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

Final Report, Volume 1, Executive Summary

June 1979

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

Rockwell International
Energy Systems Group
Canoga Park, California

U.S. Department of Energy

Solar Energy

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

VOLUME I
EXECUTIVE SUMMARY

JUNE 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
ENGINEERING CO.

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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

The conceptual design of an Advanced Central Receiver Power System using liquid sodium as a heat transport medium has been completed by a team consisting of the Energy Systems Group (prime contractor), McDonnell Douglas, Stearns-Roger, The University of Houston, and Salt River Project. The purpose of this study was to determine the technical and economic advantages of this concept for commercial-scale power plants. The concept is similar to that being studied on the water-steam programs, except that liquid sodium cools the receiver instead of water.

The Advanced Central Receiver System is composed of subsystems as pictorially shown in Figure 1. The basic area of responsibility of the team members was:

ESG	-	Overall System
	-	Receiver Subsystem
	-	Thermal Storage Subsystem
MDAC	-	Collector Subsystem with U of H as a subcontractor
	-	Master control subsystem
Stearns-Roger	-	Electric Power Generating Subsystem
	-	Receiver Tower
Salt River	-	Project-utility consultants for operations, design, and cost

This final report covers all tasks of Contract EG-77-C-03-1483. These tasks were as follows:

Task 1 - Review and Analysis of Preliminary Specification
Task 2 - Parametric Analysis
Task 3 - Select Commercial Configuration
Task 4 - Commercial Plant Conceptual Design
Task 5 - Assessment of Commercial Plant

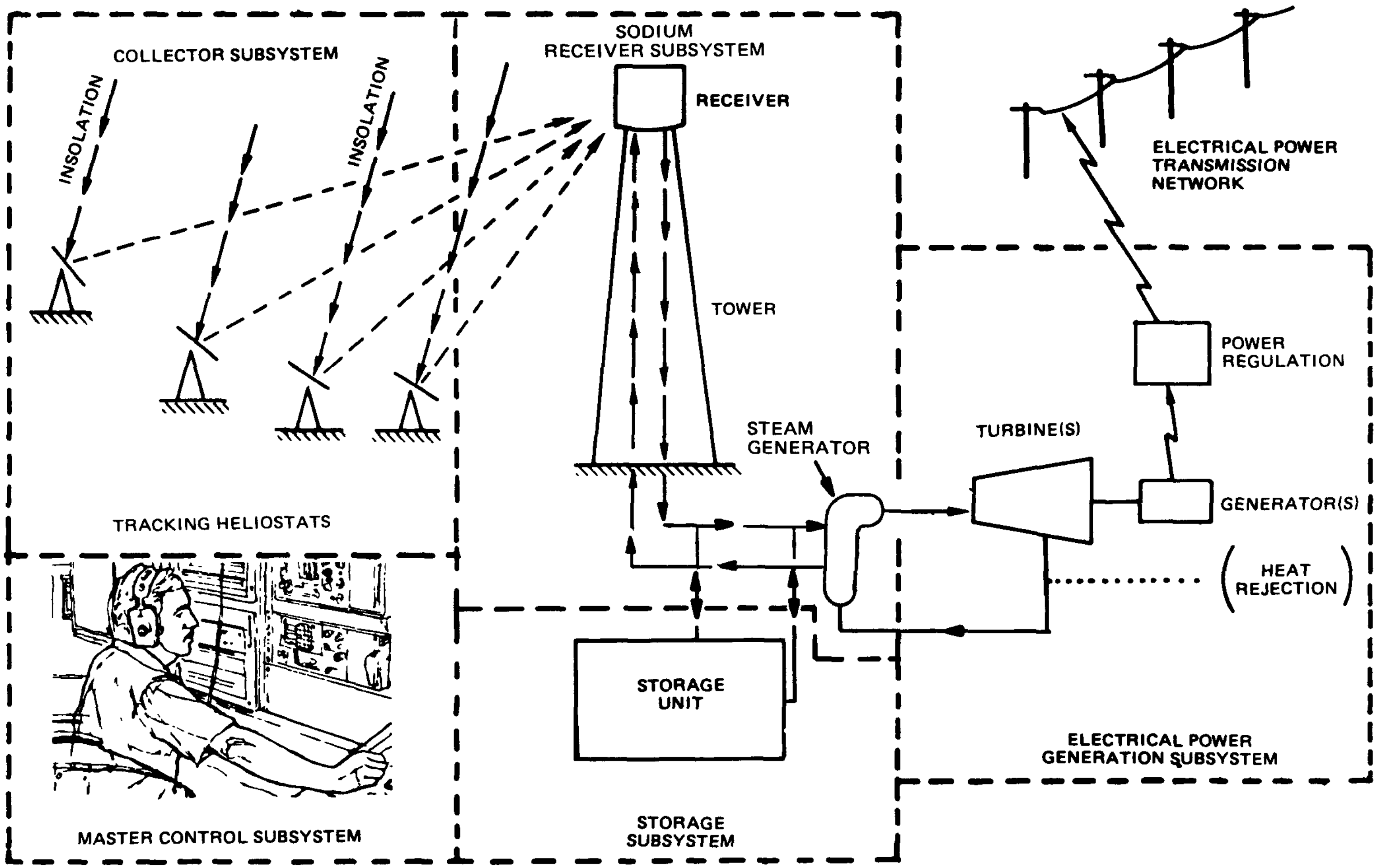

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Figure 1. Advanced Central Receiver Subsystems

Task 6 - Advanced Central Receiver Power System Development Plan
Task 7 - Program Plan
Task 8 - Reports and Data
Task 9 - Program Management
Task 10 - Safety Analysis

The baseline configuration is depicted in Figure 2. In this particular arrangement, sodium is pumped to the top of a tall tower where the receiver is located. The sodium is heated in the receiver and then flows down the tower, through a pressure reducing device, and into a large, hot storage tank that is located at ground level and whose size is made to meet a specific thermal energy storage capacity requirement. The sodium is pumped from this tank by a separate pump, through a system of steam generators, wherein heat is transferred from the sodium to water. The steam generator system consists of a separate superheater and reheater operating in parallel and an evaporator unit operating in series

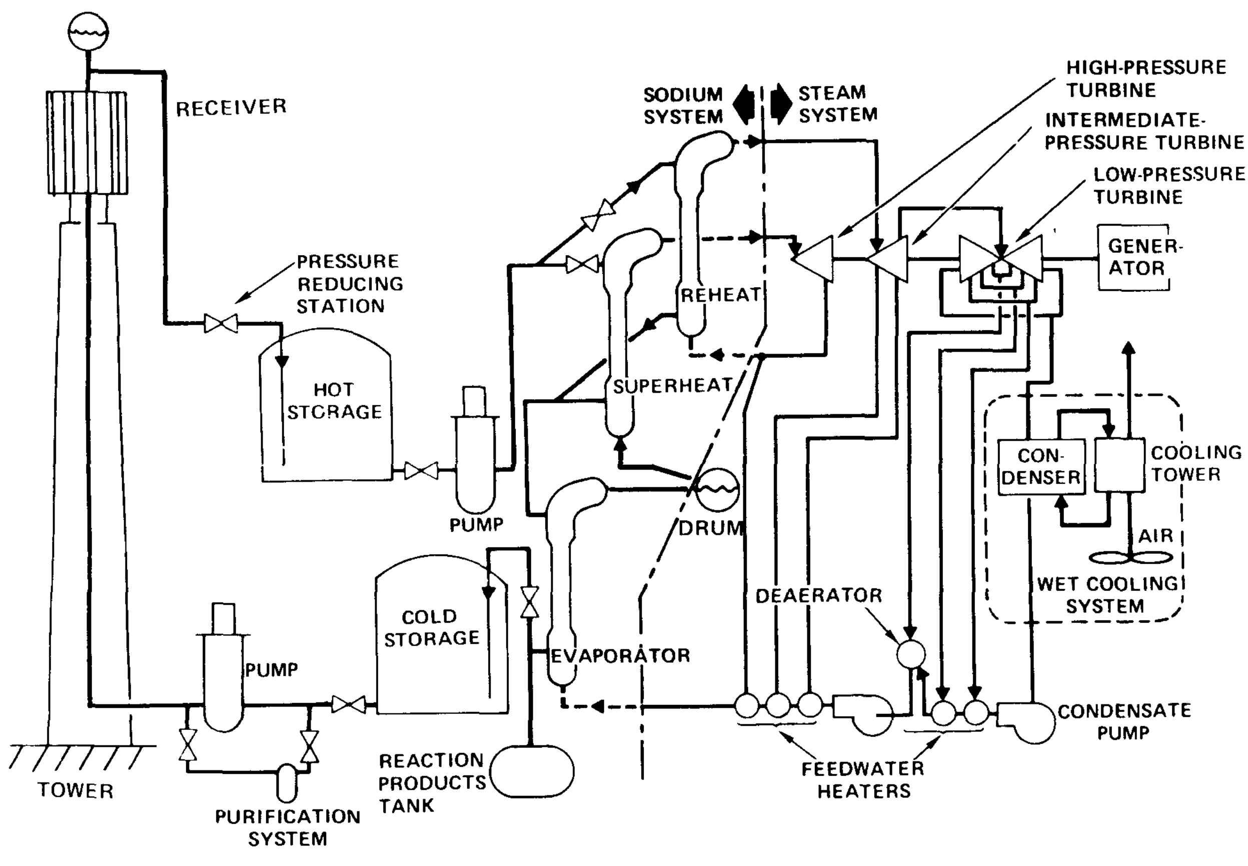

Figure 2. Sodium Cooled Advanced Central Receiver System

with the other two units. The sodium flowing from the evaporator unit is piped to a cold storage tank. From the cold storage tank, sodium is then pumped to the top of the tower to complete the cycle. The pressure reducing device (a standard drag valve) serves to mitigate the pressure caused by the static head of the receiver tower and thus allows the large tanks to operate at ambient pressure conditions. The steam generated in the steam generators is fed to a conventional "off-the-shelf," high-efficiency turbine. The steam loop operates in a conventional Rankine cycle with the steam generators serving the same purpose as a conventional boiler with water being fed to the evaporator with conventional feedwater pumps.

There are several advantages to the sodium-cooled system. One of these is that the heat transport fluid remains in the liquid state at all times; therefore, the control of the system is simpler, and there is not a large density change between inlet and outlet. A second advantage is that liquid sodium is a very good heat transfer material; consequently, the receiver can be made smaller and the heat flux can be substantially higher. A third advantage is that the heat transport fluid can also serve as the heat storage material in some considerations, and operation from storage can be accomplished under the same thermodynamic conditions as would exist when operating directly from the receiver. In addition, the receiver, which is subject to varying heat input, can be totally decoupled from the power cycle. Finally, the sodium system is capable of providing steam to a turbine at temperatures and pressures commensurate with or exceeding modern steam plant requirements and can conveniently incorporate a reheat cycle. These advantages are offset, to some extent, by the need for some additional pieces of equipment not necessarily required by a water-steam system. However, the cost of these additional items is more than compensated by the substantial increase in system efficiency.

The technical approach that was adopted on this program was to establish a reference baseline configuration and then to perform various subsystem and system-level trade studies and parametric analysis in order to evaluate various potential improvements. As superior subsystems were identified on the basis of cost, performance, and operating characteristics, the reference baseline configuration was updated. In this way, a preferred commercial system configuration was developed, designed, and evaluated on the basis of economic merit.

The initial baseline performance data of the advanced central receiver are summarized in Table 1, Column 1. This is the reference configuration against which the results of parametric analyses were compared on the program during Task 2.

After the Task 2 parametric studies, and the Task 3 effort to select the commercial configuration, the baseline commercial configuration was established as summarized in Column 2 of Table 1 during Task 4.

As a result of the assessment of the commercial plant, completed during Task 5, an optimum commercial plant size was identified based on economics. The rating of this plant is 281 MWe net. The optimum advanced baseline performance data are summarized in the last column of Table 1.

During the performance of Task 6, a conceptual design of a 10-MWe advanced central receiver pilot plant was completed. The pilot plant configuration is shown in Figure 3, and its performance data are summarized in Table 2.

The alternative advanced configuration, established during the subject study effort using an air-rock bed storage system, is shown in Figure 4. This configuration uses inexpensive rocks as the thermal storage material and air as the heat transfer media between the rock bed and the air-to-sodium heat exchanger. In order to retain complete passive buffering, 1/2 h of all-sodium storage is included in the system. The cost of this storage system appears to be marginally cost competitive at the 3-h capacity with the all-sodium storage system. For longer storage periods, such as 6-h capacity, the air-rock system is cost competitive. For a large plant with 13.4 h of storage, the cost of storage is reduced from $502/kW for an all-sodium system to $287/kW for the system shown in Figure 4 The technical characteristics of this system are described in detail in Volume II Book 1.

The sections which follow in this volume give a programmatic overview of the accomplishments of this program. Section 2 describes the 100-MWe conceptual commercial plant design. Section 3 discusses the 281-MWe optimum plant design. Section 4 describes the 10-MWe pilot plant design. Section 5 concerns itself

TABLE 1

ADVANCED CENTRAL RECEIVER BASELINE DATA SUMMARY

System	Parameter	Configuration		
		Initial Advanced Baseline	Final Advanced Baseline	Optimum Advanced Baseline
Electric	Net Power (MWe)	100	100	281
	Gross Power (MWe)	113	112	312
	Cycle Efficiency (%)	39.5	43.1	43.2
Receiver	SM	1.50	1.50	1.50
	Nominal Thermal Power (MWt)	286	260	723
	Maximum Thermal Power (MWt)	429	390	1084
	Receiver Temperature - In [°C (°F)]	288 (550)	288 (550)	288 (550)
	Receiver Temperature - Out [°C (°F)]	593 (1,100)	593 (1,100)	593 (1,100)
	Flow Rate [10^6 kg/h (10^6 lb/h)]	4.03 (8.88)	3.66 (8.07)	10.2 (22.6)
	Receiver Midpoint Elevation [m (ft)]	258 (846)	174 (571)	268 (879)
Storage (100% Power)	Operating Time (h)	3	3	3
	Energy (MWt-h)	805	740	2400
	Quantity [10^6 kg (10^6 lb)]	7.6 (16.8)	7.6 (16.8)	23 (50.4)
	Volume [10^3 m^3 (10^3 ft^3)]	9.6 (340)	9.5 (340)	28.2 (1010)
EPG	Turbine-in Pressure [MN/m^2 (psig)]	13.8 (2,000)	12.4 (1,800)	16.5 (2,400)
	Superheater Temperature [°C (°F)]	538 (1,000)	538 (1,000)	538 (1,000)
	Reheater Temperature [°C (°F)]	538 (1,000)	538 (1,000)	538 (1,000)
Collector	Mirror Area [km^2 (ft^2)]	0.705 (7.59 x 10^6)	0.692 (7.44 x 10^6)	1.99 (21.4 x 10^6)
	No. of Heliostats	18,596	14,106	40,660

TABLE 2

ADVANCED CENTRAL RECEIVER BASELINE DATA SUMMARY — PILOT PLANT

System	Parameter	Pilot Plant
Electric	Net Power (MWe)	10
	Gross Power (MWe)	11.2
	Cycle Efficiency (%)	37.1
Receiver	SM	1.2
	Nominal Thermal Power (MWt)	36.2
	Maximum Thermal Power (MWt)	30.2
	Receiver Temperature - In [^oC (^oF)]	288 (550)
	Receiver Temperature - Out [^oC (^oF)]	593 (1100)
	Flow Rate [10^6 kg/h (10^6 lb/h)]	0.337 x 10^6 (0.74 x 10^6)
	Receiver Midpoint Elevation [m (ft)]	104 (341)
Storage (100% Power)	Operating Time (h)	1.0
	Energy (MWt-h)	30.2
	Quantity [10^6 kg (10^6 lb)]	0.35 (0.775)
EPG	Turbine-in Pressure [MN/m^2 (psig)]	10.0 (1450)
	Turbine-in Temperature [^oC (^oF)]	538 (1000)
Collector	Mirror Area [m^2 (ft^2)]	52,185 (0.56 x 10^6)
	Number of Heliostats	1065

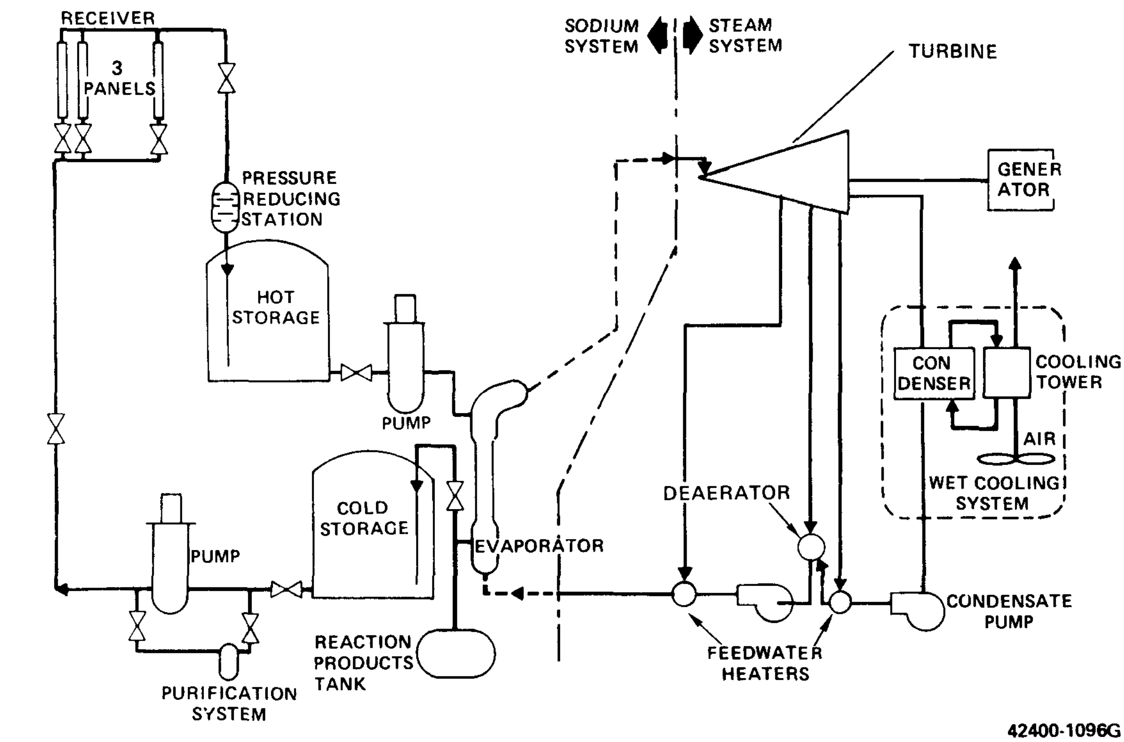

Figure 3. Advanced Central Receiver System (10-MWe Pilot Plant)

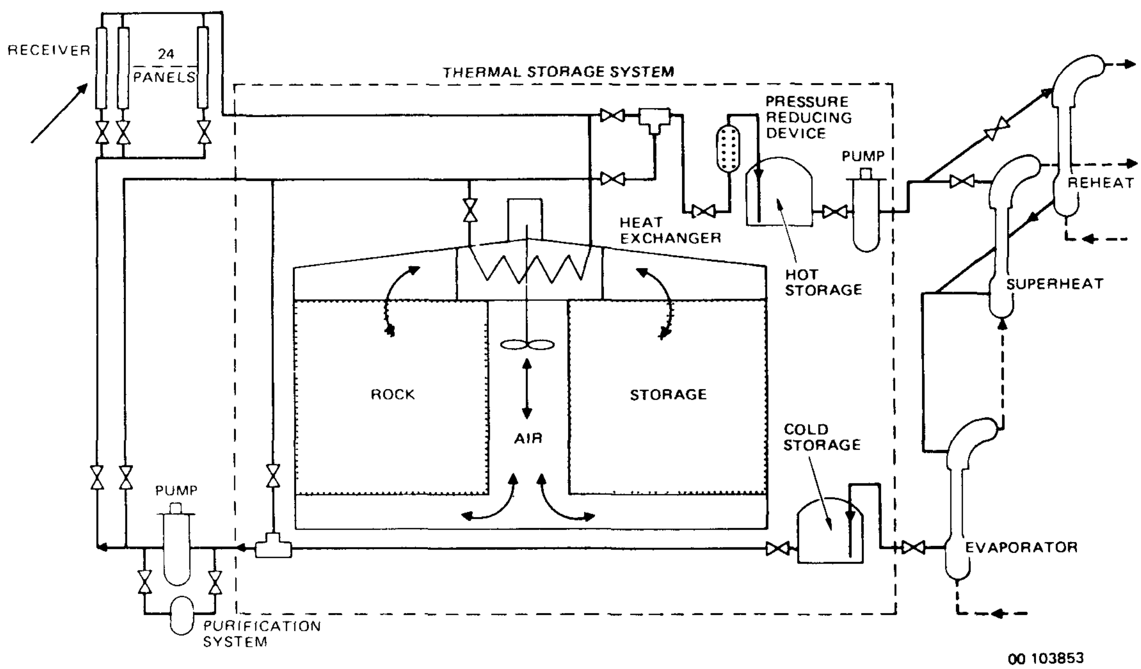

Figure 4. Advanced Central Receiver Combined Air-Rock and All-Sodium Storage

with proposed subsystem research experiments. Section 6 summarizes the commercial plant development plans and includes development requirements and cost information. Program conclusions are discussed in Section 7.

Volume II, Book 1, of this report gives a detailed description of the commercial plant conceptual design and includes data and information regarding: system description and analysis, receiver design and analysis, receiver subsystem, thermal storage subsystem, collector subsystem, electric power generating subsystem, master control subsystem, commercial system assessment, and preliminary safety analysis. Volume II, Book 2, describes, in detail, the special studies concluded during the program. These studies include: steam generator system conceptual design, heat losses from the receiver surface, heat transfer and pressure drop for rock bed thermal storage, tower hydraulic head recovery method comparison, downcomer pipe routing study, system simulation model, central receiver tower study, and mechanical and electromagnetic sodium pump comparisons. Volume II, Book 2, also contains all P&I diagrams and design data sheets.

Volume III of this report discusses the development plan and pilot plant design. Volume III topics include: pilot plant conceptual design, subsystem research experiments, and Phase II plans and schedule.

The final volume of this report, Volume IV, contains cost substantiation data and includes: commercial plant costs, optimum plant costs, pilot plant cost, and STEAC* and BUCKS* input data.

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*Acronyms for solar power plant performance and cost computer programs

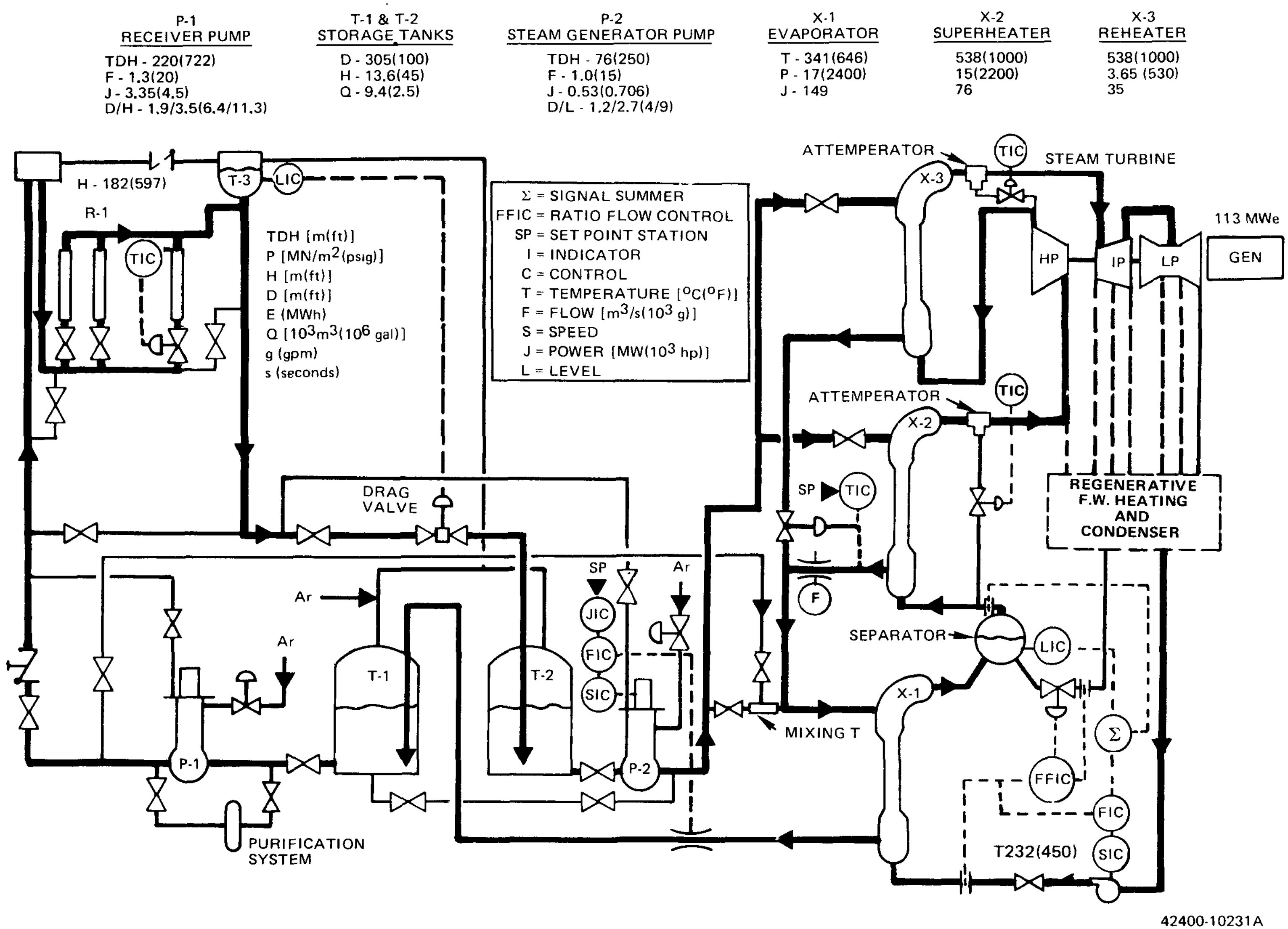

Figure 5. Advanced Central Receiver
(100 MWe)

II. 100-MWe COMMERCIAL PLANT CONCEPTUAL DESIGN

A. REQUIREMENTS

The general system requirements for the Advanced Central Receiver are shown in Table 3. These requirements are derived from the preliminary specification. The requirements of this specification identify nominal values for the power level, solar multiplier, and storage duration at 100% power. The specification permits variations in the parameters in order to provide a more cost-effective alternative plant configuration.

The reference site is established in Barstow, California, with a design life of 30 years. Wet cooling is specified. The seismic environment is given as Zone 3 with a survival ground acceleration of 0.25 g in both the horizontal and vertical directions.

The system is to have the capability of operation from storage at the 100% power level.

The heat transfer fluid and the power conversion system are not specified. The Energy Systems Group selected a sodium-cooled receiver system with a Rankine cycle power conversion system as the configuration with the promise of substantially improving system performance and reducing costs of producing electricity compared to current water-steam systems.

B. SYSTEM CONCEPTUAL DESIGN

The baseline advanced central receiver configuration, shown in Figure 5 with the performance characteristics summarized on the system Design Data Sheets of Table 4, meets the performance requirements given in Table 3. The system incorporates an external cylindrical receiver concept on a single tower 174 m (571 ft) to the receiver centerline and an all-sodium, two-tank thermal storage system. The collector field consisting of 14,100 heliostats surrounds the tower which is located to the south of the field center (north biased field). Net power output is 100 MWe with a daytime parasitic power requirement of 12 MWe,

TABLE 3

ADVANCED CENTRAL RECEIVER SYSTEM REQUIREMENTS

Design Point Power Levels	
During Receiver Operation (MWe net)	100
Operation Exclusively from Thermal Storage (MWe net)	100
Solar Multiplier (SM)	1.5
Storage Capacity (h)	3
Design Insolation (W/m^2)	950
Heat Rejection	Wet Cooling
Wet Bulb Temperature [^{o}C (^{o}F)]	23 (74)
Dry Bulb Temperature [^{o}C (^{o}F)]	28 (82.6)
Nominal Design Wind* [m/s(mph)]	3.5 (8)
Maximum Operating Wind (including gusts)[m/s (mph)]	16 (36)
Maximum Survival Wind (including gusts)[m/s (mph)]	40 (90)
Seismic Environment	Zone 3 (not near a great fault)
Operating Earthquake	TBD
Survival Earthquake, Horizontal and Vertical (g)	0.25
Availability (exclusive of sunshine)	0.9
Lifetime (years)	30

*At reference height of 10 m (30 ft)

TABLE 4

ADVANCED CENTRAL RECEIVER SYSTEM SUMMARY DATA

New Electrical Power (MWe)	100
Parasitic Power (MWe)	
Daytime	12
Nighttime	6
Insolation (W/m^2)	950
Maximum Solar Power Absorbed (MWt)	390
Nominal Solar Power Absorbed for Direct Operating (MWt)	260
Plant Net Efficiency (%)	22.9
Collector Field Configuration	Single 360^o, North Biased
Solar Multiple, Equinox Noon	1.5
Number of Heliostats	14,100
Heliostat Shape and Size [m (ft)]	Square, 7.38 x 7.42 (24.2 x 24.3)
Number of Towers-Receivers	1
Receiver Mid-Point Elevation [m (ft)]	174 (571)
Receiver Configuration	External Cylinder
Number of Receiver Panels	24
Receiver Height and Diameter [m (ft)]	16.1 x 16.1 (52.8 x 52.8)
Receiver Maximum Heat Flux (MW/m^2) (Btu/h-ft^2)	1.53 (485,100)
Sodium Temperatures [^{o}C (^{o}F)]	288/593 (550/1100)
Receiver Sodium Flow Rate [kg/h (lb/h)]	3.66 x 10^6 (8.07 x 10^6)
Steam Generator Sodium Flow Rate (direct operation) [kg/h (lb/h)]	2.45 x 10^6 (5.36 x 10^6)
Thermal Storage Capacity (MWth)	805
Total Sodium Inventory [kg (lb)]	7.6 x 10^6 (16.8 x 10^6)
Steam Generator and Reheater Type	Modular Steam Generator
Steam Conditions [kPa, ^{o}C (psia, ^{o}F)]	
Initial	12,510/538 (1815/1000)
Reheated	2,720/538 (394/1000)
Steam Flow Rate [kg/h (lb/h)]	
Daytime	3.32 x 10^5 (7.32 x 10^5)
Nighttime	3.15 x 10^5 (6.95 x 10^5)
TSS Sodium Flow Rate [kg/h (lb/h)]	2.31 x 10^6 (5.09 x 10^6)
Feedwater Temperature [^{o}C (^{o}F)]	234 (453)
Turbine Back Pressure [kPa (in. Hg)]	7. (2.0)
Heat Rejection [MW (Btu/h)]	
Daytime	158 (540 x 10^6)
Nighttime	150 (511 x 10^6)

which reduces to 6 MWe during storage only operation, since neither the collector field nor the receiver feed pump is required. Based on insolation of 950 W/m^2, the collector field mirror area is 692,000 m^2 (7.44 x 10^6 ft^2) with a total incident power of 657 MWt. The total incident power required for direct operation at 100 MWe is 437 MWt which gives a plant net efficiency of 22.9%.

The receiver consists of 24 flat panels arranged to form a right circular cylinder with a diameter of 16.1 m (53 ft) and a height of 16.1 m (53 ft).

Liquid sodium from the cold storage tank at 288^{o}C (550^{o}F) is pumped by the receiver feed pump through the receiver where the sodium is heated to 593^{o}C (1100^{o}F). The sodium flows from the receiver down the tower through a pressure reducing valve to the hot storage tank. The pressure reducing device reduces the tower static head so that the storage tank operates at atmospheric pressure with an inert cover gas such as argon. The sodium in the hot storage tank is pumped by the steam generator supply pump to the steam generator units where steam at 538^{o}C (1000^{o}F) and 12.4 Mn/m^2 (1800 psig) turbine inlet pressure is produced. The steam generator units consist of an evaporator, a superheater, and reheater units. Sodium from the evaporator returns to the cold storage tank, completing the circuit.

The electric power generating subsystem is a conventional system with a tandem compound, double-flow turbine with reheat, wet cooling system with mechanical draft cooling towers, and six feedwater heaters using turbine extraction flow. The cycle efficiency is 43.1% with 7.0 KPa (2.0 in. Hg) condenser back pressure. A steam drum is between the evaporator unit and the superheater to ensure that dry steam enters the superheater. Maximum guaranteed generator output is 112,000 kW and, at the VWO (valve wide open) rated conditions, the generator output is 116,741 kW.

C. COST SUMMARY

The capital cost estimate summary for the first commercial and Nth commercial 100-MWe advanced central receiver, sodium-cooled power plant is shown in Table 5. Each estimate is subdivided by account as required by the RFP. The

TABLE 5

100-MWe CAPITAL COST ESTIMATE
($ x 10^3)

Account Number	Account Title	1st Commercial	Nth Commercial
4100	Site, Structures, and Miscellaneous Equipment	5,381	5,271
4200	Turbine Plant Equipment	19,424	19,424
4300	Electric Plant Equipment	4,834	4,301
4400	Collector Equipment	60,596	45,820
4511	Absorber Unit	4,022	3,258
4512	Support Structure	236	236
4513	Receiver Circulation Equipment	1,526	1,190
4514	Instrumentation and Control	1,452	1,452
4515	Transportation, Field Erection, and Installation	1,315	1,315
4520	Riser Downcomer and Horizontal Piping	4,942	4,942
4530	Working Media Cost	183	183
4540/50	Tower and Foundation	3,166	3,166
4560	Steam Generator	5,144	4,110
4570	Design and Engineering	1,319	–
4600	Thermal Storage Equipment	12,086	11,400
4800	Distributables and Indirect Cost	26,988	17,565
		152,614	123,693

total capital cost estimate for the first plant is $152.6 million. The estimate for the Nth plant is $123.6 million.

The estimated operating and maintenance cost (O&M) for the first and Nth commercial plants are shown in Table 6. Again, the estimates are broken down by account. The yearly estimate of O&M costs for the first plant is $2.39 million; for the Nth plant, it is $1.37 million. All capital and O&M costs are 1978 dollars.

The busbar costs of electricity, as calculated from the estimated capital and O&M costs, are shown in Table 7. The calculational methodology and assumptions are summarized at the bottom of Table 7.

D. SUBSYSTEM DESCRIPTION

The subsystems of the sodium-cooled advanced central receiver are categorized as: the receiver, thermal storage, the collector, electric power generation, and master control. Each category will be summarized individually below.

1. Receiver Subsystem

The reference design of the sodium heat transport system (receiver) is schematically shown in Figure 6. The quantitative values of the process variables are given in Volume II, Book 2, Appendix A.

The system may be considered as two independent loops. The first loop transfers sodium from the cold storage tank, T-1, at about 288^{o}C (550^{o}F) through the receiver which heats it to ~ 593^{o}C (1100^{o}F). The sodium then flows by gravity through the drag valve to the hot storage tank, T-2. Nominal maximum flow rates are about 1.3 m^3/s (20,000) 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 nominal flow is about 1.0 m^3/s (15,000) gpm range.

TABLE 6

100-MWe ADVANCED CENTRAL RECEIVER O&M COSTS ($\$ \times 10^3$)/yr

O&M Items	First Commercial			Nth Plant		
OM100 Operations Supervision			693			301
OM200 Maintenance Materials			581			253
OM210 Spare Parts		581			253	
OM211 Turbine and Electric Plant	320			139		
OM212 Collector Equipment	195			85		
OM213 Receiver Equipment OM214 Thermal Storage Equipment	} 66			29		
OM220 Material for Repair						
OM230 Other						
OM300 Maintenance Labor			1,112			**810**
OM310 Scheduled Maintenance	1,112			**810**		
OM320 Corrective Maintenance						
Total			2,386			**1,364**

TABLE 7

LEVELIZED BUSBAR ENERGY COSTS ($\overline{BBEC}$)

Plant Power (MWe)	Storage Capacity (h)	Capital Investment (1978 $\$ \times 10^6$)	Commercial Plant	Years to Commercial Operation	Hours to Operation per Year	$\overline{BBEC}$ (mills/kWh)
	All Sodium					
100	3	152.6	1st*	8	3500	85.8
100	3	123.7	Nth†	12	3500	61.7
100	13.4	239	Nth	12	6750	61.8
281	13.4	577	Nth	12	6750	53.1
	Air-Rocks					
100	13.4	218	Nth	12	6750	56.4
281	13.4	506	Nth	12	6750	46.6

*O&M costs are 1.6% of capital costs
†O&M = 0.8% of capital investment

Notes: 6% general inflation; 8% escalation on OP&MNT; 3500 h on 3-h storage plant.

$$\overline{BBEC} = \frac{\overline{AC}}{MWh/year} = (1 + g)^{-d} \left[\overline{FCR} \cdot CI_{pv} + CRF_{k,N} \left(OP_{pv} + MNT_{pv}\right)\right]$$

Fixed Charge Rate (FCR) = 0.1483
Capital Recovery Factor (CRF) = 0.0888
X_{pv} = Present Value of X

CI = Capital Investment
OP = Operating Cost
MNT = Maintenance Cost
AC = Annualized Cost

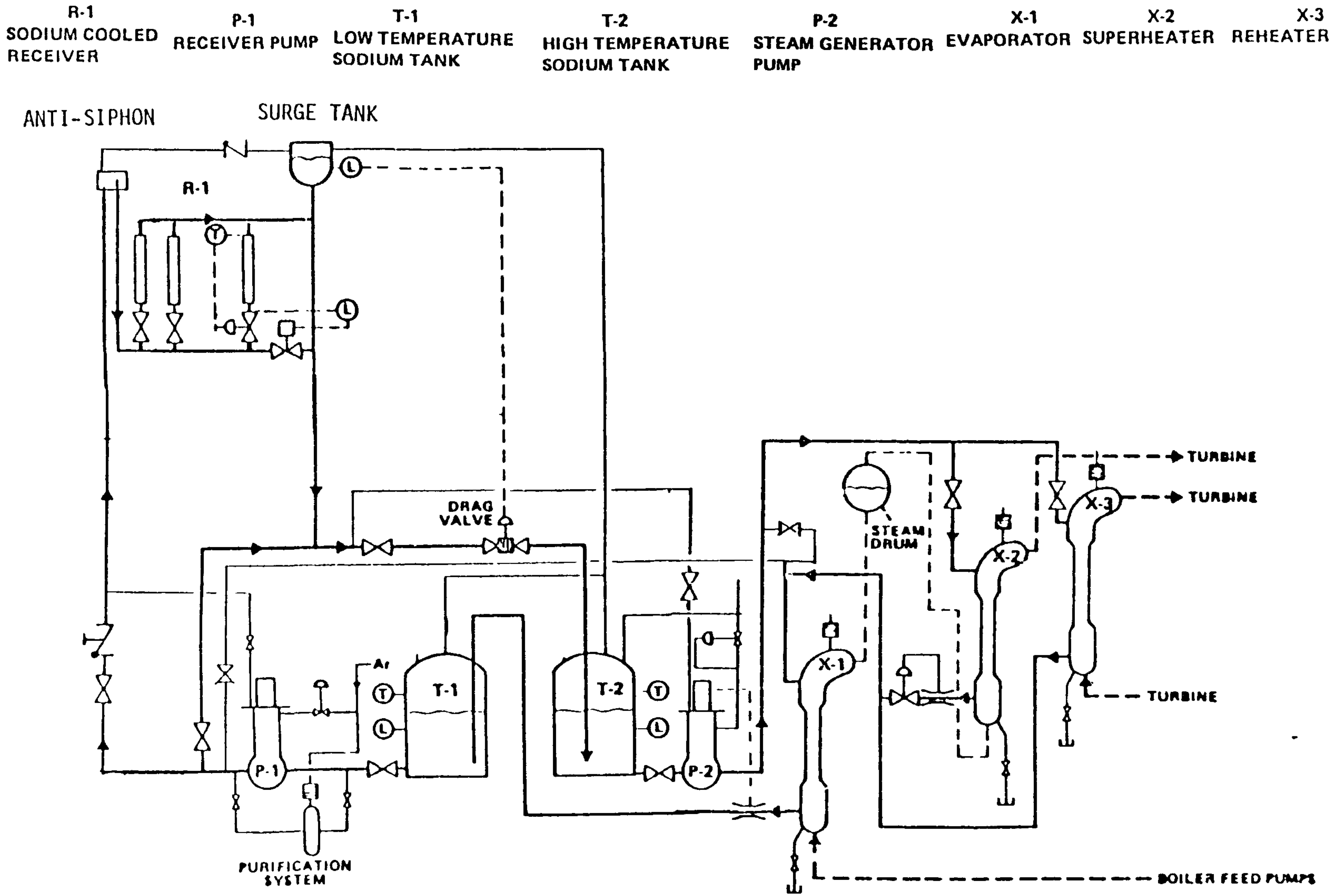

Figure 6. Sodium Heat Transport System

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-2.

Sodium circulation is provided by means of the P-1 and P-2 pumps. These are free surface "Fermi" type centrifugal pumps. The P-1 pump is a high-head [~250 m (820 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 large suction 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. The pumps are described in more detail in Volume II, Book 1, Section 4.6. Sodium flow through the receiver is modulated by the control valves on each panel to maintain the panel outlet at a constant temperature. 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 Volume II, Book 1, Section 5.

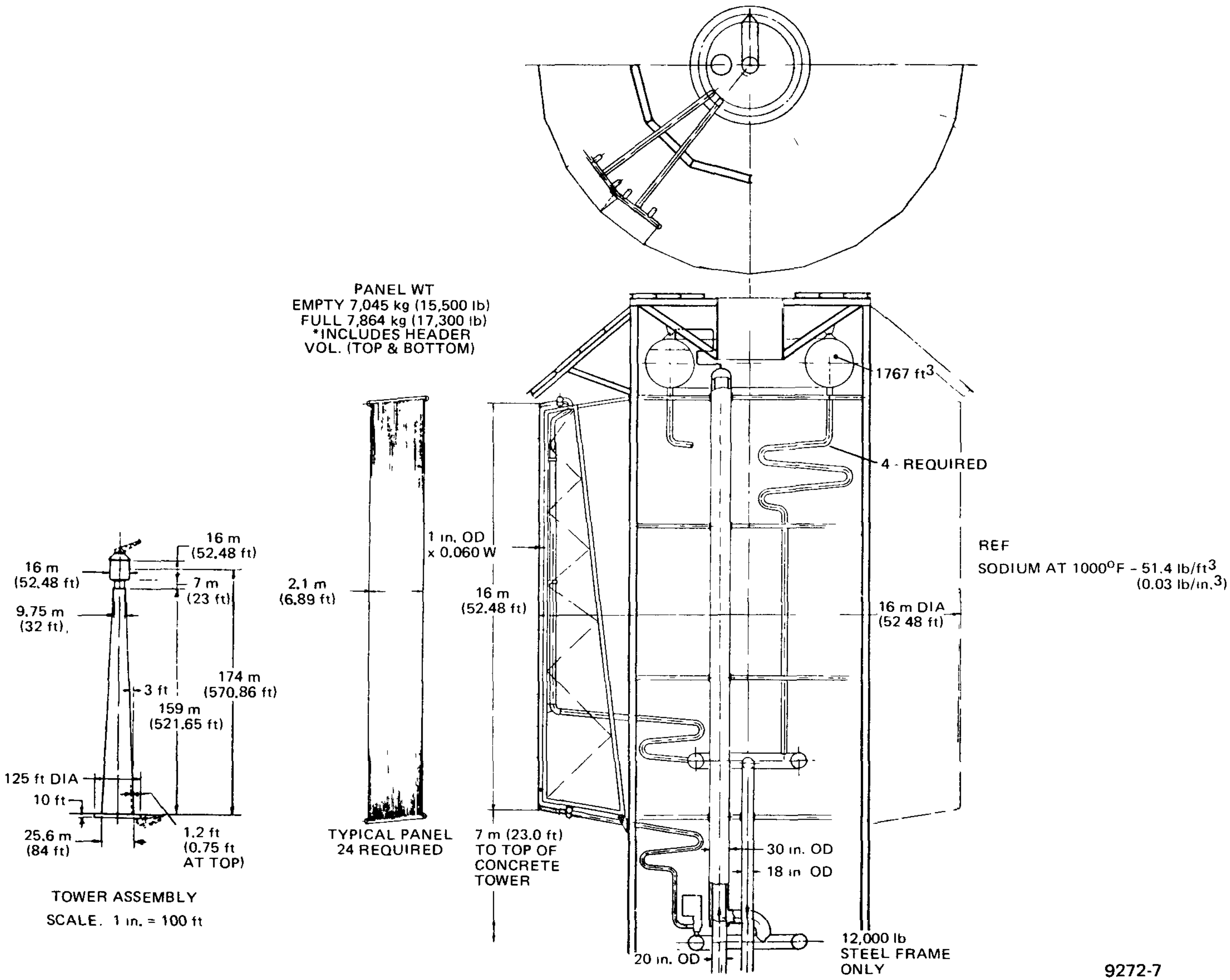

Figure 7. Central Receiver Concept

The anti-siphon system and the surge tank operate to prevent 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.

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 and return lines of the steam generating modules. The steam generators are discussed in detail in Volume II, Book 1, Section 4.5.

a. Receiver

The receiver is the most unique component in the receiver subsystem. As such, it received a great deal of attention in terms of design. Analyses are contained in Volume II, Book 1, Section 3. Topics include: requirements and design considerations, cavity versus external receiver trade study, receiver panel thermal analysis, external receiver thermal losses, the effect of light leakage between tubes, overheating of uncooled surfaces, enhanced radiation capture, and receiver tower integration. A detailed drawing of the receiver is shown in Figure 7.

2. Thermal Storage Subsystem

a. All-Sodium Storage

The all-sodium ACR concept is shown in Figure 2. The thermal storage subsystem contains the hot and cold storage liquid sodium tanks, the P-2 pump, a pressure-reducing device, and interconnecting pipe. Liquid sodium from the receiver subsystem is stored in the hot storage tank at energy rates up to 390 MWt, which corresponds to a flow rate of 3.66×10^6 kg/h (8.07×10^6 lb/h). Sodium is drawn from the hot storage tank at energy rates of up to 250 MWt [2.34×10^6 kg/h (5.29×10^6 lb/h] to generate steam for the electric power generating subsystem. Sodium from the steam generator units flows to the cold storage tank. During the day, hot sodium is accumulated by the hot tank in a sufficient quantity to store up to 3.25 h of operation at 100% rated power. With this storage arrangement, plant operation is always from storage. The steam conditions provided are the same regardless of whether the receiver loop is operating or not.

The storage tanks are 30.5 m (100 ft) in diameter with a height of 13.6 m (45 ft) for the hot storage tank and 12.3 m (41 ft) for the cold. The hot tank operating at 593^{o}C (1100^{o}F) is made of stainless steel; the cold tank at 288^{o}C (550^{o}F) is made of carbon steel. The tanks operate at ambient pressures in order to minimize cost. This requires a pressure-reducing device to dissipate the tower static head.

The pressure-reducing device for the baseline configuration consists of a nominal 18-in. drag valve. A steam generator pump in this system moves the hot sodium through the steam generator units to the cold storage tank. The receiver pump (identified in the Receiver Subsystem description) charges the hot storage tank. The steam generator pump is similar to the FFTF pump with approximately the same head and flow requirements. The developed head for this pump is 76 m (250 ft) at 0.95 m^3/s (15,000 gpm).

The design characteristics of the all-sodium ACR Thermal Storage Subsystem are presented in the design data sheets of Volume II, Book 2, Appendix A.

b. <u>Air-Rock Thermal Storage</u>

In this concept, heat absorbed in the sodium-cooled receiver is transferred, via a sodium-air heat exchanger, to a rock bed through which air is circulated. The basic idea is to use a low-cost rock bed to permit the storage of large quantities of sensible heat. The use of such a storage system permits the generation of 538^{o}C (1000^{o}F) steam when the power plant is operating on storage. The temperature capabilities of sodium-cooled receivers are such as to permit the temperature drops that occur when heat is transferred into and out from storage.

Air-rock thermal energy storage may be considered as the only storage subsystem in a solar power plant or it may be considered in combination with all-sodium storage. In either application, the structural and functional characteristics of air-rock storage are almost identical – the main difference being the speed with which the air-rock storage subsystem needs to respond to changes in plant operation. In the following, then, either application can apply.

Figure 4 shows a schematic of a plant with air-rock storage. Hot sodium from the receiver can go directly to the steam generators or to storage or both. Hot sodium, entering storage, passes through a sodium-air heat exchanger which is cooled by a flow of air driven by fans. The cooled sodium continues on to either the steam generator or the receiver or both. The heated air is circulated downward in a rock bed, heating the rocks and thus charging the storage system.

When it is desired to operate the plant on storage, the sodium passes through the heat exchanger in the reverse direction. At the same time, the fans drive the air in a reversed direction also. Thus, the stored heat in the rock bed heats the air which in turn heats the sodium in the heat exchanger. This hot sodium is circulated to the steam generator.

A diagram of the air-rock system is shown in Figure 8.

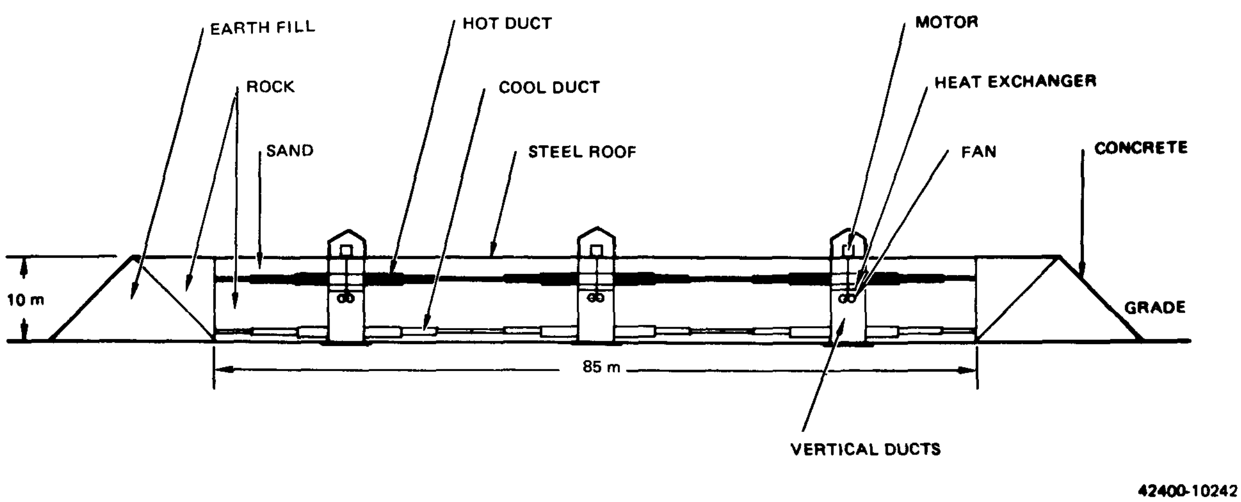

Figure 8. Air-Rock Storage System Schematic

3. Collector Subsystem

The collector subsystem includes the individual heliostats and all of the power distribution and control equipment necessary for their operation. Since the principal subsystem design requirements for the collector subsystem are set by the total power and peak heat flux delivered to the receiver, the analysis and definition of the collector subsystem are closely coupled to the receiver design parameters. In addition, because of the desire to minimize the cost of energy delivered to the system, the definition of the collector subsystem is also closely tied to the costs associated with the balance of the energy collection equipment (receiver, tower, sodium piping, and pump).

The collector subsystem is composed of a field array of heliostats; the heliostat field electronics consisting of primary and secondary power and data wiring, field transformers, distribution panels and data distribution interfaces; and the heliostat array controller which is located in the Plant Control Room and interfaces with the Master Control Subsystem. The heliostat field surrounds the receiver tower and reflects solar radiation onto the elevated receiver in a manner that satisfies system power requirements.

a. Collector Field

The baseline collector field (including the tower and receiver geometric characteristics) was arrived at as a result of a well established optimization procedure subject to constraints on the total receiver power (390 MWt net on the best cosine day at 950 W/m^2) and the peak incident heat flux (1.7 MW/m^2). The major characteristics of the resulting collector field are summarized in Table 8.

TABLE 8

COLLECTOR FIELD CHARACTERISTICS

Heliostat Size [m^2 (ft^2)]	49.05 (527.7)
Configuration	Canted
Number of Heliostats	14,100
Total Reflector Area [km^2 (ft^2)]	0.692 (7.44 x 10^6)
Receiver Size (cylindrical) [m (ft)]	
Height	16.15 (53)
Diameter	16.15 (53)
Receiver Centerline Elevation [m (ft)]	174 (571)
Land Area (excluding central exclusion) [km^2 (ft^2)]	3.06 (32.9 x 10^6)
Glass Coverage Density	22.6%
Layout Arrangement	Radial-Stagger

The collector field is defined on the basis of a cell-by-cell analysis with each computational cell being a square 147.2 by 147.2 m. The initial cell matrix is composed of 15 such cells in the east-west direction by 14 cells in the north-south direction. As a result of the optimization procedure, complete cells or fractions thereof are trimmed from the field since the placement of heliostats in these locations is not cost effective. The resulting field shape relative to the cell matrix is shown in Figure 9. Instead of the irregular trim line illustrated in this figure, the actual heliostat layout would be arranged along a continuous arc through the sawtooth outline.

b. Heliostat Assembly

The helisotat assembly is shown in Figures 10 and 11. It consists of the reflective unit, the drive unit which orients the reflective unit, the foundation which supports the heliostat, and the heliostat electronics which controls the drive unit.

Reflective Unit — In order to facilitate handling and shipping from the manufacturing facility to the installation site, the reflective unit is made up of two reflector subassemblies. Each reflector subassembly is comprised of six

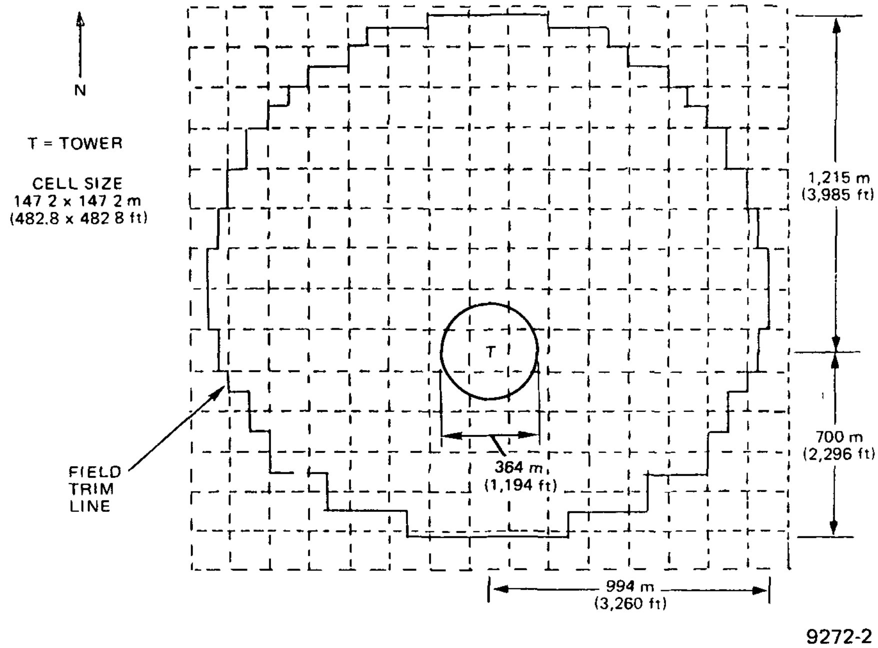

Figure 9. Baseline Collector Field Defined in Terms of Computational Cells

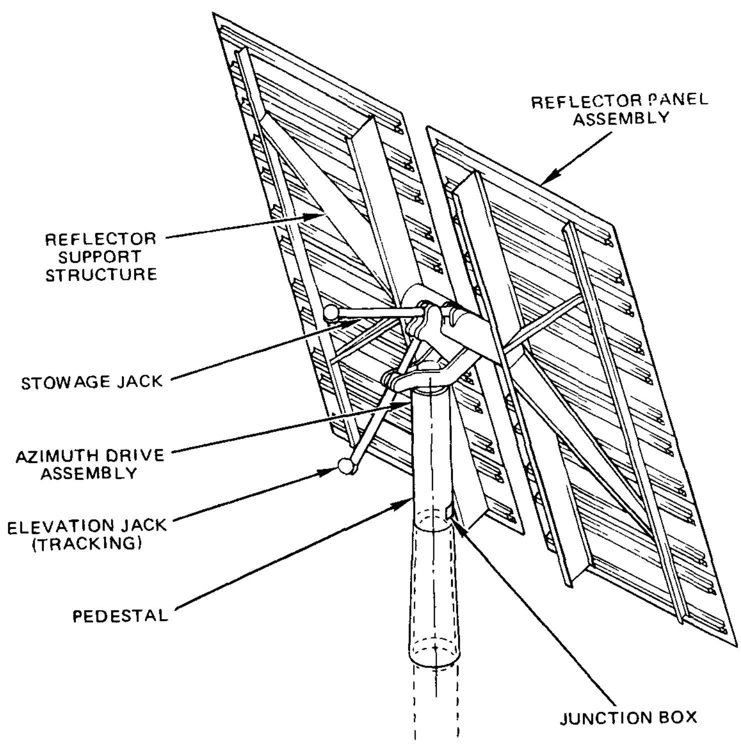

Figure 10. Primary Baseline Heliostat

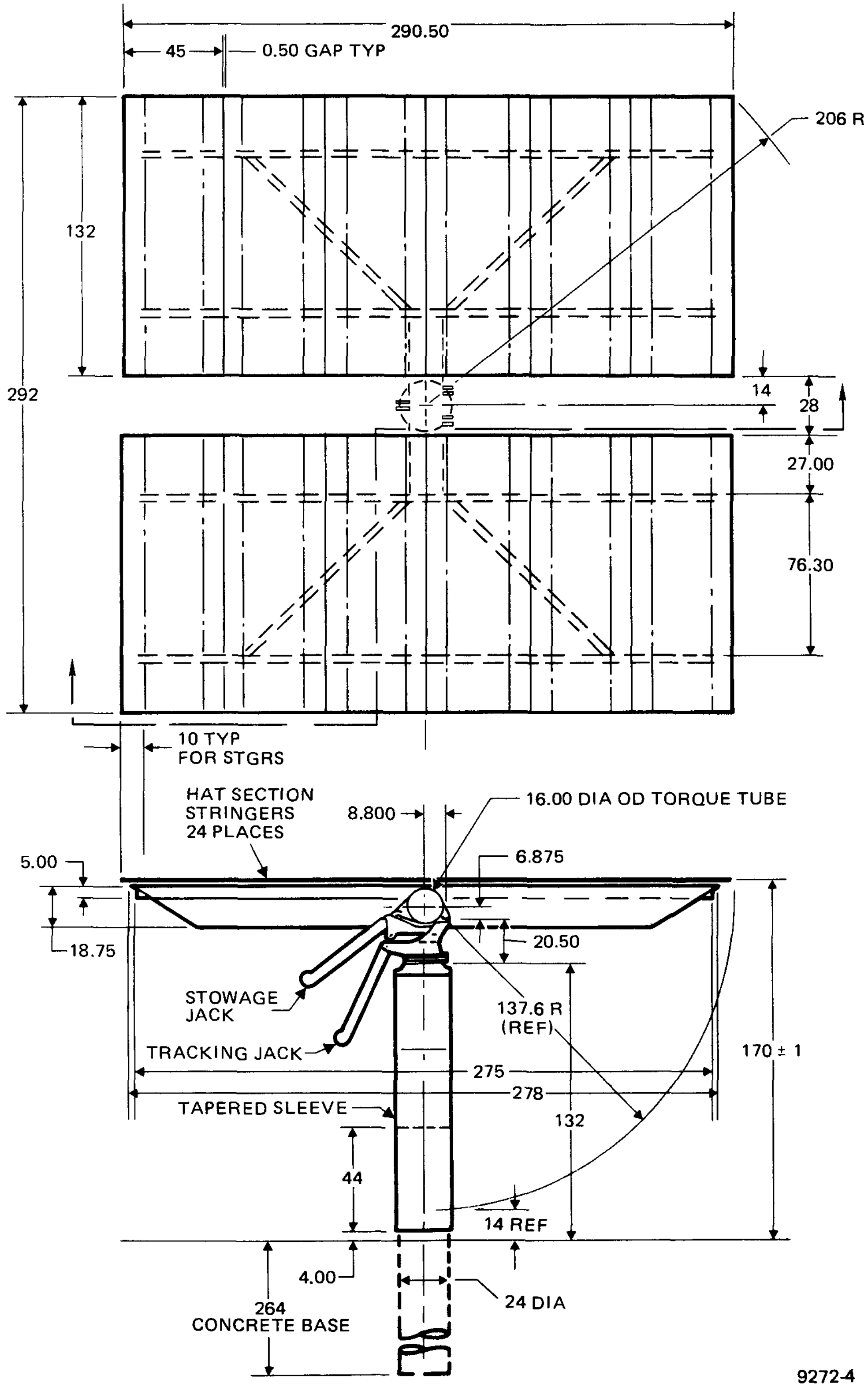

Figure 11. Heliostat Assembly
(dimensions in inches)

identical laminated mirror modules and a support frame. The mirror modules are 1.22 m (48 in.) by 3.35 (132 in.) and made of a 1.5 mm (0.060 in.) pane of fusion glass mirrored on its inner face and laminated to a 4.8 mm (0.1875 in.) float glass back plate. The clean reflectivity is estimated to be 0.92 at 0.5% iron with 0.945 at 0.01% iron.

The mirror modules are bonded to stringers which are, in turn, riveted to the cross beams. The outer cross beam is supported by two diagonal beams. All beams and stringers are made by continuous roll forming from coiled sheet stock. Each of the completed reflector subassemblies measures 3.35 m (132 in.) by 7.38 (290.5 in.).

The reflector subassemblies are assembled to the main beam at the top of the drive unit to produce a surface of 7.38 by 7.42 m (290.5 by 292 in.) with a slot of 0.71 m (28 in.) width down the middle. This gives a reflecting area of 49.0 m^2 (428 ft^2).

Drive Unit — The function of the drive unit assembly is to rotate the heliostat reflective unit about the azimuth and elevation axes. The drive unit is operated for solar tracking, emergency slewing, stowage, and maintenance activities. The drive unit consists of an azimuth rotary drive assembly, two linear actuator assemblies for elevation drive, a drag link, a main beam, and the pedestal. The azimuth travel capacity of $\pm 270^\circ$ avoids the need for configurating the drive unit as a function of position in the field. The 180° of travel about the elevation axis is required to permit inverted mirror storage. Excessive operating loads are avoided by being able to stow the mirror in <15 min in rising wind conditions.

The calendar operating life of the drive unit is 30 years. The daily activity of the drive unit will consist of moving the mirror from a stowed position to acquire the sun, tracking the sun during the day, and then returning the mirror to its stowed position at the end of the day. This life will be achieved without any scheduled maintenance activity.

4. Electric Power Generation Subsystem (EPGS)

One of the attractive features of sodium as heat transport fluid in a central receiver concept is that it can permit the use of efficient, high-temperature, high-pressure steam turbines, turbines that represent current state-of-the-art technology. It also allows the use of reheat. Because of these features, the technical approach on the electric power generation subsystem was to select the most efficient and cost-effective turbine generator system and then to design the sodium heat transport systems to meet the EPGS requirements.

The final baseline concept for the sodium-cooled central receiver utilizes the TC2F-23 turbine. A summary of EPGS performance data is shown in Table 9.

TABLE 9

REVISED BASELINE TURBINE DATA

Turbine Type —	
Last Stage Blade Length (in.)	TC2F-23
Heater Extractions	6
Gross Generator Output (MW)	
Daytime	112
Nighttime	106
Net Generator Output (MW)	
Daytime	100
Nighttime	100
Turbine Steam Conditions	
Inlet (Throttle) Steam Pressure [kPa (psia)]	12,510 (1815)
Temperature [^oC (^oF)]	538 (1000)
Reheat Steam Pressure [kPa (psia)]	2,950 (428.2)
Temperature [^oC (^oF)]	538 (1000)
Turbine Exhaust Pressure [kPa (in. HgA)]	7.0 (2.0)
Final Feedwater Temperature [^oC (^oF)]	234.2 (453.6)
Gross Turbine Cycle Efficiency (%)	43.1

At the maximum guaranteed condition, the gross heat rate is 7918 Btu/kWh, and the boiler feed pump power is 1990 kW. At the maximum valves wide open and rated pressure condition, the gross heat rate is 7917 Btu/kWh, and the boiler feed pump power is 2090 kW. The maximum turbine-generator capability (at the valves wide open, 5% overpressure condition) is estimated to be 122,505 kW with a gross heat rate of 7889 Btu/kWh and a boiler feed pump power of 2310 kW. Under the latter circumstances, the throttle flow is 101.9 kg/s (808,400 lb/h) with a final feedwater temperature of 239.6°C (463.2°F).

A P&I diagram covering the reference EPGS system is included in Volume II, Book 2, Appendix D. Details as to flow rate, major equipment items, and state points can be found there.

5. Master Control Subsystem

The master control design for the Advanced Central Receiver Solar Power Plant incorporates a centralized plant control center that links via a serial digital data bus to remote subsystem controllers. An overview of this design concept is shown in Figure 12. This design employs a distributed control system

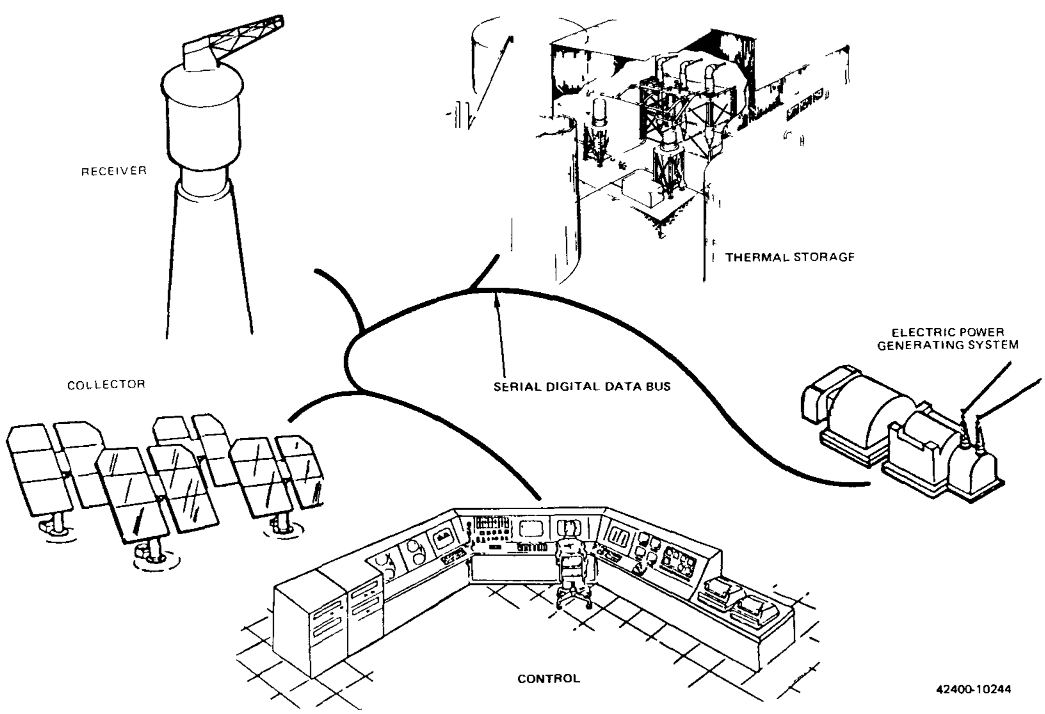

Figure 12. Distributed Control Concept

concept whereby the individual controller functions are accomplished close to the process while the integrated plant control is performed in the control center.

A vital part of the control system concept is the man-machine interface with control displays located in the control center. At this station the operator monitors and commands the operations of the plant. Programmed command sequences are initiated from the control consoles and plant status and data are monitored, displayed, and recorded here.

The control center is linked to the remote subsystem controllers using a common and redundant serial communications scheme. This scheme will utilize optical isolated fiber optic transmission.

E. SAFETY ANALYSIS

The specific safety requirements for the Advanced Central Receiver Power System — Sodium-Cooled Concept, include the conventional occupational safety requirements and requirements peculiar to a sodium-cooled solar power plant. The System Safety Program Requirements Specification for Solar Thermal Power Systems and System Safety Design Criteria for the Central Receiver Solar Thermal Power System were used as guidelines.

1. Public Safety

The three recognized potential hazards which can impact the areas beyond the site boundary are: (1) brush fires from coincident beams, (2) damage to eye tissue from excessive irradiance, and (3) sodium combustion products aerosols from a leak in the exposed receiver tubes or from a ground level fire. The first two items are controlled by providing a brush-free fenced exclusion area of 1,000 meters (3,280 ft) from the edge of the field.

The third concern, sodium combustion products, dispersed to the site boundary from leaks in the receiver or from pool fires at ground level, have been examined in detail both analytically and experimentally. The expected release given "worst case" concentrations at the site boundary are a factor of 20 less than safety limit.*

*80 mg/m^3

In addition, it is planned to limit the burning rate or the total amount of sodium combustion by the following means: (1) the tower will be monitored by closed-loop television with a fixed image reference, at the initiation of a plume, which will change the image. An alarm signal in the control room will alert the operator, and shutdown procedures will be implemented thus limiting the amount of sodium release.

It may be concluded from these results that no equipment failure or maloperation at the plant will cause a hazard to the public.

2. Personnel Safety

The plant design incorporates the requirements of the Occupational Safety and Health Administration (OSHA) and, in addition, provides safety features that protect the operators from excessive exposure to irradiance or sodium.

3. Plant Protection Features

Protecting the plant integrity is considered to be an important first step in protecting the public and operating personnel. The plant protective features protect the plant from damage that could arise from loss of load, loss of flow, focusing errors, leaks in the steam generator or leaks in the coolant boundary. There should be no operational cost penalty because of safety.

F. SPECIAL STUDIES

During the course of the sodium-cooled advanced central receiver program, several related special studies were performed. The studies included: a steam generator system conceptual design, consideration of heat losses from the receiver surface, heat transfer and pressure drop for rock bed thermal storage, a comparison of alternative ways of recovering the hydraulic head from the advanced solar receiver tower, a central receiver tower study, a comparison of mechanical and electromagnetic sodium pumps, pipe routing study of sodium downcomer piping, and a sodium-cooled advanced central receiver system simulation model. The detailed results of these studies are given in Volume II, Book 2, Appendices E through L. Each study is briefly summarized here.

1. Steam Generator Conceptual Design

This study considered various aspects of the steam generator system for the Advanced Central Receiver Power System (ACRPS). The ACRPS employs sodium as a heat transfer medium, so the steam generators are sodium heated. Requirements for the steam generator system are similar to those of the Liquid Metal Fast Breeder Reactor (LMFBR) systems resulting in a broad technical base for design of the steam generator system for the ACRPS. However, the ACRPS steam generator application places some modified requirements on the steam generator system and on the steam generator modules. These requirements are discussed in this report. At the conclusion of this study, a steam generator arrangement consisting of an evaporator unit, superheat and reheat units was developed.

2. Receiver Surface Losses

Calculations were made to determine the heat losses from the surface of the receiver of the Central Receiver Solar Power System. The heat losses considered were reflection of incident heat flux, combined natural and forced convection, and thermal radiation.

The receiver analyzed is in the form of a vertical cylinder, 16 meters (52.5 ft) in diameter, and 16 meters (52.2 ft) in height. Sodium is circulated through the receiver as a heat transport medium.

The tube surface properties are: α (absorptivity) = 0.95 and ϵ (emissivity) = 0.90.

The heat losses, in megawatts and as a percentage of thermal power incident on the receiver, have been determined for a variety of conditions: thermal power absorbed by the sodium up to 429 MWt, wind velocities up to 16.3 m/s (= 53.4 fps = 36.4 mph), and sodium inlet and outlet temperatures ranging from 288^0 to 593^0 to 454^0 to 760^0C (550^0 to 1100^0F to 850^0 to 1400^0F). The energy penalty due to these losses is $\lesssim$10% of full power which reflects the benefit of a high power density receiver.

3. Heat Transfer and Pressure Drop for Rock Bed Thermal Storage

Heat transfer and pressure drop correlations for air flow through a "fixed pebble bed" were investigated.

Equations and a time-share computer program were set up to determine the heat transfer parameter (UA), pressure drop (Δp), and fan electric power (P), for a variety of bed capacities, thermal power rates, bed sizes and porosities, particle diameters, and sphericities, etc.

Calculations were made for several cases, yielding air flow rates and velocities, bed dimensions and areas, and other parameters in addition to UA, Δp, and P (fan). These studies show that the air-rock storage system is a viable alternative to all sodium storage for >3-h storage. The air-rock storage system is selected as a potential improvement for long-duration storage capacities.

4. Comparison of Alternative Ways of Recovering Hydraulic Head of Receiver Tower

An earlier trade study examined the possibility of recovering the head by utilizing a high-pressure loop and a low-pressure loop thermally coupled by a heat exchanger. It was determined that the value of the power savings was less than the cost of the heat exchanger. This system was judged not cost effective. An additional eight other methods were examined. These schemes, their summary evaluation, and recommendations are as follows.

SUMMARY OF ALTERNATE SCHEMES

	Scheme	Result
1.	Elevated Hot Tank	Not cost effective
2.	Elevated Cold Tank	Not cost effective
3.	Parallel Storage Tanks	Not cost effective
4.	Reduced Downcomer Diameter	Net savings $0.6 x 10^6
5.	Sodium Turbo Pump Addition	Net savings $0.8 x 10^6
6.	Jet Pump Addition	Net savings $0.85 x 10^6
7.	Magnetohydrodynamic (MHD) Addition	Net savings $1.2 x 10^6
8.	Helical Rotor Generator Addition	Net savings $1.2 x 10^6

Scheme 4 was selected because it is cost effective and requires no development. As a means of improving plant efficiency, Scheme 4 is recommended for the near term and Scheme 7 for the long term.

5. Central Receiver Tower Study

This study examined advanced central receiver tower cost sensitivity to tower height and weight combinations. Also considered were seismic response and tower material quantities. The final tower selected is considered optimum within the range of considered variables.

6. Comparison of Mechanical and Electromagnetic Sodium Pumps

This study briefly evaluates typical large-scale electromagnetic and mechanical pumps, describes their characteristics, notes the advantages and disadvantages of each, and assesses their applicability to the Advanced Central Receiver Power System main sodium loops. The conclusions reached in this study are that:

1) The mechanical pump is more efficient than the electromagnetic (EM) pump (72% vs 50%). The EM pump requires a larger plant than the mechanical pump in order to supply its extra power requirement, and thus requires more capital outlay for the same size net electrical plant.
2) The capital cost of either component is about the same.
3) The reliability of the two components is about the same.
4) The raising head flow characteristics of the EM pump tends to make it unstable when it operates at head with variable flow.

The mechanical pump was chosen because it is more efficient, more stable in its operation and requires less total capital outlay.

7. Pipe Routing Study of Sodium Downcomer

Four piping configurations were developed and studied to determine the simplest routing for a 20-in. sodium downcomer line from the receiver at 600 ft above grade to the hot storage tank at grade. Multiple expansion loops with ridged support at nodal points is considered to be the most cost-effective vertical pipe support system.

8. System Simulation Model

A mathematical model describing the dynamic behavior of the sodium-cooled advanced central receiver power system was written and used to verify the receiver control methodology and simulate the receiver system under various transients of interest. The control methodology of individual panel control was verified for controlled situations with receiver mixed outlet temperatures varying $< 8^{o}F$ over the range of controlled transients examined. However, active heliostat steer-off is required during transients in which the receiver pump trips.

9. Emergency Defocusing Requirements

A special study conducted by McDonnell Douglas investigated the response of the baseline receiver to various defocusing schemes in the event of an emergency shutdown. Decay times (the time necessary for complete solar image defocusing) ranged from 5 s (a simultaneous heliostat slew) to 180 s (heliostat image passive drift-off). The receiver sodium was assumed to be stagnant but the major receiver losses were accounted for. The results of this study indicated that a sequential slew of heliostats in < 25 s was required to prevent significant sodium vaporization. These results agree with the results of a separate study, performed by ESG, described in Volume II, Book 2, Appendix L. The results of this study were used to determine the slew-off power requirements.

10. Cavity Versus External Receiver

At the initiation of this program, the baseline receiver configuration was the external type. The cavity receiver is an alternate approach that has certain advantages. One of the advantages of the cavity receiver is that it has lower parasitic losses than the external receiver. Another is that it offers better thermal control and protection from the elements.

Trade studies of cavity and external receivers were made at both the system and component levels. The system comparison involved such factors as the receiver view factor, the size, shape, and orientation of the collector, spillage, atmospheric attenuation and tower height. The component comparison considered receiver size, weight, complexity, and cost. The external receiver was chosen over the cavity receiver due to superior optical characteristics and lower capital costs.

11. Multiple Tower Concepts

This analysis was designed to define the most cost-effective collector field and receiver combination sized to absorb 429 MWt into the sodium at equinox noon with an insolation level of 950 W/m^2. The analysis investigated single and multiple fields with both external and cavity receivers.

In carrying out the optimization analysis, cost models were required for the energy collection hardware along with their sensitivity to power level and other critical sizing parameters. Eight cost factors were considered in the analysis which are listed below.

Fixed cost (independent of configuration)
Heliostats
Land
Wiring
Tower and foundation
Vertical piping
Horizontal piping

A tabular summary of the collector field and receiver configurations considered in the study is presented in Table 10. The results indicate the overall superiority of the single module, external receiver configuration from a cost of energy standpoint.

TABLE 10

SUMMARY OF COLLECTOR FIELD-RECEIVER ECONOMIC COMPARISON

Receiver Type/Size	Number of Modules	Heliostat Configuration	Cost of Energy* ($/MWht)
External/16.1 x 16.1 m	1	Noncanted	107.2
External/10 x 10 m	3	Noncanted	127.4
Aperture/17 x 17 m	1	Noncanted	128.8
19 x 19 m	1	Noncanted	128.8
19 x 19 m	1	Canted Facets	123.6
21 x 21 m	1	Noncanted	127.4
21 x 21 m	1	Canted Facets	125.8
Aperture/10 x 10 m	3	Noncanted	161.9
12 x 12 m	3	Noncanted	154.9

*Based on nominal cost assumptions

12. Draw Salt Thermal Storage

Two studies investigating the application of draw salt as a substitute for sodium as a thermal storage media were completed during the program. The first used draw salt alone and the second was a draw salt rocks thermocline system.

A brief investigation was performed to determine the delta costs associated with utilizing draw salt (45% $NaNO_3$, 55% KNO_3) in a two-loop system. Sodium would be used in the primary loop with an intermediate sodium-to-draw salt heat exchanger (IHX). The draw salt would be used in a secondary loop which includes a hot and cold thermal storage system.

The results show a net additional cost increment of $\$5.68 \times 10^6$ where the savings, which are realized by a reduced storage volume requirement and lesser cost of heat transfer storage medium, are more than offset by the cost of the IHX and added pump and the increased cost of the steam generator. The larger steam generator (1.4 area ratio) is required because of the poor heat transfer characteristics of the draw salt.

A two-loop system utilizing a thermocline thermal storage with draw salt (45% $NaNO_3$, 55% KNO_3) and rocks was investigated to determine delta costs when compared to the single-loop, all-sodium design baseline. Sodium would be used in the primary loop with an intermediate sodium-to-draw salt heat exchanger (IHX). The draw salt in the secondary loop would function as the heat transfer fluid for the steam generators and as the thermal storage medium in a draw salt-rocks thermocline-type thermal storage subsystem. Cyclic performance analyses of thermocline storage systems indicate that a utilization factor of 20% is realistic. This results in a large volume bed requirement with associated high cost of draw salt which offsets the savings in sodium inventory. The results clearly favor the all-sodium system as the most cost effective; therefore, the sodium system was retained.

13. Sodium Iron Thermal Storage System

An additional brief study investigated the possibility of employing a sodium iron thermocline energy storage system in place of the baseline all-sodium system. The use of iron is advantageous from a utilization standpoint in that 60% utilization is available. However, the required bed size is roughly the same volume as the draw salt-rocks system. It was shown that, if the capital cost of iron were 5.8¢/lb, the sodium iron system would be cost competitive with an all-sodium system. The minimum cost of iron that would meet the low carbon requirements of sodium usage is scrap pipe at 15 to 25¢/lb. Consequently, the all-sodium thermal storage system was retained in the baseline system.

14. Optimum Storage Capacity

A special study was completed which identified the optimum thermal energy storage duration for both the 100- and 300-MWe plants. The optimization parameter was the busbar energy cost of the plant. The optimum storage duration is 13.4 h with a required solar multiple of 2.8.

15. 20% Power Operation at Night

In an effort to mitigate the results of daily turbine start and stop cycles, a study was made to consider the possibility of operating at 20% output load at night. It was found that the storage requirement for this operation mode increased to 4.4 h and that the required solar multiple would be 2.05. It was decided that daily start and stop cycles be retained since the effect on the turbine is uncertain and the life penalty may not be significant. While busbar energy costs for 24-h operation can be lower, the utility must have a need for the off-peak power for the lower costs to be attractive.

Sodium ΔT Selection

Variation of the sodium loop temperature difference (ΔT) determines the quantity of sodium in the all-sodium storage system and the sodium flow rates to transport the thermal energy from the receiver and through the steam generator units. The flow rate is inversely proportional to the loop ΔT; hence, as ΔT decreases, the pump power increases because of the increased flow rate (Q) and pump head required ($\sim Q^2$).

Steam generator cost increments increase rapidly due to the heat transfer area increase resulting from the small pinch point temperature difference as the sodium loop ΔT increases.

Figure 13 presents the influence of sodium ΔT on plant costs for a reheat configuration at three steam pressure levels. While the cost differences are not large for the various conditions, the minimum condition is for a 12,400 kPa (1800 psig) turbine in-pressure with a sodium ΔT of 306^{o}C (550^{o}F). These were the values selected for the plant.

17. Turbine Pressure Selection

Qualitative considerations supporting the selection of the 12,400 kPa (1800 psig) turbine in-pressure level were as follows:

1) Availability data indicated that plant availability significantly decreased at pressures above 12,400 kPa (1800 psig).

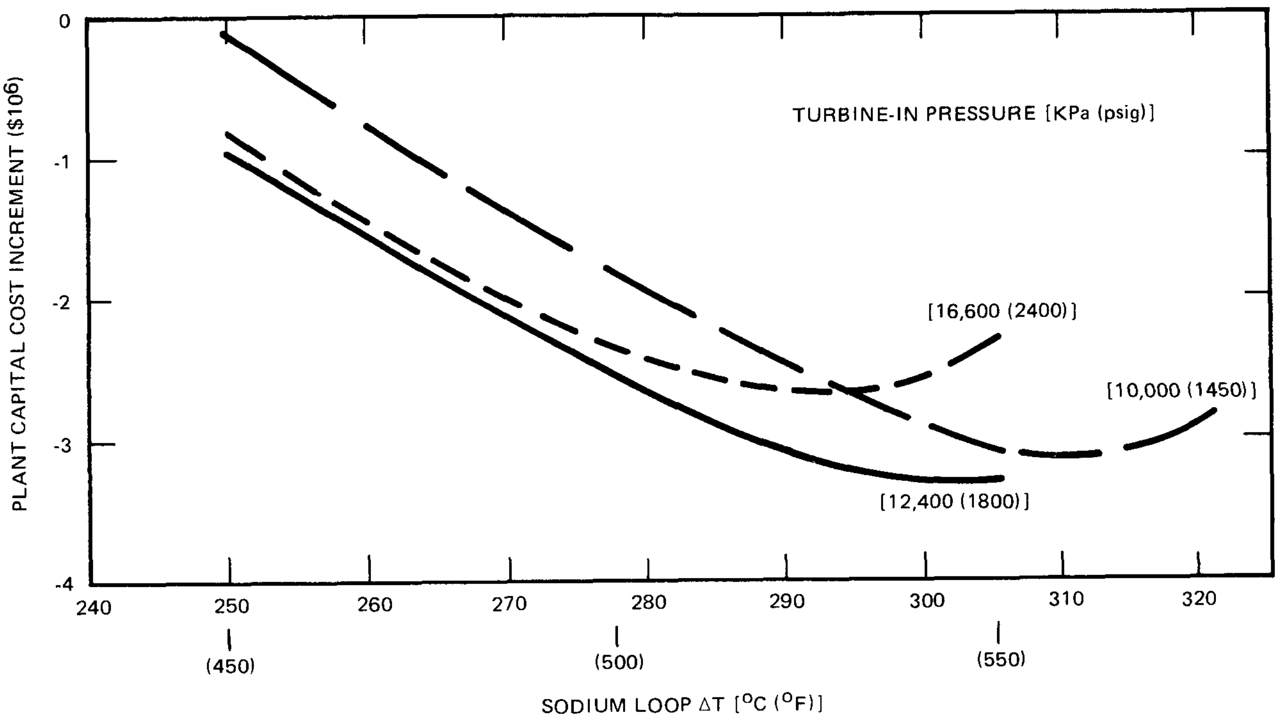

Figure 13. Summation of Plant Capital Cost Increments

2) Higher pressures tend to reduce the tube thermal stresses due to DNB (Departure from Nucleate Boiling), which would tend to support the selection of the 12,400 kPa (1800 psig) level over the 10,000 kPa (1450 psig) level.

Hence, the 12,400 kPa (1800 psig) turbine in-pressure was selected.

18. Turbine Selection

Extensive studies were made of available turbine performance and cost data in selecting the turbines for the 100-MWe and 300-MWe and pilot plant applications. The details of these studies and the selected turbines are contained in Volume II, Book 1, and Volume III.

The 100-MWe turbine selected is a 12,400 kPa (1800-psia) inlet pressure, 538°C (1000°F) reheat inlet temperature tandem compound, double flow unit. The gross cycle efficiency is 43.1%. The turbine selected for the 300-MWe plant is a 16,500 kPa (2400-psia) inlet pressure, 538°C (1000°F) inlet temperature, 538°C (1000°F) reheat inlet temperature unit similar to the 100-MWe unit. The gross cycle efficiency is 43.2%. The turbine selected for the 10-MWe pilot plant will be a standard, nonreheat, off-the-shelf commercially available unit which uses standard steam conditions in the 10- to 20-MWe size range.

19. Utility Input

Estimates of advanced central receiver plant and operating and maintenance costs were determined by the Salt River Project based on the cost data from an operating 100-MWe plant in their system.

III. 281-MWe COMMERCIAL PLANT CONCEPTUAL DESIGN

As part of Task 5, Concept Assessment, a study was made to determine the optimum sodium-cooled advanced central receiver size. The figure of merit selected for this analysis was $/MWt/year. The high relative cost of heliostats assures that this figure of merit accurately tracks busbar energy cost. The results of this study for three tower heights are summarized in Figure 14.

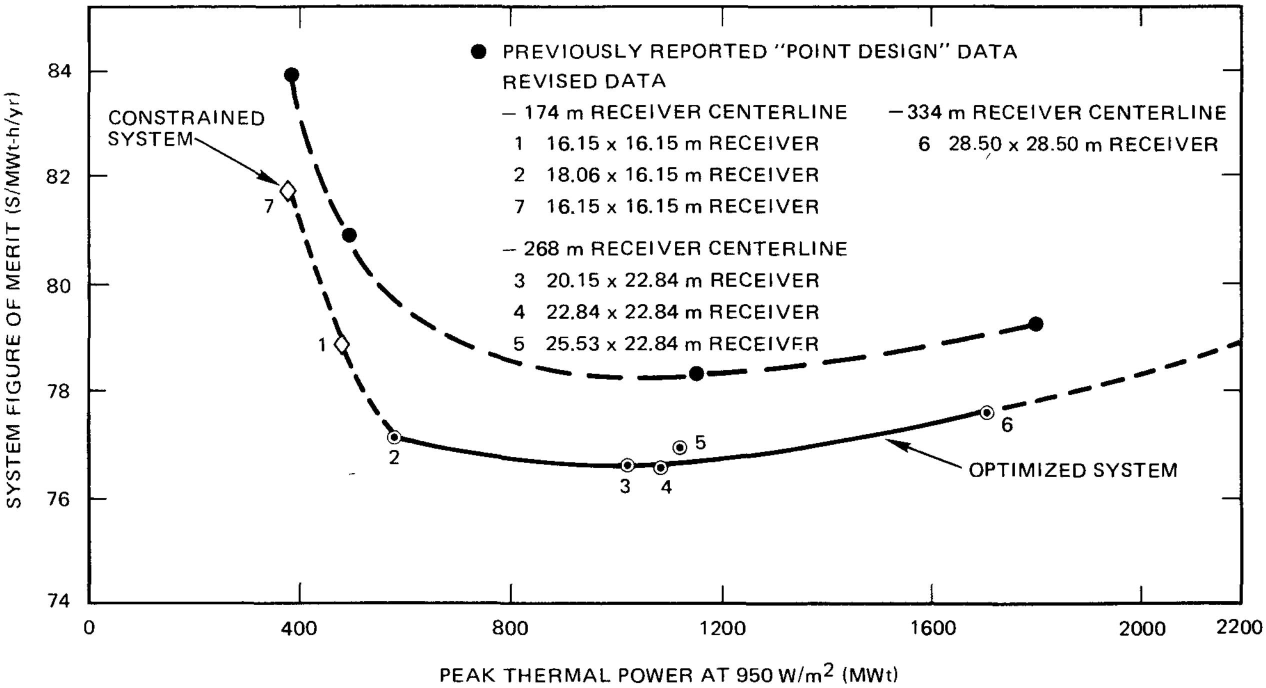

Figure 14. Expanded Thermal Capacity Optimization Analysis Results

As shown in the figure, the minimum cost of thermal energy occurs at about 1100 MWt. However, the curve at the minimum is rather flat, and the difference in cost between 600 MWt and 1400 MWt is not significant. Consequently, 1084-MWt peak power, or 281 MWe, was selected as the optimum commercial plant design point.

A conceptual design of the optimum plant is shown in Figure 15. The major difference between the optimum plant and the 100-MWe plant configuration is the addition of another evaporator and a seventh feedwater heater. The components

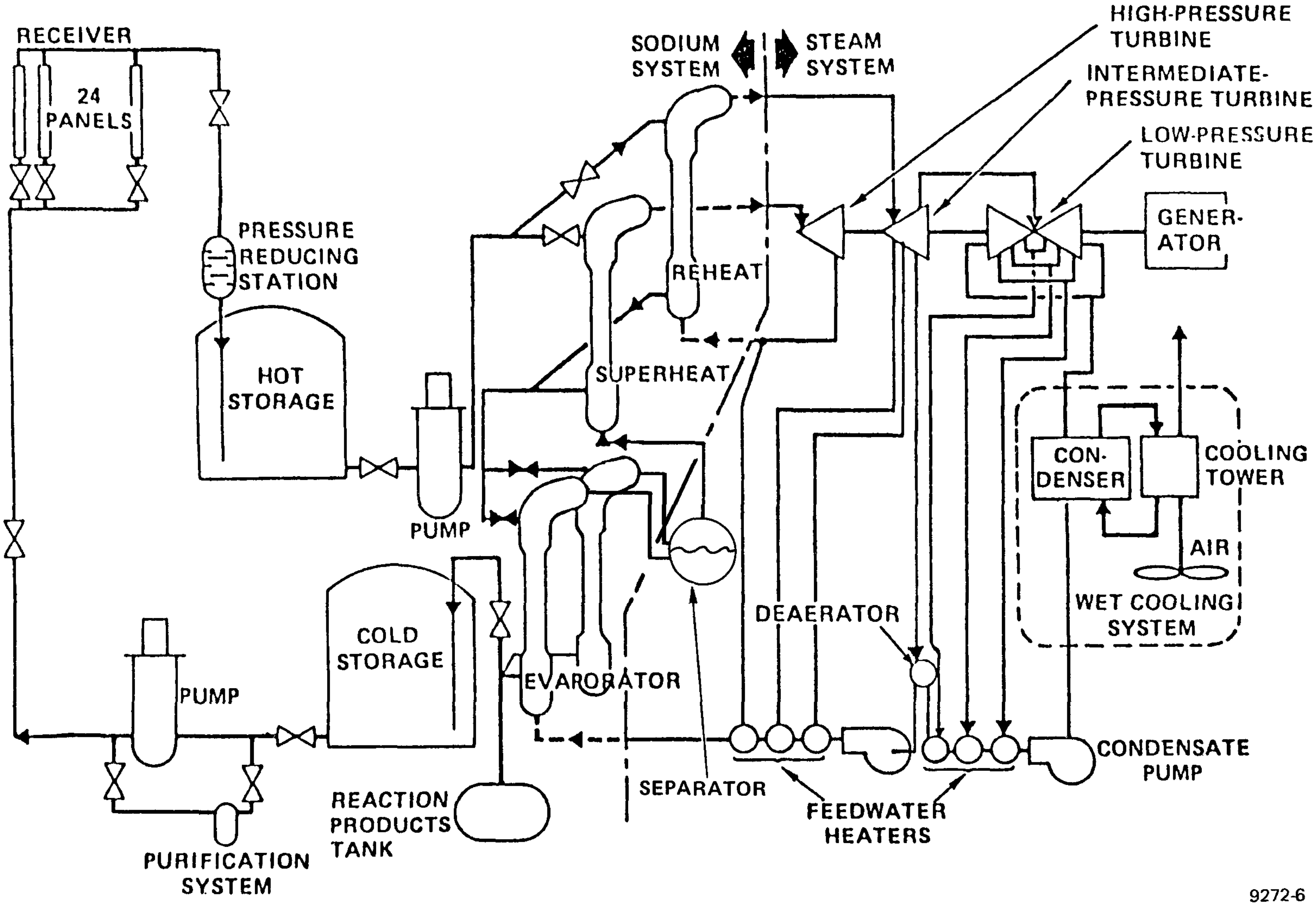

Figure 15. Advanced Central Receiver System
(300-MWe Commercial Plant)

are also enlarged to handle the required increase in capacity. A performance data summary for the optimum plant is shown in Table 11. Detailed design data sheets and P&I diagram for the optimum plant are located in Appendix D, Book 2, Volume II of this report.

TABLE 11

ADVANCED CENTRAL RECEIVER BASELINE DATA SUMMARY — OPTIMUM PLANT

System	Parameter	Optimum Plant
Electric	Net Power (MWe)	281
	Gross Power (MWe)	312
	Cycle Efficiency (%)	43.2
Receiver	SM	1.5
	Nominal Thermal Power (MWt)	723
	Maximum Thermal Power (MWt)	1084
	Receiver Temperature - In [^{o}C (^{o}F)]	288 (550)
	Receiver Temperature - Out [^{o}C (^{o}F)]	593 (1100)
	Flow Rate [10^6 kg/h (10^6 lb/h)]	10.2 (22.6)
	Receiver Midpoint ELevation [m (ft)]	268 (879)
Storage (100% Power)	Operating Time (h)	3
	Energy (MWt-h)	2350*
	Quantity [10^6 kg (10^6 lb)]	23 (50.4)
EPG	Turbine-in Pressure [MN/m^2 (psig)]	16.6 (2400)
	Superheater Temperature [^{o}C (^{o}F)]	538 (1000)
	Reheater Temperature [^{o}C (^{o}F)]	538 (1000)
Collector	Mirror Area [km^2 (ft^2)]	1.99 (21.4 x 10^6)
	No. of Heliostats	40,660

*Includes reduction in night parasitic power of 18 MWe

IV. PILOT PLANT CONCEPTUAL DESIGN

As part of Task 6, a conceptual design of a pilot plant was completed. The power level is 10 MWe, a level which is large enough to provide significant operating experience in a cost-effective manner. A diagram of the proposed pilot plant is shown in Figure 3. The significant performance data are summarized in Table 2.

Full-sized commercial receiver panels will be used in conjunction with a north-oriented heliostat field to simulate the collector and receiver. A north field was chosen to provide a cost-effective full-scale thermal environment for the panels. Flux redirectors will be employed, as required, to shape the flux at the panel surface. The use of full-scale panels will provide significant panel design, manufacturing, installation, and operation experience which should accelerate the introduction of sodium-cooled advanced central receivers.

Some of the component designs and hardware to be used in the pilot plant are already available. For example, a sodium pump with a capacity of 3100 gpm is available for use as a steam generator pump. The modular steam generator that has been selected for the pilot plant has been designed and tested, and the design can be used as the basis for the 10-MWe system. Certain tanks and valves may also exist in inventory and may be capable of use in the plant.

All of the components of the commercial plant will be present in the pilot plant, except the superheater and reheater. Hence, meaningful system-type design, construction, installation, operation, and maintenance experience will be gained from the pilot plant.

V. SUBSYSTEM RESEARCH EXPERIMENTS

Three subsystem research experiments are proposed to develop the sodium-cooled advanced central receiver system to the pilot plant stage. The first experiment is a 5-MWt panel test. The second is an air-rock thermal energy storage. The third is the thermal cycling of candidate rock materials.

The 5-MWt receiver panel test would be conducted at Sandia's Solar Thermal Test Facility (STTF). Its objectives would be to verify receiver panel design at full flow values under actual solar radiation conditions. A schematic diagram of the test is shown in Figures 16a and b. This experiment would use an existing pump and designs for the sodium purification unit and valves. The estimated cost of this SRE is $1,100,000, including engineering, fabrication, and sodium loop operation.*

The thermal energy storage SRE would characterize thermocline thermodynamics, determine pressure differential as a function of cycling and rock size, determine system time constants, and verify the stability of rocks. This test could be carried out using existing support facilities at the Thermal Transient Facility (TTF) at the Energy Technology Engineering Center, California. A diagram of the test article is shown in Figures 17a and b. The estimated cost of this SRE is $166,000, including design engineering, test article fabrication, and 4 months of operation.

The thermal cycling of candidate rock material would provide significant thermophysical properties on candidate rock types. The estimated cost of this SRE is $48,000.

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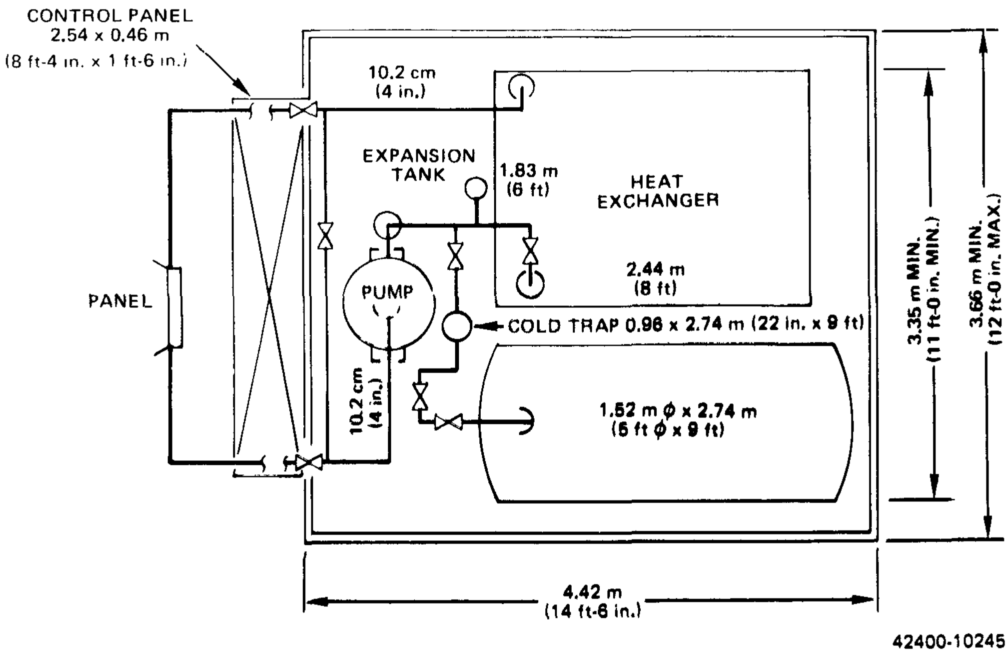
*STTF Facility operating is assumed to be covered by existing operating budgets.



a. Plan

b. Elevation

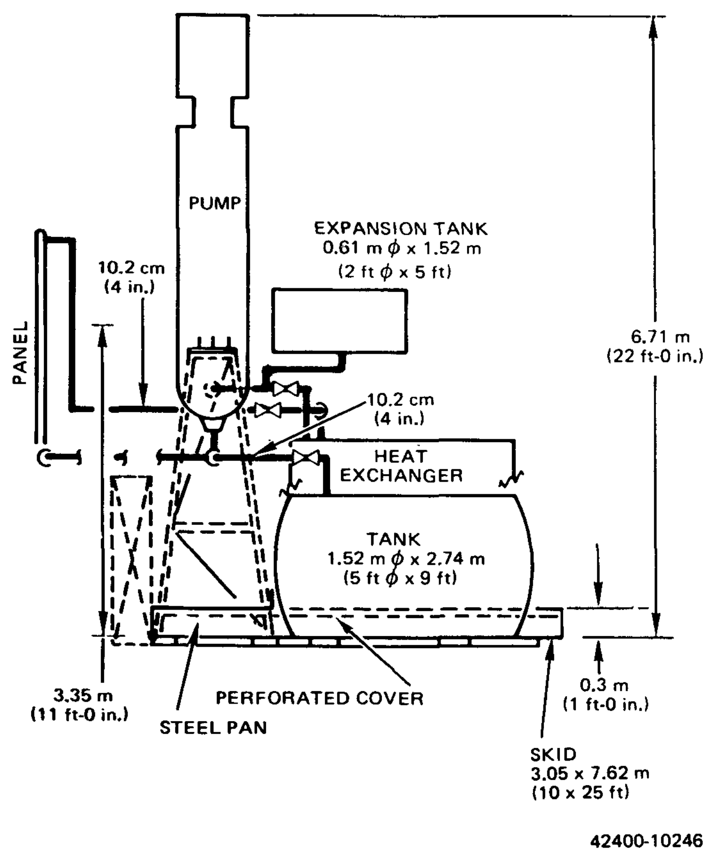
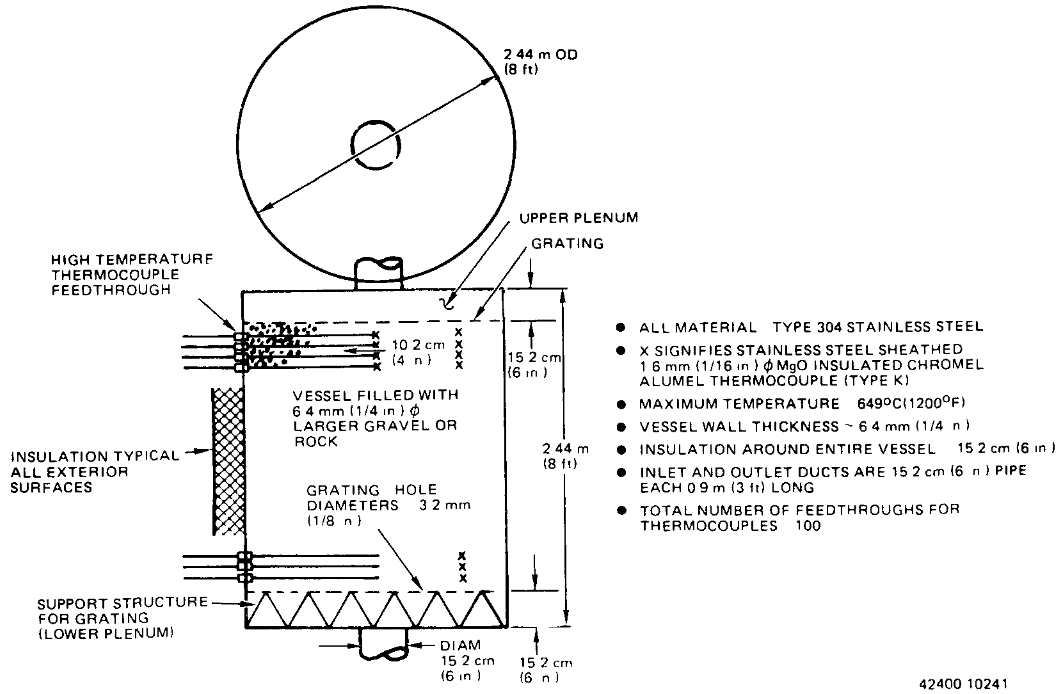
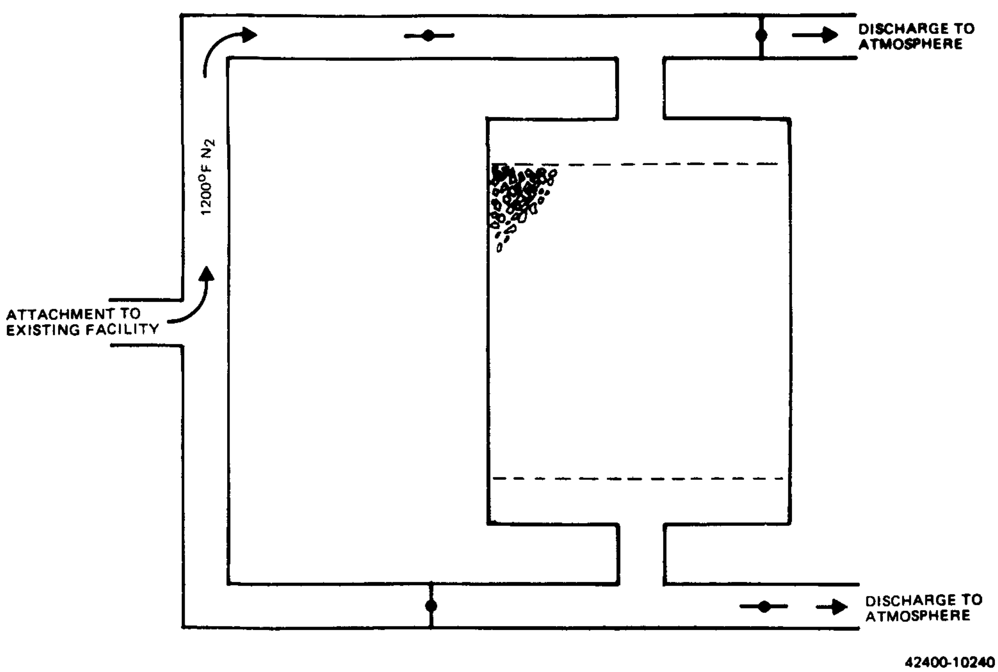


Figure 16. 5-MWt SRE



a. Schematic of Test Article



b. Schematic of Air-Rock Thermocline Test

Figure 17. Air-Rock Thermal Energy Storage Subsystem Research Experiment

VI. DEVELOPMENT PLAN

A. REQUIREMENTS

One of the objectives of Task 6 under the Phase I program is to "estimate time and resources required to bring the conceptual design of the Advanced Central Power System identified in Task 4 into being." In order to meet this objective, the major uncertainties that exist in the conceptual design of the commercial-scale plant were identified and various ways to reduce or eliminate these uncertainties were formulated.

The major uncertainties, as has been indicated on previous occasions during the Phase I contract, appear to be in the receiver component. Although this component has many similarities to sodium-to-water steam generators and to sodium heaters, there are sufficient differences to warrant a development program in order to verify the design that has been selected to date. The heat transfer, optics, and stress analyses that were carried out on the Phase I program have shown that further analytical work and some experimental data will be required before a demonstration or critical module plant can be designed and constructed. The experimental data can be obtained by conducting small-scale tests and/or through the design, construction, operation, and analysis of the performance of a pilot plant.

A total of four subsystem research experiments was identified, each meeting, to some degree, one or more of the basic criteria that were needed in order to resolve receiver design uncertainties. The most important criterion was to simulate as nearly as possible the peak heat flux that would be expected to occur in the commercial-scale receiver. A second criterion was to simulate the expected stress levels and cyclic application of these levels. Out of the four possibilities, only one, a 5-MWt receiver SRE utilizing the 5-MWt Sandia Solar Thermal Test Facility, was ultimately chosen as part of the program plan. The other three – a radiant heat test (either at the Energy Technology Engineering Center or at Sandia), a sodium-heated test panel, and a high-heat flux, high-cycle test at the White Sands Solar Facility – were judged to be, from an overall viewpoint, less cost effective.

One other area of concern that was identified during the Phase I contract was the projected performance of the alternate, air-rock, thermal energy storage (TES) system. This concern centered around the behavior of the thermocline under long term, diurnal, charge and discharge cycles and, especially, around the thermal stability of ordinary rock under temperature cycling at the high temperatures inherently required in this type of thermal energy storage scheme. In order to resolve these areas of uncertainties, two SRE's were conceptually designed and described.

The first consists of a 2.4-m (7.9-ft) diameter by 2.4-m (7.9-ft) high vessel containing a selected type and size of rock into which are embedded a large number of thermocouples. By means of these thermocouples, the temperatures throughout the bed can be determined as a function of space, time, gas flow rate, and inlet gas temperature. An existing facility, the Transient Test Facility, at the Energy Technology Engineering Center is to be used to provide the gas at preselected temperatures and flow rates; consequently, only the test article must be fabricated and only a minor amount of facility modification is needed to carry out this SRE.

The second SRE dealing with the air-rock TES system was designed to resolve questions about the stability of rock under thermal cycling. This experiment is a relatively inexpensive, laboratory-scale effort involving a small quantity of rock that can be thermally cycled over a large number of cycles. Various types of low-cost rocks that are characteristic of the region in which a particular solar plant is to be located can be studied and evaluated.

Thus, a total of three SRE's were selected for study under Phase II of the program, and all three were incorporated into a total of five different long-range plans that are designed to bring the conceptual design of the sodium-cooled, solar, central-receiver power plant into being. The long-range plans 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. Also included in the plans are the identification of major milestones, overall schedules, and budget and planning type of cost estimates. The five major plans (and one subplan) involve tradeoffs of schedule against costs and development risks, and represent various approaches that can be taken in the development and demonstration of the sodium-cooled concept.

B. PLANS, COSTS, AND SCHEDULES

Plan A consists of the preliminary design, final design, construction, and operation of a three-panel receiver pilot plant that produces 10 MW of electrical energy. It also incorporates the preliminary design, final design, and construction of a 100-MWe demonstration plant, in addition to the three SRE's discussed above. This approach to the development of the sodium-cooled concept results in the initiation of the operation of the commercial-scale critical module (demonstration plant) in late 1987 and is very roughly estimated to require funding of the order of $255 million to reach that point. The overall schedule and estimated costs applying to Plan A, as well as the other plans to be discussed below, can be found in Section 4.0 of Volume III. This plan has been worked out in somewhat more detail than the others; consequently, a more detailed schedule showing the various tasks and task interactions has been developed (see Section 4.2.6). A tentative allocation of responsibilities among the team members (ESG, MDAC, Stearns-Roger, and the Salt River Project) has also been developed and is shown on the detailed schedule for Phase II of Plan A.

Plan B is identical to Plan A except that the Electric Power Generating Subsystem, the Thermal Energy Storage Subsystem, and the Sodium-to-Water Steam Generator are deleted from the three-panel receiver pilot plant. As a consequence, no electric power is generated, but a significant reduction in the cost of the pilot plant can be realized. In place of the steam generator, a commercially-procured dump heat exchanger will be employed. The elimination of the steam generator and steam turbine, both of which are critical delivery items, permits a shorter overall schedule for Plan B; the initiation of operation of the critical module is estimated to be approximately mid-1986. The total cost is estimated at $242 million.

A variation of Plan B which would resolve any uncertainties connected with the operation of the steam generator in a sodium plant at sodium inlet temperatures up to 593^{o}C (1100^{o}F) was developed. Relative to Plan B, the cost may be slightly higher for the overall development program. One of the attractive features of Plan B and its variation is that the pilot plant can be designed to permit one to add on various subsystems (storage, EPGS, etc.) at a later time.

Plan C, which probably represents the maximum risk, but minimum initial cost and shortest schedule, involves the deletion of the pilot plant entirely. In order to verify the design of the commercial-scale receiver, a more extensive series of tests of various designs will be done at the STTF. This approach, the development of the sodium-cooled concept, results in an estimated start of initiation of operation of the 100-MWe critical module in mid-1985. A rough estimate of overall cost for Plan C is $202 million. If this plan were followed, it is recognized that modifications in the demonstration plant may need to be made during testing and operation in order to meet all of the original design, performance, and operational goals. In general, this procedure can be very cost effective since it results in the production of full-scale hardware at an early date.

Plan D was developed with the intent of verifying the operation, as a system, of all the plant components except the receiver. Thus, Plan D is similar to A except that a 35-MWt heat transport loop is designed and constructed and installed at the ETEC for testing. Because a major fraction of the required components (pumps, sodium heaters, and condensers) are already available at that facility, some cost savings can be realized relative to the construction of a pilot plant that would require a tower, a heliostat field, and a receiver. The design verification of the receiver for the commercial-scale critical module can be achieved, however, only by extensive testing of small-scale units at the 5-MWt STTF. In Plan D, the start of initiation of the operation of the critical module is estimated to be the end of Calendar Year 1987, about the same as for Plan A. Overall costs are estimated to be about $215 million, a value somewhat lower than that for Plan A.

Plan E is identical to Plan A except that the pilot plant would involve a 360^0 receiver and a surrounding heliostat field. Because of the desirability to match the heat fluxes on the receiver of a 100-MWe plant, the power level in the pilot plant would be of the order of 38 MWe. In order to achieve the required flux levels, special canting and focusing of each heliostat would be required.

This factor, plus the need for a higher power heat transport loop to handle the 38-MWe power production, would result in a very substantial increase in pilot plant cost. The exact degree of increase could not, however, be worked out within the time and budget limitations of the program.

On the basis of the work carried out to date, the initial 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 achieve the performance goals that have been established.

Throughout the preparation of these program plans, consideration has been given to the use, where possible, of existing equipment and facilities. Two existing pumps, one 500 gpm and the other 3100 gpm, have been identified for possible use with the 5-MWt STTF sodium test loop and the 10-MWe pilot plant, respectively. Considerable cost savings may be possible by using, in the commercial-size solar plant, some of the steam generators and pumps now being fabricated for the Clinch River Breeder Reactor if that system is not actually built.

VII. CONCLUSIONS

The sodium-cooled advanced central receiver solar power plant concept has several technical advantages over similar water steam systems. The heat transport fluid remains in the liquid state at all times. The sodium heat transfer fluid has superior heat transfer properties. The receiver is smaller, lighter, and its heat flux considerably higher. The heat transport fluid and thermal storage fluid are the same, resulting in superior system performance from storage and receiver-electric power generation system decoupling. Finally, the sodium system supplies steam to the turbine at temperatures and pressures commensurate with modern steam plant requirements and conveniently incorporates a reheat cycle.

In addition to technical superiority, the sodium-cooled advanced central receiver concept is very attractive economically. An estimate of the first plant busbar energy cost ($\overline{BBEC}$) is 85.8 mills/kWh. An N^{th} plant $\overline{BBEC}$ is estimated to be 61.7 mills/kWh. The capital cost estimates for the first and N^{th} plants are $1526/kWe and $1237/kWe, respectively, with 3 h of storage capacity. These low capital and $\overline{BBEC}$ costs are due to the high system efficiency and receiver flux levels available with the sodium system.

The sodium-cooled advanced central receiver concept has the potential for expanded plant size and storage capacity. As part of this project, the optimum plant size was identified as 281 MWe and the optimum storage capacity was selected to be 13.4 h. Both these potential plant improvements result in further decreases in busbar energy costs. At the same storage capacity, the increase in plant size to 281 MWe can lower $\overline{BBEC}$ by 15%. The storage capacity study showed that $\overline{BBEC}$ is reduced by 17% by increasing capacity from 3 h to 13.4 h.

There is a low development risk associated with the sodium-cooled advanced central receiver concept. All components except the receiver have either been previously designed, developed, or tested as part of the ongoing liquid metal fast breeder reactor program. A logical development program has been proposed to bring the ACR receiver and system design to a mature level and this includes fabrication and testing under actual solar operating conditions. A pilot plant design has been identified which will give a cost-effective indication of the true potential of this concept.

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