-MW(th) Solar-Thermal Conversion ull-System Experiment

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EPRI AP-2435-SY
Project 1509-1
Summary Report
August 1982

Prepared by
Boeing Engineering & Construction Company
Seattle, Washington

ELECTRIC POWER RESEARCH INSTITUTE

1-MW(th) Solar-Thermal Conversion Full-System Experiment

AP-2435-SY
Research Project 1509-1

Summary Report, August 1982

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Advanced Power Systems Division

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NOTICE

Prepared by
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Seattle, Washington

Abstract

Solar-thermal conversion systems have potential for widespread use by the electric utility industry. Applications being considered include repowering of existing fossil fuel units, solar "stand alone" units, and solar-fossil hybrid units. The objective of the overall EPRI Solar-Thermal Program is to develop equipment, analytical methods, cost information, and operating experience necessary to introduce a new electric power generation resource to the utility industry's list of options.

Early EPRI funded studies showed potential benefits of Brayton-cycle concepts used in a solar-fossil hybrid mode of operation. A central receiver power plant design concept was developed. A development program was prepared which would progress in an orderly manner from a model receiver, through an experimental system, to a pilot plant. The initial phase of that program began in July, 1976 with the design, fabrication, and testing of a 1 MW_t Bench Model Solar Receiver.

Testing was carried out at the DOE-Central Receiver Test Facility from October, 1978 to March, 1979. The solar testing was successfully completed and demonstrated the feasibility of solar energy conversion using a gas-cooled receiver.

The next step toward commercial utilization of solar power systems is the design and construction of an experimental system where all power generation elements are assembled and operated as a single unit. EPRI has initiated this activity by awarding a contract to Boeing Engineering and Construction (BEC) to design, assemble, and operate a Solar-Fossil Hybrid Full System Experiment.

A key goal is to obtain significant involvement of utilities to ensure development of an acceptable concept. The project will be conducted with direct participation of a Utility Test and Operating Group in the various phases of the experiment.

EPRI Perspective

Project Description

This summary report gives an overview of the progress made during the 18-month Phase I effort of EPRI RP1509, Solar-Thermal Full System Experiment. This is one of a number of projects in the EPRI Solar-Thermal Subprogram involved with the development of solar central receiver hardware and systems for future use by utilities. The main emphasis of the EPRI projects is on systems that use Brayton-cycle (gas turbine) equipment; this is complementary to the federal solar thermal efforts, which emphasize Rankine-cycle (steam turbine) systems.

RP1509-1 involves the planning and design of a complete Brayton-cycle solar central receiver experimental system that would include all components of a commercial-size electric utility solar power plant. This project builds on earlier work that developed (1) a 1-MW(th) gas-cooled solar receiver (EPRI Interim Summary Report ER-1101-SY, Design and Fabrication of a 1 MWt Bench Model Solar Receiver, and a forthcoming EPRI report for RP377-3 entitled Design, Fabrication, and Testing of a 1-MW(th) Bench-Model Solar Receiver) and (2) modifications for a gas turbine which would operate from either solar energy or fossil fuel (a forthcoming EPRI report for RP1270-1 entitled "Centaur Gas Turbine Modification and Development for Solar-Fossil Hybrid Operation"). Although this experiment is in the 100-kW(e)-size range, it could address most of the significant questions associated with much larger units. Because of the size of the experiment, the attempt to reuse the 1-MW(th) solar receiver, and the limitations in the test facility, system performance is expected to be lower than larger size units.

Project Objectives

The objective of the overall project is to demonstrate the technical feasibility of a complete Brayton-cycle, solar-fossil hybrid central receiver system. This is a necessary, although not sufficient, step to bring this concept to commercial availability and to add it to the list of electric utility power generation options.

The major objectives in this Phase I effort are (1) to plan and design the experiment in detail and (2) to organize a utility Test and Operating Group that would be directly involved in the development and operation of the experiment throughout all phases of the project.

Project Results

The Phase I effort produced the design of an experiment that would, if successful, demonstrate the capability and flexibility of the Brayton-cycle, solar-fossil hybrid central receiver concept. Engineering and performance models were developed that would, when validated with actual test results, be used with confidence in designing and estimating the performance of larger Brayton-cycle, solar-fossil hybrid power plants.

A significant benefit to the project was the interest, involvement, and direct technical support provided by the utility personnel in the utility Test and Operating Group, especially in the area of the experiment's master control system. A digital control and data collection system was designed and built for the experiment. The utility personnel worked closely with the contractor to produce a system that was accurate, responsive, and easily used by utility power plant operators not familiar with digital control hardware. This close involvement and the beneficial results obtained clearly demonstrated the value of including not only the research and engineering personnel but also the operating personnel in the development programs of new technologies.

J. E. Bigger, Project Manager
Advanced Power Systems Division

Background

Since 1974, BEC has been conducting studies and research in high temperature, gas cooled, solar central receiver concepts under the direction of EPRI. The initial contract, RP377-1, had as its objectives the examination of technical feasibility of the closed Brayton-cycle concept, the development of a receiver conceptual design, and the definition of critical technical problems.

A 1 MW_t solar receiver was designed, fabricated, and solar tested during the period of 1976-1979. This metal-tube receiver was developed for EPRI on Contracts RP377-2 and RP377-3. Successful completion of the model receiver tests provided the technology and one major hardware component for a complete solar-electric power system.

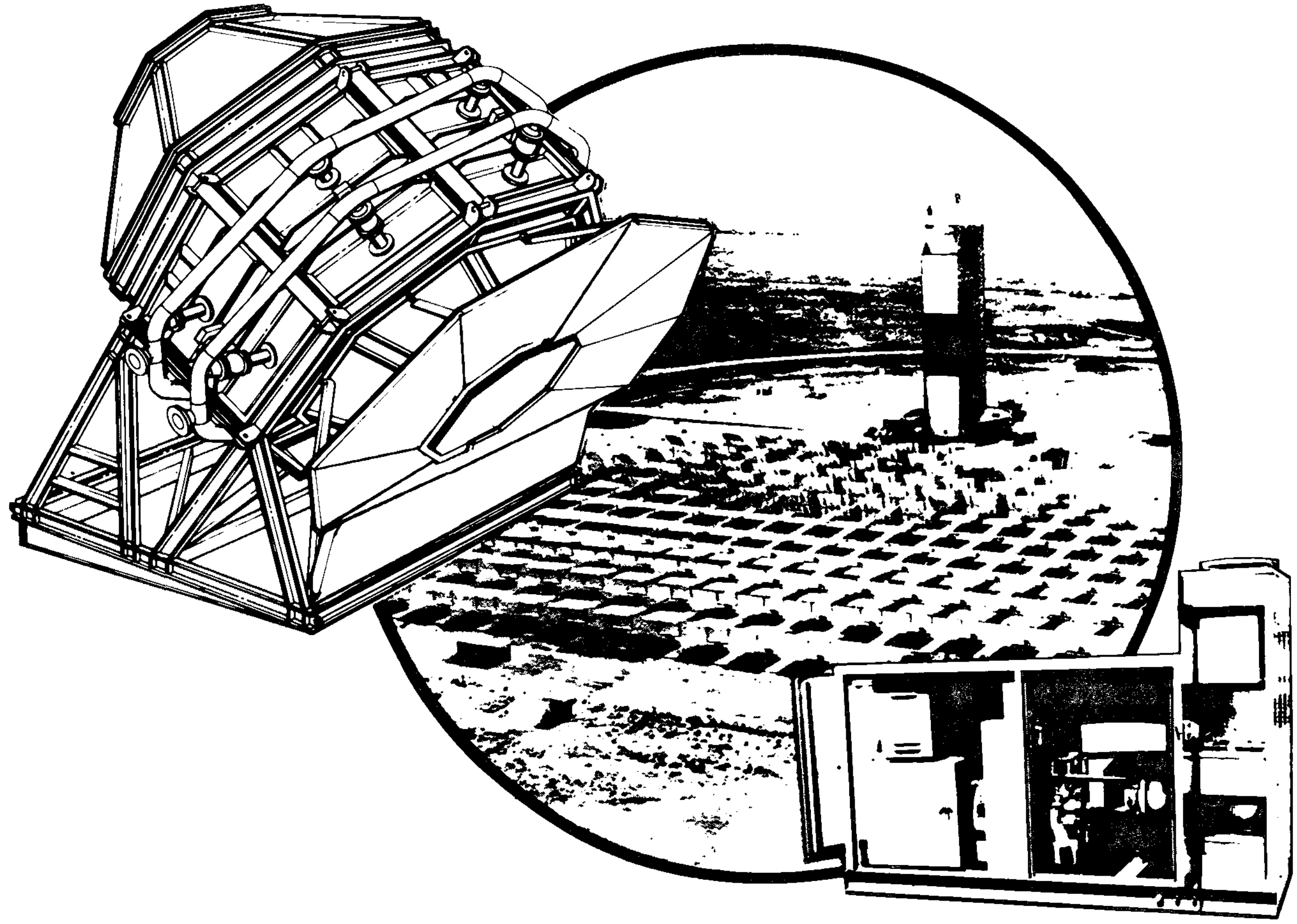
In July, 1980, EPRI contracted with BEC for the first phase of a project to design, fabricate and conduct a Full System Experiment (FSE). Phase I was performed under EPRI contract RP1509-1 and consisted of performing studies, selecting hardware, preparing a design, and performing test planning. A major task was the establishment of a Utility Test & Operating group to participate in the program under the lead Utility, Public Service Company of New Mexico.

Solar Turbines Incorporated, as an EPRI contractor, has been developing and characterizing the performance of a liquid-fueled trim combustor for adaptation to a commercial gas turbine. The combustor was intended to be used in conjunction with an external source of heated air, the solar receiver, to power a turbine in a solar-hybrid mode. A scale-model trim combustor was designed and tested on EPRI Contract RP 1270. This scale model was the correct size for adapting to the Solar-Titan gas turbine selected for the Full System Experiment program; thus providing another major tested hardware component.

The results of the Phase I study are highlighted in this report.

FSE Program Elements

Solar Hybrid Full System Experiment



Summary

The next step in the progression to commercial utilization of gas-cooled solar power systems (central receivers) is the design and construction of an experiment where all elements of the power generation system are assembled and operated as a single cohesive unit. EPRI has initiated this activity with the award of contract RP 1509 to design, assemble, and operate a Solar-Hybrid Full System Experiment. Maximum utilization of existing components is a key goal. Thus, the solar receiver technology and components of the Bench Model Receiver (RP377) and the tower and heliostat field of the Central Receiver Test Facility will be employed. Additional components include the Solar-Titan gas turbine-generator and a parallel arrangement trim combustor employing fossil fuel to supplement solar operation. The major elements of the experiment are shown on the facing page.

EPRI plans to demonstrate the technical feasibility of a Brayton-cycle, solar-thermal concept by integrating a modified gas turbine with a metal tube solar receiver, and operating the complete system as a hybrid solar-fossil unit for testing and training purposes. This will provide an opportunity to address the major design, integration, performance and operation issues. It will also provide a system on which utility personnel can obtain experience.

The Full System Experiment will be conducted in three phases. Phase I, recently completed, was an eighteen month design and planning effort, initiated July 1, 1980. The second phase is twenty-five months, and involves hardware modification and fabrication. Authorization for Phase II was given June 1, 1981, and several major purchases such as the turbine, master control computer, and console components have been made. Phase III, a twelve month effort, will involve installing the system at the CRTF, performing the system checkout and characterization, conducting the utility training and operation phase, and evaluating the results. The entire project will be completed in early 1984.

Table of Contents

1. Introduction

The Full System Experiment is an important step in the development of solar power generating options for utilities. The objectives of this overall program are: to demonstrate the technical feasibility of a complete Brayton-cycle solar-thermal concept, to provide a complete operating system on which utility personnel can obtain experience, and to provide an opportunity for direct utility input to the further development of the concept. The specific project objectives are shown on Figure 1.

The three phases of the program are: Phase I Design; Phase II -Manufacture and Assembly; Phase III -Solar Testing and Operation. This report describes the work accomplished in Phase I. Subsequent Reports will describe Phase II and Phase III results.

Phase I Tasks

The Phase I effort had seven tasks, depicted on Figure 1. The first task was to establish criteria for selection of utility groups to participate in the program. The selection process was accomplished by the lead utility, PNM. The second task involved definition of the Full System Experiment design concept by means of trade and optimization studies. The third task selected the turbine best suited for the experiment and designed the combustor and fuel system modifications for adapting a current production Solar-Titan gas turbine. Solar Turbines Incorporated performed this task as a subcontractor to BEC. The fourth task was the design of the solar-fossil hybrid system with supporting analyses and performance predictions. The fifth task involved preliminary test planning to define instrumentation and the checkout, experimental and utility operating test sequences. The sixth task defined the experiment and test facility interfaces to assure a smooth flow of events for components and participants. The seventh task was the preparation of a work plan for the next phase.

Figure 1. Phase I Program Description

Objectives

- Demonstrate technical feasiblity of complete solar fossil hybrid concept in a near-operational environment
- Address design, performance, test and operational issues pertaining to central receiver power plant
- Involve utilities in design and test decisions
- Obtain direct utility participation in training and system operation
- Evaluate potential of concept to meet future utility needs.

Phase I Tasks

1980						1981									
J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O

Task 1 Utility test and operating group implementation
Task 2 Concept definition
Task 3 Turbine selection
Task 4 System design
Task 5 Preliminary test plans
Task 6 Solar test facility interfaces
Task 7 Phase II work plan

2. Utility Test and Operating Group

Because of the importance of utility input in the development of solar-thermal systems, this work is being performed in close cooperation with a Utility "Test and Operating Group". Utilities participating in this group include those shown in Figure 2.

The group of utility participants was selected, organized, and coordinated by the lead utility, Public Service Company of New Mexico (PNM), to participate in the planning and operating aspects of the program. This organizational effort was performed as a part of Task 1. The Utility Test and Operating Group has helped to identify critical items to be considered in the experiment and have given guidance relative to design, operation and maintenance so as to obtain information consistent with utility needs and practice. Of particular importance has been the support given in the design of the Master Control System. It is expected that this support will continue during Phase II. The Utility Test and Operating Group will provide teams of personnel to participate in the training and operational aspects of Phase III.

The make-up of these groups is expected to include power plant design, operations, and dispatch personnel. As the operational phase of the program proceeds, each utility team will conduct an independent evaluation of the concept and experiment and provide suggestions and recommendations for future efforts.

Figure 2. Participating Utilities

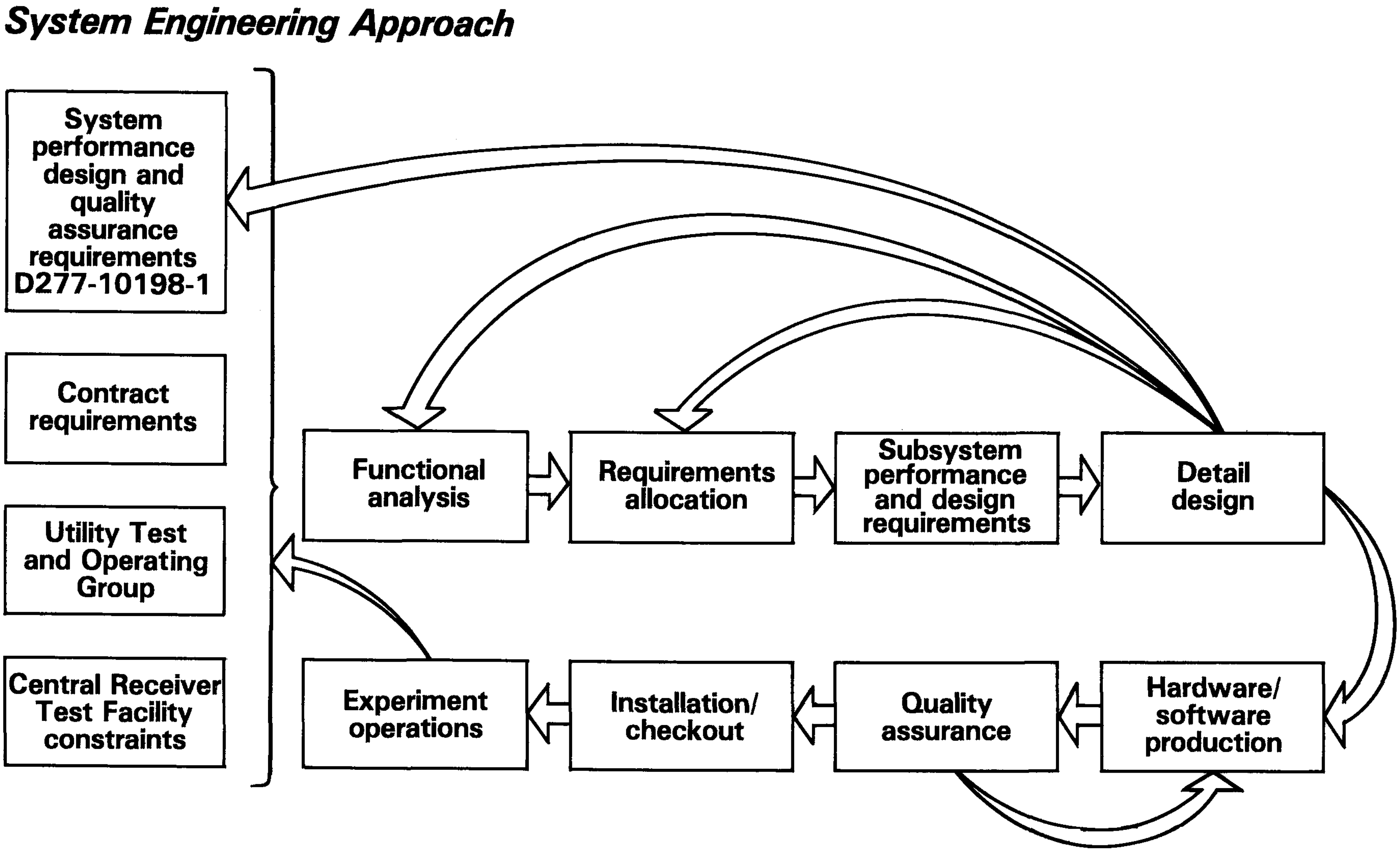
1. Arizona Public Service Company
2. Brazos Electric Power Cooperative, Inc.
3. Austin Electric Dept.
4. Bonneville Power Administration
5. El Paso Electric Co.
6. Plains Electric G&T Cooperative, Inc.
7. Public Service Co. of Colorado
8. Public Service Co. of New Mexico
9. Southern California Edison Co.
10. Virginia Electric and Power Co.
11. Gulf States Utilities Co.
12. Oklahoma Gas and Electric Co.
13. Electrical Research Institute-Mexico

3. System Description

System Engineering Approach

A systems engineering approach, shown graphically in Figure 3, was used to control and direct the development of the design concept. A System Specification Document was established for performance, design and quality assurance requirements. This document along with inputs from the utility groups, the Central Receiver Test Facility and contractual requirements constituted the controls exercised over the design as it progressed. Additional design requirements were levied at the subsystem and detail level as functional analyses were completed. Establishment of interfaces with the Central Receiver Test Facility was a major effort to assure the proper design and function of components upon arrival at the test site. Detail design development was accomplished by frequent appraisal of performance in light of established requirements. Design reviews compared component or system function with the pre-established requirements.

The subsequent fabrication, installation and checkout activities of Phases II and III will be structured for frequent quality control review in order to assure function and provide the product assurance data needed for later preparation of a program data package. The data package is an experimenter requirement for testing at the Central Receiver Test Facility. The final check in the system engineering flow of events will be the comparison of operational characteristics of the experiment with the initially established requirements, shown on the left hand side of the flow diagram of Figure 3.

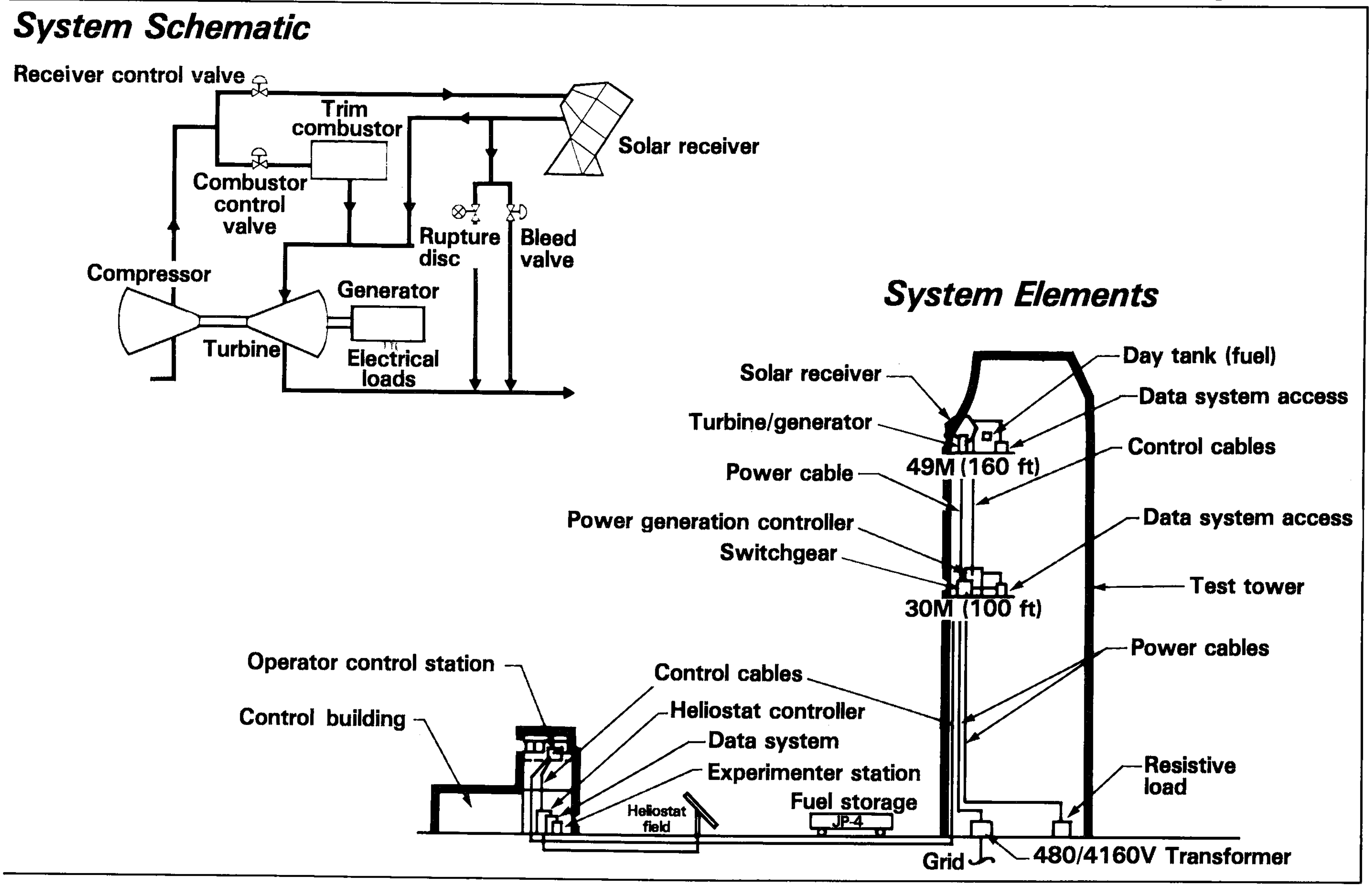

System Engineering Approach
System performance design and quality assurance requirements D277-10198-1
Contract requirements
Utility Test and Operating Group
Central Receiver Test Facility constraints
Functional analysis
Requirements allocation
Subsystem performance and design requirements
Detail design
Hardware/ software production
Quality assurance
Installation/ checkout
Experiment operations

System Elements

Major elements of the Full System Experiment (FSE) are shown in the lower part of Figure 4. The components include the tower, heliostat field and controls, control building, JP-4 fuel supply system, and the electric connections to the resistive load or the grid. These components will be provided by the government-owned Central Receiver Test Facility. Components which will be supplied by Boeing Engineering and Construction Company to complete the system are: the solar receiver; turbine-generator, operator control console, switchgear, power generation controller and cabling. The Boeing Engineering and Construction Company supplied components will be integrated with the test facility to provide a complete solar-electric power generating system. All functions were designed to be computer controlled to provide automatic operation, excepting the heliostat command function. The 49m (160 ft) level of the tower has been assigned for location of the receiver and turbine-generator. The power generation controls and elements of the switchgear will be located on the 30m (100 ft) level. Two electrical loads will be provided by the test facility. One will be a variable resistive load bank and the other an intertie to the 4160V Kirtland Air Force Base power distribution network.

The upper portion of Figure 4 shows the power generation system schematic. The system was designed to provide controlled flow to either the solar receiver or trim combustor or both. Ambient air entering the inlet of the compressor stage will be compressed and delivered to the system. Modulation of the combustor control (V1C) valve will provide the desired flow division to solar receiver and/or trim combustor. Heated air from these sources drives the turbine and in turn, the generator. Emergency vent paths through a bleed valve or a rupture disc were designed in the system for protection in the event of loss-of-load.

Figure 4. System Elements/Integration



System Schematic

System Elements

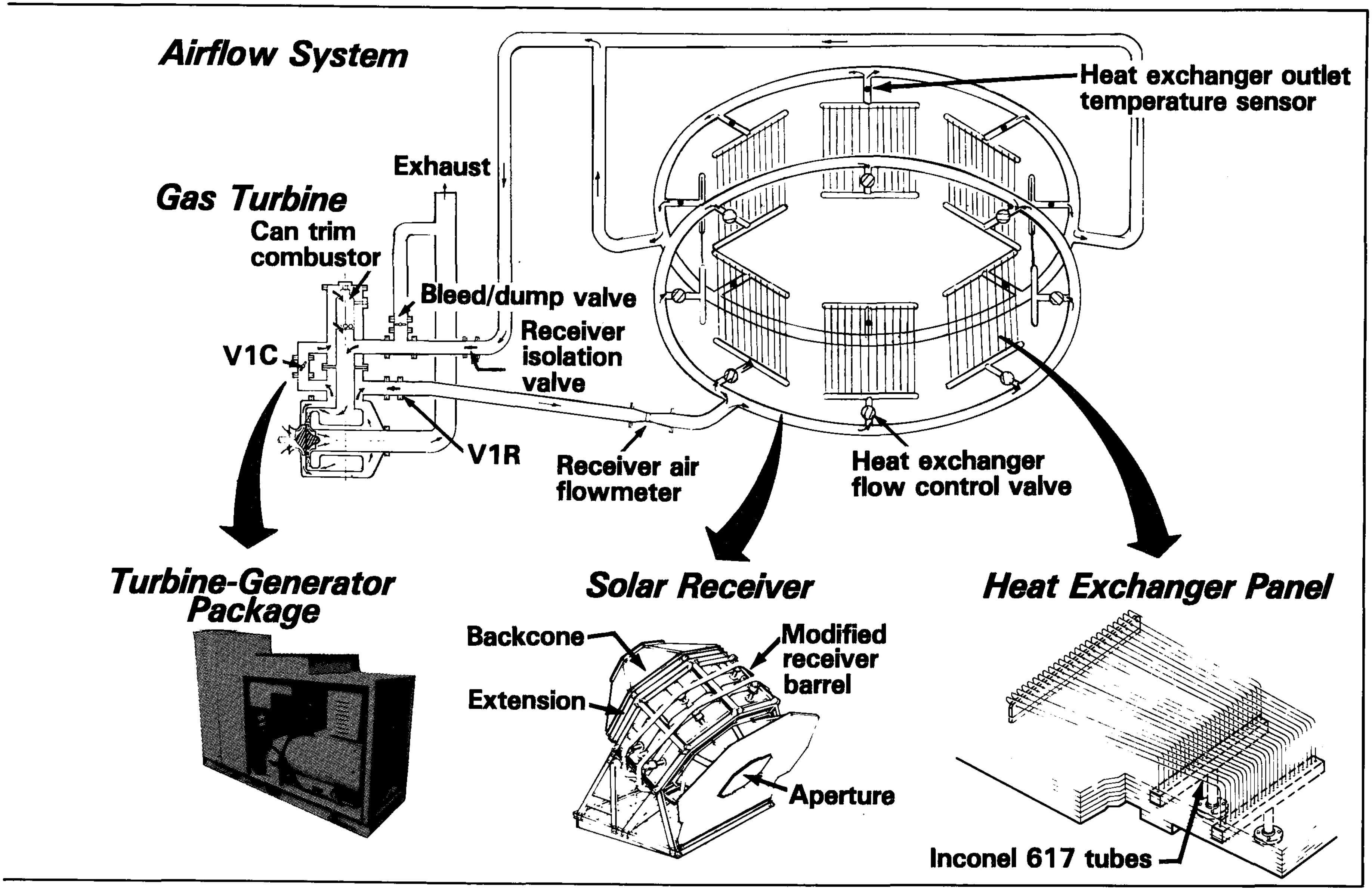
Power Conversion

Figure 5 shows the major power conversion elements designed for use in the Full System Experiment. The Turbine-Generator package is a complete power generation unit offered by Alturdyne of San Diego, California. It contains a 90kWe Titan gas turbine, produced by Solar Turbines, Inc.; an electric generator; and all necessary control equipment. The gas turbine takes ambient air, compresses it in a radial compressor, heats it by fuel combustion and expands it in the power turbine. This single shaft turbine operates at 61,000 RPM and is connected to the 3600 RPM generator through a gearbox.

Based on the Phase 1 designs, the gas turbine will be modified to operate in the solar-fossil hybrid mode by Solar Turbines Inc. Modifications will include: a high-turn-down combustor, new ducting for parallel combustor and receiver flow paths, and addition of the bleed/dump valve. The modified gas turbine will be started on fossil fuel with the receiver control valve (V1R) closed. During solar-only and solar-fossil operation, the receiver control valve will be open. Division of the air between the combustor and the solar receiver will be accomplished by the combustor control valve (V1C). The eight receiver heat exchanger valves will modulate the flow rate to obtain a constant 816°C (1500°F) receiver outlet temperature. The trim combustor was designed to accommodate these changes in flowrate and by fuel modulation, to produce outlet temperatures varying from 316°C (600°F) to 1260°C (2300°F). During solar-fossil operation these two sources will be utilized to produce a constant electrical output.

The solar receiver is the unit previously tested, but with modifications to operate in the experiment. Based on test experience, the design was changed to increase its performance and reliability. The aperture was redesigned, the cavity insulation design was improved, and the receiver barrel was lengthened to reduce the peak solar flux levels in the backcone. The heat exchanger design was changed although the tube material remains the same, Inconel 617.

Figure 5. Power Conversion Elements



Control System

The Full System Experiment (FSE) control system will provide automatic, remotely supervised operation of all processes by a single operator. The major elements of the control system are shown in Figure 6.

The system was designed to provide operator supervision from the Master Control System (MCS) console located in the control building. Heliostat field control, provided by CRTF, will receive commands from and transmit data to the MCS via the communication link between the two controllers. The heliostat master controller will be operated by CRTF personnel.

The power generation and distribution systems will be controlled by the Electric Power Generation System Controller (EPGSC). These components are located on various levels of the tower. The EPGSC receives commands from and transmits data to the MCS via the communication link between these two controllers.

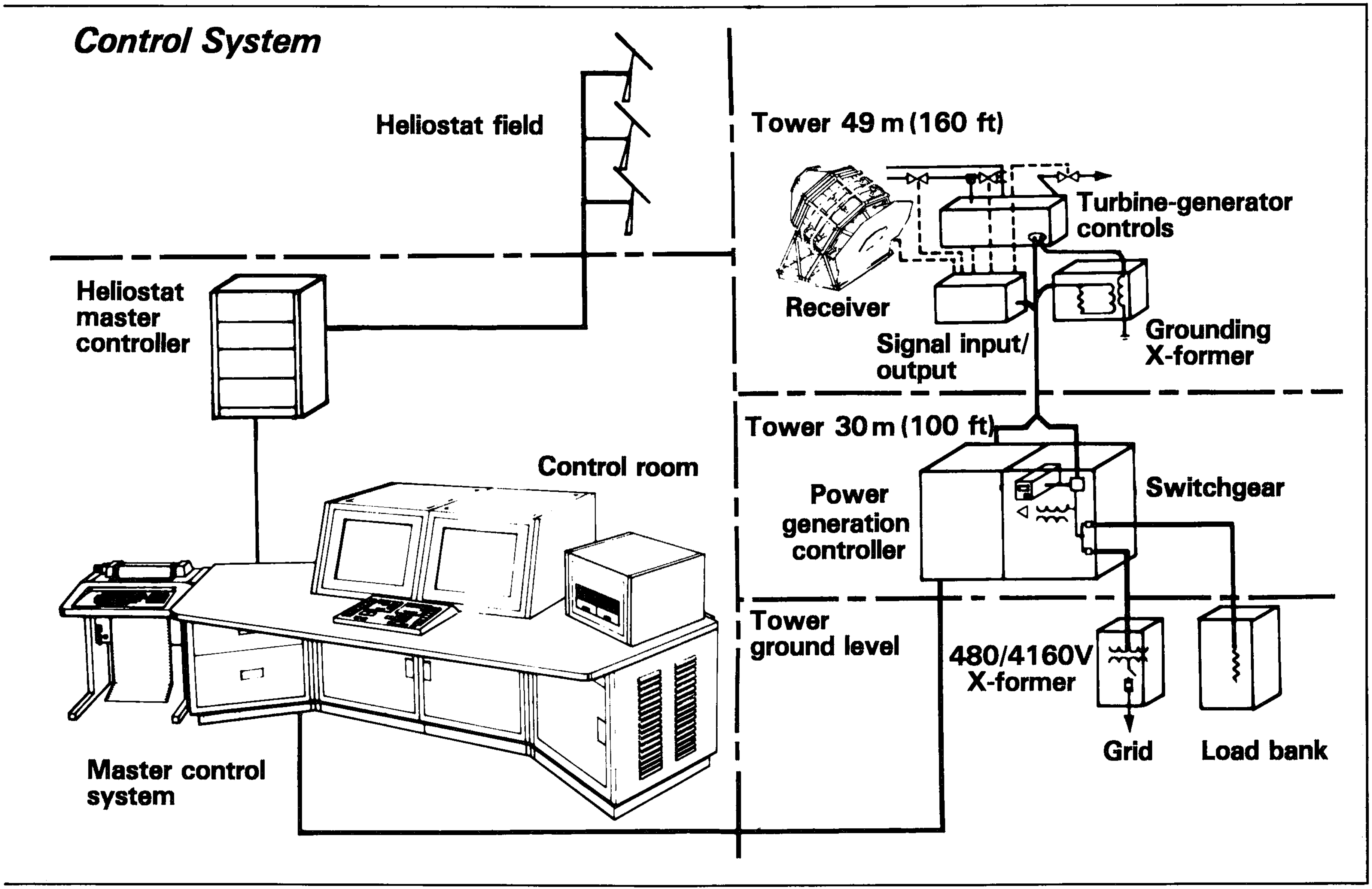
The generator and electric power distribution controls were designed as part of the switchgear. Electric power from the generator can be sent to either the resistive load bank or to the Kirtland Air Force Base grid via a 480/4160V transformer.

Signals to and from the power generation components located on the 49m (160 ft) tower level will be routed through input/output connections at the same level to minimize the length of cable runs.

Heliostat Field

Only a portion of the available 222 heliostats were selected for the FSE tests. Generally, 50 to 100 heliostats will be used depending on the time of year. The order in which these heliostats will be selected is based on a priority list. The list was selected to obtain maximum thermal input without exceeding the allowable solar flux impingement on heat exchanger tubes or cavity wall insulation.

Figure 6. System Components



4. System Operating Capabilities

Solar-Hybrid Operation

In this mode, the gas turbine will be driven from a mixture of air heated by fossil fuel combustion and by solar energy. The fossil fuel combustion supplements the solar-heated air to maintain the desired electrical output. The receiver/combustor heat balance will be adjusted to correspond to the insolation level and electrical demand. The system schematic in Figure 7 illustrates the system air flow. Pertinent thermodynamic state point data are presented for the design condition.

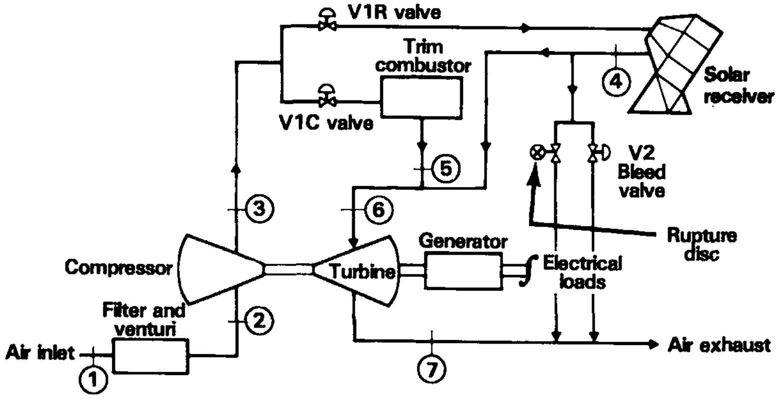
System level operation constraints are visualized by the use of the operation window concept also shown in Figure 7. The boundaries of the operation window are formed by hardware or operational limits. The maximum allowable combustor airflow occurs at the minimum receiver airflow required to insure turbulent heat exchanger flow. The minimum allowable combustor airflow for stable fossil fuel combustion has been experimentally determined at 10% of the total flow. The maximum allowable combustor outlet air temperature of 1260°C (2300°F) provides acceptable combustor metal liner temperatures. The maximum turbine inlet temperature of 882°C (1620°F) forms the remaining portion of the upper operation window boundary. The lower boundary is formed by the pilot level fuel flow of 2.7 kg/hr (6 lbm/hr).

Within the system operation windows, isolines of constant turbine inlet temperature and electrical output are depicted. Acceptable system operation will be possible over a wide range of operating conditions. Preferred operation in the upper left-hand portion of the window provides both high solar contribution and high electrical output.

Heliostats are targeted on the receiver aperture in increments. The effect of incremental heliostat addition for a particular operating condition is also shown.

Figure 7. Solar-Hybrid Characteristics

Baseline Solar-Hybrid System Schematic



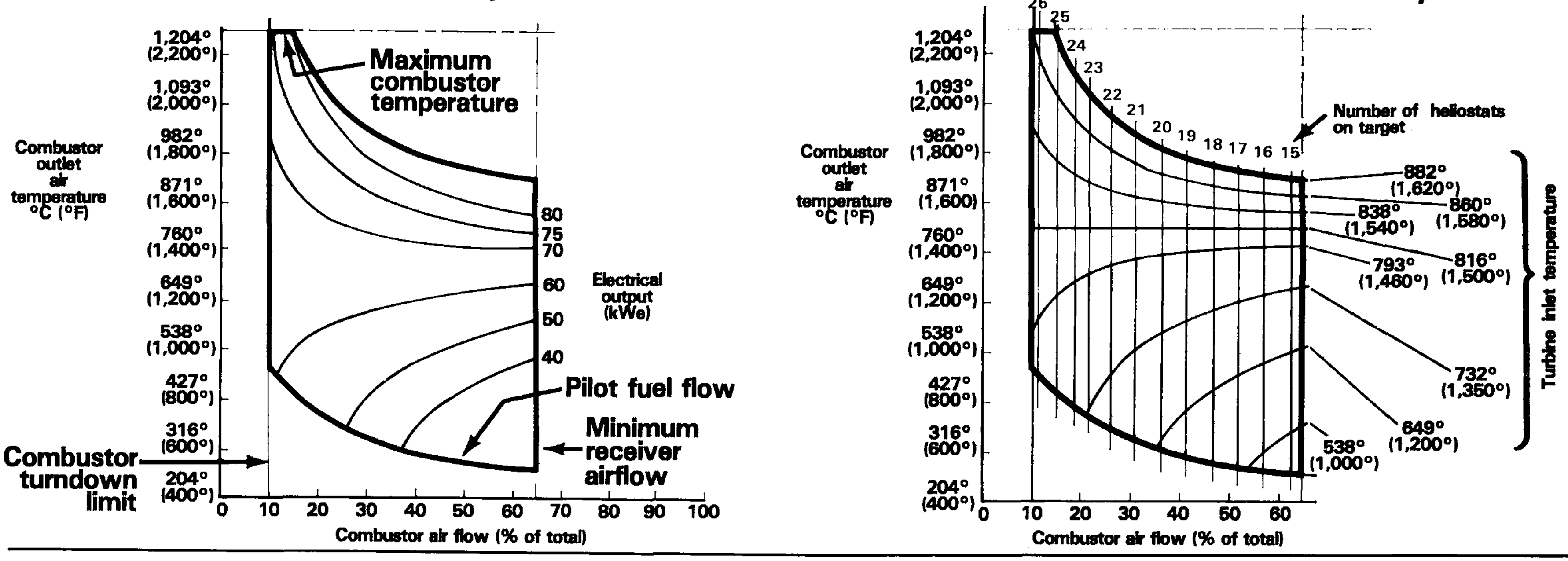
Solar input = 628 KW_t
Net elec (solar) = 61.4 KWe
Net elec (fossil) = 18.7 KWe
Insolation = 950 W/m^2

Schematic location	Design point data		
	Temperature °C (°F)	Pressure MPa (psia)	Mass flow Kg/s (lbm/s)
1	16° (60°)	0.09 (12.2)	0.72 (1.59)
2	16° (60°)	0.089 (11.9)	0.72 (1.59)
3	197° (386°)	0.34 (47.9)	0.72 (1.59)
4	816° (1,500°)	0.32 (44.8)	0.62 (1.36)
5	1,246° (2,275°)	0.32 (44.8)	0.11 (0.24)
6	882° (1,620°)	0.32 (44.8)	0.72 (1.59)
7	620° (1,148°)	0.09 (12.2)	0.72 (1.59)

Solar-Hybrid Operation Window

Constant Electrical Output

Constant Turbine Inlet Temperature



Solar-Only Operation

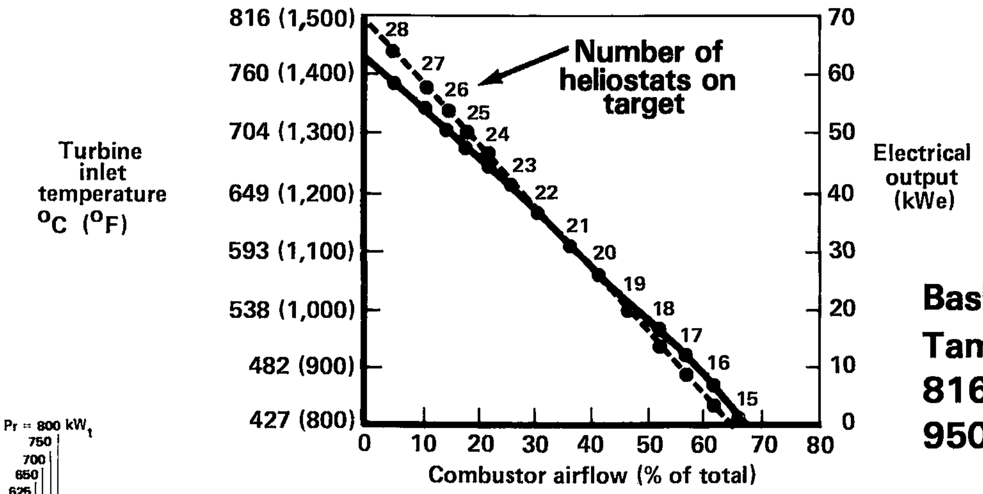
In the solar-only operation mode, fossil fuel combustion will be terminated, however airflow will continue to be directed through both the receiver and the combustor as illustrated on the schematic of Figure 7. The receiver outlet air temperature will be maintained at a constant set-point value. The balance of the airflow from the compressor stage will be bypassed unheated through the combustor to mix with the hot receiver air. This provides a reserve of coolant in the event more receiver airflow is required by increased insolation. This reserve air will be obtained by further closing of the combustor valve V1C. System operation is illustrated in Figure 8. A one-to-one correspondence exists between solar input, turbine inlet temperature, and electrical output (upper graph).

In the solar-only mode thermal power is available in discrete steps as supplied by the heliostat field. The solar input is a function of the selected heliostats on target, the insolation level, the time of day, and the day of the year. A nomograph (lower graph) illustrates the predicted performance for the Central Receiver Test Facility heliostat field. For given values of insolation and receiver input power, an effective field mirror area is required. The actual required mirror area is larger because of variable optical losses such as shadowing, blocking, mirror reflectance and atmospheric turbulence. The cumulative effect on the effective field area is represented for March 21.

The nomograph is used to select the number of heliostats required to produce the desired power at various times of the day. The time of day data is presented as solar noon and hours preceeding solar noon. Hours after solar noon are also represented by these curves, for instance, 11:00 a.m. is equivalent to 1:00 p.m.

Figure 8. Solar-Only Operating Characteristics

Solar-Only System Operation



—— Electrical output

--- Turbine inlet temperature

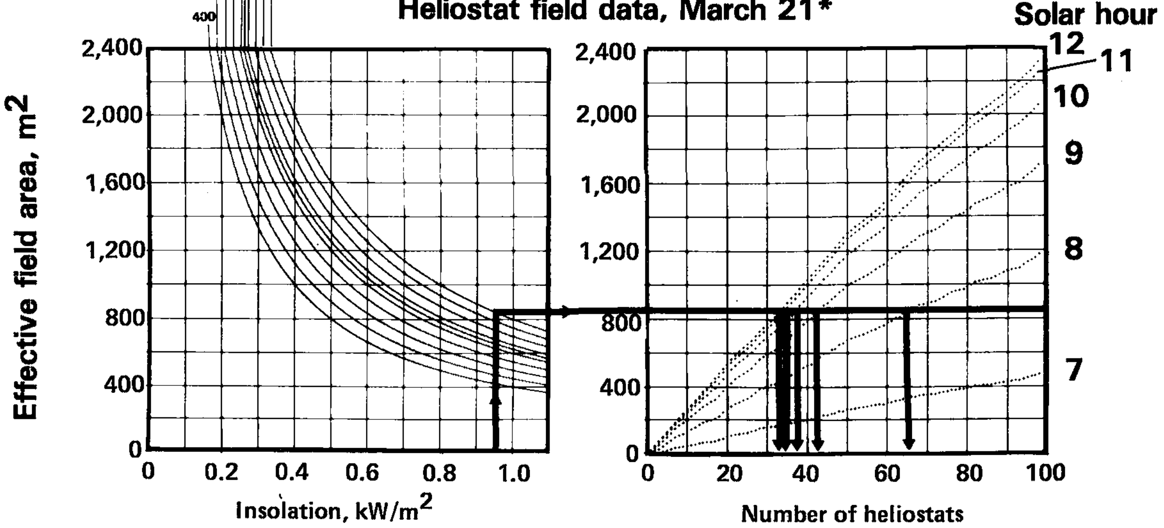
Basis:

Tamb = 15.6°C (60°F)

816°C (1,500°F) receiver outlet

950 W/m²

Solar Power



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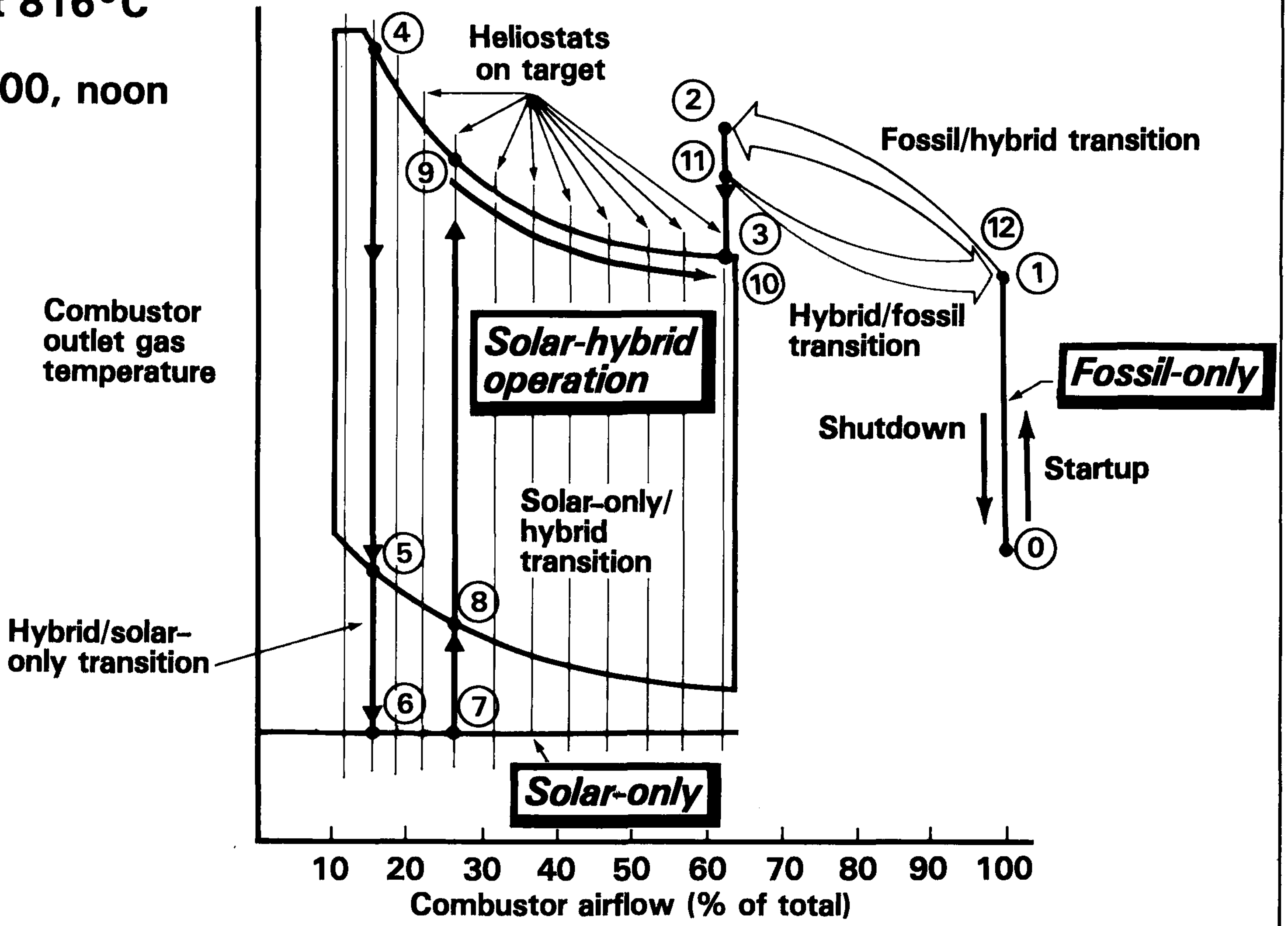
Operating Transitions

Figure 9 presents a system operation window showing step-by-step transitions between the various operating modes. System startup will be accomplished in the fossil-only mode and begins at ⓪→① in the graph. The transition from fossil-only to solar-hybrid ①→② is accomplished by admitting airflow to the receiver and adding heliostats on target. As the receiver outlet air temperature increases to the setpoint value 816°C (1500°F), the combustor outlet temperature will decrease ②→③ . At ③ the system is on the upper bound of the solar-hybrid operating window (maximum turbine inlet temperature and electrical output). Further heliostat addition will increase the solar input to the receiver, which requires increased massflow to maintain the outlet setpoint temperature. The increasing receiver mass flow will decrease the combustor mass flow thus moving the operation point to the left on the window ③→④ . The solar-hybrid to solar-only transition will require reduction of the fuel flow to the pilot level ④→⑤ then extinguishing the pilot fuel flow ⑤→⑥ . In the solar-only mode, heliostats can be added moving the operation further to the left. The solar-only to solar-hybrid transition will require combustor relight, not presently within the capability of the system. The combustor relight will be accomplished in the 10-30% flow range. The transition to solar-hybrid will be accomplished by relighting the combustor at the pilot fuel flow ⑦→⑧ then returning to the hybrid operation condition ⑧→⑨ . The solar-hybrid to fossil-only transition will be accomplished by moving to the minimum receiver flow region ⑨→⑩ by removing heliostats. As the minimum receiver airflow is approached the receiver outlet air temperature will begin to fall below the setpoint value. This drop in receiver exit air temperature will be made up by increasing combustor exit air temperature ⑩→⑪ to maintain turbine inlet temperature. By removing heliostats and closing off all receiver airflow, the entire compressor flow will then pass through the combustor ⑪→⑫ and the combustor will control the turbine.

Figure 9. Operating Transitions

- T_{amb} = 16°C (60°F)
- Receiver outlet 816°C (1,500°F)
- 21 March, 12:00, noon
- 950 W/m^2



5. Cavity Receiver Design

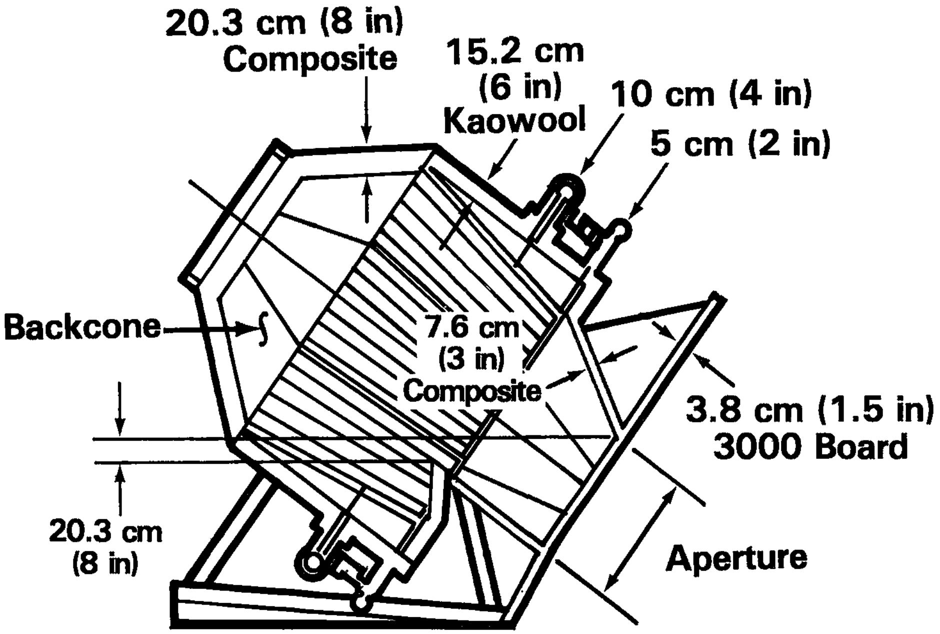
Figure 10 shows an inboard profile of the solar receiver and describes its most important dimensions and design-point operating conditions. The solar receiver was designed to carry the full airflow from the compressor stage of the gas turbine. From 32 to 100 percent of the compressor output could be diverted to the receiver and heated with solar energy. A total of 186 heat exchanger tubes were used to carry and heat this airflow. Nearly half the cavity wall area was occupied by heat exchanger tubes.

The FSE solar receiver incorporated reflective/-reradiative redistribution of input solar flux. This design concept was successfully demonstrated in the Bench Model Receiver solar test program RP377-3. After entering the aperture, solar flux illuminated a bare insulation wall, the backcone. Its semi-hemispherical shape was critical for the radiant heat balance of the receiver cavity. Because of this shape, solar input power was nearly equally delivered to all heat exchanger tubes. This provided equal radiant heating of heat exchangers even though backcone illumination was nonuniform and variable with time.

Optimization of the cavity and aperture shapes was a critical design consideration. Air circulation within the cavity and through the aperture (convective flow) lowered efficiency and distorted the cavity (radiant) heat balance. By locating the aperture as low as possible, its upper rim trapped hot air within most of the cavity. About 70 percent of the heat exchangers were within this static air zone. Viewed horizontally from the front, the exposed aperture opening was only 20cm (8 in) high. Air circulation through the aperture was reduced by a factor of two compared to the Bench Model Solar Receiver.

High temperature insulation materials were selected to conserve solar heat and protect the receiver structure from excessive temperatures. Material choices were based on their service temperature limits and the design requirements.

Figure 10. Receiver Characteristics



I. Design point conditions	
Maximum airflow rate - kg/sec (lb/sec)	0.85 (1.87)
Inlet air pressure MPa - (psia)	.368 (53.4)
Inlet air temperature - °C (°F)	173 (343)
Outlet air pressure - MPa (psia)	.334 (48.4)
Outlet air temperature - °C (°F)	816 (1500)
Solar input - kW_t	825
Thermal output - kW_t	595
Date/time of day	Equinox Mar 21/noon
Direct solar flux - W/m^2	950
Ambient temperature - °C (°F)	-6.3 (21)
II. Cavity geometry	
Octagonal aperture dimensions - m (in)	1.36 (53.5) wide 1.2 (46.8) high
Aperture area - m^2 (ft^2)	1.38 (14.8)
Aperture plane inclination - degrees from vertical	36°
Aperture location - m (ft) toward field from return bend of Hx tube	2.80 (9.19)
Total cavity wall area - m^2 (ft^2)	34.0 (366)
III. Heat exchanger system	
Tube inside diameter - mm (in)	9.40 (.370)
Tube outside diameter - mm (in)	12.7 (.50)
Tube heated length - m (ft)	3.06 (10.0)
Tube total length - m (ft)	3.84 (12.6)
Panel width on wall - m (ft)	1.09 (3.59) max
Panel length on wall - m (ft)	1.79 (5.88)
Individual panel flow control	Yes
Total number of panels	8
Number of tubes per panel	24 panels 3,7,1,2,8 22 panels 4,5,6
Design pressure loss (% of inlet)	7.3
Total number of tubes	186
Total heated tube inside area - m^2 (ft^2)	16.7 (180)
Total heated tube outside area - m^2 (ft^2)	22.6 (243)
Average tube absorbed heat flux, outer - kW/m^2	26.2
Peak tube temperature °C (°F)	890 (1,636)
Average tube temperature °C (°F)	715 (1,318)
Reynolds No. Maximum	16,000
Average	9,850
Minimum	3,700
IV. Backcone	
Peak solar flux kW/M^2	200
Average solar flux kW/m^2	94
Backcone wall area m^2 (ft^2)	8.67 (93.3)
Peak insulation temperature °C (°F)	1,294 (2,360)

Receiver Solar Input

The receiver was designed to use the field of heliostats at The Central Receiver Test Facility. Detailed analyses were conducted to determine which of the heliostats were preferred and how many of them were needed for full power operation. Data on Figure 11 summarize the heliostat requirements for a March day. With clear sky conditions, 27 heliostats will be required to produce full power at noon. More heliostats are needed during hazy sky conditions and during early morning and late afternoon operation.

The first incident solar flux that falls on receiver components was determined by analysis of the heliostat field and the receiver cavity. Maximum flux levels, which constituted worst case design conditions for heated components of the receiver, are also shown enclosed in boxes. These values established maximum receiver thermal design requirements.

Receiver Thermal Performance

Figure 11 portrays receiver thermal performance as a function of operational stages. Maximum heat losses that were predicted for the receiver are shown. Thermal performance was evaluated by comparing heat delivered to the air stream with heat reflected by the heliostat field. The highest receiver efficiency will occur during solar-only operation on a cold day. It will receive about 825 kWt and deliver 595 kWt. The solar receiver exhibits a nearly constant heat loss rate for both solar-only and solar-hybrid operation.

Receiver Temperatures

Receiver insulation and structure temperatures were computed for a full day of maximum power operation on a March day. A summary of the local maximum values is shown on the Figure. These maximum values did not occur simultaneously but instead were a function of heliostats in use.

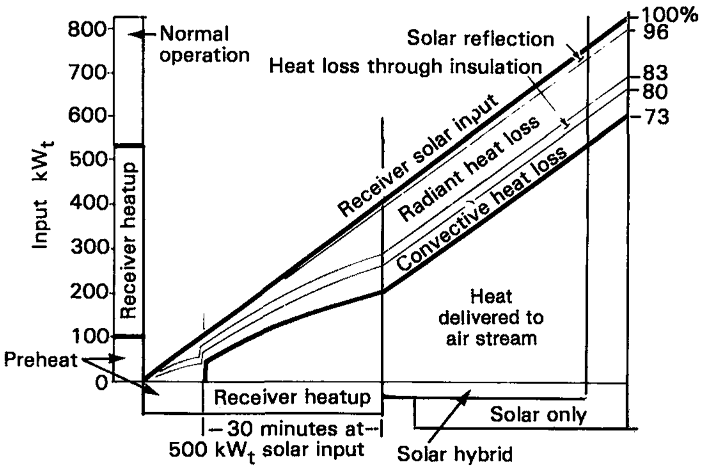
Figure 11. Design Conditions

Receiver Solar Input

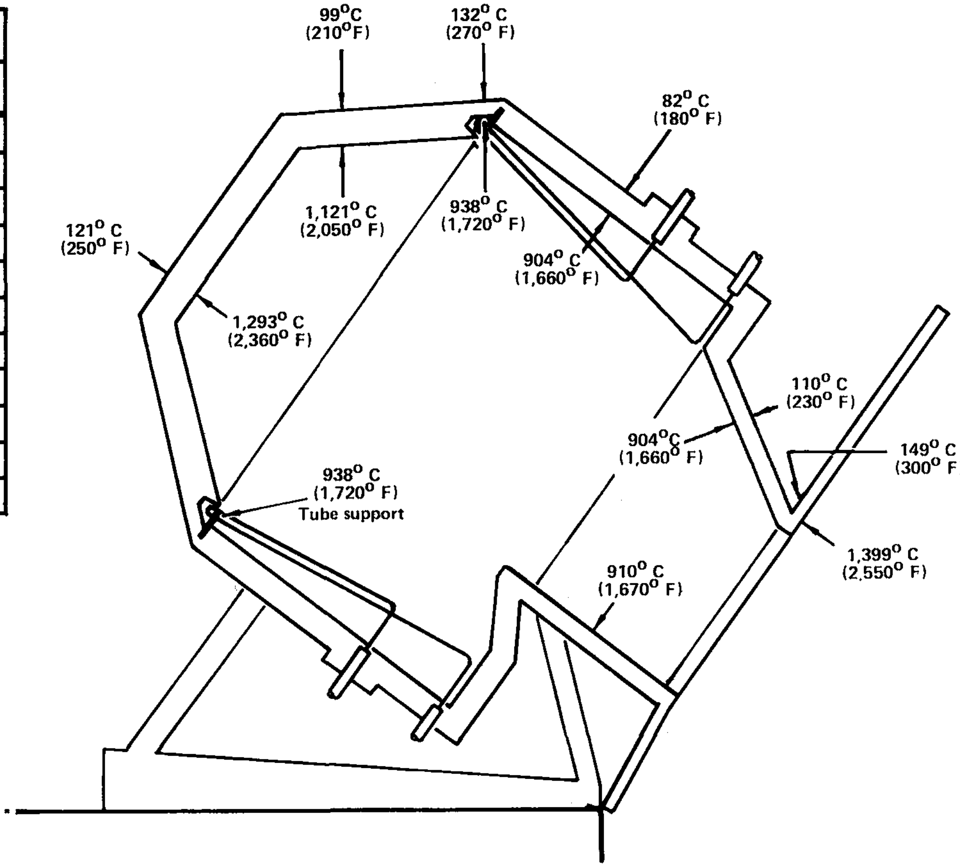
Time (Hours from solar noon)	Direct solar flux (W/m²)	Heliostats on target	Receiver solar input (kW$_t$)	Maximum solar flux incident on receiver (kW/m²)		
				Aperture shield	Back cone	Heat exchanger
0	536	60	800	276	171	17.0
	700	46	809	304	178	21.0
	900	33	806	237	196	17.0
	1,075	27	797	186	175	19.0
2	600	60	806	368	168	17.4
	800	44	804	350	169	22.0
	1,055	31	805	280	184	17.4
3	700	60	796	414	176	16.5
	1,025	40	809	377	176	15.6
4	966	60	752	453	184	18.1
5	825	60	256	176	63	7.3

Receiver Thermal Performance

-7°C (20°F) Ambient temperature



Receiver Temperatures



Basis

- **Maximum receiver power level solar only on -7°C (20°F) day**
- **Insolation ≤1,075 W/m²**

Insulation Selection

Operating temperatures required for Brayton cycle turbomachinery and the reflective/reradiative design required for cavity thermal balance resulted in very high temperatures on parts of the receiver backcone. Further analysis and laboratory tests of the Bench Model Receiver insulation showed that temperatures up to 1600°C (2910°F) had occurred during earlier solar tests on RP377. Extensive testing of insulation materials in Boeing's High Flux Test Facility provided two important results. No available lightweight commercial insulation could survive rapid thermal cycling and exposure to 1600°C, however, temperatures of up to 1300°C (2370°F) were readily accommodated by several materials. The 3000 ST® Board manufactured by Babcock and Wilcox, and selected for use in the FSE receiver, did not begin to degrade until the surface temperature reached 1430°C (2600°F).

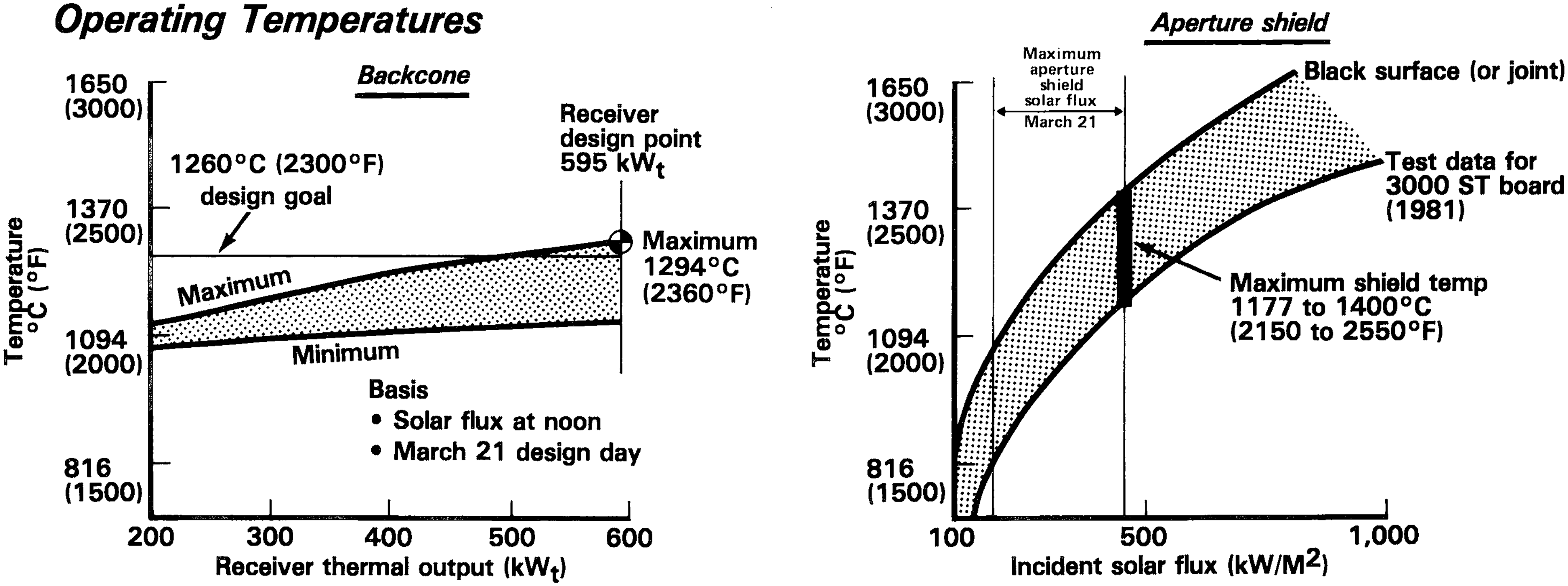
The selected receiver geometry and the utilization of specific heliostats provided for operation within these critical insulation temperature limits. The backcone insulation design will experience temperatures below 1300°C (2360°F). Local temperatures at fasteners and joints are estimated to be as much as 125°C (257°F) higher than the panel average, but still substantially below the limit for localized material degradation. The backcone insulation design constitutes a carefully implemented demonstration of the state-of-the-art of high temperature insulation design.

Backcone and aperture shield temperature predictions were made. Maximum temperatures for a range of operating conditions are shown on Figure 12. The insulation design verification test results are also shown. An extensive evaluation of high temperature insulations was conducted by Boeing under EPRI contract RP1521-1*, which led to selection of the FSE receiver insulation design concept.

*Final report now in preparation.

Figure 12. Insulation Design

Operating Temperatures



Test Results

	Backcone		Aperture shield	
Facility	Boeing High Flux Test Facility	Georgia Inst. of Technology	White Sands	Central Receiver Test Facility
Sample configuration	Simulated receiver wall, including joints and fasteners. 3000 ST Board first incident flux surface		3000 Board (Material purchased in 1978)	
Sample size	0.32 m (1.1 ft) diameter	0.46 x 0.61 m (1.5 x 2.0 ft)	5 cm (1.97 in) dia.	15 cm (6 in) square
Demonstrated performance limit	1430°C (2606°F)	1480°C (2696°F)	800 kW/m^2	750 kW/m^2

Structural Design/Analysis

Design criteria for the receiver structure are summarized in Figure 13. Temperature-related criteria for heat exchanger components will be discussed in Section 6. The design criteria are similar to those used in industrial steel construction. In the installed operating condition, the receiver was designed to withstand 0.5g seismic acceleration acting laterally. A peak non-operating wind speed of 193KM/hr (120 miles per hour) was specified which resulted in a design stagnation pressure of 181Kg/m^2 (37 psf).

Allowable stresses for the structural steel materials used in the receiver were based on American Institute of Steel Construction specifications. In general, the structure was of A36 steel with the exception of the manifold leaf spring supports. These were designed of A588 steel with the attendant higher yield strength.

Stress Analysis Summary

Stress analyses were performed on major receiver components including; the main frame; lifting lugs; weather shield and aperture shield. All components complied with the design criteria.

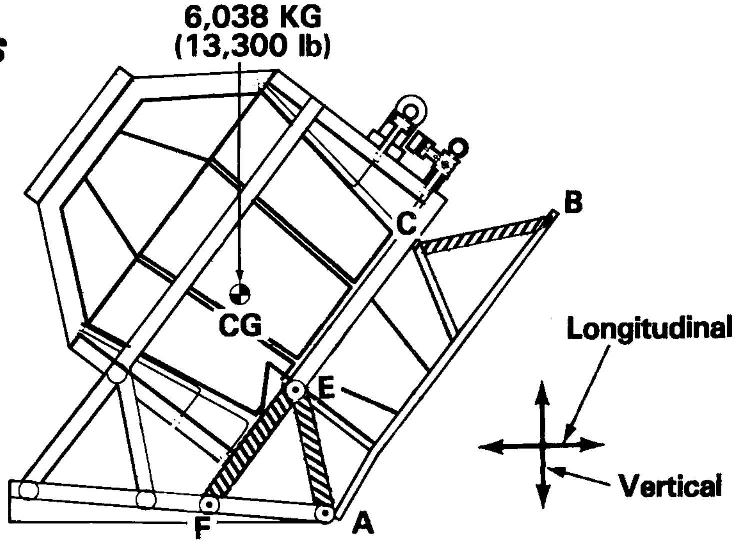
Figure 13 shows several members that were analyzed. The receiver weight and center of gravity are also shown. Member EF received its maximum loading due to the seismic condition. This produced a compressive stress of 15.8MPa (2286 psi). The allowable compressive stress was 49MPa (7100 psi). Member AE received its maximum loading due to handling/transport conditions. This produced a compressive stress of 34.8MPa (5044 psi). The allowable compressive stress was 98MPa (14200 psi). Member BC received its maximum loading from the non-operating wind condition. This produced a compressive stress of 5.9MPa (850 psi). The allowable compressive stress was 117.2MPa (17000 psi).

Figure 13. Structural Analysis

Structural Design Criteria

Condition	Wind (Any direction) (Including gust) Km/hr (M/hr)	Seismic (Lateral direction) g's	Snow/ Ice Kg/m² (lb/ft²)	Handling/Transport (Peak accelerations) g's
Operating	18 (11) (Mean)	± 0.5	—	— —
Non-operating	193 (120) (Extreme)	—	24 (5.0)	— —
Handling/transport	48 (30)	—	—	Vertical = ±3.0 Longitudinal = ± 2.0 Lateral = ±1.0

Support Structure Analysis



6. Heat Transport System

The system was designed with the receiver and combustor as parallel airflow paths between the compressor outlet and the turbine inlet. The receiver flow was further subdivided into eight parallel paths through flow control valves and heat exchanger panels. When both the combustor control valve (V1C) and the receiver panel valves are fully open, the flow split will be approximately 60/40, as shown on Figure 14. Increasing flow will be forced through either flow path by closing the valve(s) in the other path. One valve is always fully open. The receiver panel and V1C valve angles required to accomplish the full range of receiver flowrates are tabulated on Figure 14 as functions of the operating mode. The action of V1R, the receiver shutoff valve, is also described.

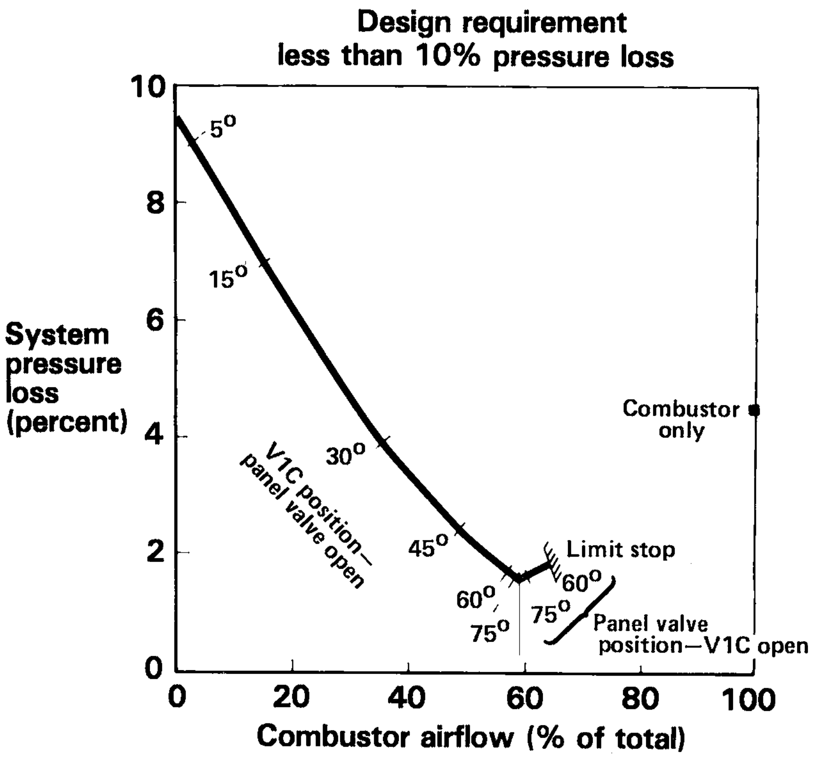
In combustor-only operation the compressor→to turbine pressure loss will be 4.5 percent. When the receiver is brought on line the pressure loss will fall below 2 percent and increases to 9.5 percent when the receiver carries all the airflow.

Valve V1C moves toward the closed position during solar only operation. The sensitivity of this valve is low. At the 3 degree minimum opening angle it produces a receiver outlet temperature change of 3.2°C (5.7°F) per degree of valve motion. As it nears fully open position, it will exhibit a change of about 0.6°C (1.1°F) per degree of valve motion. Pressure drop across the open valve is 19 percent of the combustor path loss, increasing to 100 percent as it closes.

The control sensitivity and authority of receiver panel valves was important in the design. The valves needed to modulate airflow through the eight heat exchanger panels to produce equal outlet temperatures. Valve pressure losses will range from 3.5 to 38 percent of the combined panel-plus-valve pressure loss as they move from open to closed positions. Control sensitivity will vary from about 0.3°C (0.5°F) to 5.6°C (10°F) per degree of valve motion from the open to closed positions.

Figure 14. Airflow System Operation

Air Flow Performance



Air Flow Control

FSE operating mode	Receiver flow Kg/sec (lb/sec)	V1R	V1C	Receiver panel valves
Fossil only	0.01 (0.02) to 0.01 (0.03)	Against closed limit stop	Fully open	Against closed limit stop
Solar standby		1-2 degrees open		About 60 degrees open
Receiver heatup	0.30 (0.65) to 0.33 (0.73)	Fully open		
Hybrid	0.30 (0.65) to 0.36 (0.79)			Modulating to control 8 panel outlet temp
Hybrid	0.36 (0.79) to 0.76 (1.68)		Modulating to control highest power heat exchanger 3 to 90 degrees	Modulating to control 7 panel outlet temperatures
Solar only	0.36 (0.79) to 0.85 (1.87)			

Basis

- -7°C (20°F) design day
- Normal operating temperature achieved

Thermal Design

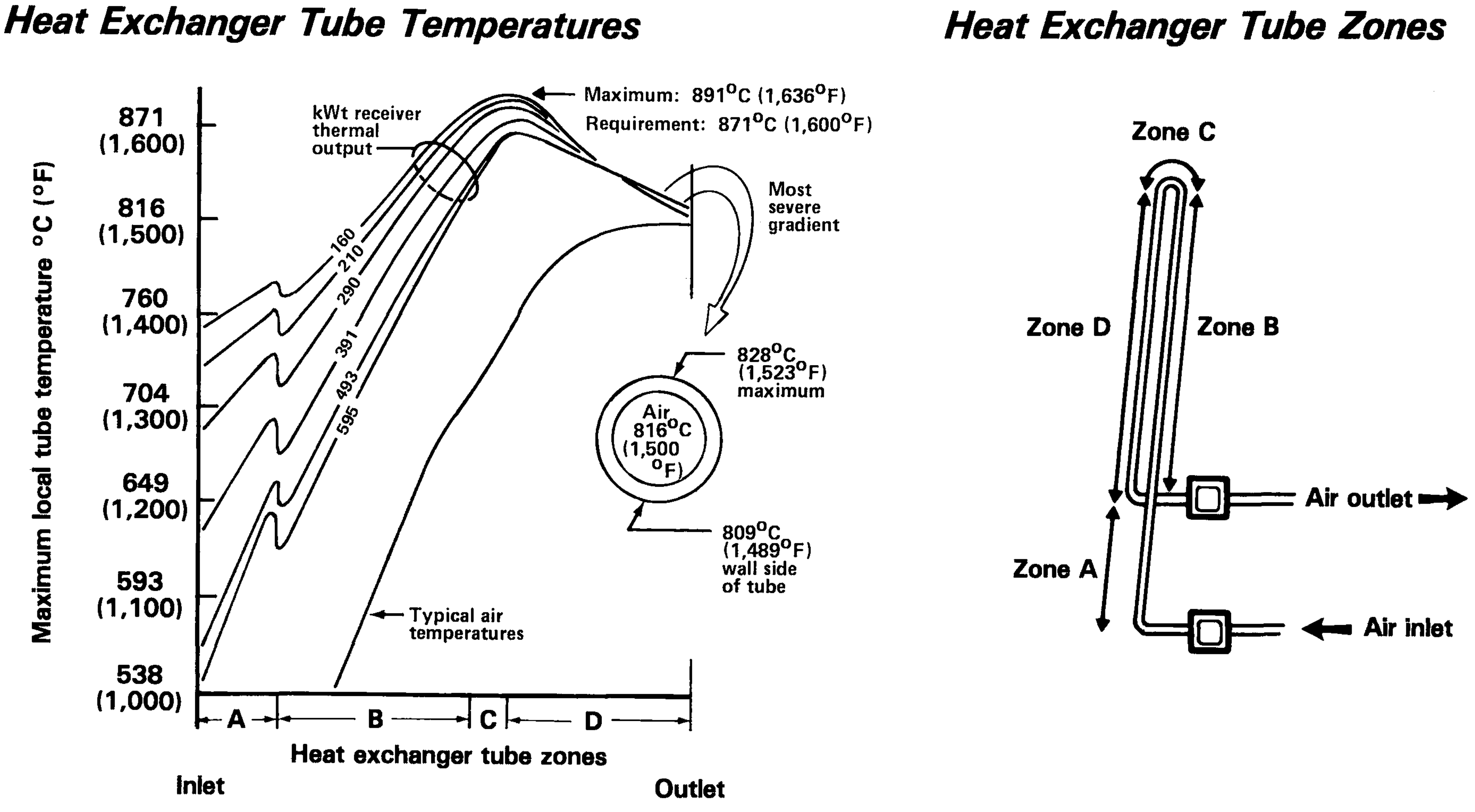
The receiver was designed with air-in-tube heat exchangers to deliver solar heat to the turbine-generator. A total of 186 parallel flow tubes, 12.7 mm (0.5 in) outside diameter and 3.86 m (12.6 ft) long, were configured into a u-bend shape as shown in Figure 15, and located along the cylindrical walls of the receiver. The tube pitch spacing ranged from 3.0 to 3.7 tube diameters. This spacing reduced tube thermal gradients by allowing radiated heat to pass between the tubes and heat the back surfaces.

The u-bend configuration with the inlet leg located behind the outlet was designed to match thermal environment gradients along the cavity wall. The point at which the tube exited the cavity (end of Zone D) was selected by comparing tube and cavity temperatures, wherein extending the return leg further into Zone A would cause internal airflow to be cooled rather than heated. The design of inlet and return legs also provided nearly equal thermal growth, minimizing tubing stresses.

Predicted tubing and typical air temperatures are shown on Figure 15 as functions of receiver thermal output and location along the tube. The maximum tube temperatures occurred on the side facing the cavity. The most severe cavity-side to wall-side tube gradient was 19°C (34°F) at the outlet end. A 160 or 210 kW_t receiver thermal output corresponds to startup. Tube temperatures will peak at 850°C (1636°F) during startup, and are expected to be considerably lower during most of the operating lifetime. The heat exchanger thermal analysis model used here defined 102 local tube temperatures. These were used in the detailed heat exchanger stress analysis.

The tube u-bend (Zone C) was protected by the backcone insulation wall. This enclosure reduced localized tube thermal gradients and stresses.

Figure 15. Heat Exchanger Tube Temperatures



Heat Exchanger Tube Temperatures

Heat Exchanger Tube Zones

Heat Exchanger Design Criteria

Design of the heat exchanger components was based on a service life of 1,000 hours at peak operating temperatures. The peak predicted heat exchanger tubing temperature was 891°C (1636°F). Other component temperatures ranged down to the receiver inlet air temperature. In addition to the structural load conditions given in Figure 13, these component temperatures were used to analyze heat exchanger stresses and deflections. Heat exchanger tubing, headers, and connector pipes were required to have a design limit operating pressure capability of 0.28 MPa (41 psi).

Material Stress Allowables

Structural integrity of heat exchanger components was assured by using analysis procedures and allowable stresses given in the ANSI B31.1 Power Piping Code (Figure 16) and from vendor furnished data. The governing stress allowable was stress rupture.

Stress Analysis Results

Analysis of the heat-exchanger tubing was performed using separate ANSYS finite element computer models for typical heat exchanger tubes located at the top, side and bottom of the cavity. The 595 kW_t receiver output condition was used because it had the highest tubing temperature gradients. The side panel location exhibited the highest stresses. Margins-of-safety based on the temperature-dependent allowable stresses are shown in Figure 16 for the side panel location.

The governing 1,000 hour service condition was pressure + gravity which resulted in an ample minimum margin-of-safety of +0.3 in the side panel location. This margin lowered slightly to +0.2 for the combined pressure + gravity + seismic condition. Thermal stress conditions due to cyclic heating and cooling did not govern the heat exchanger tubing design.

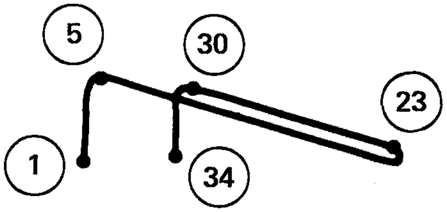
Figure 16. Heat Exchanger Structural Analysis

Material Stress Allowables

ANSI B31.1 Power piping allowables per:
- ASME boiler code
  - Section VIII division 1 - Pressure vessels
  - Appendix P, paragraph P-1

At temperatures in the creep range the maximum allowable stress value for all materials shall not exceed the lowest of the following:

FSE Design 1,000 hour life	Maximum allowable stress for Inconel 617 at 871°C (1,600°F) MPa (lbs/in^2)
100% of average stress for total creep = 1%	36.7 (5,200)
67% of the average stress for rupture at the end of 1,000 hours	42.3 (6,000)
80% of the minimum stress for rupture at the end of 1,000 hours	36.0 (5,100)



Stress Analysis Results

		Load condition											
		Pressure + gravity			Pressure + gravity + earthquake			Thermal expansion			Combined pressure + gravity + thermal		
Grid location	Temp °C (°F)	Max. stress MPa (psi)	Allowable stress MPa (psi)	Margin of safety	Max. stress MPa (psi)	Allowable stress MPa (psi)	Margin of safety	Max. stress MPa (psi)	Allowable stress MPa (psi)	Margin of safety	Max. stress MPa (psi)	Allowable stress MPa (psi)	Margin of safety
①	262 (504)	22.1 (3,129)	169.4 (24,000)	6.7	30.5 (4,316)	146.8 (20,800)	5.7	31.2 (4,421)	273.9 (38,815)	7.8	39.1 (5,534)	443.3 (62,815)	10.4
⑤	567 (1,052)	21.5 (3,040)	147.5 (20,900)	5.9	29.1 (4,130)	177.0 (25,080)	5.1	19.9 (2,819)	268.4 (38,035)	12.5	18.4 (2,608)	415.9 (58,935)	21.6
㉓	844 (1,552)	10.5 (1,490)	45.9 (6,500)	3.4	14.1 (1,996)	55.0 (7,800)	2.9	19.8 (2,805)	243.0 (34,435)	11.3	20.4 (2,884)	288.9 (40,935)	13.2
㉚	808 (1,487)	39.6 (5,614)	59.3 (8,400)	0.5	54.0 (7,653)	71.1 (10,080)	0.3	78.7 (11,149)	246.4 (34,910)	2.1	77.0 (10,909)	309.6 (43,310)	3.0
㉞	817 (1,503)	42.4 (6,005)	55.8 (7,900)	0.3	55.7 (7,896)	66.9 (9,480)	0.2	69.4 (9,831)	245.5 (34,785)	2.5	76.9 (10,896)	301.2 (42,685)	2.9

7. Electric Power Generation

The power generation system design was based on a commercially-available turbine – generator set marketed by Alturdyne of San Diego, CA., shown in Figure 17. The 480 volt, 60 Hz, 3600 rpm generator will be driven through a reduction gearbox by a Solar Turbines Inc. Titan T-62T-32 gas turbine. The package incorporated all necessary lubrication, fuel, control and electrical systems within a weatherproof, skid-mounted enclosure. Combustion air will be admitted to the turbine through a filter mounted on the roof of the enclosure.

The turbine nominal design point characteristics are: (1) Output Power 90 kWe, sea level, 26.7°C (80°F); (2) Air Flow 0.91 kg/sec (2.0 lb/ s); (3) Pressure Ratio 4:1; (4) Speed 61,000 rpm; (5) Turbine Inlet Gas Temperature 882°C (1620°F). Design modifications for conversion to the FSE application included an external can combustor, fuel and safety system changes.

Trim Combustor

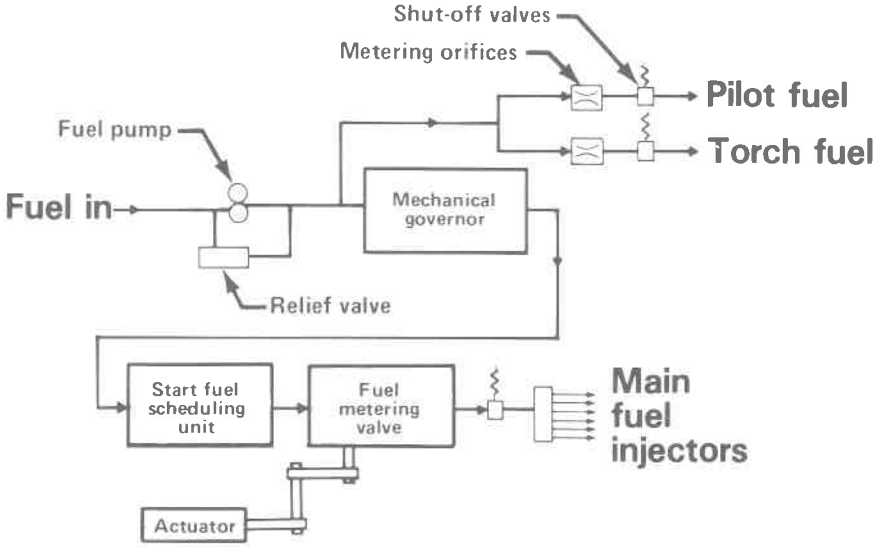
The JP-4 fueled trim combustor was the result of the EPRI RP1270-1 development program. The 15 cm (5.9 in) diameter can combustor incorporated a two-stage, air-blast fuel injection system and was tested at Titan turbine conditions. The combustor was capable of operating over a 10:1 airflow turndown range at outlet gas temperatures up to 1278°C (2300°F). A constant pilot fuel flow of 2.7 kg/hr (6 lb/hr) was required to maintain combustion. JP-4 was selected for low emissions.

Fuel System

The modified fuel system design retained some components of the standard fuel control system: the high-and low-pressure pumps, start fuel scheduling unit, and mechanical flyball governor. The standard main fuel metering valve will be modified to accommodate the increased range of fuel turn-down. Additional high-pressure fuel feeds will be added to the combustor torch ignitor and pilot injector through solenoid shut-off valves and metering orifices.

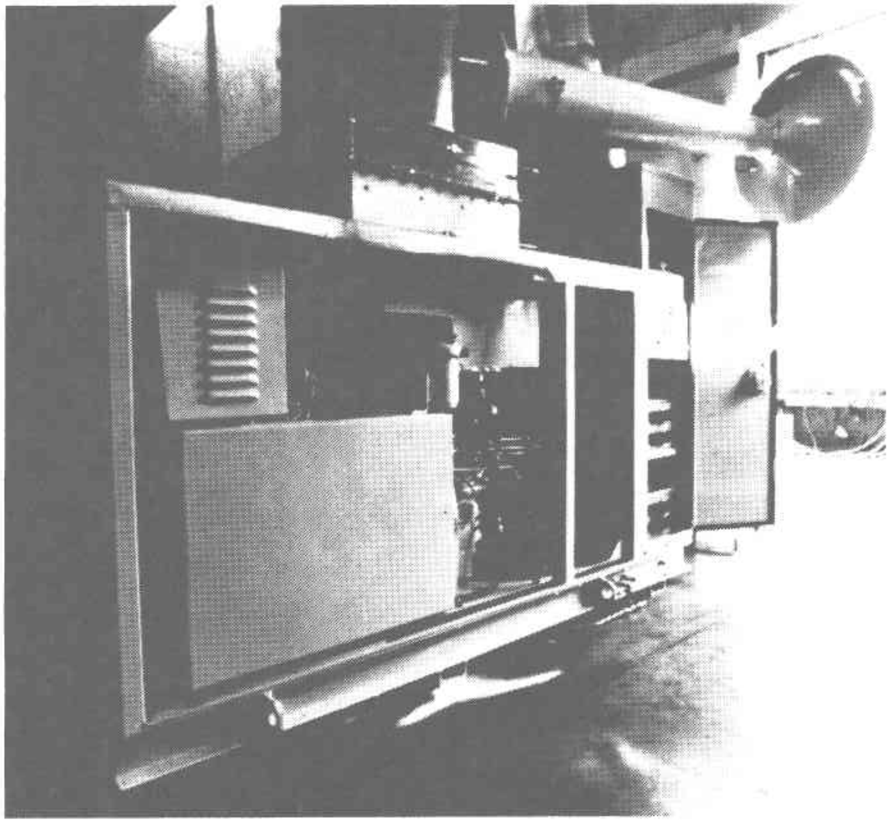
Figure 17. Alturdyne Turbine—Generator

Modified Fuel System Schematic



- Retain mechanical governor as backup
- Modify fuel metering valve
- Constant fuel flow to torch and pilot

Unit in Test Cell



Flow Ducting Modifications

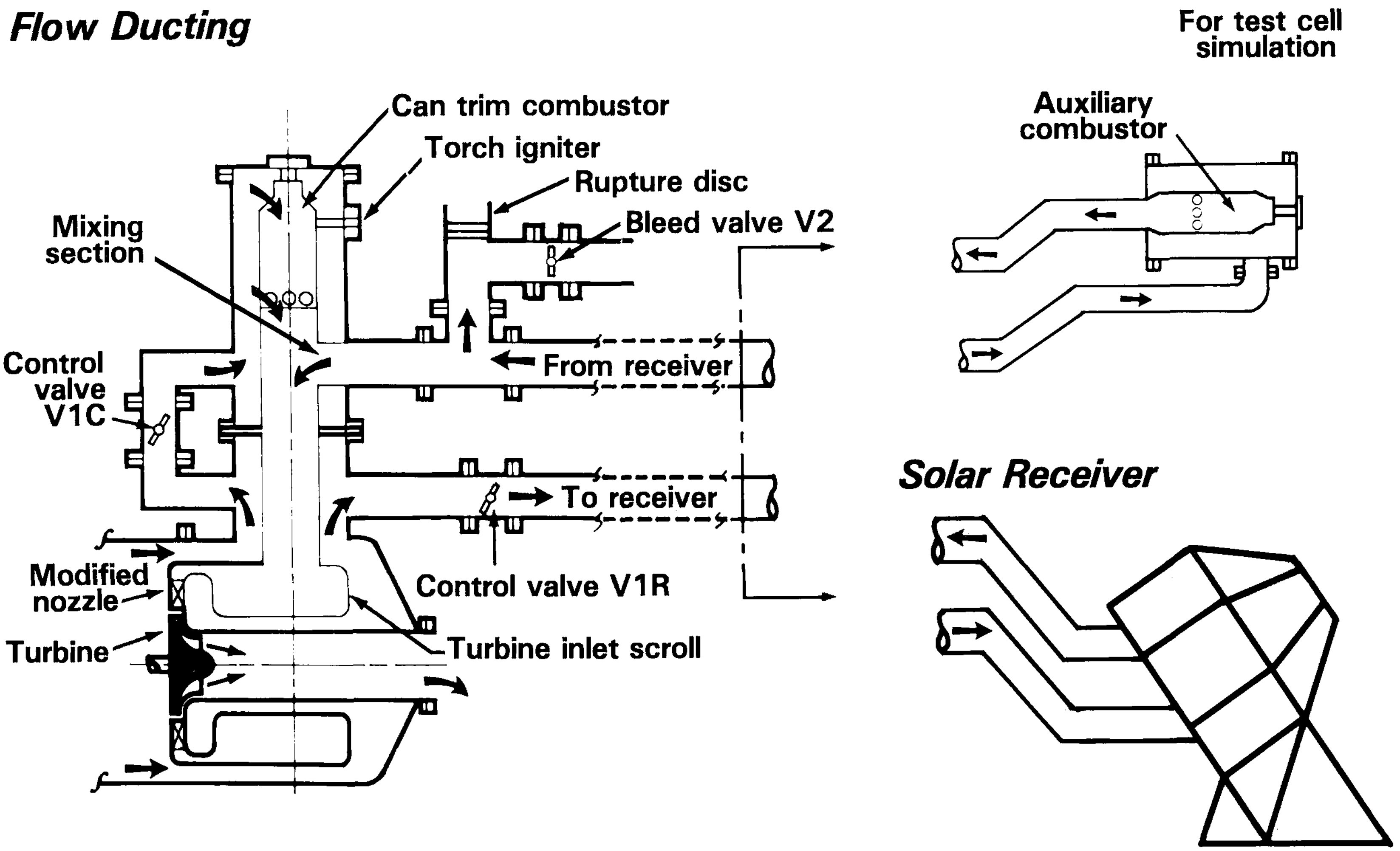
The turbine ducting modifications were designed to provide dual air flow paths to the combustor and to the solar receiver. Key features of the flow ducting and hardware modifications were: (1) Modified Turbine Nozzle -enlarged nozzle throats to obtain adequate surge margin at the higher hot-side pressure losses imposed by the solar receiver; (2) Mixing Section -a Tee mixing duct where the combustor exhaust combined with the solar receiver outlet flow; (3) Turbine Inlet Duct -a scroll duct that directed the mixed combustor/receiver flow into the turbine nozzle; (4) Flow Valves -pneumatically-actuated trunnion valves to control the air flow split between the combustor (V1C) and receiver (V1R); (5) Bleed Valve (V2) -a hydraulic-actuated fast acting trunnion valve used to bleed excess thermal energy from the turbine during off-load transients, and (6) Rupture Disc -an explosively-activated disc triggered by an emergency engine overspeed condition. The modified flow system is shown in Figure 18.

Testing and evaluation of the modified flow ducting and combustor prior to shipment to the solar test facility will be conducted at Solar Turbines Inc. and will involve the use of an auxiliary combustor to simulate the thermal output of the solar receiver. This will permit test cell operation, in the automatic control mode, with all elements of the power conversion system in place. The connections were designed to be interchangeable with either the solar receiver for mating at the solar test facility or the auxiliary combustor at Solar Turbines Inc.

Fire Safety Systems

The use of JP-4 as the fossil fuel required incorporation of fire safety systems to reduce the hazard to the experiment and facility. Two separate, interconnected safety systems were incorporated for fire prevention and suppression. A centrifugal blower external to the enclosure was selected for continuous operation to purge through vents in the package floor. A halon flood system was included in the event of a fire in the enclosure

Figure 18. Gas Turbine Modifications



8. Power Conversion Efficiency

The system efficiency train for operation in both solar-hybrid and solar-only modes is illustrated in Figure 19. Typical ambient conditions of 15.6°C (60°F) temperature and 1751 m (5746 ft.) altitude are assumed. The graph begins with the thermal power delivered into the receiver.

The system efficiency was dictated largely by the selection of the Solar Titan turbine. This small turbine has a low, 4 atmosphere, operating pressure and high, 621°C (1150°F) exhaust temperature. Receiver thermal conversion efficiency is directly proportional to both the inlet air pressure and the percentage of pressure lost due to flow resistance. Combustion turbines in common utility usage typically have operating pressures of 8 atmospheres. In this case a much higher receiver efficiency could be achieved.

The FSE receiver design point is a 10 percent pressure loss during cold day (-7°C) solar-only operation. A higher receiver thermal conversion efficiency would be possible if the pressure loss was on the order of 17 to 20 percent as demonstrated in tests of the Bench Model Receiver (RP377).

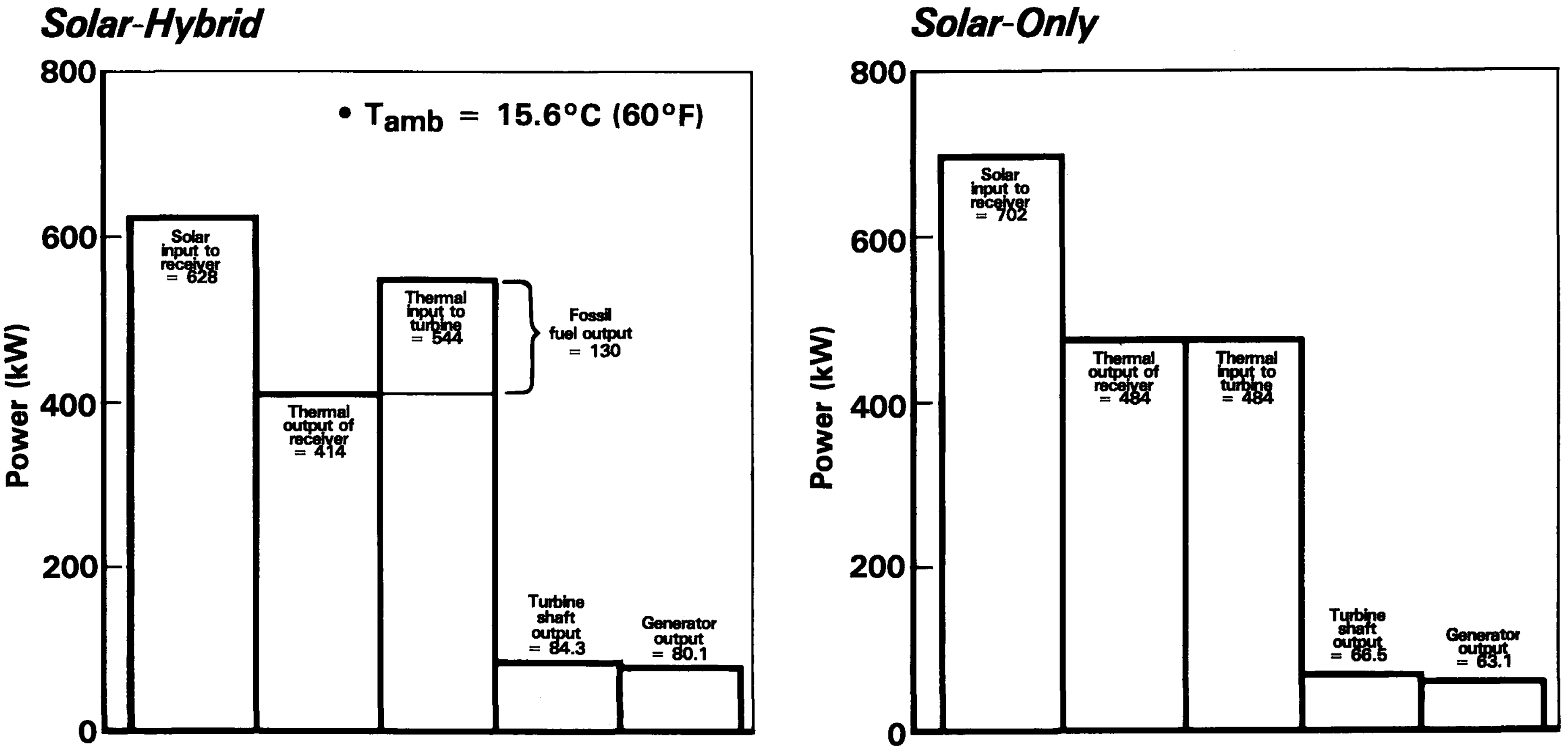
Solar-Hybrid Operation

A 12.7 percent thermal-to-electric conversion efficiency is predicted for testing in the solar-hybrid mode. The high turbine exhaust gas temperature, 621°C (1150°F), would make a combined cycle attractive, although not planned for this program. Efficiencies from 15 to 17 percent could be expected with a steam bottoming cycle.

Solar-Only Operation

Solar receiver conversion efficiency will be higher in this operating mode because nearly the entire airflow is directed through the receiver and the system is operated at a higher pressure loss. The thermal-to-electric conversion efficiency will be lower, 9 percent, because turbine inlet temperature and the resulting cycle efficiency are lower.

Figure 19. System Efficiency Train



Solar-Hybrid

- Turbine inlet temperature = 882°C (1620°F)
- Receiver efficiency = 66%
- Turbine cycle efficiency = 15.5%
- Generator efficiency = 95%

Solar-Only

- Turbine inlet temperature = 812°C (1493°F)
- Receiver efficiency = 68.9%
- Turbine cycle efficiency = 13.7%
- Generator efficiency = 95%

9. Control System

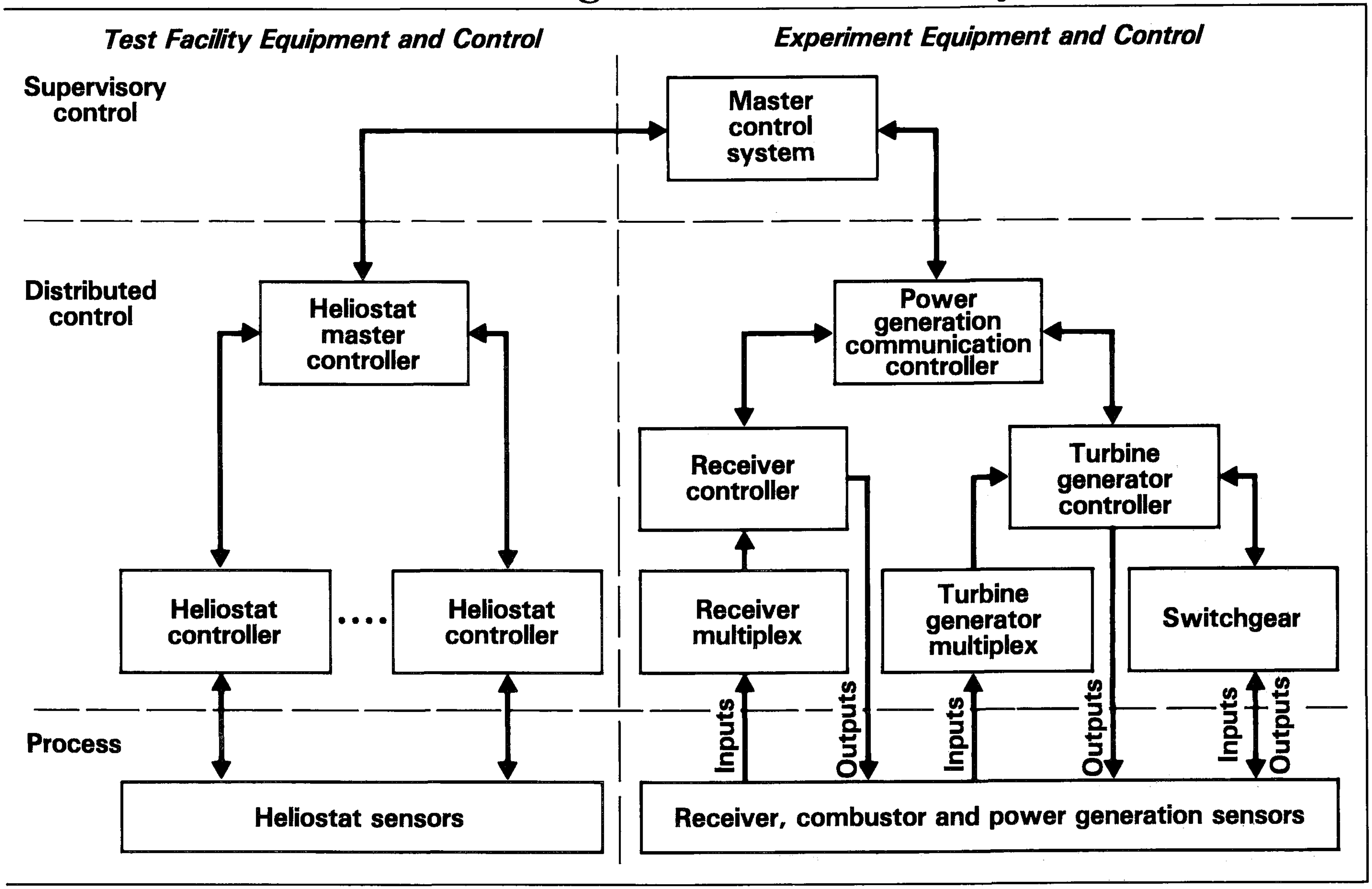
The Full System Experiment control system was designed to provide coordinated control and protection for the receiver, combustor, turbine-generator and the heliostat field.

The highest level in the FSE control system hierarchy was designed to be occupied by the Master Control System (MCS). Figure 20 describes the control hierarchy. The coordination of the various subsystems, i.e. supervisory control, will be provided by the MCS. The man-machine interface will be provided by the MCS. Major control functions of the MCS design include: 1) automatic sequencing during startup and shutdown: 2) automatic sequencing during mode changes upon an operator command; 3) automatic receiver heating control.

The number of heliostats on target will be controlled by a closed-loop algorithm residing in the MCS in either one of the two modes of heliostat control: constant solar or maximum solar.

The direct control of the experiment will be provided by a set of distributed controllers. These controllers were designed to receive their sequencing commands and set-points from the MCS and transmit equipment status to the MCS. Control and protection algorithms will reside in the distributed controllers. The controllers were selected to perform the following major control functions: 1) Heliostat Master Controller controls the sequence of heliostat application from a predefined test field; 2) Heliostat Controllers perform the tracking control functions; 3) Power Generation Communication Controller controls the information flow between MCS and the power generation system, 4) Receiver Controller controls the temperature of the eight receiver heat exchanger panels; 5) Turbine Controller controls the turbine speed and power and the switchgear sequencing according to the mode requested by the Master Control System.

Figure 20. Control System Hierarchy



Control Console

The console, Figure 21, was designed to house the master control electronic hardware and to provide the man-machine interface. Design requirements were: 1) operation of the experiment from a central location by a single operator; 2) operator command entry that was simple and unambiguous; 3) display and recording of adequate information; 4) operator training capability.

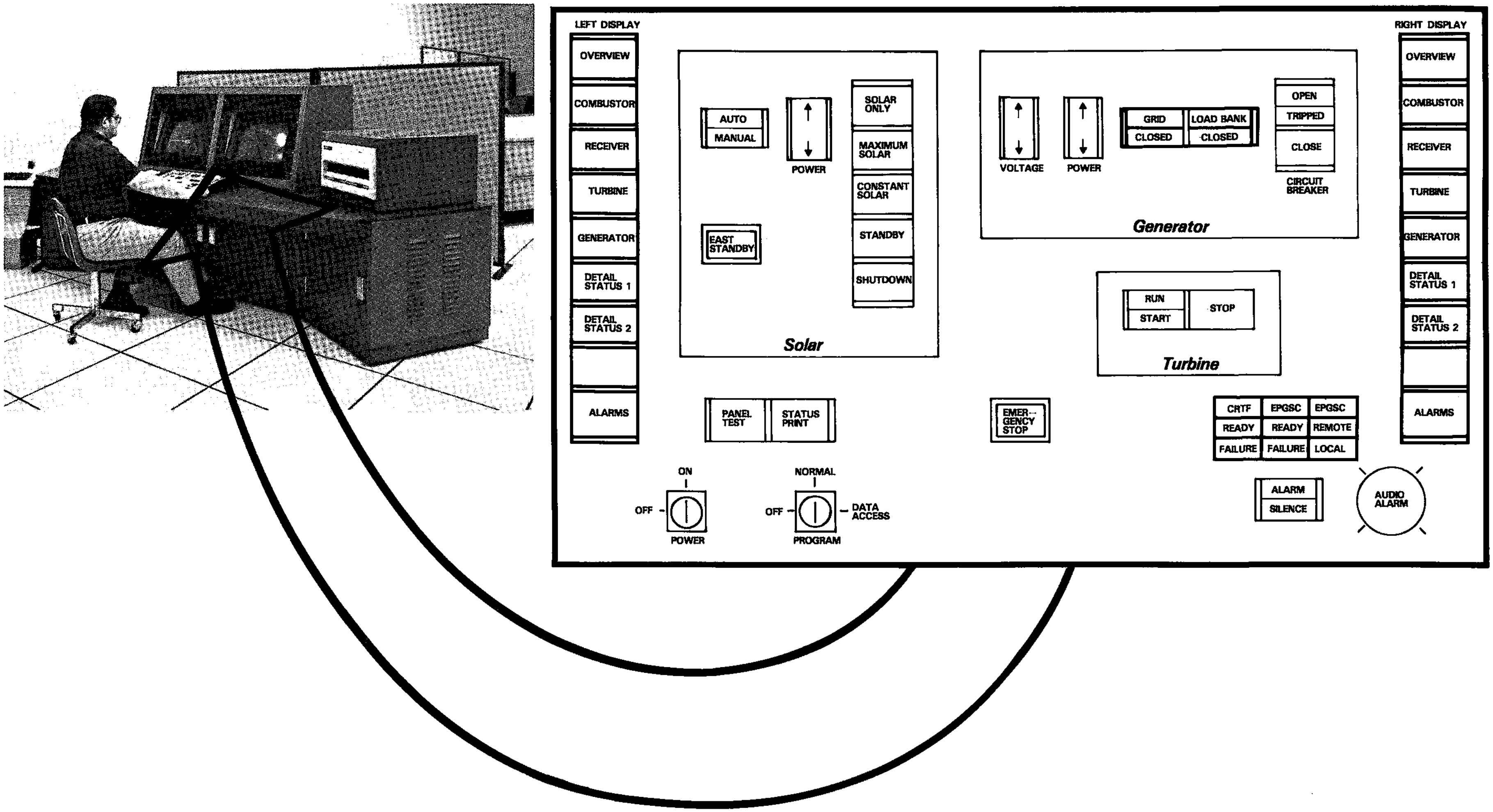
Major components of the console design were: 1) Digital Equipment Corporation, PDP 11/23 computer; 2) printing terminal, 180 characters per second; 3) dual 8" floppy disc drives; 4) two color cathode ray tubes; 5) control panel, custom designed with substantial input from the Utility Test and Operating group.

Control Panel

The control panel was designed to contain the functions required to operate the system. This included switches, audio alarm and signal lights. The switches and signal lights were grouped and labeled to minimize operator error. The signal light group was located in the lower right-hand corner of the panel. The CRTF and EPGSC Ready/Failure indicators refer to the respective communication channels with the test facility and power generation controllers.

The switches were designed for backlighting, providing both switching and indicating functions. The switch lights were controlled by the software, independently of the switch position, thus indicating the status of the controlled equipment and not the status of the switch. The setpoint rocker switches in "Solar" and "Generator" groupings were designed to move setpoints up or down. Prevention of dangerous conditions, or switch interlocking, was designed in the control software.

Figure 21. Master Control Hardware


Master Control Console

Control Panel

Operator Displays

Two color cathode ray tubes were selected for displaying measurements and status of system processes to the operator. The displays, called pages, were grouped by functions. A page will contain information that can be displayed on a single cathode ray tube as illustrated by Figure 22. High information content is displayed in a small area. Graphics and colors were used in the design of displays so that the operator can quickly find the desired information. The Utility Test & Operating Group was instrumental in evaluating and reviewing information displays.

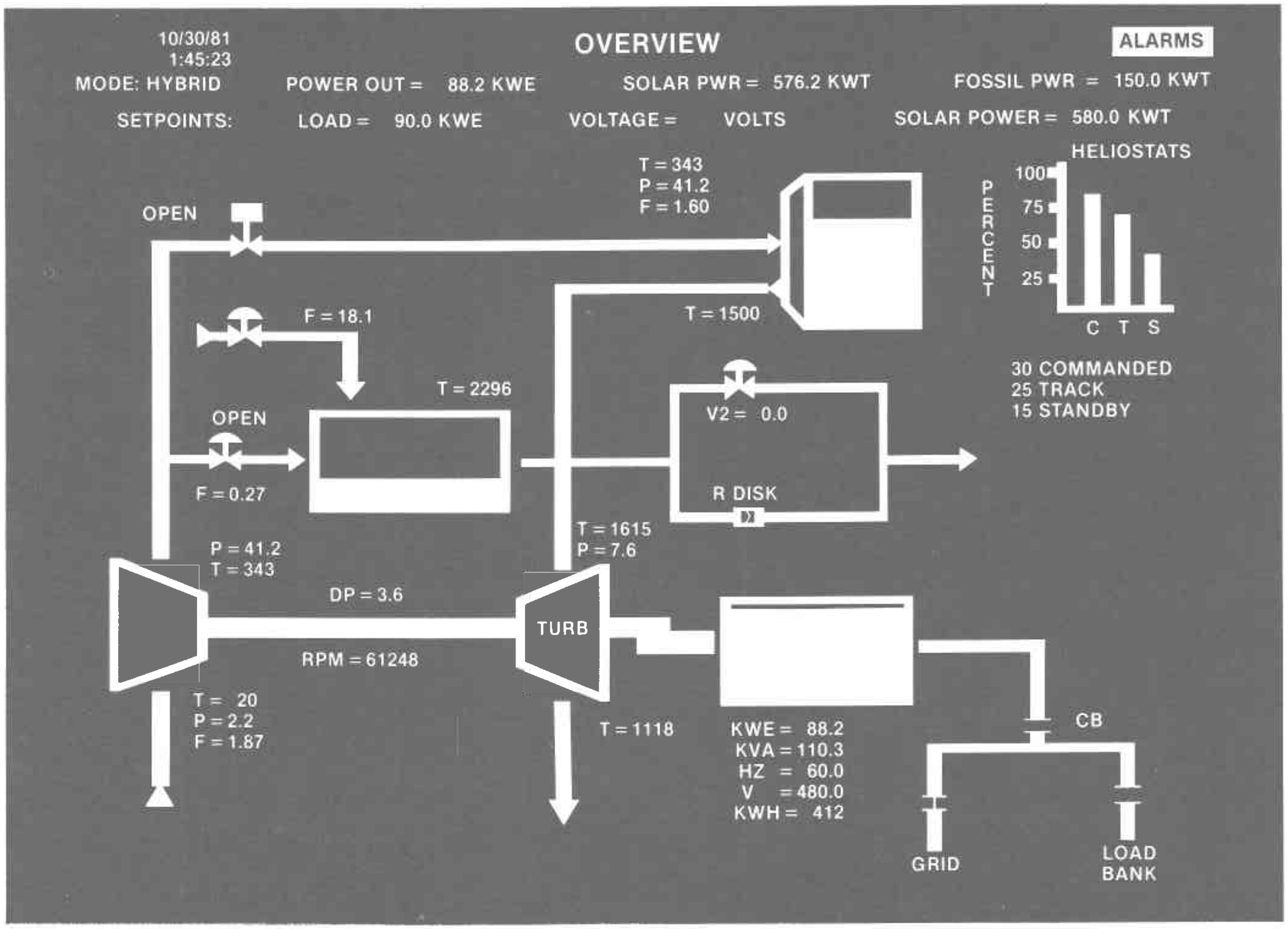
The header at the top of the page contains key information on: time, alarm indication (flashing for a new alarm and steady for an active acknowledged alarm), operating mode status, power production rates, and load setpoints. The header will be repeated on each display page. Other information displayed on the screen relates to the functions currently displayed.

Eight pages of displays were designed. Five are graphical representations of system functions. Three are for tabular data. The graphical displays are: (1) Overview (Figure 22) -will provide the operator with the most important measured and computed variables describing the system. The color scheme used in the overview will be used on all graphics. The generator, combustor and receiver are represented by color blocks which will display a color fill level proportional to produced power; (2) Combustor; (3) Receiver (Figure 23); (4) Turbine (Figure 23); and (5) Generator displays are of the applicable section of the overview and show similar information.

The tabular displays available to the operator are: (1) Detail Status 1 (Figure 24) -will summarize the most important measurements and setpoints; (2) Detail Status 2 will summarize the status of the two-state devices or logical derived variables; (3) Alarms (Figure 24) -will summarize all active alarms, including time of initial detection.

Figure 22. Operator Displays

Overview



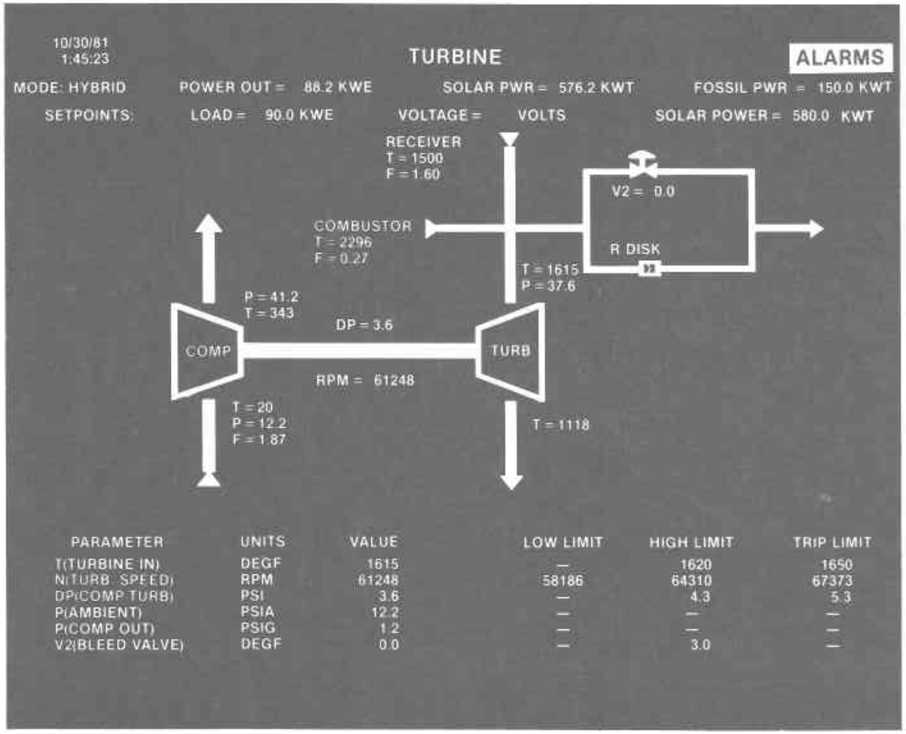
10/30/81
1:45:23

OVERVIEW

MODE: HYBRID
POWER OUT = 88.2 KWE
SOLAR PWR = 576.2 KWT
FOSSIL PWR = 150.0 KWT
SETPOINTS:
LOAD = 90.0 KWE
VOLTAGE = VOLTS
SOLAR POWER = 580.0 KWT

Figure 23. Operator Displays

Turbine



10/30/81
1:45:23

TURBINE

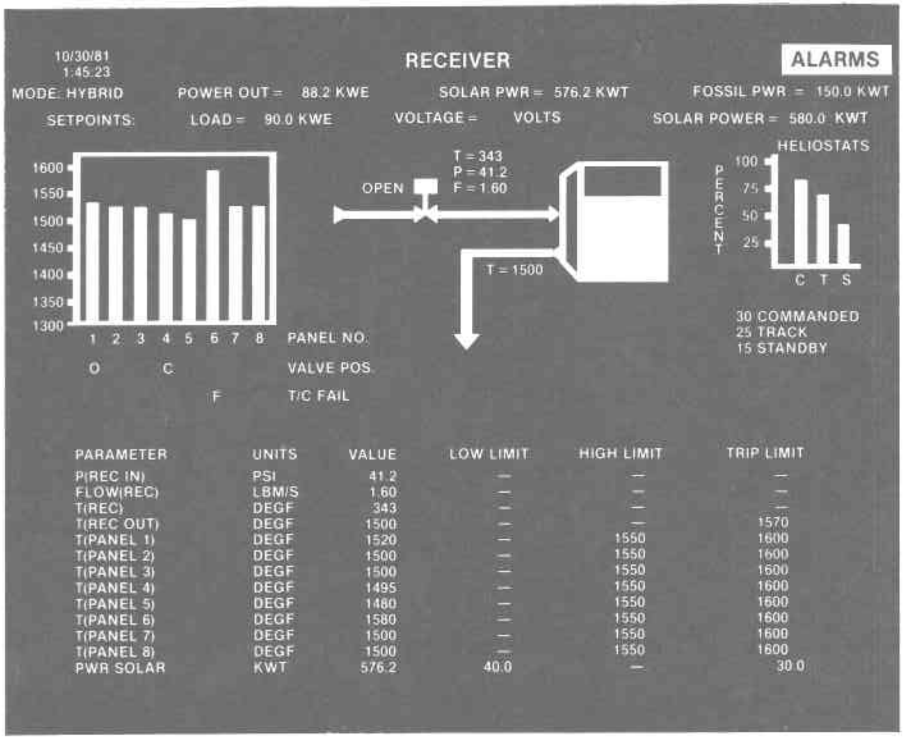
ALARMS

MODE: HYBRID POWER OUT = 88.2 KWE SOLAR PWR = 576.2 KWT FOSSIL PWR = 150.0 KWT

SETPOINTS: LOAD = 90.0 KWE VOLTAGE = VOLTS SOLAR POWER = 580.0 KWT

PARAMETER	UNITS	VALUE	LOW LIMIT	HIGH LIMIT	TRIP LIMIT
T(TURBINE IN)	DEGF	1615	—	1620	1650
N(TURB. SPEED)	RPM	61248	58186	64310	67373
DP(COMP TURB)	PSI	3.6	—	4.3	5.3
P(AMBIENT)	PSIA	12.2	—	—	—
P(COMP OUT)	PSIG	1.2	—	—	—
V2(BLEED VALVE)	DEGF	0.0	—	3.0	—

Receiver



10/30/81
1:45:23

RECEIVER

ALARMS

MODE: HYBRID POWER OUT = 88.2 KWE SOLAR PWR = 576.2 KWT FOSSIL PWR = 150.0 KWT

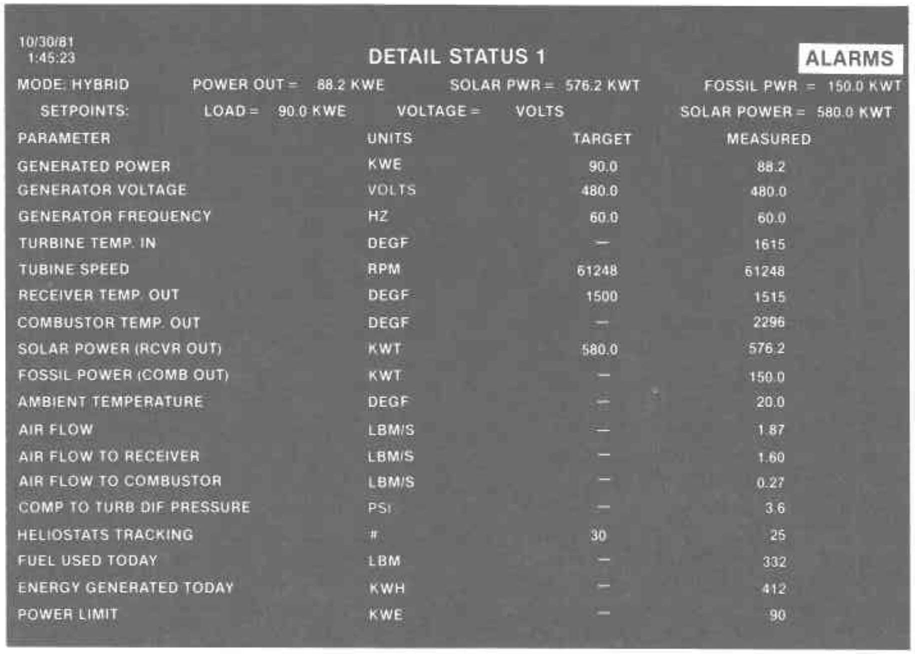
SETPOINTS: LOAD = 90.0 KWE VOLTAGE = VOLTS SOLAR POWER = 580.0 KWT

30 COMMANDED
25 TRACK
15 STANDBY

PARAMETER	UNITS	VALUE	LOW LIMIT	HIGH LIMIT	TRIP LIMIT
P(REC IN)	PSI	41.2	—	—	—
FLOW(REC)	LBM/S	1.60	—	—	—
T(REC)	DEGF	343	—	—	—
T(REC OUT)	DEGF	1500	—	—	1570
T(PANEL 1)	DEGF	1520	—	1550	1600
T(PANEL 2)	DEGF	1500	—	1550	1600
T(PANEL 3)	DEGF	1500	—	1550	1600
T(PANEL 4)	DEGF	1495	—	1550	1600
T(PANEL 5)	DEGF	1480	—	1550	1600
T(PANEL 6)	DEGF	1580	—	1550	1600
T(PANEL 7)	DEGF	1500	—	1550	1600
T(PANEL 8)	DEGF	1500	—	1550	1600
PWR SOLAR	KWT	576.2	40.0	—	30.0

Figure 24. Operator Displays

Detail Status 1



```
10/30/81
 1:45:23                         DETAIL STATUS 1                              ALARMS
MODE: HYBRID      POWER OUT =  88.2 KWE      SOLAR PWR =  576.2 KWT      FOSSIL PWR =  150.0 KWT
  SETPOINTS:        LOAD =   90.0 KWE      VOLTAGE =      VOLTS       SOLAR POWER =  580.0 KWT
PARAMETER                       UNITS                 TARGET          MEASURED
GENERATED POWER                 KWE                    90.0             88.2
GENERATOR VOLTAGE               VOLTS                 480.0            480.0
GENERATOR FREQUENCY             HZ                     60.0             60.0
TURBINE TEMP. IN                DEGF                    —               1615
TUBINE SPEED                    RPM                   61248            61248
RECEIVER TEMP. OUT              DEGF                   1500             1515
COMBUSTOR TEMP. OUT             DEGF                    —               2296
SOLAR POWER (RCVR OUT)          KWT                   580.0            576.2
FOSSIL POWER (COMB OUT)         KWT                     —              150.0
AMBIENT TEMPERATURE             DEGF                    —               20.0
AIR FLOW                        LBM/S                   —               1.87
AIR FLOW TO RECEIVER            LBM/S                   —               1.60
AIR FLOW TO COMBUSTOR           LBM/S                   —               0.27
COMP TO TURB DIF PRESSURE       PSI                     —                3.6
HELIOSTATS TRACKING             #                      30                 25
FUEL USED TODAY                 LBM                     —                332
ENERGY GENERATED TODAY          KWH                     —                412
POWER LIMIT                     KWE                     —                 90
```

Alarms

```
   10/30/81
    1:45:23                          ALARMS                                   ALARMS
MODE: HYBRID     POWER OUT =   88.2 KWE      SOLAR PWR =  576.2 KWT      FOSSIL PWR =  150.0 KWT
  SETPOINTS:       LOAD =   90.0 KWE      VOLTAGE =      VOLTS       SOLAR POWER =  580.0  KWT


                    TIME        DESCRIPTION
                     830        DAY TANK LEVEL LOW
                    1145        PANEL 6 THERMOCOUPLE FAILED
                    1308        PANEL 6 TEMP. OVER HIGH LIMIT
```

Power Generation Control Functions

Data acquisition and control functions of the electric power generation system will be provided by the power generation controller. The data acquired will be of two general types: measurement of analog variables; and determination of the state of discrete variables.

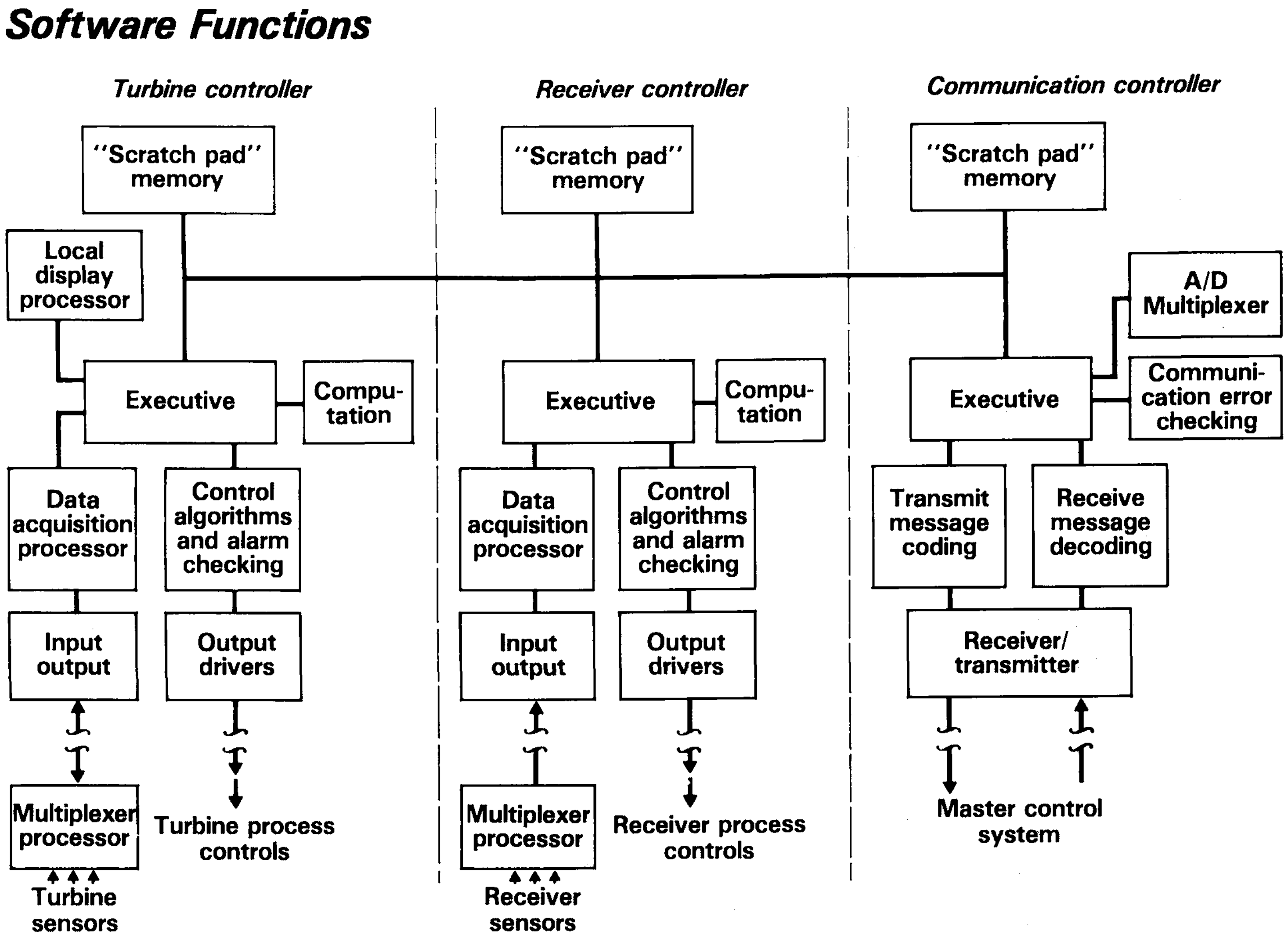
The power generation controller was designed to acquire commands and setpoints from the Master Control System, and perform turbine and receiver startup, generator load switching and receiver and turbine shutdown sequencing as commanded by the Master Control System. The controller will also stop the system when a critical fault is detected. Closed-loop controls implemented in the power generation controller are: temperature control of each of the receiver heat exchanger panels; turbine speed control; turbine fuel control. The power generation controller was assigned the responsibility for communication control with the MCS, thus enabling the controller to execute a safe shutdown in case of communication failure.

The power generation control was designed with three micro-computer "controllers" that will work in unison, and each will be responsible for one major group of control functions. The three controllers and their respective software modules are shown in Figure 25.

Hardware Configuration

The power generation control electronics were designed for packaging in two cabinets. The data acquisition input/output unit (shown in Figure 6) will be installed at the 49m (160 ft.) level of the tower. The control unit will be installed at the 30m (100 ft.) level. This unit will contain the three controllers communicating with each other via dedicated interfaces with information temporarily stored in memory locations called "scratch pads". A local control panel, at the 30m level, was designed for use in initial check-out and troubleshooting while in fossil-only operation.

Figure 25. Power Generation Controller



Simulation Capability

The capability to simulate some of the major system processes was designed into the Master Control System. The simulator design was governed by these requirements: 1) process dynamics were simplified to a level enabling real time operation; 2) process dynamics with time constants of less than one second were assumed to act instantaneously; 3) processes not affecting Master Control operation were not modelled; 4) provide simulated process element failures and force the model into abnormal conditions; 5) maximize incorporation of Master Control operational software. The simulator will provide the following: 1) checkout of Master Control operational software; 2) low-cost and low-risk operator training; 3) a means to familiarize utility personnel with system operation; 4) a portable demonstration unit.

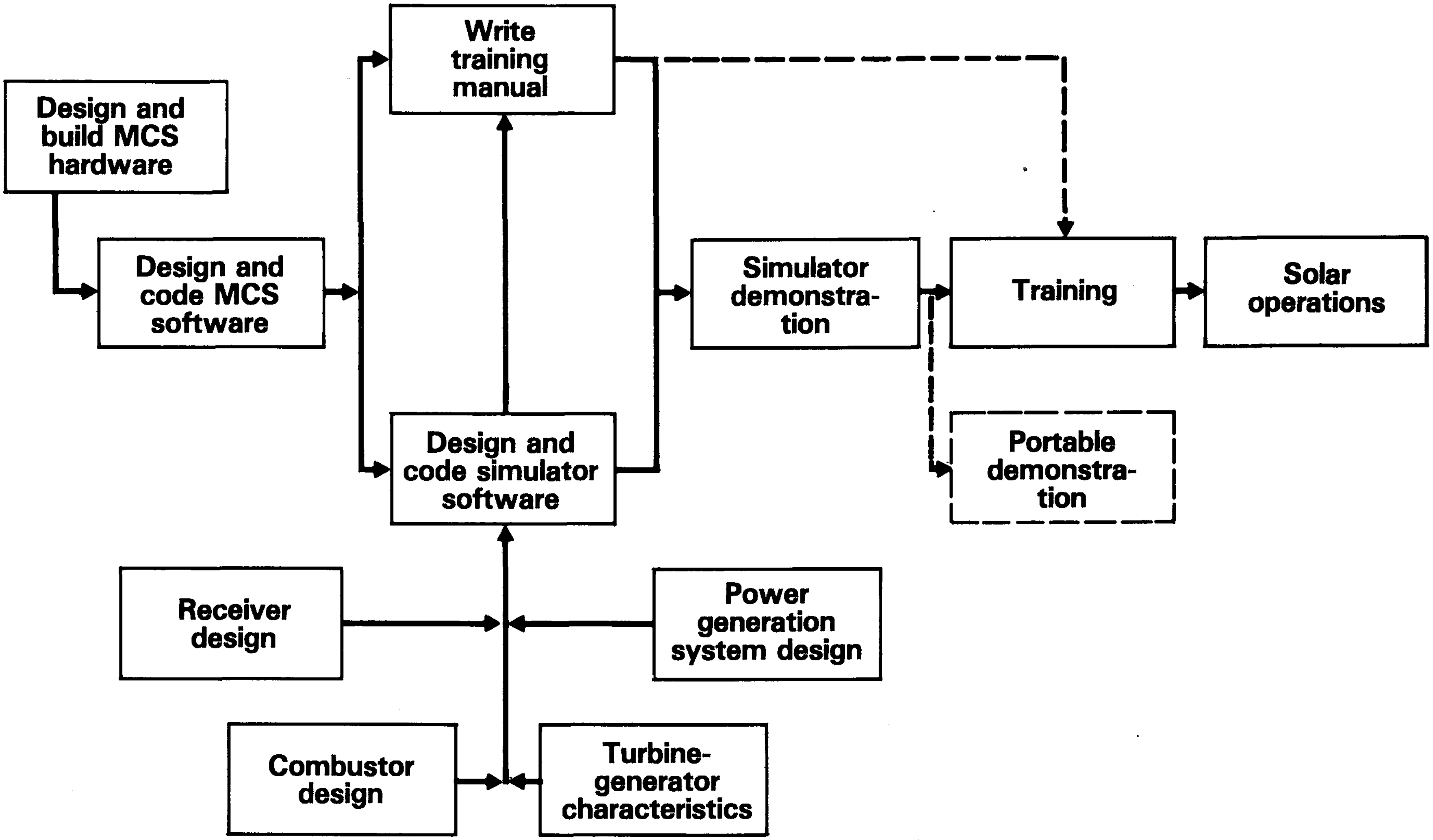
Simulation Hardware and Software

The simulation models and simulation software will reside entirely within the MCS control hardware. The communication links to the heliostat master controller and to the power generation controller will be inactive during simulation.

Operator Training

A major advantage of the simulator is that it will enable operator training and system familiarization before operating the experiment. Normal training will require an instructor and one trainee. The instructor will create various daily profiles of insolation and ambient temperatures. Cloud fronts and maximum number of heliostats may also be included. Once the trainee is familiar with the console and normal operation, then the instructor can proceed to create abnormal events requiring a decision by the operator. A typical operating day can be simulated in approximately two hours. A flow diagram of the activities leading to the introduction, training, and ultimately to system operation, by utility personnel is shown in Figure 26.

Figure 26. Operator Training Plan



10. Subsystem—System Checkout

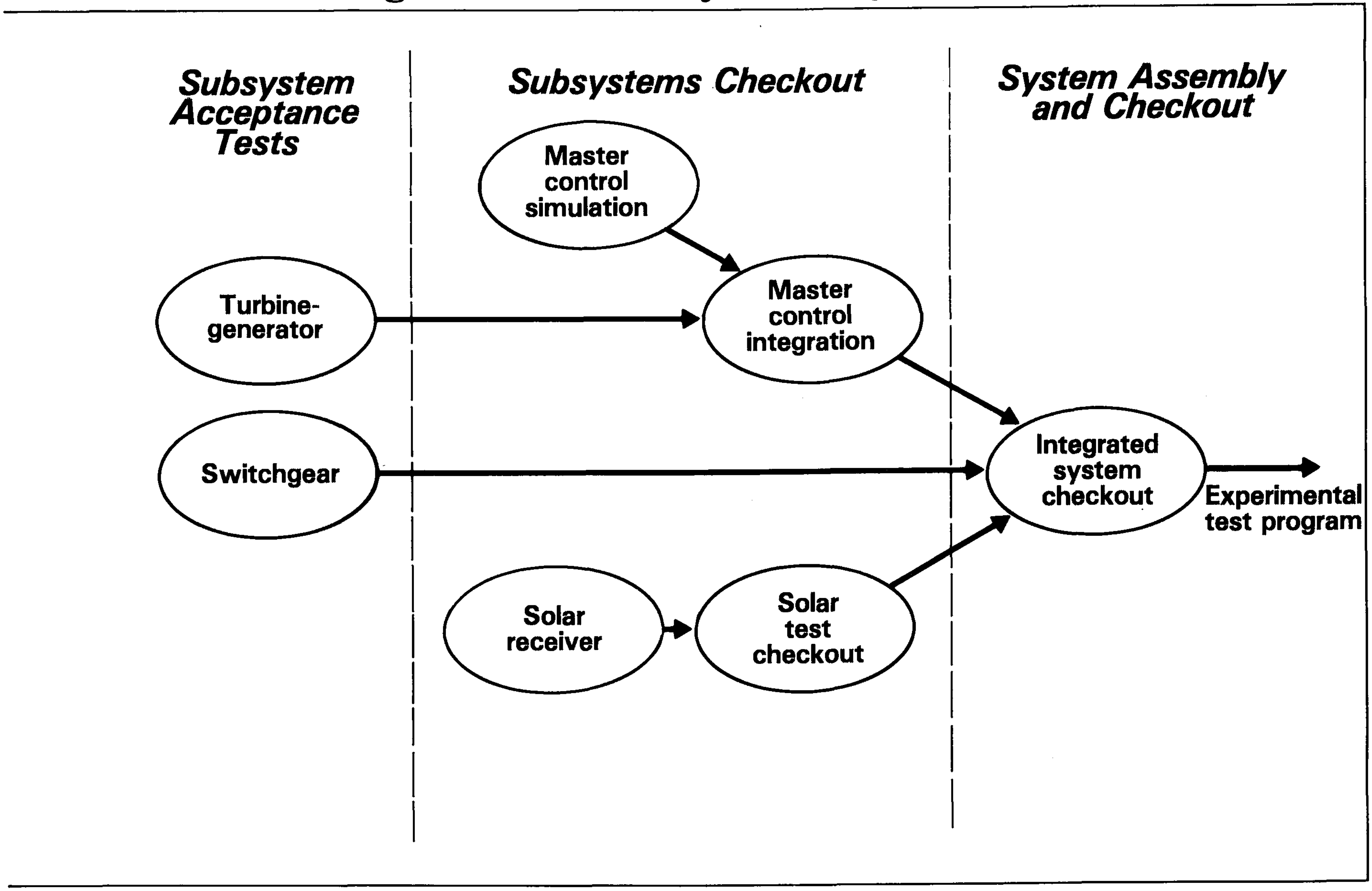
A subsystem -system checkout procedure was adopted for the Full System Experiment in order to establish confidence and gain experience in a step-by-step manner. This approach is expected to minimize problems and produce a high degree of success in the solar tests that follow. Figure 27 illustrates major checkout events.

Checkout begins with the hardware procurements. These are acceptance tested to pre-established performance requirements, then integrated into the next higher level of subsystem. Two examples are the turbine-generator and the switchgear.

Subsystem checkout of the control system is accomplished by means of the system simulator, which also serves as a training device. This approach will permit evaluation of system process software with the opportunity for early detection of problems and corrective action. The next step will integrate the Master Control System with the power generation controller and perform fossil-fuel cell tests at Solar Turbines, Inc. The solar receiver will be simulated with an auxiliary combustor, thereby all elements of the FSE will be represented, excepting the heliostats (see Figure 18).

The solar receiver will be checked-out initially by verifying instrumentation and by leak testing of the heat transport system. Upon completion, the receiver will be installed on the test tower and a series of tests will be run to checkout the heliostat field/receiver interface, adjust and verify heat exchanger panel flow distribution and check the test readiness of this subsystem. The receiver tests will start without solar power and as confidence is gained, increasing levels of solar energy will be applied. After receiver tests are completed, the entire system will be assembled on the test tower and the control system integrated and checked-out. A series of fossil-fuel tests will follow, and finally the heliostats will be used for solar-hybrid operation. At this point the system will be ready for the experimental test program.

Figure 27. Subsystem-System Checkout Logic



11. Full System Experiment Test Planning

A preliminary test plan was developed during Phase I as a conceptual framework for Phase II detailed test planning. The left hand chart of Figure 28 shows the scope of test planning activity for the program.

The test planning effort outlined for Phase II- includes the testing of each major subsystem and component which comprise the Full System Experiment to assure proper functioning of each, prior to system assembly and testing.

Phase III testing was defined in three parts: 1) a checkout and verification phase to demonstrate the safe operation of the assembled system; 2) an experimental phase to learn about the characteristics of the system and to validate the design and performance models; and 3) an operational phase which directly involves utility personnel in system operation.

In addition, preliminary test planning defined system instrumentation and a plan for data acquisition and reduction.

Test Plan Development

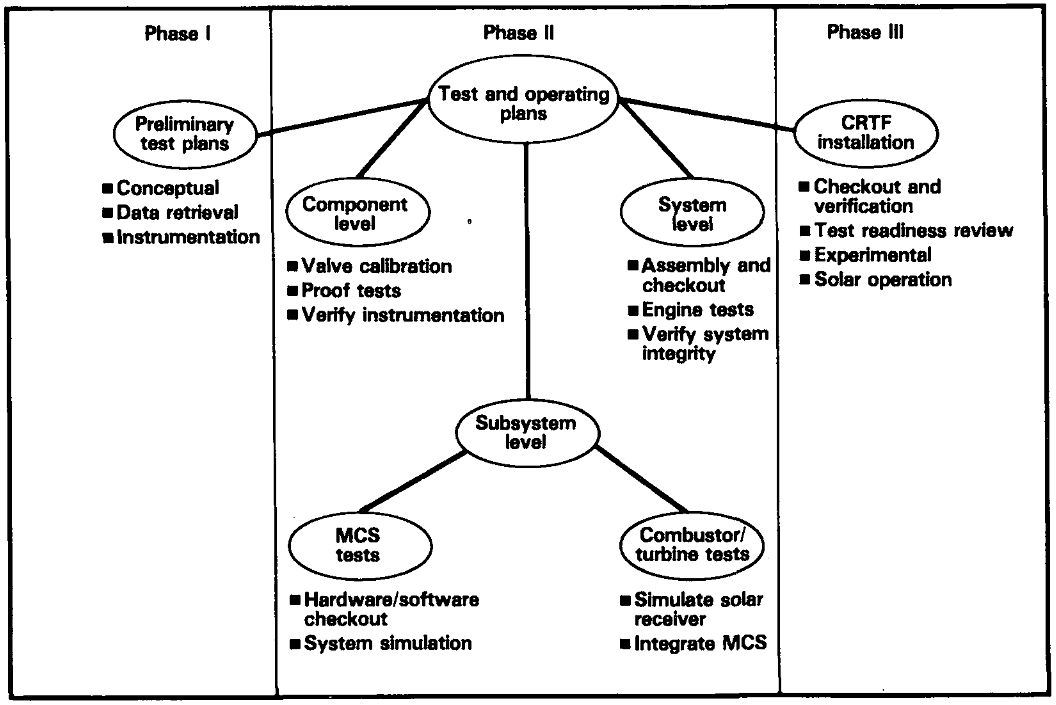
The test plan was developed by first defining test objectives and goals which would safely checkout and verify the system and its components; build operating confidence and experience; and investigate system performance and operational limits.

In defining these objectives a full understanding of the design, including performance characteristics and limits of each subsystem and component, was necessary. Performance parameters were defined by several analytical performance models.

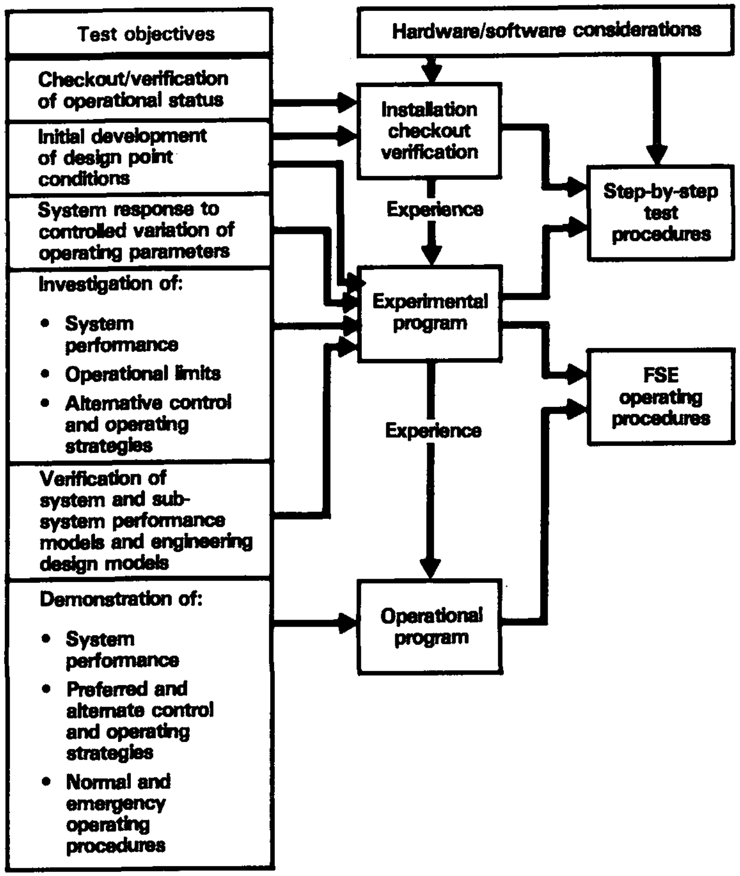
The right-hand chart in Figure 28 shows the test objectives and how they were developed into the overall test planning. As shown, each phase of testing will not only fulfill certain objectives, but will also provided operating experience which will be demonstrated during the next phase of testing.

Figure 28. Test Plan Hierarchy

FSE Test Planning



Plan Development



Data Acquisition and Control

Two separate data systems will be used in testing the Full System Experiment. The Master Control data system will provide the control functions necessary to operate the experiment, with the exception of the heliostat field which is controlled by the test facility. The experimental data system will provide the display and storage of data not vital to system operation, and will also provide information on heliostats and aperture flux measurements. The systems are shown schematically in Figure 29.

Control Data

The FSE data acquisition and control system was designed to be responsible for all control functions of the experiment and data acquisition and communication necessary to support those functions. This was intended to represent a typical installation for a solar-hybrid power plant. The control data system was designed as a stand-alone unit with the exception of the alarm and heliostat field shutdown function provided by the test facility data system.

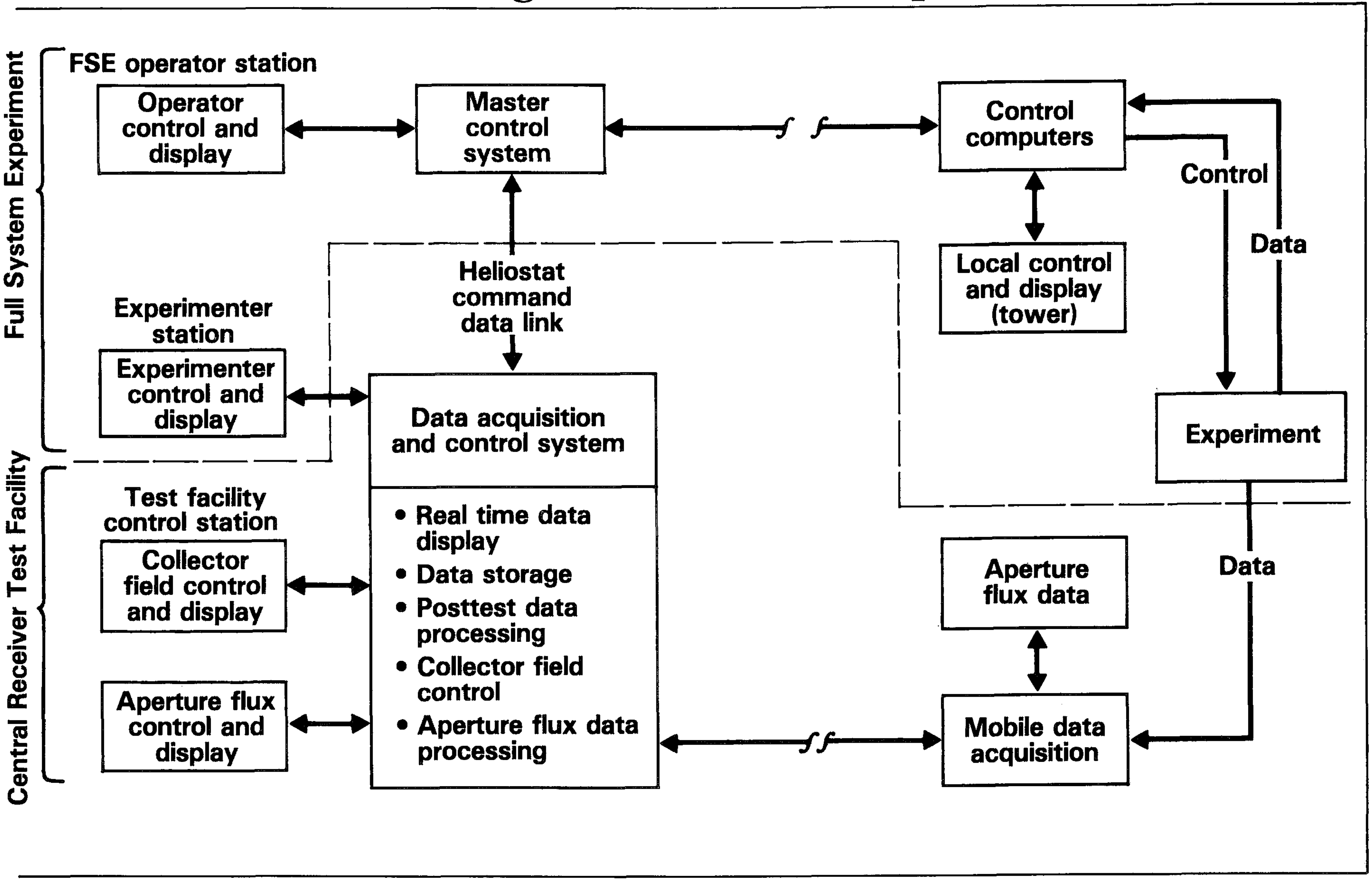
Experimental Data

The Central Receiver Test Facility data acquisition system will be responsible for collection, recording and processing all system experimental data.

During the preliminary test planning, various data measurements were defined which would monitor the system operation during test, provide verification of system performance with test predictions, and establish a data base from which to analyze the system operation.

In addition to the experiment data, information needed to support the Full System Experiment monitoring functions and performance calculations was defined. These included real-time measurement of aperture flux, metrological data and heliostat field operation data. All these systems will be monitored, controlled, and data will be collected by the Central Receiver Test Facility data acquisition and control system.

Figure 29. Data Acquisition and Control



Experimental Instrumentation

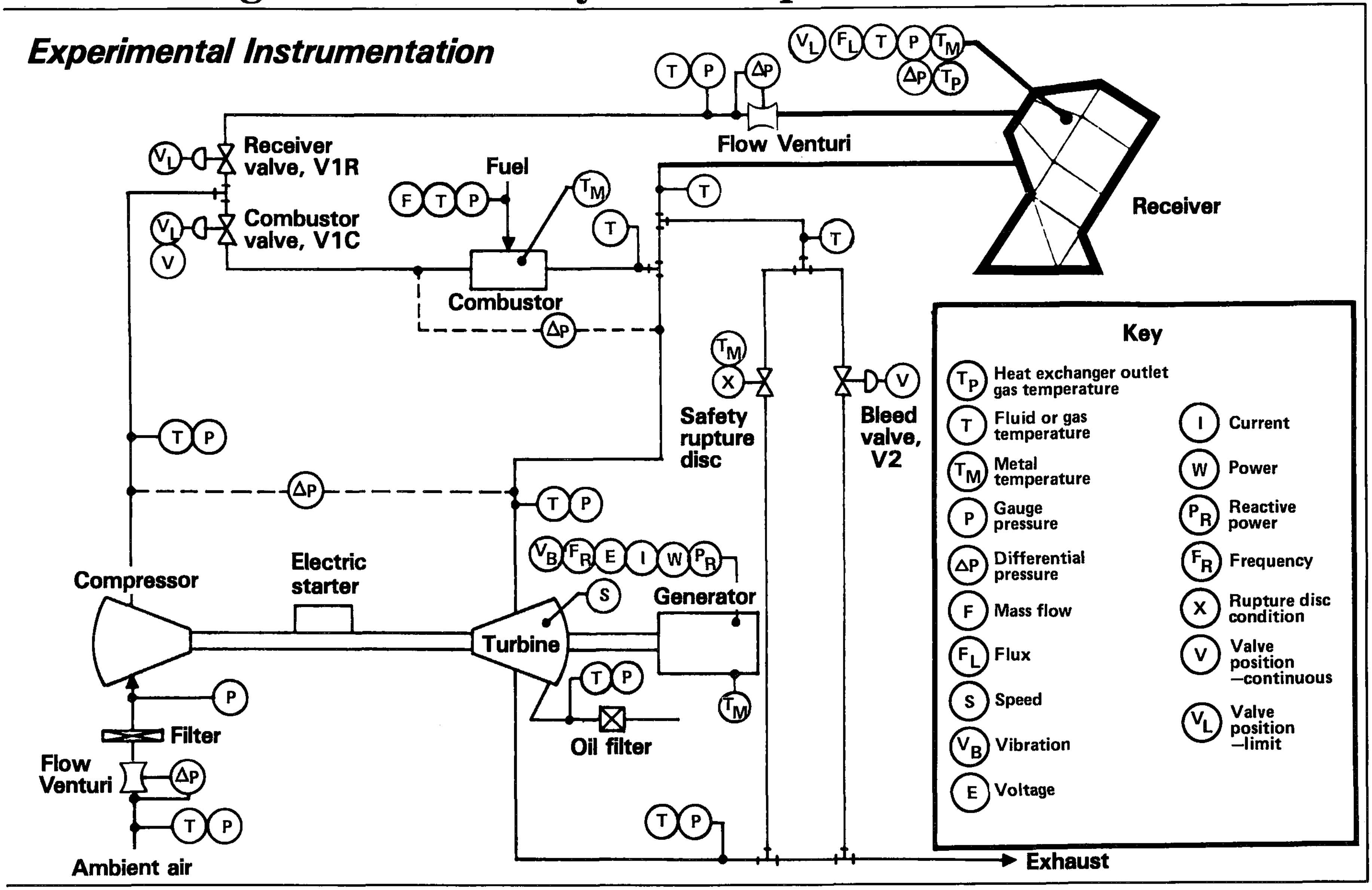
Experimental instrumentation is categorized as that instrumentation not utilized directly in the control or operation of the system. Experimental instrumentation types, locations, parameter spans and calibrations were selected to monitor components, measure data which will verify analyses, and provide a data base for system operations. A total of 258 experimental instrumentation sensors and associated data channels were selected. Principal data measurement points are shown schematically in Figure 30. In selecting instrumentation for the FSE, previous Bench-Model testing experience provided a basis for modifying, continuing and improving certain instrumentation types and methods.

All Full System Experiment instrumentation was selected to provide durability and accuracy and be replaceable, where possible. Instrumentation calibration errors were identified and methods have been defined to minimize them. Error propagation through measurement, data transmittal and calculation will be defined and examined during the Phase II detail test planning.

Control Instrumentation

The Full System Experiment control system instrumentation was selected to be independent of the experimental data instrumentation. This redundancy was planned for several reasons: 1) all experimental data could be collected and processed independent of the control system; 2) there were technical differences between the two data systems which dictated independent instrumentation; and 3) the experimental instrumentation could be used as control instrumentation backup in case of failure. A total of 86 control system instrumentation sensors and channels were utilized.

Figure 30. Full System Experiment Instrumentation



Experimental Instrumentation

Experimenter Functions

The Boeing experimenter will be positioned at the experimenter's station in the control room. The experimenter will have no direct system control capability, but will be in communication with the FSE control station. The division between operator and experimenter functions was selected to allow operation of the system in a manner as close as possible to a conventional power plant while independently gathering experimental performance data. The functions of the experimenter have been defined to include: 1) monitoring data measurements during test to verify operating conditions and system performance; 2) collecting experimental data from the system and auxiliary metrological and aperture flux data and 3) posttest data reduction, processing and evaluation.

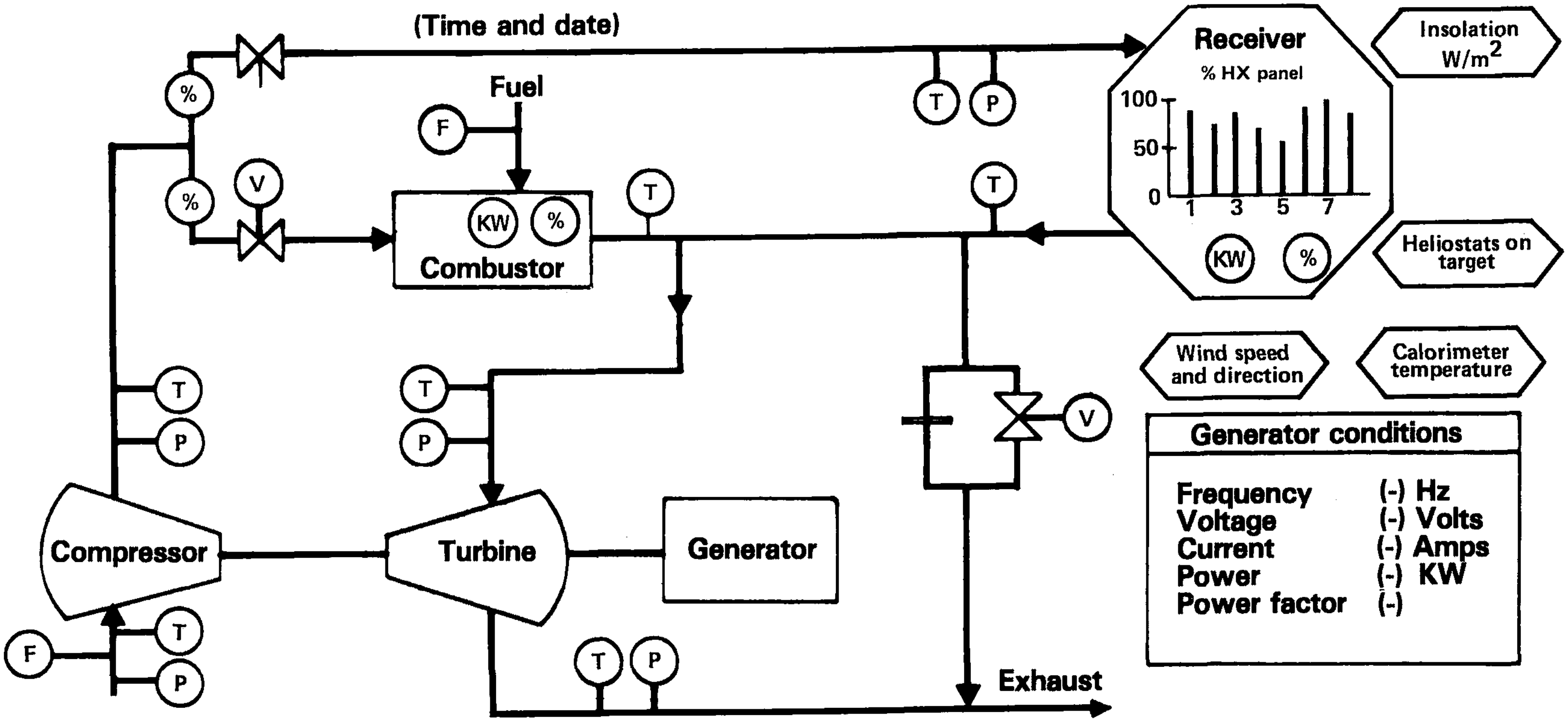
Experimenter's Station

The experimenter's station will be provided by the test facility for use by the FSE experimenter. The station will supply the experimenter with real-time displays of all experimental data by means of several display consoles. A colorgraphics unit (three-color CRT) with a flow system schematic background and real-time data measurements, as shown in Figure 31, was developed for the primary display . The display will allow the experimenter to monitor the overall performance and condition of the system during test and operation. All experimental data is available to the experimenter and is grouped in logical formats and displayed on several black and white CRT units. An alarm display monitors those channels which require close observation. In addition, several real-time plotters are available to aid in performance evaluation during test.

Data Processing

A preliminary plan for posttest experimental data reduction was developed which provides the experimenter with a test data printout, selected data plots, and a magnetic tape of all data collected.

Figure 31. Experimenter's Display



Generator conditions

Frequency	(-) Hz
Voltage	(-) Volts
Current	(-) Amps
Power	(-) KW
Power factor	(-)

Receiver data	Units	1	2	3	4	5	6	7	8
HX air outlet temp	Deg.	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
HX Δ pressure	PSID	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Max. tube temp	Deg.	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Aperture shield temp	Deg.	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
HX flux	KW/m^2	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Max. flux	KW/m^2	Backwall	(-)	Backcone	(-)	(-)			
Max. temp	Deg.		(-)		(-)	(-)			

12. Future Effort

The next major program effort is the fabrication, assembly and checkout of major system components in Phase II. This phase was initiated in June 1981 with the ordering of long lead materials and design of control system software. The major Phase II work packages are shown in Figure 32. There are five tasks in Phase II. Task 1 performs the solar receiver modifications, using elements of the previously tested 1 $MW_{(th)}$ Bench Model Solar receiver. Task 2 is performed largely by Solar Turbines Inc. and involves trim combustor modifications, turbine modifications for hybridizing, testing, and development of the power generation control system. Task 3 combines analyses, software development, and fabrication of several major components. Task 4 is dedicated to test planning, an ongoing activity with several review points in Phase II. Task 5 prepares the work statement, costs and schedule for Phase III, the testing portion of the program.

Phase III Planning

Phase III is envisioned as a twelve month effort, starting with system checkout and verification of components installed on the test tower. The checkout task is expected to require 2 months. After all elements are operational an experimental test program will be conducted to characterize the system; this is scheduled for six months. Next will come the utility operating program, including utility personnel training and familiarization. The operating program is scheduled for four months. Upon completion of the operating program, a period of time will be directed towards evaluation and assessment of system operational characteristics. Independent evaluation and recommendations will be obtained from the utility participants and other test personnel for improvements in system operation and capabilities. An appraisal of how the system meets the utilities' needs will be made.

Figure 32. Phase II Work Plan

	Major Work Packages	1981				1982				1983	
		1	2	3	4	1	2	3	4	1	2
Task 1	Heat exchanger fabrication						■	■			
	Receiver rework					■	■	■			
	Backcone insulation design (RP1521-1)				■						
	Backcone insulation fabrication						■				
	Receiver assembly and checkout							■	■		
Task 2	Turbine characteristics			■	■						
	Turbine modifications					■	■	■	■		
	Power generation control hardware and software			■	■	■	■	■	■		
Task 3	Computer and console			■	■						
	Master control hardware and software			■	■	■	■	■	■		
	Piping redesign and fabrication			■	■	■	■				
	Heat exchanger material order			■	■						
	Switchgear fabrication				■						
	System dynamic analysis								■	■	
	System checkout (Albuquerque)									■	
Task 4	Test planning				■	■	■	■	■	■	
	Test plan, data package								■		
	Test procedure, records								■	■	
Task 5	Phase III work plan									■	

EPRI AP-2435-SY

Below are five index cards that allow for filing according to the four cross-references in addition to the title of the report. A brief abstract describing the major subject area covered in the report is included on each card.

EPRI

EPRI AP-2435-SY
RP1509-1
Summary Report
August 1982

1-MW(th) Solar-Thermal Conversion Full-System Experiment

Contractor: Boeing Engineering & Construction Company

Phase I of a project to plan and design a complete Brayton-cycle solar central receiver experimental system is reviewed. Each of the major subsystems in this solar-fossil hybrid concept is described, including the digital control and data collection subsystems. The estimated operating capabilities of the experiment, along with the outline of the test and operating plans, are described. Fabrication of the experiment and solar testing will be conducted in Phases II and III, respectively. 74 pp.

EPRI Project Manager: J. E. Bigger

Cross-References:
1. EPRI AP-2435-SY
2. RP1509-1
3. Solar Power Systems Program
4. Solar-Thermal Conversion

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Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

EPRI AP-2435-SY

EPRI

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SOLAR POWER SYSTEMS PROGRAM

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