot plant panel. The other ancillary tests would not effect panel design or would require too long a postponement of the panel fabrication to be realistic. The experimental phase of the program is scheduled to be completed with sufficient time to permit updating of the preliminary design of the receiver based on experimental data.

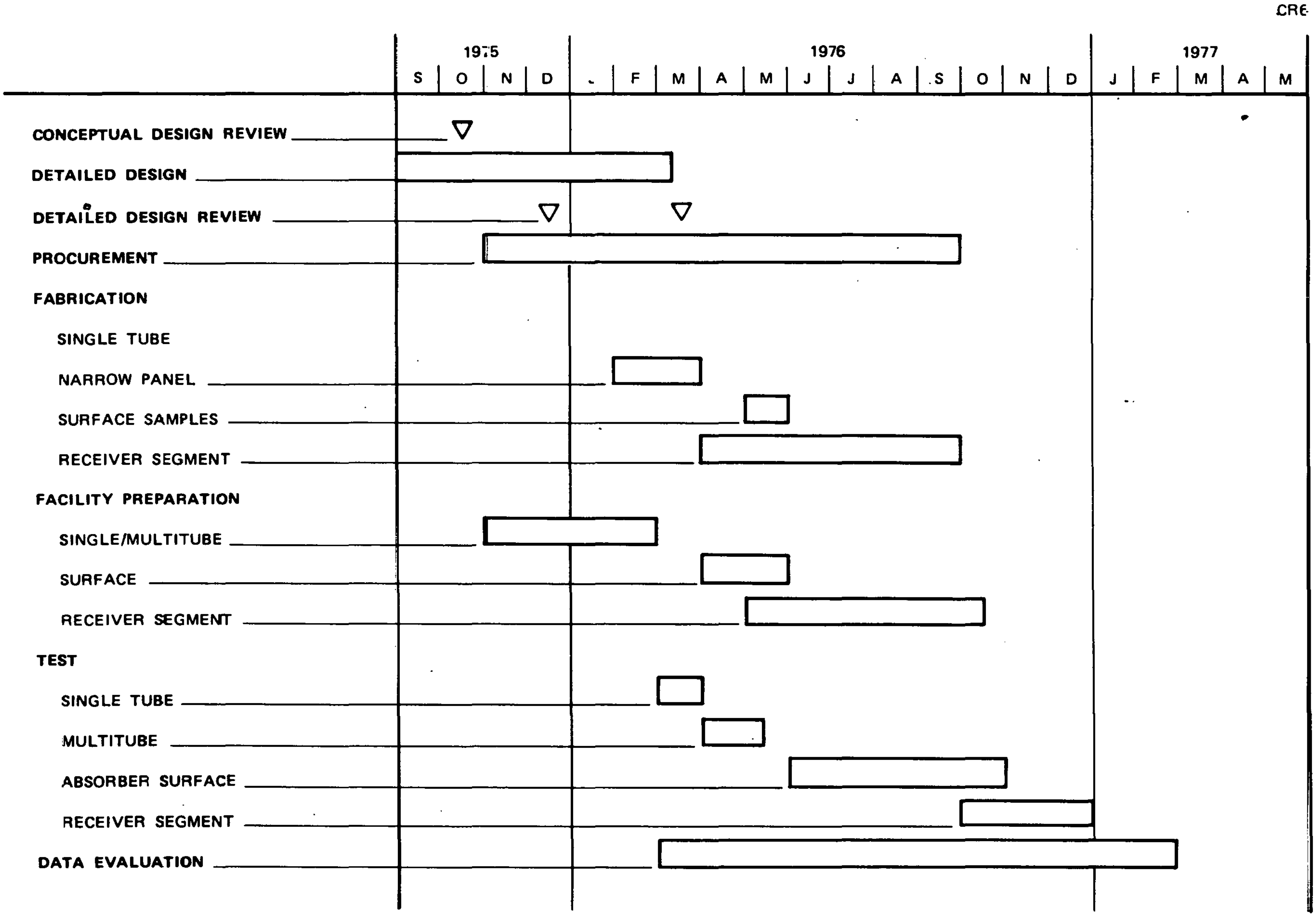

Figure 4-7. Overall Receiver SRE Schedule

Section 5
THERMAL STORAGE SUBSYSTEM

5.1 REQUIREMENTS SUMMARY

A major operational requirement of the thermal storage subsystem is to buffer the electrical generating subsystem from short term variations in insolation; another is to extend the system's generating capacity into periods with low or no insolation.

As a buffer between the solar portion of the plant and the electrical generating portion, the thermal storage subsystem (TSS) can protect the turbine from rapid variations in inlet conditions as insolation changes due to the clouds passing over the collector field.

The second major requirement of the TSS is to extend the plant's generating capacity into periods without insolation. Peak loads for southwestern utilities usually occur for periods up to six hours after sundown. Providing generating capacity for these six hours will allow the solar plant to accrue credit for capacity displacement.

Another significant function of the TSS is assisting in the matching of annual fluctuations in solar insolation to the sizing of the electrical generating portions of the plant. If the electrical subsystem is sized for the peak summer noon insolation, its full capacity is unused for most of the year. If it is sized much smaller, a great deal of solar energy is lost unless it can be stored. Trade studies showed that six hours of storage provides approximately the optimum size for this capacity in a commercial plant.

5.2 PRELIMINARY BASELINE DESIGN SUMMARY

The 10-MWe 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.

In the cyclical operation, heating of the bed (charging) is achieved by removing 236°C (425°F) temperature fluid from the bottom of the bed, heating it in a heat exchanger with steam from the receiver, and returning 302°C (575°F) fluid to the top of the tank. The fluid flow is reversed for heat extraction (Figure 5-1).

Figure 5-2 is a schematic diagram of the thermal storage subsystem, showing all major components, lines, and major control concepts. Table 5-1 summarizes the principal characteristics of the subsystem and major components. As shown in Figure 5-2, the subsystem can be considered in three major parts: (1) the central thermal storage unit, (2) the thermal charging loop, and (3) the heat-extraction loop. In the charging loop, energy is removed for the receiver steam and stored in the thermal storage unit tank. A commercial petroleum-base, heat-transfer fluid (Caloria HT-43) is used to permit economical ambient pressure storage in the tank. The extraction loop utilizes the fluid to remove energy from the storage unit

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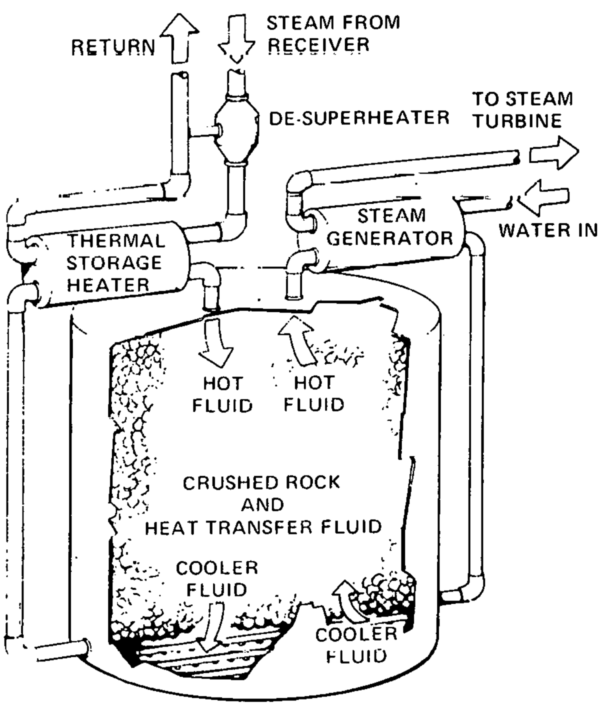

Figure 5-1. Thermal Storage Subsystem

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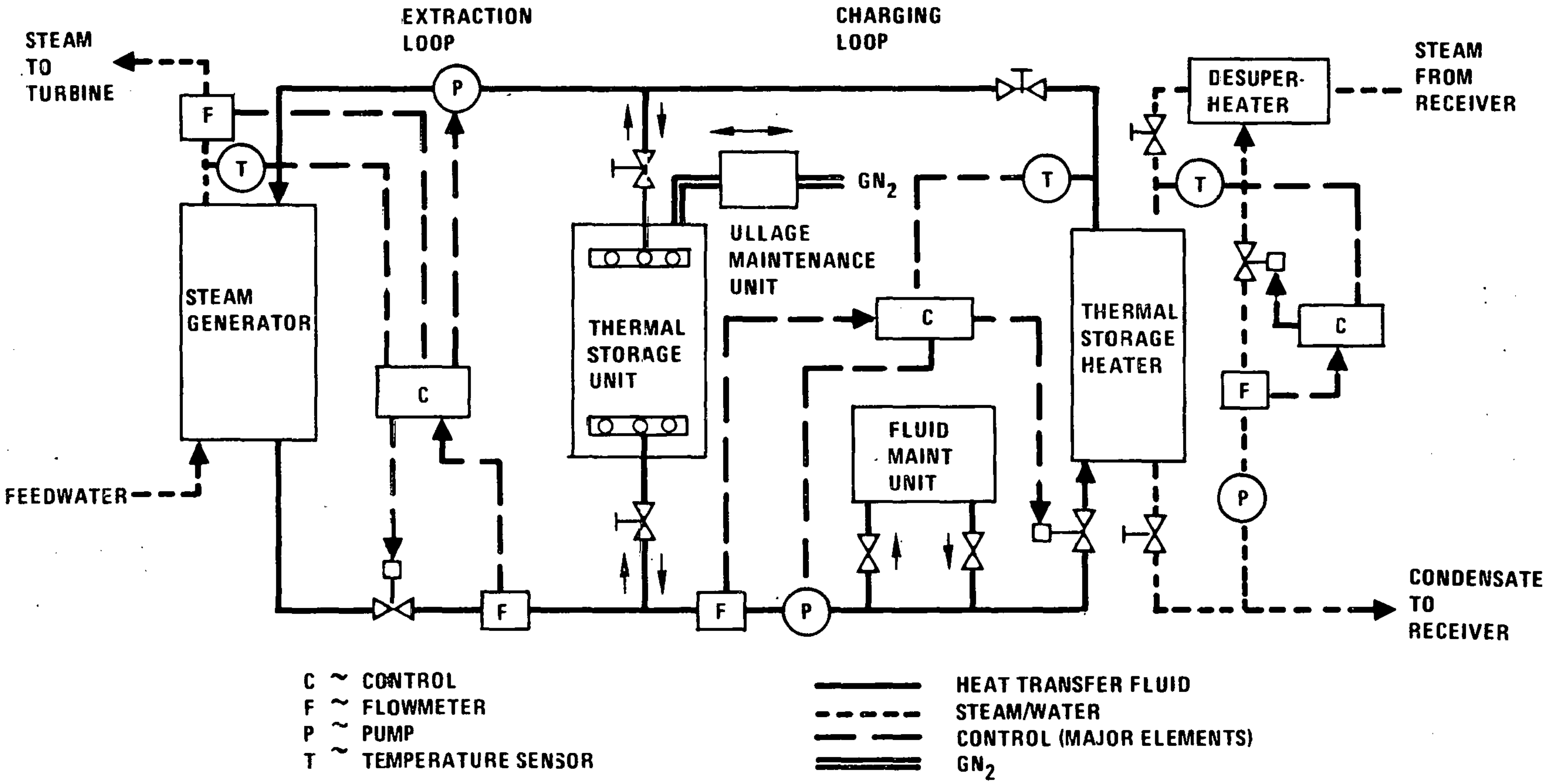

Figure 5-2. Pilot Plant Thermal Storage Subsystem Schematic

Table 5-1

PILOT PLANT THERMAL STORAGE
SUBSYSTEM DESCRIPTION

Assembly	Description
Thermal storage unit	Cylindrical tank, axis vertical, above ground, 19.4m (63.7 ft) ID, 17.3m (56.8 ft) high; 9.59×10^6kg (10,600 ton) crushed granite rock, $1.18 \times 10^6 \ell$ (312,000 gal) of Caloria HT-43; ASTM A537 structural steel.
Thermal storage heater	U-tube, baffled counterflow exchanger, two-pass shell, carbon steel construction.
Steam generator	U-tube, baffled counterflow heat exchangers, two-pass shell, carbon steel construction.
Desuperheater	Direct contact, water injection type.
Fluid charging/extraction loop pumps	Centrifugal, high temperature.
Fluid maintenance unit	Filtration and vacuum distillation.
Ullage maintenance unit	Storage and control of gaseous nitrogen ullage gas.

and produces steam for either power plant operation or heating the feed-water returned to the receiver for operation with low solar insolation. The following subsections provide additional details, each dealing with a major component or assembly of the subsystem.

5.3 THERMAL STORAGE UNIT

The design details of the thermal storage unit for the pilot plant are shown in Figure 5-3 and Table 5-2.

Three different design bases were defined for evaluating structural loads on the thermal storage tank: (1) fluid hydrostatic pressure, (2) fluid plus rock active load, and (3) fluid plus rock passive load. The first basis for design uses the normal hydrostatic pressure exerted on the tank wall by a full tank of fluid. The tank contents for the second and third design conditions were assumed to be 25 volume percent oil and 75 volume percent granite rock. Conventional methods from soil mechanics were used to calculate oil plus

SHELL COURSE SCHEDULE
(ASTM A537 STRUCTURAL STEEL)

COURSE	HEIGHT, M (FT)	PLATE THICKNESS, MM (IN.)
1 (BOTTOM)	1.83 (6)	34.4 (1.35)
2	1.83 (6)	31.0 (1.22)
3	1.83 (6)	27.0 (1.06)
4	1.83 (6)	23.0 (0.90)
5	1.83 (6)	19.0 (0.75)
6	1.83 (6)	15.0 (0.59)
7	1.83 (6)	11.0 (0.43)
8	1.83 (6)	7.0 (0.27)
9 (TOP)	2.68 (8.8)	6.35 (0.25)

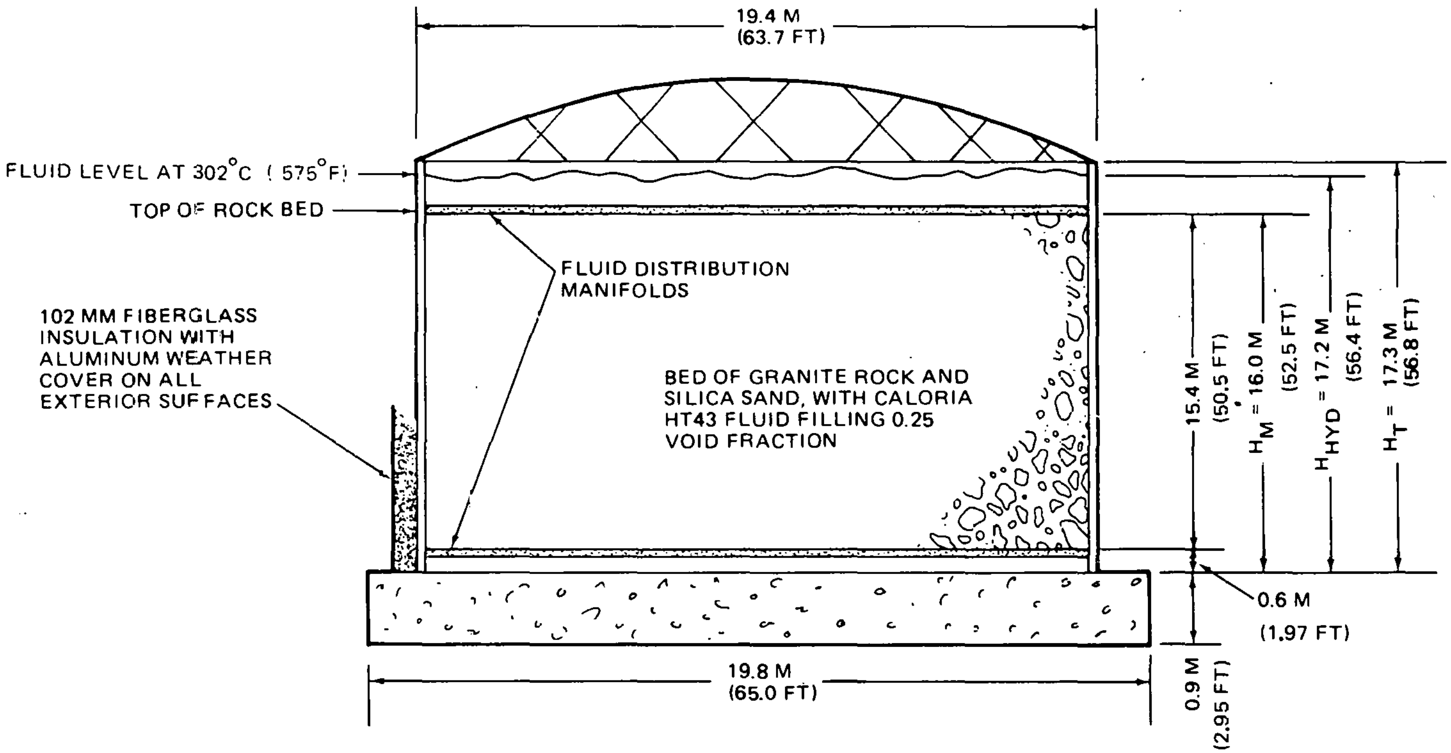

Figure 5-3. Preliminary Baseline Design for 10-MWe Pilot Plant Thermal Storage Unit

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Table 5-2

THERMAL STORAGE UNIT BASELINE DESIGN FOR 10-MWc PILOT PLANT

Tank configuration:	Cylindrical, axis vertical, installed above ground
Tank size:	19.4m (63.7 ft) ID by 17.3m (56.8 ft) high; 5125 m^3 (181,000 ft^3, 1,350,000 gal) inside volume; 296 m^2 inside cross-sectional area.
Solid storage media:	Crushed granite rock and coarse silica sand (approximately 2:1 rock:sand by volume); 9.59 x 10^6 kg (21.1 x 10^6 lb, 10,600 ton); mean solids diameters are 10 mm (rock), 1 mm (sand); 0.25 void fraction.
Liquid storage medium:	Caloria HT43 heat transfer fluid, 1.02 x 10^6 kg, 1.18 x 10^6 liters (312,000 gal) with volumes measured at 21°C (70°F).
Operating temperature range:	218 to 302°C (425 to 575°F). Maximum exit temperature drop during extraction = 8.3°C (15°F).
Tank structural details:	Fabricated of ASTM A537 structural steel with field-welded construction: plate thickness for shell courses varies from 6.35 mm (0.25 in) to 34.4 mm (1.35 in) with schedule given in Figure 5-3; bottom is 6.35 mm (0.25 in) plate; roof is single skin with trusses covering 296 m^2 tank cross-sectional area; total weight of tank roof, shell and bottom = 195,000 kg (215 ton).
Insulation:	Roof and sides covered with 102 mm (4 in) of insulation (open pore fiberglass) with corrugated aluminum weather cover: 19.8m (65.0-ft) diameter by 0.91m (3-ft) thick insulating perlitic concrete base.

rock loads applied to the tank wall. Two different kinds of pressures may develop during a thermal cycle: (1) active pressure which develops when the tank is loaded with the combination of fluid and rock, and (2) the passive pressure which develops because of preferential settling of the rock during thermal cycling.

When the tank heats, the rock may settle vertically because it does not have tensile continuity. Upon cooling, the tank wall tries to displace the rock and fluid mixture. This displacement is resisted by the internal friction of the mixture. In the broadest sense, the term passive earth pressure indicates the resistance of a mass of soil against displacement by lateral pressure.

The final basis selected for the pilot plant preliminary baseline design is to use the most conservative of the three design bases, i.e., the load from fluid hydrostatic plus rock passive pressure. Experimental data will be obtained during prequalification tests and during the operation of the main subsection research experiments (SRE) thermal storage tank to establish actual loads exerted by the rock on the tank. The pilot plant design will then be modified near the end of this program to reflect the test data. It is significant that there is no difference in the design of the SRE tank between the three design load bases, since this particular tank is below code minimum plate thickness, even with the passive load criterion.

Parametric cost estimates were made for three cases: (1) all-liquid thermal storage, (2) dual medium storage with the tank designed for the active load, and (3) dual medium storage with the tank designed for the passive load. The results indicate that the dual medium concept provides a significant cost saving when compared to all-liquid systems for even the most conservative dual medium tank designs (passive load). Substitution of an appreciable portion of the fluid with rocks at 1/70 of the cost (3¢/lb for granite versus 20¢/lb for the heat transfer fluid) results in a substantial cost saving. Although the use of the rock increases the tank costs, the tank cost is only a fraction of the fluid cost. Further, the rock primarily influences the tank wall cost, which is only a portion of the total tank cost (roof and insulation are not affected by the rock) and the increased wall thickness is required only in the lower portion of the wall. The upper portion of the tank wall remains at the minimum gage thickness required by the American Petroleum Institute code.

The strong contribution of fluid cost (and relatively less important contribution of tank cost) is seen for both 10-MWe and 100-MWe sizes in Figure 5-4. With all-liquid systems the cost of the heat transfer fluid is 85 to 90 percent of the total cost of the thermal storage unit.

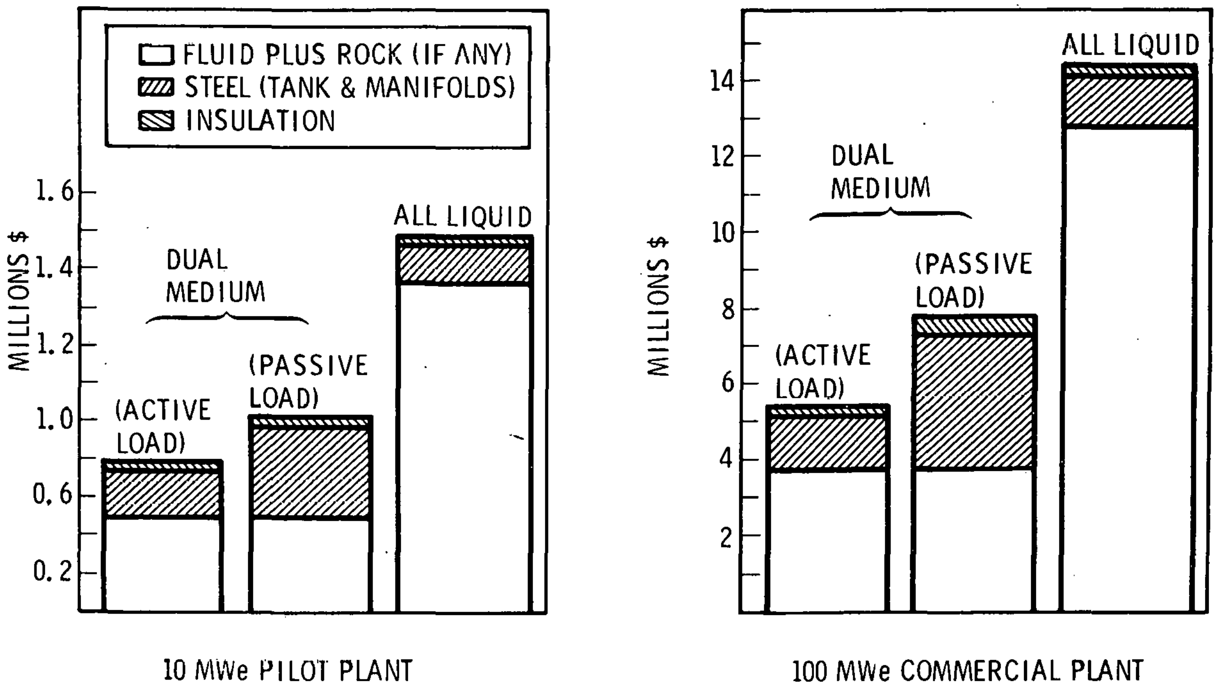

Figure 5-4. Pilot Plant and Commercial Systems Thermal Storage Unit Costs

5.4 THERMAL STORAGE HEATER AND DESUPERHEATER

The thermal storage heater (TSH) is the element of the TSS that transfers heat from incoming steam to the thermal storage heat transfer fluid. The desuperheater (DSH) provides saturated vapor to the TSH by mixing of TSH effluent (water) with the superheated steam from the receiver. They are described in the following paragraphs.

The pilot plant TSH preliminary baseline design consists of one commercial TSH heat exchanger unit, of the size used in multiple units for a 100-MWe commercial plant, but scaled somewhat in size in proportion to flowrate and heat loads. Figure 5-5 presents the baseline design of the pilot plant TSH. It may be desirable to provide two smaller exchangers for the pilot plant, although this would sacrifice some direct operating experience with exchangers close to those for commercial plant designs.

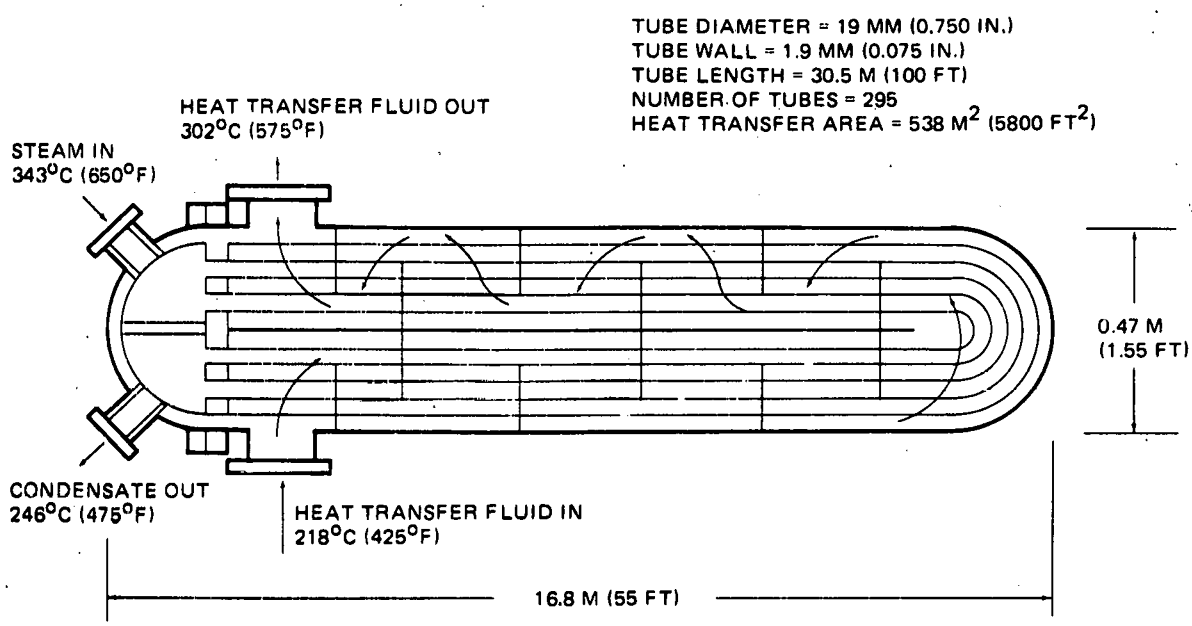

Figure 5-5. Thermal Storage Heater for 10-MWe Pilot Plant Preliminary Baseline Design

The DSH consists of an atomizing probe which injects water into the steam path through a series of nozzles. The DSH is an off-the-shelf commercial item.

5.5 STEAM GENERATOR

The TSS steam generator converts the thermal energy stored in the TSS heat transfer fluid to superheated steam to supply the electrical generation subsystem during periods of low, intermittent, or no solar insolation. The steam generator is required to function in two basic operational modes. First, during late afternoon periods when solar insolation is reasonably steady but yet too low to provide sufficient energy to generate the nominal 10-MWe electrical output and also permit turbine steam extraction for adequate feedwater heating, the TSS steam generator will provide the steam to the electrical generation subsystem high-pressure feedwater heater. Second, during periods of intermittent solar insolation (clouds) or extended operation with no insolation, the steam generator will provide sufficient steam to the turbogenerator to produce 7 MWe.

Figure 5-6 provides a cutaway view of the selected design.

5.6 ULLAGE MAINTENANCE UNIT

The objective of this unit is to provide a controlled-pressure, inert gas atmosphere in the thermal storage unit (TSU) to reduce flammability and prevent long-term oxidation of the heat transfer fluid. The ullage pressure must be controlled within a moderately narrow band to avoid underpressurizing or overpressurizing the tank. When the fluid (Caloria HT43) is heated from 218° to 302°C (425° to 575°F), the volume expands by about 8 percent. If the inert gas in the ullage were not released, the pressure would rise above the allowable upper limit. The gas released must be replaced or stored and returned to the ullage space during the cooling cycle since an equal amount of gas is required to prevent the pressure from going below the allowable lower limit as the fluid cools and contracts.

These functions must be accomplished in as simple a manner as possible with minimum capital, maintenance, and operating costs. The design also

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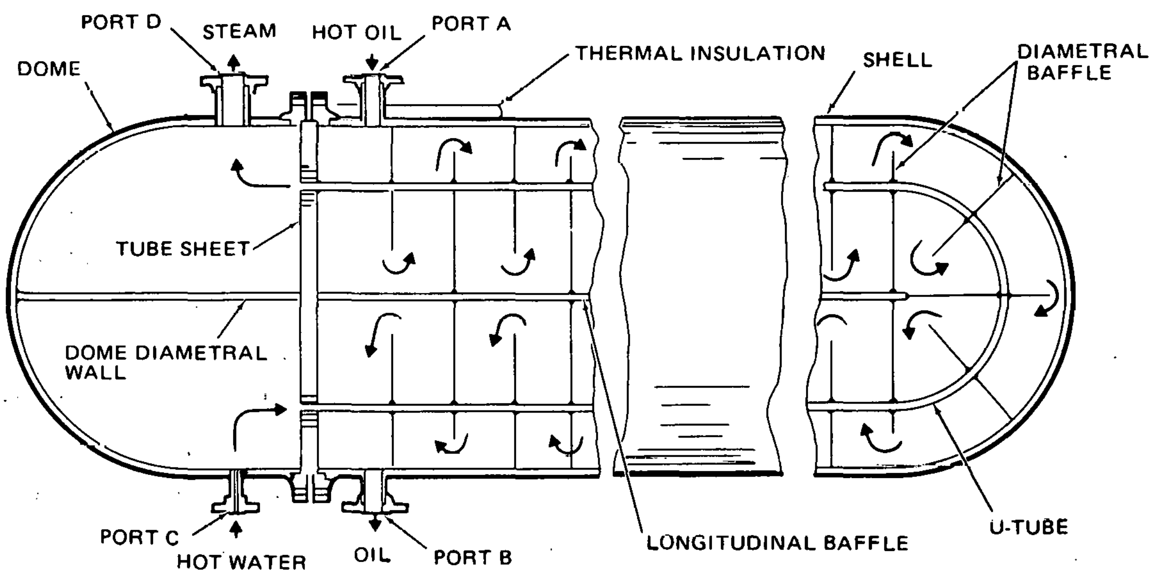

Figure 5-6. Steam Generator Cutaway

must permit reliable operational control and have the flexibility and measurement capabilities needed for the 10-MWe pilot plant. Data obtained with the pilot plant will be used both for demonstrating performance at the 10-MWe level and to permit realistic design scale-up to commercial size systems.

The ullage maintenance unit selected for the 10-MWe pilot plant preliminary baseline design is of a type which recovers the ullage gas, compresses it for storage, and reuses it for each daily storage cycle. The major features of the unit are shown in conceptual form in Figure 5-7.

5.7 FLUID MAINTENANCE UNIT

The general requirement imposed on the fluid maintenance unit is that it maintain the heat transfer fluid in satisfactory condition for continual operation of the TSS. Some of the detailed requirements to be met by the unit are dependent on the results of the prequalification tests being conducted to determine fluid stability, degradation products, and degradation rates.

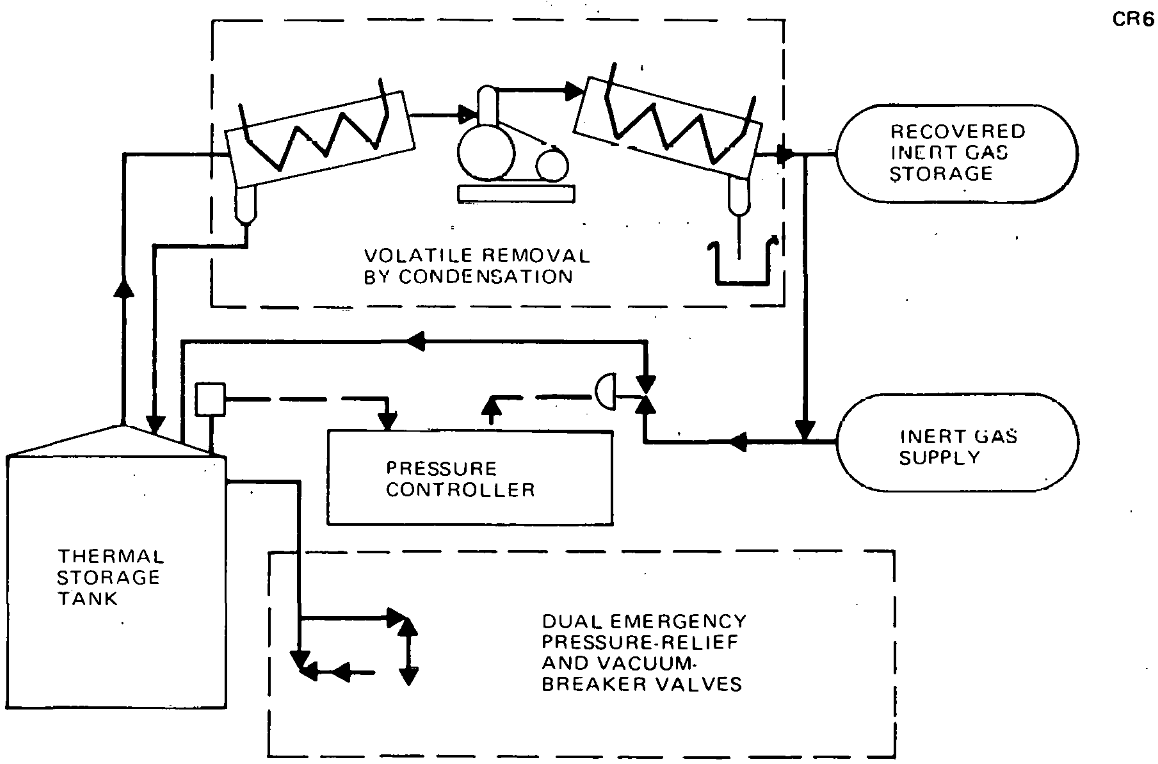

Figure 5-7. Conceptual Schematic Diagram of Ullage Maintenance Unit for 10-MWe Pilot Plant Preliminary Baseline Design

The fluid maintenance unit for the 10-MWe pilot plant is shown schematically in Figure 5-8. It performs three functions to maintain fluid stably within its operating range: (1) filtration to remove suspended solids, (2) distillation of a side stream to remove high boiling compounds, and (3) addition of fresh makeup fluid to replace the material removed. The unit is designed to use existing commercial components.

5.8 SUBSYSTEM RESEARCH EXPERIMENTS

The thermal storage subsystem research experiments (SRE) are designed to minimize any risk inherent in the pilot plant design by establishing a firm technical data base in each design area. Fortunately, the TSS concept has a sound base of commercial experience. Most of the equipment, materials, flow loops, and controls include commercial components that are available; therefore, unique features of this program requiring development are minimized.

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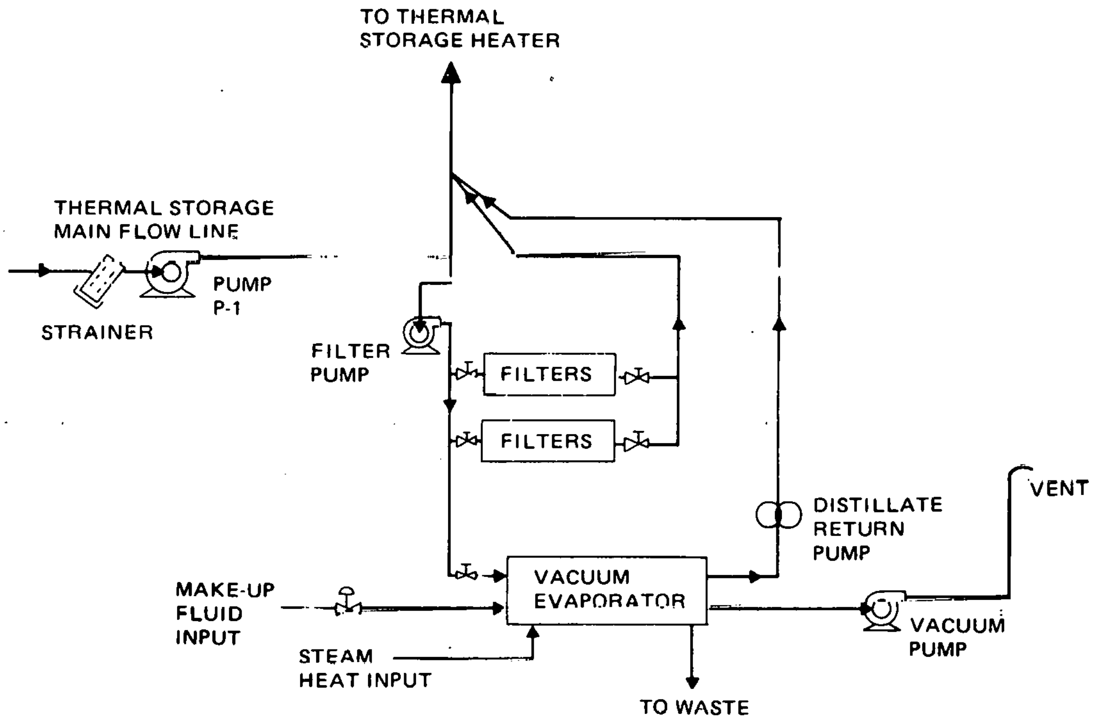

Figure 5-8. Fluid Maintenance Unit Preliminary Baseline Design for 10-MWe Pilot Plant

These assessments indicate that the primary tests for the SRE should involve large scale thermocline establishment, high temperature stability of candidate heat transfer fluids in contact with rock and metallic surfaces, and tank stresses induced by interaction with the rock bed.

5.8.1 SRE Requirements

Requirements for the SRE tests are summarized in Table 5-3. The SRE program consists of two series of tests: (1) prequalification tests and (2) model subsystem tests.

5.8.2 SRE Prequalification Tests

Thermal stability and compatibility tests are designed on a laboratory scale to demonstrate the fluid characteristics when subjected to long-term exposure to operating temperatures. The tests are being conducted on three commercially available fluids which may be capable of meeting the requirements of the thermal storage system: Exxon Caloria HT43, Monsanto Therminol 55, and Monsanto Therminol 66.

Table 5-3
THERMAL STORAGE TEST REQUIREMENTS

Design consideration	SRE Test Requirement
Heat-transfer fluid thermal stability	Duration tests at maximum operating temperatures, 288° to 316°C (550° to 600°F).
Heat-transfer fluid compatibility	Duration tests with fluids exposed to subsystem materials.
Heat exchanger surface fouling	Duration tests with fluid exposed to hot metal surfaces.
Subsystem operating characteristics	4-MWhth thermal storage unit test with charging and extraction fluid velocities identical to pilot plant conditions
Rock bed/tank interactions	Strain measurements during SRE subsystem tests

The objectives of the fluid thermal stability and compatibility tests are (1) to determine the ability of the heat transfer fluids Caloria HT43 (formerly Humbletherm 500), Therminol 55, and Therminol 66 to function stably at 288° to 316°C for extended periods of time; (2) to assess the high temperature, long-term compatibility of these heat transfer fluids with rock and materials of construction (stainless steel, carbon steel) which will be in contact with fluid in the thermal storage unit; and (3) to determine the rate and extent of fouling of heat transfer surfaces by Caloria HT43 and Therminol 66.

Laboratory test setups will be run from a period near the beginning of the program until the end of the contract. Fluid thermal stability tests will involve fluids held at a constant temperature under an inert gas container in contact with rock and typical metal construction materials heated to various maximum working temperatures. Initially the tests were scheduled to be conducted with two fluids: Caloria HT43 and Therminol 55. Subsequently, an additional fluid, Therminol 66, was added as a backup. Periodic sampling and measurements will be made of the fluids to determine the stability and compatibility with the materials. The tests are now being conducted at laboratory scale under controlled conditions.

Fouling tests to determine deposits (if any) that may form on high temperature heat transfer surfaces have only recently begun.

5.8.3 <u>SRE Model Subsystem Tests</u>

5.8.3.1 Test Objectives

The basic objectives of the thermal storage SRE model system tests are to:

A. Evaluate charging and extraction capabilities of a scalable TSU.

B. Obtain performance of the TSU over all ranges of equivalent operating conditions in the pilot plant.

C. Demonstrate stable operation for high, low, intermittent, and no insolation conditions.

D. Demonstrate changeover capabilities from one operating mode to another and emergency response modes.

E. Develop requirements and techniques for treating the heat transfer fluid to permit 30-year lifetime with makeup.

F. Determine the additional strain on container walls from tank/rock interaction during repeated thermal cycling.

5.8.3.2 Test Hardware Description

The thermal storage model subsystem consists of a TSU, two fluid circulation pumps, an ullage maintenance unit, a fluid maintenance unit, and associated controls, valves, and sensors. These will be integrated with the existing steam generator facility at Rocketdyne's Santa Susana Field Laboratory (SSFL), which contains the heat transfer fluid heaters and steam generators needed to simulate thermal charging and heat extracting (Figure 5-9).

A basic flow schematic of the subsystem for the SRE is given in Figure 5-10. The SRE model subsystem has the same three major constituents as the pilot plant and commercial thermal storage system: (1) a central thermal storage unit, (2) a charging loop, and (3) an energy extraction loop.

The SRE model tank is a 0.8-scale version of the pilot plant with respect to tank height which is the primary TSU scaling parameter. The SRE model TSU will store 4 MWhth of extractable energy with charge and discharge rate capability up to 5 MWth. The fluid velocity in the bed during charging and extraction will match the range of the pilot plant preliminary baseline design. In addition, the model subsystem tests will include fluid velocities above and below those of the pilot plant range, thus developing a basis for evaluating an even broader range of design conditions for both the pilot plant and subsequent commercial plants.

Many parameters of the model system tests will be identical to the pilot plant (e.g., rock bed characteristics, heat transfer fluid, operating modes, and charging and discharging velocities, hold times, and operating temperature differences) in order to establish a firm engineering base for the thermal storage subsystem performance.

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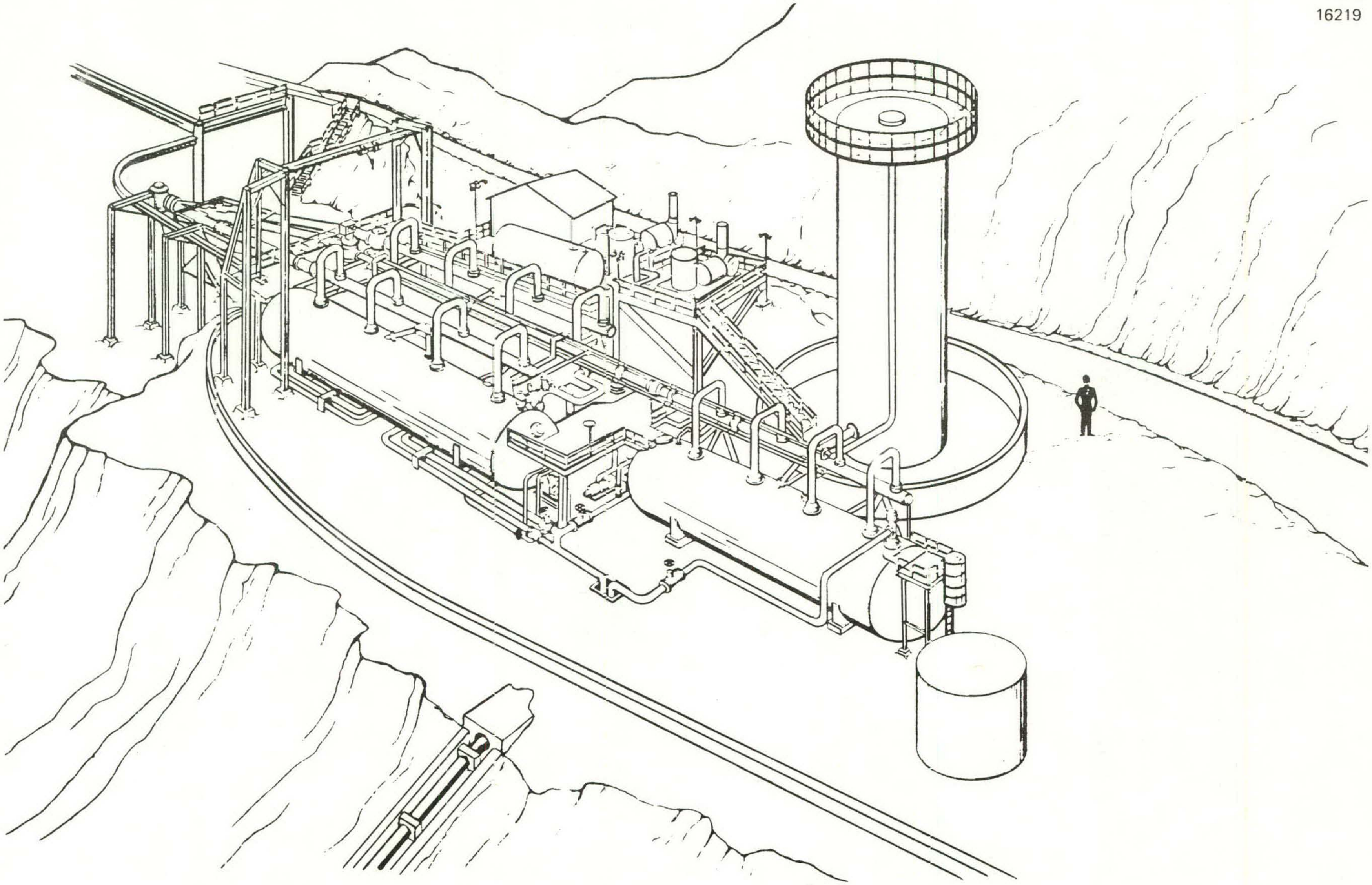

Figure 5-9. Thermal Storage Test Site

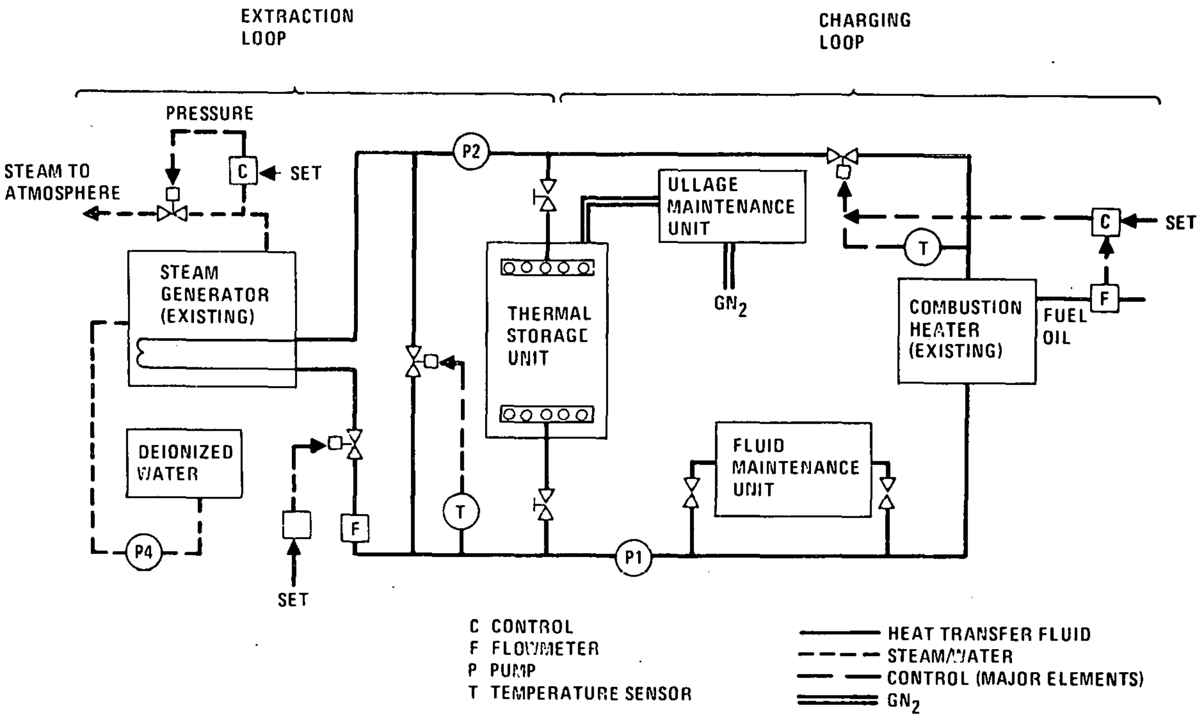

Figure 5-10. Thermal Storage SRE Subsystem Schematic

The thermal charging function is provided by a direct combustion heater which can satisfactorily simulate the pilot plant thermal storage heater function. The SRE model subsystem steam generators will permit simulation of the wide range heat extraction mode experienced in the pilot plant.

Strain measurements will be made periodically at various locations on the tank wall. These data will be correlated with the thermal cycling environment that is imposed during the test program, to establish the design loading to be used for the pilot plant TSU preliminary design.

5.8.4 Overall Schedule

The overall schedule for the thermal storage SRE is presented in Figure 5-11.

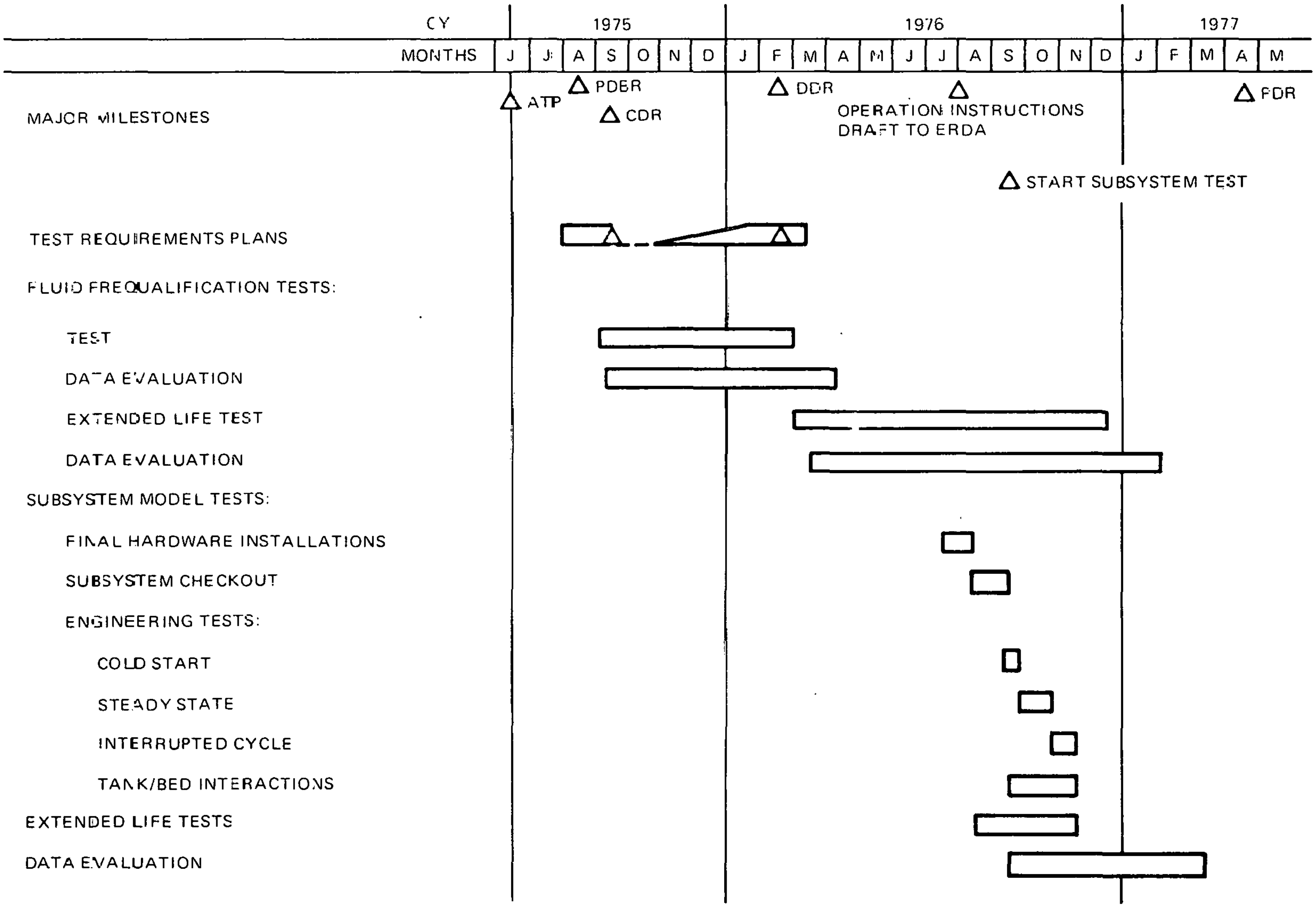

Figure 5-11. SRE Test Program Schedule

Section 6
COLLECTOR SUBSYSTEM

6.1 REQUIREMENTS SUMMARY

The top level subsystem requirements include a cost-effective field layout (as described for the commercial system) and safe operation in each of the system operating modes, during transition between modes, and in the event of system failures such as loss of receiver coolant flow.

The primary reflective surface requirements are to have the maximum cost-effective reflectivity and the durability to survive a desert environment for the 30-year plant design lifetime. The environment includes wind, precipitation, hail, and blowing sand and dust.

The heliostat must also survive the desert environment, including peak gust wind speeds up to 46.4 mps (104 mph), temperatures from -30°C (22°F) to +60°C (140°F), hailstones up to 25 mm (1 in), earthquake loads typical of seismic Zone III, snow up to 0.3m (12 in) and ice up to 5 mm (2 in). The heliostat must reflect the sun to the receiver with a combined beam tracking error and beam dispersion error of 6 to 10 mrad mean plus 2σ. The lower beam error applies to the outer regions of the field where the longer slant range makes angular beam errors result in larger distance errors at the receiver. A summary of the beam error requirements for the outer field is given in Table 6-1.

The controls system must accomplish the pointing of the heliostats continuously during normal tracking, as well as orient the heliostats for sun acquisition; stowage for nonoperational times; feathering for high winds, especially with blowing sand or dust; cleaning and maintenance, and emergency defocus to protect the receiver in the event of system failure.

Table 6-1
BEAM POSITIONING ERROR SUMMARY

Error Category	Error (mrad) Horizontal Mean		Horizontal ±2σ	Vertical Mean		Vertical ±2σ
Beam sensor misalignment	0.2		0.5	0.2		0.5
Beam sensor pedestal deflection	0.2		0.5	1.0		0.5
Electrical bias	0.1		1.0	0.1		1.0
Reflector surface errors	0.2		2.8	0.2		2.8
Reflector drive gain	0.2		0.4	0.2		0.4
Reflector drive threshold	0.5		0.2	0.5		0.2
	1.4	±	3.1	2.2	±	3.1
Allowable errors (M+2σ)	6 mrad			6 mrad		

6.2 SUBSYSTEM SUMMARY DESCRIPTION

The collector subsystem is illustrated in Figure 6-1. Principal assemblies are the heliostats and field controllers. The heliostats are comprised of a reflective surface to concentrate the sun's light on the receiver, a two-axis tracking mechanism to continuously orient the reflective surface to correctly position the reflected beam on the receiver, control sensors to provide closed-loop control of the heliostat, and a pedestal/foundation to support the heliostat. Each field controller provides closed-loop control for about 25 heliostats, as well as communication with the plant master control.

6.3 REFLECTIVE SURFACE

The reflective surface is front-surface-silvered, 6.34 mm (1/4 in) float glass. The silver is chemically deposited by commercial means. A thin, clear acrylic coating is deposited on top of the silver to protect it from oxidation, chemical attack, and blowing dust. This reflective surface was selected on the basis of a projected high specular reflectivity and a projected low cost for high-volume production. The evaluation of reflective surfaces is shown in Table 6-2. The candidate surfaces were selected on the basis of adequate surface flatness, reflectivity, low cost, and durability. The reflectivity

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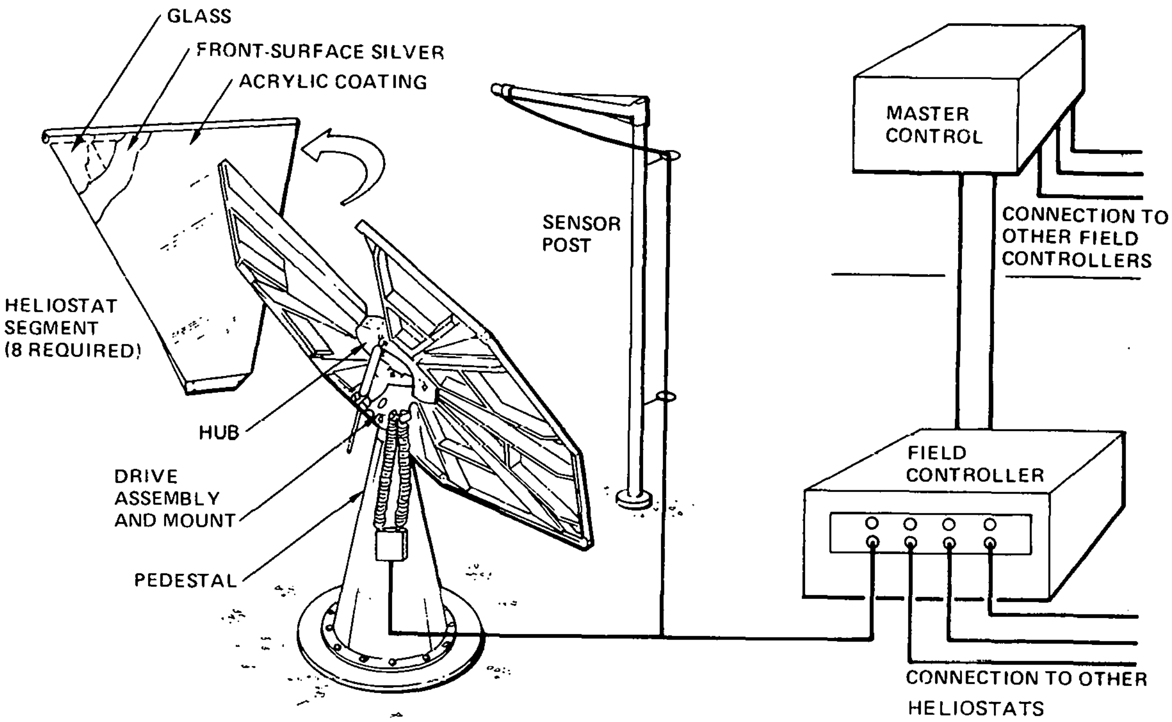

Figure 6-1. Collector Subsystem

values are representative or typical of the measured performance of the mirrors. The reflectivity of glass mirrors varies with the iron content, glass thickness, and silvering process. The costs are based on commercial plant production volumes. The effective cost adjusts the actual cost for the reflectivity, i.e., the extra heliostats, tower, piping, and receiver required to make up for a lower reflectivity. In calculating effective cost, the base cost of a heliostat without reflective surface is first taken. Then the allocated portion of the tower subsystem is added to form the base cost. The reflective surface cost is then added and the result is ratioed by reflectivity. Then the base cost is subtracted, with the difference being the effective cost.

It is clearly seen from Table 6-2 that the front surface mirror is the most cost effective. While there is some development risk in this approach, the potential gain warrants the risk. The second choice is the 6.35 mm (1/4 in) low iron float glass second surface mirror. Unfortunately, low iron glass is not made commercially by the float process at this time. It may, however, be possible to obtain this glass for the pilot plant.

Table 6-2

REFLECTIVE SURFACE SELECTION

Mirror	Reflectivity	Cost ($/m²)	Effective Cost ($/m²)
Laminated glass (0.1% Fe)	82	17.5	27.5
Laminated glass (0.01% Fe)	90	~18.5	20.4
Front surface glass	92	8	8
Commercial float (0.1% Fe)	65	7.2	36.5
Low iron float (0.01% Fe)	86	~8	13.0

Effective cost = actual cost + allocated cost to replace lost power due to low reflectivity

6.4 REFLECTOR SUPPORT STRUCTURE

The reflective surface support structure serves to support the glass against wind and gravity loads and to maintain surface flatness. The structure is illustrated in Figure 6-2. The structure and the glass are segmented for transportability. The reflector consists of eight trapezoidal segments mounted to a central hub, forming an octagon. The segments are canted at a 5-mrad angle to provide a measure of focusing for the pilot plant. This focusing is not required for the commercial plant. The segments are supported on rolled steel channel beams and bolted to the hub. The hub is formed of two draw-pressed halves with a tee-shaped internal shear web connecting to the hinge and actuator attach points.

The reflective surface size has been optimized at about 6.1 m (20 ft) across the flats. The optimization showed a rather flat minimum in the diameter range from 6.1 to 7.6 m (25 ft). The dominant features of the optimization are the costs of structure, foundation and pedestal, drive unit, control electronics, and transportation.

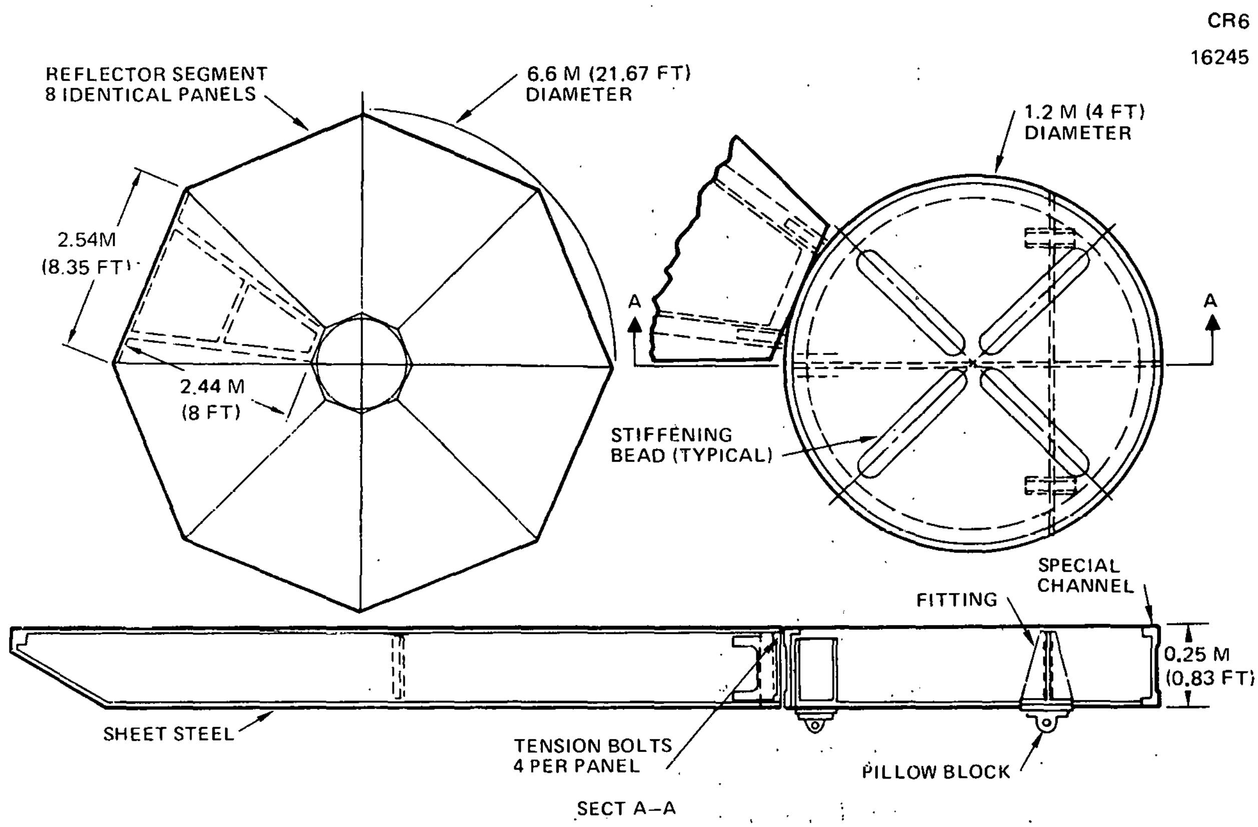

Figure 6-2. Reflector Support Structure

6.5 DRIVE UNIT

The drive unit, Figure 6-3, incorporates an elevation/azimuth gimbal mount. The elevation actuator is a linear machine screw jack. The azimuth actuator uses a harmonic drive for the output stage. Both actuators are driven by 220v, 3ϕ ac motors with integral 30:1 gear heads. The motors are rated at 1/15 horsepower and 1, 750 rpm. The elevation actuator uses a 6.3 turns per cm machine screw (16 turns per in). The average final drive ratio is 82, 838:1. The azimuth train uses a 15:1 worm gear and a 242:1 harmonic drive for a final drive ratio of 108, 900:1. The drive unit housing is comprised of two deep draw pressed parts. The outer part, seen in Figure 6-3, supports the linear actuator and the hinge points for the elevation axis. The inner part provides a mounting for the harmonic drive. Both motors are externally mounted for easy access for maintenance or repair.

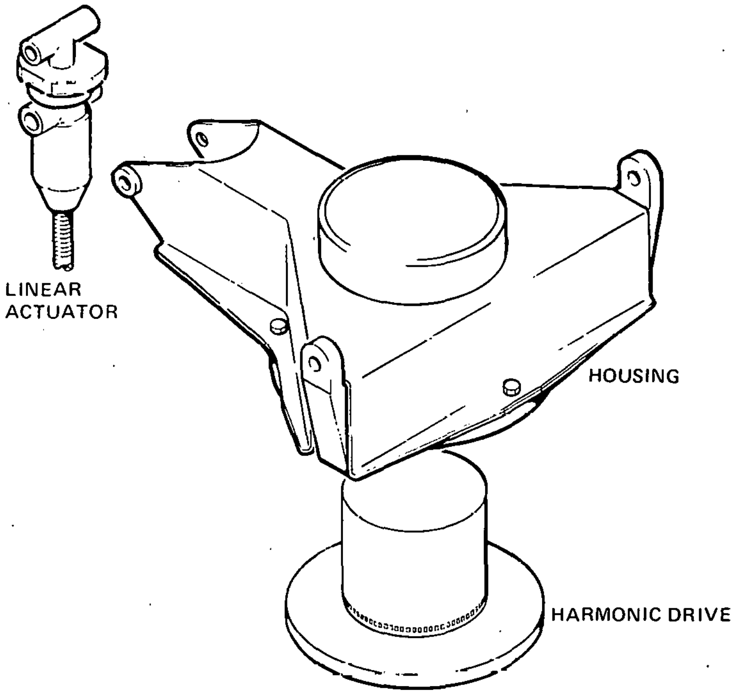

Figure 6-3. Drive Unit Housing

6.6 PEDESTAL/FOUNDATION

The heliostat pedestal/foundation supports the reflective surface above the ground to provide operating ground clearance and to provide for horizontal stowage of the reflective surface above the region of blowing sand in the event of severe storms. The pedestal (Figure 6-4) is a hollow sheet metal cone about 3m (9 ft) high. The cone is filled with sand to provide ballast against overturning moments. The top of the cone is provided with a mating flange for attachment of the drive unit. The bottom of the cone has a flange to mate to anchor bolts in the foundation.

The foundation is made of reinforced concrete. A slab of 2.1m (84 in) diameter is buried 0.3m (12 in) below the ground line. A raised portion extends above the ground line to mate to the cone. Backfill over the slab adds to the ballast resisting the overturning moment.

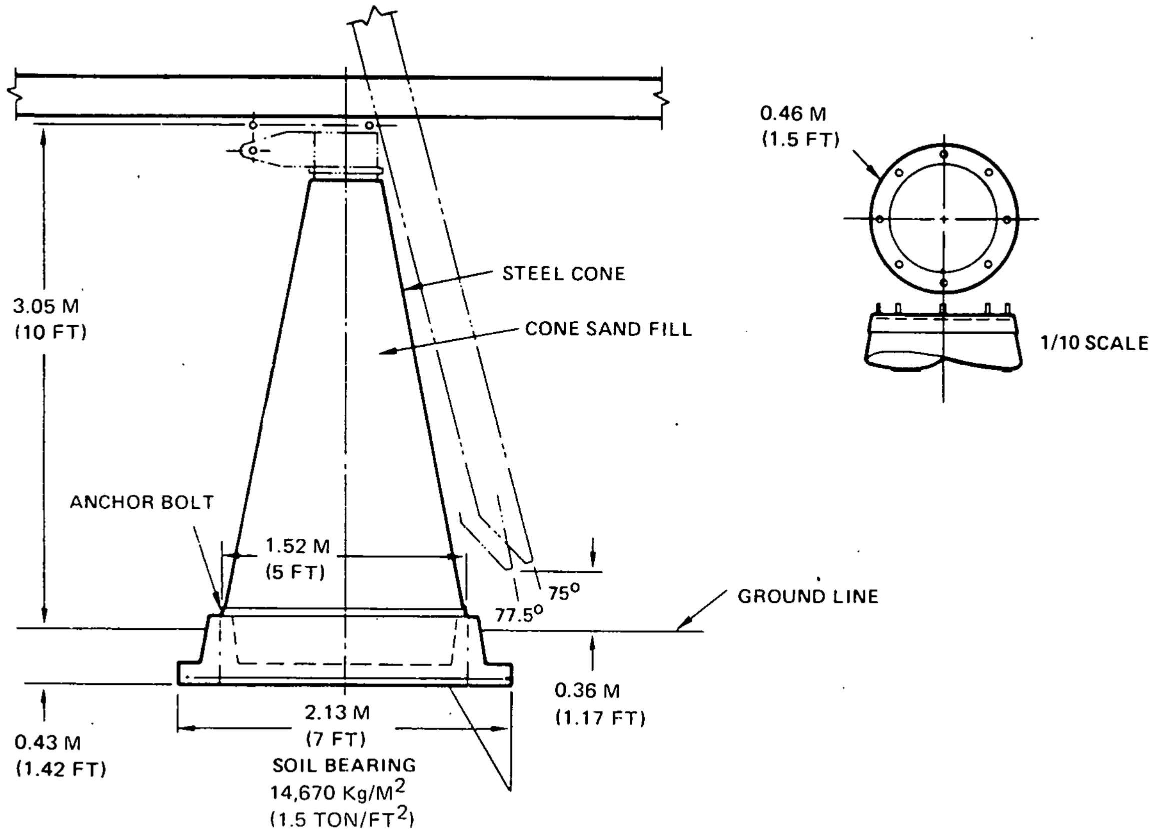

Figure 6-4. Heliostat Pedestal Foundation

6.7 CONTROL SENSORS

Two separate sets of control sensors are employed for closed loop steering of the reflective surface. For normal tracking, a beam sensor is mounted on the line of sight to the receiver, Figure 6-1. The beam sensor is boresighted on the receiver and measures angular errors in the direction of the beam reflected from the heliostat with respect to the line of sight to the receiver. The sensor is null-seeking and gives zero output signal when the reflective surface is correctly aligned. The beam sensor also incorporates a total insolation measurement which is used for automatic gain control and also used to determine whether there is adequate sunlight for normal tracking.

The beam sensor is mounted on a separate post. The post configuration will vary over the field to accomodate varying requirements of line of sight to the receiver. A typical beam sensor post is shown in Figure 6-5. The boom on the post is sized for an intermediate distance from the tower. Approximately 28 percent of the heliostats are in the field angle range from 30 to 45 degrees as measured vertically from the tower. The 9 percent of the heliostats

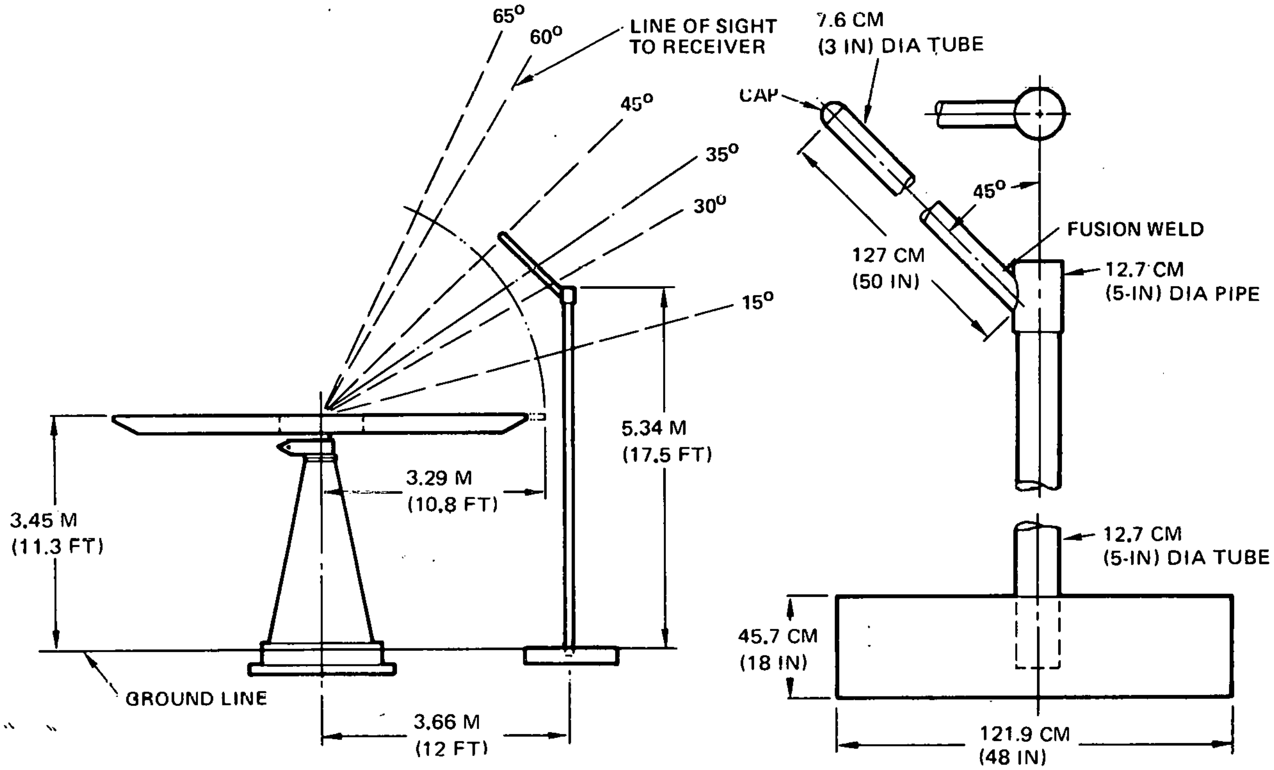

Figure 6-5. Beam Sensor Post

closer to the tower will use a 2.5m (100 in) boom. The 63 percent of the heliostats outside this angle range will require no boom.

Position potentiometers are included in the drive axes to measure the angular positions of the gimbal axes. These measurements are used for closed-loop steering of the heliostat for the non-sun tracking modes of operation. The gimbal axis position measurements are also used for coordinate transformation between the beam sensor axes and the gimbal axes.

6.8 FIELD CONTROLLER

The field controller serves as a communication link between the master control and the heliostat, and provides closed-loop control for the heliostat, power to the heliostat drive motors and control sensors, and fault detection for the system.

The collector subsystem must be able to operate in several different modes: normal tracking, sun acquisition, normal stowage, severe storm stowage, tracking during intermittent cloud cover, and positioning for cleaning or maintenance. The modes other than normal tracking can all be characterized by gimbal axis position commands that are common to all of the heliostats under the control of a single field controller. These modes are lumped together in a single commanded steering mode, as far as the field controller is concerned. The master control determines the gimbal axis positions to be assumed and commands the field controller to these positions. The position potentiometers on each heliostat are used to provide closed-loop steering to the correct orientation. During normal tracking, the field controller functions autonomously, using error signals from the beam sensor to achieve closed-loop tracking.

The operation of the field controller is illustrated in Figure 6-6. Control sensor signals from the individual heliostats are multiplexed so that the heliostats are sampled sequentially. The individual control sensor signals are then multiplexed, filtered, and converted to digital signals. A digital processor converts the control signals to error signals and determines the degree of correction required in terms of power cycles. A separate portion of the field controller serves as an power bus. Three phase, 200v ac power is

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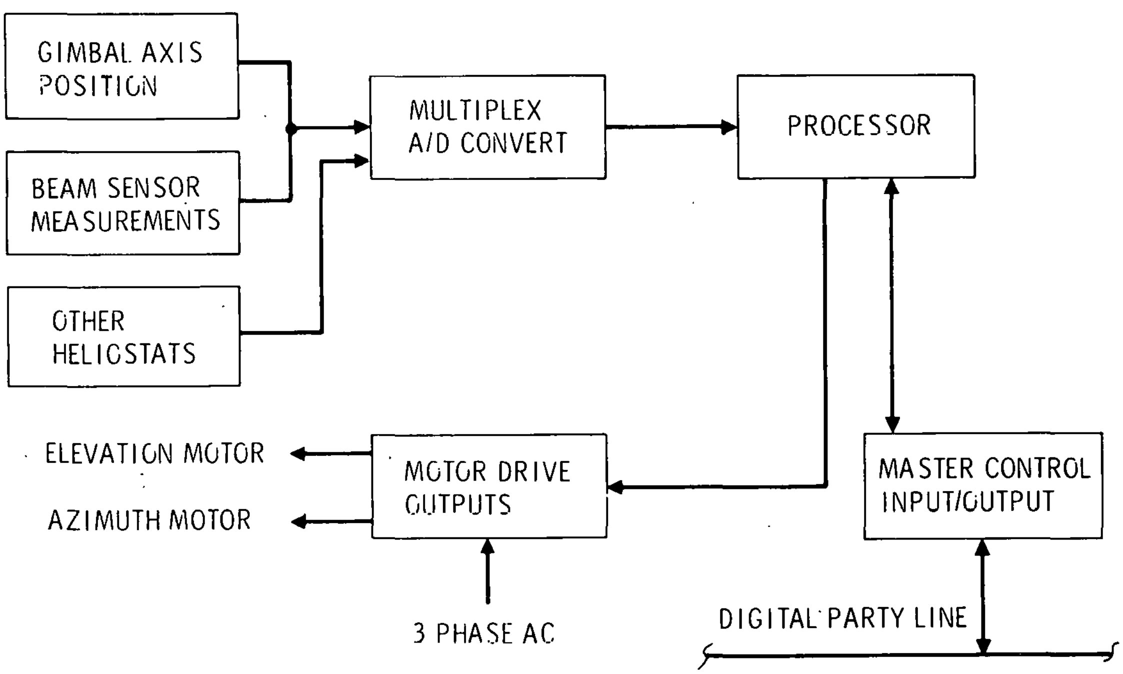

Figure 6-6. Field Controller

output from the bus in alternating drive cycles. The phases are arranged to provide for alternating clockwise and counterclockwise motor drive cycles by phase switching. The output electronics sample the motor drive commands from the digital processor and cause the motors to be driven for the appropriate number of current cycles in the appropriate direction to null out the control sensor error.

A manual control input is provided for each heliostat at the heliostat, using a portable power supply. In addition, individual heliostats can be addressed and commanded separately from the master control.

6.9 SUBSYSTEM RESEARCH EXPERIMENTS

A series of laboratory and field tests is planned for the subsystem research experiments. The laboratory tests are illustrated in Figure 6-7.

A complete heliostat will be subjected to structural testing in the structures laboratory at MDAC, Huntington Beach. The heliostat will be loaded to

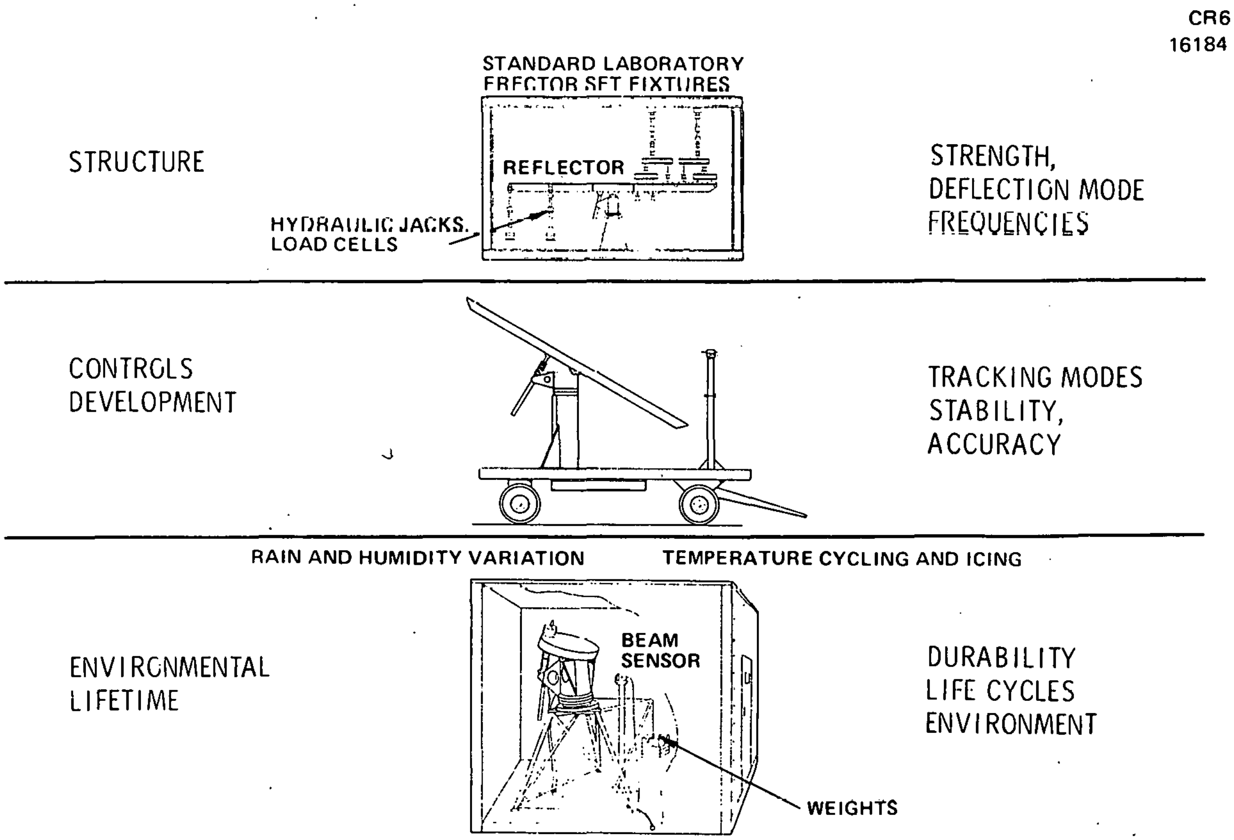

Figure 6-7. Collector SRE Lab Tests

simulate the effects of wind and gravity loads in all orientations. The test objectives include the verification of adequate structural strength, the verification of deflections within tolerances under operational wind conditions, and the determination of vibrational modes, frequencies, and damping characteristics in support of dynamic analyses.

Controls development tests will be conducted on a heliostat in the MDAC solar test laboratory at Huntington Beach. Controls algorithms and micro-programs will be developed and verified during actual sun tracking and simulated command tracking. The test objectives include verification of tracking modes, controls stability, and pointing accuracy.

Environmental and lifetime testing will be conducted on a complete drive-unit and hub with controls sensors and on a reflector segment in environmental chambers at MDAC and the Approved Engineering Test Laboratory in Canoga Park, California (or equivalent test laboratory). The test objectives include durability, life cycles, MTBF (mean time between failures), and environmental survival, including effects of temperature and temperature cycling, dust, rain, hail, icing, and humidity.

Following the laboratory tests and concurrent with the environment/ lifetime tests, a heliostat array test will be conducted at Naval Weapons Center in China Lake, California. The array test is illustrated by Figure 6-8. A fixed array of four heliostats will be emplaced to the north of the range towers at Randsburg Wash. These heliostats will be used to measure beam quality, multiple beam overalp, and tracking characteristics of multiple heliostats under the control of a single field controller. Data on shading and blocking and wind loading with a heliostat array will also be obtained. A fifth heliostat mounted on a trailer will be used to obtain data on tracking accuracy at extreme points in the field. These points include remote sites, sites requiring severe tracking angles, and a site resulting in a tracking singularity.

Data from the subsystem research experiments and the preliminary baseline design described above will be used to generate a preliminary design for the pilot plant during the final six months of this contract.

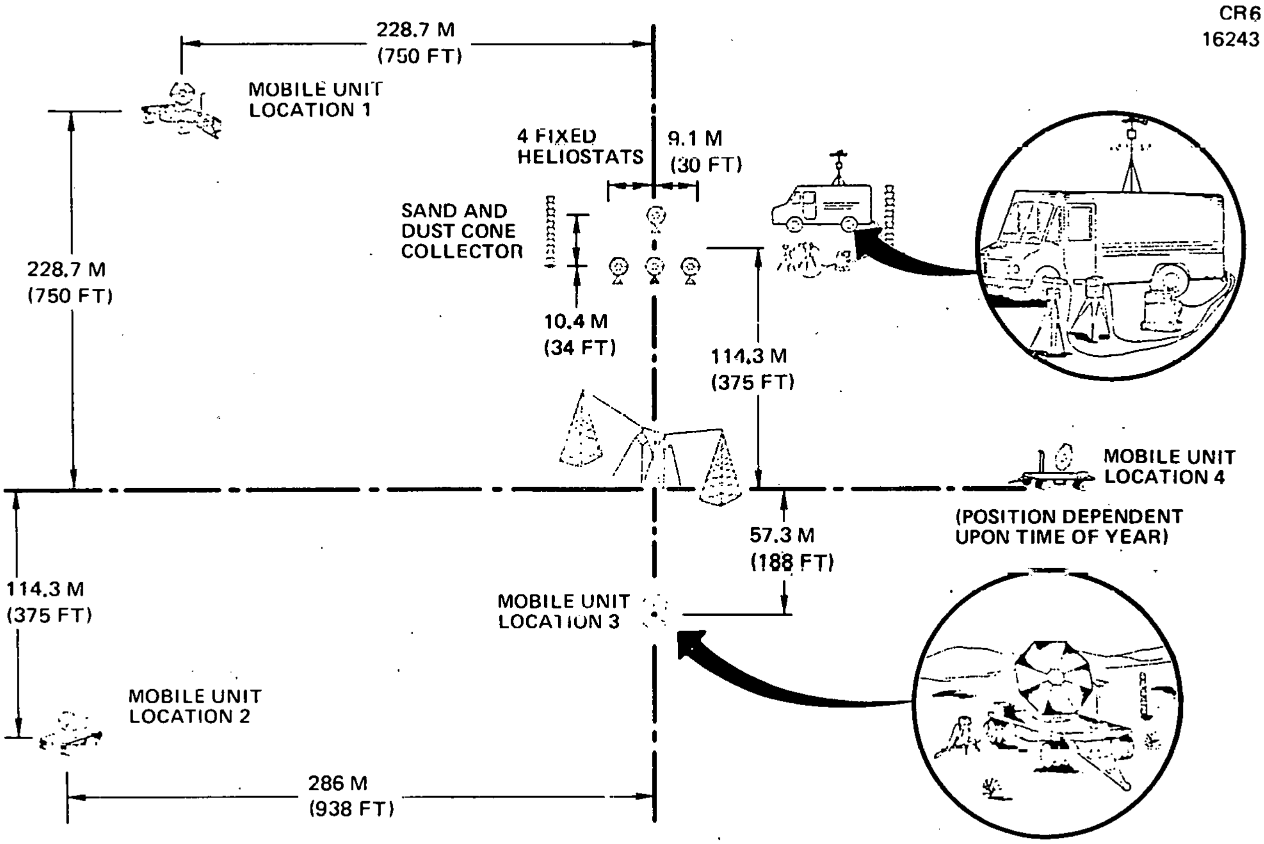

Figure 6-8. Heliostat Array Test Locations:

DISTRIBUTION LIST
STD Category UC-62

Solar Thermal

Ptd.	Standard Distribution
1	A. D. LITTLE INC., VICE PRES. (ERDA)
1	ADVANCED RESEARCH PROJECTS AGENCY (HQAP)
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