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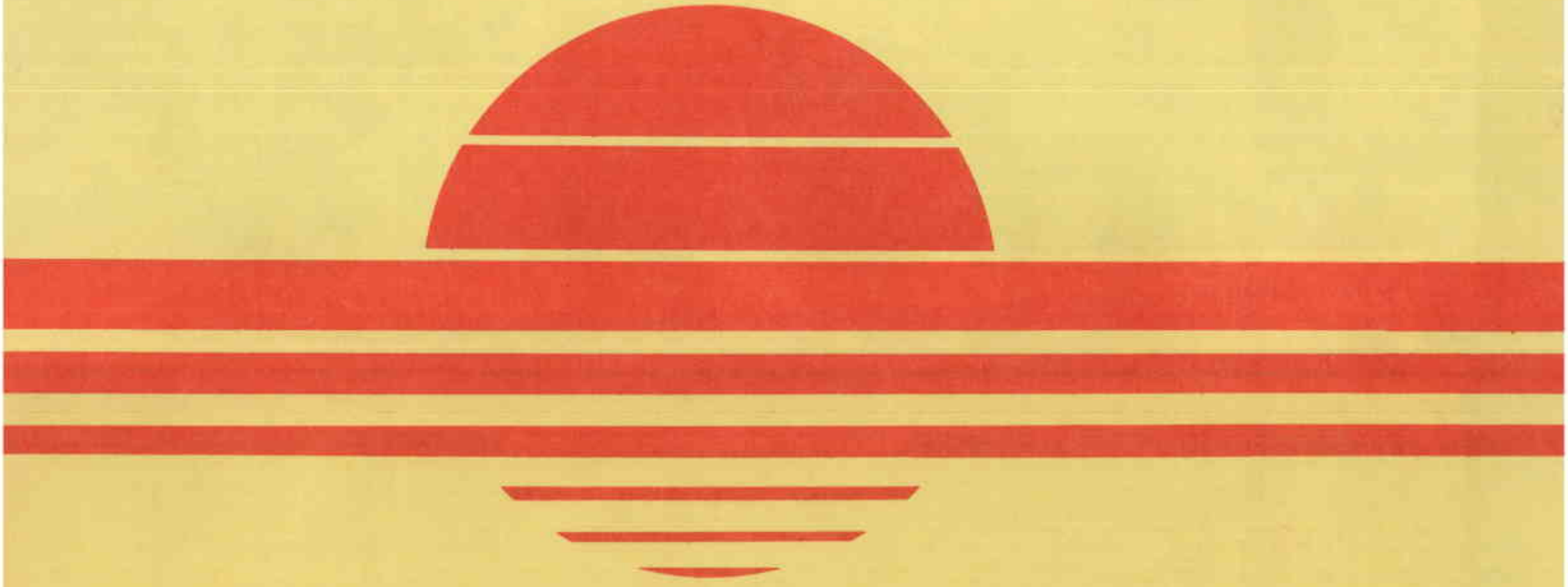
CONCEPTUAL DESIGN OF ADVANCED CENTRAL RECEIVER POWER SYSTEMS SODIUM-COOLED RECEIVER CONCEPT

Final Report, Volume 3, Development Plan and Pilot Plant Description

March 1979

Work Performed Under Contract No. EG-77-C-03-1483

Rockwell International
Canoga Park, California



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CONCEPTUAL DESIGN OF ADVANCED CENTRAL RECEIVER POWER SYSTEMS SODIUM-COOLED RECEIVER CONCEPT FINAL REPORT

VOLUME III

DEVELOPMENT PLAN AND PILOT PLANT DESCRIPTION

MARCH 1979

PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
AS PART OF
CONTRACT NO. EG-77-C-03-1483

Rockwell International
Energy Systems Group

University of Houston Founded 1927

McDONNELL DOUGLAS CORPORATION

Salt River Project
WATER POWER

Stearns-Roger

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PREFACE

This report is submitted by the Energy Systems Group to the Department of Energy under Contract EG-77-C-03-1483 as final documentation. This Conceptual Design Report summarizes the analyses, design, planning, and cost efforts performed between October 1, 1977 and September 1, 1978. The report is submitted in four volumes, as follows:

Volume I	Executive Summary
Volume II	Book 1, Commercial Plant Conceptual Design
	Book 2, Appendices
Volume III	Development Plan and Pilot Plant Description
Volume IV	Commercial and Pilot Plant Cost Data

The principal contractors supporting the Rockwell International Energy Systems Group, in this conceptual design effort, together with the main areas of responsibility, included McDonnell Douglas Aircraft Corporation as responsible for the Collector and Master Control Subsystem; Stearns-Roger Services, Inc. as responsible for Electric Power Generating Subsystem, Tower Design and Civil Engineering; and Salt River Project as the Utility Consultant. The University of Houston supported McDonnell Douglas in the Collector Field Studies. Personnel contributing to this design program and to the final report included:

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I. INTRODUCTION

This volume encompasses Task 6 of the Phase I effort on the Advanced Central Receiver. This task included developing a plan to bring the commercial plant conceptual design into being. The base version of the plan includes a pilot plant to be designed and constructed during Phases II and III, three subsystem research experiments to be performed during Phase II, and the design and construction of a commercial demonstration plant. These plans are discussed in detail, as well as several options which could reduce both cost and schedule to achieve the overall goal of a commercial-sized demonstration plant.

In evaluating pilot plant characteristics, emphasis was placed on representing commercial plant receiver characteristics and total system operation. In considering total system operation, it was recognized that a water-steam pilot plant would already be in operation, hence certain systems will already have been tested. These include 360^0 collector field and receiver operating characteristics, master control subsystem operation, and EPG subsystem. Based on this experience, tests of these subsystems can be considered of secondary importance.

Several receiver configurations were investigated consisting of from one to five full-size panels, with the objective of representing peak north side power for a 100-MWe plant as well as the peak flux value of about 1.4 MW/m^2. This goal was accomplished with a 5-panel receiver; however, the power to the edge panels is very low. Hence, with little loss, these panels can be eliminated to give a 3-panel configuration. The total absorbed thermal power is about 38 MWt, which is sufficient for about 10 MWe. A plant of this size is described in the following sections.

TABLE 1

ADVANCED CENTRAL RECEIVER SYSTEM REQUIREMENTS

	System Requirements	Source
Design Point Power Levels		
During Receiver Operation (MWe net)	10	ESG
Operation Exclusively from Thermal Storage (MWe net)	10	ESG
Solar Multiplier (SM)	1.2	ESG
Storage Capacity (h)	1	ESG
Design Insolation (W/m^2)	950	100 MWe CD†
Receiver Outlet Temperature [°C (°F)]	593 (1100)	100 MWe CD†
Steam Generator Outlet Temperature [°C (°F)]	538 (1000)	100 MWe CD†
Heat Rejection	Wet Cooling	100 MWe CD†
Wet Bulb Temperature [°C (°F)]	23 (74)	100 MWe CD†
Dry Bulb Temperature [°C (°F)]	28 (82.6)	100 MWe CD†
Nominal Design Wind* [m/s (mph)]	3.5 (8)	100 MWe CD†
Maximum Operating Wind (including gusts)* [m/s (mph)]	16 (36)	100 MWe CD†
Maximum Survival Wind (including gusts)* [m/s (mph)]	40 (90)	100 MWe CD†
Seismic Environment	Zone 3 (not near a great fault)	100 MWe CD†
Survival Earthquake Horizontal and Vertical (g)	0.25	100 MWe CD†
Availability (exclusive of sunshine)	0.9	100 MWe CD†
Lifetime (years)	30	100 MWe CD†
Reference Site	Barstow, CA	100 MWe CD†

*At reference height of 10 m (30 ft).
†100-MWe conceptual design.

II. CONCEPTUAL DESIGN OF PILOT PLANT

A. PILOT PLANT REQUIREMENTS

The guidelines for the pilot plant were established as given in the following paragraphs.

1. Design Objectives

1) The pilot plant shall provide design verification and operational information to substantiate and support the design of a commercial-scale demonstration plant.
2) In particular, the pilot plant shall provide design verification and operational information to substantiate and support the design of the receiver for a commercial-scale demonstration plant. (The principal area of concern is cycle fatigue and stress failures.)

2. Design Requirements

The basic design requirements are given in Table 1, with the source of the requirement identified on the far right of Table 1.

Based on thermal power available from a 3-panel full-sized receiver, a power level of 10 MWe is selected as a reference design point. The receiver is considered to be a cylindrical segment of three, full-sized panels (i.e., for the 100-MWe conceptual design). The collector field is designed to provide the same maximum flux distribution as for the 100-MWe conceptual design. Full-sized receiver panels are recommended as allowing the most realistic demonstration of the structural adequacy of the receiver design for the 100-MWe design, allowing simple extrapolation of results for a larger 300-MWe plant design and demonstrating the fabrication, transportation, and erection characteristics of the design. The 10-MWe size is considered of sufficient size to demonstrate the significant system operation and control of a sodium-cooled solar plant design at a reasonable cost. This size may also allow surplus sodium components such as pumps, valves, and tanks to be used to further reduce cost.

Direct and storage power generating capability for the pilot plant will be the same since this was an important requirement for the 100-MWe design.

The solar multiplier (SM) is estimated to be 1.2 in order to supply a 1-h storage capability. The 1 h of storage capability was selected to provide demonstration of the buffering capability of the all-sodium storage system and yet demonstrate significant nighttime operation from storage without the cost of a longer duration storage capacity.

The receiver outlet temperature will be 594^{o}C (1100^{o}F), the same as for the 100-MWe plant, in order to demonstrate sodium system capability and operation at this temperature condition. Since reheat turbines are not available in the small 10-MWe size, reheat capability will not be provided. The steam generator will be a once-through unit of the MSG design. A once-through unit will be of sufficient size to represent the commercial-scale units. Steam outlet temperatures up to 538^{o}C (1000^{o}F) will be provided for demonstration purposes, though the turbine may be limited to lower temperatures. An attemporator will be used to reduce steam temperatures. The steam generator unit is expected to be nearly identical to the ESG MSG in physical size and design.

B. PILOT PLANT RECEIVER SUBSYSTEM

1. Pilot Plant Receiver

The proposed pilot plant has a receiver with three panels which are very nearly identical with the panels on the 100-MWe receiver. The pilot plant receiver has a mid-point elevation of 104 m (341 ft), a height of 16.1 m (52.8 ft), and a width of 6.3 m (20.7 ft). The maximum absorbed thermal power is 36.2 MWt, and the maximum incident heat flux is 1.53 MWt/m^2 which compares with 1.37 MWt/m^2 in the 100-MWe design. Receiver layout drawings are shown in Figures 1 and 2.

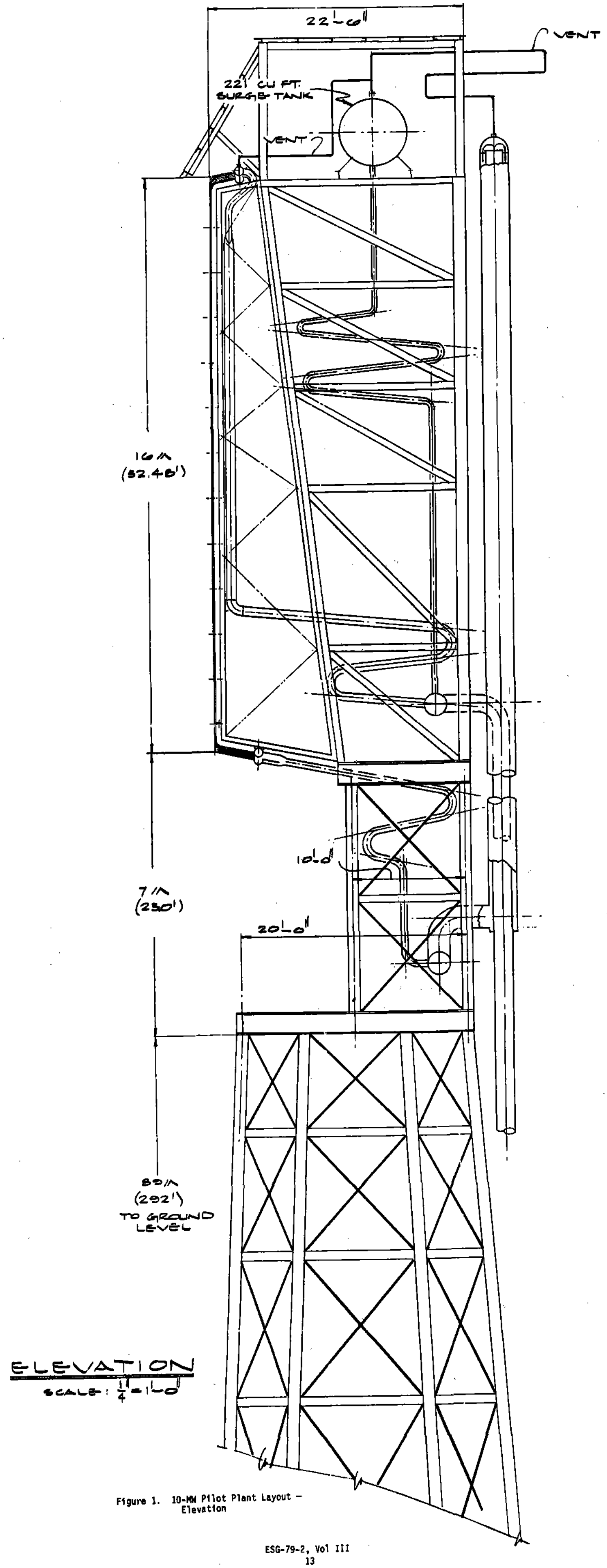

Figure 1. 10-MW Pilot Plant Layout — Elevation

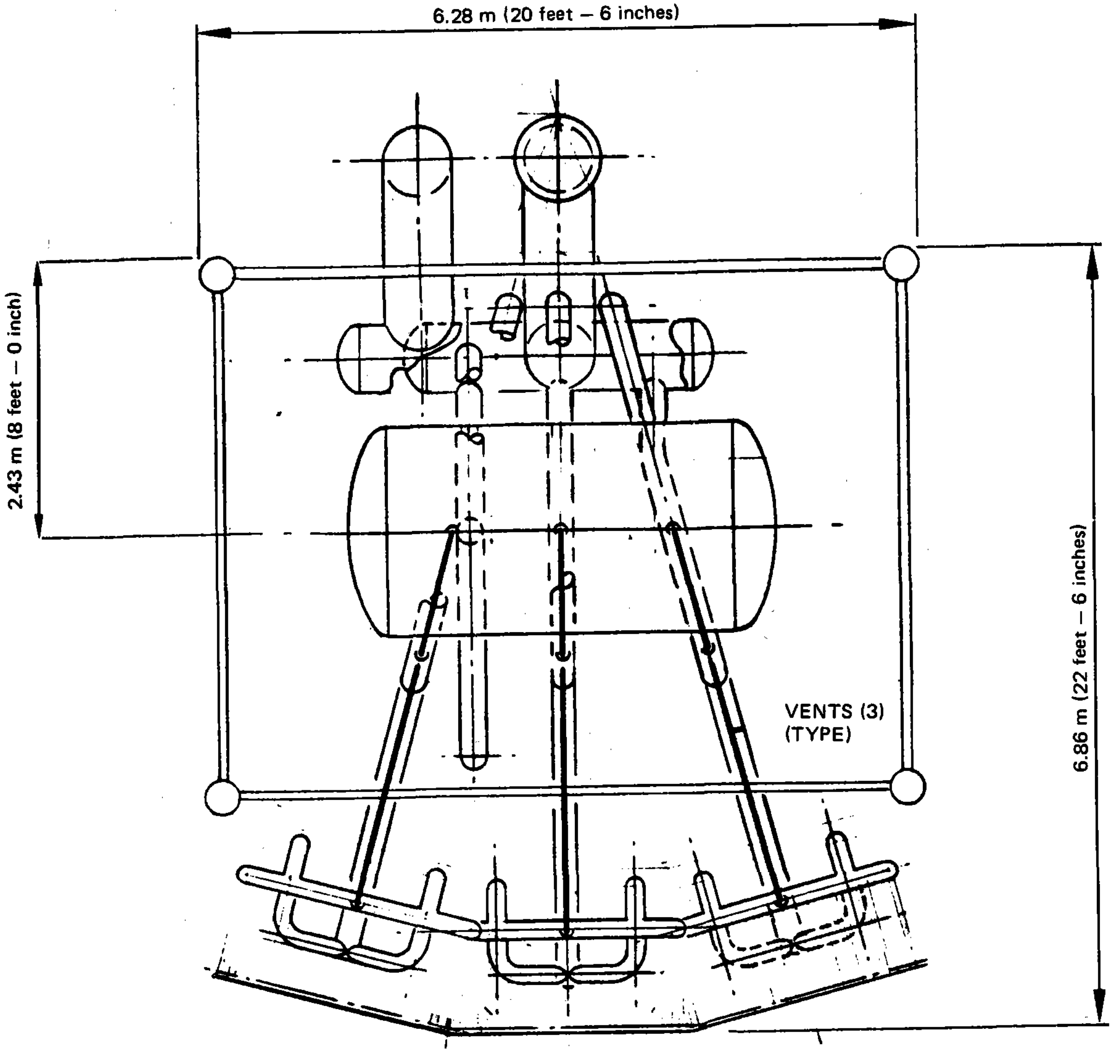

Figure 2. 10-MW Pilot Plan Layout – Plan

The maximum sodium flow rate is 3.37 kg/h x 10^5 (7.41 x 10^5 lb/h) with the sodium entering the receiver at 288°C (550°F) and leaving at 594°C (1100°F). Since there are three panels instead of 24 and the flow rate is 9.3% of the 100-MWe design, the tube diameter can be the same as the 100-MWe receiver, namely, 1.91 cm (0.75 in.).

Other features of the panel are about the same as in the 100-MWe design. There are 110 tubes per panel with an inlet manifold at the lower end and an outlet manifold. The tubes will be welded or brazed in groups of three – each group being attached to the receiver structure by brackets that can slide to accommodate thermal expansion. It is currently believed that welding or brazing all the tubes in a panel into a continuous sheet would result in high stresses at the heat fluxes and in high flux gradients. This approach, however, remains a possibility to minimize the problem of light leakage between tubes.

Each receiver panel will be supported by a strongback constructed of steel box beams - each beam being a 15 cm (6 in.) square made of 0.95 cm (3/8 in.) steel. This support is especially important in a few-panel receiver where the wind loads are more severe. Thermal insulation will be employed behind each panel to protect the structure and to reduce thermal losses. A sodium expansion tank having a volume of 6.3 m^3 (221 ft^3) will be located above the panels. An anti-siphon pipe will be provided to prevent the panels from suddenly running dry in the event of pump failure.

The central panel will receive a heat input of about 25 MWt, which is comparable to that of a 100-MWe north-facing panel at equinox noon. The lateral thermal gradients are expected to be somewhat more severe. The two side panels will have heat inputs of about 5-MWt each, which is about that of a south-facing panel. These panels will have appreciable lateral heat flux gradients. Most of the test data will be obtained from the central panel.

Data that will be obtained from the panel will include the following:

1) Sodium inlet temperatures
2) Sodium outlet temperatures – both local and average

3) Selected panel tube temperatures
4) Selected panel strain gauge measurements
5) Dimensional stability
6) Extent of and damage caused by light leakage
7) Efficacy of thermal expansion accommodation techniques
8) Overall heat balance and heat losses
9) Thermal insulation effectiveness
10) Control of panel sodium flow
11) Transient effects (startup, shutdown, overnight conditions, erratic insolation, effect of precipitation)
12) Mechanical and thermal effect of winds
13) Natural convection problems
14) Effect of sodium leaks (deliberate or accidental).

2. Requirements

The Receiver Subsystem functional requirements are given in Table 2. These requirements are derived from the optimized performance characteristics of the EPGS, collector, and master control subsystem, which in turn satisfy the requirements of the ACR Specification.* There are additional operational and sodium system requirements as follows:

1) Transport up to 39 MWt to storage or 7 MWt to storage and 32 MWt to the steam generator simultaneously or 32 MWt from storage to the steam generator.
2) Provide for the control of the receiver outlet sodium temperature and the evaporator temperature.
3) Provide for anti-siphoning of the receiver sodium.
4) Provide protection against reverse flow through the receiver.
5) Provide for purging and filling and draining the system sodium for maintenance.

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*"Advanced Central Receiver Program Requirements," A-10270, Sandia Laboratories (March 16, 1978)

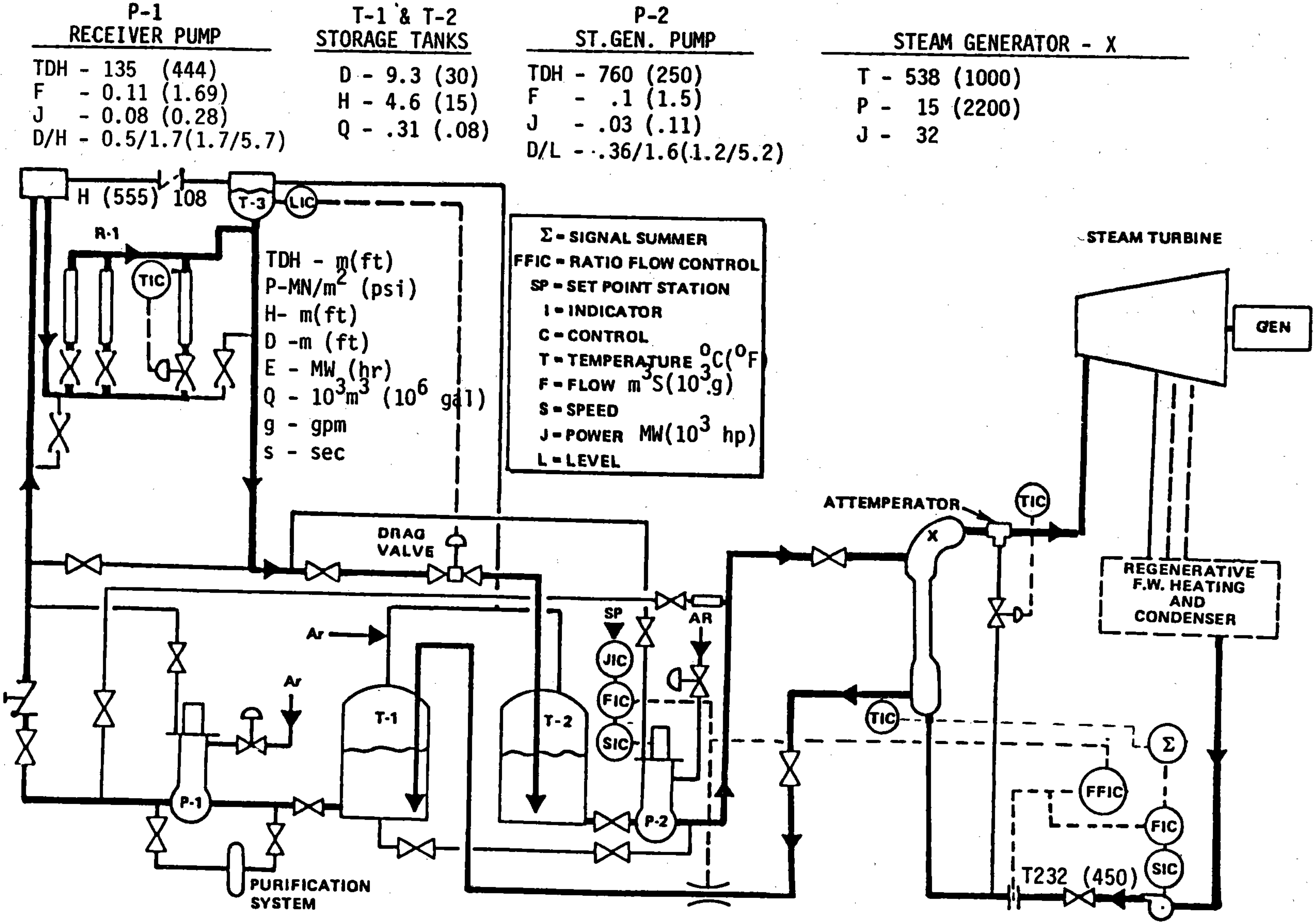

Figure 3. Advanced Central Receiver — 10 MWe

9272-17

6) Provide for draining the receiver system on a daily basis.

7) Provide for maintaining the purity of the sodium below 15 ppm O_2 and 1 ppm H_2.

TABLE 2

ADVANCED CENTRAL RECEIVER — RECEIVER SUBSYSTEM FUNCTIONAL REQUIREMENTS

Parameter	Requirement
Nominal Thermal Power (MWt)	32
Maximum Thermal Power (MWt)	38.4
Receiver Mid-Point Elevation [m (ft)]	104 (341)
Water-Steam Side	
Feedwater Temperature, in [^{0}C (^{0}F)]	234 (453)
Steam Temperature, out [^{0}C (^{0}F)]	538 (1000)
Reduced Power Operation (%)	10 - 100
Transient Operation (Power)	
10% to 100% or 100% to 10% (s)	90

3. Design Characteristics (For Detailed Quantification, see Appendix A)

The reference design of the sodium heat transport system is schematically shown in Figure 3. The quantitative values of the process variables are given in Appendix A.

The system can be considered to operate as two independent loops. The first loop transfers sodium from the cold storage tank, T-1, at about 288^{0}C (550^{0}F) through the receiver which heats it to ~593^{0}C (1100^{0}F). The sodium then flows by gravity through the drag valve to the hot storage tank, T-2. Maximum flow rates are about 0.11 m^3/s (1,700) gpm. The second loop transports sodium from the hot storage tank through the sodium heated superheater and reheater, through the evaporator and then to the cold storage tank, T-1. The maximum flow is about in the 0.10 m^3/s (1,500) gpm range.

Provided there is some reserve in Tank T-1, the first loop operates to transfer all of the energy received by the receiver to storage independent of the steam generator power requirements. As the insolation varies, the flow is modulated to maintain a constant receiver outlet temperature. The second system, after some storage accumulation in Tank T-2, operates independently of the insolation. The storage tank being in series in the loop functions as thermal inertia and thermal capacitance thus protecting the pumps and the steam generating equipment from thermal shocks from the sodium. The independence of the second loop permits level loading the power output which minimizes thermal cycling of the steam generators. The stored energy accumulates or is drawn upon automatically since it is simply the difference between the inflow and outflow of Tank T-1.

Sodium circulation is provided by means of the P-1 and P-2 pumps. These are free surface "Fermi" type pump centrifugal pumps. The P-1 pump is a high-head (~135 m (444 ft) TDH) two-speed (full speed and 25% speed), single-stage centrifugal pump. The lower speed is only used at plant startup. The bearing flow at startup is provided by opening the block valve in the supply line to the pump bearing. Immediately after the pump starts, the pump discharge pressure supplies the hydrostatic bearing. The pump suction side stop valve is required for maintenance. The free surface level is maintained by pressurizing the pump ullage with argon. The P-2 pump is a variable speed, single-stage pump of the same type as the P-1 pump. The speed control is a modified Kramer system which operates as a straight induction motor at full speed. Sodium is supplied to the pump hydrostatic bearing at startup by means of a line connected to the downcomer. The in-the-pump level is controlled by argon pressurization. Sodium flow through the receiver is modulated by the control valves on each panel to maintain the panel outlet temperature constant. The surge tank permits these fast acting valves to operate independently of the drag valve. The drag valve reduces the sodium pressure to near atmospheric pressure to match the pressure requirements of the storage tank. The flow in the downcomer line is modulated to maintain the sodium level in the surge tank fixed. The storage tanks and the drag valve are discussed in Subsection II-D.

The sodium flow in the steam generator loop is set by the power requirements. It is planned to operate this system in a load forcing mode at various fixed power levels as required for the maximum utilization of the plant. The variable speed drive on the P-2 pump has a 5:1 turndown ratio which provides base flow settings. Trim control is provided by control valves in the supply line of the steam generator.

The anti-siphon system and the surge tank operate to prevent the draining of the sodium from the receiver on loss of pump power. The anti-siphon device also prevents backflow in this event which would draw hot sodium into the cold header and riser.

4. Operations

Tentative operating sequence outlines, based on test experience with sodium systems, are presented in Tables 3 through 7. The outlines are as follows: (1) Table 3, Prestartup, gives the basic steps required for preparing the system to receive sodium; (2) Table 4, Initial Startup, gives the steps required for bringing the sodium systems up to cold leg temperature for the first time; (3) Table 5 gives the steps needed to bring the sodium and steam system to part load. The system is leveled at 1/2 full power to permit its characteristics to be examined before preceding to full power. Subsequent cold startups should be possible in 4 h or less, depending on the starting temperature (never $<300^{0}$F); (4) Table 6, Shutdown, gives the steps needed to secure the plant for an expeditious startup the following day; and (5) Table 7, provides the hot startup sequence for full power operation by 0815 midwinter. The steam generator cooldown characteristics are given in Figure 4.

Because of the complete buffering action that is provided by the all-sodium storage system between the receiver and the steam generator system, low solar power operating conditions are accommodated by throttling the receiver independently of the steam generator and electric power generating system. Basically, if the energy input exceeds the turbine requirement, the storage system automatically accumulates the excess. If the turbine demands more energy than the receiver is collecting, the difference is automatically drawn from storage. The maximum stored energy is set at 1 to 0 h of full-power operations.

TABLE 3

OPERATIONS PRESTARTUP

Checkout Instrumentation
Preheat Sodium Systems to 150°C (300°F)
Purge with Argon
Heat Tank Car
Fill Storage Tank 9 Cars — 5 Days

TABLE 4

OPERATIONS INITIAL STARTUP — FIRST DAY

	Clock Time
Sunrise	0730
Preheat Receiver — Solar — 200°C (400°F)	0800
Start P-1 Pump	
Fill Riser and Downcomer to Receiver Bypass Line	0830
Open Drag Valve Part Way	
Circulate Sodium — Bypass Steam Generator — 174°C (350°F)	
Fill Dry Steam Generator with Sodium and Circulate	0900
Close Receiver Bypass and Fill Receiver	0930
Raise Sodium Temperature to 270°C (525°F) with Solar Heating	1030
Circulate Sodium and Check Out the System	
Shut Down System — Drain Receiver to Standby	1600
Sundown	1645

TABLE 5

OPERATIONS STARTUP — SECOND DAY

	Clock Time
Heat Feedwater on Bypass Flow	0500
Pressurize Steam Generator to $\sim$6.89 Mn/m^2 (1000 psi)	
Admit Water to Steam Generator 260°C (500°F)	0600
Start Sodium Flow	0600
Flash Steam to Condenser	0615
Balance Water, Steam, and Sodium Temperature	0630
Stepwise Raise and Spread at Log Mean ΔT	
Roll Turbine (Minimum — 40% Pressure — 100°F Superheat)	0715
Sunrise — Power to Grid	0730
Stepwise Increase Steam Temperature and Flow Level at 1/2 Power	0815

TABLE 6

OPERATIONS SHUTDOWN — SECOND DAY

	Clock Time
Reduce Load to 10%	1630
Collapse the Log Mean ΔT	
Trip Turbine — Dump to Condenser	1730
Bypass Steam Generator — Sodium and H_2O — Unit Dry	
Isolate — Full Sodium — No H_2O	1800

TABLE 7

OPERATIONS STARTUP — THIRD DAY

	Clock Time
Heat Feedwater on Bypass Flow	0500
Pressurize Evaporator to $\sim$6.89 Mn/m^2 (1000 psi)	
Admit Water to Steam Generator 260°C (500°F)	0600
Start Sodium Flow from Bypass Line	0600
Flash Steam through to Condenser	0615
Balance Water Steam and Sodium Temperatures	0630
Stepwise Raise and Spread Log Mean ΔT	
Close Bypass Line	0710
Roll Turbine	
Sunrise Power to Grid	0730
Fill Receiver and Circulate to Storage	0730
Stepwise Increase Steam Temperature and Flow and Power	
Level at Full Power	0800

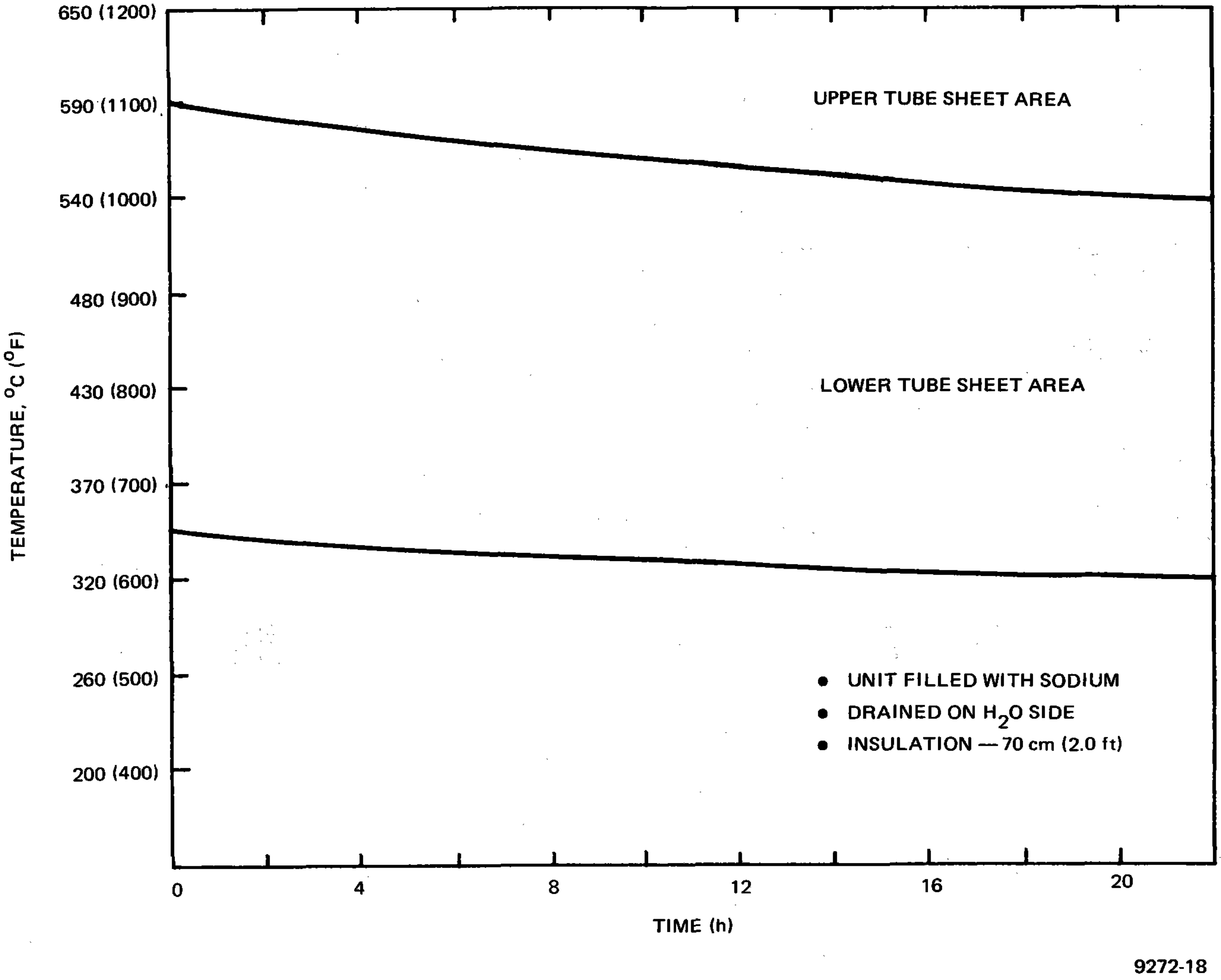

Figure 4. Superheater Cooldown

5. Steam Generator

The reference design utilized three steam generator units: an evaporator, a superheater, and a reheater. The evaporator is made of unstabilized 2-1/4 Cr - 1 Mo ferritic steel. This material was chosen because of its excellent resistance to chloride stress corrosion cracking in an aqueous environment, and the excellent and extensive field experience with it. The superheater and reheater units are made of Type 304 austenitic stainless steel. This material is used because its higher strength at the design temperature makes it cost effective compared to the 2-1/4 Cr - 1 Mo material. Chloride stress corrosion is only initiated in aqueous solution, which contains chlorine ions; thus, if the bulk liquid is kept out of the stainless steel units, chloride stress corrosion does not become a problem. To accomplish this, in the reference design a combined steam drum and steam separator was installed between the evaporator and the superheater and reheater to assure that no bulk would be carried over to the stainless steel units. The units are shown mounted vertically to avoid problems which could arise due to temperature stratification on the sodium side.

For the pilot plant, it appears to be less expensive to use a single unit once-through steam generator. Since we wish to retain the 1000°F outlet temperature to simulate the 100-MWe plant, we need to choose a high-temperature material or relax the steam generator requirements. Our preferred approach at this time is to select Type 304 stainless steel and control the chloride ion concentration in the feedwater. This is the approach used on the sodium reactor experimental (SRE) plant by the Southern California Edison Company.* In this approach, a full-flow mixed bed demineralizer was used in the feedwater loop and, in addition, all the makeup water was taken from a very large supply tank filled with ultra-pure water. This tank was constantly monitored and served as a buffer to the system. This approach worked successfully for over 6-1/2 years. At the end of the project, the steam generator was sectioned and found to be in excellent condition.

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*C. Starr and R. W. Dickinson, "Sodium Graphite Reactors," Addison-Wesley, Inc., p 226 (1958)

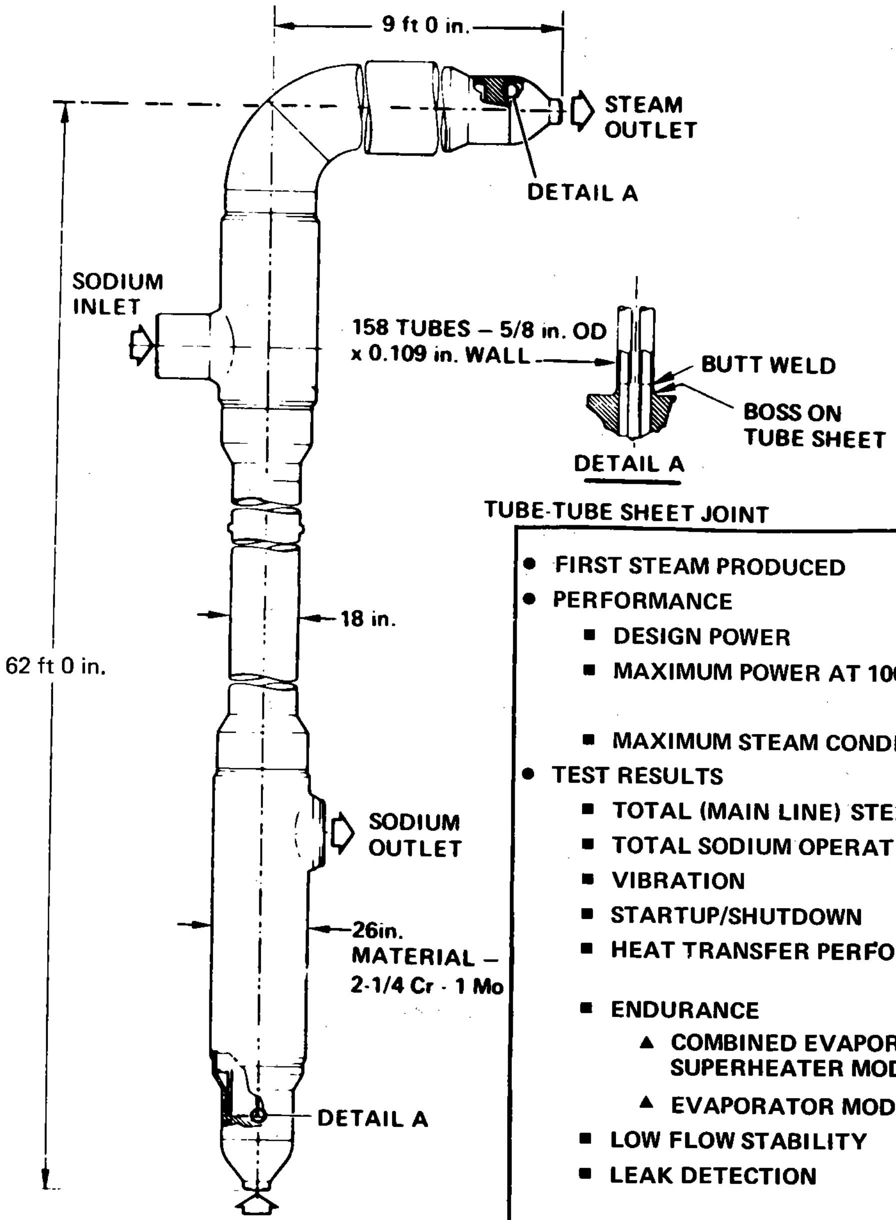
The physical features of the evaporator unit are shown in Figure 5. The water and steam flow through the tubes because this is the high pressure side of the unit, and the sodium flows in the shell. The "hockey stick" configuration allows individual tubes to deflect during thermal transients, thus virtually eliminating axial tube stresses during thermal transient events. The sodium flow bypasses the bend section because the tubes are supported in the horizontal plane only in this region, elsewhere the tube support plates suppress any potential tube vibration due to flow. A unit, similar to the one shown, has been built and tested in sodium. A summary of the test results is given in Figure 5. It is to be noted that the boss shown in Detail A in this figure is milled out of the solid tubesheet forging, thus the autogeneous butt weld provides a tube-to-tubesheet weld that can be 100% x-rayed. The performance characteristics of these units correlate well with the engineering predictions. The correlations are shown in Figure 6.

The pump type for the P-1 and P-2 pumps is shown schematically in Figure 7. The overall dimensions and hydraulic characteristics of these pumps are given in the Design Data Sheets.

C. THERMAL STORAGE SUBSYSTEM FOR 10-MWe PILOT PLANT

The thermal storage subsystem design proposed for the 10-MWe pilot plant is the all-sodium hot and cold tank concept similar to that for the 100-MWe baseline. The thermal storage system contains the hot and cold storage liquid sodium tanks, the sodium pump for the steam generator system, and a pressure-reducing device to dissipate the tower static head. This concept permits low-pressure design for the storage tanks.

Figure 8 shows typical diurnal variations in absorbed thermal power. The ordinate is normalized in decimal fraction of maximum thermal power. The area under a particular curve is then the thermal energy absorbed over a given time period. A horizontal line representing a solar multiple of 1.2 has been drawn on the curves. For the equinox curve, the solar multiple of 1.2 indicates a normal direct operating time of 7.6 h. The shaded area represents the excess



• FIRST STEAM PRODUCED	7-9-72
• PERFORMANCE	
■ DESIGN POWER	28.4 Mwt
■ MAXIMUM POWER AT 100% FLOW	32.1 Mwt (FOR 2400 psig STEAM) 33.8 Mwt (FOR 1450 psig STEAM)
■ MAXIMUM STEAM CONDITIONS	2430 psig/930°F
• TEST RESULTS	
■ TOTAL (MAIN LINE) STEAMING TIME	4015 hr
■ TOTAL SODIUM OPERATING TIME	9305 hr
■ VIBRATION	LEVELS LOW, SAFE
■ STARTUP/SHUTDOWN	37 CYCLES, STABLE
■ HEAT TRANSFER PERFORMANCE	PARAMETRIC DATA OBTAINED FROM 1450 TO 2450 psig
■ ENDURANCE	
▲ COMBINED EVAPORATOR/ SUPERHEATER MODE	500 hr
▲ EVAPORATOR MODE	500 hr
■ LOW FLOW STABILITY	STABLE, ALL CONDITIONS OF INTEREST
■ LEAK DETECTION	DETECTABILITY OF 10^{-6} lb/sec H_2O DEMONSTRATION
■ TRANSIENTS	INTEGRITY MAINTAINED

Figure 5. Highlights of LMEC-SCTI Test of ESG MSG

74-M20-15-44

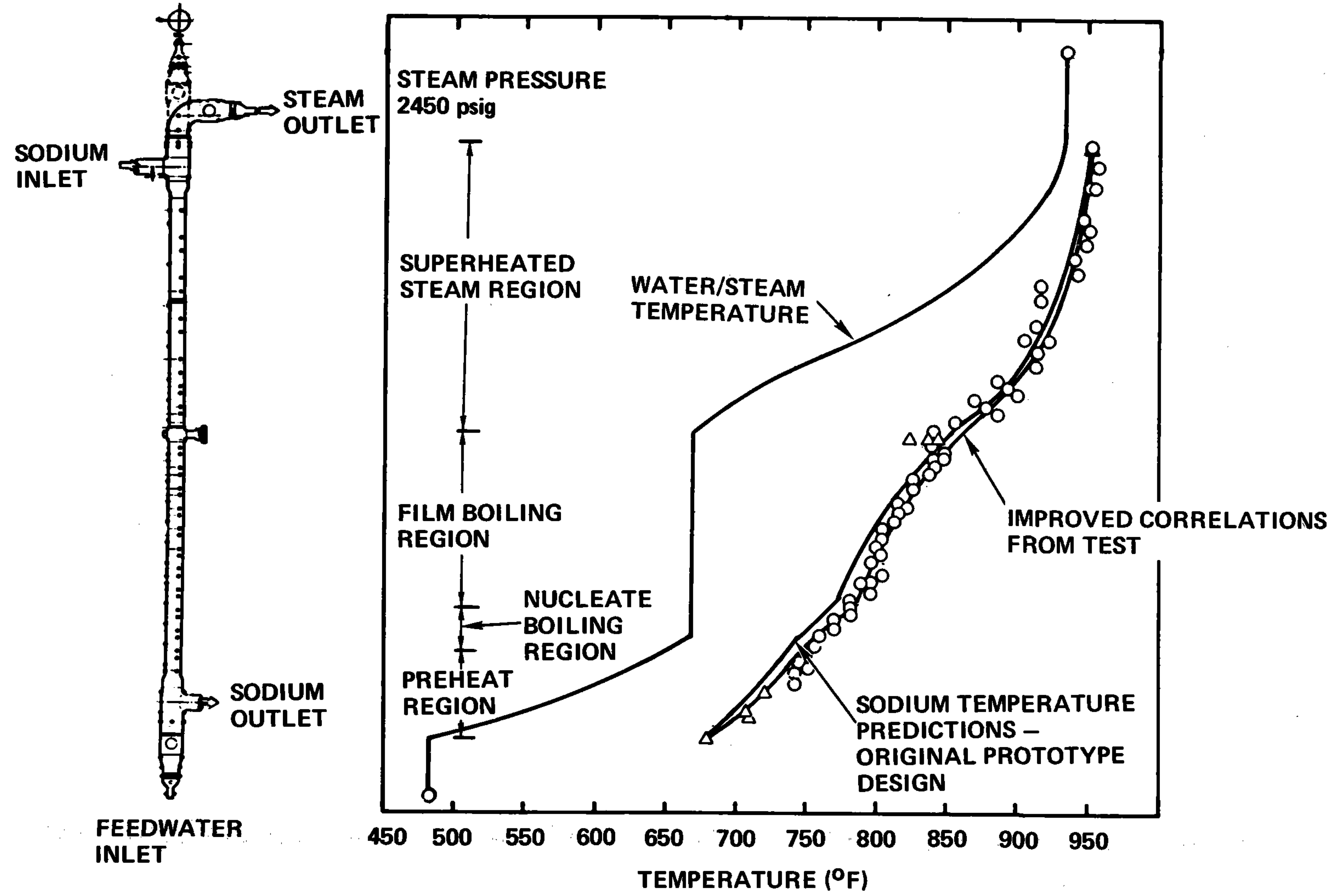


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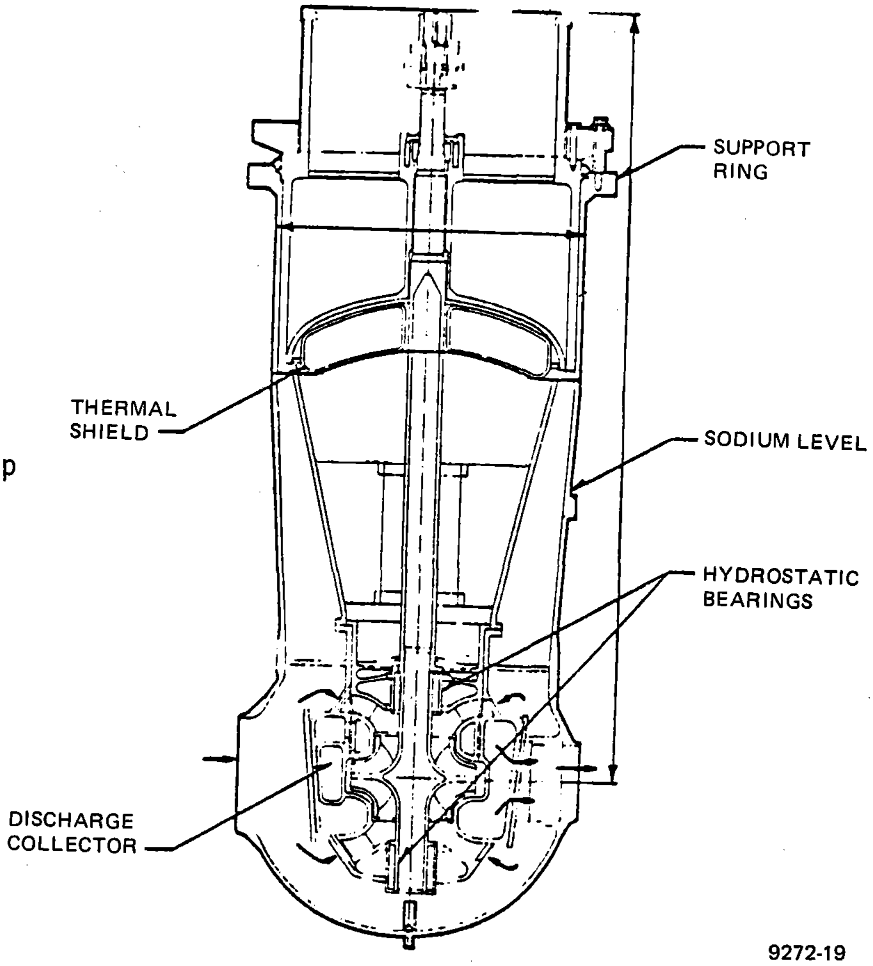
Figure 6. Modular Steam Generator Test Results

Figure 7. Reference Pump



energy available for thermal storage. The shaded area is ~15% of the area under the SM = 1.2 line and represents about 1.15 h of operation from storage at maximum thermal power extraction rate. This is compatible with the 1-h thermal storage capacity parameter chosen for the pilot plant.

The thermal storage subsystem can be charged by introducing sodium into the hot tank at rates up to 100% of the receiver thermal power (36.2 MWt). This maximum charging rate corresponds to a sodium flow rate of 0.338×10^6 kg/h (0.744×10^6 lb/h). Sodium is pumped from the hot storage tank at flow rates up to 0.281×10^6 kg/h (0.618×10^6 lb/h) to generate steam for the turbo-generator system. After flowing through the steam generators, the sodium flows to the cold sodium storage tanks. With the all-sodium thermal storage system, plant operation is always from storage. The steam conditions are the same whether or not the receiver subsystem loop is in operation.

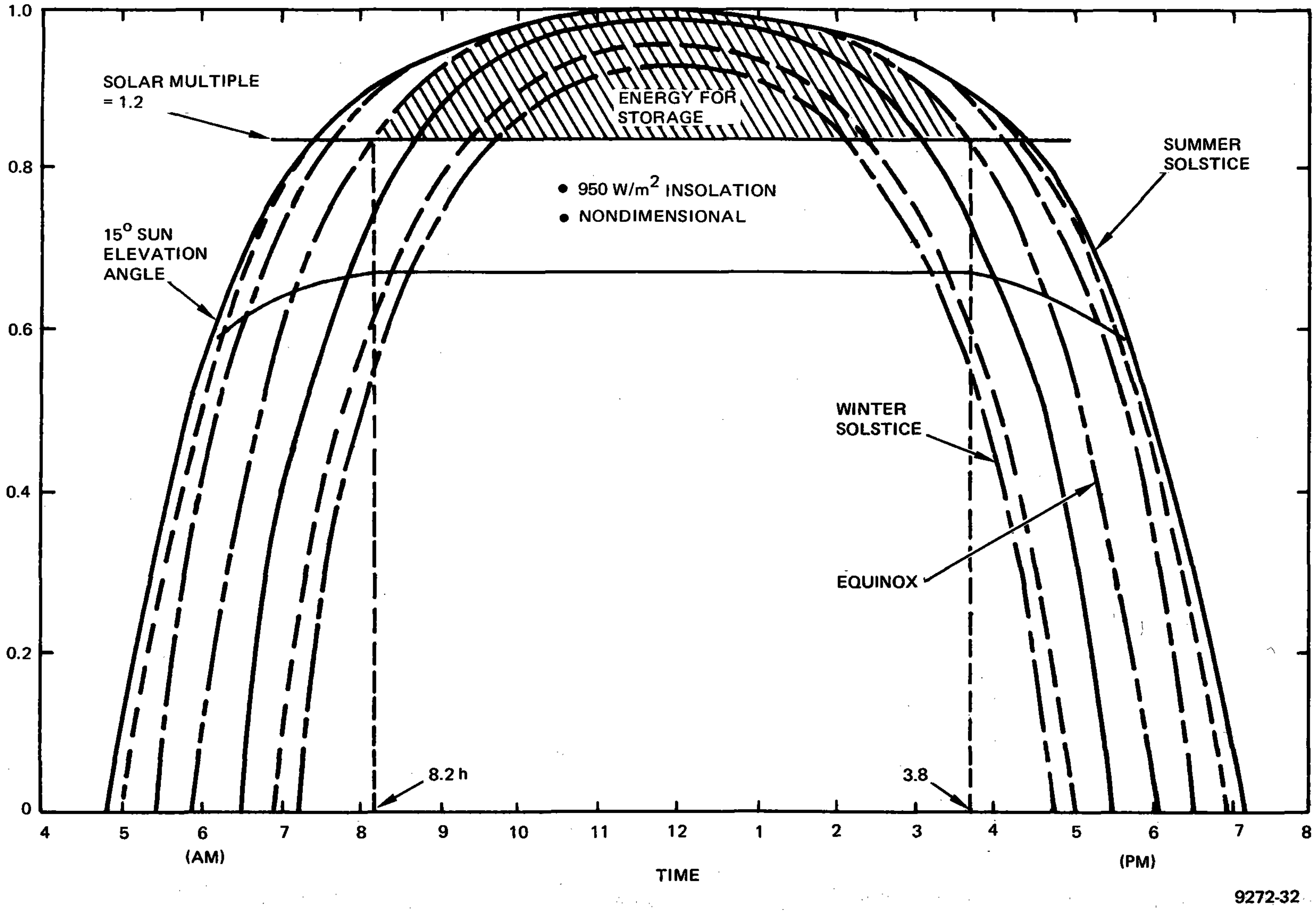


Figure 8. Diurnal Variations in Absorbed Thermal Power

The storage tanks are 10 m (33 ft) in diameter with a height of 5.2 m (17 ft). Since the hot tank operates at 593°C (1100°F), it is made of stainless steel; the cold tank operating at 288°C (550°F) is made of carbon steel. The tanks operate at static head pressures only to minimize design and construction costs. This requires a pressure-reducing device to dissipate the tower static head. There is a total of 0.28×10^6 kg (0.62×10^6 lb) of sodium in the thermal storage subsystem.

The pressure-reducing device for the baseline configuration consists of a nominal 6-in. drag valve. This exact size valve exists and has been tested successfully in the sodium components test loop at the Energy Technology and Engineering Center (ETEC) of Energy Systems Group. A steam generator pump in this system would move the sodium from the hot storage tank through the steam generator to the cold storage tank. The steam generator pump has a capacity of 0.095 m^3/s (1500 gpm) at a developed head of 76 m (250 ft). A pump of this capacity may be found in the equipment inventory at ETEC.

The thermal storage subsystem functional requirements are presented in Table 8. The design characteristics of the all-sodium 10-MWe pilot plant ACR thermal storage subsystem are presented in the design data sheets of Appendix A.

TABLE 8

10-MWe PILOT PLANT ADVANCED CENTRAL RECEIVER THERMAL STORAGE SUBSYSTEM FUNCTIONAL REQUIREMENTS

Parameter	Requirements
Thermal Storage Capacity (MWt-h)	30.2
Maximum Charging Rate (MWt)	36.2
Maximum Extraction Rate (MWt)	30.2
Time at Maximum Extraction Rate (h)	1
Temperature Conditions	Generate Steam at 1000°F $^{+10}_{-50}$

Alternative Air-Rock Storage for Pilot Plant

The pilot plant has a requirement for 1 h of storage at a nominal discharge thermal power of 30.2 MWt and a maximum charge rate of 36.2 MWt. If air-rock storage were considered for the pilot plant, an appropriate design would be to use one module of the nine storage modules in the 100-MWe air-rock design. One of these modules has an active region measuring 28.8 m (94.6 ft) on a side and 10 m (33 ft) in height. The single module consists of six heat exchangers and fans contained in and supported by six vertical ducts made of high-temperature concrete. Each vertical duct has six horizontal concrete hot ducts at the upper part of the rock bed and six horizontal concrete cool ducts near the bottom of the bed.

As in the 100-MWe design, the active region would be enclosed by earth and rock, a 3-m (10 ft) layer of sand or soil would insulate the top of the bed, and a corrugated sheet metal roof lying on the sand or soil would cover the storage region.

The active rock bed would be 6 m (20 ft) thick and have an effective plan view area of 775 m^2 (8330 ft^2). The rock would have a nominal size of 3 to 4 cm (1.2 to 1.6 in.) and be packed with a void fraction of 39%.

Since the thermal power, air flow, and bed frontal area are scaled down from the 100-MWe design to about the same degree, the parasitic fan power in the storage system is also scaled down. Thus, the discharge fan power is about 2% or 0.20 MWe, the maximum fan power is 5% or 0.50 MWe, and the average parasitic drain based on 1 h of storage is about 0.25% or about 0.025 MWe.

The above storage system is over-designed in that it has a nominal 3-h storage capacity. With little loss in performance, the storage capacity can be extended to 12 h. However, there is little economic incentive to employ a smaller rock bed since it is the heat exchangers and fans that control the storage system costs, and these components are determined by the thermal power charge and discharge rates, and are independent of the storage capacity. The above-proposed test module is just like one of the nine modules used in a 100-MWe plant and one of the 25 modules that makes up a 281-MWe plant, so this test would constitute a full-scale test of the storage system. As discussed in Volume II of this report, the air-rock storage can be combined with all-sodium storage to provide the large capacity of the former with the good response and buffering characteristics of the latter. Figure 9 shows the modular construction of 10-MWe, 100-MWe, and 281-MWe air-rock storage systems.

D. COLLECTOR SUBSYSTEM

The definition for the collector subsystem for the advanced system pilot plant was established as a result of an analysis which began by identifying the critical verification issues affecting both the collector field and receiver. A listing of some of these issues, along with comments related to their importance or potential verification by other previously built central receiver systems, is presented in Table 9.

TABLE 9

PILOT PLANT VERIFICATION ISSUES
(Collector - Receiver Related)

Issue	Comment
Commercial Collector Field	Verified in water-steam programs
Heliostat Operation-Control	Verified in water-steam programs (except emergency defocus)
Peak Receiver Heat Flux	Can be demonstrated on single panel
Peak Receiver Thermal Power	Single panel issue
Operation and Control	Requires multipanel simulation
Verify Full Scale Hardware	Individual panel critical element
360^0 Receiver Demonstration	360^0 receiver not critical verification issue
Low Hardware Cost	Minimize number of components-maximize performance

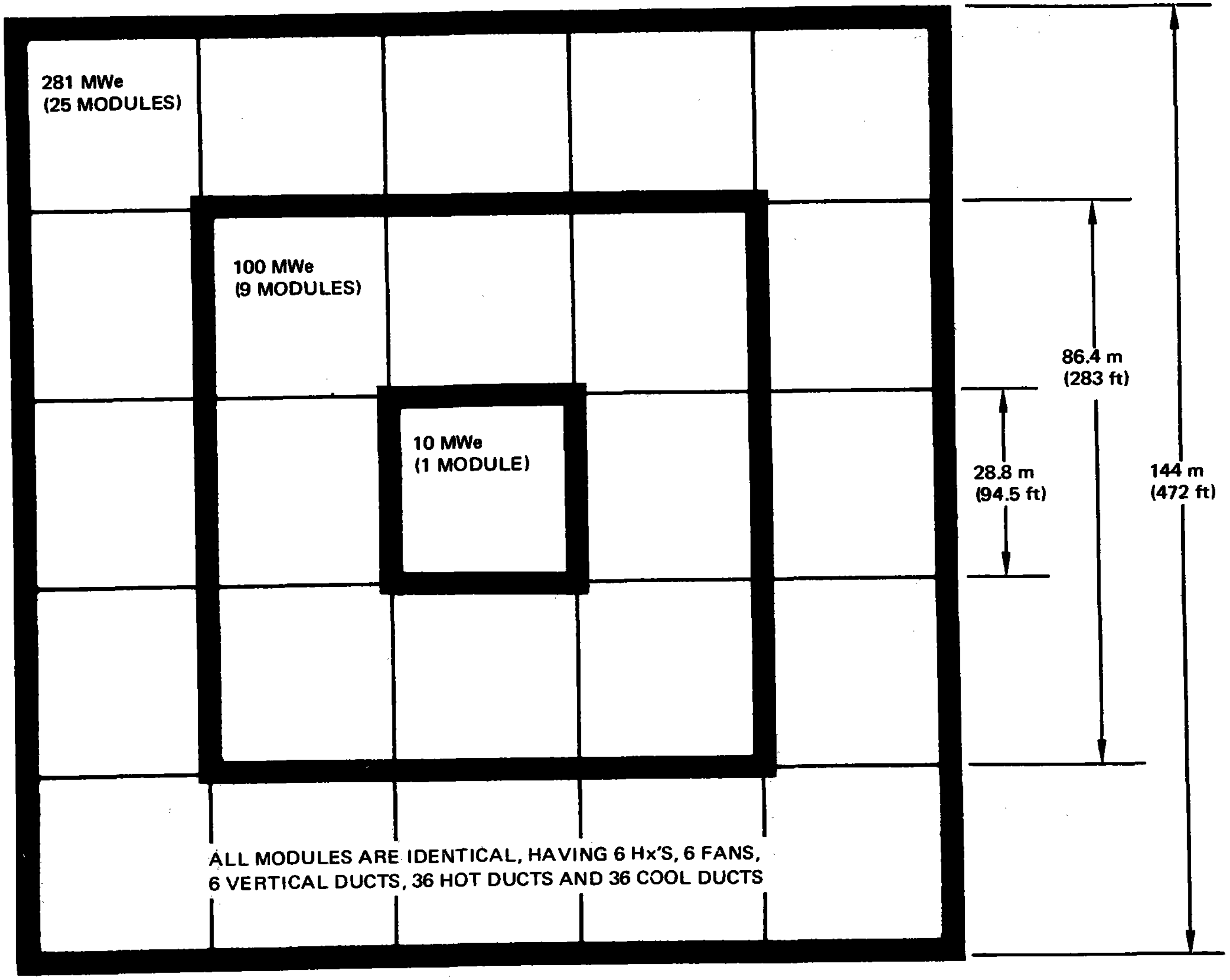


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Figure 9. Outline of Three Air-Rock Storage Systems

For the most part, issues related exclusively to the heliostats or collector are of secondary concern for this pilot plant since these issues will be addressed through the activities carried out as part of the water-steam central receiver programs. As a result, the collector-receiver related issues center most strongly on receiver-related factors which are unique to the sodium system. These issues involve concerns related to:

Peak receiver heat flux
Peak receiver thermal power
Verification of full-scale receiver hardware
Receiver operation and control.

The first three of these issues involve things affecting a single panel, since each panel is the basic heat transfer element which must withstand a specified peak heat flux and total incident power. By verifying a full-sized panel under conditions replicating commercial receiver operation, most of the thermodynamic, heat transfer, and thermal-structural issues will be satisfied. The need to verify receiver operation and control necessarily requires the use of multiple receiver panels to properly simulate fluid dynamic and flow control conditions. In this context, however, it is not necessary to build and test a full 360^0 cylindrical receiver to simulate operation and control since a substantially lower number of panels could be used to provide the same information at lower cost to both the receiver and collector field while preserving the possibility of duplicating commercial levels of peak heat flux and thermal power on individual panels.

In arriving at the preferred approach to the pilot plant collector field and receiver configurations, a more formalized comparative analysis was carried out between a 360^0 collector field and receiver configuration in comparison to a north side collector field and partial cylindrical receiver. The preferred design approach, on an issue-by-issue basis, is summarized in Table 10. Based on information contained in the previous table, three of the first four preferred issues for a 360^0 collector field and receiver (excluding the issue related to receiver operation and control) involve issues of marginal importance for the sodium system pilot plant. Even the operation and control issue can be addressed adequately with less than a full 360° receiver. As a result, one is hard pressed to justify the use of a 360° approach to the design of the collector field and receiver, especially when other more critical issues related to heat flux, thermal power, and full-scale hardware are not easily verified by this approach to pilot plant design.

TABLE 10

EVALUATION OF ALTERNATIVE DESIGNS

Issues	Design Approach	
	Scaled Commercial Receiver (360° Collector Field)	Partial Receiver (North Field)
Commercial Collector Field	X	
Heliostat Operation and Control	X	
Peak Receiver Heat Flux		X
Peak Receiver Thermal Power		X
Receiver Operation and Control	X	X
Verify Full Scale Hardware		X
360° Receiver Demonstration	X	
Low Hardware Cost		X
[Capable of satisfying Pilot Plant thermal power requirements]	X	X

X - Preferred Approach

By contrast, a north field combined with a segment of a full-sized commercial receiver is better suited to addressing these critical issues. By aiming all heliostats at a common spot or along the vertical centerline of a commercial panel, heat flux and panel power levels approaching those of a commercial receiver panel can be duplicated with a minimum number of heliostats on full-scale hardware. Because of incident beam size, additional panels can be included as required to maintain the interception factor at a reasonable level while protecting supporting structure. With the use of multiple panels, the issues related to receiver control and operation can also be verified. For these reasons, the north side collector field combined with a receiver which is a segment of a full-sized commercial receiver was selected as the preferred approach to pilot plant.

Although a cost comparison between the two approaches to pilot plant design was not explicitly carried out, previous work carried out to define a water-steam pilot plant indicated the economic advantage in adopting the north side collector field with a limited receiver for plants in this power range (~10 MWe). This would be even more significant in the case of the sodium pilot plant if the requirement to produce commercial thermal power and heat flux levels was maintained which was not true in the corresponding water-steam pilot plant design. Since the more expensive approach was selected for the water-steam pilot plant to simulate all geometric factors of the anticipated commercial collector field and receiver, it is felt that it would be redundant to repeat this portion of the simulation at the necessarily higher cost.

The approach selected to quantify the pilot plant collector field and receiver characteristics was to direct all energy to a central point on a commercial-sized, north-facing receiver panel while additional panels were added as required to provide adequate beam interception. An optimization analysis was carried out to define the collector field which would satisfy the pilot plant objectives. The input data used to carry out the optimization analysis are shown in the following tabulation.

Assumed Cost Model

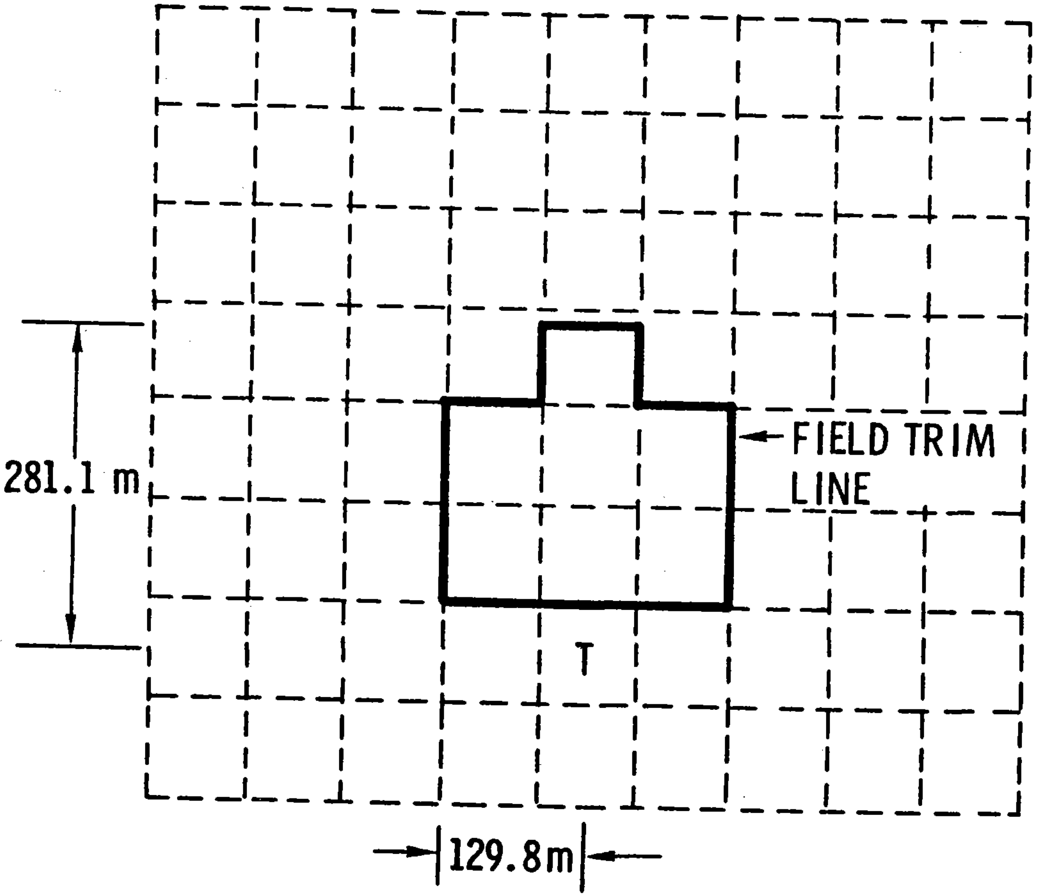
Heliostat - $\$250/m^2$ (Pilot Plant Production)
Receiver - No Cost (Not Subject to Optimization)
Tower - $\$106.5\ (H)^2$ (H = Distance to Top of Structure [m])
Pump - $750/hp
Piping - Same as Commercial System Model
Land - Same as Commercial System Model
Wiring - Commercial Model X (1.5)

These data reflect estimates which were made related to pilot plant particular costs. For this optimization, the costs associated with the receiver have been ignored since it is assumed that the receiver will be there as a basic piece of test hardware and the balance of the system should be configured to maximize the cost effectiveness of the test.

Current optimization analyses have been designed to optimize the energy collection portion of the system on the basis of annual energy. The desirability to optimize on the basis of annual energy must be questioned since this is a verification plant which is not as sensitive to long-term economics of power production. The final definition of the proper optimization criteria will depend on whether the pilot plant is envisioned as a long-term power producer for a utility or as a test facility that can be used to subsequently verify other advanced concepts after the sodium system pilot plant is completed. As these factors are finalized through combined DOE-Contractor solar program activities, proper optimization criteria can be established and employed to produce a pilot plant design which best suits the plant's long-term role.

For comparative purposes, two north field pilot plant configurations were defined. The first configuration was defined to match the peak incident heat flux anticipated for a commercial receiver panel, while the second case was intended to match both the commercial panel peak heat flux and peak thermal power.

The results for the first configuration (match peak heat flux) are shown in Figures 10 and 11. Figure 10 shows the collector field configuration relative to the tower and the computational cell matrix used in the analysis. For this case, approximately 387 heliostats would be contained in the cells immediately to the north of the tower. The heliostat configuration is identical to the baseline commercial system heliostat (49 m^2) defined in Volume II, Section 6.3, except that the reflector panels are assumed to be canted and curved (focused) on a custom basis for each heliostat location. The analytical model attempts to approximate these surfaces by assuming reduced size flat reflector panels. The total beam error budget of 2.3 mr assumed for the analysis, which



T = TOWER

RECEIVER ℄ ELEV = 104 m

NO. HELIOSTATS = 387

AVE GROUND COVERAGE ≃ 0.37

COMPUTATIONAL CELL SIZE
86.5 X 86.5 m

HELIOSTAT CHARACTERISTICS

BEAM ERROR = 2.3 mr (1σ)

APPROXIMATE CUSTOM CANT – PERFECT FOCUS

AIM POINT – CENTER PANEL

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Figure 10. Pilot Plant Collector Field Layout – Match Peak Heat Flux of Commercial Receiver

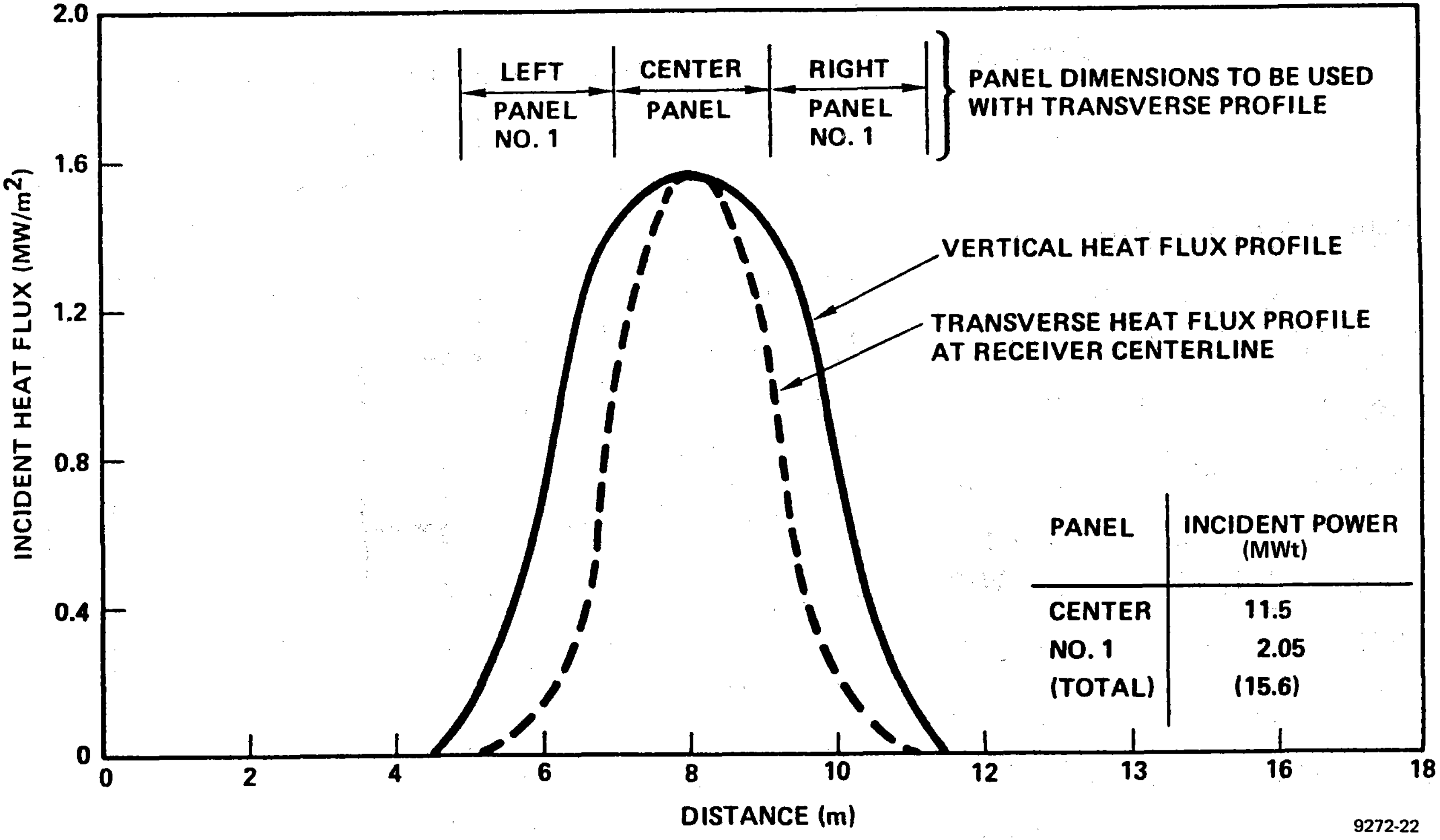


Figure 11. Receiver Heat Flux Distribution — Match Peak Heat Flux of Commercial Receiver

is smaller than the 2.8 mr value used in the commercial analysis, also adds to produce a small, high concentration image from each heliostat. The rationale for using a smaller error budget is again based on the recognition of the pilot plant verification objectives. The larger error budget corresponds with the commercial requirement to maintain in-spec performance from 0 to 40°C (32 to 104°F) and at sustained winds to 12 m/s (26.8 mph). In a pilot plant situation, it seems inappropriate to impose as severe a temperature and wind criteria since out-of-spec operation at the temperature and wind extremes would not impair the validity of the test and verification program. On the other hand, by assuming the smaller error budget, smaller, higher intensity images can be assumed which can produce high heat fluxes with a minimum number of heliostats, although these images would not be maintained at all operating times during the year.

The corresponding heat flux characteristics in both a vertical and transverse direction are shown in Figure 11. The vertical heat flux profile, which occurs along the centerline of the commercial panel (center panel on the receiver), begins at approximately the 4.5 m elevation, peaks at approximately 8 m elevation, and approaches 0 at the 11.5 m location. For a full-sized (16.5 m high) panel, a significant portion of the top and bottom of the panel would experience no significant heat input. By spreading the images over the surface to rectify this problem, the peak flux intensity would no longer be maintained.

For comparative purposes, the transverse heat flux profile that exists along a horizontal line at the receiver centerline is also shown. The horizontal dimensions for three commercial receiver panels are shown at the top of the figure. It shows that a significant portion of the power strikes the center panel while the transverse profile falls rapidly to zero as one moves farther out on the left or right side panel. It indicates that most or all of the incident power would be intercepted by a three-panel receiver, although extreme transverse gradients would be experienced by the left and right side panels.

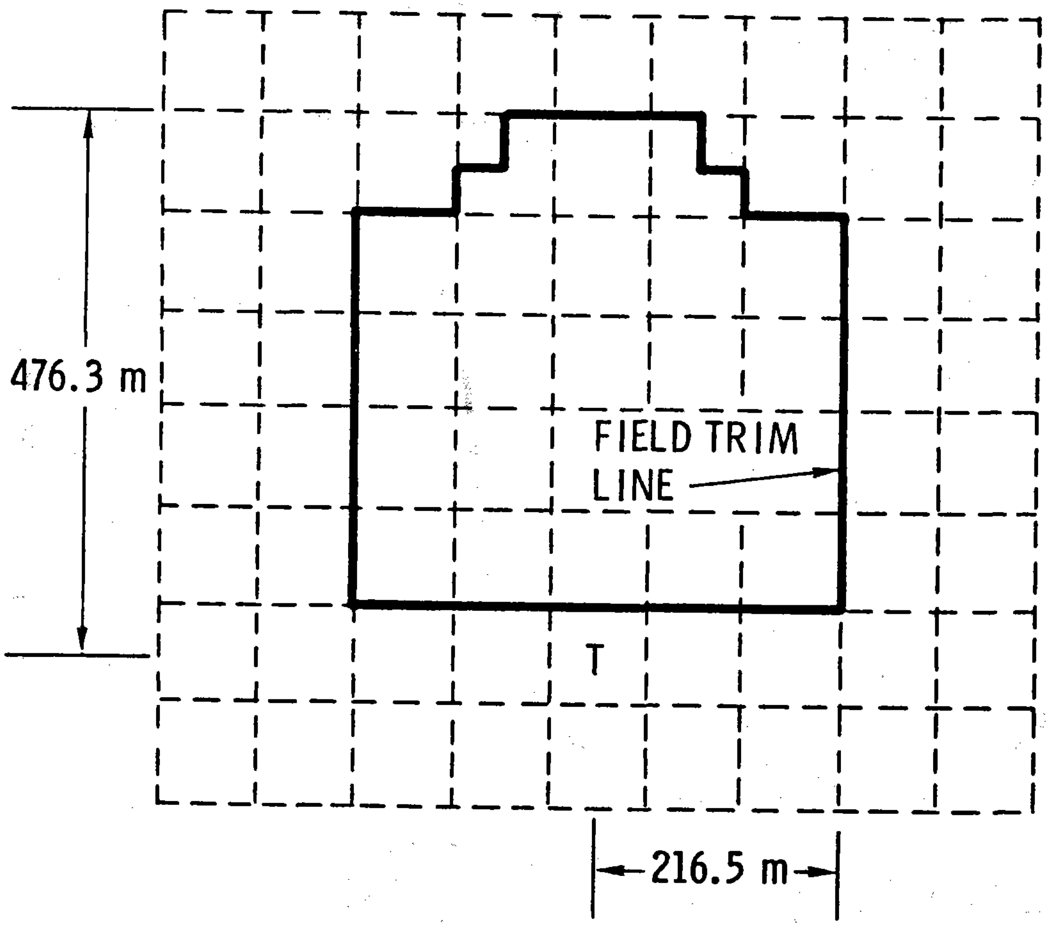
Also shown in Figure 11 is the predicted incident power level for each panel. It is seen that an approximate ratio in power of 6:1 between the center test panel and a side panel would exist for this configuration. Variations of this magnitude would not provide a meaningful simulation of multipanel receiver operation at a commercial level since a normal max/min power ratio would be ~3:1 between north and south facing panels. In addition, the total power of 15.6 MWt would be insufficient to operate a power conversion subsystem anywhere near a 10-MWe rating.

The second north field configuration considered was defined so that both the peak heat flux and incident thermal power for a full-sized commercial receiver panel were simulated. This field was arrived at by adding heliostats to the previous system and adjusting the aim strategy until both requirements were simultaneously satisfied.

The resulting pilot plant field characteristics are shown in Figure 12. As indicated, substantially more computational cells are retained to satisfy the higher power level with 1065 custom canted, perfectly focused heliostats being required. The error budget of 2.3 mr was retained from the previous analysis.

The corresponding transverse and vertical heat flux data along with an estimate of the incident power levels for each panel are shown in Figure 13. It is seen that a vertical aim strategy is employed to limit peak heat flux while adding sufficient power to match the commercial level. In this case, the top and bottom 2 m portion of the center panel is deficient in incident heat flux. By adjusting the vertical aim strategy, however, this problem could be eliminated. The transverse profile as indicated affects slightly more than the center three panels. Because the outer panels experience such a low flux level, they could be replaced with flux redirectors which could also go a long way to alleviate some of the transverse gradient which would exist across the left and right No. 1 panels.

In addition to matching the incident panel power for a commercial panel, the ~3:1 ratio in power between the center panel and either the right or left No. 1 panels makes this an attractive configuration for the simulation of multiple panel operation since this ratio closely matches variations between north



T = TOWER

RECEIVER ℄ ELEV = 104 m

NO. HELIOSTATS = 1065

AVE. GROUND COVERAGE ≃ 0.27

COMPUTATIONAL CELL SIZE
86.5 X 86.5 m

HELIOSTAT CHARACTERISTICS

- BEAM ERROR = 2.3 mr (1σ)
- APPROXIMATE CUSTOM CANT – PERFECT FOCUS
- AIM POINT – CENTER PANEL (VERTICAL STRATEGY ONLY)

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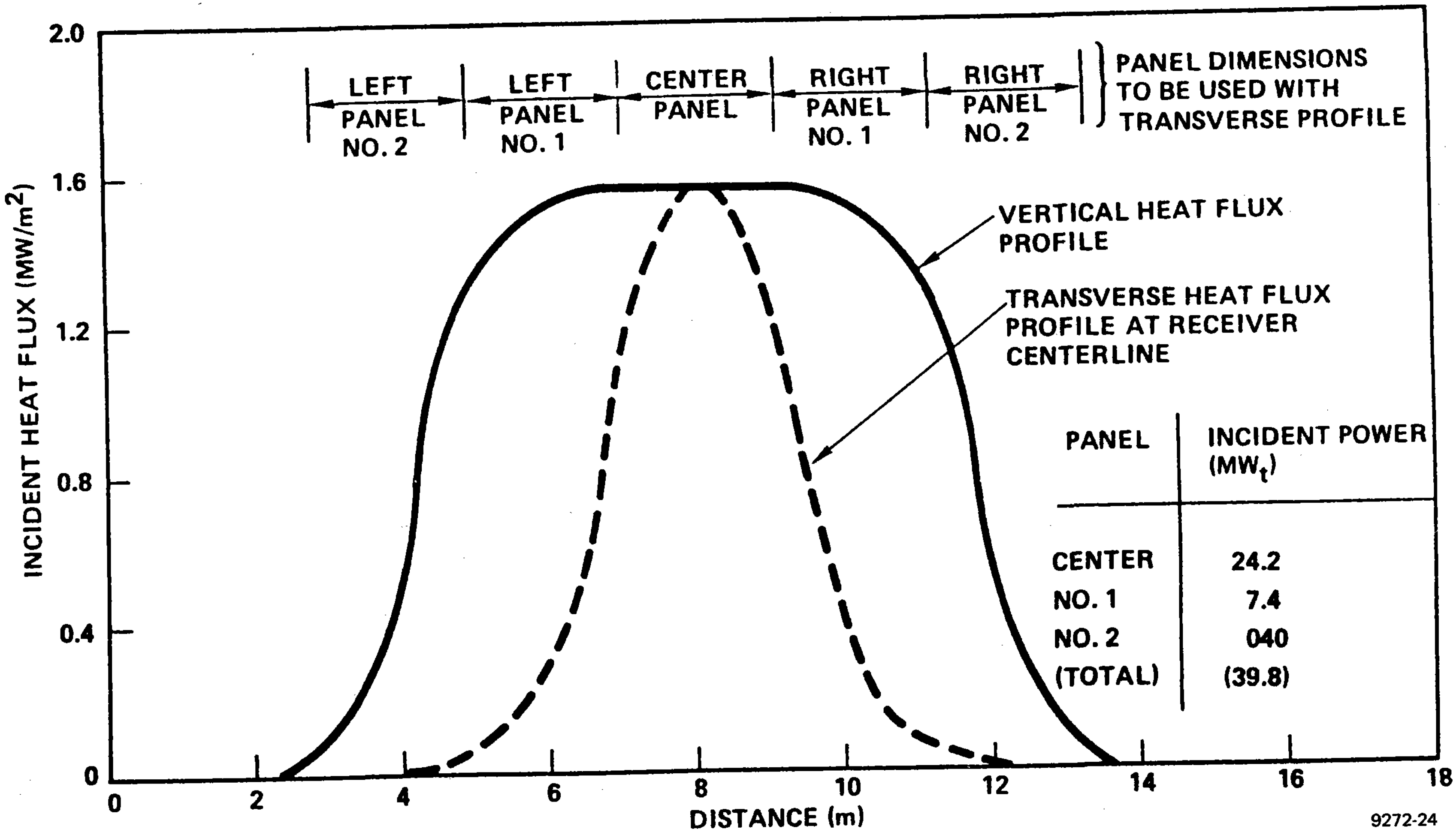
Figure 12. Pilot Plant Collector Field Layout – Match Peak Heat Flux and Panel Power of Commercial Receiver



PANEL	INCIDENT POWER (MW_t)
CENTER	24.2
NO. 1	7.4
NO. 2	040
(TOTAL)	(39.8)

Figure 13. Receiver Heat Flux Distribution — Match Peak Heat Flux and Panel Power of Commercial Receiver

and south facing commercial panels. The total power level of 39.8 MWt also provides the ability of this plant to power an electrical power subsystem of about the 10-MWe capacity. For these reasons, this collector field, tower, and receiver configuration was selected as the conceptual baseline for the advanced system pilot plant.

It should be emphasized that the pilot plant definition presented in this section is of a conceptual level only and should not be construed as final design configurations. Detailed studies carried out during the preliminary design phase for the pilot plant will be required to finalize the configuration. Both system and subsystem issues will be considered in these expanded analyses.

System design guidelines will emerge as a result of joint analysis between DOE and the ESG engineering team which will serve as ground rules for the pilot plant design. These issues include the need for utility participation and the subsequent objective of electrical power generation, overall pilot plant budget, the need to maintain in-spec operation over a significant range of ambient temperatures and wind speeds, test activities carried out at other existing central receiver pilot plants, and the potential role of this pilot plant in the demonstration of other advanced system concepts.

Collector subsystem related issues which can influence the final pilot plant configuration include the compromise between high performance and cost effective heliostat design. Clearly, the custom cant-custom focus approach to maximize optical performance is not compatible with the goal of commonality as dictated from a manufacturing and spare parts standpoint. Off-axis abberation is also a factor that must be carefully considered in developing a preliminary pilot plant design. Other factors include the accuracy of the analytical representation of a heliostat surface and the potential impact of any flux redirectors which may be employed on the receiver.

E. ELECTRIC POWER GENERATING SUBSYSTEM

With the three-panel, full-size receiver design, the collectable energy is indicated to be about 38 MWt. This power implied a net generating capability of about 10 MWe. Additional guidelines for selecting a turbine for the pilot plant were:

1) Commercially available turbines for installation in the mid-1980's
2) Use standard turbine designs and metallurgy, thus minimizing technical risk
3) Use standard steam conditions for turbines in the 10 MWe size range best representing the commercial plant design.

Since reheat is not available for turbines of this size, the steam generator arrangement was simplified to include a single unit to provide a once-through to superheat capability, as discussed in previous sections. A selection of turbine-generator combination is given in Table 11, each with a rating of 10,500 kWe. All combinations are single shell, single flow turbines with either 25.4 cm (10-in.) or 28.9 cm (11.4-in.) last stage blade (LSB) length. All units supplied three feedwater heaters with a typical cycle arrangement as shown in Figure 14. Wet cooling was assumed, with conditions to give 6.77 kPa (2.0-in. Hg abs) turbine exhaust pressure. The ten cases presented in Table 11 show the increasing cycle efficiency with increasing turbine inlet temperature and to a lesser extent with increasing turbine inlet pressure.

In order to determine the most cost-effective turbine arrangement, the system cost increment as a function of cycle efficiency was determined. This increment for the pilot plant is $\$0.5 \times 10^6$ for a one-point change in efficiency. Table 11 shows the increment in turbine cost and the system cost increment (decrement) for each of the configurations referenced to Case 1 as a base condition. This comparison shows Cases 5 and 10 to be the most cost effective (largest net negative increment) with a small advantage for Case 10. However, Case 5, with a 10-in. last stage blade length, was selected earlier in the study and is retained as the pilot plant reference configuration to give a cycle efficiency of 37.1% as shown in Table 12.

TABLE 11

CANDIDATE PILOT PLANT TURBINE PERFORMANCE AND COST
(Sheet 1 of 2)

Basis

Turbine Type:	Single Shell, Single Flow, 10.0 in. LSB*, Rating 10,500 kWe (14,375 kVA)
Number of Heaters:	3
Final FW Temperature:	195°C (383°F)

	Preliminary Data				
Throttle Pressure [MPa (psig)]	4.14 (600)	5.86 (850)	8.62 (1,250)	10.00 (1,450)	10.00 (1,450)
Throttle Temperature [°C (°F)]	440 (825)	482 (900)	510 (950)	510 (950)	538 (1000)
Exhaust Pressure [kPa (in.-Hg abs)]	6.77 (2.0)	6.77 (2.0)	6.77 (2.0)	6.77 (2.0)	6.77 (2.0)
Gross Turbine Heat Rate [kJ/kW-h (Btu/kW-h)]	11,363 (10,771)	10,664 (10,108)	10,088 (9,562)	10,050 (9,526)	9,709 (9,203)
Gross Cycle Efficiency (η %) $\Delta\eta$ (%)	31.68 Base	33.76 0.08	35.69 4.01	35.82 4.14	37.08 5.40
Estimated Turbine Generator Cost ($\$10^3$)	1,863	1,938	2,014	2,014	2,049
① Δ Turbine Generator ($)	Base	75	151	151	186
② Δ System Cost ($\$10^3$)	Base	-40	-2000	-2070	-2700
Δ Net Cost ① + ② ($\$10^3$)	—	+35	-1849	-1920	-2510

*Last stage blade (length)

TABLE 11

CANDIDATE PILOT PLANT TURBINE PERFORMANCE AND COST
(Sheet 2 of 2)

Basis

Turbine Type:	Single Shell, Single Flow, 11.4 in. LSB, Rating 10,500 kWe (14,375 kVA)
Number Heaters:	3
Final FW Temperature:	195°C (383°F)

	Preliminary Data				
Throttle Pressure [MPa (psig)]	4.14 (600)	5.86 (850)	8.62 (1,250)	10.00 (1,450)	10.00 (1,450)
Throttle Temperature [°C (°F)]	440 (825)	482 (900)	510 (950)	510 (950)	538 (1000)
Exhaust Pressure [kPa (in.-Hg abs)]	6.77 (2.0)	6.77 (2.0)	6.77 (2.0)	6.77 (2.0)	6.77 (2.0)
Gross Turbine Heat Rate [kJ/kW-h (Btu/kW-h)]	11,194 (10,610)	10,505 (9,957)	9,937 (9,419)	9,862 (9,348)	9,564 (9,065)
Gross Cycle Efficiency (%) $\Delta\eta$ (%)	32.16 0.48	34.27 2.59	36.23 4.55	36.51 4.83	37.65 5.97
Estimated Turbine Generator Cost ($\$10^3$)	2,053	2,122	2,185	2,185	2,245
① Δ Turbine Generator ($)	190	260	322	322	382
② Δ System Cost ($\$10^3$)	-240	-1300	-2280	-2420	-2990
Δ Net Cost ① + ② ($\$10^3$)	-60	-1040	-1960	-2100	-2600

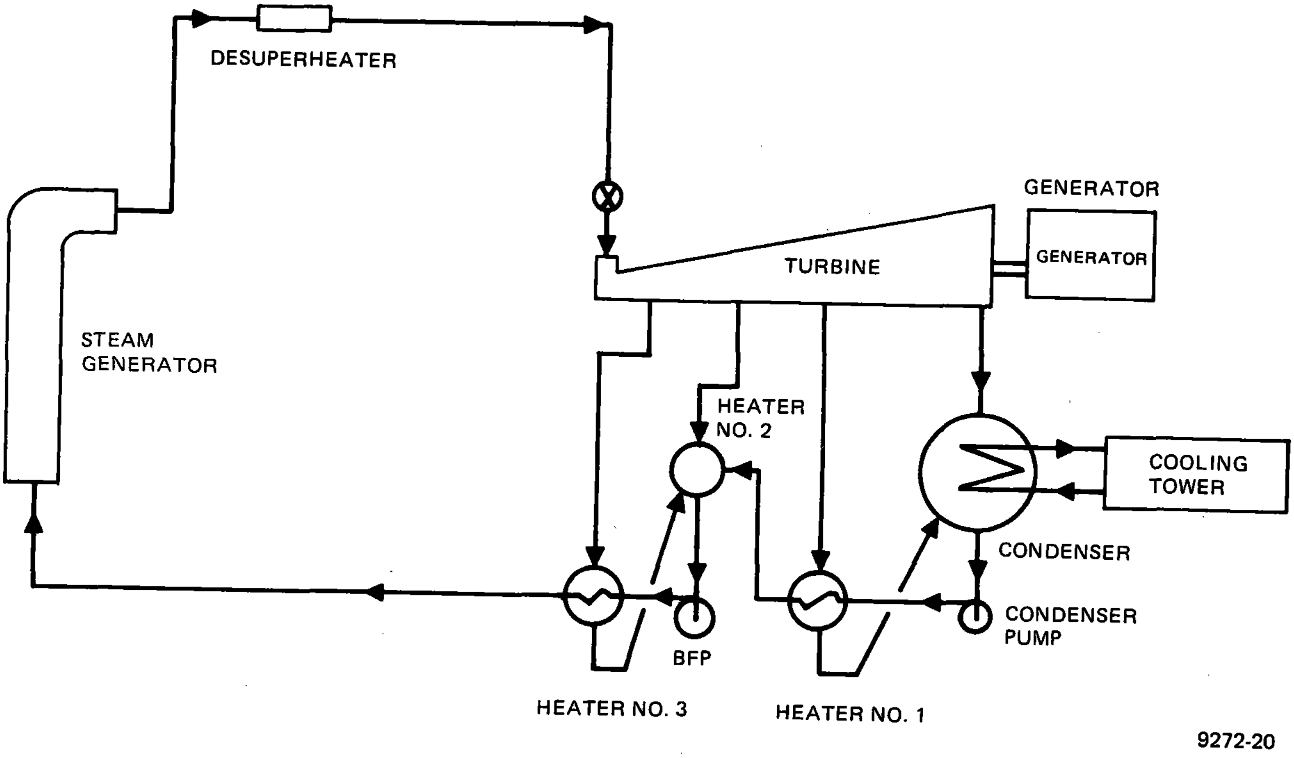


Figure 14. Pilot Plant Turbine Cycle

Figure 15 shows a schematic arrangement of the tower for the pilot plant. A steel tower is used based on the results of a trade study for the water-steam power plant which indicated that for towers of this height, a steel structure was less expensive. This study is considered to be valid for the subject pilot plant.

F. MASTER CONTROL PILOT PLANT

The master control subsystem for the pilot plant shown in Figure 16 will require the hardware and software described to monitor and control the commercial 100-MWe plant (reference: Section 8.0 to Vol II) with the following exception:

> The pilot plant will utilize an independent stand-alone data acquisition and collection system to accommodate experimental and performance instrumentation requirements.

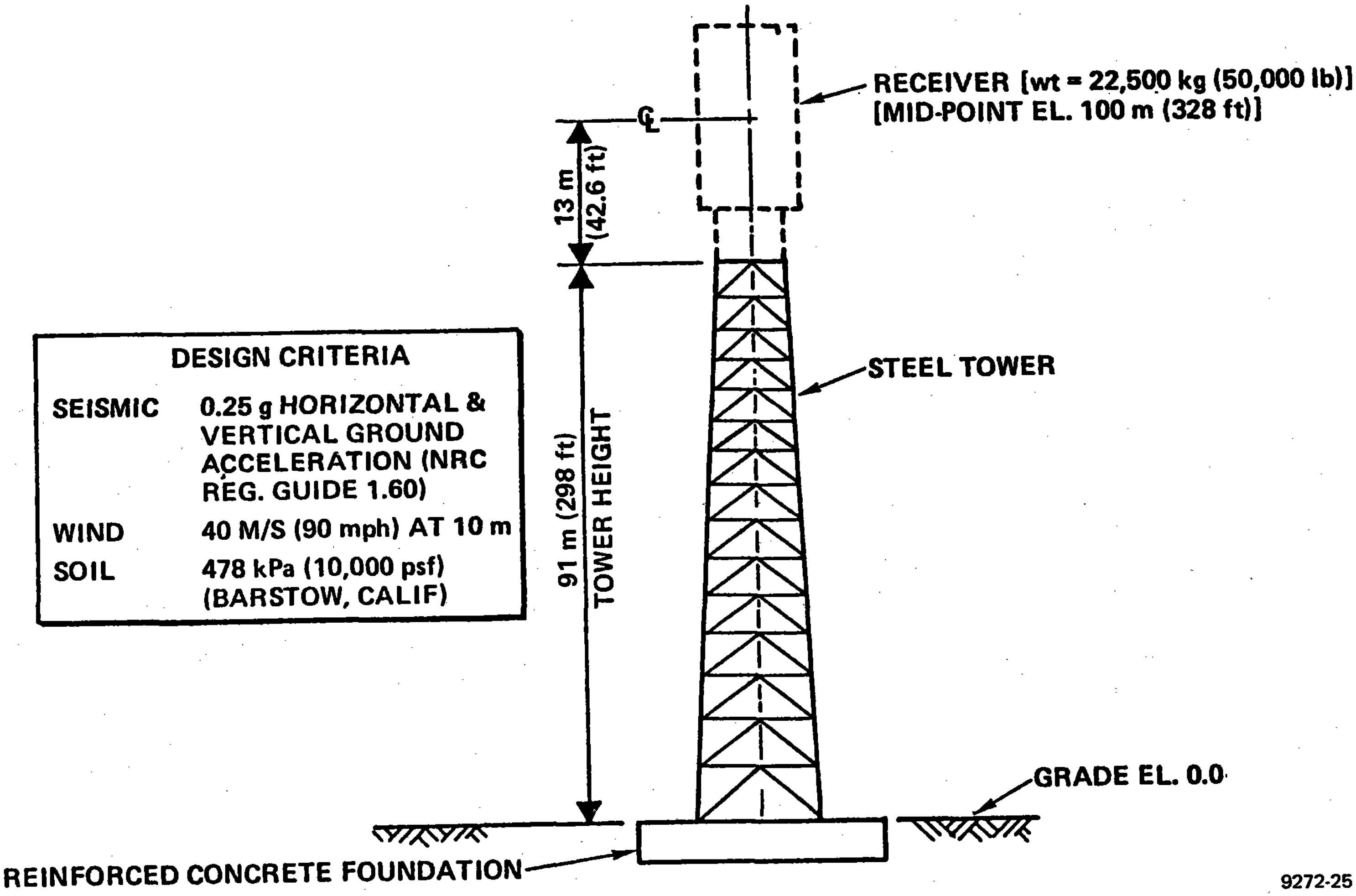


Figure 15. Pilot Plant Receiver Tower

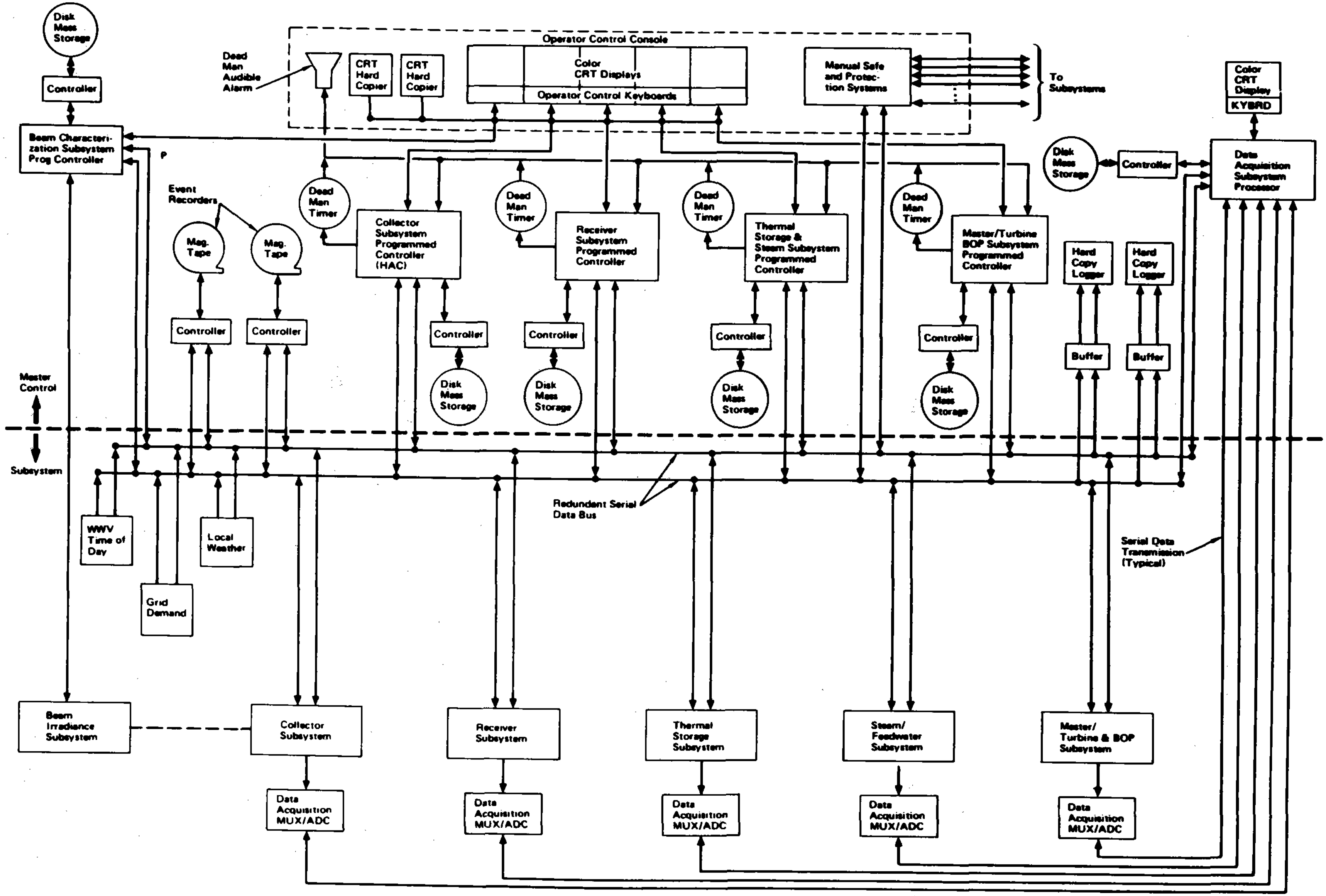


Figure 16. Master Control Subsystem — Block Diagram

TABLE 12

SELECTED PILOT PLANT TURBINE-GENERATOR CHARACTERISTICS

Turbine Type	Single Shell, Single Flow (10.0-in.-LSB) 3 Extraction, Condensing
Rating	11,200 kW (14,000 kVa)
Throttle Pressure	10.0 MPa (1,450 psig)
Throttle Temperature	538°C (1000°F)
Exhaust Pressure.	6.77 kPa (2.0-in.-Hg abs)
Number Heaters	3
Final Feedwater Temperature	204°C (400°F)
Gross Turbine Heat Rate (Est.)	9,709 kJ/kW-h (9,203 Btu/kW-h)
Gross Cycle Efficiency (Est.)	37.1%

Because the pilot plant configuration requires a fewer number of receiver panels (3) than used for the 100-MWe plant (24), the quantity of instrumentation for receiver control functions of master control would be reduced. This reduction, however, is believed to be offset by the addition of panel monitor temperatures from an estimated 15 per panel for the commercial plant to an estimated 80 per panel for for the pilot plant. The additional thermocouples will be used to establish heliostat aim strategies under various operational and insolation conditions.

For the pilot plant it is proposed that an independent stand-alone data acquisition and collection subsystem be used to acquire, reduce, and store data evaluating plant and subsystem unit performance. This system shown in Figure 17 would be interfaced to the redundant serial data bus to acquire MCS

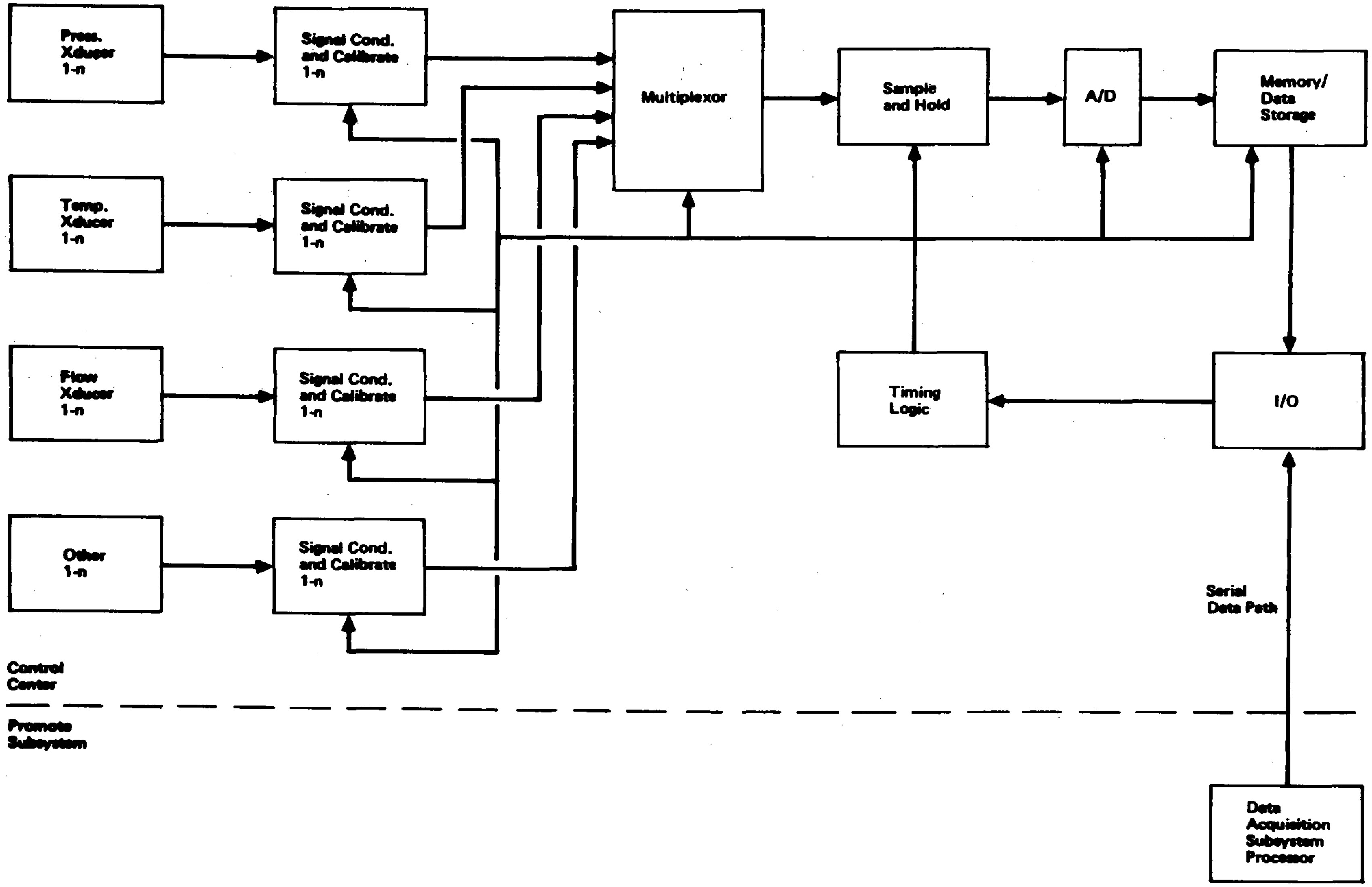


Figure 17. Data Acquisition Subsystem — Block Diagram

control and performance parameters. A second serial digital interface would connect to each of the remote subsystems where analog and digital measurements would be transformed and formatted for transmission to the data collection system.

An independent system control and display console would provide the engineer and operator with the capability to command and view raw and reduced data. Through this control and display console, the operator will be able to select the measurements to be sampled, the rate of sampling, and the length of time to sample.

Software modules in the data acquisition and collection subsystem will perform the following functions:

Configure the data acquisition and collection system operation (i.e., measurements to be sampled, sample rate, sample interval).
Calibrate the raw data to engineering form.
Manage the collected data using time and event tagging, merging, and editing routines.
Store data for display and analysis.
Output data to the operator terminal for review.
Diagnose data acquisition and collection subsystem hardware performance.

G. PILOT PLANT COST

The estimated pilot plant construction costs are given in Table 13. The details of the plant construction costs are presented in Volume IV. The estimated cost breakdown by fiscal year is shown in Table 14. These costs are budgetary and planning estimates, and are presented without overhead and fee.

TABLE 13

ADVANCED CENTRAL RECEIVER 10-MWe PILOT PLANT CONSTRUCTION COSTS

CBS	Subsystem	Cost/1000 ($)
4100	Site, Structures, etc.	1,427
4200	Turbine Plant Equipment	4,880
4300	Electric Plant Equipment	3,154
4400	Collector Equipment	10,550
4500	Receiver Equipment	8,063
4600	Thermal Storage Equipment	1,471
4800	Distributables and Indirect	9,761
	Total	39,306
Phase II Engineering	(Preliminary Design)	1,455
		40,761*

*Without overhead and fee

TABLE 14

PILOT PLANT DEVELOPMENT COSTS BY FISCAL YEAR*

Item	Fiscal Year ($000)				
	79	80	81	82	83
Phase II	22	633			
Phase III, Final Design and Construction		3,723	26,136	9,447	Operation
Total	827	4,356	26,136	9,447	

*Without overhead and fee

III. SUBSYSTEM RESEARCH EXPERIMENTS

This section presents several subsystem research experiments (SRE) that have been evaluated in terms of supporting the pilot plant and advancing the development of the advanced central receiver system. The purpose of these experiments is to test components or systems for which an adequate experience base does not exist and/or to provide verification of analytic results. The sodium-cooled receiver is a new component, but it is generally considered that adequate performance and structural analysis techniques are available. However, verification testing appears to be highly desirable, in order to avoid extensive in-plant development.

For the air-rock storage concept, the uncertainties concern the durability of the rock material under repeated thermal cycling and the operational characteristics. The basic analysis techniques are believed to be adequate and industrial experience is available in a pebble bed heater but with a different operational use.

All other components of an advanced receiver system are considered to have an adequate experience base.

A. RECEIVER CYCLING TEST (ETEC)

This test would use a subsection of a receiver panel to obtain the effects of thermal cycling in the tubes and panel structure. The test requires a sodium flow capability and a radiant heat source to simulate the flux distribution on a receiver panel from a collector field. Purpose of this test was to confirm fatigue life of the receiver. A critical evaluation of the proposed test indicates that the flux distribution will not be sufficiently severe or the accumulated cycles sufficiently high to provide satisfactory quantitative data. The test is consequently given a low priority in the development planning in the next section.

The test article is a subsection of one of the 24 panels that form the complete receiver. The test article is about 1/18 the size of a panel, i.e., 1/2 the width with 58 tubes and a height of 6 ft. Test article details are shown in Figures 18 and 19. The energy flux on a full-sized panel varies with its location on the receivers such as shown in Table 15. This table also shows the characteristics of the test panel. The average energy flux on a north-facing full-size panel is 1 MWt/m^2 with a peak flux of 1.67 m^2 as shown in Figure 20. The average flux on a south-facing panel is 0.25 MWt/m^2. Since the test article is about 2 m^2, the maximum power input could be 2 MW. While it is desirable to test at these levels, the tests can be accomplished at reduced power levels representative of the average panel or south panel by reducing the sodium coolant flow rates and still achieve similar panel temperature gradients. However, the tube crown temperatures will be reduced slightly. The flux distribution on a full-size panel is as shown in Figure 20. For the test panel, a similar distribution is desirable but compressed to a 6-ft length.

In the design of Figure 19, both the upper and lower manifold are fixed to the support structure. Panel expansion and contraction are accommodated primarily by the lower horizontal run of tubing from the panel face to the manifold. This horizontal run is also designed to accept input energy spillover from the panel face. For the test article, the horizontal run of tube is reduced in length in proportion to the height reduction in order to keep the mechanical load condition on this run and the manifold due to thermal expansion similar for the test article and the full-size panel.

The test article panel is mounted to the backup support structure with clips similar to the full-size panel. Two inches of insulation are placed between the panel and the support structure. The backup support I-beams are attached to tower support guides which allow differential thermal expansion movements of the panel with respect to the tower structure.

B. TEST FACILITY REQUIREMENTS

The subject test article requires a test facility with liquid sodium flow circulation capability of 100 gpm and a heat rejection capability of up to 2 MWt. A radiant energy source of up to 2 MWt is desirable, but radiant energy

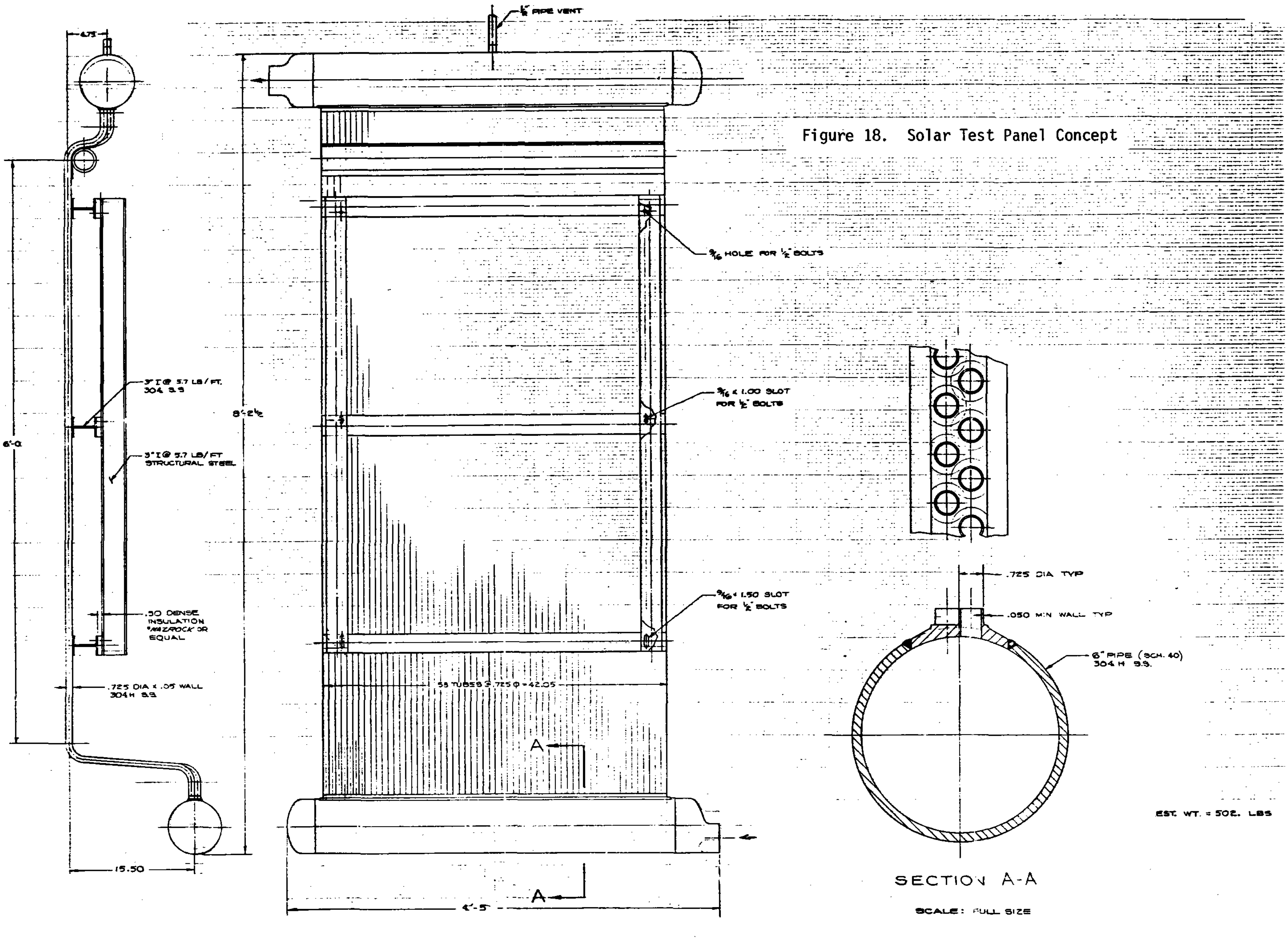


Figure 18. Solar Test Panel Concept

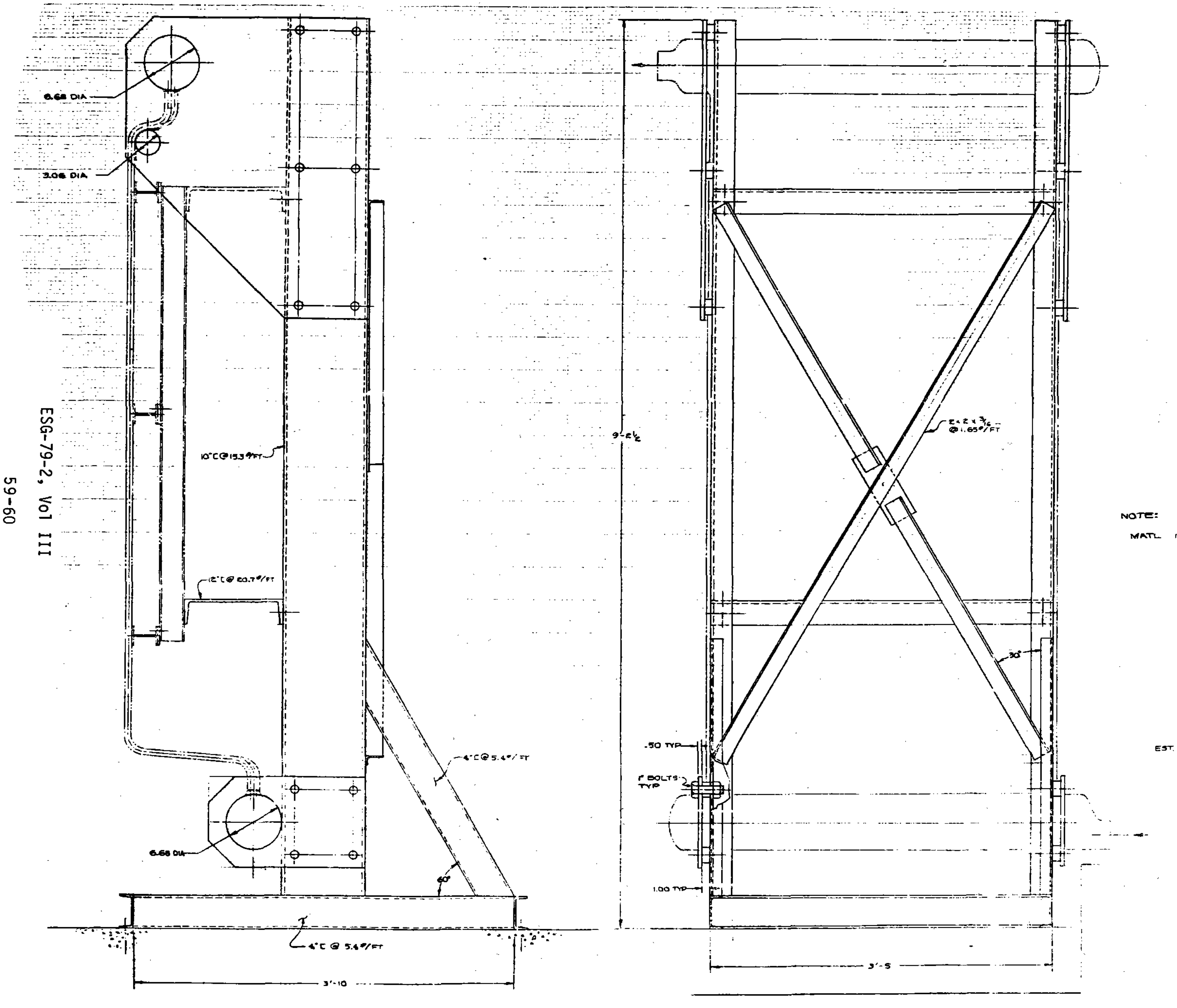


Figure 19. Test Stand (Solar Test Panel)

TABLE 15

100-MWe RECEIVER CHARACTERISTICS

	Panel			Test Panel*
	North	Ave	South	
Power (MWt)	37	20.2	9.2	1.05
Panel Area (m^2)	37.4	37.4	37.4	1.95
Ave Flux (MW/m^2)	0.99	0.54	0.25	0.54
Flow Rate (kg/s) lb/s	96.8 212.5	52.3 116.0	24 52.8	2.8 6.1
No. of Tubes	116	116	116	58
Flow per Tube [cm^3/s (gpm)]	981 (15.57)	535 (8.5)	244 (3.87)	57 (0.9)
Tube ID [cm (in.)]	1.6 (0.625)	1.6 (0.625)	1.6 (0.625)	1.6 (0.625)
Velocity in Tube [m/s (ft/s)]	4.5 (14.9)	2.5 (8.13)	1.12 (3.7)	0.27 (0.9)
Manifold Dia [cm (in.)]	25.4 (10)	25.4 (10)	25.4 (10)	15.2 (6)
Velocity in Manifold [m/s (ft/s)]	2.2 (7.4)	1.22 (4.03)	0.56 (1.83)	0.18 (0.58)
Panel Supply Pipe [cm (in.)]	15.2 (6)	15.2 (6)	15.2 (6)	5.1 (2.0)
Velocity in Supply Pipe [m/s (ft/s)]	6.1 (20.0)	3.3 (10.9)	1.5 (5.0)	3.0 (10)
Width [cm (in.)]	5.6 (2.2)	5.6 (2.2)	5.6 (2.2)	2.7 (1.07)
Length [cm (in.)]	43 (17)	43 (17)	43 (17)	4.6 (1.83)

*Based on average flux conditions

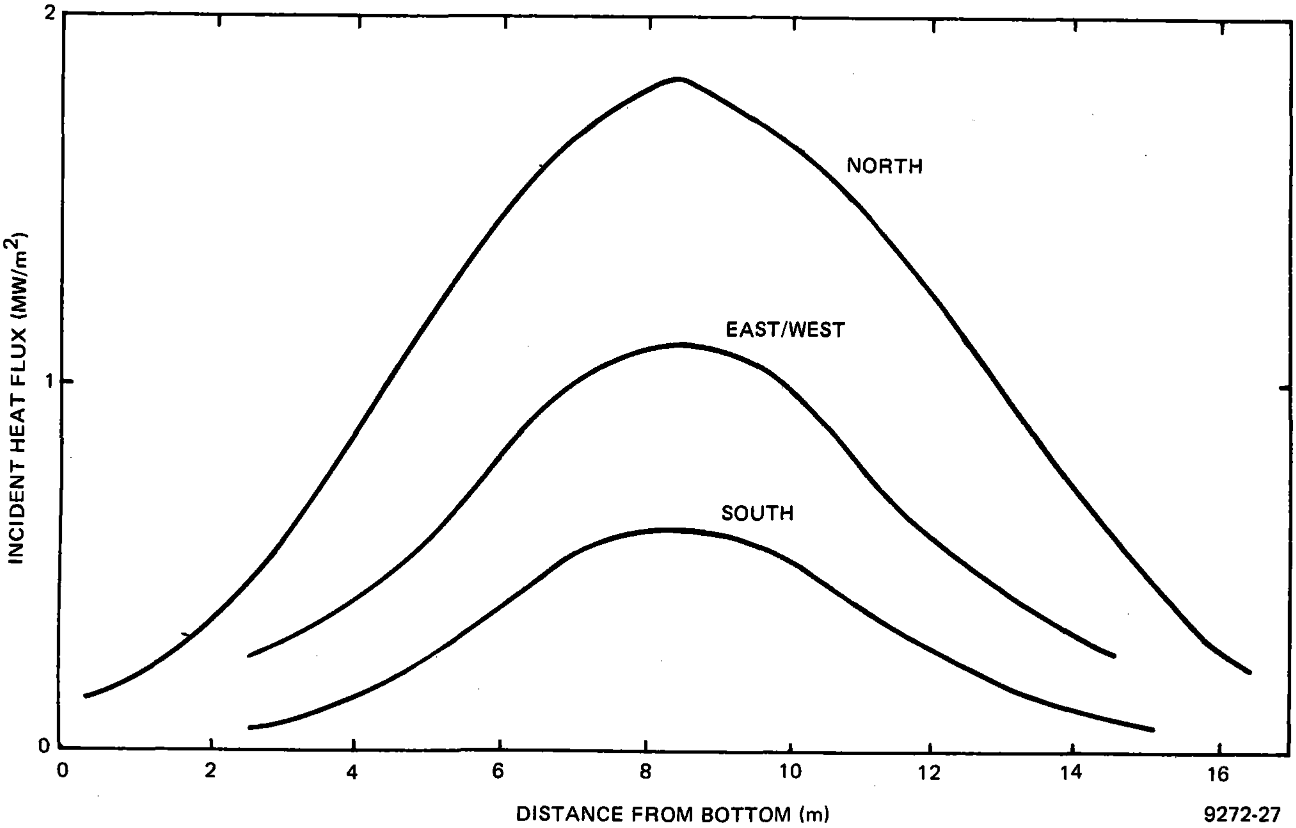


Figure 20. Receiver Heat Flux Profiles Equinox Noon

to 0.5 MW is considered to be acceptable. A facility with this combination of capabilities does not currently exist, though the separate capabilities exist at different locations.

The Energy Technology Engineering Center (ETEC) operated by ESG for DOE has several suitable liquid sodium flow circulating facilities with satisfactory heat rejection equipment. To use these sodium facilities, a radiant energy source must be provided, such as an electric powered heat lamp array. Georgia Tech and Sandia, Albuquerque, both have mirror collector fields with 400 kWt and 5 MWt radiant energy available. For these facilities, liquid sodium flow capability with heat rejection must be provided.

A study of the best facility option to pursue is beyond the scope of this proposal. The following observations are made:

1) The most economic short-term solution is probably to provide a radiant energy source at an ETEC sodium facility. A radiation source may be available from other DOE test programs such as the Martin-Marietta test of the 1-MWt cavity receiver or the Minneapolis-Honeywell 5-MWt test program. While radiant energy solar simulators can probably achieve an energy flux of 0.05 MWt/m^2, a higher level to simulate the peak of the profile of Figure 20 probably is not attainable.

2) A long-term solution may be to install a sodium loop at Georgia Tech or Sandia, Albuquerque. At Georgia Tech, the entire facility is required to provide about 40% of full power testing. At Sandia, only 20% of the collector field is required for full power testing. ESG has designed, built, and operated many small sodium loops and would welcome the opportunity to design and build a small loop at one of the solar facilities. The appendix shows a flow schematic of a 5-MWt sodium test loop. Design data sheets are included for the major sodium components. A similar flow schematic with component reduced to the appropriate size could also be used for the Georgia Tech facility. ESG also has knowledge about certain sodium components such as pumps and heat exchangers that may be available from other programs and hence reduce the cost of such a supporting facility.

C. TEST PROGRAM

A tentative test program is outlined in Table 16. A 4-mo test effort is indicated with about 1000 h of test time. The various test sequences are based on 8-h days, but if a collector field provides the radiant energy, the actual length of the day will vary with the time of the year.

The initial steps of the test program provide for the dry and wet checkout of the test article. This is followed by testing to determine steady-state flow performance, control performance, and the transient tests. A total of 764 thermal transient cycles are included consisting of an approximately equal

TABLE 16

PROPOSED TEST PROGRAM — 1-MWt FEATURE TEST

Number	Test Event	Conditions				Start-Stop Cycles	Duration (h)
		Temperature In/Out (^oF)	Pressure (psia)	Flow Rate (gpm)	Power (%)		
1	Checkout — Dry						8
2	Fill						
3	Checkout — Wet	400→300	20-50	0-100		1	8
4	Drain*	800				1	
5	Fill	550					
6	Checkout	550→1100	35	0-100		1	8
7	Drain	550					
8	Fill	550					
9	Steady-State Performance	550/800	35	10-100	10-50	1	8
10	Drain — Fill	550					
11	Steady-State Performance	550/1100	35	10-100	10-10	1	8
12	Drain — Fill	550					
13	Control Performance	550/1100		10-100	10-100	1	8
14	Drain	550					
	Transient Tests						
15	Fill	550					
16	Run	550/1100	35	10-100	10-100	1	1/2
17	Hold	550	Low	2	0	1	1/2
18	Run	550/1100	35	10-100	10-100	1	1/4
19	Drain-Cooldown	550					5 min/25 min
20	Preheat-Fill	550					10 min/5 min
21	Emergency Drain	1100	35	0	100→0	1	1 min
22	Fill	550					1/4
23-38	Repeat 16, 17					8	8 h
39	Drain	550					1/2
40	Fill						1/4
41-136	Repeat 16, 17					48	48 h
137	Drain					1	1/2
138	Examine Test Article	ambient					16 h
139	Fill						1/4
140-163	Repeat 18, 19, and 20					8	8 h
164	Repeat 21	1100				1	1 min
165	Fill						1/4
166-261	Repeat 16, 17					48	48 h
262	Drain					1	1/2
263	Repeat 138	ambient					16
264-487	Repeat 40-263					107	138
488-711	Repeat 40-263					107	138
712-935	Repeat 40-263					107	138
936-1,159	Repeat 40-263					107	138
1,160-1,383	Repeat 40-263					107	138
1,384-1,607	Repeat 40-263					107	138
TOTAL						764	1,016

*Fill is preceded by preheat of test article to required temperature. Drain is followed by a cooldown to ambient.

number of run-hold cycles and run-drain-fill cycles. The former cycles are representative of temporary cloud conditions while the latter are representative of the day-night cycles.

Upon completion of the scheduled testing, the option exists to continue testing depending on the results of preliminary data analysis, the physical examinations, and facility availability.

D. DATA REQUIREMENTS

The test article will be supplied with 40 thermocouples. This instrumentation must be supplemented with facility instrumentation.

The test article will include a 2-in. flow control valve and a panel outlet temperature sensor. A temperature sensing control device will control the valve position to maintain outlet temperature constant. This simple scheme will be used to determine basic control characteristics.

Test data are to be recorded on magnetic tape, processed by test organization and supplied to the user in engineering units. The data processing techniques, instrumentation, calibration characteristics, curves, or curve fits shall be available to the user for inspection. Instrumentation calibrations shall be current and traceable to NBS standards.

One of the test objectives is to determine flow distribution for the tubes. This will be accomplished by examining individual tube outlet temperature as determined from tube surface thermocouples. The radiant energy flux distribution must be known in order to relate these temperature measurements to tube flow rates.

E. AIR-ROCK THERMAL CYCLING — SUBSYSTEM RESEARCH EXPERIMENTS

A test in which a portion of an air-rock storage bed is thermally cycles under conditions closely resembling actual storage operation is discussed in this section. This test would answer the questions concerning the thermal and mechanical performance of this concept.

1. Objectives

1) Measure the pressure drop across the bed and compare with predicted ΔP for the same conditions of temperature, pressure, and mass flow rate.
2) Repeatedly thermally cycle the bed by charging it with hot air and discharging it with cool air while measuring the temperature profile from top to bottom in the bed. Compare the measured temperature profile with analytical predictions.
3) Measure the air flow distribution in the bed to determine if it is uniform.
4) Allow the bed to remain inactive for one or more days and measure the flattening of the temperature profile. Compare the measurements with analytical predictions.
5) After the bed is charged, begin discharge operations after delays of zero up to long (several days) time periods. Measure the time it takes for the discharge air to reach normal cycle temperatures.
6) Incorporate various kinds of rock in the rock bed and determine the changes, if any, that occur in the physical condition of the rock and in the performance, such as the pressure drop.
7) Incorporate some high-temperature concrete in the test article in the form of ducts or other forms to determine their structural integrity in a thermally cycled rock bed.

2. Purpose of Test

1) Pressure drop measurements are necessary as they indicate what the fan power requirements would be in a full-scale bed. Pressure drop measurements also provide a way to determine the rock bed flow distribution. Pressure drop can be calculated if the sphericity of the rock is known, but the sphericity is not an

easily measured property. It is simpler and more accurate to measure the pressure drop directly.

2) The chief purpose of this test is to determine the temperature profiles in the rock bed as it is thermally cycled, from which the utilization of the bed can be ascertained. A high utilization is desirable as the rock bed size can then be smaller and more economical. Computer programs are available which can predict the rock bed temperature profiles for idealized rock beds. Actual tests are needed to prove out these programs and to determine the thermal characteristics of real rock beds.

3) Air flow distribution in a test of this type is determined by the uniformity of the rock bed packing and by the duct geometry. High utilization of the bed depends on a uniform air flow distribution. It is important to measure air flow distribution to prove that there are no regions where the flow is unusually high or low.

4) When a rock bed storage system is shut down overnight or longer, it is important for the temperature profile to remain relatively unchanged so that the utilization of the bed remains high. While analytical methods are available to predict the temperature changes in idealized rock beds, it is important to check the analysis with tests on real rock beds.

5) When a bed is partially or fully charged, it should be ready to provide maximum cycle temperatures with little or no delay. A common occurrence will be to shift from a charge to discharge mode in perhaps a few seconds. At this time, the temperature of the bed will not have degraded and cycle temperatures will be adequate. However, if there is a long delay before discharge begins, the top of the bed may cool off some and cause some drop in cycle temperature and loss of performance.

3. Air-Rock Thermal Test Approach

Figure 21 shows a schematic of the proposed air-rock thermal cycle test. Gas such as air or nitrogen will be supplied at the upper and lower temperature

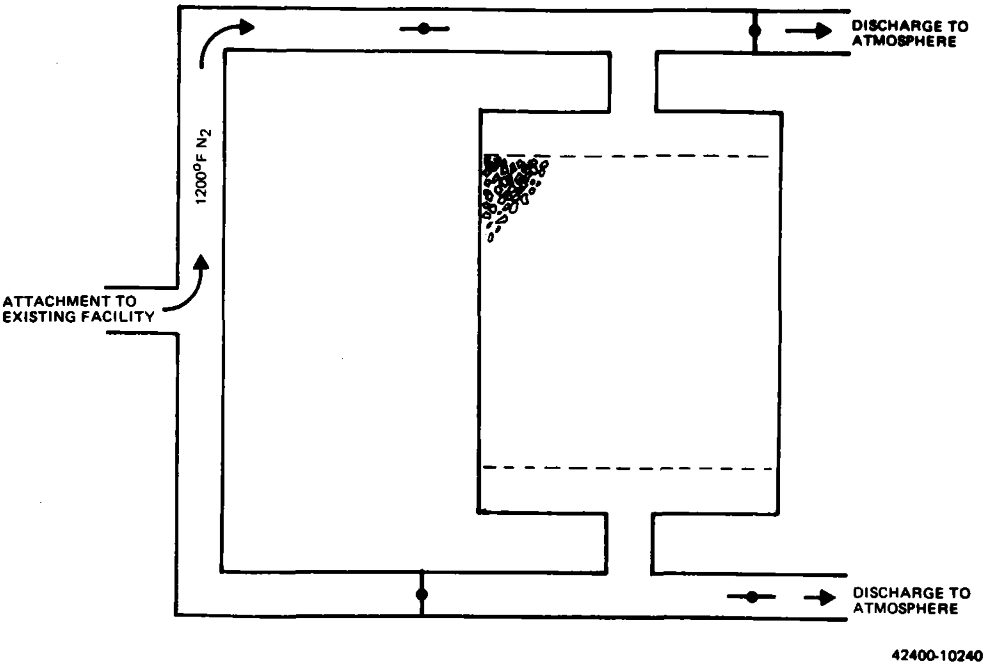
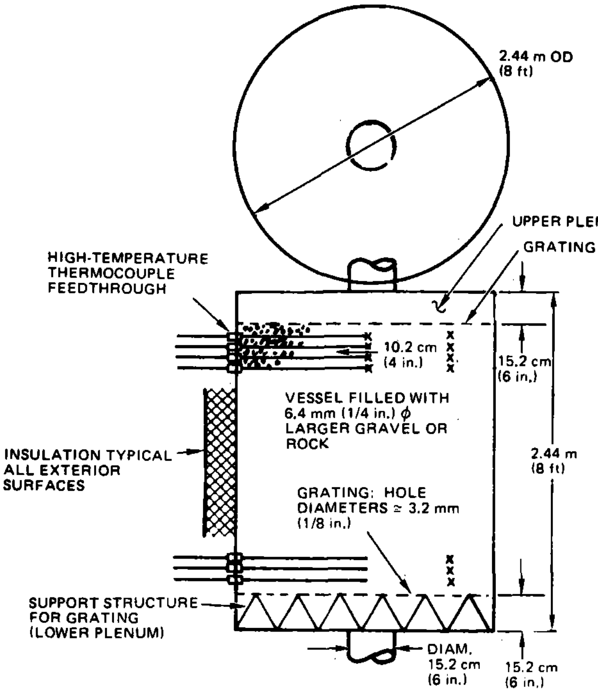


Figure 21. Air-Rock Thermal Energy Storage Subsystem Research Experiment



- ALL MATERIAL: TYPE 304 STAINLESS STEEL
- X SIGNIFIES STAINLESS STEEL SHEATHED 1.6 mm (1/16 in.) ϕ MgO INSULATED CHROMEL-ALUMEL THERMOCOUPLE (TYPE K)
- MAXIMUM TEMPERATURE = 649°C(1200°F)
- VESSEL WALL THICKNESS ~ 6.4 mm (1/4 in.)
- INSULATION AROUND ENTIRE VESSEL ~ 15.2 cm (6 in.)
- INLET AND OUTLET DUCTS ARE 15.2 cm (6 in.) PIPE, EACH 0.9 m (3 ft) LONG
- TOTAL NUMBER OF FEEDTHROUGHS FOR THERMOCOUPLES = 100

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Figure 22. Air-Rock Thermal Energy Storage Subsystem Research Experiment — Test Article

limits of the rock bed - roughly 650°C (1200°F) and 340°C (650°F). The rock bed will be contained in a tank with a plenum at the top and bottom. The rock bed will be charged with hot gas which the piping and valves will direct into the top of the bed and out the bottom. After several hours, the gas flow will be reversed so that relatively cool gas will be directed into the bottom of the bed and out the top. This thermal cycling will be repeated a number of times until the temperature profiles recur essentially with no change.

During this time, pressure taps above and below the bed will provide data on the bed pressure drop. Thermocouples will be distributed from top to bottom in the bed giving an accurate measurement of the bed temperatures at various times during the thermal cycling. These thermocouple readings will also be used to measure the temperature decay during inactive periods and the behavior of the thermocline during startup on storage.

Figure 22 shows a typical arrangement of this SRE. Stainless steel may be used for the tank although high-temperature concrete is also under consideration. All sides of the tank will be insulated minimizing any distortion of the thermocline and thermal losses.

The minimum diameter of the tank will be set by the effect of the wall on the centerline temperature measurements. It is expected that a diameter of several feet will be adequate. It would be desirable to have the height of the rock bed comparable to that in the reference design which is currently 6 m (20 ft). However, a smaller height would provide adequate test data.

Consideration will be given to the test of more than one type of rock bed in which the composition, size, and void fraction of the rocks are varied. Also under consideration is the use of some high-temperature concrete in the test article.

F. FIVE-MWt RECEIVER SRE

It is proposed to test receiver panels at the 5-MWt Solar Thermal Test Facility (STTF) at Sandia-Albuquerque. A full-size, 100 MWe plant, north-facing panel requires 25 MWt. A test panel with 1/10 the area will allow testing at the maximum commercial plant design flux.

1. SRE Objectives

The objectives of this SRE are as follows:

1) Verify the panel design at the maximum design absorbed flux at about 1.37 MWt/m^2
2) Verify the panel design under actual solar radiation conditions
3) Determine panel performance under cyclic conditions.

The limitations of this SRE are:

1) The receiver panel is small compared with a 100-MWe plant panel, being only 3.0 by 1.0 m instead of 16.1 x 2.1 m
2) The number of cycles is very limited in comparison with the 10,000 cycles expected in a commercial plant.

2. SRE Description

It is proposed that ESG build the complete test assembly for this SRE — the sodium loop, as well as the test article. The assembly would be manufactured in the Canoga Park facility and shipped to Sandia-Albuquerque as a unit, except that the pump would be shipped separately.

The engineering of the sodium loop would require about 4-months work. Construction would occupy another 3 to 4 months, followed by about 2 months for shipping and onsite fabrication and assembly. The actual operation of the test would be over a 3-month period.

Assuming 80 days of testing and four cycles/day, total number of cycles is 320 — far short of the 10,000 cycles in the commercial plant. However, even this number of cycles will provide important information on the panel mechanical integrity.

Table 17 lists the sodium system data for the 5.0-MWt SRE. The loop would have an inlet temperature of 288 (550°F), an outlet temperature of 593 (1100°F), and a flow rate of 13.1 kg/s (28.5 lb/s). The sodium pump would have a flow rate of 0.0347 m^3/s (550 gpm). The sodium piping would be 10.1-cm (4-in.) Schedule 40 pipe.

Table 18 lists the pump design characteristics for the sodium loop. In the first column is the design of the preferred pump for this SRE, while in the second column is an available pump at ETEC which meets requirements. While the latter pump does not have enough developed head, this is not necessarily a problem. The pump can be mounted at the top of the tower in a skid-mounted arrangement. Also, the tower head in the downcomer would not necessarily be lost, which then would reduce the pump head requirements, even if the pump were on the ground.

A dump heat exchanger for the 5-MWt system will be required. Table 19 lists the characteristics of this DHX. The DHX is of conventional design, having finned 2.5-cm (1.0-in) tubes with 465-m^2 (5000-ft^2) air-side surface area.

Figure 23 shows a plan view of the test panel and the sodium loop in a skid-mounted package at the tower top. The sodium loop skid in this view has a length of 4.42 m (14.5 ft) and a width of 3.65 m (12 ft). Figure 24 is an end view of the sodium loop on the tower. The overall height, which is largely determined by the pump, is 6.7/m (22 ft).

3. SRE Purpose

While this is a test of a small panel (10% of a full-size panel) it will provide considerable data for the verification of the receiver design. Stresses induced by the T-bar across the tubes and the mechanical restraints on the tubes will be similar to those in the commercial plant, and will occur over a sufficient length of panel (3 m) to provide realistic test data. Similarly, the stresses induced by the T-bar across the tube wall will be those of the commercial design. The sliding brackets that attach the tubes to the structure also

TABLE 17

5-MWt RECEIVER TEST — SODIUM SYSTEM DATA

Parameter	System Requirements
Maximum Power (MWt)	5
Receiver Temperature (°F)	
In	550
Out	1100
Flow Rate (lb/s)	28.5
Tower Height (ft)	
Receiver Base	200
Receiver Top	212
Tower Base Static Pressure (psi)	81
System Sodium Volume (gal)	1000
Main Pump (gpm)	550, Centrifugal
DHX (MWt)	5, Airblast, finned tube
Drain Tank, vol/size (gal/ft x ft)	1250/5 x 9 CS
Expansion Tank, vol/size (gal/ft x ft)	100/2 x 5 CS
Main Flow Pipe	
Hot Leg	
Diameter (in.)	4, Schedule 40 SS
Length (ft)	380
Cold Leg	
Diameter (in.)	4, Schedule 40 CS
Length (ft)	520

TABLE 18
5-MWt RECEIVER TEST — PUMP DESIGN CHARACTERISTICS

Physical Description	Receiver Pump	Los Alamos Pump* in Storage at LMEC
Quantity	1	1
Height, w/motor (ft)		11
Tank Size (ft)		2.5
Inlet Nozzle (in.)	4	4
Outlet Nozzle (in.)	4	4
Dry Weight w/motor (lb)		unknown
Type		centrifugal, single suction
Motor		
Size (hp)	40	25
Dimensions w/coupling (ft)	TBD	2.5 x 5
Voltage	440	440
Cooling	Air	
Pump Operating Conditions		
Developed Head (ft)	200	130
Flow Rate (lb/h)	1.03×10^5-2.09×10^5	2×10^5
Speed (rpm)	TBD	1710
Temperature (^oF)	550-800	1200^o
Sodium Volume (gal)	100	100
NPSH (ft)	150	unknown
Discharge Head (ft)	350	
Speed Control (%)	20-100	10-100
Pump Power, η = 70% (hp)	30	19
Design Conditions		
Developed Heat (ft)	200	130
Flow Rate (gpm)	520	500
Speed (rpm)	TBD	1710
Temperature (^oF)	800	1200
NPSH (min. required) (ft)	40	unknown
Code	Sect. VIII, Div. 1	unknown

*Sleeve bearing, eddy current coupling

TABLE 19

5-MWt RECEIVER TEST — DUMP HEAT EXCHANGER

Physical Description	System Requirements
Number of Units	1
Envelope Size (ft)	
Height	7
Width	8
Depth	6
Weight (lb)	TBD
Sodium Vol (gal)	125
Heat Transfer Area (ft^2)	5000
Tube Type	1-in. finned
Material	stainless steel
Fan Drive (hp)	120
<u>Operating Conditions</u>	
Thermal Capacity (MWt)	5
LMDT (^{o}F)	480
Sodium Side	
Flow Rate (lb/h)	1.03×10^5-2.09×10^5
Temperature (^{o}F)	
In	1100
Out	550-800
Pressure Drop (psi)	20
Air Side	
Flow Rate (lb/h)	4×10^5
Temperature (^{o}F)	
In	80
Out	500
Pressure Drop (in. H_2O)	11

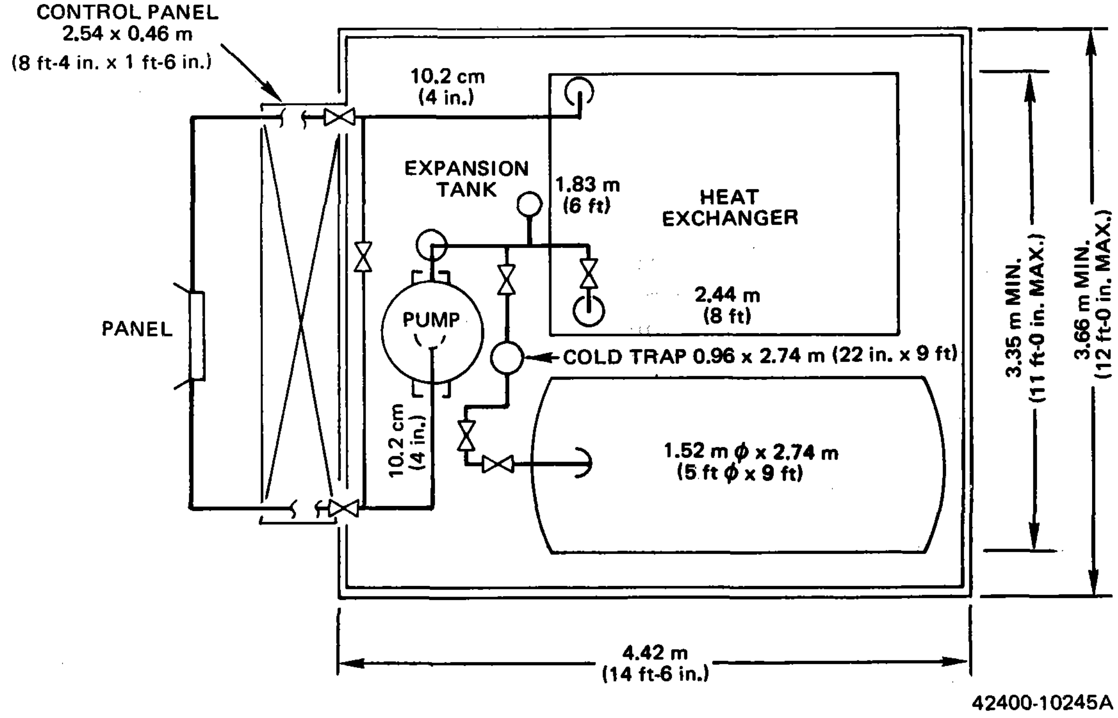

Figure 23. Plan View of Test Panel

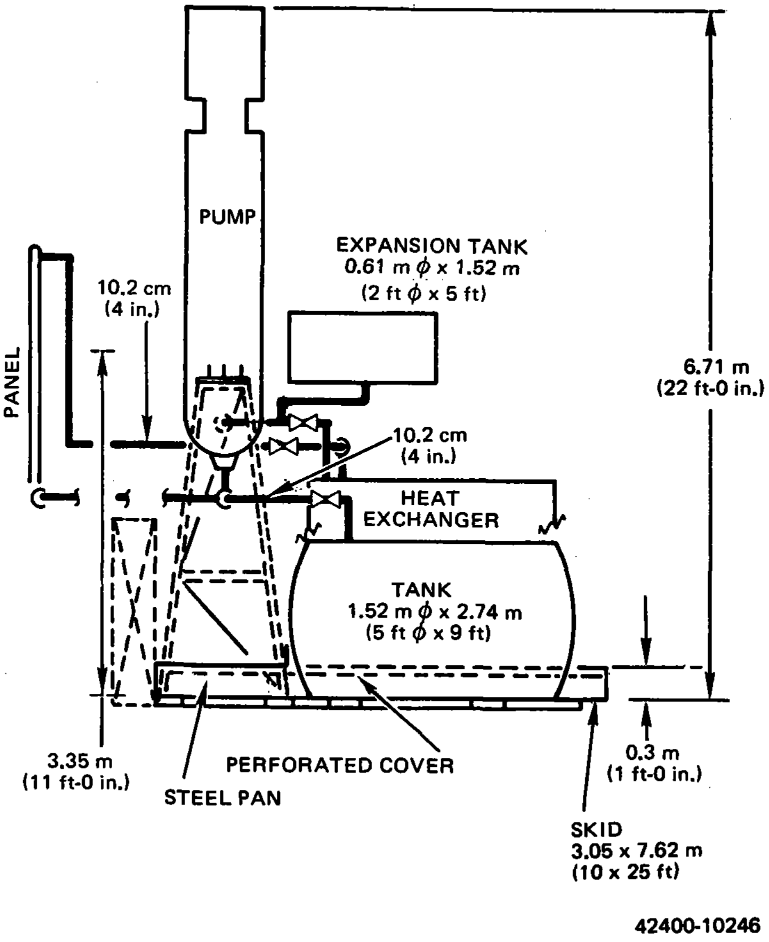

Figure 24. End View of Sodium Loop on Tower

will be tested, although not to the extent as in an actual design. Data on piping stresses will be obtained. If the test panel is welded (or brazed) into a single bonded assembly, this test would provide some indication of the structural adequacy of this approach. The integrity of the tube-to-manifold joints would be verified by this SRE.

G. RECEIVER SRE WITH SODIUM HEATING

Since radiant heating and solar heating of receiver panels have limitations, consideration can be given to sodium heating of receiver test panels. This can be done by placing a channel containing hot sodium over the panel to be tested and maintaining a suitable ΔT between the heating sodium in the channel and the heated sodium in the panel tubes. By maintaining a ΔT of about 165°C (300°F) between the sodium loops, a heat flux comparable to the maximum expected in the receiver (1.5 to 2.0 MWt/m^2) can be achieved.

Figure 25 shows a schematic of such a test. In the hot loop, sodium is heated by a fossil-fuel heat source. Sodium is brought into the test section at a temperature well above that of the desired panel test temperature. Heat flows into the test panel at a rate proportional to the ΔT that is maintained. This heat is dissipated by a dump heat exchanger to the atmosphere. The heat supplied to the hot loop and the flow rates in both loops determine the temperatures and the variation of the ΔT along the test section. The ΔT and hence the local heat flux can be varied linearly along the test section. A more sophisticated loop arrangement may be able to more closely match the ΔT variation with that in an actual panel.

The heat flux will be nearly constant over the 180° heated side of each tube, whereas in an actual receiver the heat flux will be at a maximum near the crown of the tubes. The sodium heating channel will have to be welded to the test panel and will, therefore, affect the thermal expansion of the latter. Available sodium test facilities at ETEC can deliver the thermal power and sodium temperatures required for tests of this type. A complete evaluation of sodium heating of test panels has not been made at this time. It does appear that high, well controlled, heat fluxes in large (full-size) panels can be achieved.

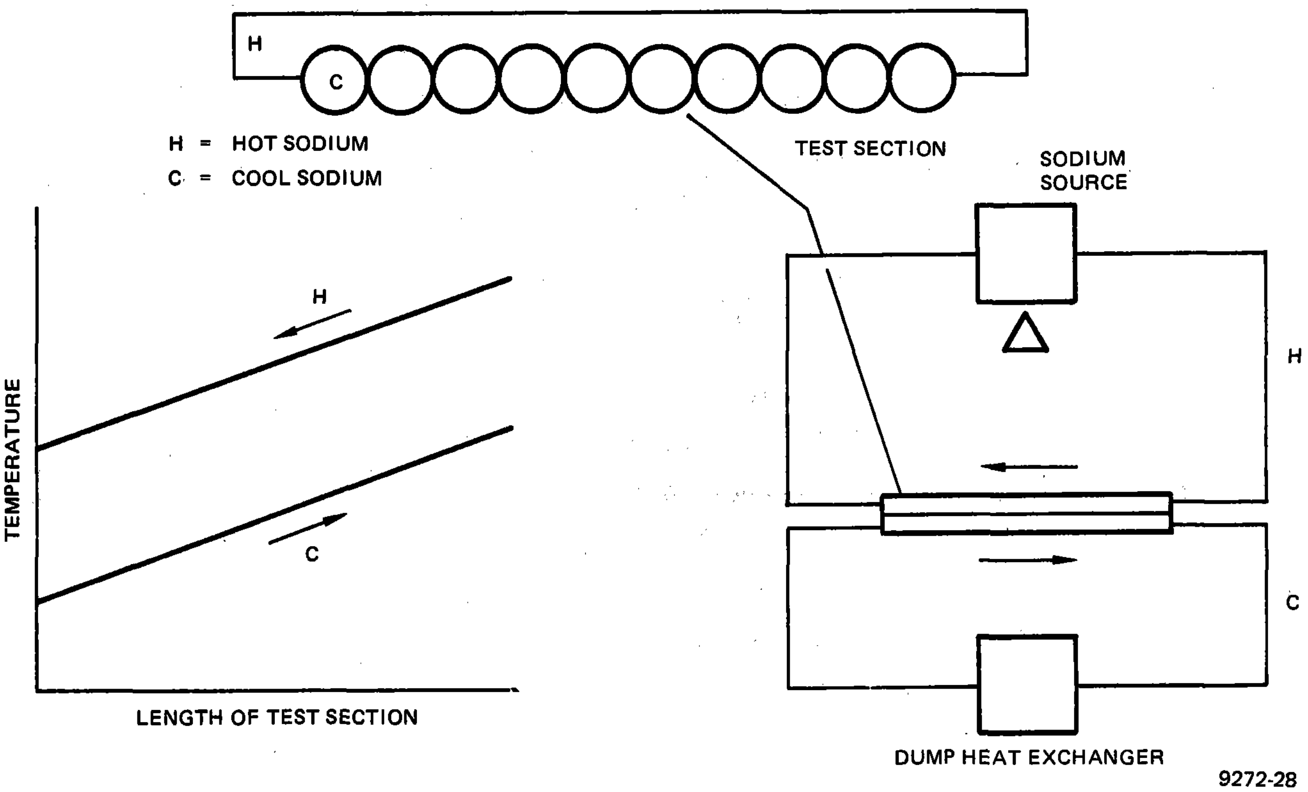

Figure 25. Sodium Heated Receiver Panel SRE

H. HEAT STORAGE MATERIALS THERMAL CYCLING SRE

A test to conduct accelerated thermal cycling of candidate low cost heat storage materials (such as rock) for application to ACR thermal storage subsystems is discussed here. This testing would evaluate selected materials with respect to their potential for successful use in thermoclines operating at temperatures representative of ACR Solar Power plants. This SRE is materials oriented and not specifically related to thermocline performance. Test article-apparatus size is not critical except that end effects will be minimized.

1. Objectives

1) Evaluate candidate thermal storage materials for application to ACR thermal storage subsystems.

2) Conduct thermal cycling tests at temperatures representative of ACR solar power plants.
3) Subject candidate materials to mechanical loading representative of the physical stresses which can be expected in the thermal storage system thermocline application.
4) Determine on a statistically valid basis the before and after testing thermophysical properties of the candidate materials pertinent to the thermal storage application.

2. Purpose of Test

1) An evaluation of candidate materials for application to thermal storage systems is necessary to determine the practicality of alternate concepts under consideration.
2) Accelerated thermal cycling tests under mechanical loading will indicate which materials are most promising for further development activities.
3) Accelerated thermal cycling test under load will also help validate long term effects on candidate materials operating at ACR temperatures and similar conditions.

3. Materials Thermal Cycling Test Approach

Figure 26 presents a schematic diagram of the proposed storage materials thermal cycling SRE. Air at the high temperature limit of the ACR solar power plant cycle, ~650^{0}C (1200^{0}F), will be supplied at one side of the test article consisting of the candidate materials under suitable loading. Flow rates and heating rates will be similar to those anticipated for the ACR application. Ambient cooling air or air at ACR low temperature limit will be introduced for cooling cycles. Temperature transients for the candidate materials will be limited to ~120^{0}C/h (216^{0}F/h) for both heating and cooling cycles. These rates are three to five times greater than the thermal transients predicted and will provide data on an accelerated time scale.

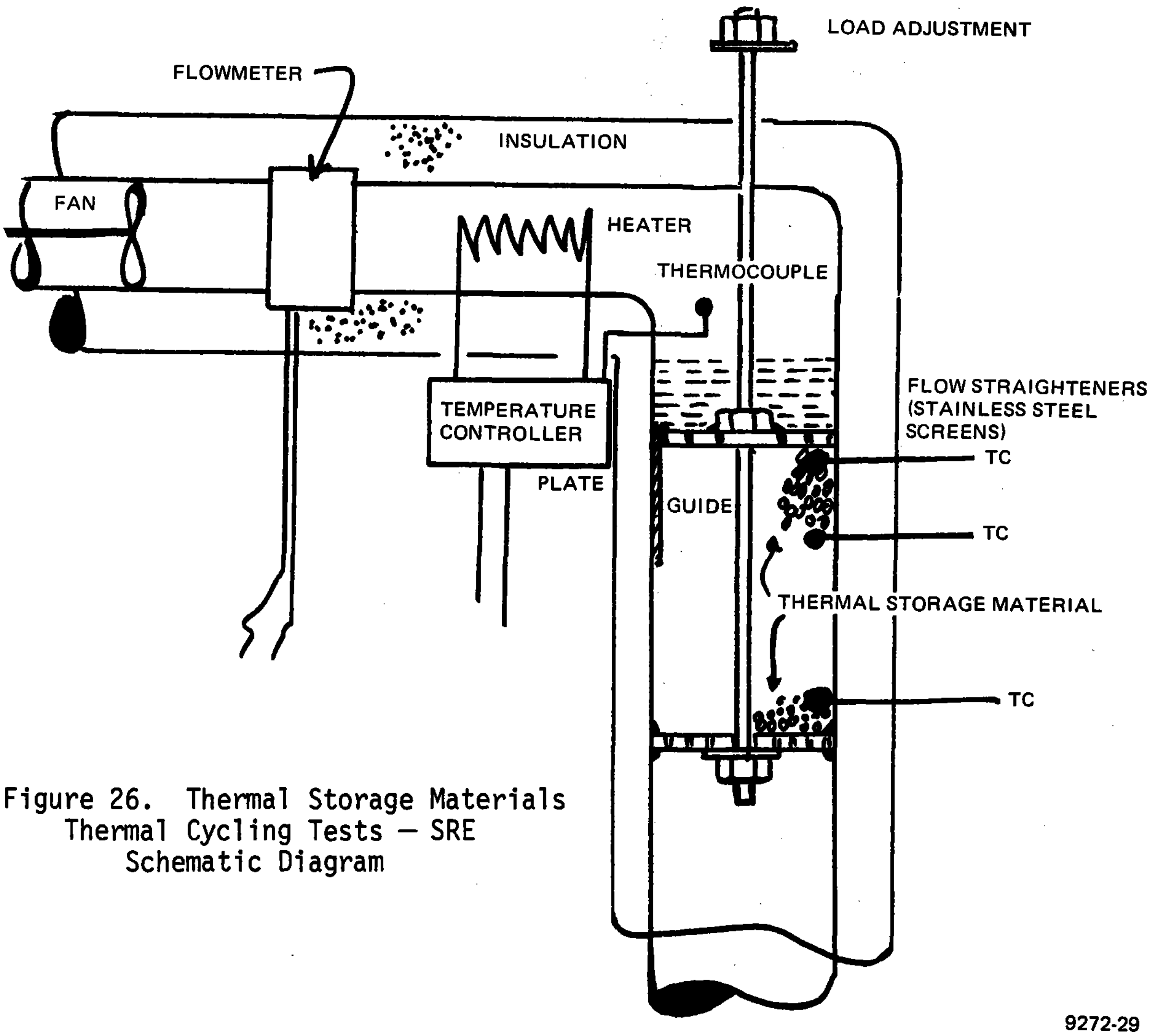

Figure 26. Thermal Storage Materials Thermal Cycling Tests — SRE Schematic Diagram

Adequate instrumentation will be provided to determine temperature versus time histories for selected material sample pieces. Air flow rates would be measured and temperature control would be provided by programmable temperature indicator-controllers based on the bulk temperature of the test materials.

Representative before and after test samples will be selected and used to determine thermophysical material properties by standard materials laboratory techniques. Pertinent changes resulting from the testing will be noted. Statistically adequate samples would be taken for these before and after tests.

I. RECEIVER PANEL SRE USING WHITE SANDS FURNACE

The solar furnace at White Sands is capable of heat fluxes up to 4.0 MWt/m^2 and has a total power of 30 kWt. It has the additional capability of being turned on and off in a few milliseconds and remaining on for 0.5 s to several minutes. A limitation of this furnace is the small size of the high heat flux region. The region receiving 4.0 MWt/m^2 measures only 3 cm across, while the area receiving 1.60 MWt/m^2 or greater measures only 11 cm. Such concentrated heating is not adequate for testing panels but could be useful for testing small tube groups and subpanels. At the high heat fluxes and short cycle periods possible, certain accelerated tests could be run combining very high stresses with a large number of cycles but at the expense of accepting very short hold times. The stress analysis and evaluation of this accelerated testing has not yet been performed. While having some attractive features, an SRE based on use of the White Sands 30-kWt solar furnace appears to be less useful than, for example, the 5-MWt STTF SRE.

IV. PLANS AND SCHEDULES FOR DEVELOPMENT OF A COMMERCIAL SODIUM-COOLED CENTRAL RECEIVER POWER PLANT

A. OVERVIEW

The objectives of Task 6 (Development Plan for the Advanced Central Receiver Power System) as stated in the RFP are to "(1) estimate time and resources required to bring the conceptual design of the Advanced Central Power System identified in Task 4 into being, and (2) to identify and discuss factors affecting the development and commercial acceptability of the Advanced Central Power System." The tasks that were suggested in the RFP for achieving these goals were (1) to identify and describe a pilot plant (Task 6.1), (2) to conceptually design a pilot plant (Task 6.2), (3) to identify subsystem research experiments (Task 6.3), and (4) to develop experimental plans. Tasks 6.1, 6.2, and 6.3 were accomplished under Phase I of the program and are described in final form in the preceding section of this volume of the final report. This section of the final report deals with the results of Task 6.4 which required that preliminary R&D plans and schedules for the SRE's and for the Pilot Plant be formulated. The plans include the establishment of major milestones, overall schedules, estimated costs, and the schedule and cost impacts of alternate approaches that would result in a trade-off of schedule and costs against development risks.

B. RESEARCH AND DEVELOPMENT PLANS

1. SRE Selection Criteria

The major area of uncertainty in the development of the baseline, sodium-cooled, central receiver concept into an economically viable, technically sound, and commercially acceptable power plant for the production of electrical energy has been found, on the basis of the Phase I work, to be the receiver. It is the only component in the system that does not have a direct counterpart in sodium-cooled, thermal test loops or in sodium-cooled, nuclear power plants, and it is the only component that has not been tested under the wide variety of conditions typical of other sodium components. The basic uncertainty here concerns the creep fatigue behavior of the receiver tubes under high-heat flux cycling conditions.

It is recognized, of course, that the particular sodium loop configuration needed for a solar plant has not been assembled and that questions about the interaction of different parts of the system or different components, some operating at relatively high temperatures, can arise for the specific operating parameters and conditions typical of the solar cycle. However, these latter points are not generally considered serious enough to warrant the installation of a test loop that incorporates scaled-down versions of each component although this approach has been considered. Furthermore, the analyses that were performed on Phase I of the program relative to the sodium system dynamic behavior have shown that no instabilities are likely to occur; consequently, these questions could be reasonably expected to be resolved during pilot plant or demonstration plant operation.

The baseline, commercial-scale system incorporates all-sodium storage where storage times are of the order of 3 to 4 hours. For longer storage times, an alternate, air-rock, thermal energy storage concept that appears to be more cost effective has been identified, designed, and described, partially on the Phase I effort and partially on Company funding. Several questions have been raised about this concept, questions having to do with the characteristics of the thermocline under multiple cycling conditions, with the stability of the rocks under thermal cycling, and with the dynamic behavior of the rock bed under actual operating conditions.

As a result of our studies to date, we have, therefore, identified two principle areas of concern to be addressed by subsystem research experiments: the stress and creep-fatigue behavior of the receiver, and the thermodynamic characteristics of the air-rock thermocline storage concept. These two concerns are the basis for the identification of the matrix of six SRE's described and discussed in Section III. The basic criteria used in the selection and conceptual layouts of the four SRE's dealing with the receiver were (1) to achieve the peak heat fluxes that are characteristic of the receivers in the optimum, sodium-cooled plant (e.g., ~1.4 to 1.9 MWt/m^2); (2) to obtain, by heating or by external mechanical means, realistic stresses in the test article to be studied; (3) to utilize reasonably large test articles so that some specific design features can be simulated (e.g., tube-to-manifold weld joints); (4) to obtain cycle frequencies from a few minutes (to obtain accelerated cycle life data) to several hours (to obtain real time cycle behavior); and (5) to be able to obtain a reasonably large number of cycles at the low frequencies. The latter criterion implies that facility time can be made available and that the heat source will have sufficient lifetime itself to permit long-term testing. This lifetime question is of some concern with respect to a radiant heat source since experience to date has shown that resistance heaters have been subject to early failure when operated at high-heat fluxes.

2. SRE's Not Considered Cost-Effective to Pursue

The receiver cycling SRE (see Subsection III.A) was originally devised as a convenient method for studying creep fatigue in receiver panels with dimensions of the order of 0.30 m x 7.6 m or 1.1 m x 1.8 m or some inbetween size with a comparable area. As originally conceived, this SRE utilized a radiant panel to simulate the solar heat flux. Two options are available. In one case, the panel (test article) could be fabricated, along with a 2-MWt sodium, heat-transport loop, and used at an existing radiant-heat test facility (Rockwell International's B-1 Division or the Sandia weapons simulation facilities, for example). In the other case, the panel could be fabricated, along with a radiant-heat test facility, and used at an existing sodium test loop. Such a loop, including pumps, coolers, purification systems, etc., is available at the Energy Technology Engineering Center (ETEC). Since a recommendation is being made for the Phase II program to design and fabricate a 5-MWt test loop for use at the 5-MWt STFF in connection with another proposed SRE, the former approach was determined to be the most cost effective since a sodium loop would be available in any case. Also, a very approximate estimate of the cost of a new radiant heat facility to be installed at ETEC was quite high (i.e., of the order of \$1.4 M). Furthermore, this cost is estimated to exceed the cost of the 5 MWt sodium, heat-transport loop.

A detailed review of this proposed SRE indicated substantial limitations. In view of the fact that it did not appear feasible to obtain heat fluxes much greater than about 0.8 to 1.0 MW/m^2 and the fact that the heating element (graphite) lifetime was somewhat limited for long-term experiments, it was concluded that the SRE would not be cost effective to pursue, especially if a 5-MWt STTF receiver test were to be performed. Thus, further consideration of this SRE was eliminated in the development of the long-range plan for the sodium-cooled, solar concept. It should be noted, however, that restrictions regarding the use of the 5-MWt STTF for the test of a sodium receiver panel could make it necessary to reexamine this SRE in order to obtain some design information, however limited it might be.

In view of the heat flux limitation imposed by a radiant heat source, very brief consideration was given on the Phase I Program to the use of a facility such as the 30-kWt White Sands solar furnace. This SRE (see Subsection III.I above) would involve a very small test article (a few centimeters on a side), but would achieve high heat fluxes, well within the required range. High cycle frequencies could also readily be obtained. In addition, because of its small size, cycling to failure could probably be handled in view of the small sodium inventory required and in view of the remoteness of the facility. However, since externally applied stresses would probably be needed and the test article would be so extremely small, it was decided not to pursue this concept further in terms of long-range planning. From the stress analyst's viewpoint, however, a test involving sufficient cycles to cause failure may be beneficial as a means of verifying failure predictions.

One other SRE that was considered briefly in the development of the Program Plan for Phases II, III, IV, and V was one involving the use of hot (650^{o}C) sodium as a heat source (see Subsection III.G above). This SRE would be conducted at ETEC where large heat sources (70-MWt fossil-fired sodium heaters) are already available, along with the necessary pump, dump heat exchanger, etc. Very high heat fluxes could be achieved, the test article could be large, cycle frequencies could be lowered to perhaps 3 to 4 h, and realistic structural loading conditions could be achieved. However, the test lacks an obvious visual relationship to the usual panel environment, and data interpretation is more difficult and less direct than for tests using radiant energy. Thus, this SRE has not been considered further for long-range planning.

3. Recommended SRE's

On the basis of technical as well as cost consideration, the recommendation is to undertake only the 5-MWt Receiver SRE at the STTF. Although a 5-MWt sodium, heat-transport loop will have to be designed and fabricated for use at STTF, it appears to be more cost effective to build the loop and take it to the existing solar facility than to build a radiant test system and take it to the existing sodium facility (ETEC). Tests involving more than one receiver design concept may, however, be necessary at STTF in order to resolve uncertainties pertaining to the overall receiver design, creep fatigue, and cycle life. Although panel sizes will be restricted to about 3 m high by 1 m wide, the required peak fluxes appear to be achievable. Such panels are reasonably large and, therefore, realistic load conditions can be achieved by using actual panel support devices and actual tube-to-manifold joints.

The recommended approach insofar as the air-rock thermal energy storage concept is concerned is that both SRE's be funded during Phase II of the program.

4. Other Program Plan Elements

In addition to the consideration of the six SRE's, the overall, long-term plans developed under the Phase I effort included consideration of the design, construction, and operation of a pilot plant, with and without an electric power generation subsystem, and the design and construction of a commercial-scale (~100 MWe) demonstration (critical module) plant. These plans have been developed in conformance with the phasing that was outlined in the RFP for Phase I of the program. The phasing guidelines consisted of the following parts:

Phase I — Current Program (now essentially complete) — A 12-month phase in which widespread system and subsystem parametric analyses are performed; a conceptual design of the preferred commercial-scale system is prepared and assessed; and a development plan prepared in which Subsystem Research Experiments (SRE's) and a Pilot Plant are identified and conceptually designed, and schedule and costs estimated.

Phase II — A subsystem research and preliminary design phase during which these SRE's defined in Phase I are refined, fabricated, and tested; preliminary designs of the pilot plant identified in Phase I are prepared; the commercial-scale plant design is refined, and detailed costs and schedules are prepared.

Phase III — The pilot plant design is finalized, and the facility is constructed and operated; its performance is analyzed; and a preliminary design and demonstration project plan for a commercial-scale plant is prepared, including schedules and costs.

Phase IV — Detailed design of a commercial-scale plant is developed; detailed plans, costs, and schedules are prepared; and an environmental impact statement is prepared and submitted.

In order to evaluate the entire effort that would have to be carried out in order to proceed from the end of Phase I (at this point in time) to the beginning of the operation of a commercial-scale demonstration (critical module) plant, a Phase V, consisting of the construction of a 100-MWe critical module, has been added to the overall schedule and cost estimate.

5. Program Plans for Phases I, II, III, IV, and V

The following plans represent various approaches that can be taken in realizing the development and demonstration of a sodium-cooled, solar central receiver power plant concept. The plans differ somewhat in financial risk and also in the time that it is estimated to take to reach the final goal — namely, the initiation of operation of a demonstration or critical module plant.

a. Plan A

1) Few-Panel Pilot Plant Producing 10-MWe Power
2) 5-MWt Receiver SRE*
3) Air-Rock Thermocline SRE†
4) Commercial-Scale, Critical Module, Demonstration Plant

The plan consists of the four main features identified above. It results in the initiation of the operation of a commercial-scale critical module in late 1987 (see Figure 27), and very roughly is estimated to require about $255 M to accomplish.[§] An extremely approximate budget and planning cost breakdown is given in Table 20. It is a relatively low-risk approach since it incorporates a fully operational, approximately 10 MWe, pilot plant of the type described in Section II above. The receiver for this pilot plant consists of only three panels, but peak-heat fluxes characteristic of a 100-MWe commercial-scale north facing panel are achieved, and these panels are full-size replicas of the 100-MWe commercial-scale receiver panels. One hour of storage is used in order to achieve a reasonable compromise between capital cost and sufficient simulation of the operational-performance characteristics of the all-sodium storage concept.

A study (see Subsection IV-f here) was performed under the Phase I program to determine the characteristics of a 360° receiver and field relative to the few-panel approach. Not only are the number of heliostats required for the 360° pilot plant much greater, (~5070 vs ~1045) but the heliostats glass panels must have custom cant and custom focus in order to maintain the design point heat flux of 1.37 MW/m^2. In the process of achieving these conditions, the power

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*This SRE is described in detail in Subsection III-F of this report. It will be referred to henceforth in this discussion as the 5-MWt Receiver SRE. It includes design, fabrication, and assembly of a completely self-contained (including heat rejection) 500-gpm, sodium loop that will be shipped to the 5-MWt STFF and be raised by elevator to the top of the tower where it will be raised by elevator to the top of the tower where it will be connected to the receiver panel which is also to be designed and fabricated by ESG.

[†] This SRE is described in detail in Subsection III-E of this report. It will be referred to henceforth in this discussion as the Air-Rock Thermocline SRE. It includes the design and construction of a test article only. The test facility already exists at the ETEC.

[§] All costs shown in connection with these plans are of a budget-and-planning nature only and are based on success oriented tasks.

TABLE 20

PLAN A — ESTIMATED COSTS

Task No.	Task Description	Cost ($1000)		
		Engineering	Fabrication and Construction	Operation
1.0	Pilot Plant Preliminary Design	2,050	0	0
2.0	Pilot Plant Final Design	4,000	0	0
3.0	Pilot Plant Construction	3,350	40,000	0
4.0	Pilot Plant C/O and Operation	3,650	0	3,000†
5.0	Subsystem Research Experiments			
5.1	5-MWt Receiver Test	393	650	138
5.2	Air-Rock Thermocline	111	42	88
5.3	Rock Cycling	14	20	26
6.0	Commercial Scale Update	182	0	0
7.0	Demonstration Plant Preliminary Design	6,000	0	0
8.0	Demonstration Plant Final Design	9,000	0	0
9.0	Demonstration Plant Construction	8,300	174,000	0
	Total	37,050	214,712	3,252
		Grand Total — $255,014		

†2 years for staff of 20 people

PLAN A

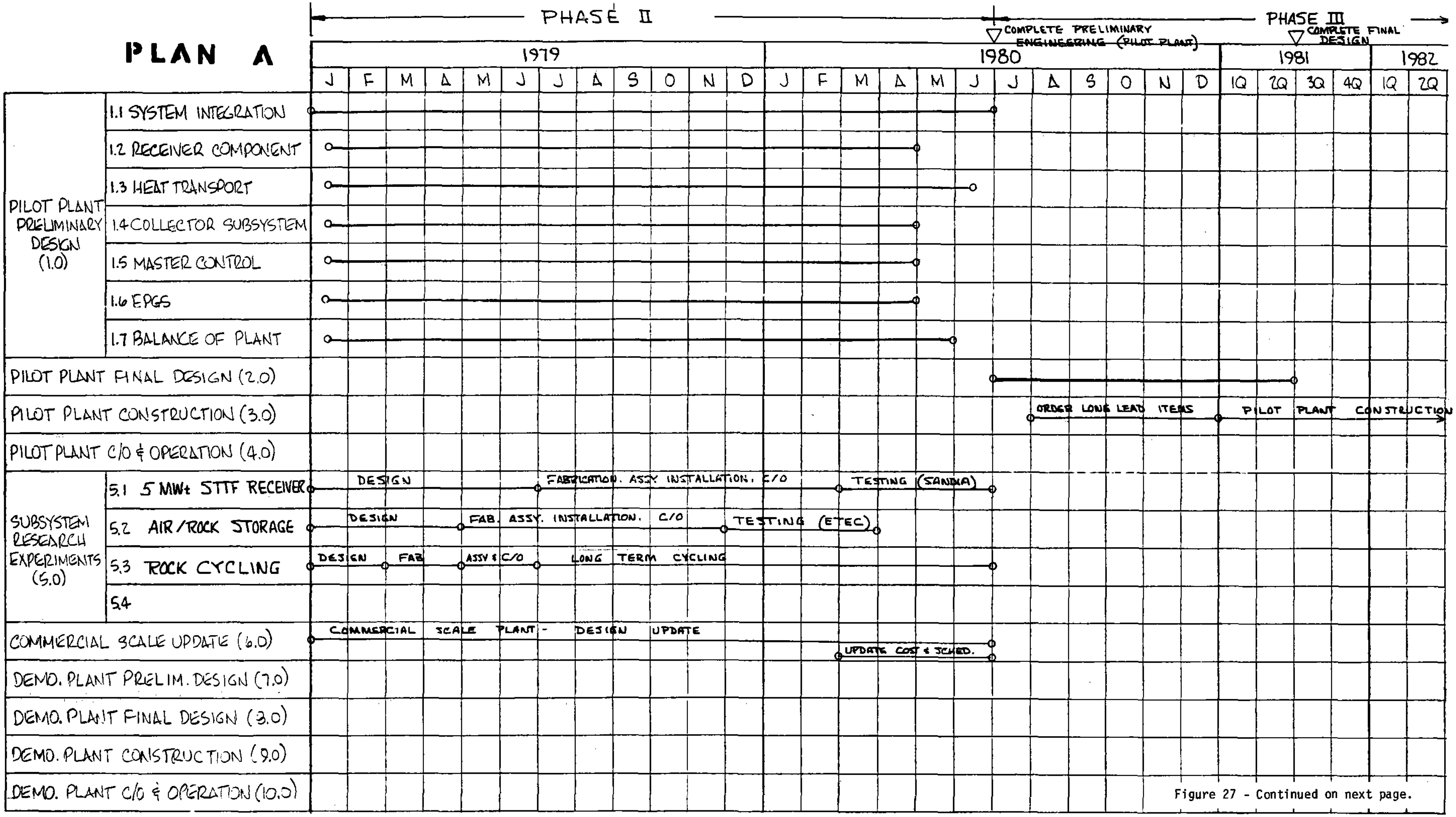

Figure 27 - Continued on next page.

PLAN A

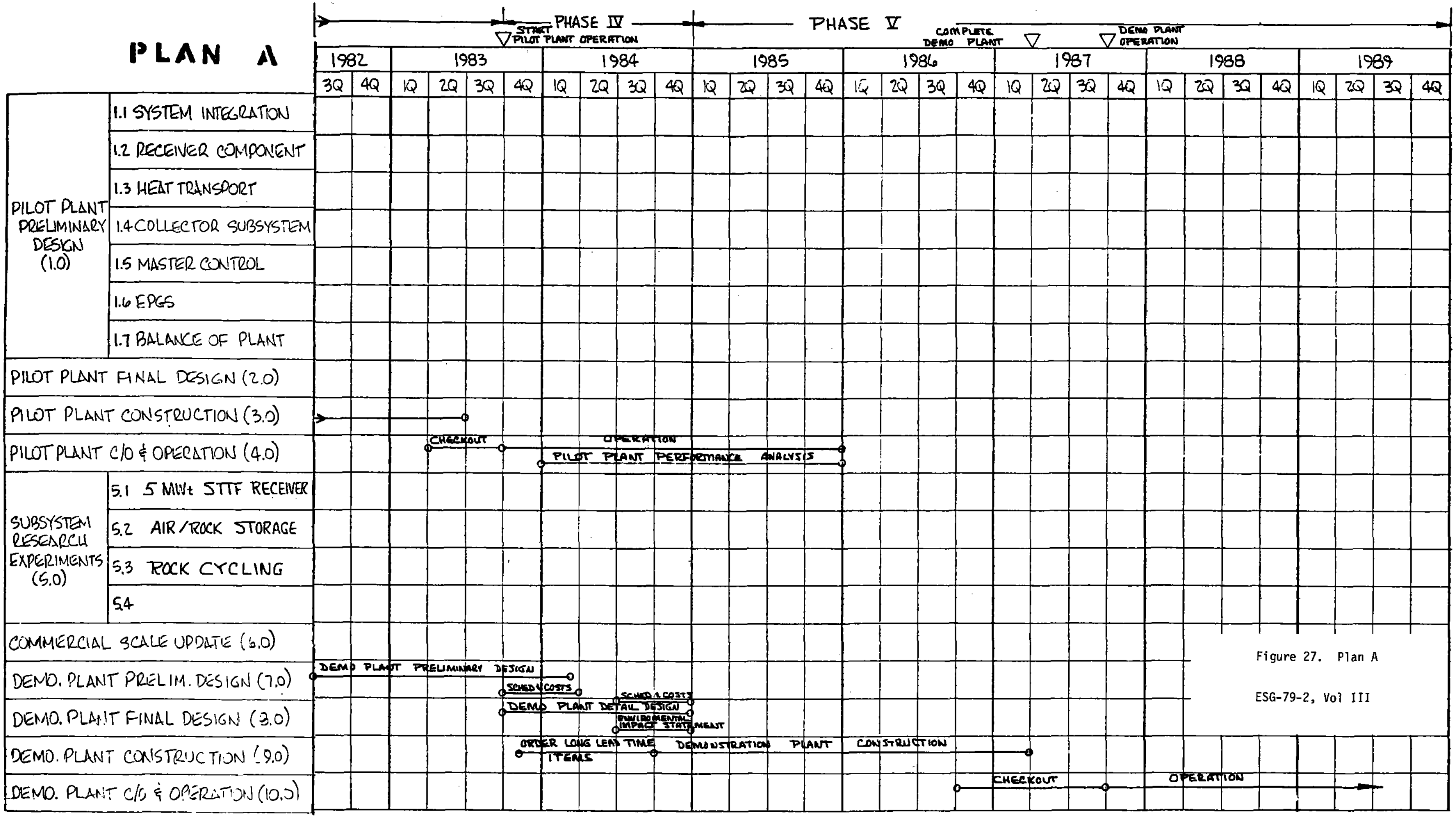

Figure 27. Plan A

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level would have to be of the order of 40 MWe; therefore, the size of the plant and its cost will be greater. Thus, it appears to be cost effective to design and construct a few-panel pilot plant. Its limitations are relatively few; one of these is that the full daily operational characteristics of the plant are not exactly simulated.

The preliminary design of the pilot plant is expected according to this plan to be completed within 18 months from ATP. This 18-month period encompasses the complete Phase II effort. The length of time of the preliminary design effort is largely set by the 5-MWt receiver SRE and the need to factor the results of this experiment into the pilot plant preliminary design. It has been estimated that this SRE will require at least 18 months in order to perform the design of the sodium loop and receiver test panel, to carry out the fabrication, to deliver the sodium-loop skid and panel to the STTF site, to assemble the two systems together, to check the systems out, and to perform 2 or 3 months of testing. The cost of the testing effort is not included in the Table 20 costs and is assumed to be covered by the STTF operations funding, although we have included the cost of operating the loop and analyzing the data in the cost estimate contained in Table 20.

Other tasks shown in Figure 27 that constitute the Phase II effort are: (1) the design, fabrication, assembly, installation, and test of a 2.4-m diam by 2.4-m high air-rock thermal energy storage system, (2) a laboratory-scale experiment designed to investigate the capability of various types of rocks to withstand thermal cycling over the same temperature range and at the same rate as would be found in a full-scale air-rock storage system, and (3) an update of the commercial-scale concept that has been developed under the Phase I program.

The scope of work to be performed on the commercial plant conceptual design update will consist of a review of the Phase I design relative to current program objectives. Design and test information obtained from other Phase II activities or from other DOE solar-related programs will be included in the commercial plant concept in order to maintain a current configuration. Revised system performance parameters will be developed and the Design Data Sheets revised. Receiver design and performance characteristics will receive special consideration, particularly with regard to stress problems in the receiver panels. The storage concept will be reviewed to select the most cost-effective storage system. The choice will be between the current all-sodium concept and the air-rocks concept. This decision will be based in part on the results of the air-rock Phase II test results. Layout drawings and process flow diagrams will be updated to depict the updated plant arrangement concept and the basic heat transport and electrical generation systems. Layout drawings will be updated for the receiver, thermal storage system, and steam generator concepts. The basic concept for the instrument, control, and plant protective systems will be defined. Thermal, hydraulic, and stress analyses will be performed to support concept definitions of the receiver, thermal storage system, and steam generators. Studies and reviews will also be performed to support concept studies of other major components and heat transport systems. A commercial plant cost estimate and a Phase III and IV development plan will be prepared. A schedule which includes the preliminary and final design, construction, and checkout phases leading to plant operation will be prepared.

Relative to other phases of Plan A, Phase III shall consist of the final design of the pilot plant described above, the construction and checkout of that plant, and a preliminary design of the commercial-scale demonstration (critical module) plant. The start of operation of the pilot plant is projected to be about the beginning of the fourth quarter of Calendar Year 1983. The critical item that sets the overall schedule for the pilot plant construction is the turbine-generator. Stearns-Roger personnel have estimated that it will require 30 months from ATP to the start of operation of the 10-MWe turbine, and an additional 5 months before full-time operation can be achieved. The overall elapsed time allowed for the plant construction, including the ordering of long-lead-time items, is therefore 35 months (August 1, 1980 to July 30, 1983). Thus, the turbine will have to be ordered largely on the basis of work conducted under the Phase II preliminary design.

The phasing of the demonstration plant preliminary design task has been laid out such a way that the information gathered from ~5 months of operation of the pilot plant can be factored into the preliminary design. The detailed design of the commercial plant will overlap the preliminary design by about

5 months and will benefit from about 15 months of operation of the pilot plant. Thus, the commercial-scale critical module design will incorporate the modifications and improvements that result from actual operating experience on a sodium-cooled, solar system. In view of its larger size, a 42-month overall construction schedule for the critical module has been assumed, including about a year for the ordering of long-lead-time items. As with the pilot plant, the turbine-generator is the pacing item, although an analysis of the construction of the sodium-to-water steam generator indicates that it may have an equally tight schedule. In this case also, the turbine-generator and the major forgings for the steam generator will have to be ordered largely on the basis of preliminary design work.

A 2-year operating schedule for the pilot plant has been assumed in all plans in which a pilot plant is included, although the design criteria are assumed to apply to a 30-year operating life. The estimated costs associated with Plan A (Table 20), therefore, include only a staff for 2 years of operations. No costs for operating the demonstration plant critical module have been considered, nor has a definite operating time been considered. It is assumed, for planning purposes, that operations will start in the latter half of Calendar Year 1987 and continue indefinitely.

Because this plan appears to meet most closely the guidelines provided by DOE for the preparation of the Phase II proposal, the overall schedule for Plan A up to and including the demonstration plant final design has been developed in considerably more detail than that shown in Figure 27. This more detailed schedule, showing the interrelationships between the various tasks and subtasks and the split in responsibilities between the various team members, is shown in Figure 28 and Figure 29.

b. Plan B (Figure 4-4)

Few-Panel, Solar, "Receiver Module" Plant with Dump Heat Exchanger
5-MWt Receiver SRE
Air-Rock Thermocline SRE
Commercial-Scale, Critical Module, Demonstration Plant

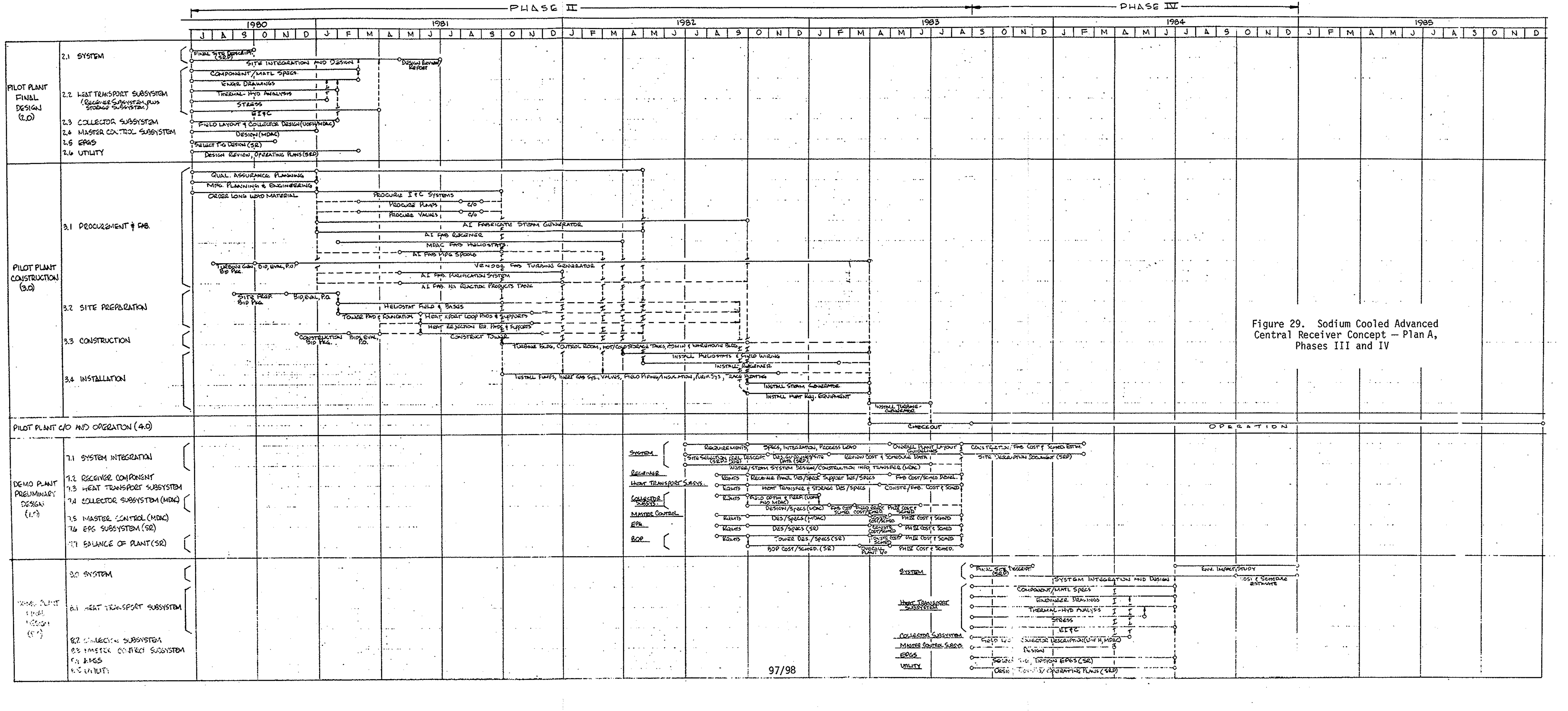

Figure 29. Sodium Cooled Advanced Central Receiver Concept — Plan A, Phases III and IV

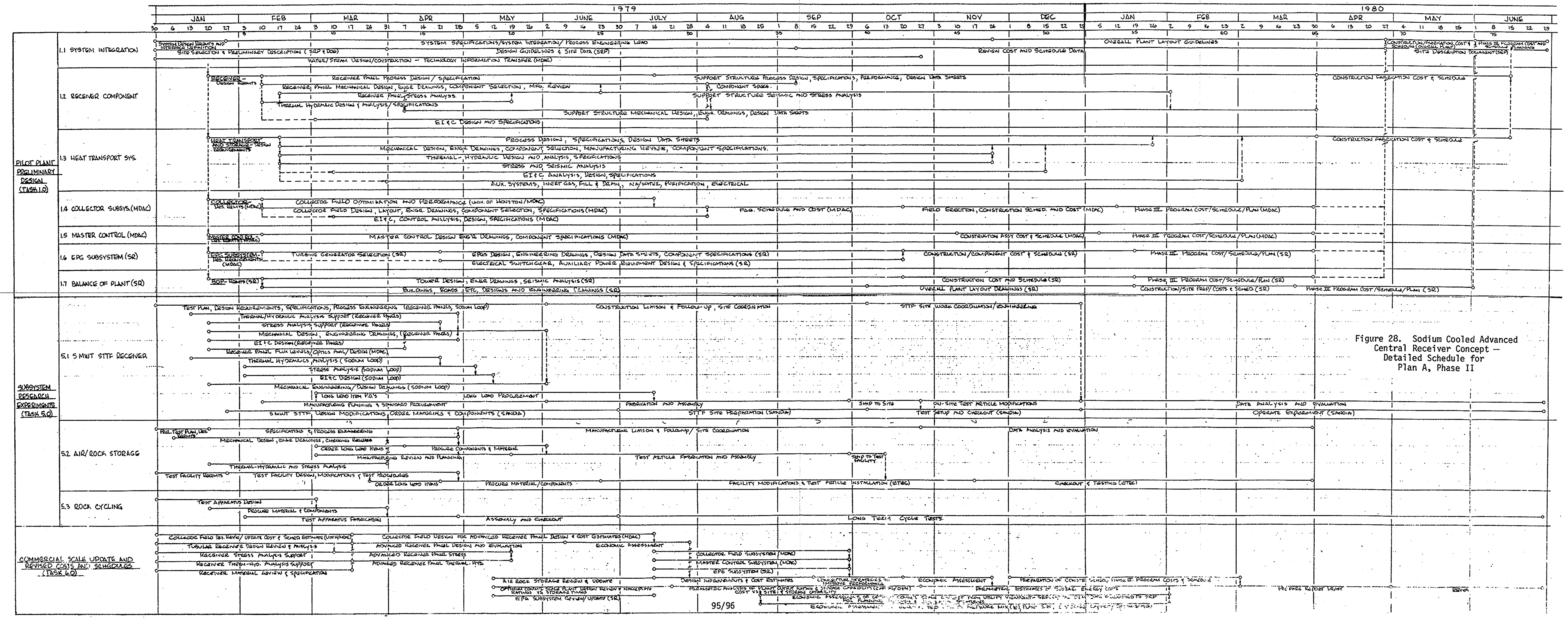

Figure 28. Sodium Cooled Advanced Central Receiver Concept — Detailed Schedule for Plan A, Phase II

This plan consists of the four main features identified above. It results in the initiation of operation of a commercial-scale, demonstration plant toward the end of calendar year 1986, a time slightly earlier than that projected for Plan A. However, Plan B results in significantly lower "pilot plant" construction cost as indicated in Table 21. The overall cost for Plan B is very roughly estimated at $242 M, up to the initiation of operation of the commercial-scale, critical module. The overall schedule for Plan B is shown in Figure 30.

The few-panel, solar receiver module, as defined here, is identical to the 10-MWe pilot plant described in Plan A, except that no electric power generation subsystem or thermal energy storage system is included. In order to dissipate the heat energy absorbed by the three-panel pilot plant receiver, a 38-MWt dump heat exchanger is incorporated into the plant in the manner shown in Figure 31. This concept has two advantages insofar as the overall development of the sodium-cooled concept is concerned: (1) it results in a lower capital investment in the small-scale "pilot" plant, and (2) it accelerates the overall concept development schedule. The limitations are that electrical energy is not actually produced, the operating and design features of storage are not demonstrated, and the operation of the ESG modular steam generator (MSG) at high temperatures is not verified.* It has been concluded, however, that, from the standpoint of the state-of-the-art of sodium technology, little is to be gained by fabricating and operating an all-sodium storage system. Similar systems, but somewhat smaller in size, are routinely used in high-temperature sodium loops.

The MSG represents more of a concern, although it has been tentatively concluded that the higher temperature design point does not economically justify building a unit for the receiver module plant. Plan B-1, which is discussed here, is an option on Plan B that includes an MSG if it is deemed ultimately that such an add-on is necessary. The steam generator that would be fabricated and operated in the 10-MWe pilot plant described for Plan A would be very similar to the MSG that was built and tested by ESG several years ago. The only

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*The MSG was extensively tested up to 510°C (950°F) several years ago.

TABLE 21

PLAN B — ESTIMATED COSTS

Task No.	Task Description	Cost ($1000)		
		Engineering	Fabrication and Construction	Operation
1.0	Pilot Plant Preliminary Design	1,400	0	0
2.0	Pilot Plant Final Design	2,700	0	0
3.0	Pilot Plant Construction	2,200	32,000	0
4.0	Pilot Plant C/O and Operation	2,400	0	2,000
5.0	Subsystem Research Experiments			
5.1	5-MWt Receiver Test	393	650	138
5.2	Air-Rock Thermocline	111	42	88
5.3	Rock Cycling	14	20	26
6.0	Commercial Scale Update	182	0	0
7.0	Demonstration Plant Preliminary Design	6,000	0	0
8.0	Demonstration Plant Final Design	9,000	0	0
9.0	Demonstration Plant Construction	8,300	174,000	0
	Total	32,700	206,712	2,252
		Grand Total — $241,664		

PLAN B

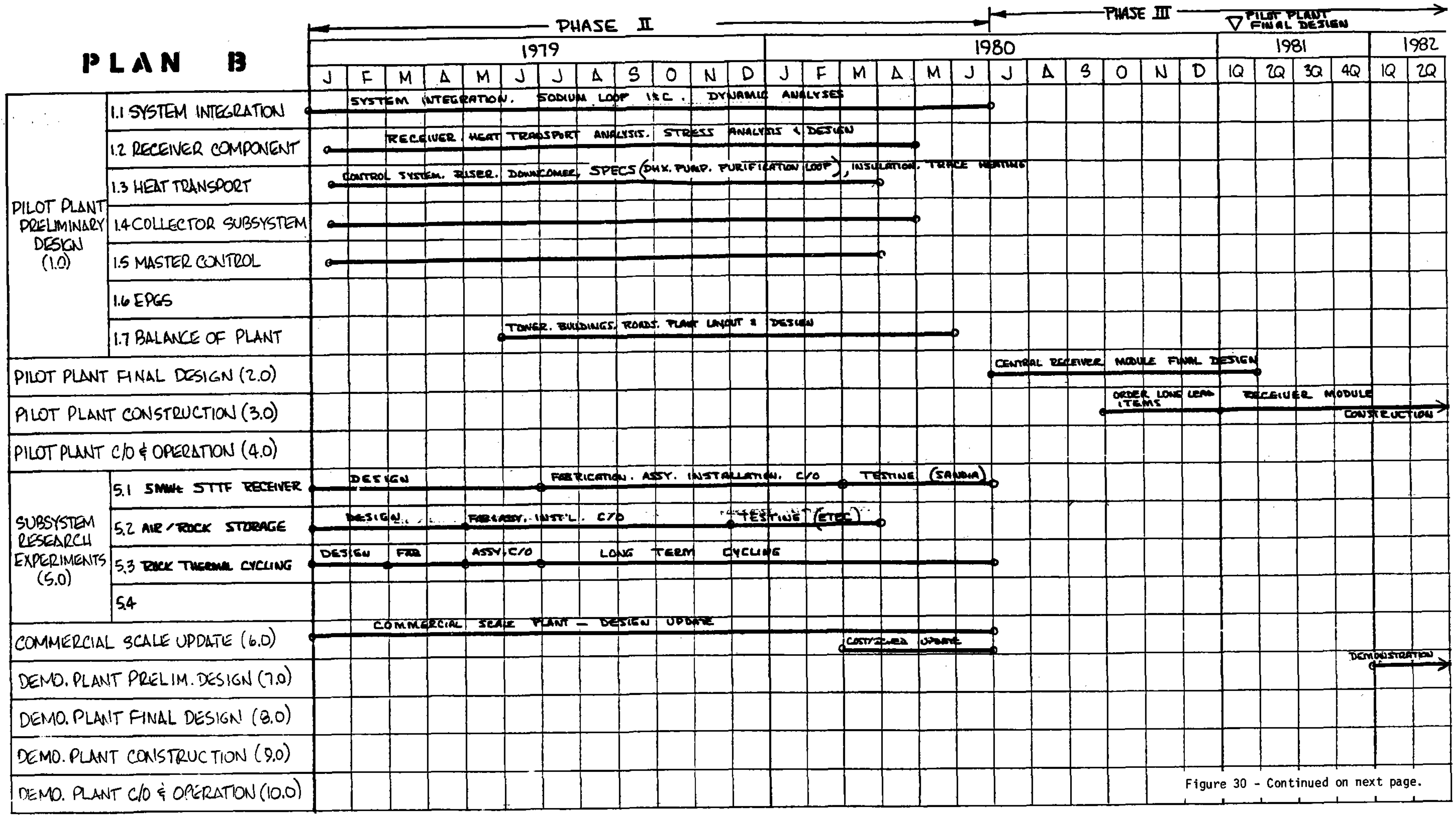

Figure 30 - Continued on next page.

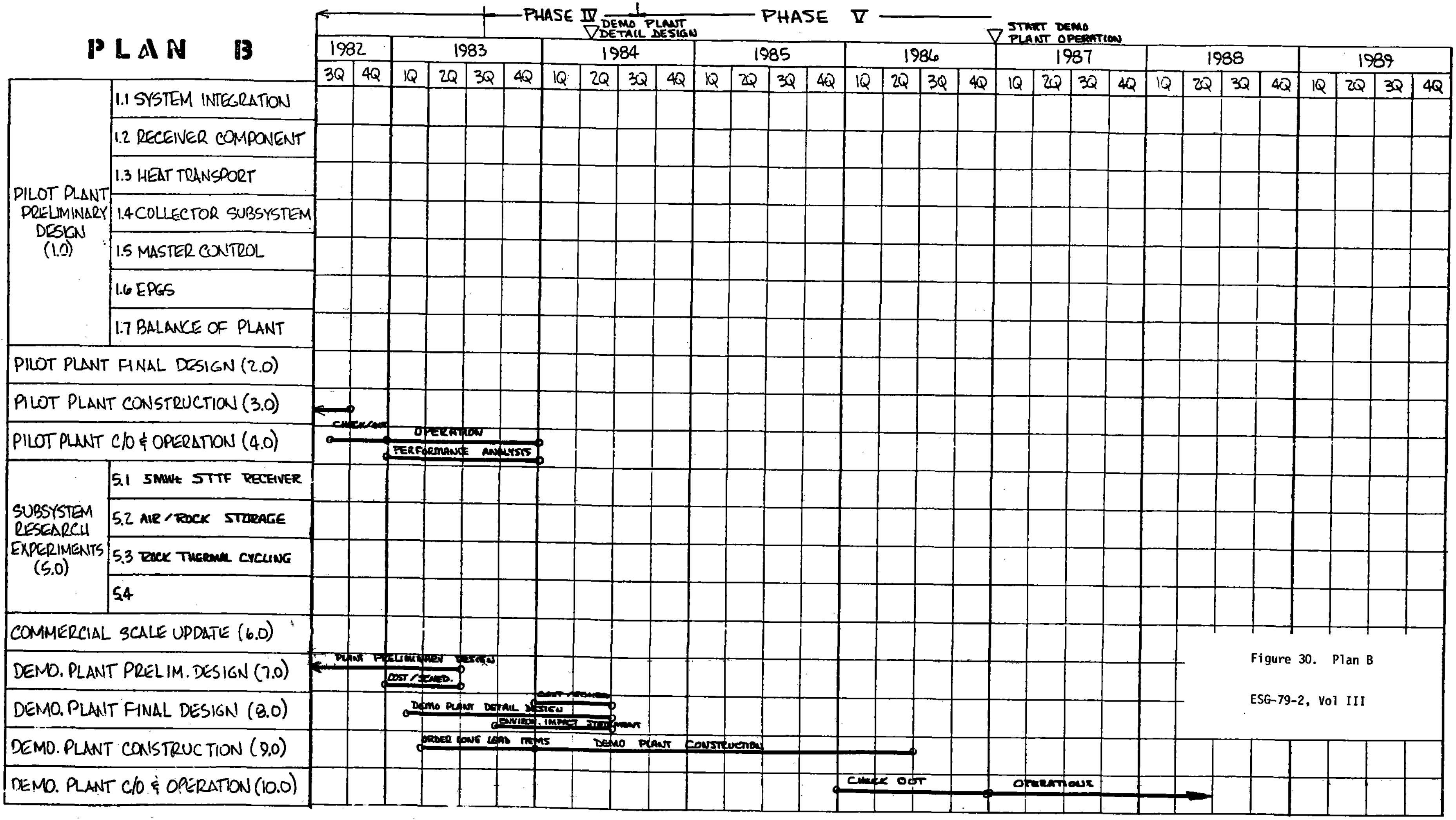

Figure 30. Plan B

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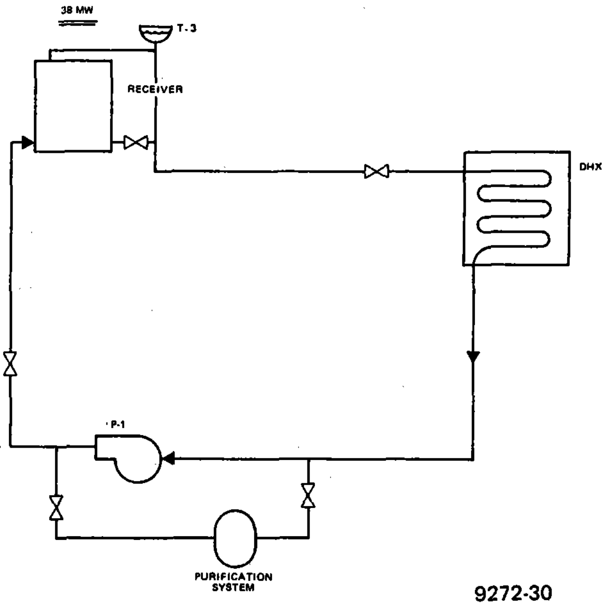

Figure 31. Receiver Module Plant

difference would be that an operating sodium inlet temperature of 594°C (1100°F) would be used, whereas, in the MSG tests, the maximum temperature achieved was 510°C (950°F).

It is generally agreed that there is no need to generate electrical energy since the behavior of the EPGS side of the plant is very well understood. This position is valid because the steam turbines selected for use in the sodium solar concepts are "standard" systems that have been built and operated for a number of years and represent modern steam plant technology.

Thus, except for the "aesthetic" appeal of actually producing electrical energy, the "receiver module" plant would meet the principal objective of the Plan A pilot plant — namely, the development of a sodium-cooled receiver, and the demonstration of its performance and cycle life. By deleting the MSG, storage, and the EPGS in going from Plan A to Plan B, the pilot plant preliminary design task also is significantly reduced in cost.

The other tasks comprising Plan B do not differ significantly from those described in Plan A, except that the construction time for the receiver module plant is reduced to 24 months. The critical path in this construction plan is dictated by the fabrication time for the three-panel receiver.

c. Plan B-1

Few-Panel, Solar, "Receiver Module" Plant with Steam Generator
5-MWt Receiver SRE
Air-Rock Thermocline SRE
Commercial-Scale, Critical Module, Demonstration Plant

This plan is a variation of Plan B above and results in added work in those tasks concerned with the preliminary and final design of the "receiver module" plant and with construction of that plant. However, the overall risk in the development of the sodium concept is probably reduced. In this plan, the receiver module plant consists basically of a three-panel receiver, a steam generator, and a pump. No EPGS or storage system is included, but a large steam-condensing system would be used to condense the steam produced by the steam generator. This plan circumvents some of the concerns previously expressed relative to the verification of the operation of a steam generator at 1100^{0}F.

The preliminary design effort would be increased in scope to include the design of the 594^{0}C (1100^{0}F) MSG and, since the cost of the MSG is substantially greater than that for a DHX and a large steam-condensing system would be needed, the plant construction cost would be increased. One additional feature that this plan offers in the overall development of the sodium-cooled concept is that, once the receiver module plant with the steam generator has been built and operated, it would be possible to add a storage system and add in EPGS incrementally. Funding commitments for these add-ons could also be obtained incrementally on the basis of such major milestones as successful operation with the MSG only, followed by successful operation with the thermal energy storage system included. The penalty incurred by this reduced-risk approach is basically one of time, added cost for the large condensing unit that would not be needed when the EPGS is added, and increased engineering time that follows from performing the job in distinct and separate time periods. This drawback can, however, be partially circumvented by designing the plant initially to conform to all of the design features ultimately contemplated.

d. Plan C (Figure 32) (Maximum Risk)

Extensive 5-MWt Receiver SRE
Air-Rock Thermocline
Commercial-Scale, Critical Module, Demonstration Plant

This plan has the highest risk of all those developed and reviewed to date, but a substantial reduction in the time to reach commercialization could be expected. Its basic feature is that the pilot plant concept is totally eliminated in the development plan for the sodium-cooled, solar, central receiver power plant. Since the major objective of the pilot plant is to resolve design uncertainties in the receiver component, another approach to this problem has been identified. This approach is to perform more extensive and additional 5-MWt receiver SRE's, including the possibility of several concepts being examined in detail. A concentrated 5-month effort under the task designated "Commercial-Scale Update" would be undertaken initially in order to identify in detail the stress and cycle life problems, if any, associated with the commercial-scale receiver panels. This work would include more extensive thermal and stress analyses than could be undertaken in Phase I. Once these problems were more exactly defined, a test panel for use with the 0.032-m^3/s (500-gpm) sodium test loop would be designed and fabricated in order to verify one or more specific design features. Other panels would also be designed and fabricated in order to obtain additional or different types of information. The results of tests on the first or second panel would also be factored into the later panel designs as required.

In parallel with the work being conducted on the 5-MWt receiver, on the air-rock storage, and on the rock cycle SRE's, the preliminary design of the commercial-size, critical module will be undertaken. This work will be built directly upon the conceptual design studies for the 100-MWe power plant in Phase I. This preliminary design effort will cover an elapsed time of 2 years and 3 months in order to be able to incorporate into the preliminary design of the critical module the results of the experiments conducted at the 5-MWt STTF and to be able to make a cost-effective decision relative to the use of the all-sodium vs the air-rock concept for storage in the 100-MWe plant.

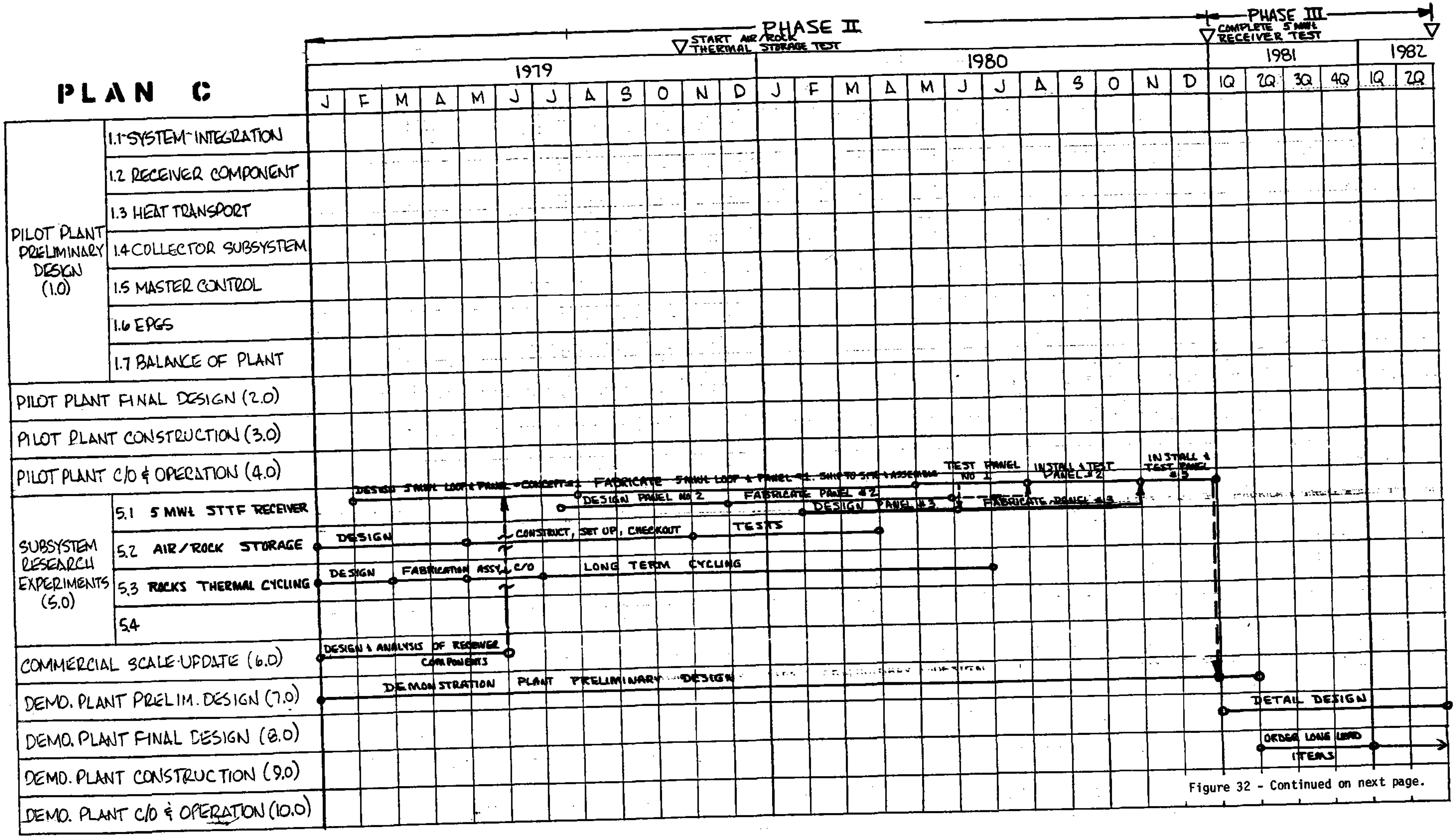

Figure 32 - Continued on next page.

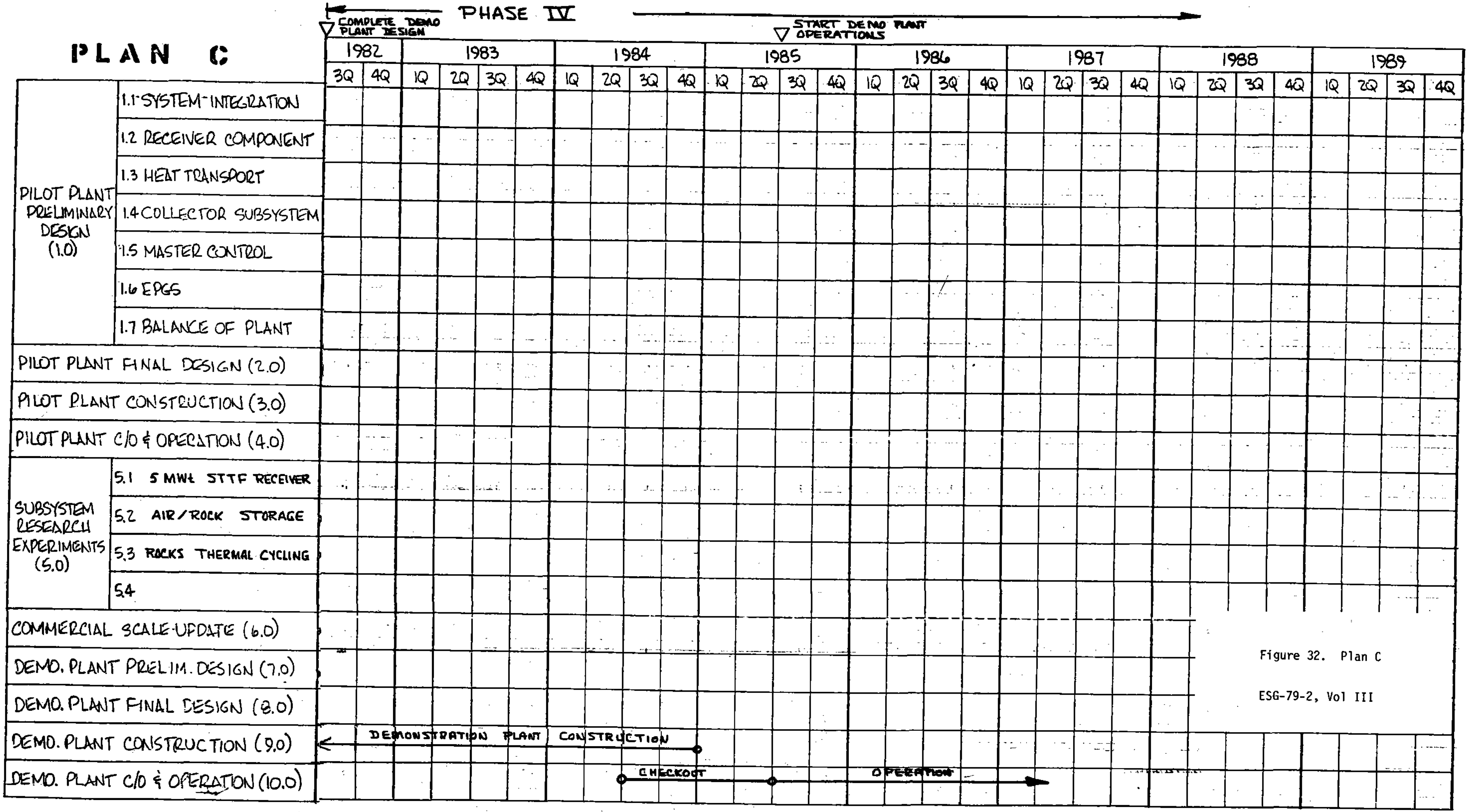

Figure 32. Plan C

ESG-79-2, Vol III

Other aspects of this plan are the same as those outlined in Plan A insofar as the scopes of work for the air-rock thermocline SRE, the rock cycling SRE, and the commercial plant preliminary and final design studies are concerned. The elimination of the pilot plant allows, however, the date for initiation of demonstration plant operation to be moved up to mid-1985 as can be seen in Figure 32. Estimates of overall costs for the development program, following this plan, are given in Table 22.

e. Plan D (Figure 33)

35-MWt Test of Sodium Loop at 594°C (no Receiver)
Extensive 5-MWt Receiver SRE
Air-Rock Thermocline SRE
Commercial Scale, Critical Module, Demonstration Plant

This proposed plan consists of the substitution of the "receiver module" plant in Plan B by a 35-MWt sodium loop incorporating a drag valve, hot storage tank, steam generator pump, steam generator (MSG), cold storage tank, and a receiver pump. An existing 35-MWt fossil-fired sodium heater* located at the ETEC would be used as the heat source. Also, an existing 35-MWt steam condenser unit located at ETEC would be used to condense the steam generated. One or more pumps would also be available.

The advantage that can be realized by following this plan is that the performances of all major sodium components are verified as a system at the peak operating temperature to which each component would be expected to go. Such a plan of action is not generally considered necessary by the Solar Project Team at ESG since each component, in one size or another, has been operated in the past at or near the planned temperature, although all of them have not been operated in the particular loop configuration that is typical of a solar plant. By eliminating a commercial-scale receiver panel test, the costs of a heliostat field, downcomer, riser, and tower are eliminated.

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*The current capacity is 70 MWt, but a 35-MWt loop appears to be adequate to verify the performance of all components, including the MSG, at the 594°C temperature.

TABLE 22

PLAN C — ESTIMATED COSTS

Task No.	Task Description	Cost ($1000)		
		Engineering	Fabrication and Construction	Operation
1.0	Pilot Plant Preliminary Design			
2.0	Pilot Plant Final Design			
3.0	Pilot Plant Construction			
4.0	Pilot Plant C/O and Operation			
5.0	Subsystem Research Experiments			
5.1	5-MWt Receiver Test	1,000	750	300
5.2	Air-Rock Thermocline	111	42	88
5.3	Rock Cycling	14	20	26
6.0	Commercial Scale Update	500	0	0
7.0	Demonstration Plant Preliminary Design	8,000	0	0
8.0	Demonstration Plant Final Design	9,000	0	0
9.0	Demonstration Plant Construction	8,300	174,000	0
	Total	26,925	174,812	414
		Grand Total — $202,151		

PLAN D

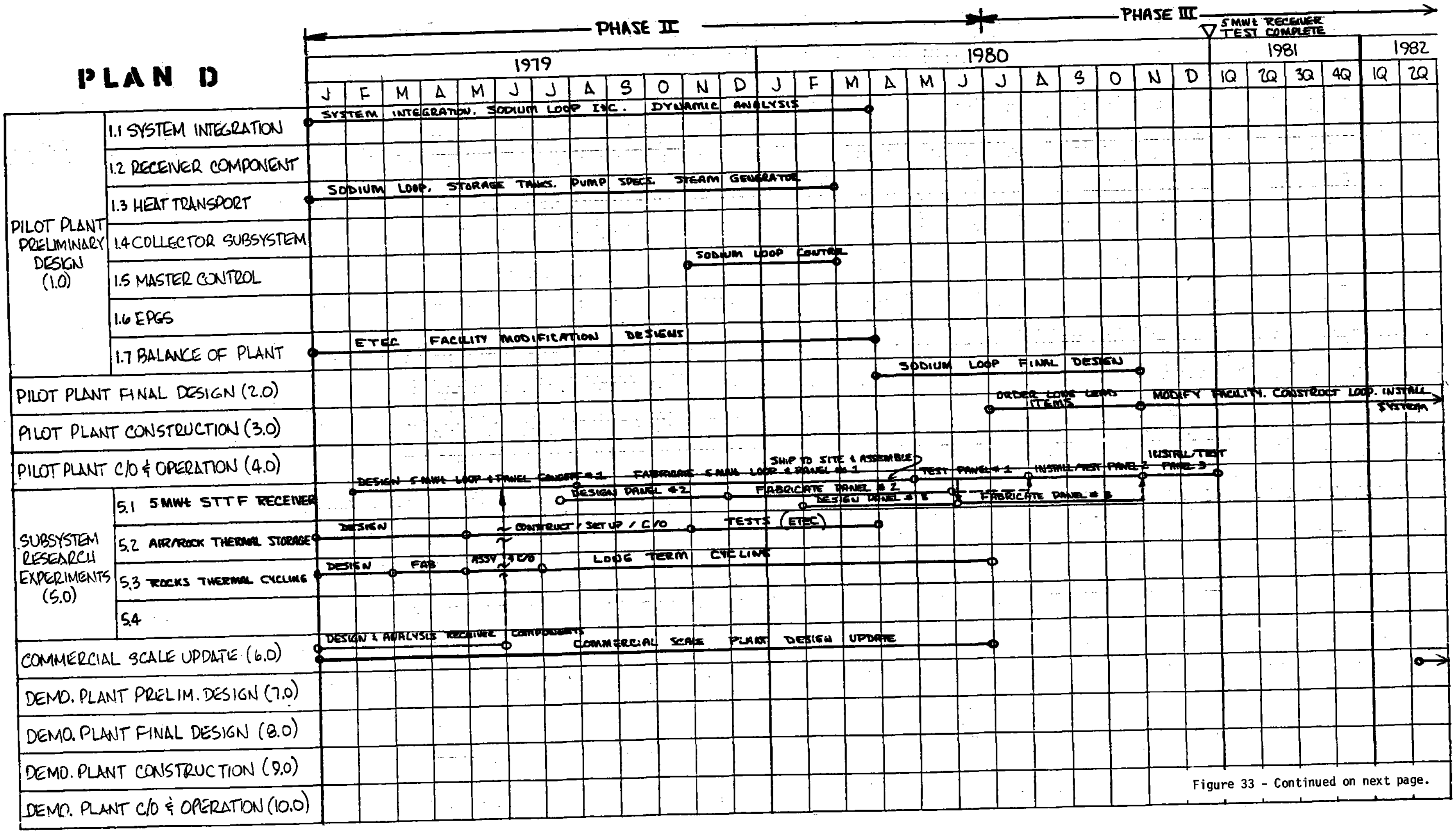

Figure 33 - Continued on next page.

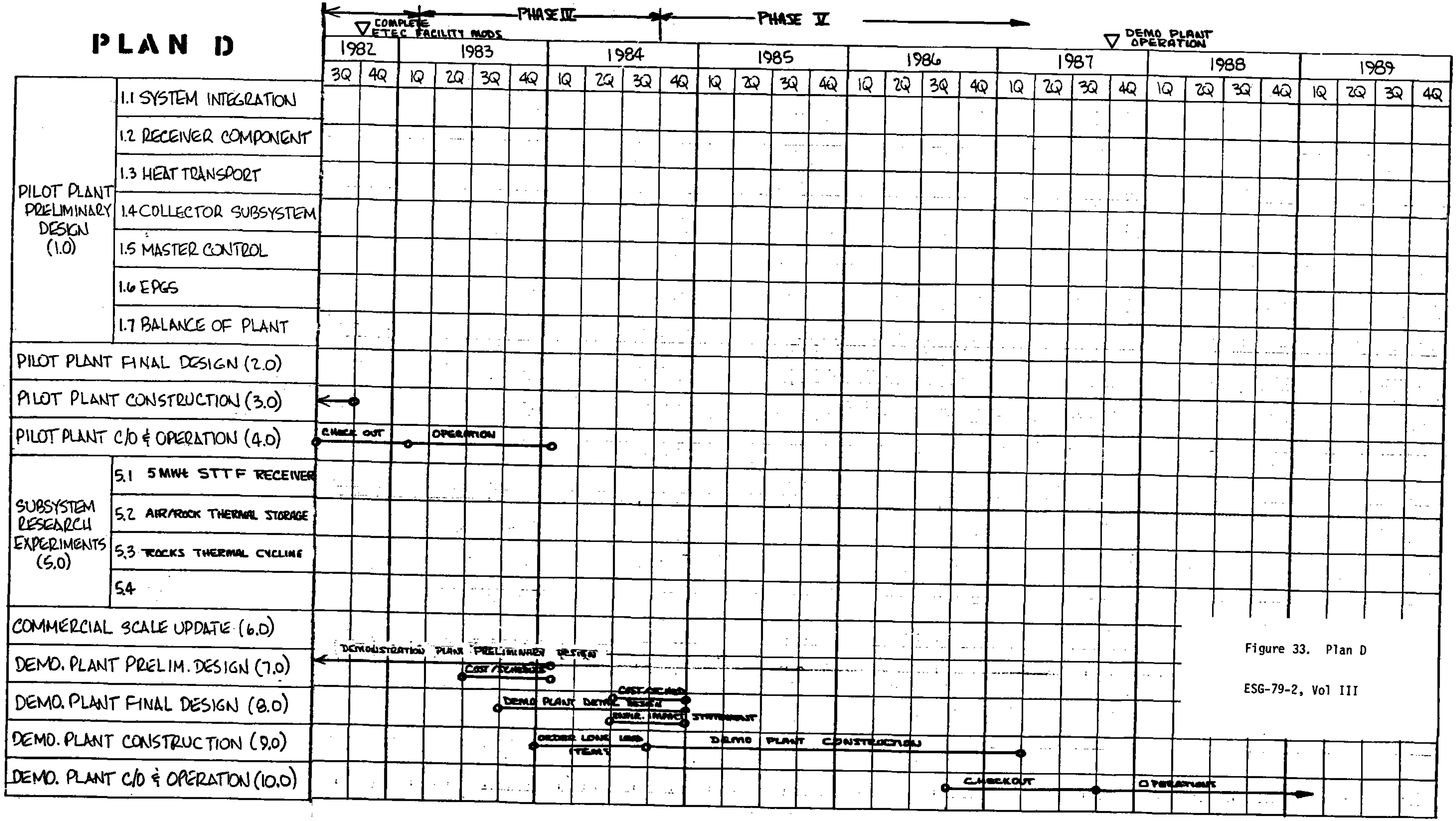

Figure 33. Plan D

ESG-79-2, Vol III

The limitation imposed by this plan is that no test of a commercial-size receiver is conducted as it would be in Plans A and B for example. To offset this situation, an extensive series of 5-MWt STTF test of reduced-sized panels would be undertaken in a manner identical to that outlined in Plan C.

The overall schedule for Plan D is shown in Figure 33 and shows that initial operation of the demonstration plant could be achieved toward the end of Calendar Year 1987. The overall program cost is contained in Table 23.

f. Plan E (Minimum Risk)

360° Receiver, 38-MWe Pilot Plant
5-MWt Receiver SRE
Air-Rock Thermocline SRE
Commercial-Scale, Critical Module, Demonstration Plant

This plan is identical to Plan A except that the pilot plant contains a full, 360°, external receiver, about 10 m high by 10 m in diameter, and produces, because of heat flux criteria, about 38 MWe. The total number of heliostats in the surrounding field would be of the order of 5,000; consequently, the collector subsystem cost would be high relative to the 1,045 heliostats for the 10-MWe, few-panel receiver and collector system. Since the power level is calculated to be a factor of about four greater, the cost of the heat transport and other plant subsystems would be greater. Generally, the total costs for such a development program for the sodium-cooled central receiver would be substantially higher than for Plan A.

This plan would, however, involve minimum risk in the sense that the pilot plant would, in fact, be a minature version of a commercial-scale plant and, therefore, simulate most of its performance characteristics, and probably all of its operational characteristics. However, the receiver panels would be less than commercial-scale size so that no direct simulation would exist there.

A conceptual assessment of a 360° pilot plant design for the Advanced Sodium Central Receiver System was carried out under the Phase I effort in order

TABLE 23

PLAN D — ESTIMATED COSTS

Task No.	Task Description	Cost ($1000)		
		Engineering	Fabrication and Construction	Operation
1.0	Pilot Plant Preliminary Design	680		
2.0	Pilot Plant Final Design	1,300		
3.0	Pilot Plant Construction	1,100	8,000	
4.0	Pilot Plant C/O and Operation	1,200		1,000
5.0	Subsystem Research Experiments			
5.1	5-MWt Receiver Test	1,000	750	300
5.2	Air-Rock Thermocline	111	42	88
5.3	Rock Cycling	14	20	26
6.0	Commercial Scale Update	500	0	0
7.0	Demonstration Plant Preliminary Design	8,000	0	0
8.0	Demonstration Plant Final Design	9,000	0	0
9.0	Demonstration Plant Construction	8,300	174,000	0
	Total	31,205	182,812	1,414
		Grand Total - $215,431		

to determine the relative attractiveness of this design approach. The resulting conclusions were arrived at as a result of a highly simplified analysis which considered only "1st order" effects. It is felt, however, that these conclusions are valid, even though an in-depth computer analysis may change the numerical values which were actually derived in this analysis.

The objective of this work was to conceptually describe a 360^0 pilot plant configuration and compare it with previous study results developed for a north-field, 3-panel receiver pilot plant configuration. The guidelines used in this analysis for the 360^0 pilot plant included:

Maintain collector field geometric similarity with the commercial system configuration.

Maintain commercial system peak heat flux levels.

Maintain the same relative power distribution around the circumference of the receiver as anticipated for the commercial receiver.

The logical starting point for this analysis was the current 100-MWe commercial system design with a peak heat flux of 1.37 MW/m^2. It should be noted that this system employs canted heliostats (all at the same range) and a single-point-aim strategy. Therefore, without changing the design of the heliostats (through custom-canting and focusing) or reducing the heliostat error budget, the pilot plant that would be required to simulate the commercial system, as defined by the three previous design guidelines, is the commercial system itself.

By adopting a custom-cant and custom-focus approach to the design of the heliostats, it is possible to reduce the number of heliostats, while maintaining the design point peak heat flux level and obtaining a corresponding reduction in total power. Figure 34 shows an approximate comparison of the northside vertical heat flux profile for the current commercial system design and an estimated profile that would be realized if a custom-cant, custom-focus approach (with a reduced heliostat error budget) were employed using the same collector field. The conclusions are that:

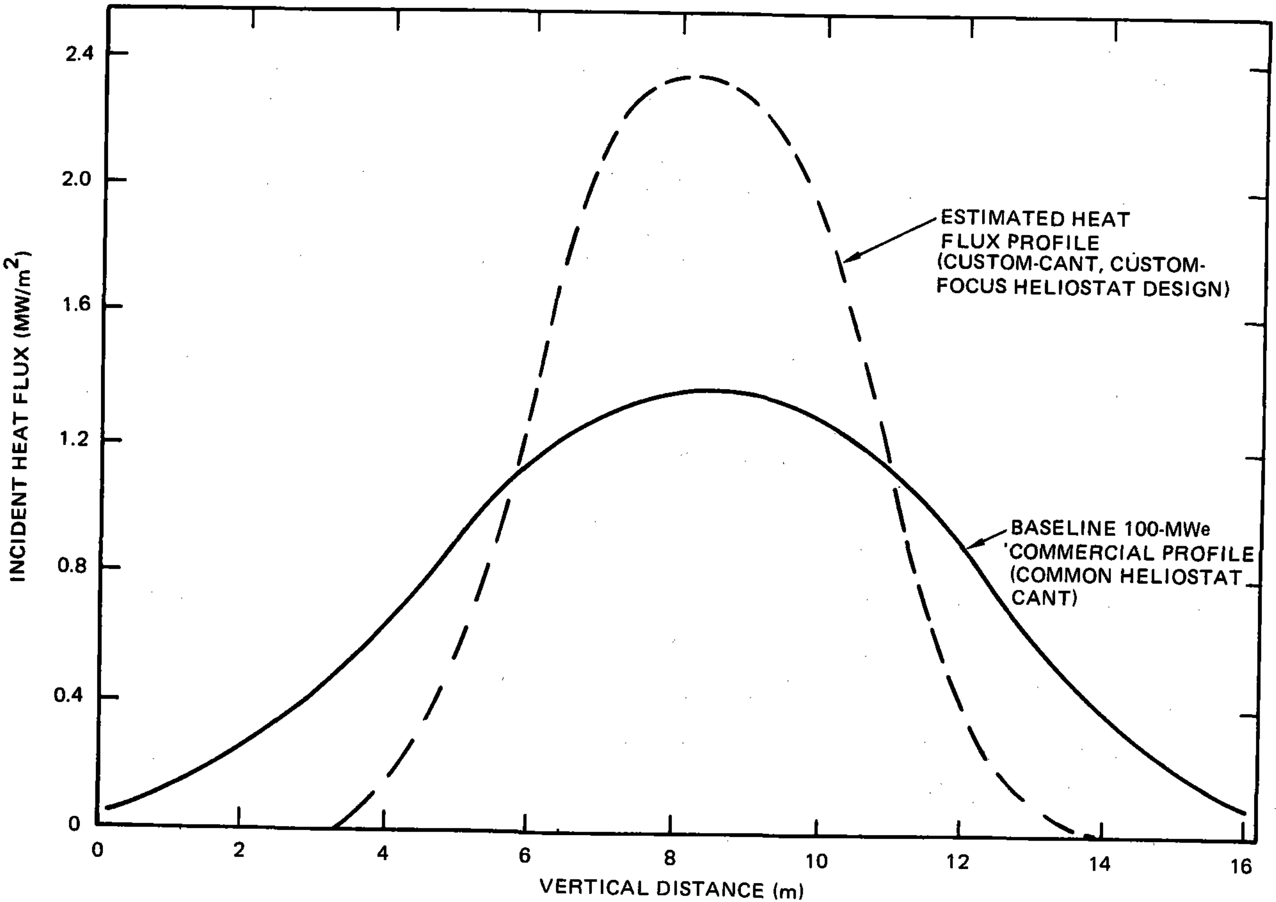

Figure 34. Heat Flux Profile Comparison (North Side)

1) A significantly higher peak heat flux can be realized on the north panel, a conclusion that indicates that a reduction in the number of heliostats (custom-canted, custom-focused) can be made to re-establish the peak flux at the design level of 1.37 MW/m^2.
2) The small image size will permit a reduction in receiver size from 16.15 m to 10 m. For the current analysis, it is assumed that this reduction occurs in both the height and diameter dimensions of the receiver. (Off-axis aberration effects have been ignored.)

If it is assumed that the number of heliostats can be adjusted by the relationships established on the basis of this heat flux profile, i.e., the complete field scales in direct response to scaling required on the north side, the following adjustments can be made in the number of heliostats.

$$\left(\begin{matrix}\text{Heliostat}\\\text{Number}\end{matrix}\right) = \begin{matrix}\text{Commercial}\\\text{Heliostat No.}\end{matrix} \cdot \left(\frac{\text{Peak Flux 1}}{\text{Peak Flux 2}}\right) \left(\frac{\text{Receiver Diameter 2}}{\text{Receiver Diameter 1}}\right)$$

$$= (14106) \left(\frac{1.37}{2.36}\right) \left(\frac{10}{16.15}\right) = 5{,}070 \text{ heliostats}$$

The diameter correction factor was included to account for the fact that for constant power, the heat flux intensity varies inversely with receiver circumference. The result indicates that, through simple scaling down from a commercial system, ~9,000 heliostats could be eliminated while still maintaining the desired design guidelines and objectives.

Since the design of the actual 360^0 pilot plant would be developed from an optimization analysis which employs fairly expensive "early" heliostats, that analysis would tend to further reduce the number of heliostats by improving their optical performance. This situation would be accomplished by increasing the separation distances between heliostats and raising the tower height to improve the field cosine effects. It is estimated that these effects may reduce the number of heliostats required by an additional ~5%.

$$(\text{Heliostat Number}) = 5{,}070\ (0.95) = 4{,}816 \text{ heliostats}$$

However, this approach would tend to compromise the objective of geometric similarity with the commercial system.

In terms of estimating new values for the receiver centerline elevation and thermal power rating, it is appropriate to apply the following scaling relationships:

1) Receiver elevation $\propto (\text{Power})^{0.5}$
2) Power $\propto$ (Number of Heliostats)

The resulting values based on scaling from the current commercial system without tower height adjustments to improve optical performance are:

$$\text{Power} = 390 \text{ MWt} \left(\frac{5070}{14106}\right) = 140 \text{ MWt}$$

$$\text{Receiver Elevation} = 174 \text{ m} \left(\frac{140}{390}\right)^{0.5} = 104 \text{ m}$$

Assuming a solar multiple of 1.3 for the pilot plant and a net cycle conversion efficiency of 35%, a 38-MWe turbine-generator would be required to match the energy collection capability of the collector field and receiver.

Based on this "1st order" analysis, the following conclusions have been established:

1) A commercial-sized collector field and receiver is required to simulate commercial heat flux conditions if custom-canting and custom-focusing (or some version thereof) is not adopted.
2) Canting and focusing of heliostats improves concentration which allows for a reduction in the required number of heliostats and in the size of the receiver.
3) The minimum number of heliostats required for a pilot plant is ~5,000 while ~140 MWt is produced.

C. CONCLUSIONS

On the basis of the plans considered above, the conclusion is that Plan C is the most cost-effective plan of action for proceeding from the end of the Phase I effort toward the development of a commercially viable concept that would produce electrical energy in a utility grid at competitive costs. This plan has somewhat higher risk and may necessitate modifications in the demonstration plant in order to ultimately achieve the performance goals that have been established.

APPENDIX A

PILOT PLANT DATA

CONTENTS: SUMMARY DATA
DESIGN DATA SHEETS
PIPING AND INSTRUMENTATION
DRAWINGS

TABLE A

ADVANCED CENTRAL RECEIVER SYSTEM SUMMARY DATA — PILOT PLANT

Net Electrical Power (MWe)	10
Parasitic Power (MWe)	
Daytime	1.2
Nighttime	0.6
Insolation (W/m^2)	950
Maximum Solar Power Absorbed (MWt)	36.2
Nominal Solar Power Absorbed for Direct Operating (MWt)	30.2
Collector Field Configuration	North
Solar Multiple, Equinox Noon	1.2
Number of Heliostats	1065 (Inverted)
Heliostat Shape and Size [m (ft)]	Square, 7.4 x 7.4 (24.2 x 24.3)
Number of Towers-Receivers	1
Receiver Midpoint Elevation [m (ft)]	104 (341)
Receiver *Configuration*	External *Cylinder*
Number of Receiver Panels	3
Receiver Height and Diameter [m (ft)]	16.1 x 6.3 (52.8 x 20.7)
Receiver Maximum Heat Flux (MW/M^2)	1.53
Sodium Temperatures [$^\circ$C ($^\circ$F)]	288/593 (550/1100)
Receiver Sodium Flow Rate [kg/h (lb/h)]	0.337×10^6 (0.741×10^6)
Steam Generator Sodium Flow Rate (Direct Operation) [kg/h (lb/h)]	0.281×10^6 (0.018×10^6)
Thermal Storage Capacity (MWth)	30.2
Total Sodium Inventory [kg (lb)]	0.352×10^6 (0.775×10^6)
Steam Generator and Reheater Type	Modular Steam Generator
Steam Conditions [MN/m^2, $^\circ$C (psia, $^\circ$F)]	
Initial	10.10, 538 (1465, 1000)
Steam Flow Rate [kg/h (lb/h)]	
Daytime	0.42×10^5 (0.929×10^5)
Nighttime	0.405×10^5 (0.893×10^5)
TSS Sodium Flow Rate [kg/h (lb/h)]	0.297×10^6 (0.655×10^6
Feedwater Temperature [$^\circ$C ($^\circ$F)]	234 (453)
Turbine Back Pressure [MN/m^2 (in. Hg)]	0.007 (2.0)
Heat Rejection [MW (Btu/h)]	
Daytime	22 (75×10^6)
Nighttime	21.2 (72×10^6)

RECEIVER SUBSYSTEM

PILOT PLANT

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	DESIGN DATA SHEET	TITLE ADVANCED CENTRAL RECEIVER PILOT PLANT RECEIVER SUBSYSTEM	NUMBER
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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		RECEIVER SUBSYSTEM					
		Nominal Thermal Power	MWt	30.2			
		Maximum Thermal Power	MWt	36.2			
		Receiver Temperature					
		- In	^{o}C (^{o}F)	288 (550			
		- Out	^{o}C (^{o}F)	593 (1100)			
		Flow Rate - Maximum Receiver	kg/h (lb/h)	0.338×10^{6} (0.744×10^{-6})			
		- Maximum Steam Generator	kg/h (lb/h)	0.282×10^{6} 0.62×10^{6})			
		Volume of Sodium in Subsystem	m^{3} (gal)	34.1 (9,000)			
		Weight of Sodium in Subsystem	kg (lb)	29,100 (69,100)			
		Pump Outlet Pressure	MN/m^{2} (psia)	1.75 (255)			
		Pump Inlet Pressure	MN/m^{2} (psia)	0.10 (15)			
		Total Radiation and Convection Loss	%	9% at Peak Power 12.5% at 50% Power			

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DESIGN DATA SHEET

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		RECEIVER SUBSYSTEM (Cont.)					
		Steam Generator, Sodium Side					Tube and Shell Hockey Stick
		- Temperature In	^{o}C (^{o}F)	593 (1100)			
		- Temperature Out	^{o}C (^{o}F)	288 (550)			
		- Power	MWt	32			
		Pumps - Number and Type					Fixed Speed, Double Suction Centrifugal, Single Stage
		Receiver - Size (H x W) and Type	m x m (ft x ft)	16.1 x 6.3 (53 x 20.7)			External 3 Panel Segment of Cylinder
		Large Valves, 20 cm (8 in.) Block		2			CS, Riser and Pump Return
		20 cm (8 in.) Check		1			CS, Riser
		10 cm (4 in.) Block		1			SS, Downcomer
		8 cm (3 in.) Control		1			SS, Superheater Control
		5 cm (2 in.) Control		3			SS, Receiver Panel Control
		3 cm (1 in.) Control		1			SS, Reheater Control

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		RECEIVER SUBSYSTEM (Cont.)					
		Large Pipe Length, 20 cm (8 in.)	m (ft)	427 (1400)			CS and SS
		10 cm (4 in.)	m (ft)	427 (1400)			SS
		Receiver Assembly					
		Width of Circular Segment	m (ft)	6.3 (20.7)			
		Height	m (ft)	16.1 (53)			
		Receiver Midpoint Elevation	m (ft)	100 (328)			
		Receiver Maximum Elevation	m (ft)	110 (328)			
		Number of Absorber Panels		3			
		Receiver Weight					
		Total	kg (lb)	34,000 (75,000)			
		Pressure Parts	kg (lb)	12,300 (27,000)			
		Absorber Panel					
		Height	m (ft)	16.1 (53)			
		Width	m (ft)	2.1 (6.9)			
		Number of Tubes		110			
		Tube OD	cm (in.)	1.91 (0.75)			
		Tube ID	cm (in.)	1.65 (0.65)			

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DESIGN DATA SHEET

NEW REV.	NO.	ITEM	DESIGN POINT UNIT	VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		Absorber Panel (Cont.)					
		Tube Material					CRES 304H
		Solar Surface Coating					Pyromark
		Panel Insulation	cm (in.)	15.2 (6)			Closed-Pore Fiberglass
		Thermal Expansion	cm (in.)	12.7 (5)			Flexible Tube Bends
		Absorptivity, Minimum		0.95			
		Peak Heat Flux	MW/m^2 ($Btu/in.^2 s$)	1.53 (0.94)			
		Outlet Temperature	^{o}C (^{o}F)	593 (1100)			
		Inlet Temperature	^{o}C (^{o}F)	288 (550)			
		Maximum Tube Surface Temperature	^{o}C (^{o}F)	635 (1175)			
		Tower Assembly					
		Construction					Steel
		Height	m (ft)	87 (285)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>Riser</u>					
		Nominal Pipe ID	cm (in.)	20 (8)			
		Nominal Wall Thickness					Schedule 40
		Material		CS			
		Design Temperature	^oC (^oF)	371 (700)			
		Design Pressure ANSI B31.1		207 (300)			
		Maximum Flow Rate	kg/h (lb/h)	0.338×10^6 0.744×10^6			
		Velocity at Maximum Flow Rate	m/s (ft/s)	3.99 (13.1)			
		<u>Downcomer</u>					
		Nominal Pipe ID	cm (in.)	10.2 (4)			
		Nominal Wall Thickness					Schedule 40
		Material					304H
		Design Temperature	^oC (^oF)	593 (1100)			
		Design Pressure ANSI B31.1		207 (300)			
		Maximum Flow Rate	kg/h (lb/h)	0.337×10^6 (0.74×10^6)			
		Velocity at Maximum Flow Rate	m/s (ft/s)	14.4 (47.3)			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		RECEIVER PUMP					
		<u>Physical Description</u>					
		Quantity		1			
		Number of Stages		1			
		<u>Motor</u>					
		Size	MW (hp)	0.22 (300)			

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		<u>Pump Operating Conditions</u>					
		Developed Head	m (ft)	129 (423)			
		Flow Rate	kg/h (lb/h)	0.338 x 10^6 (0.744 x 10^6)			
		Speed	rpm	3540			
		Temperature	^{o}C (^{o}F)	288 (550)			
		Sodium Volume	m^3 (gal)	TBD			
		NPSH	m (ft)	9.1 (30)			
		Speed Control	%	10 to 100			
		Pump Power (η = 78%)	kW (hp)	207 (278)			
		<u>Design Conditions</u>					
		Developed Head	m (ft)	135 (444)			
		Flow Rate	m^3/s (gpm)	0.09 (1700)			
		Speed	rpm	3540			
		Temperature	^{o}C (^{o}F)	315 (600)			
		NPSH (minimum required)	m (ft)	9.1 (30)			
		Code					

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		STEAM GENERATOR					
		Physical Description					
		Quantity		1			
		Type					Tube and Shell Hockey Stick Once-Through
		Height	m (ft)	27.4 (90)			
		Width	m (ft)	4.27 (14)			
		Shell diameter	m (in.)	6.10 (20)			
		Heat Transfer Area	m^2 $(ft)^2$	229 (2470)			
		Number of Tubes		195			
		Tube Size	cm (in.)	1.59 (5/8) 0.307 (0.121)			
		Tube Wall Thickness	cm (in.)	0.19 (0.075)			
		Material					316 Stainless Steel
		Sodium Nozzle OD/Thickness	cm (in.)	TBD			
		Tubesheet Diameter/Thickness	cm (in.)	50.8/12.7 (20/5)			
		Steam Nozzle OD/Thickness	cm (in.)	TBD			
		Weight	kg (ton)	16,400 (18)			

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		Operating Conditions					
		Sodium Side:					
		Flow	kg/h (lb/h)	0.294×10^6 (0.655×10^6)			
		Inlet Temperature	°C (°F)	594 (1100)			
		Outlet Temperature	°C (°F)	288 (550)			
		Pressure Drop	MN/m^2	0.207 (30)			
		Duty	MWt	32			
		Water/Steam:					
		Flow	kg/h (lb/h)	0.473×10^5 (1.043×10^5)			
		Inlet Temperature	°C (°F)	234 (453)			
		Outlet Temperature	°C (°F)	538 (1000)			
		Pressure	MN/m^2	12.76 (1850)			
		Pressure Drop	MN/m^2 (psi)	2.07 (300)			
		Design Conditions:					
		Pressure-Sodium Side	MN/m^2 (psi)	2.07 (300)			
		Pressure-Steam Side	MN/m^2 (psig)	15.17 (2200)			
		Temperature	°C (°F)	538 (1100)			
		Code					

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THERMAL STORAGE SUBSYSTEM

ALL-SODIUM STORAGE

PILOT PLANT

TABLE 20

PLAN A — ESTIMATED COSTS

Task No.	Task Description	Cost ($1000)		
		Engineering	Fabrication and Construction	Operation
1.0	Pilot Plant Preliminary Design	2,050	0	0
2.0	Pilot Plant Final Design	4,000	0	0
3.0	Pilot Plant Construction	3,350	40,000	0
4.0	Pilot Plant C/O and Operation	3,650	0	3,000†
5.0	Subsystem Research Experiments			
5.1	5-MWt Receiver Test	393	650	138
5.2	Air-Rock Thermocline	111	42	88
5.3	Rock Cycling	14	20	26
6.0	Commercial Scale Update	182	0	0
7.0	Demonstration Plant Preliminary Design	6,000	0	0
8.0	Demonstration Plant Final Design	9,000	0	0
9.0	Demonstration Plant Construction	8,300	174,000	0
	Total	37,050	214,712	3,252
		Grand Total — $255,014		

†2 years for staff of 20 people

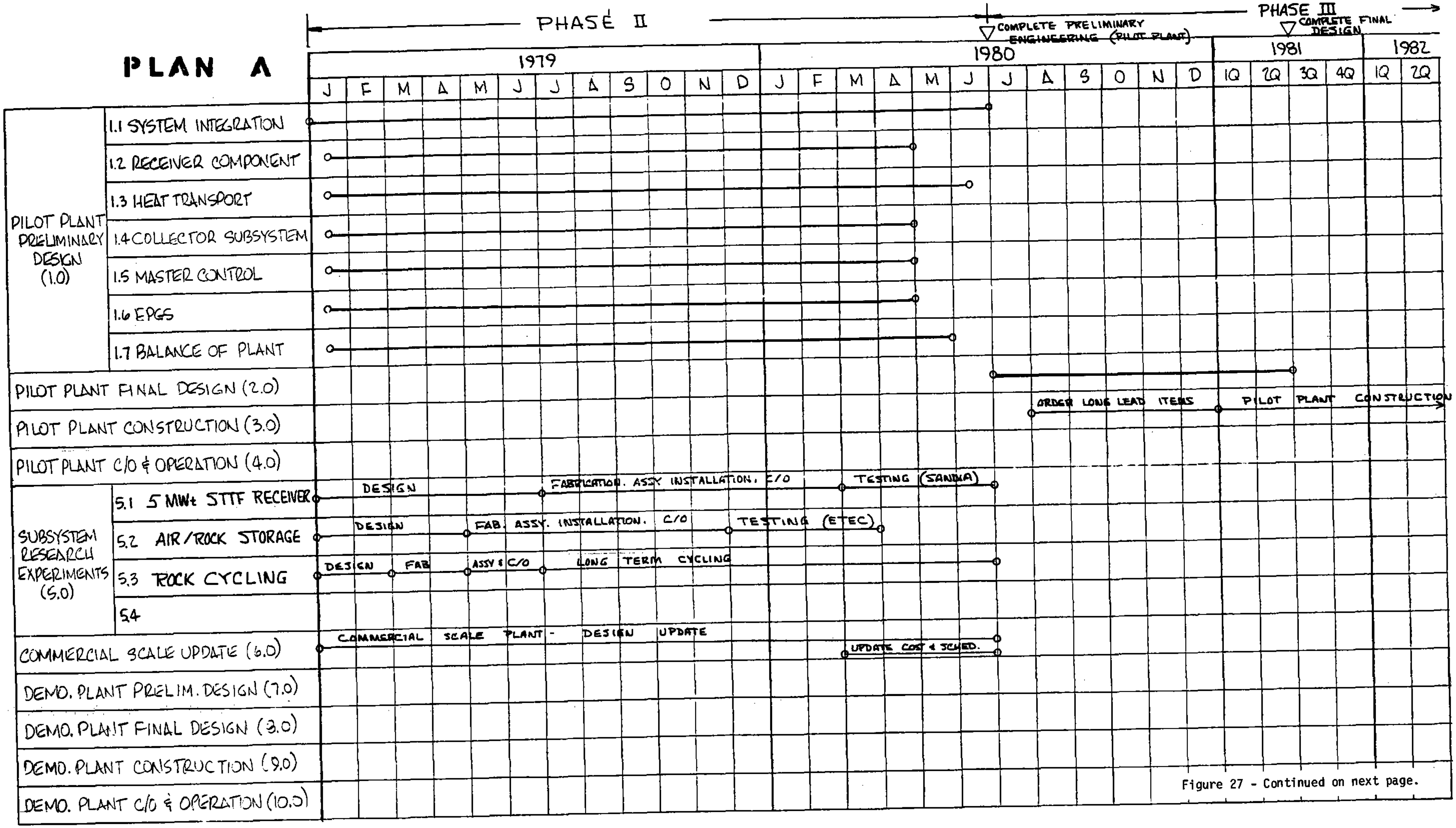

Figure 27 - Continued on next page.

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		<u>High Temperature Sodium Tank</u>					
		Type					Cylindrical API Type
		Diameter	m (ft)	10 (33)			
		Height	m (ft)	5.2 (17)			
		Wall Thickness		TBD			
		Top	cm (in.)	0.635 (0.25)			
		Bottom	cm (in.)	0.635 (0.25)			
		Volume	m^3 (gal)	4.5 (0.11 x 10^6)			
		Tank Material, Thickness	cm (in.)	TBD			Type 304 SS
		Insulation, Roof and Walls	cm (in.)	30.5 (12)			Calcium Silicate with Aluminum Weather Protection
		Base Insulation	m (ft)	1 (3)			Perlitic Concrete
		Electric Preheat-Temperature Maintenance	kw	540			
		Number of High Temperature Tanks		1			
		High Sodium Temperature	°C (°F)	593 (1100°F)			
		Ullage Maintenance Unit					Argon

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		STEAM GENERATOR PUMP					
		<u>Physical Description</u>					
		Quantity		1			
		Number of Stages		1			
		<u>Motor</u>					
		Size	MW (hp)	0.11 (150)			

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concluded that the SRE would not be cost effective to pursue, especially if a 5-MWt STTF receiver test were to be performed. Thus, further consideration of this SRE was eliminated in the development of the long-range plan for the sodium-cooled, solar concept. It should be noted, however, that restrictions regarding the use of the 5-MWt STTF for the test of a sodium receiver panel could make it necessary to reexamine this SRE in order to obtain some design information, however limited it might be.

In view of the heat flux limitation imposed by a radiant heat source, very brief consideration was given on the Phase I Program to the use of a facility such as the 30-kWt White Sands solar furnace. This SRE (see Subsection III.I above) would involve a very small test article (a few centimeters on a side), but would achieve high heat fluxes, well within the required range. High cycle frequencies could also readily be obtained. In addition, because of its small size, cycling to failure could probably be handled in view of the small sodium inventory required and in view of the remoteness of the facility. However, since externally applied stresses would probably be needed and the test article would be so extremely small, it was decided not to pursue this concept further in terms of long-range planning. From the stress analyst's viewpoint, however, a test involving sufficient cycles to cause failure may be beneficial as a means of verifying failure predictions.

One other SRE that was considered briefly in the development of the Program Plan for Phases II, III, IV, and V was one involving the use of hot (650^{0}C) sodium as a heat source (see Subsection III.G above). This SRE would be conducted at ETEC where large heat sources (70-MWt fossil-fired sodium heaters) are already available, along with the necessary pump, dump heat exchanger, etc. Very high heat fluxes could be achieved, the test article could be large, cycle frequencies could be lowered to perhaps 3 to 4 h, and realistic structural loading conditions could be achieved. However, the test lacks an obvious visual relationship to the usual panel environment, and data interpretation is more difficult and less direct than for tests using radiant energy. Thus, this SRE has not been considered further for long-range planning.

3. Recommended SRE's

On the basis of technical as well as cost consideration, the recommendation is to undertake only the 5-MWt Receiver SRE at the STTF. Although a 5-MWt sodium, heat-transport loop will have to be designed and fabricated for use at STTF, it appears to be more cost effective to build the loop and take it to the existing solar facility than to build a radiant test system and take it to the existing sodium facility (ETEC). Tests involving more than one receiver design concept may, however, be necessary at STTF in order to resolve uncertainties pertaining to the overall receiver design, creep fatigue, and cycle life. Although panel sizes will be restricted to about 3 m high by 1 m wide, the required peak fluxes appear to be achievable. Such panels are reasonably large and, therefore, realistic load conditions can be achieved by using actual panel support devices and actual tube-to-manifold joints.

The recommended approach insofar as the air-rock thermal energy storage concept is concerned is that both SRE's be funded during Phase II of the program.

4. Other Program Plan Elements

In addition to the consideration of the six SRE's, the overall, long-term plans developed under the Phase I effort included consideration of the design, construction, and operation of a pilot plant, with and without an electric power generation subsystem, and the design and construction of a commercial-scale (~100 MWe) demonstration (critical module) plant. These plans have been developed in conformance with the phasing that was outlined in the RFP for Phase I of the program. The phasing guidelines consisted of the following parts:

Phase I – Current Program (now essentially complete) – A 12-month phase in which widespread system and subsystem parametric analyses are performed; a conceptual design of the preferred commercial-scale system is prepared and assessed; and a development plan prepared in which Subsystem Research Experiments (SRE's) and a Pilot Plant are identified and conceptually designed, and schedule and costs estimated.

COLLECTOR

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		GENERAL					
		Total Field Area (Excluding Central Exclusion)	$10^5 m^2$ ($10^5 ft^2$)	1.68 (18.11)			
		Number of Heliostats	—	1,065			
		Total Mirror Area	$10^5 m^2$ ($10^5 ft^2$)	0.522 (5.62)			
		Peak Power @ 950 W/m^2 (Incident)	MW	39.8			
		Annual Collectable Energy	MWht	74,600			
		Tower Height	m (ft)	89 (292)			
		Receiver Centerline Elevation	m (ft)	104 (341)			
		Heliostat Arrangement	—	Radial Stagger			
		Aim Strategy	—	Center Panel Vertical Aim			
		Peak Receiver Heat Flux	MW/m^2	∿1.5 Incident			

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			UNIT	VALUE			
		<u>Heliostat</u>					
		Reflector Shape	–	Rectangular			
		Reflector Envelope	m (ft)	7.38 x 7.42 (24.21 x 24.33)			
		Mirror Type		Second Surface, Silvered Fusion-Float Laminated Glass			
		Mirror Area	m^2 (ft^2)	49.05 (528)			
		Average Reflectivity		0.91			
		Drive System					
		Elevation		Dual Screw Jacks 3 θ, 480 V ac			
		Azimuth		Harmonic Drive 3 θ, 480 V ac			
		Reflected Beam Accuracy	(mr)	2.3			
		Drive Rate					
		Elevation	deg/min	15			
		Azimuth	deg/min	15			

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
		Cant Range					Canted and Curved for Range
		Electrical Draw					
		Motor Running (Steady State)	amp	1.5			
		Motor Start Surge Current	amp	3.0			
		Time Average Power Draw (per heliostat)	watts	∿39			
		Individual Heliostat Availability	—	0.9999			
		Field Electronics					
		Primary Feeder Power	voltage	2400			
		Primary Feeder Cable	AWG	#4			
		Secondary Feeder Power	voltage	480			
		Data Network	—	Fiber Optics			

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ELECTRIC POWER GENERATION

PILOT PLANT

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
		Turbine					
		Type					Tandum Compound, Single-Flow, Extraction, Condensing Turbine
		Rating	(kWe)	11,000			
		Heater Extractions					
		Shaft Speed	(rpm)	3,600			
		Last Stage Bucket Size	cm (in.)	28.9 (11.4)			
		Throttle Flow Control Mode		9203			Steam Generator-Turbine Coordinated Control
		Heat Rate	Btu/kWh	9207			
		Generator					
		Generator Rating	(kVA)	16,000			
		Power Factor		0.85			
		Output Voltage	(volts)	13,800			
		Frequency	(Hz)	60			
		Cooling					Air-Cooled
		Exciter					Static Excitation System
		Shaft Speed	(rpm)	3,600			
		Condenser					
		Type					Shell and Tube, 2-Pass
		Surface	m^2 (ft^2)	1,115 (12,000)			
		Tube Material		90-10 Copper			ASTM BIII, Alloy 706
		Tube Diameter OD	mm (in.)	19.05 (0.75)			
		Tube Wall Thickness 20 BWG	mm (in.)	0.89 (0.035)			

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			UNIT	VALUE			
		Condenser (Continued)					
		Tube Length, Effect	m (ft)	6.1 (20)			
		Condenser Pressure	kPa (in.-Hg abs)	7.0 (2.0)			
		Heat Rejection	MW (Btu/h)	26 (90 x 10^6)			
		Cooling Water Flow	m^3 (gpm)	0.725 (11,500)			
		Water Velocity	m/s (fps)	2.18 (7.16)			
		Cooling Water In	°C (°F)	28.9 (84.0)			
		Cooling Water Out	°C (°F)	38 (100)			
		Condenser Air Removal		—			Mechanical Vacuum Pump (2-full capacity)
		Cooling Tower					
		Quantity		1			
		Type					Mechanical Draft, Cross Flow
		Number of Cells		2			
		Fan Motor Size	kW (hp)	74.6 (100)			
		Design Wet Bulb Temperature	°C (°F)	23 (74.0)			
		Cold Water Temperature	°C (°F)	28.9 (84.0)			
		Hot Water Temperature	°C (°F)	38 (100)			
		Circulating Water Flow	m^3/s (gpm)	0.8 (12,000)			
		Heat Rejection	MW (Btu/h)	28 (595 x 10^6)			

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TEN-TATIVE	FIRM	REFERENCES AND REMARKS
		Feedwater Heaters					
		Low Pressure Heater Number		1			Horizontal, Stainless Steel Tubes, Carbon Steel Shell with Drain Cooler, Maximum Tube Side Pressure: 2.2 kPa (315 psia)
		Dearator Number		1			Stainless Steel Trays and Vent Condenser, Carbon Steel Shell, Horizontal Condensate Storage Section 62.5 m^3 (16,500 gal), Pressure Rating; 0.45 MPa (65 psia)
		High Pressure Heaters Number		2			Horizontal, Carbon Steel Tubes, Carbon Steel Shell with Drain Cooler, Maximum Tube Side Pressure: 20.68 MPa (3,000 psia)
		Feedwater Treatment					
		Equipment					
		- Inline Polishing Demineralizers					2 Full-Capacity Units
		- Makeup Water Demineralizers					2 Full-Capacity Units
		Chemicals					
		- pH Control					Ammonia
		- Oxygen Scavenger					Hydrazine

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MASTER CONTROL

PILOT PLANT

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NEW REV.	NO.	ITEM	DESIGN POINT		TEN-TATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	1	Plant Central Control Console (1)					
		Length	ft	25	X		
		Depth	ft	2	X		
		Height	ft	4	X		
N	2	Control Processors (6)					
		Throughput	KOPS/s	350	X		
		Primary Storage Capacity	16-Bit words	48,000	X		
N	3	Secondary Control Processor Storage (6)					
		Capacity	Megabits	25	X		
		Access Time	ms	35	X		
		Latency	ms	15	X		
N	4	Hardcopy Logger (2)					
		Characters	per line	132	X		
		Speed	lines/ min	300	X		
N	5	Recorders, Magnetic (2)					
		Density	Bits/in.	500/800	X		
		Speed	in./s	45			
N	6	Safing - Control Panel (1)	TBD	TBD			
N	7	Serial Digital Data Bus (2)					
		Throughput	KBits/s	1500	X		
N	8	Color CRT Displays (6)					
		Raster Scan	No. Lines	256 x 512	X		
		Colors	No.	4			

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NEW REV.	NO.	ITEM	DESIGN POINT UNIT	DESIGN POINT VALUE	TENTATIVE	FIRM	REFERENCES AND REMARKS
N	9	PID Controllers (100)					
		Microprocessor Loop Update Rate	per s	3	X		
		Scaling	%	0 - 100	X		
		Resolution	Bits	12			
		Output	MV	4-20			
N	10	Discrete Controllers (125)					
		Resolution	Bits	12	X		
		Output	MV	4 - 20			
N	11	Analog Data Acquisition (350)					
		Normal Rate	Chan/s	350			
		Emergency Rate	Chan/s	200,000			
		Resolution	Bits	12			
		Multiplexing	Type	Sequential			
N	12	Analog Outputs (TBD)	TBD	TBD	X		
N	13	Closed Circuit Television (4)			X		
		Monitor Size	in.	19			
		Camera	TBD	TBD			
		Auto Pan/Tilt	Degrees	90			
		Zoom	TBD	TBD			
N	14	Uninterruptible Power Source					
		10 Input	V ac	115 ± 10%			
		Regulated 10 Output	V ac	115 ± 2%			

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NEW REV.	NO.	ITEM	DESIGN POINT		TENTATIVE	FIRM	REFERENCES AND REMARKS
			UNIT	VALUE			
N	14	Uninterruptible Power Source (Cont.)					
		Storage Battery Capacity	h	0.5			
		Derated Power	KVA	TBD			
N	15	Time of Day Reference					
		Input-WWV Synch.	Hertz	1000	X		
		Output - Time of Day BCD Format	Bits	32	X		
N	16	Annunciator Panel	Functions	25	X		
N	17	Local Weather Station					
		Wind	MPH Degrees	80 360			
		Barometric Pressure	in. Hg	26 - 34			
		Humidity	Percent/ Rel	0 - 100			
		Solar Radiation	9M/cm^2/ min	0.36 - 2.0 Microns			
		Precipitation	in	20			
		Temperature	^{o}F	-15, +50			
N	18	Experimental Performance Data Acquisition System (5)					
		Chan Sec Each	Chan/s	10,000	X		
		Resolution Each	Bits	10 Bits + Sign			
		Multiplexing Each	Type	Random			

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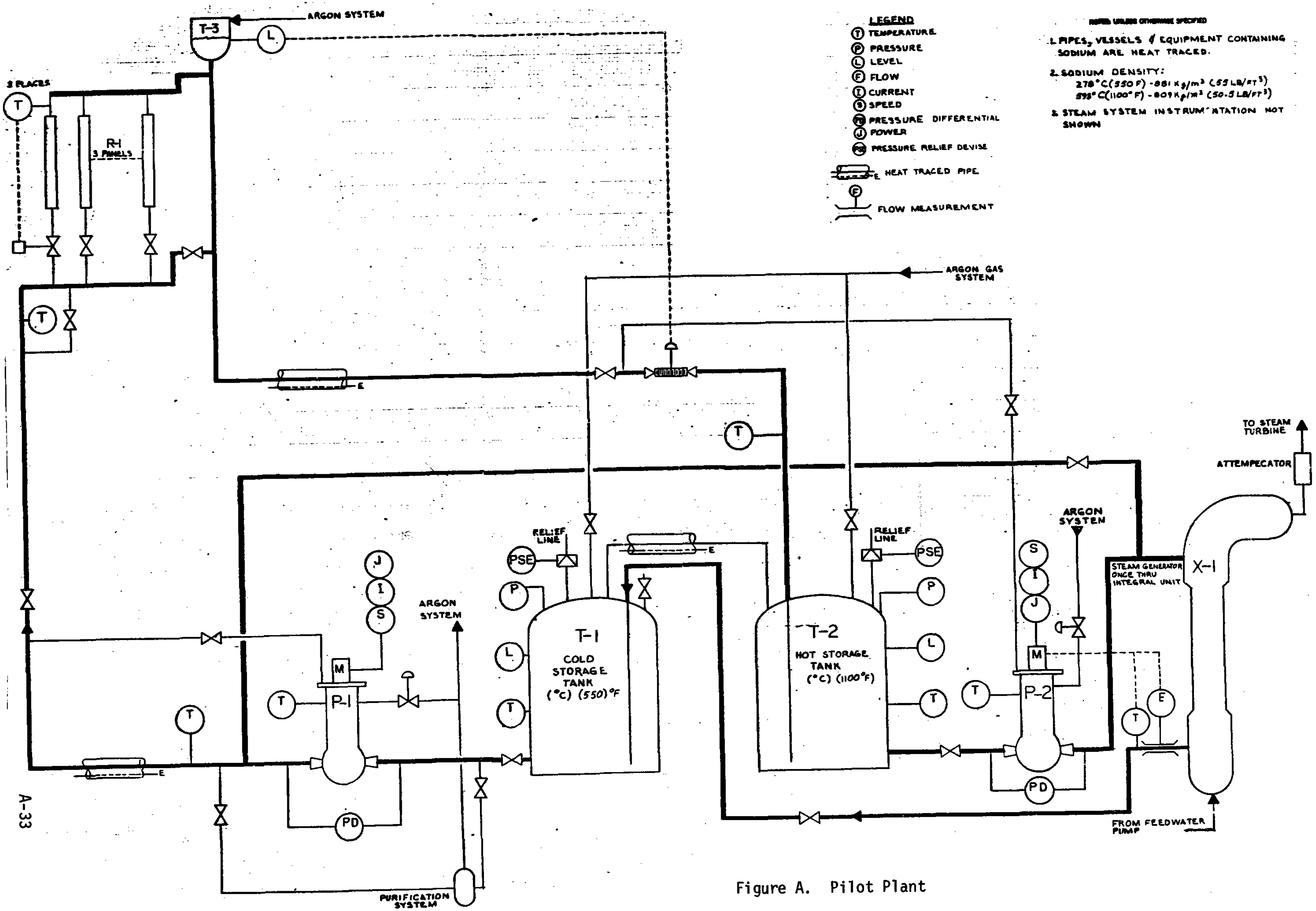

Figure A. Pilot Plant

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