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SOLAR CENTRAL RECEIVER HYBRID POWER SYSTEMS SODIUM-COOLED RECEIVER CONCEPT. FINAL REPORT

Volume 2, Book 2. Conceptual Design, Sections 5 and 6

January 1980

Work Performed Under Contract No. AC03-78ET20567

Rockwell International
Energy Systems Group
Canoga Park, California

U.S. Department of Energy

Solar Energy

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VOLUME II, BOOK 2
CONCEPTUAL DESIGN
SECTIONS 5 AND 6

JANUARY 1980

PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
AS PART OF
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Rockwell International
Energy Systems Group

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Salt River Project
Stearns-Roger
Babcock & Wilcox
SRI International

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5.0 CONCEPTUAL DESIGN AND COST/PERFORMANCE ESTIMATES

5.1 INTRODUCTION

Detailed conceptual designs of the selected Solar Central Receiver Hybrid Power system concepts for the 0.8 solar multiple (SM) and 1.4 SM plants are presented in this section. Cost estimates are also presented for both plants based on the conceptual designs.

5.1.1 System Requirements

System requirements for the hybrid plant are based on the "Requirements Definition" document, as stated in Reference 4-1. The key requirements are listed in Table 5-1.

5.1.2 System Performance

The system performance for the hybrid plant is summarized in Table 1-1 in Section 1 of this report.

TABLE 5-1

HYBRID SYSTEM REQUIREMENTS

(Sheet 1 of 3)

Solar Multiplier (SM)	0.8	1.4
Storage Capacity	90 min.	3 hr
Design Point Power Levels:		
During Receiver Operation	100 MWe Net	100 MWe Net
Operation exclusively from Thermal Storage	N/A	100 MWe
Design Insulation	950 W/m^2	
Heat Rejection	Wet Cooling	
Wet Bulb Temperature	23^oC (74^oF)	
Dry Bulb Temperature	28^oC (82.6^oF)	
Nominal Design Wind*	3.5 m/s (8 mph)	
Maximum Operating Wind (Including Gusts)*	16 m/s (36 mph)	
Maximum Survival Wind (Including Gusts)*	40 m/s (90 mph)	
Seismic Environment:	Zone 3	
Survival Earthquake Horizontal and Vertical	0.25 g	
Availability (Exclusive of Sunshine)	0.9	
Lifetime	30 years	

*At reference height of 10 m (30 ft).

TABLE 5-1

HYBRID SYSTEM REQUIREMENTS

(Sheet 2 of 3)

1	Electrical Power Output (independent of insolation level)	100 MWe
2	Field/Receiver Power Ratio (FRPR) (also study alternate FRPR's)	At least 1
3	Heat Rejection	Wet cooling may be employed
4	Operating Lifetime	30 years
5	Plant Availability	90%
6	Initial Year of Operation	1990
7	Reference Baseline Fuel Costs	
	a. Fuel Oils	
	Residual fuel oil	
	1% sulfur	\$2/MBTU
	0.3-0.5% Sulfur	\$2.2/MBTU
	Distillate fuel oil (#2)	\$2.35/MBTU
	b. Coal	\$1/MBTU
	c Synthetic oil	\$3/MBTU
8	Fuel Escalation Range	6% to 15% per year
9	Reference Site	Barstow, Calif.
10	Insolation - Direct Normal at	950 watts/m^2
11	Wind Speed at reference height of 10 m (ft)	3.5 m/s (8 mph)
12	Temperatures - Wet Bulb	23°C (74°F)
	Dry Bulb	28°C (82.6°F)
13	Operating Ambient Air Temperature Range	-30° to $+50^\circ$C (-20° to $+120^\circ$F)
14	Earthquake	UBC Zone 3

TABLE 5-1

HYBRID SYSTEM REQUIREMENTS

(Sheet 3 of 3)

15	Survival			
	a. Winds - Maximum speed	40 m/s (90 mph)		
	b. Static snow load	240 Pa (5 lb/ft^2)		
	c. Rain - Average annual	750 mm (30 in.)		
	- Maximum 24-hr rate	75 mm (3 in.)		
16	Air Quality Control Standards			
		Pounds/million BTU		
	Emission Limits:	SO_x	NO_x	Partic.
	a. Coal fired	0.8	0.7	0.1
	b. Oil fired	0.8	0.3	-
	c. Gas fired	-	0.2	-

5.2 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 is 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). These factors were treated in the subsystem analysis discussed in Section 3.2.

The information presented in this section will review the major requirements, present characteristics of the baseline collector subsystem design, and discuss the performance of the collector subsystems for the 0.8 and 1.4 solar multiple system.

The collector selected as a baseline for this study is the McDonnell Douglas Prototype Heliostat. This heliostat and some of its pertinent design features are shown in Figure 5-1. This heliostat is designed to meet or exceed the requirements listed in the Solar Central Receiver Hybrid Power System Requirements Definition, Enclosure III, Exhibit I, Attachment 1 (as revised) Solar Central Receiver Hybrid Power System RFP No. ET-78-R-03-2051, June 19, 1978.

5.2.1 Collector Subsystem Requirements

The principal subsystem design requirements are summarized in Table 5-2. They are divided into subsystem and individual heliostat requirements. From a subsystem standpoint, two collector fields were designed to yield 208 and 364 MW of net absorbed power into the sodium at equinox noon with an insolation of 950 W/m^2. From a receiver design standpoint, the collector subsystem shall be designed and operated so that the peak receiver heat flux is < 1.50 MW/m^2. In addition, because of cost considerations, it is necessary to design a subsystem with a long life and high availability.

REFLECTOR SHAPE	7M X 7M SQUARE	
MIRROR AREA	$49M^2$	
NUMBER OF MIRROR MODULES	12	
MIRROR MODULE SIZE	1.22M X 3.35M	
MIRROR CONSTRUCTION	LAMINATED GLASS 1.5MM ON 4.8MM	
REFLECTIVITY	0.92-0.945 (DEPENDING ON IRON CONTENT AND OXIDATION STATE)	
REFLECTOR CONFIGURATION	CANTED	
BEAM ERROR	2.83 MR	
SLEW RATE	15 DEGREES/SEC	
DRIVE	AZIMUTH: HARMONIC DRIVE	ELEVATION: LINEAR ACTUATORS
CONTROL SIGNAL DISTRIBUTION	FIBER OPTICS	

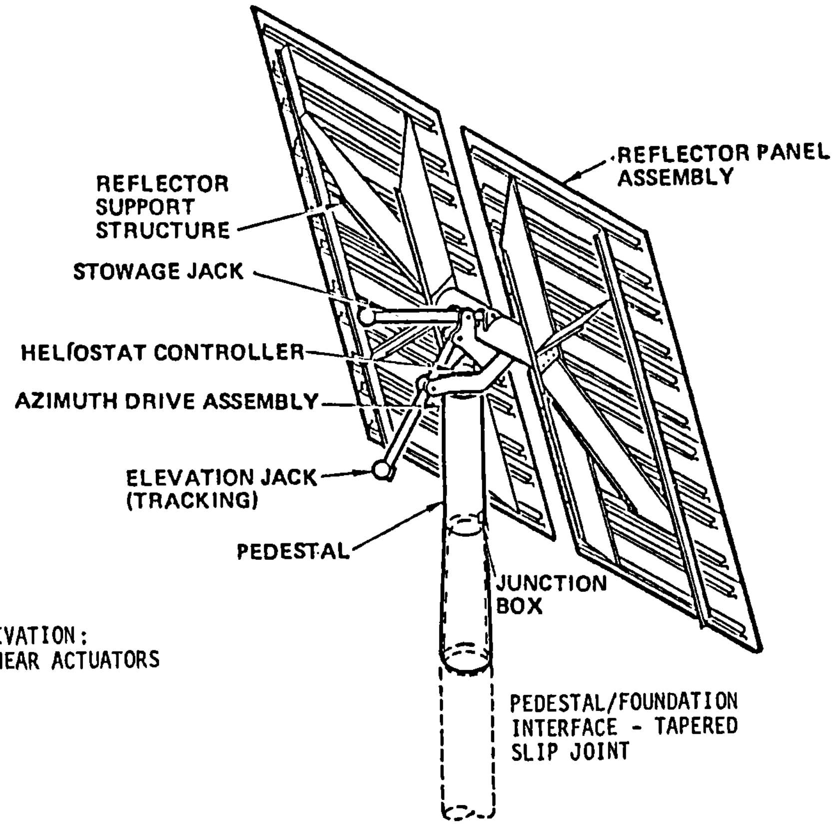


Figure 5-1. Prototype Heliostat Baseline

TABLE 5-2

COLLECTOR SUBSYSTEM DESIGN REQUIREMENTS

(Sheet 1 of 2)

Subsystem	Solar Multiple 0.8	Solar Multiple 1.4
Peak Absorbed Power (MWt) at 950 w/m^2	208	364
Peak Incident Receiver Flux (MW/m^2)	<1.5	
Field Design and Layout Criteria	Minimize Cost of Annual Energy	
Time to Initiate Emergency Slew or Other Protective Action (Sec)	N/A	<0.5
Availability	>0.97	
Lifetime (years)	30	
Heliostat		
Reflector Configuration	Canted	
Slew Rate (deg/min)	15	
Reflector Pointing Error (mr)	1.5	
Beam Quality Error (mr)	2.2	
Aim Strategy	2 point (above + below equator)	
(Operation within Specification)		
Temperature [°C (°F)]	-30 to 50 (-20 to 120)	
Wind Speed		
Sustained [m/s (mph)]	12.0 (26.8)	
Gusting [m/s (mph)]	16 (36)	
(Survive)		
Temperature [°C (°F)]	-30 to 50 (-20 to 120)	
Dust Devil Wind Speed [m/s (mph)]	18 (40)	
Wind Speed - Gusting [m/s (mph)]		
• At Angle of Attack = ± 10°	40 (90)	
• At any Angle of attack	22 (50)	
Seismic Acceleration (g)	Zone 3, Uniform Building Code	
Precipitation		
Rain		
(Average Annual [mm (in)]	750 (30)	
(Maximum 24 hr Rate) [mm (in)]	75 (3)	

TABLE 5-2

COLLECTOR SUBSYSTEM DESIGN REQUIREMENTS

(Sheet 2 of 2)

Heliostat	Solar Multiple 0.8	Solar Multiple 1.4
Snow Load [Pa (psf)]	240 (5)	
Snow Deposition Rate m (ft)/24 hrs	.3 (1)	
Sleet Buildup (mm (in)]	50 (2)	
Hail, (Special Gravity)	0.9	
(Any Orientation) [mm (in)] Diameter at a velocity M/S (ft/sec)	20 (.75) at 20 m/s (65 fps)	
(Vertical Stowed Position) [mm (in)]	25 (1) at 23 m/s (75 fps)	
Sand/Dust	Survive tests per MIL-STD-810B, Method 510.	
Lightning		
Direct Hit	Destruction Allowed	
Adjacent Strike	Survive	

For an individual heliostat, it is important to minimize reflected image size to maximize the high concentration ratio potential of the sodium system. As a result, it is desirable to have heliostats which can employ canted reflector panels and a tight constraint on reflector pointing and beam quality errors. These values must also be a result of cost effective heliostat design in order to ensure that the complete energy collection portion of the system, including the receiver, tower, etc., are cost effective. The heliostat requirements shown in Table 5-2 reflect extensive design and performance optimization analyses which have been carried out as part of the MDAC Prototype Heliostat contract.

The balance of the information represents environmental conditions to be used in the design of the subsystem equipment. The first portion of the data represents limits in which the heliostat equipment will operate within its design specification. The second portion represents environmental factors which the heliostat equipment must survive. Since the plant is not operating during these extreme conditions, no limit on reflected beam accuracy is imposed in conjunction with these survival conditions.

5.2.2 Collector Design

The heliostat assembly is shown in Figures 5-2 and 5-3. 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 identical laminated mirror modules and a support frame. The mirror modules are 1.22 m (48") by 3.35 (132") and made of a 1.5 mm (0.060") pane of fusion glass mirrored on its inner face and laminated to a 4.8 mm (0.1875") float glass back lite. The clean reflectivity is estimated to be 0.92 at 0.05% iron and 0.945 at 0.01% iron.

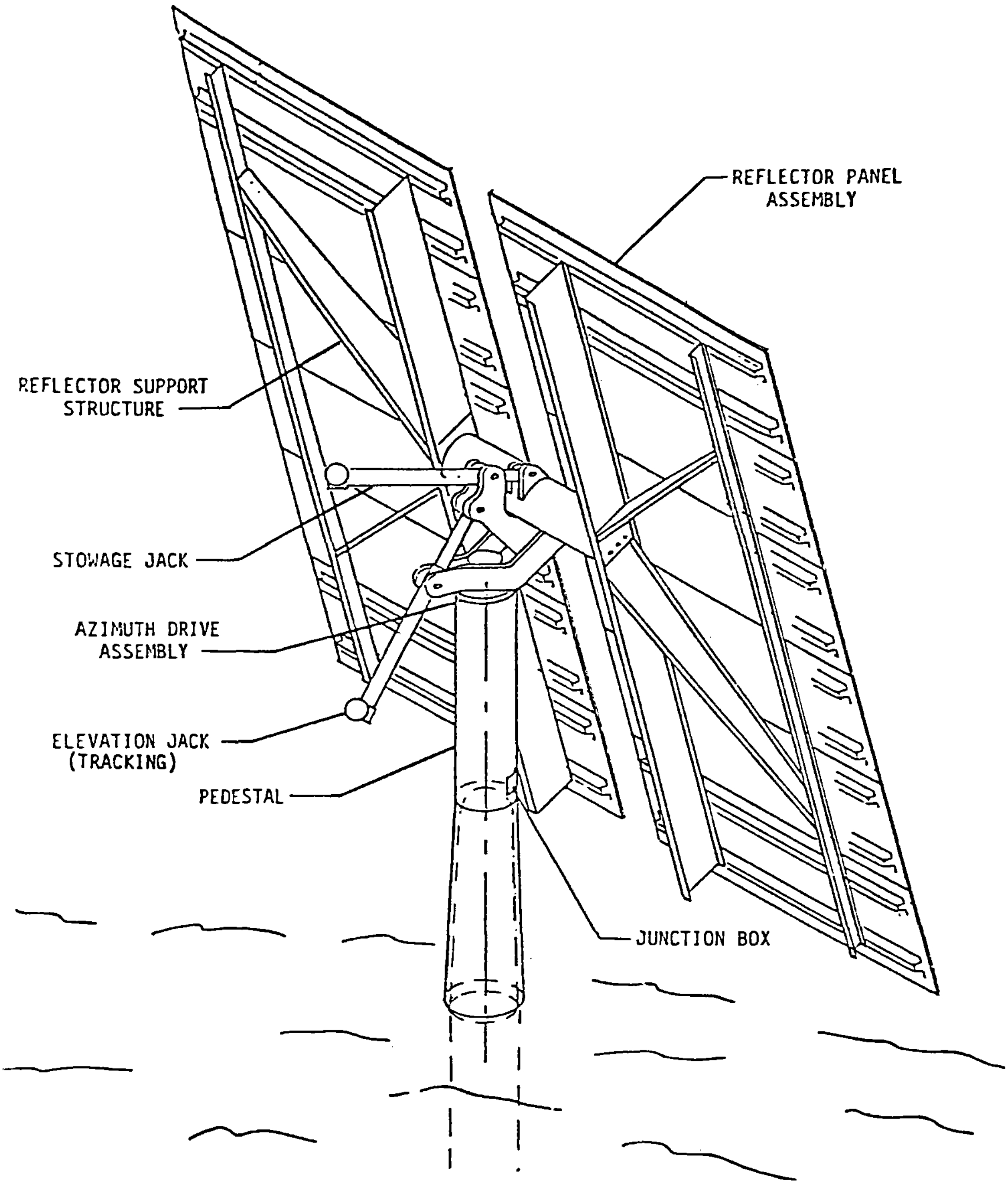


Figure 5-2. Primary Baseline Heliostat

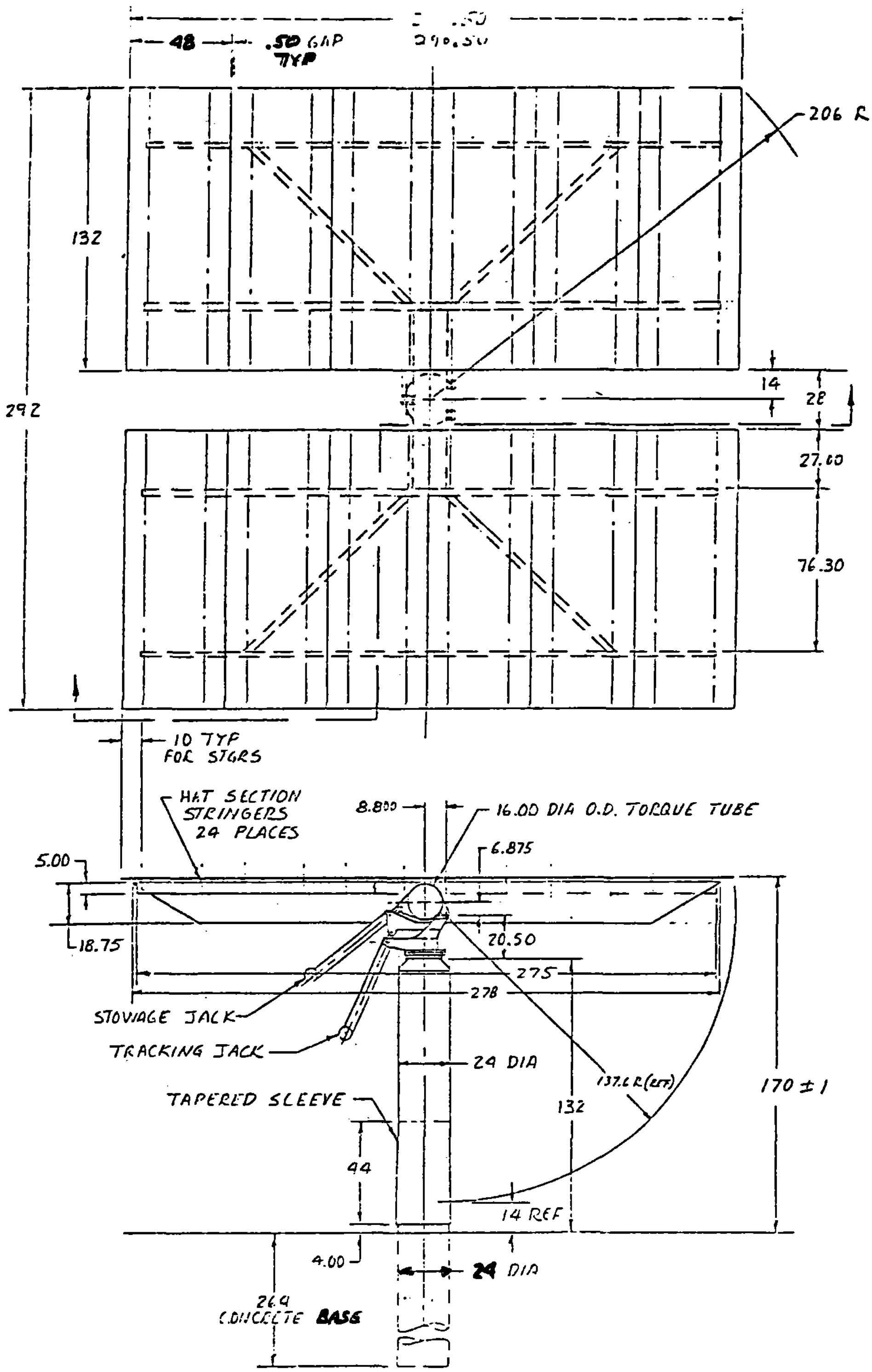


Figure 5-3. Primary Baseline Heliostat (Elevation)

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 x 7.42 m (290.5 x 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 (528 ft^2).

In order to achieve high performance at low cost, glass with a high degree of flatness and with high transmission properties over the solar spectrum is required. Because of its high absorption characteristics, iron oxide content in the glass must be kept to a minimum. For these reasons, Corning Fusion sheet glass (~0.05 wt % Fe), low iron float glass (~0.05 wt % Fe) and clear float glass (~0.08 wt % Fe), were investigated. Corning Fusion glass was selected because of its high reflectance properties, its adequate flatness, and reasonable costs. Although low iron float is flatter, and the extrapolated value of reflectance efficiency after silvering at a glass thickness of 1.5 mm (0.060 in.) approaches Fusion glass, it cannot be made in that thickness. Currently, the thinnest float glass available is 2.1 mm (0.083 in.) thick which would lower the extrapolated reflectance efficiency to 92%. A value of 0.912 was used for performance calculations.

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 for 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 ±270 degrees avoids the need for configurating the drive unit as a function of position in the field. The 180 degrees 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 less than 15 minutes 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.

Azimuth Drive Assembly

Movement of the heliostat assembly in azimuth is achieved with a harmonic drive train powered by a 480 volt, 3 phase, 249 watt (1/3 hp) bi-directional induction motor.

The major elements of the harmonic drive are the wave generator, the circular spline and the flexspline. The harmonic drive input is accomplished by rotation of the wave generator by the motor. The wave generator distorts the flexspline locally, so that some of the flexspline teeth engage circular spline teeth. Rotation of the points of engagement of the spline teeth cause relative motion of the flexspline to the circular spline. By attaching the circular spline to the pedestal and the flexspline to the azimuth housing, the output becomes rotation of the azimuth housing about the azimuth axis.

Elevation Actuators - Two linear actuators acting in conjunction with the drag link cause the main beam assembly to rotate about the elevation axis. Each actuator must have the capacity to rotate the torque tube 90 degrees, to satisfy the requirement for a maximum travel of 180 degrees. While the two actuators are identical, one is used daily as a tracking actuator, and the other, the stowing actuator, is used occasionally, possibly 30 times a year, when inverted storage may be required. The stowing actuator is preloaded into a structural stop, when the sun is being tracked, to eliminate its backlash from the system.

The elevation jacks each have identical 1/4 HP 480 volt, 3 phase, 60 Hz bi-directional motors driving a helicon gear affixed to the nut of a ball screw.

Main Beam

The central torque tube type main beam connects the two reflector sub-assemblies together and ties the reflector unit to the elevation hinge and the elevating jacks at the top of the drive unit assembly. The main beam carries all the air-loads and dead weight loads from the reflector unit to the pedestal as bending, torsion and shear. The main beam is 2.08 meters (82.0 inches) long, of circular cross-section, 0.406 meter (16 inches) in outside diameter (outside) formed of 12 gage steel sheet, and hot-dip galvanized after fabrication. End plates are fusion welded to each end and machined flat and parallel to provide accurate location for the reflector subassemblies. Tapered holes in the reflector sub-assemblies and conical bolts provide accurate angular location of the sub-assemblies relative to each other.

In the slot between the two six-panel reflector subassemblies, the main beam has lugs of steel plate welded to it. Four of these lugs, in line, serve as the support and the elevation hinge line. They are attached to the drive housing at the top of the pedestal with two pins. The other two lugs are the mount for the elevating jack (actually, the stowing jack) through which the elevation rotational forces are applied to the reflector.

Pedestal

The support for the heliostat is provided by a pedestal 3.18 meters (125 inches) high to provide clearance with the ground when the reflector is elevated at an angle. It is fabricated of 0.61 meter (24 inches) diameter spiral welded steel pipe with a wall thickness of 2.66 mm (0.1046 inch). The lower 1.12 meter (44 inches) of the length is expanded to produce a slight taper to obtain a wedged, slip-joint attachment with the foundation on installation. A recessed junction box is located in the pedestal 1.37 meters (4.5 feet) above its lower end. Underground electrical lines are routed externally from the ground to the box, then through the box and up the inside of the pedestal. The drive unit housing is welded to the top of the pedestal.

A draw pressed dome is fusion welded to the top of the pedestal. A bolt circle in the dome provides a bolted interface to the circular spline in the azimuth drive unit.

The foundation is a concrete pier, 24" in diameter. The pier extends about 4' above grade and 20' below. A tapered steel shell establishes the mounting surface to the pedestal and serves as a form for the protruding end of the pier.

Heliostat Electronics

The heliostat electronics subassembly includes:

o Pedestal Junction/Circuit Breaker Box - located on the pedestal and interfaces with the field power and data network.

o Cabling - A single cable takes power to and data to/from the heliostat controller box on the drive unit to/from the junction box. A second set of cables go from the controller box to the motors/sensors.

o Heliostat Controller - A microprocessor in the heliostat controller does all command calculations. The microprocessor interfaces directly with motor switching network, sensor, and communication link.

o Motors/Sensors - Incremental encoders and switching networks are mounted on the motor shaft.

The heliostat electronics receives signals from the data network and relays messages to the next heliostat in the chain. Open-loop tracking algorithms are used to determine the required heliostat position. The difference between the calculated position and actual position is used as an error signal for turning the motors on/off. The signal from the incremental encoder is used to determine the actual position by counting motor turns. The accumulated turns are stored in non-volatile electrically erasable memory (EAROM); therefore, if power should be lost, the position reference of the heliostat will not be lost.

The electronic components are located at five different locations on the heliostat as shown in Figure 5-4. The Heliostat Controller is located in an electrical J-box on the drive unit. This location was selected over a ground location in order to give added protection from the environment and ground activity, and to minimize the heliostat wire required. A junction box is located on the pedestal which contains a circuit breaker, plug connectors, and terminators for the incoming power and communication fibers. Power to a heliostat can be controlled by activating the circuit breaker switch. A manual control box can be plugged into the pedestal junction box for local control of the heliostat. Local manual control isolates this heliostat without affecting the control of any other heliostat in the field.

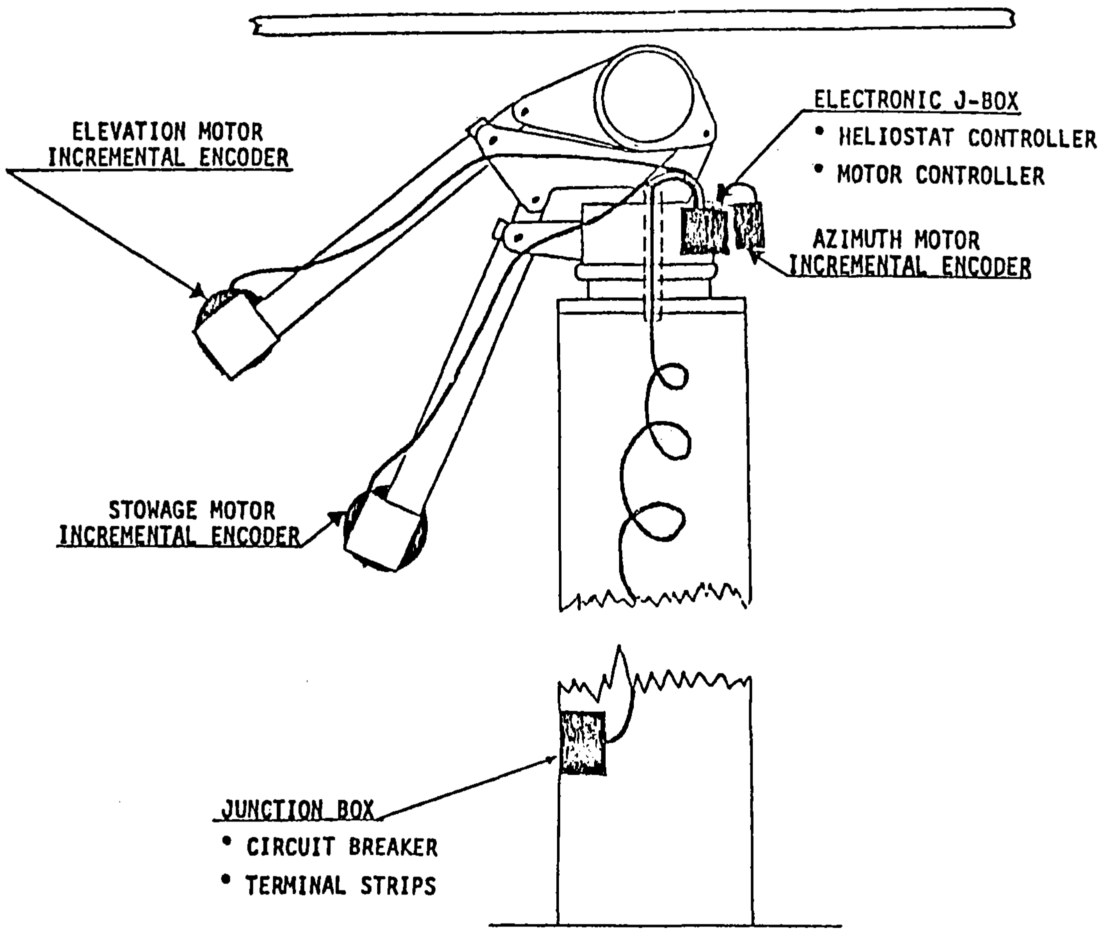


Figure 5-4. Heliostat Electronic Assembly

Pedestal Junction/Circuit Breaker Box

The secondary feeder cable enters the heliostat pedestal and terminates in a junction box located on the side of the pedestal. The junction box is illustrated in Figure 5-4. The recessed box contains a circuit breaker which joins the incoming and outgoing cables and noninterchangeable fiber optic connectors. On the inside of the pedestal, the circuit breaker is wired directly into the cable leading to the heliostat controller.

An internal protective cover will be required to provide personnel protection from the 480 volt terminations after the wire installations are made.

The cutout will also contain a cover for environmental protection. The cover will be designed to prevent water from flowing into it and will be sufficiently tight to exclude dust and prevent the formation of significant quantities of ice. The box will have a drain hole inside the pedestal to prevent the accumulation of significant quantities of water.

It is important that proper phasing be maintained in the power distribution network. Therefore, cables will be terminated in the factory with crimp or ring terminals which will only connect in one manner. Also, the fiber optic connectors will be male and female, with the male used for the incoming signal and the female for outgoing to prevent any possibility of reversing.

Cabling

The heliostat pedestal wiring consists of 3 conductor, #16 AWG, 480 volt, copper wire with aluminum sheath for power distribution and twin lead optical fiber cable for data transmission. The cable runs from the junction box in the pedestal to the heliostat controller mounted on the drive unit. In order to route the cable past the gimbal axis, a hollow shaft has been designed into the center of the azimuth axis. The cable will be routed through the shaft, thus allowing for rotation and elevation of the heliostat without putting stress on the power cable. To allow for 270° rotation of the azimuth gimbal, a section of cable is left slack inside the pedestal. The cable and other components are completely wired in the factory; hence, the only field wiring required is to connect the secondary feeder to the junction box.

Heliostat Controller

The Heliostat Controller is a microprocessor based unit which interfaces with the Heliostat Array Controller and the motor/sensor system.

The main functions of the Heliostat Controller are to respond to the commands from the Heliostat Array Controller, send information to the Heliostat Array Controller, calculate commands for moving the heliostat from one position to another position, and to keep track of heliostat orientation. Heliostat orientation is determined by counting the number of turns the motor makes. The processor contains a non-volatile memory (EAROM) where the motor counts are kept. Even if the power should fail, the heliostat will not lose the number of motor turns or its reference position.

It is estimated that in the 1985 time period, the required capabilities of the Heliostat Controller will easily be available in a single chip micro-processor.

The current trend and demand also indicates that microprocessors will be available with electrically erasable ROM's (EAROM) within the next year or two.

The communication interface consists of a differential line transceiver which receives serial data and transfers parallel data to the processor (the process is reversed for transmitting data). The address bits are decoded in the processor and, if they agree with the address of this heliostat, the message is decoded and executed.

Calculation of equations for control of the heliostats are done in the Heliostat Controller with inputs from the Heliostat Array Controller. Using a transmitted time signal, the Heliostat Controller updates its clock, calculates the sun angles, the gimbal angle required for reflecting the beam onto the target, the error signal between the actual gimbal angles and the commanded gimbal angles, and the motor command for reducing the error signal.

If the operating mode should be changed from tracking on the receiver to emergency slew off the receiver, a single command is transmitted to each Data Distribution Interface which transmits the message to each heliostat assigned to it. The Heliostat Controller then commands the reflected beam to move from the receiver to an aim point near the receiver. The Heliostat Controller maintains the beam at this aim point until the operating mode is changed by the Heliostat Array Controller. The Heliostat Controller will continue tracking even if the communication link with the heliostat array controller is lost.

Motors/Sensors

Besides the armature and field, the motor housing contains the motor control switching network and in incremental encoder.

The control (direction and on/off) of the 3Ø motors is accomplished by the heliostat controller switching the motors on and off to produce the required motion.

Incremental encoders are mounted at the base of each of the three drive motors to provide control feedback data. The encoder is designed to provide the controller with information concerning the direction and the number of revolutions of each motor.

The incremental encoder is designed with two Hall - effect transducers. A ferrous metal vane mounted on the motor shaft produces an interrupt in each of the transducer's magnetic fields at intervals slightly out of phase depending on the direction of rotation.

The encoder sensors are environmentally sealed in durable plastic casing. Dust and dirty atmospheric conditions produce no damage or inaccuracy due to the magnetic operation of the units.

The encoder has an accuracy to within one motor revolution. This is equivalent to a deflection of 0.144 milliradian in heliostat azimuth and approximately 0.144 millradians in elevation.

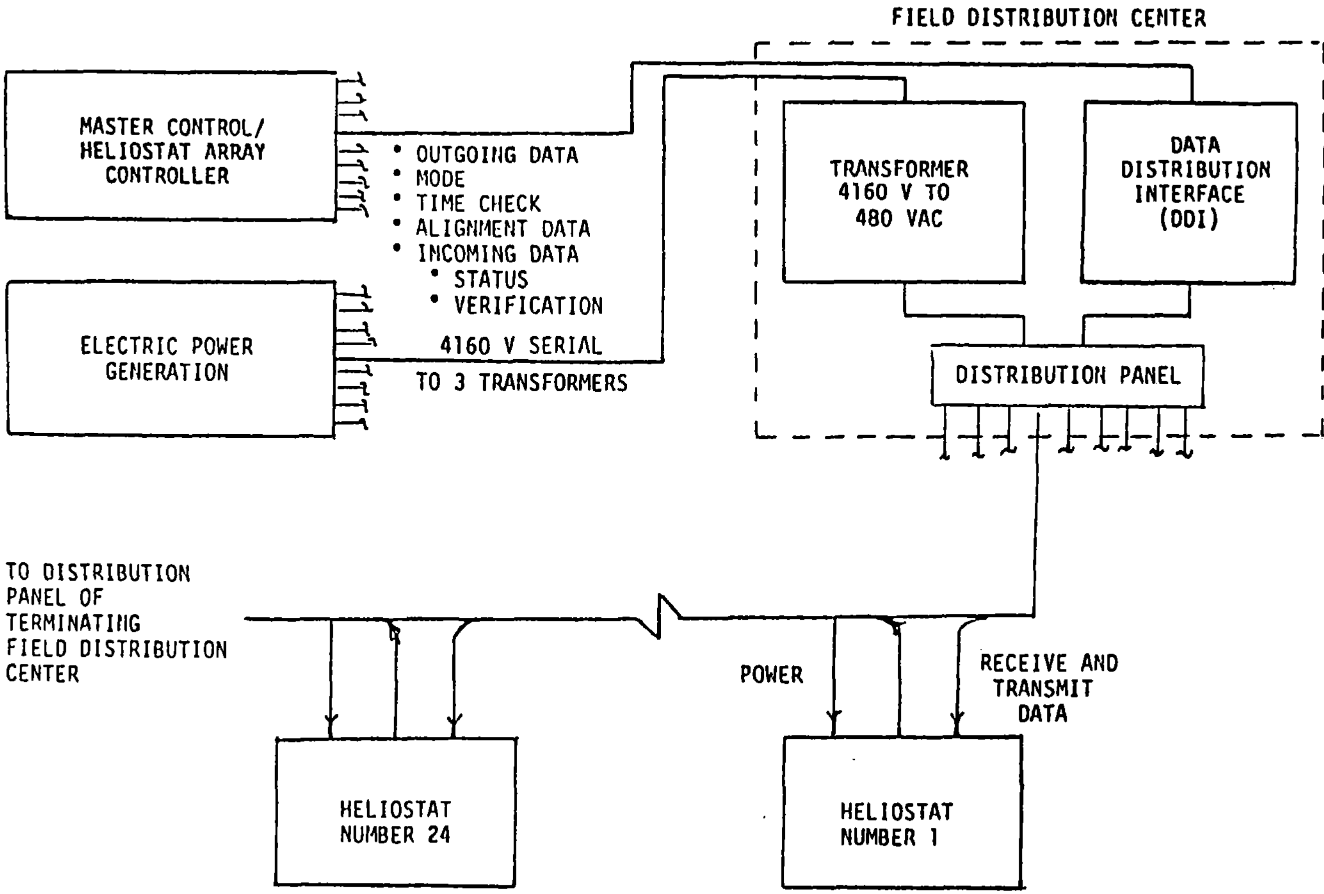


Figure 5-5. Collector Field Electronics

Field Electronics

The field electronics for the collector deliver power and control data to the heliostats and return information on the heliostat status to the master control.

Data Distribution Network

There are four basic electronic components that are used in controlling the heliostats in the collector field (Reference Figure 5-5). They consist of a Heliostat Array Controller (HAC) located in the master control building which commands operating modes, transmits and coordinates reference time, and requests and receives data on heliostat performance. Information from the HAC is communicated via serial data transmission to the Heliostat Controllers (HC) which in turn provide the necessary calculations and tracking command signals to the drive motors. A Data Distribution Interface (DDI) between the HAC and the HC is used to distribute the commands down the appropriate line.

The data distribution interface receives data from the heliostat array controller via either of two redundant lines and logic networks. The redundancy provided should prevent loss of control of more than a few heliostats at a time. The logic network decodes the data and addresses it to the correct secondary data feeder and the intended heliostat.

The secondary data feeders from a DDI connect each heliostat on the line in a series hookup. Data received by a heliostat controller are decoded and, if addressed to the heliostat, the data are retained and a message relayed onto the next heliostat, and hence to a data distribution interface at the end of the line. If the data were not addressed to the heliostat, the message is relayed to the next heliostat.

If the operating mode should be changed from tracking on the receiver to emergency slew off the receiver, a single command is transmitted to each DDI which transmits the message to each heliostat assigned to it. The heliostat

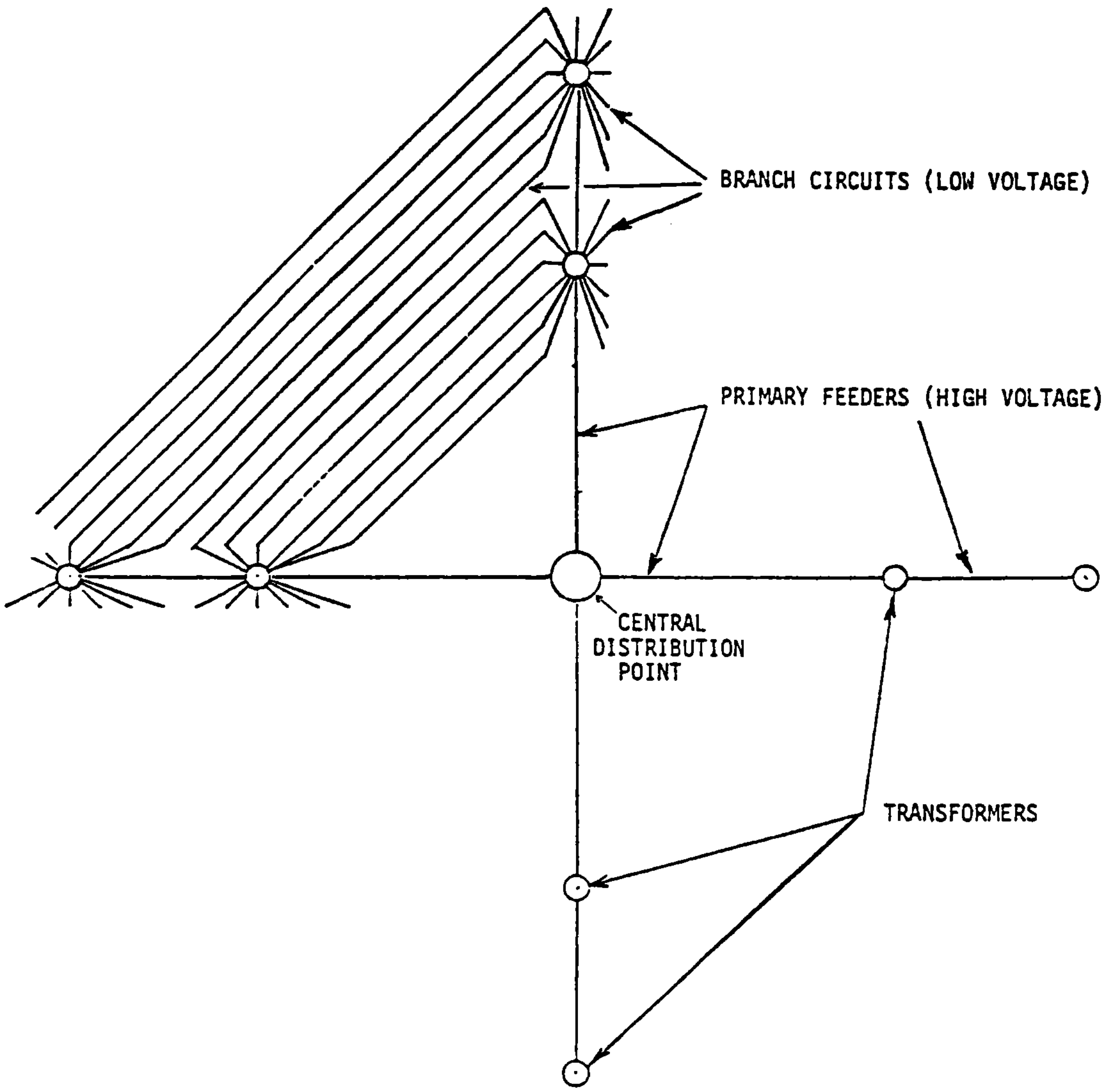


Figure 5-6. Hybrid Radial Network

controller then commands the reflected beam to move from the receiver to an aim point near the receiver. The HC maintains the beam at this aim point until the operating mode is changed by HAC.

All data links use fiberoptics. The communication link consists of an optical transmitter unit compatible in bandwidth to the heliostat array controller, a fiber optic communication line and a photodetector receiver for converting optical signals to their digital equivalents.

The unique advantages of optical transmission over electrical transmission make its use attractive in both performance and cost. Optical fiber transmission offers wider bandwidth and smaller cable cross-section than previously possible. In addition, since fiber optic cables neither pick up nor emit electron magnetic radiation and offer total electrical isolation, the problems of RFI, EMI, EMP, ground loops and sparking associated with electrical cables can be eliminated. These qualities of fiber cable allow the data transmission lines to be incorporated with existing power lines in a single cable, thus allowing for simplified routing and installation. The primary data link has, therefore, been designed coincident with the primary field wiring (Reference Figure 5.2-6). All cables are designed for direct burial to provide adequate protection at minimum cost.

Power Distribution Network

The power distribution network provides 480 V 60 Hz AC power to the heliostat drive motors. The wiring configuration is designed to incorporate the lower cost of a radial configuration and the reliability of a network system. The field (Figure 5-6) consists of a primary distribution system originating from a central distribution point, each feeder of which provides power for two or three transformers collocated with the data distribution interfaces (DDI). The transformers are 225 KVA with a primary of 4160 volts and secondary of 480 V. Each transformer will supply power to 12 to 16 groups by a number of branch circuits, each of which feeds approximately 24 heliostats.

The continuous run from transformer to transformer permits the small gauge, low voltage branch circuit to operate as a secondary main in the case of a

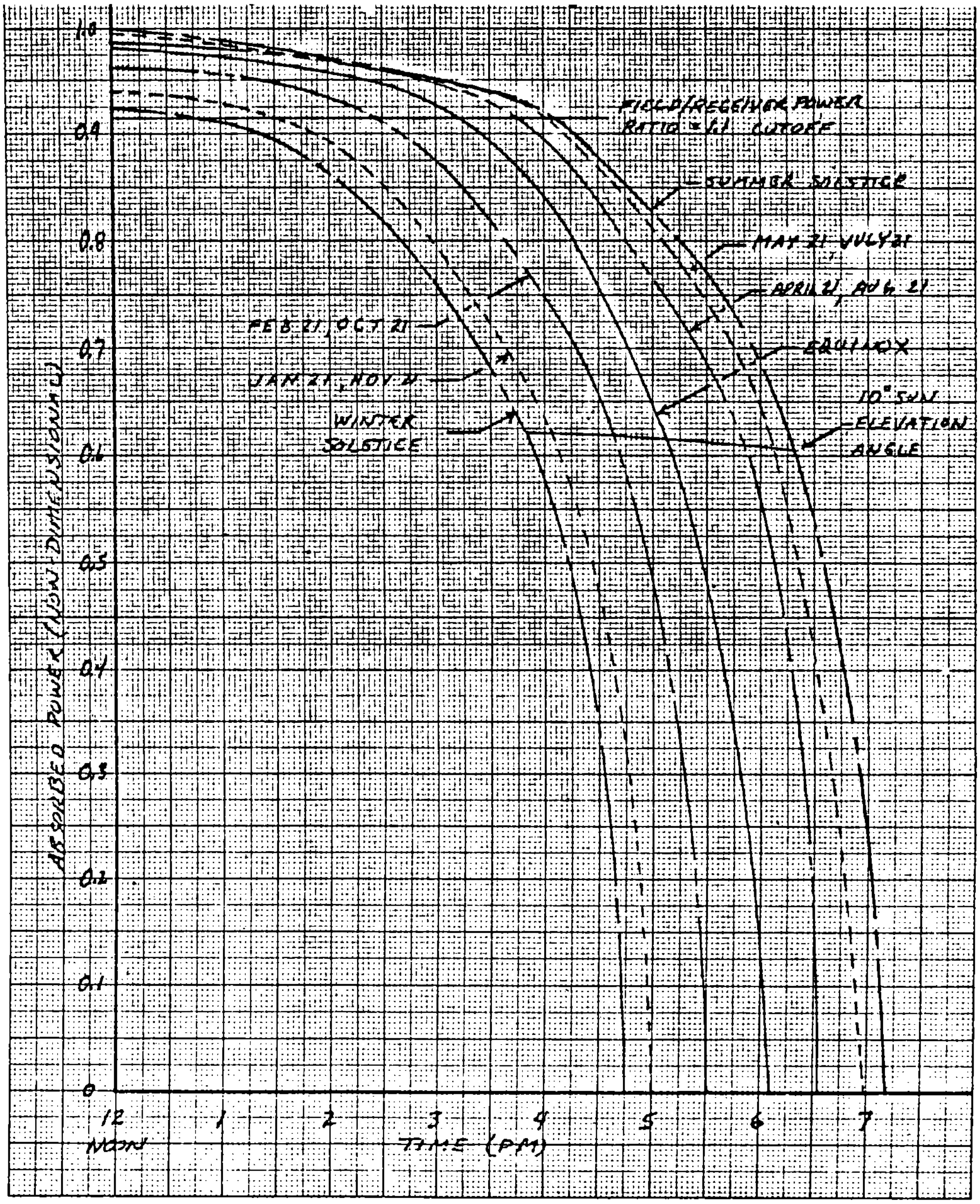


Figure 5-7. Hybrid Power System Clear Day Collection Characteristics (950 W/m^2 Insolation)

transformer failure. This hybrid radial system is not totally redundant since the heliostats normally supplied by a transformer which has failed are not supplied sufficiently for normal operation, but are able to drive into a stowage position or carry out emergency maneuvers which increase the operating safety of the field.

5.2.3 Collector Subsystem Performance

Collector subsystems have been defined for two reference 100 MWe systems (one operates at a solar multiple of 0.8 and the other at 1.4) and the preferred commercial system (PCS). 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 which satisfies system power requirements. Normalized diurnal solar system performance is shown on Figure 5-7 and is representative of both 100 MWE reference systems. Figure 5-8 gives the performance of the PCS.

100 MWe Solar Multiple 0.8 Field

The baseline collector field (including the tower and receiver geometric characteristics) for the solar multiple 0.8 field was arrived at as a result of a well established optimization procedure subject to constraints on the total receiver power (208 MWt net on equinox noon at 950 W/m^2) and the peak incident heat flux (<1.5 MW/m^2). The system was further constrained to operate at a field/receiver power ratio of 1.1.

The collector field is defined on the basis of a cell-by-cell analysis with each computational cell being a square 134.2 x 134.2 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 5-9, along with the major characteristics of the system.

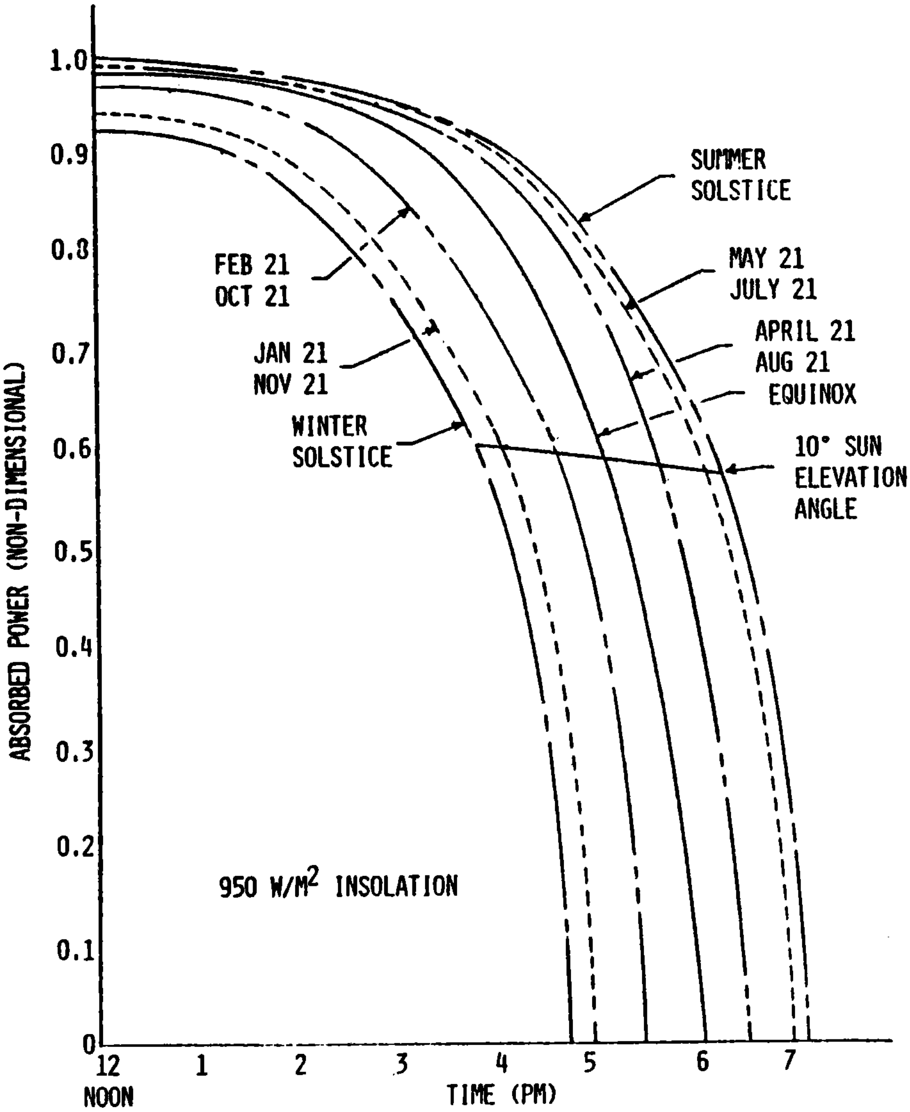
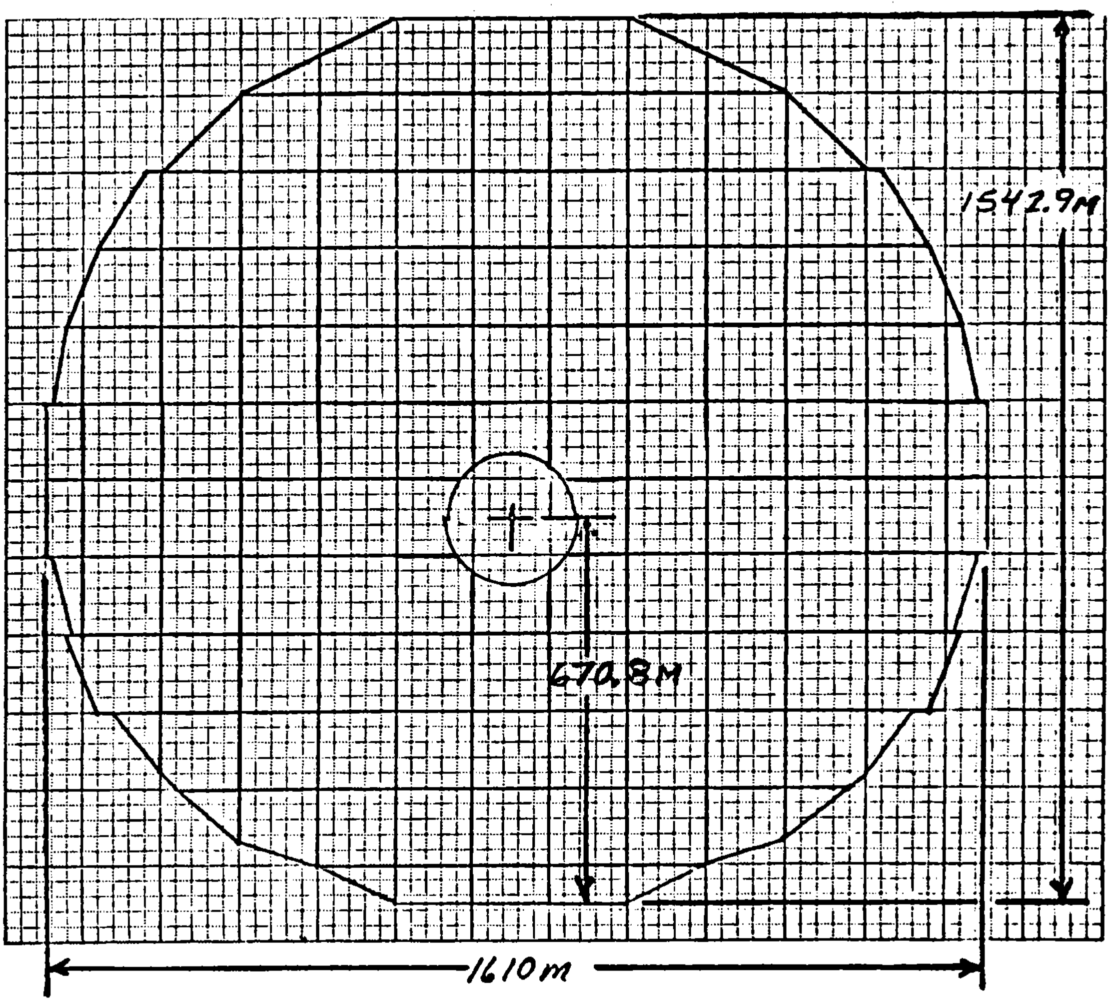


Figure 5-8. Clear Day Performance — Preferred Commercial System



Cosine modified to reduce receiver north/south flux ratio

Field sized for field/receiver power ratio = 1.1

Number of heliostats - 8,496

Glass area = 416,729 m^2

Land area - 2,003,504 m^2

Annual energy (FRPR = 1.1) = 540,289 MWt-h

Tower height = 120 m

Receiver size - 13.5 m (L) x 10.4 m (D)

Figure 5-9. Solar Multiple = 0.8 Field Layout

			10	31	46	46	46	31	10			
		22	48	52	56	57	56	52	48	22		
	22	50	57	64	69	72	69	64	57	50	22	
	48	57	67	80	90	95	90	80	67	57	48	
11	52	64	80	100	121	131	121	100	80	64	52	11
22	56	69	90	121	153	137	153	121	90	69	56	22
23	57	72	95	131	117		117	131	95	72	57	23
11	56	69	90	121	153	136	153	121	90	69	56	11
	52	64	80	100	121	131	121	100	80	64	52	
	12	50	67	80	90	95	90	80	67	50	12	
		12	42	67	69	72	69	64	42	12		
				13	28	28	28	13				

Figure 5-10. Number of Heliostats per Cell
Solar Multiple = 0.8 Field
100 MWe

The actual number of heliostats contained in each of the cells is shown in Figure 5-10. The location of the tower is in the crosshatched cell. Cells to the top of the table represent cells located to the north of the tower.

The heliostat spacing information for each cell is contained in a nondimensional form in Figures 5-11 and 5-12. Figure 5-11 shows the radial spacing data along a line which is normal to the ray extending from the tower. For clarity, Figure 5-13 shows how these data are applied to cells immediately northeast and southeast of the tower. Each of these figures represents the eastern half of the field with the tower located along the left edge of the table. Because of east-west symmetry, the mirror image of this data holds for the west side of the collector field. A constant (7.39773 m) should be multiplied times each of the tabular values to arrive at the appropriate dimensional spacing. This value corresponds to a characteristic heliostat dimension.

The fraction of ground covered or heliostat packing density is shown in Figure 5-14 on a per cell basis. The mirror weighted field average (defined as $\sum_{1}^{n} H_n P_n$/Total number of heliostats, where H is the number of heliostats in a cell and P is the packing density of the cell for each of n cells) is as noted 0.208.

The interception factor throughout the field is shown in Figure 5-15. The field average is 0.954.

Diurnal values are shown for each month starting with summer solstice over the PM half of the day for cosine, shadowing and blocking and overall solar system efficiency including receiver thermal losses in Figures 5-16 through 5-19. The values are shown at six equal time increments starting with noon and ending at the solar time at which the 10° acquisition cutoff is reached. Time weighted averages are shown on each figure and are used in determining annual average performance. The system efficiency is calculated at the reference insolation of 950 W/m^2 at all times. Figure 5-18 shows the efficiency constrained by the 1.1 field receiver power ratio. Since the insolation is assumed constant and the field is controlled to a constant thermal output of 208 MWt or below, the efficiency is constant over a portion of each day shown. Figure 5-19 shows the unconstrained efficiencies.

Solar Multiple = 0.8 Field
100 MWe

$$\frac{\text{SPACING(M)}}{7.39773\text{M}} = \text{TABLE VALUE}$$

Field Symmetrical About
North-South Line

N

6.631	6.723	6.993	7.496			
5.526	5.635	5.950	6.443	7.151		
4.489	4.621	5.000	5.581	6.250	7.151	
3.475	3.642	4.068	4.751	5.581	6.507	
2.474	2.706	3.302	4.108	5.000	6.067	7.201
2.046	2.090	2.679	3.642	4.666	5.746	6.923
	2.110	2.474	3.509	4.577	5.690	6.828
2.191	2.312	2.785	3.713	4.712	5.802	6.989
2.572	2.812	3.366	4.188	5.147	6.185	
3.475	3.678	4.188	4.937	5.800	6.762	
4.577	4.712	5.147	5.800	6.621		
5.854	5.969	6.303				

S

Figure 5-11. Non-Dimensional Heliostat Radial Spacing by Cell

Solar Multiple = 0.8 Field
100 MWe

$$\frac{\text{SPACING(M)}}{7.39773\text{M}} = \text{TABLE VALUE}$$

Field Symmetrical About
North-South Line

N

2.016	2.012	2.018	2.038			
2.004	1.996	1.997	2.006	2.024		
1.993	1.983	1.990	1.994	2.015	2.039	
1.990	1.980	1.995	1.999	2.010	2.028	
2.004	1.997	1.996	2.003	2.012	2.017	2.041
2.070	2.026	2.028	2.012	2.004	2.013	2.037
	2.005	2.015	2.003	2.004	2.018	2.049
1.917	1.768	1.951	1.987	2.011	2.032	2.072
1.893	1.917	2.001	2.030	2.043	2.066	
2.129	2.064	2.058	2.063	2.099	2.139	
2.212	2.159	2.144	2.139	2.176		
2.298	2.244	2.256				

S

Figure 5-12. Non-Dimensional Heliostat Azimuthal Spacing by Cell

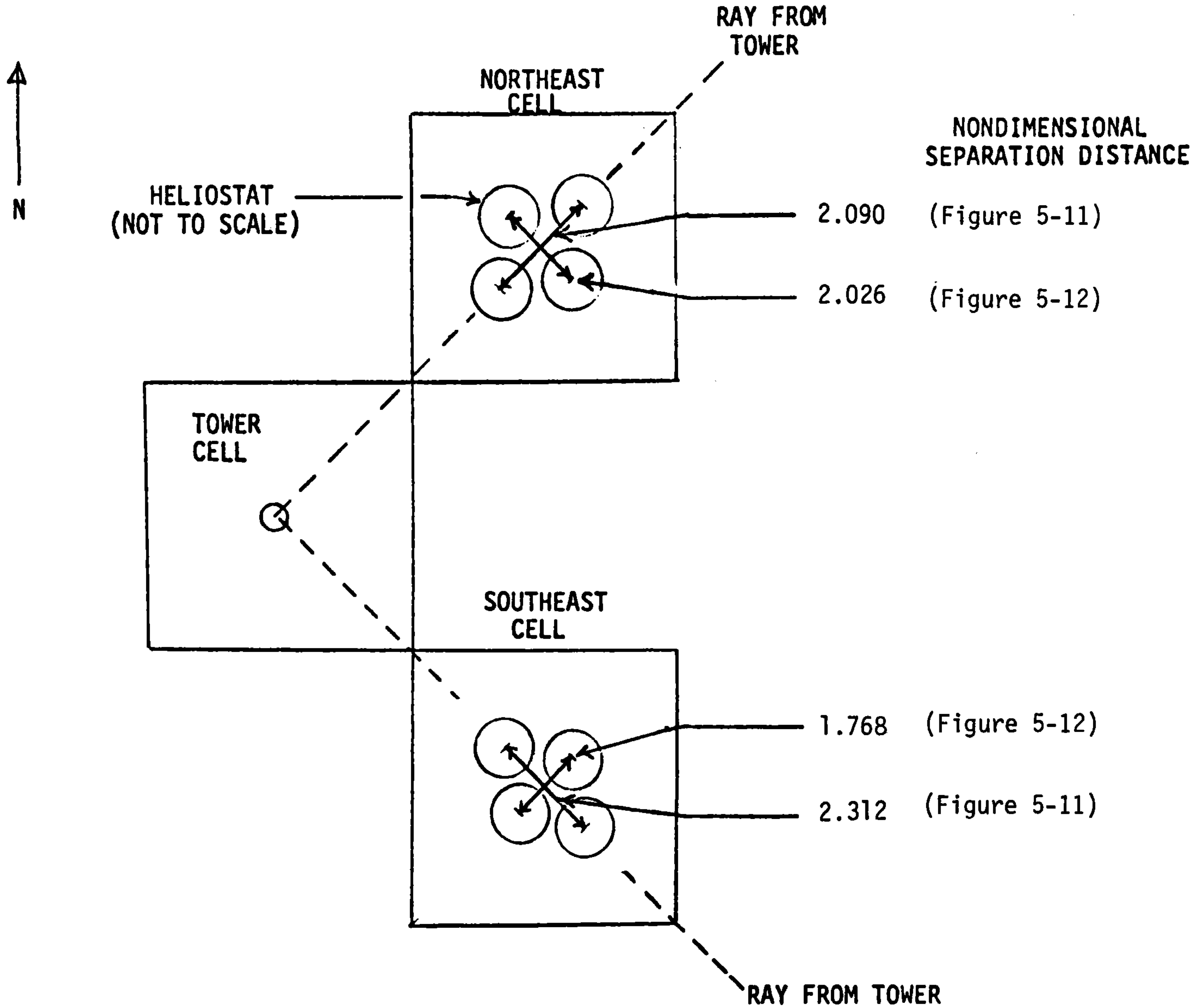


Figure 5-13. Utilization of Heliostat Spacing Data from Cell-by-Cell

100 MWe
SOLAR MULTIPLE = 0.8 FIELD

			0.113	0.120	0.126	0.127	0.126	0.120	0.113			
		0.119	0.131	0.143	0.152	0.155	0.152	0.143	0.131	0.119		
	0.119	0.136	0.155	0.174	0.189	0.195	0.189	0.174	0.155	0.136	0.119	
	0.131	0.155	0.184	0.217	0.246	0.258	0.246	0.217	0.184	0.155	0.131	
0.120	0.143	0.174	0.217	0.273	0.330	0.356	0.330	0.273	0.217	0.174	0.143	0.120
0.126	0.152	0.189	0.246	0.330	0.417	0.425	0.417	0.330	0.246	0.189	0.152	0.126
0.127	0.155	0.195	0.258	0.356	0.425	0.	0.425	0.356	0.258	0.195	0.155	0.127
0.126	0.152	0.189	0.246	0.330	0.417	0.425	0.417	0.330	0.246	0.189	0.152	0.126
	0.143	0.174	0.217	0.273	0.330	0.356	0.330	0.273	0.217	0.174	0.143	
	0.131	0.155	0.184	0.217	0.246	0.258	0.246	0.217	0.184	0.155	0.131	
		0.136	0.155	0.174	0.189	0.195	0.189	0.174	0.155	0.136		
				0.143	0.152	0.155	0.152	0.143				

MIRROR WEIGHTED FIELD AVERAGE = 0.208

Figure 5-14. Fraction of Ground Covered

100 MWe

SOLAR MULTIPLE = 0.8 FIELD

			0.819	0.850	0.868	0.872	0.868	0.850	0.819			
		0.845	0.884	0.906	0.916	0.918	0.916	0.907	0.884	0.845		
	0.844	0.894	0.922	0.943	0.955	0.958	0.955	0.943	0.922	0.894	0.844	
	0.885	0.923	0.954	0.971	0.979	0.981	0.979	0.971	0.954	0.923	0.885	
0.849	0.909	0.948	0.973	0.984	0.990	0.991	0.990	0.984	0.973	0.947	0.909	0.849
0.868	0.920	0.960	0.981	0.990	0.995	0.993	0.995	0.990	0.981	0.960	0.920	0.868
0.872	0.925	0.964	0.984	0.992	0.995	0.	0.995	0.992	0.984	0.964	0.925	0.872
0.866	0.920	0.960	0.981	0.989	0.994	0.995	0.994	0.989	0.981	0.960	0.920	0.866
	0.908	0.946	0.971	0.982	0.985	0.989	0.986	0.982	0.971	0.946	0.908	
	0.880	0.924	0.948	0.963	0.967	0.964	0.967	0.963	0.948	0.924	0.880	
		0.889	0.923	0.939	0.947	0.946	0.947	0.939	0.923	0.889		
				0.901	0.913	0.914	0.913	0.901				

MIRROR WEIGHTED FIELD AVERAGE = 0.954

Figure 5-15. Interception Factors by Cell

SOLAR MULTIPLE = 0.8 FIELD

100 MWe

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	0.8029	0.7984	0.7852	0.7638	0.7356	0.7023	0.6664
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	0.8022	0.7978	0.7850	0.7642	0.7366	0.7038	0.6681
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	0.7982	0.7942	0.7824	0.7633	0.7377	0.7069	0.6728
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	0.7879	0.7845	0.7745	0.7582	0.7363	0.7095	0.6793
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	0.7726	0.7700	0.7621	0.7493	0.7319	0.7104	0.6857
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	0.7577	0.7557	0.7497	0.7399	0.7265	0.7099	0.6906
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	0.7515	0.7498	0.7446	0.7360	0.7242	0.7095	0.6924

TIME WEIGHTED ANNUAL FIELD AVERAGE = 0.7507

Figure 5-16. Annual Summary of Cosines

SOLAR MULTIPLE = 0.8 FIELD

100 MWe

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	0.9836	0.9785	0.9767	0.9837	0.9849	0.9292	0.7862
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	0.9806	0.9774	0.9771	0.9843	0.9852	0.9261	0.7816
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	0.9769	0.9761	0.9791	0.9855	0.9835	0.9205	0.7649
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	0.9797	0.9808	0.9846	0.9881	0.9756	0.9128	0.7637
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	0.9871	0.9870	0.9879	0.9819	0.9563	0.8901	0.7838
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	0.9859	0.9847	0.9789	0.9650	0.9275	0.8625	0.7663
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	0.9799	0.9780	0.9708	0.9533	0.9134	0.8519	0.7614

TIME WEIGHTED ANNUAL FIELD AVERAGE = 0.9315

Figure 5-17. Annual Summary of Shadowing and Blocking

100 MWe Solar Multiple = 0.8 Field
Insolation = 950 W/m^2

ANNUAL SUMMARY OF SYSTEM EFFICIENCIES, CONSTRAINED BY FIELD/RECEIVER POWER RATIO

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	← 0.523 → (0. to 4.18)					0.473	0.361
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	← 0.523 → (0. to 4.07)					0.472	0.360
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	← 0.523 → (0. to 3.81)					0.471	0.351
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	← 0.523 → (0. to 3.45)					0.468	0.355
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	← 0.523 → (0. to 2.30)				0.512	0.454	0.373
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	← 0.523 (0. to 2.04)				0.489	0.435	0.366
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	← 0.523 → (0. to 1.28)			0.514	0.479	0.428	0.364

TIME WEIGHTED ANNUAL AVERAGE = 0.489

Figure 5-18. Field Efficiencies

100 MWe Solar Multiple = 0.8 Field
Insolation = 950 W/m^2

ANNUAL SUMMARY OF SYSTEM EFFICIENCIES, UNCONSTRAINED BY FIELD RECEIVER POWER RATIO

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	0.589	0.583	0.572	0.559	0.537	0.473	0.361
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	0.587	0.581	0.572	0.560	0.537	0.472	0.360
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	0.581	0.578	0.571	0.559	0.537	0.471	0.351
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	0.575	0.573	0.567	0.556	0.530	0.468	0.355
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	0.567	0.564	0.559	0.544	0.512	0.454	0.373
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	0.553	0.550	0.542	0.524	0.489	0.435	0.366
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	0.544	0.541	0.532	0.514	0.479	0.428	0.364

TIME WEIGHTED ANNUAL FIELD AVERAGE = 0.522

Figure 5-19. Field Efficiencies

Figure 5-20 is a waterfall or stairstep representation of the solar system efficiency at summer and winter noon and for the annual average. These efficiencies are based on clear day performance.

A receiver flux contour map for the solar multiple 0.8 field at equinox noon is shown in Figure 5-21. The receiver is shown unfolded with the north panel in the middle and the south panel at the right and lefthand sides. The contours are in ten percent increments ranging from 10 percent (1) to 90 percent (9) of the difference between minimum and maximum flux. The effect of the two point aim strategy is apparent when comparing the top to bottom spread of the 90 percent (9) contour line to the dotted line representing a typical 90 percent contour for a single point aim system.

Solar Multiple 1.4 Field

Corresponding field characteristics and performance data similar in format to the 0.8 solar multiple field has been generated for the solar multiple 1.4 100 MWe reference system. This system is optimized to produce 304 MWt on equinox noon at 950 W/m^2 insolationand is also constrained to a peak incident heat flux of less than 1.5 MW/m^2. Since this system utilizes three hours of thermal storage and therefore operates at a solar multiple of >1.0, the concept of field/receiver power ratio is not applicable and is in fact constrained to 1.0.

As was the case with the SM 0.8 field, this field was defined on a cell by cell analysis. However, in this case the cells are 167.7 m x 167.7 m. The cell size is defined by the relationship:

Cell area (m^2) = 5/4 the tower height (m) squared
(where tower height is the optical height)

Figure 5-22 shows the field layout for the solar multiple 1.4 field along with pertinent size nad performance data. As with the SM 0.8 field, the cosine trim factor was modified to reduce the receiver north/south flux ratio, as discussed in Section 3.2.2.

Solar Multiple = 0.8 Field

100 MWe

950 W/m^2 Insolation

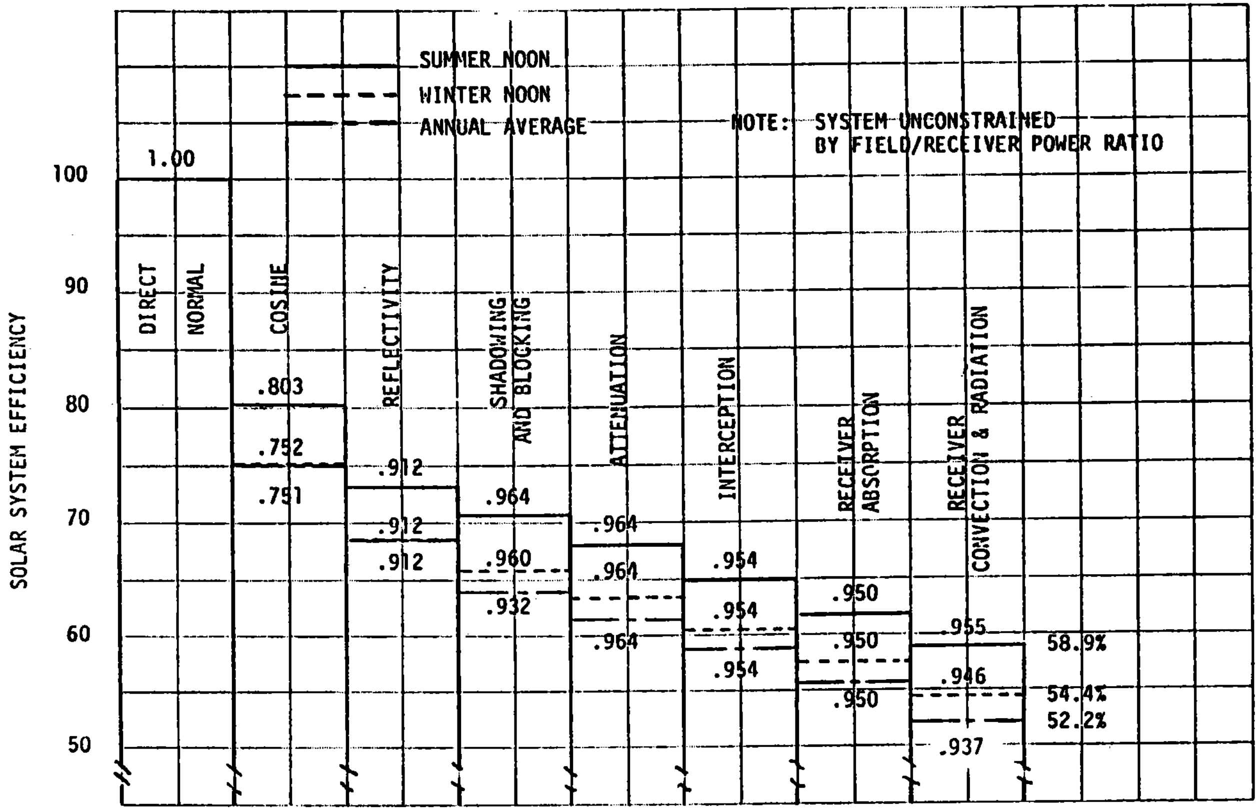


Figure 5-20. Solar System Efficiency

100 MWe Solar Multiple = 0.8 Field

Two Point Aim

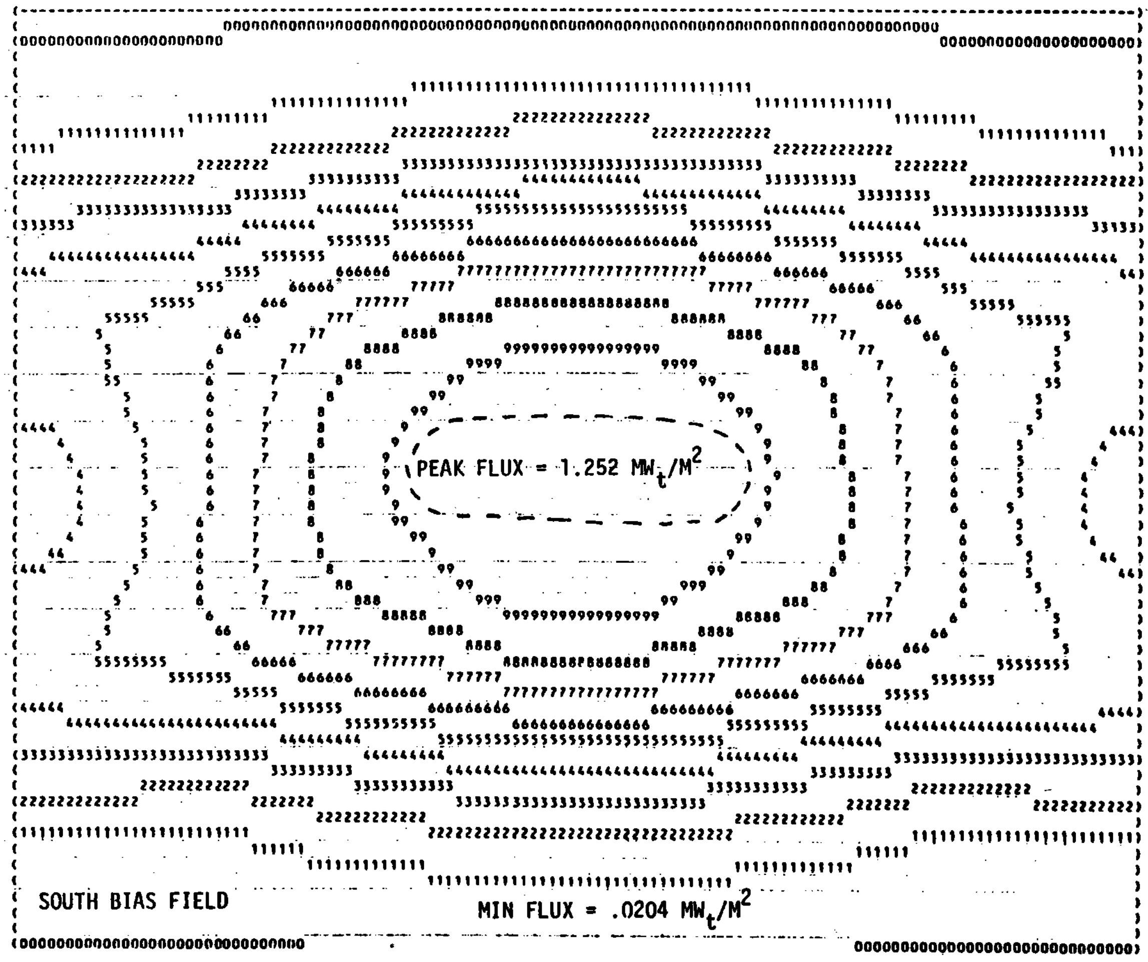
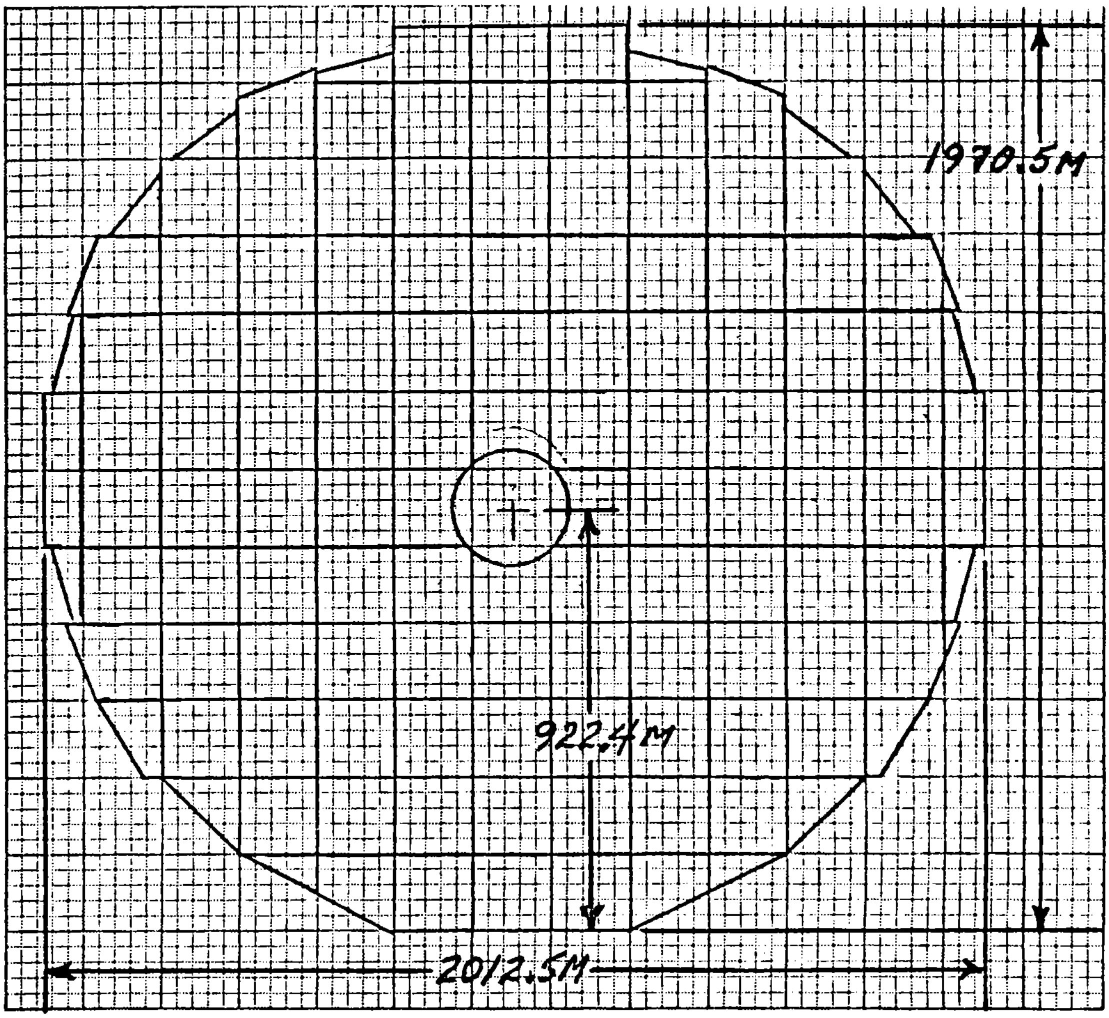


Figure 5-21. Receiver Flux Map



Cosine Modified to Reduce Receiver North/South Flux Ratio

Number of Heliostats = 13,251

Glass Area = 663,205 m^2

Land Area = 3,113,639 m^2

Annual Energy = 898,328 MWt-h

Tower Height = 150 m

Receiver Size = 15.3 m (L) x 13.0 m (D)

Figure 5-22. Solar Multiple = 1.4 Field Layout (100 MWe)

The number of heliostats and their spacing within each cell are shown in Figures 5-23 through 5-25. Figures 5-26 and 5-27 give the packing density and interception data by cell. Diurnal variation, in the same format as that for the 0.8 solar multiple field, is given for cosine, shadowing and blocking, and field efficiency factors in Figures 5-28 through 5-30.

Figure 5-31 shows a system efficiency waterfall chart for the 1.4 solar multiple field for the same operating periods as shown for the solar multiple 0.8 system. The overall efficiency is slightly higher at each operating period of this larger system.

The equinox noon receiver flux contour map for this system is shown in Figure 5-32. The calculated peak flux slightly exceeds the design constraint of 1.5 MW/m^2; however, it is felt that with slightly wider spreading of the aim points, this value could be reduced to below 1.5 MW/m^2 without any appreciable loss in performance due to increased spillage.

Preferred Commercial System

Field performance and design characteristics data were generated for the preferred commercial system in the same format as that used for the 100 MWe systems. The field is optimized to produce 1600 MWt at equinox noon with 950 W/m^2 direct normal insolation.

As with the other fields, a cell by cell analysis was used to define the system. The cell size is defined in the same manner as were the previously described systems. The cell size corresponding to the 330 m (optical height) tower for this system is 369.0 m x 369.0 m. Field size and characteistic data are shown in Figure 5-33. Subsequent to the field optimizations done for the 100 MWe baseline systems, a receiver trade study showed no significant advantage to reducing the front to back (north to south) receiver power rates, therefore, this field was optimized using a more conventional time philosophy and was not biased to the south as were the previous (100 MWe) fields.

Heliostat number and location data are shown in Figures 5-34 through 5-36. The heliostat ground coverage density is shown in Figure 5-37 on a cell by

SOLAR MULTIPLE 1.4 FIELD

100 MWe

				20	56	57	56	20				
		21	75	81	86	88	86	81	75	21		
	21	77	88	99	108	112	108	99	88	77	21	
	75	88	105	124	141	148	141	124	105	88	75	
21	81	99	124	157	190	206	190	157	124	99	81	21
39	86	108	141	190	241	214	241	190	141	108	86	39
39	88	112	148	206	183		183	206	148	112	88	39
21	86	108	141	190	241	213	241	190	141	108	86	21
	81	99	124	157	190	206	190	157	124	99	81	
	40	88	105	124	141	148	141	124	105	88	40	
		42	88	99	108	112	108	99	88	42		
			22	64	86	88	86	64	22			

Figure 5-23. Number of Heliostats per Cell

Solar Multiple = 1.4 Field
100 MWe

$\frac{\text{SPACING(M)}}{7.39773\text{M}}$ = TABLE VALUE

Field Symmetrical About
North-South Line

N

6.631	6.723	7.062				
5.526	5.635	5.950	6.507	7.151		
4.489	4.621	5.000	5.526	6.312	7.221	
3.475	3.642	4.068	4.751	5.561	6.571	
2.474	2.679	3.302	4.108	5.000	6.067	7.201
2.050	2.090	2.679	3.642	4.666	5.746	6.989
	2.112	2.474	3.509	4.577	5.690	6.894
2.195	2.314	2.785	3.713	4.712	5.802	7.056
2.572	2.785	3.366	4.188	5.098	6.185	
3.442	3.642	4.188	4.890	5.800	6.826	
4.533	4.712	5.098	5.800	6.683		
5.854	5.969	6.362	7.017			

S

Figure 5-24. Non-Dimensional Heliostat Radial Spacing by Cell

Solar Multiple = 1.4 Field
100 MWe

$$\frac{\text{SPACING(M)}}{7.39773\text{M}} = \text{TABLE VALUE}$$

Field Symmetrical About North-South Line

N ↑ (North-South line along first column) ↓ S

2.024	2.022	2.027				
2.000	1.993	1.999	2.010	2.038		
1.989	1.979	1.986	1.996	2.017	2.050	
1.938	1.977	1.992	1.996	2.007	2.033	
2.003	2.012	1.994	2.000	2.009	2.020	2.056
2.067	2.026	2.026	2.010	2.001	2.013	2.047
	2.004	2.014	2.000	2.001	2.017	2.060
1.912	1.766	1.947	1.983	2.007	2.032	2.087
1.887	1.926	1.994	2.024	2.046	2.074	
2.115	2.058	2.045	2.061	2.100	2.157	
2.198	2.141	2.140	2.142	2.194		
2.296	2.250	2.274	2.300			

Figure 5-25. Non-Dimensional Heliostat Azimuthal Spacing by Cell

SOLAR MULTIPLE = 1.4 FIELD

100 MWe

				0.119	0.124	0.126	0.124	0.119				
		0.117	0.130	0.142	0.150	0.154	0.150	0.142	0.130	0.117		
	0.117	0.134	0.154	0.173	0.188	0.195	0.188	0.173	0.154	0.134	0.117	
	0.130	0.154	0.183	0.216	0.246	C.259	0.246	0.216	0.183	0.154	0.130	
0.119	0.142	C.173	0.216	0.273	0.332	C.359	0.332	0.273	0.216	0.173	0.142	C.119
0.124	0.150	0.188	0.246	0.332	0.420	0.425	0.420	0.332	0.246	0.188	0.150	0.124
0.126	0.154	C.195	0.259	0.359	0.425	C.	0.425	0.359	0.259	0.195	0.154	C.126
0.124	0.150	0.188	0.246	0.332	0.420	0.425	0.420	0.332	0.246	0.188	0.150	0.124
	0.142	0.173	0.216	0.273	0.332	0.359	0.332	0.273	0.216	0.173	0.142	
	0.130	0.154	0.183	0.216	0.246	0.259	0.246	0.216	0.183	0.154	0.130	
		0.134	0.154	0.173	0.188	C.195	0.188	0.173	0.154	0.134		
			0.130	0.142	0.150	C.154	0.15C	0.142	0.130			

MIRROR WEIGHTED FIELD AVERAGE = 0.213

Figure 5-26. Fraction of Ground Covered

SOLAR MULTIPLE = 1.4 FIELD
100 MWe

				0.840	0.861	0.868	0.861	0.840				
		0.834	0.881	0.915	0.932	0.937	0.932	0.915	0.881	0.834		
	0.834	0.895	0.938	0.961	0.972	0.975	0.972	0.961	0.938	0.895	0.834	
	0.881	0.938	0.970	0.985	0.991	0.992	0.991	0.985	0.970	0.938	0.881	
0.839	0.914	0.962	0.985	0.994	0.997	0.998	0.997	0.994	0.985	0.962	0.914	0.839
0.860	0.932	0.974	0.992	0.997	0.999	0.999	0.999	0.997	0.992	0.974	0.932	0.860
0.865	0.937	0.977	0.993	0.998	0.999	0.	0.999	0.998	0.993	0.977	0.937	0.865
0.858	0.930	0.973	0.991	0.997	0.999	1.000	0.999	0.997	0.991	0.973	0.930	0.858
	0.911	0.960	0.984	0.993	0.996	0.998	0.996	0.993	0.984	0.960	0.911	
	0.875	0.933	0.966	0.980	0.986	0.986	0.986	0.980	0.966	0.933	0.875	
		0.886	0.930	0.955	0.965	0.967	0.965	0.955	0.930	0.886		
			0.870	0.903	0.920	0.925	0.920	0.903	0.870			

MIRROR WEIGHTED FIELD AVERAGE = 0.967

Figure 5-27. Interception Factors by Cell

SOLAR MULTIPLE = 1.4 FIELD

100 MWe

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	0.8023	0.7980	0.7853	0.7650	0.7380	0.7063	0.6721
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	0.8009	0.7967	0.7844	0.7646	0.7382	0.7069	0.6730
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	0.7952	0.7914	0.7801	0.7617	0.7372	0.7078	0.6753
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	0.7826	0.7794	0.7698	0.7542	0.7331	0.7074	0.6786
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	0.7652	0.7626	0.7551	0.7427	0.7260	0.7054	0.6817
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	0.7487	0.7467	0.7410	0.7315	0.7187	0.7027	0.6841
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	0.7419	0.7402	0.7352	0.7269	0.7156	0.7014	0.6850

TIME WEIGHTED ANNUAL AVERAGE = 0.724

Figure 5-28. Annual Summary of Cosines

SOLAR MULTIPLE = 1.4 FIELD

100 MWe

HOUR =		0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY =	93	0.9835	0.9783	0.9765	0.9837	0.9842	0.9273	0.7820
HOUR =		0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY =	124	0.9805	0.9771	0.9769	0.9842	0.9844	0.9239	0.7773
HOUR =		0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY =	155	0.9767	0.9759	0.9789	0.9852	0.9827	0.9179	0.7596
HOUR =		0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY =	186	0.9795	0.9806	0.9843	0.9877	0.9745	0.9106	0.7587
HOUR =		0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY =	216	0.9868	0.9866	0.9874	0.9809	0.9548	0.8874	0.7805
HOUR =		0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY =	246	0.9851	0.9339	0.9778	0.9637	0.9257	0.8593	0.7625
HOUR =		0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY =	276	0.9790	0.9770	0.9697	0.9518	0.9112	0.8486	0.7576

TIME WEIGHTED ANNUAL AVERAGE = 0.966

Figure 5-29. Annual Summary of Shadowing and Blocking

100 MWe Solar Multiple = 1.4 Field

INSOLATION = 950 W/M^2

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	0.596	0.589	0.579	0.567	0.545	0.481	0.368
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	0.593	0.587	0.578	0.567	0.545	0.479	0.367
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	0.586	0.583	0.576	0.565	0.542	0.476	0.355
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	0.578	0.576	0.570	0.560	0.533	0.471	0.357
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	0.568	0.566	0.560	0.545	0.514	0.455	0.374
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	0.553	0.550	0.541	0.524	0.489	0.434	0.365
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	0.543	0.540	0.531	0.513	0.477	0.426	0.362

TIME WEIGHTED ANNUAL AVERAGE = 0.526

Figure 5-30. Field Efficiencies

100 MWe Solar Multiple = 1.4 Field
950 W/m² Insolation

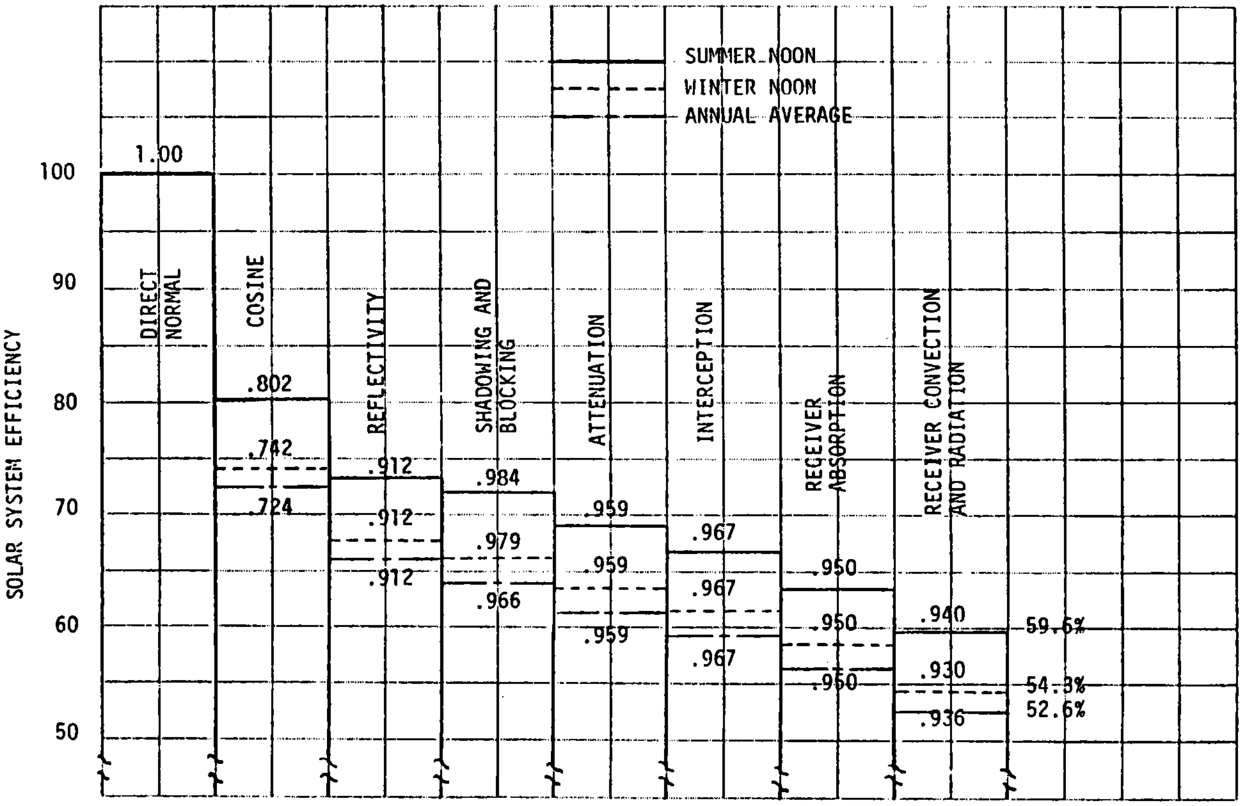


Figure 5-31. Solar System Efficiency

100 Mwe Solar Multiple = 1.4 Field

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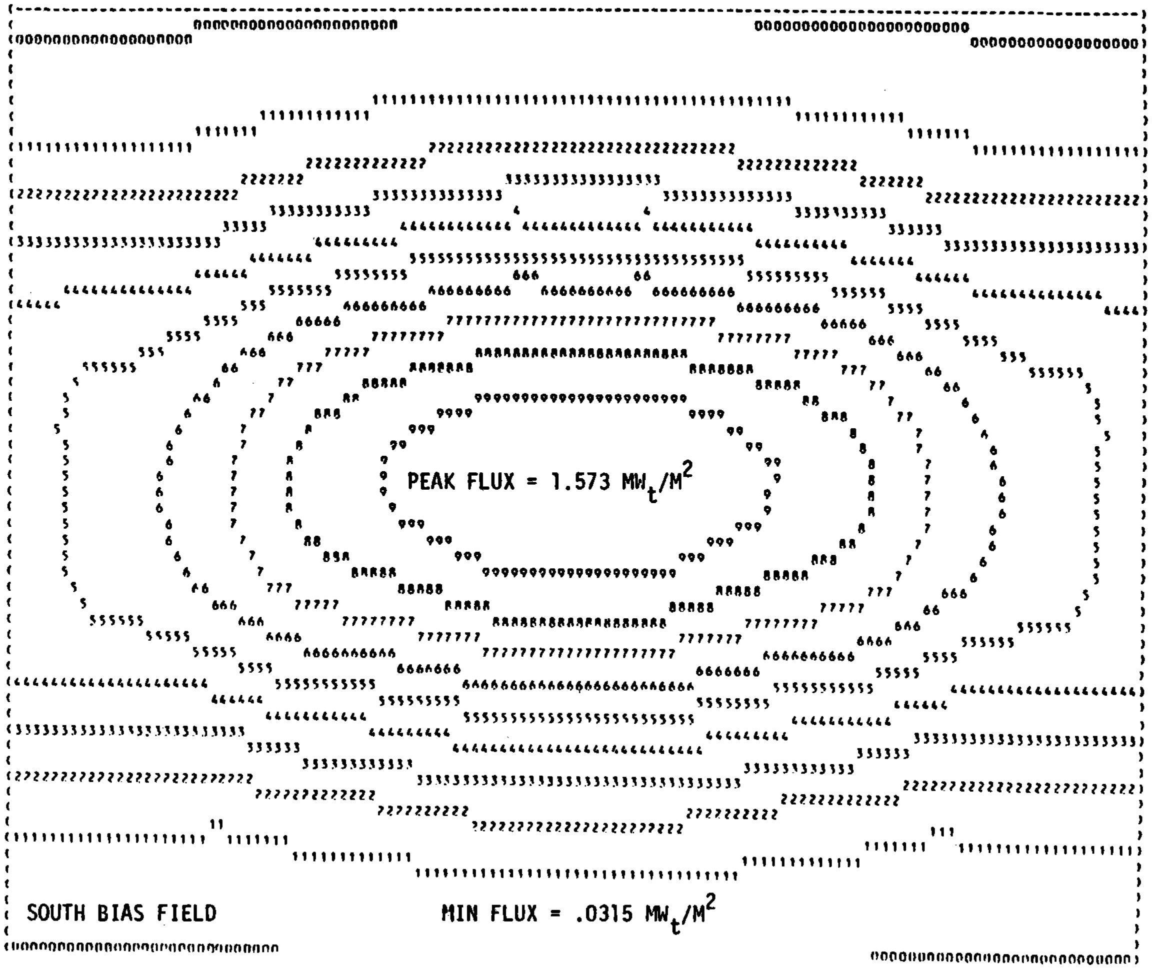

Figure 5-32. Receiver Flux Map

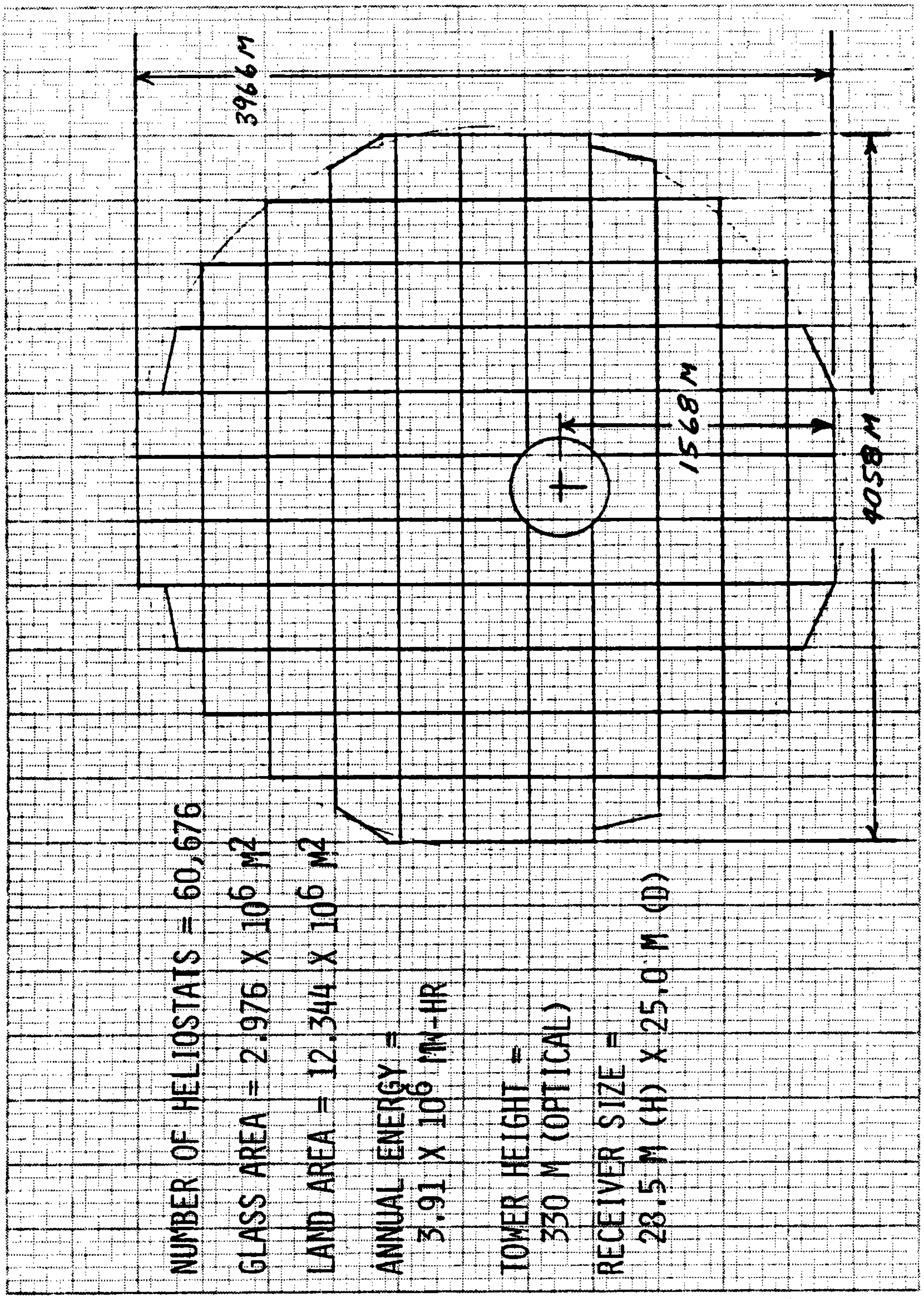

Figure 5-33. Preferred Commercial System

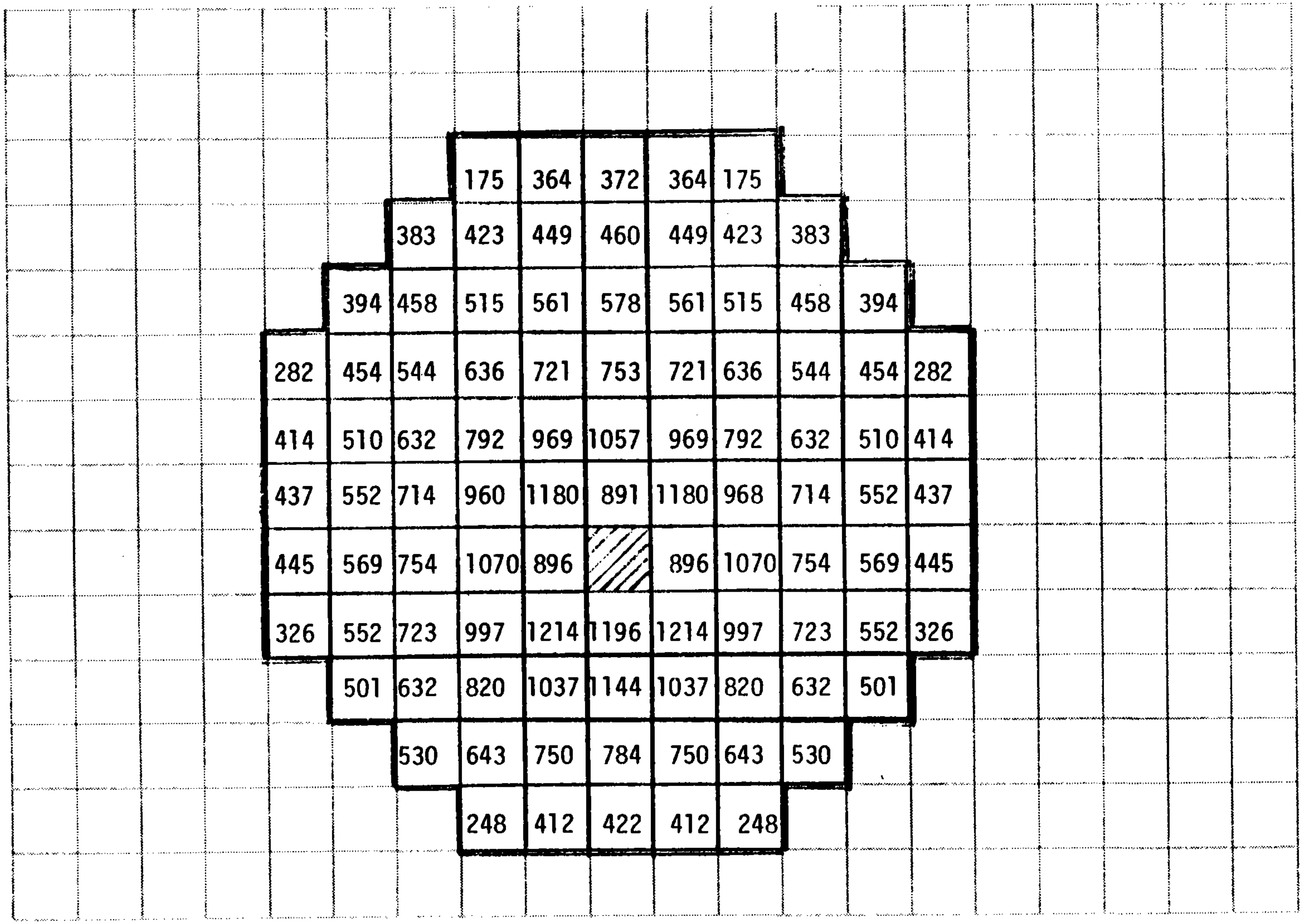

Figure 5-34. Number of Heliostats per Cell — Preferred Commercial System

$$\frac{\text{SPACING (M)}}{7.39\ 773\ \text{M}} = \text{TABLE VALUE}$$

Field Symmetrical About North-South Lane

N

6.631	6.790	7.062			
5.471	5.635	5.950	6.507		
4.400	4.576	4.951	5.526	6.312	
3.403	3.571	4.023	4.657	5.526	6.571
2.401	2.626	3.233	4.029	4.951	6.008
2.187	2.153	2.626	3.571	4.621	5.746
	1.862	2.401	3.408	4.439	5.635
1.862	2.305	2.706	3.607	4.621	5.746
2.474	2.679	3.270	4.068	5.000	
3.172	3.430	3.988	4.751		
4.268	4.435	4.951			

S

Figure 5-35. Non-Dimensional Heliostat Radial Spacing by Cell — Preferred Commercial System

$$\frac{\text{SPACING (M)}}{7.39773\ \text{M}} = \text{TABLE VALUE}$$

Field Symmetrical About North-South Line

N

2.032	2.028	2.044			
1.990	1.980	1.992	2.013		
1.965	1.942	1.963	1.980	2.016	
1.950	1.939	1.951	1.973	1.995	2.036
1.967	1.961	1.948	1.964	1.983	2.016
1.921	1.953	1.962	1.959	1.962	1.994
	2.237	1.942	1.945	1.958	1.997
2.237	1.777	1.850	1.916	1.959	2.010
1.762	1.795	1.862	1.945	1.958	
2.008	1.942	1.949	1.986		
2.087	2.035	2.049			

S

Figure 5-36. Non-Dimensional Heliostat Azimuthal Spacing by Cell — Preferred Commercial System

			0.122	0.128	0.130	0.128	0.122			
		0.134	0.147	0.156	0.160	0.156	0.147	0.134		
	0.139	0.160	0.181	0.198	0.205	0.198	0.181	0.160	0.139	
0.134	0.160	0.192	0.229	0.262	0.276	0.262	0.229	0.192	0.160	0.134
0.147	0.181	0.229	0.292	0.355	0.382	0.355	0.292	0.229	0.181	0.147
0.156	0.198	0.262	0.355	0.430	0.423	0.430	0.355	0.262	0.198	0.156
0.160	0.205	0.276	0.382	0.423	0.	0.423	0.382	0.276	0.205	0.160
0.156	0.198	0.262	0.355	0.430	0.423	0.430	0.355	0.262	0.198	0.156
	0.181	0.229	0.292	0.355	0.382	0.355	0.292	0.229	0.181	
		0.192	0.229	0.262	0.276	0.262	0.229	0.192		
			0.181	0.198	0.205	0.198	0.181			

Mirror Weighted Field Average = 0.238

Figure 5-37. Fraction of Ground Covered by Cell — Preferred Commercial System

			0.751	0.775	0.783	0.775	0.751			
		0.801	0.845	0.871	0.880	0.871	0.845	0.801		
	0.819	0.881	0.925	0.949	0.956	0.949	0.925	0.881	0.819	
0.802	0.882	0.942	0.978	0.994	0.993	0.994	0.978	0.942	0.882	0.802
0.847	0.926	0.979	1.00	1.00	1.00	1.00	1.00	0.979	0.926	0.847
0.874	0.951	0.995	1.00	1.00	1.00	1.00	1.00	0.995	0.951	0.874
0.884	0.959	0.999	1.00	1.00	0.	1.00	1.00	0.999	0.959	0.884
0.876	0.953	0.995	1.00	1.00	1.00	1.00	1.00	0.995	0.953	0.876
	0.929	0.980	1.00	1.00	1.00	1.00	1.00	0.980	0.929	
		0.946	0.990	0.995	0.999	0.995	0.990	0.946		
			0.929	0.953	0.963	0.953	0.929			

Mirror Weighted Field Average = 0.962

Figure 5-38. Interception Factors by Cell — Preferred Commercial System cell basis. Interception data by cell is shown in Figure 5-38. Figures 5-39 through 5-41 give the diurnal variation of the field for the cosine, shadowing and blocking and overall field efficiencies.

A system efficiency waterfall chart for the preferred commercial system is shown in Figure 5-42. Data are presented for summer and winter noon along with the annual average.

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	0.8124	0.8075	0.7931	0.7698	0.7399	0.7020	0.6618
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	0.8126	0.8079	0.7939	0.7712	0.7410	0.7048	0.6659
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	0.8109	0.8065	0.7937	0.7729	0.7450	0.7111	0.6732
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	0.8032	0.7996	0.7898	0.7712	0.7473	0.7180	0.6846
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	0.7903	0.7874	0.7790	0.7651	0.7462	0.7229	0.6959
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	0.7769	0.7747	0.7683	0.7577	0.7433	0.7253	0.7042
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	0.7712	0.7693	0.7637	0.7544	0.7417	0.7258	0.7072

Time Weighted Annual Average = 0.752

Figure 5-39. Annual Summary of Cosines — Preferred Commercial System

HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93	0.9718	0.9674	0.9662	0.9738	0.9690	0.9059	0.7542
HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124	0.9692	0.9661	0.9666	0.9741	0.9684	0.9028	0.7505
HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155	0.9661	0.9657	0.9684	0.9747	0.9669	0.8963	0.7303
HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186	0.9691	0.9706	0.9743	0.9748	0.9577	0.8874	0.7259
HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216	0.9757	0.9747	0.9747	0.9645	0.9361	0.8642	0.7471
HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246	0.9691	0.9682	0.9612	0.9448	0.9052	0.8347	0.7292
HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276	0.9614	0.9603	0.9518	0.9317	0.8895	0.8231	0.7250

Time Weighted Annual Average = 0.932

Figure 5-40. Annual Summary of Shadowing and Blocking — Preferred Commercial System

	HOUR =	0.	1.05	2.09	3.14	4.18	5.23	6.28
DAY = 93		0.578	0.572	0.561	0.548	0.519	0.450	0.336
	HOUR =	0.	1.02	2.04	3.06	4.07	5.09	6.11
DAY = 124		0.576	0.571	0.561	0.548	0.520	0.450	0.337
	HOUR =	0.	0.95	1.90	2.85	3.81	4.76	5.71
DAY = 155		0.572	0.569	0.561	0.549	0.521	0.450	0.327
	HOUR =	0.	0.86	1.72	2.59	3.45	4.31	5.17
DAY = 186		0.567	0.566	0.560	0.546	0.515	0.449	0.332
	HOUR =	0.	0.77	1.53	2.30	3.06	3.83	4.60
DAY = 216		0.560	0.557	0.550	0.532	0.499	0.437	0.353
	HOUR =	0.	0.68	1.36	2.04	2.71	3.39	4.07
DAY = 246		0.544	0.541	0.532	0.512	0.476	0.419	0.347
	HOUR =	0.	0.64	1.28	1.92	2.56	3.20	3.85
DAY = 276		0.534	0.531	0.521	0.501	0.465	0.412	0.345

Time Weighted Annual Average = 49.6%

Figure 5-41. Annual Summary of Field Efficiencies — Preferred Commercial System

950 W/m^2 Insolation

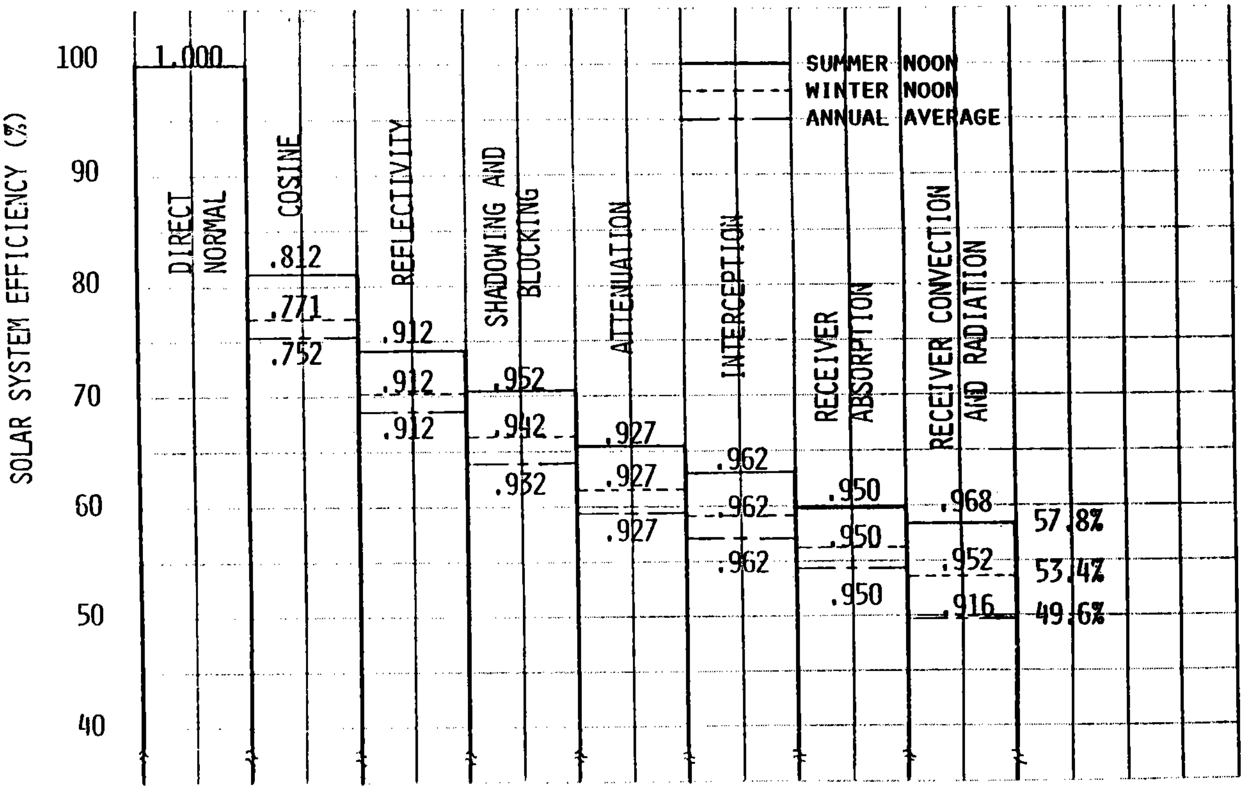

Figure 5-42. Solar System Efficiency — Preferred Commercial System

SUMMARY

The receiver subsystem functional requirements for the 0.8 SM and 1.4 SM plants are specified. System descriptions are presented. The 0.8 SM receiver subsystem operates as a closed loop system, whereas the 1.4 SM subsystem can be considered to operate as two independent loops. Receiver size selected for the 0.8 SM design is 10.4 m (34 ft) in diameter and 13.5 m (44.4 ft) in height consisting of 18 panels. The receiver for the 1.4 SM plant is 13.0 m (42.6 ft) in diameter and 15.3 m (50.2 ft) in height consisting of 24 panels. Receiver heat losses were estimated based on previous studies made for the ACR plant design. Pumps, piping and valves for the sodium receiver subsystem are specified based on past sodium operating and test experience. A beief description of each of the sodium auxiliary systems that support the main system is given.

5.3 RECEIVER SUBSYSTEM

The receiver subsystem contains the receiver, the receiver pump, the steam generator units, and the main sodium piping, including the riser and downcomer in the tower. The steam generator units are included with the receiver subsystem.

The thermal buffering subsystem for the 0.8 SM design concept includes only the added components needed to provide the necessary buffering operation at full power. Power generation can continue as long as hot sodium is produced by the sodium heater without regard for the transient conditions at the receiver due, for example, to passing cloud fronts.

For the 1.4 SM concept, the thermal storage subsystem includes the hot and cold sodium storage tanks, the stem generator sodium pump, and the associated sodium piping and drag valve.

5.3.1 Receiver Subsystem Requirements

The receiver susbystem functional requirements are given in Table 5-3. These requirements are derived from the optimized performance characteristics of the EPG, collector, and master control subsystem, which in turn satisfy the requirements of the hybrid specification of Reference 1. There are additonal operational and sodium system requirements as follows:

1) Transport up to 208 MWt to the steam generator for the 0.8 SM concept. Transport up to 364 MWt to storage or 104 MWt to storage and 260 MWt to the steam generator simultaneously, or 260 MWt from storage to the steam generator for the 1.4 SM concept.

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.

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

7) Provide for maintaining the purity of the sodium below 2.0 ppm O_2 and 1 ppm H_2.

TABLE 5-3

RECEIVER SUBSYSTEM FUNCTIONAL REQUIREMENTS

Solar Multiple	0.8 SM	1.4 SM
Parameter	Requirement	Requirement
Nominal Thermal Power (MWt)	208	364
Maximum Thermal Power (MWt)	260	364
Receiver Mid-Point Elevation, m (ft)	124 (407	
Water/Steam Side		
Feedwater Temperature, In [^{o}C (^{o}F)]	234 (483.5)	234 (483.5)
Evaporator Temperature, Out [^{o}C (^{o}F)]	341 (636)	341 (636)
Steam Temperature, Out [^{o}C (^{o}F)]	538 (1000)	538 (1000)
Reheat Temperature		
In [^{o}C (^{o}F)]	342 (586)	342 (586)
Out [^{o}C (^{o}F)]	538 (1000)	538 (1000)
Reduced Power Operation, %	20 – 100	0 – 100
Transient Operation, Power (cloud cover)		
20% to 100% or 100% to 20%, s	80	

The reference designs of the sodium heat transport system for the 0.8 SM and 1.4 SM are schematically shown in Figures 5-43 and 5-44, respectively. The quantitative values of the process variables are given in the data lists in Appendix E and F.

5.3.1.1 Receiver Subsystem for 0.8 SM

The 0.8 SM receiver subsystem operates as a closed loop system. Sodium circulation in the loop is provided by means of the receiver pump, P-1. Sodium is circulated at 288^{o}C (550^{o}F) from the pump up to the inlet line to the cold buffer tanks (T-1) at the top of the receiver tower; then, through the receiver, where the sodium temperature is raised to 593^{o}C (1100^{o}F), to the hot buffer tanks (T-2); from the hot buffer tanks (T-2) the sodium flow is split and is circulated through the superheater (X-2) and reheater (X-3) which are piped in parallel, and then the stream is combined and passes through the evaporator (X-1) and back to the receiver pump (P-1) suction, thus closing the loop.

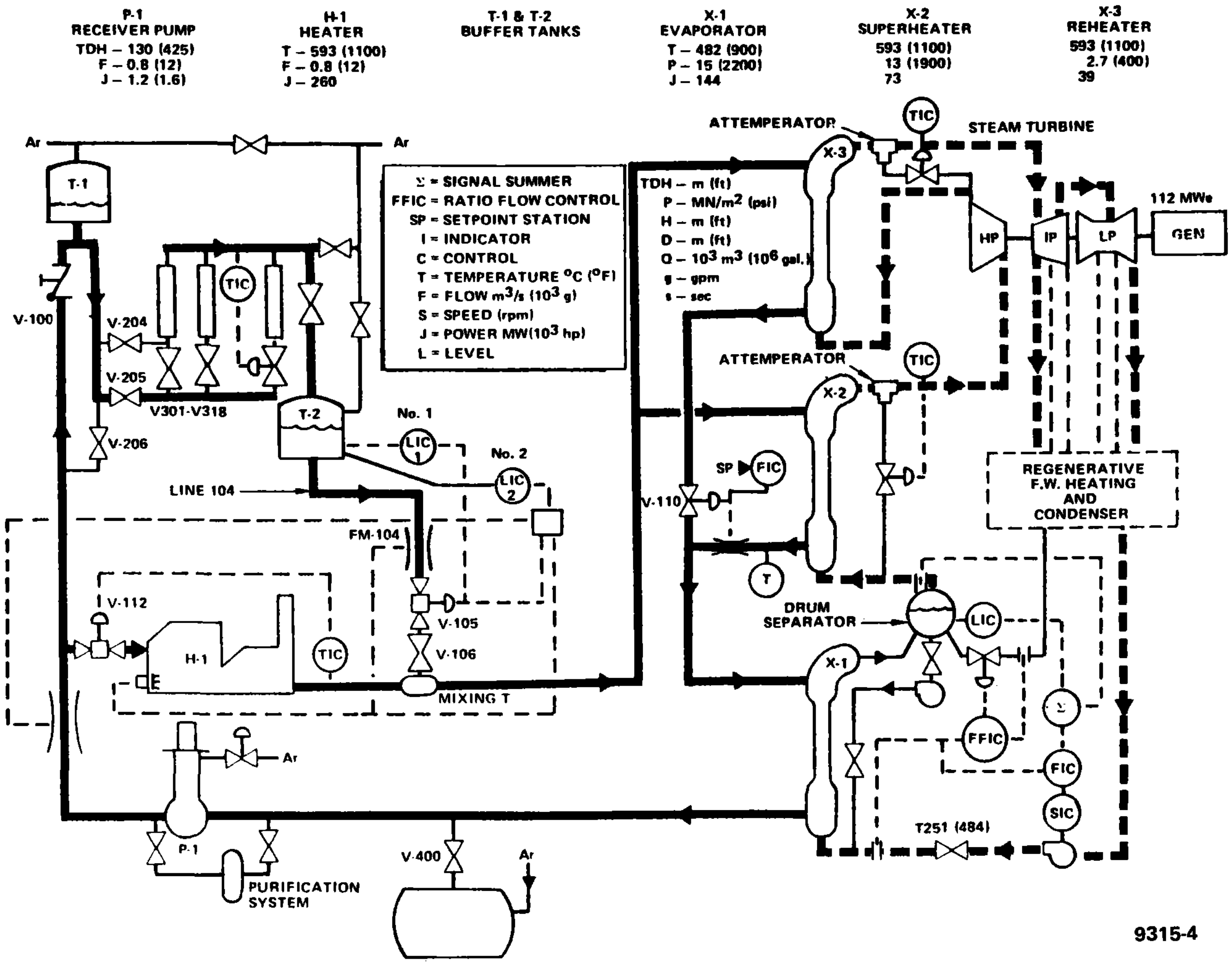

Figure 5-43. Solar (100 MWe 0.8 SM) Central Receiver Hybrid Power System

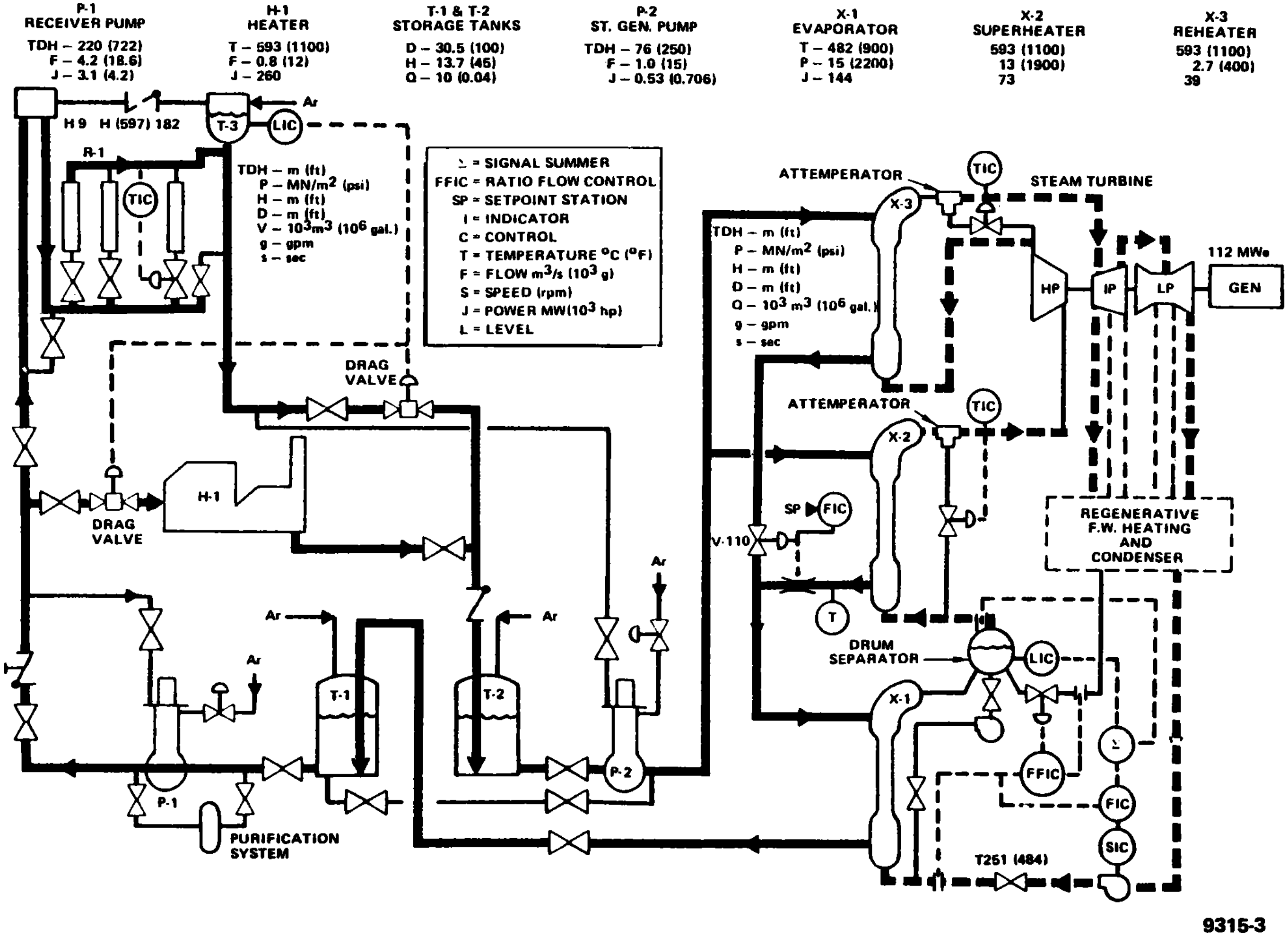

Figure 5-44. Solar (100 MWe 1.4 SM) Central Receiver Hybrid Power System

The cold buffer tanks are pressurized with argon gas to ~0.24 Pg (35 psig), and the hot buffer tanks are maintained at approximately atmospheric pressure under a blanket of argon gas. The plant is designed to operate with a solar multiple of 0.8. When the solar receiver is furnishing 208 MWt (80%) of heat to the steam generator, the non-solar subsystem provides the remaining 52 MWt (20%) of the heat required by the steam generator to develop a net electrical plant output of 100 MWe.

Sodium flow through the receiver is modulated by the control valves on each panel to maintain the panel outlet temperature constant.

The check valve and the cold tanks operate to prevent the draining of the sodium from the receiver on loss of pump power.

5.3.1.2 Receiver Subsystem for 1.4 SM

The 1.4 SM receiver subsystem can be considered to operate as two independent loops. The first loop transfers sodium from the cold storage tank, T-1, at 288°C (550°F) through the receiver, which heats it to 593°C (1100°F). The sodium then flows by gravity through the drag valve to the hot storage tank, T-2. Nominal maximum flow rates are about 1.1 m^3/s (17,000) gpm. The second loop transports sodium from the hot storage tank through the sodium-heated superheater and re-heater, through the evaporator, and then to the cold storage tank, T-1. The maximum nominal flow is about 0.8 m^3/s (12,000) 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 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 [$\sim$220 m (722 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 Section 3.3.9.

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 Section 5.4.

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 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.

TABLE 5-4

OPERATIONS PRE-STARTUP

- Check Out Instrumentation
- Preheat Sodium Systems to 150°C (300°F)
- Purge with Argon
- Heat Tank Car
- Fill Drain Tank 12 Cars--12 Days*

*An alternate procedure is to fill 25% in 25 days, start limited operations and complete filling as required.

TABLE 5-5

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 Control Valve Part Way	
. Circulate Sodium - Bypass Steam Generator - 174°C (350°F)	
. Fill Dry Steam Generator with Na and Circulate	0900
. Close Receiver Bypass and Fill Receiver and Cold Tanks	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

Operations

Tentative operating sequence outlines, based on test experience with sodium systems, are presented in Tables 5-4 through 5-8. Outlines are as follows: (1) Table 5-4, Prestartup, gives the basic steps required for preparing the system to receive sodium; (2) Table 5-5, Initial Startup, gives the steps required for bringing the sodium systems up to cold leg temperature for the first time; (3) Table 5-6 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 proceeding to full power. Subsequent cold startups should be possible in 4 h or less, depending on the starting temperature (never <149°C (300°F); (4) Table 5-7, Shutdown, gives the steps needed to secure the plant for an expeditious startup the following day; and (5) Table 5-8, provides the hot startup sequence for full power operation by 0815 midwinter. The steam generator cooldown characteristics are given in Figure 5-45. The startup and operating steps for the operation of the steam system is given in Section 3.6.4.

5.3.2 Receiver Design

The receiver type selected for the hybrid plant is an external configuration. Previous studies made for the ACR plant, comparing cavity with external receivers, showed that the latter lead to lower capital costs and cost of power. The maximum absorbed thermal power is 208 MWt for the 0.8 SM and 364 MWt for the 1.4 SM plant.

For the 0.8 SM conceptual design, the receiver is cylindrical in shape, 10.4 m (34 ft) in diameter and 13.5 m (44.4 ft) in height with an external energy-absorbing surface consisting of 18 panels. Each panel has 96 stainless steel 1.9 cm (0.75-in.) OD tubes connected to a common manifold. With a single-point aim strategy, peak receiver heat flux is limited to 1.5 MW/m^2 to achieve a tube life of not <10,000 cycles. The receiver is shown in Figure 5-46.

For the 1.4 SM, the receiver is 16.0 m (53 ft) in diameter and 16.0 m (53 ft) in height consisting of 24 panels.

The design lifetime of the receiver is 30 years although it is anticipated that panels may be replaced from time to time. The average maximum temperature reached by the receiver panels is estimated to be 608°C (1125°F).

TABLE 5-6

OPERATIONS STARTUP - SECOND DAY

	Clock Time
. Heat Feedwater on Bypass Flow	0500
. Pressurize Evaporator to ~6.89 MN/m^2 (1000 psi)	
. Admit Water to Evaporator 260°C (500°F)	0600
. Start Na Flow	0600
. Flash Steam to S.H. and R.H. - Condenser	0615
. Balance Water, Steam, and Na Temperature	0630
. Stepwise Raise and Spread at Log Mean ΔT	
. Roll Turbine (Min. - 40% Press. - 100°F.S.H.)	0715
. Sunrise - Power to Grid	0730
. Stepwise Increase Steam Temperature and Flow	
. Level at 1/2 Power	0815

TABLE 5-7

OPERATIONS SHUTDOWN - SECOND DAY

	Clock Time
. Reduce Load to 20%	1630
. Collapse the Log Mean ΔT	
. Trip Turbine - Dump to Condenser	1730
. Bypass Evaporator - Na and H_2O - Evaporator Dry	
. Isolate - Full Na - NO H_2O	1800

TABLE 5-8

OPERATION STARTUP — THIRD DAY

	Clock Time
. Heat Feedwater on Bypass Flow	0500
. Pressurize Evaporator to ~6.89 MN/m^2 (1000 psi)	
. Admit Water to Evaporator 260°C (500°F)	0600
. Start Na Flow from Bypass Line	0600
. Flash Steam through S.H. and R.H. to Condenser	0615
. Balance Water Steam and Na 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

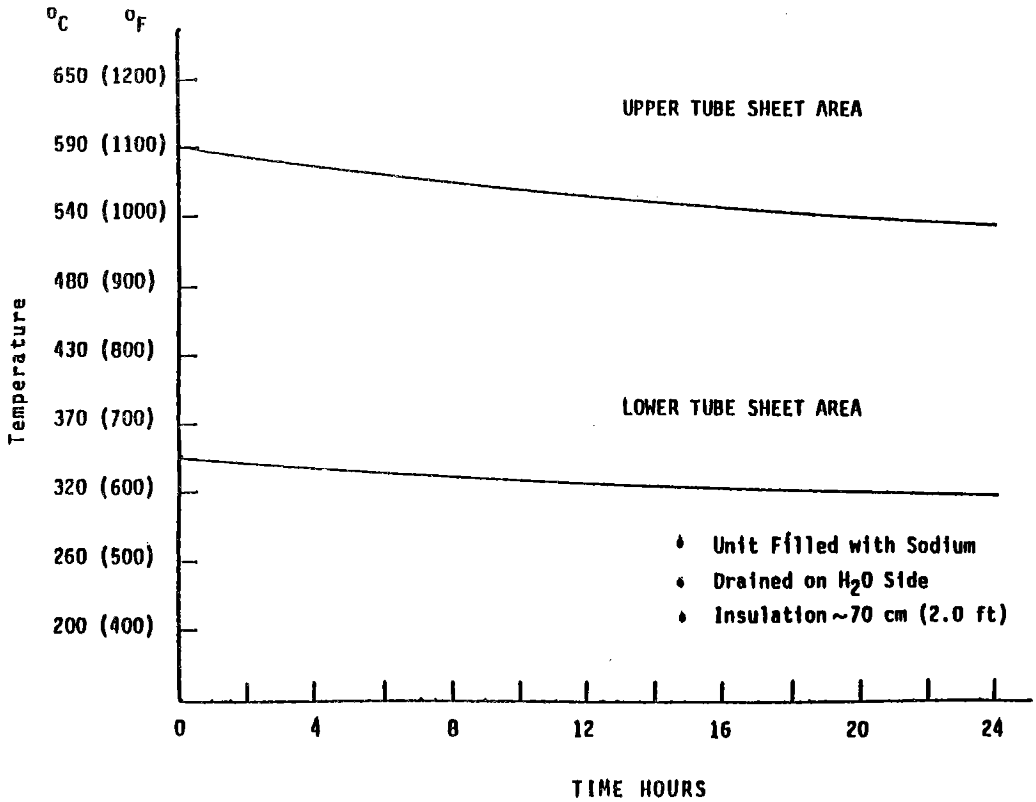

Figure 5-45. Superheater Cooldown

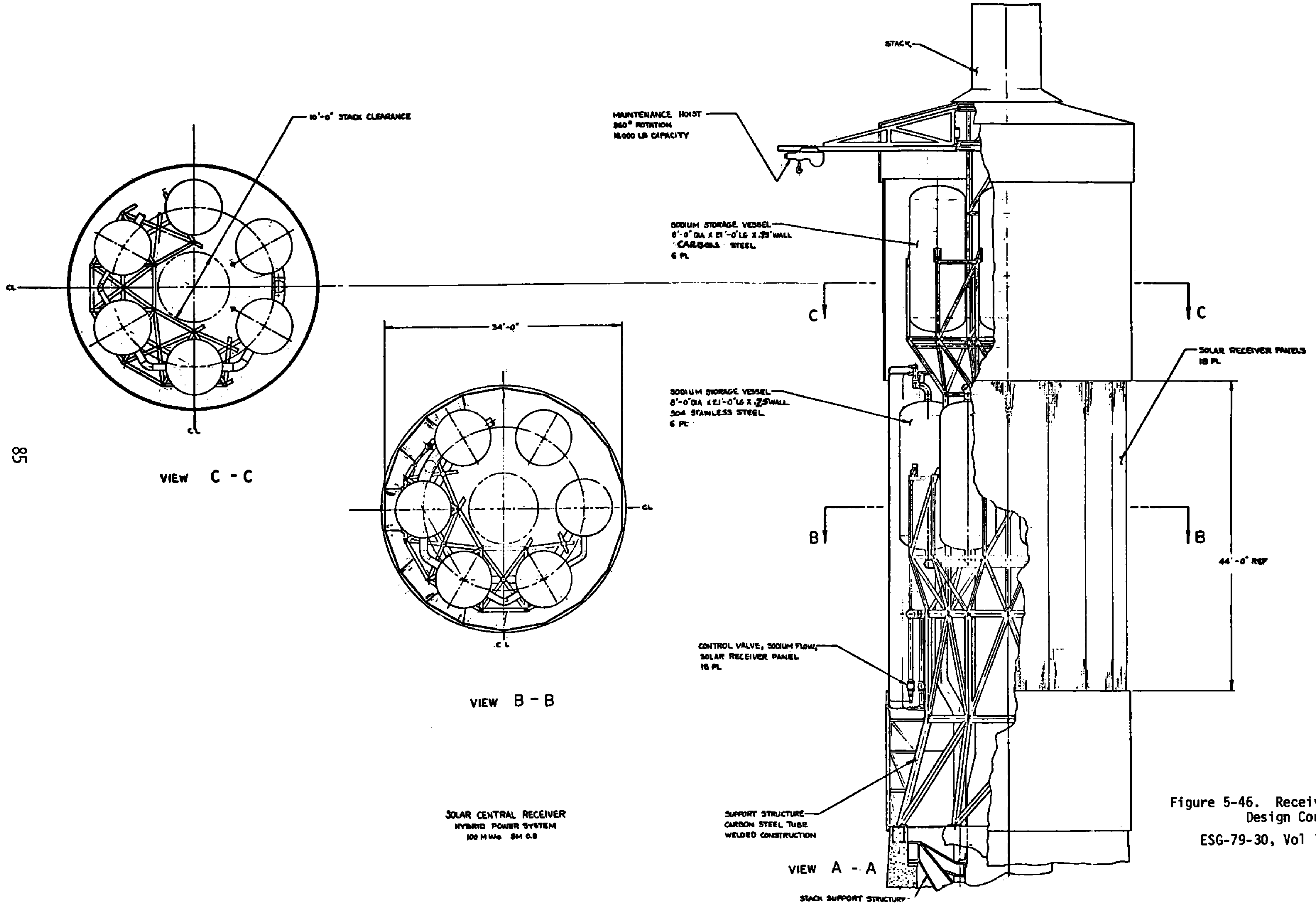

Figure 5-46. Receiver Conceptual Design Concept

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The plant will be in Seismic Zone 3. Both horizontal and vertical accelerations will be about 0.25 g. The nominal design wind at the receiver is 5.4 m/s (12.0 mph) while the maximum operating wind is 22 m/s (50 mph).

The receiver will be exposed to ambient temperatures in the range of -30^{o}C (-22^{o}F) to +50^{o}C (122^{o}F). The plan is to drain the receiver each night to prevnet sodium freeze-up which occurs at 98^{o}C (208^{o}F).

5.3.2.1 Receiver for 0.8 SM Plant

The conceptual receiver design for the 0.8 SM plant, shown in Figure 5-46, consists of the following items:

1) Structural steel interface structure
2) Coolant riser and distribution manifold
3) Cold Buffer tanks
4) Solar panel inlet piping and coolant flow control valves
5) Solar panels with inlet and outlet manifold and panel backup structure
6) Solar panel outlet piping and downcomer
7) Hot buffer tanks
8) Cover gas and vent lines
9) Heaters, insulation, and instrumentation (temperature and pressure)
10) Miscellaneous equipment and facilities (lights, power, hoists, catwalks, passive shields, lightning protection, water, first aid, etc.)

The sodium riser is 51-cm (20-in.) pipe. The riser connects to a 36-cm (14-in.) pipe tee which connects two 36-cm (14-in.) pipe branch connections to a 20-cm (8-in.) ring header. The 20-cm (8-in.) ring header is connected to the inlet nozzles of the six cold buffering tanks. A similar piping arrangement is used to connect the cold buffering tanks to the receiver, the receiver to the hot buffering tanks, and the hot buffering tanks to the 51-cm (20-in.) downcomer pipe.

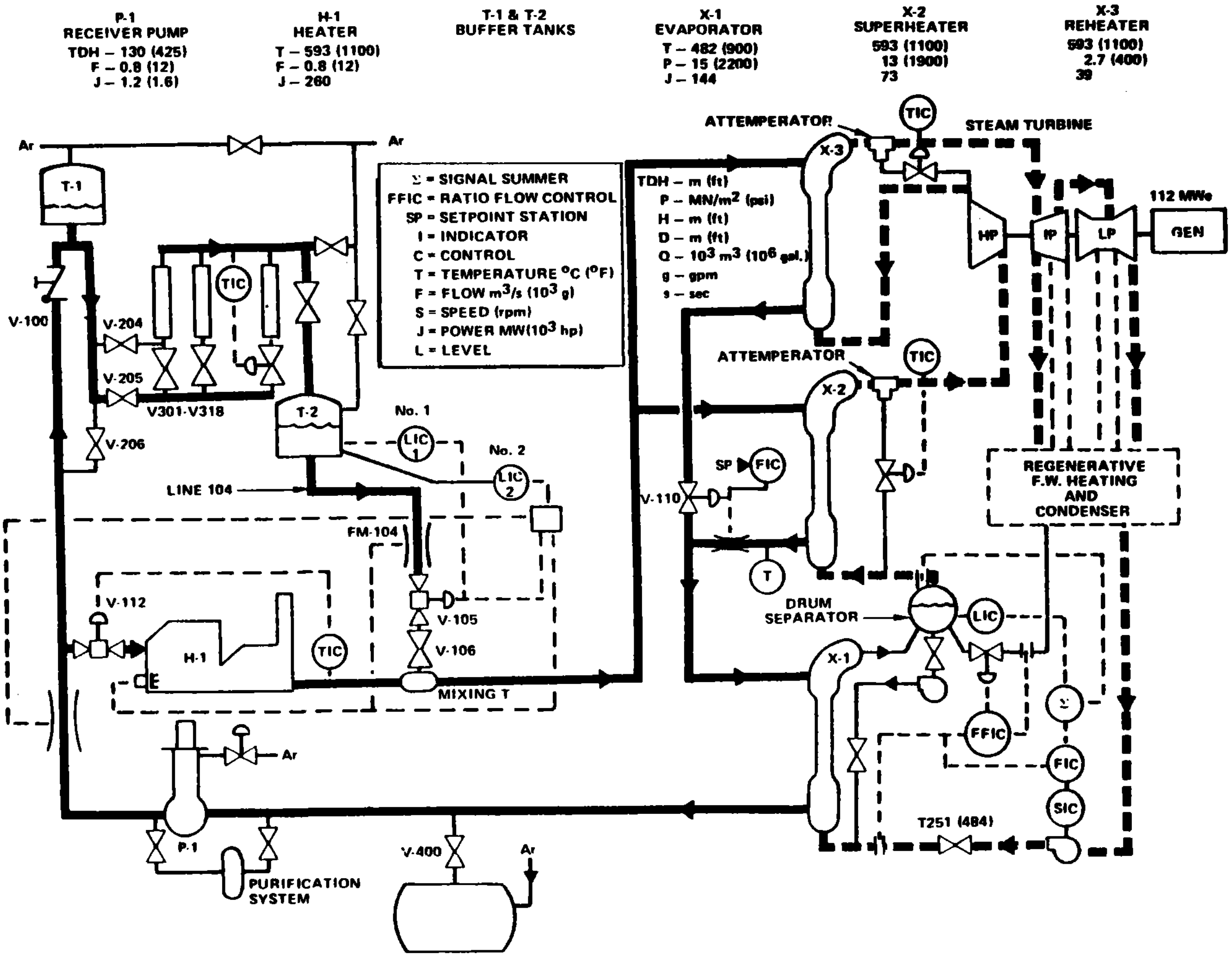

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Figure 5-47. Process Diagram (0.8 SM)

The inlet piping for each panel, as well as for the control valve, is nominally 15.2 cm (6 in.). Sodium-cooled panels are the same basic design as those used in the Advanced Central Receiver System. Each panel has 96 tubes 1.9-cm (3/4-in.) OD, 0.127-cm (0.05-in.) wall.

The cold buffering tanks are the high point in the receiver system; they retain the cover gas during receiver operation and fill the void when the sodium level is lowered for standby. Trace heaters heat all headware with the exception of the panels. The panels will be heated by solar radiation prior to addition of coolant. The back of the panels, as well as all plumbing and valves, will be covered with insulation.

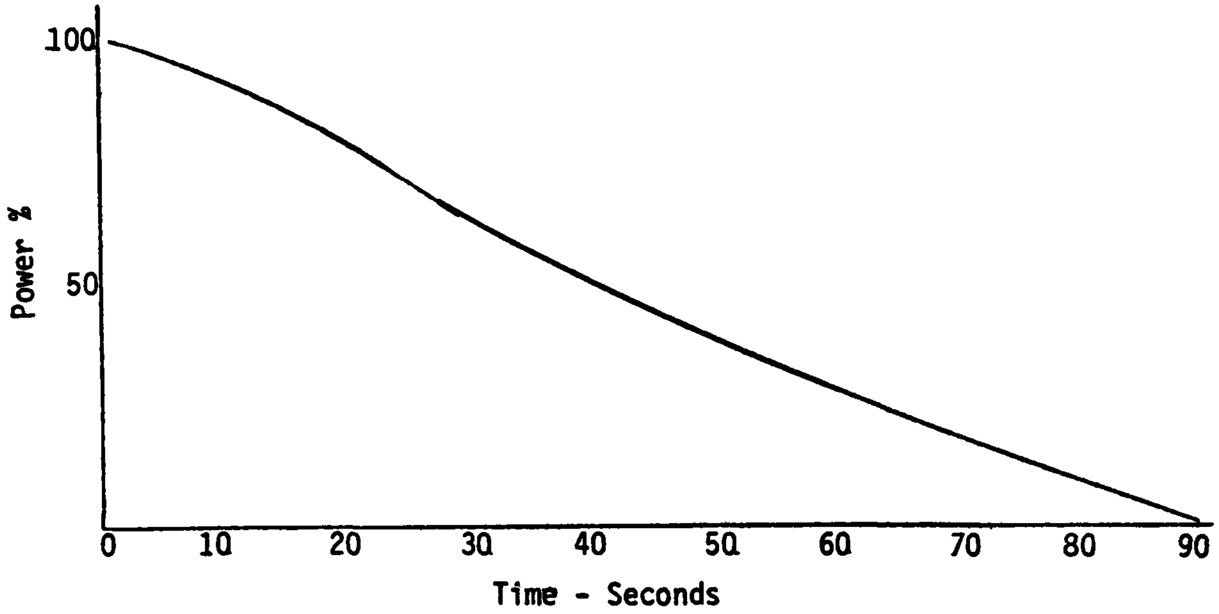
SYSTEM RESPONSE TO LOSS OF P-1 PUMP AND LOSS OF SUN TRANSIENTS

Solar Multiple = 0.8

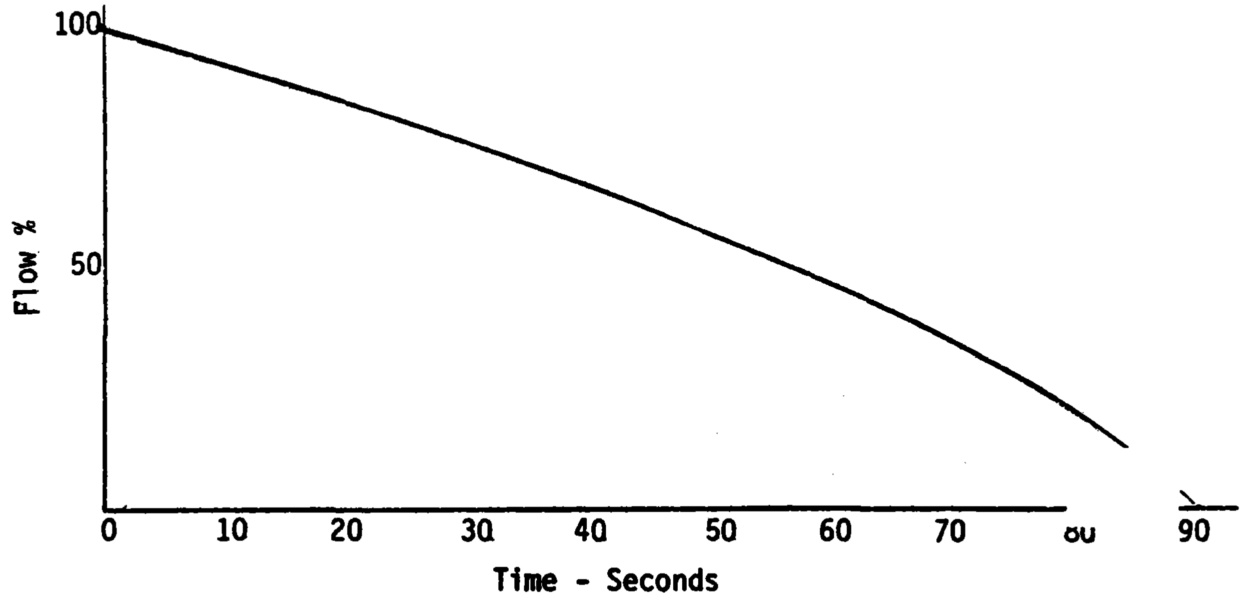
The plant conceptual design with a solar multiple of 0.8 does not provide thermal storage capacity, as such, but some degree of protection against transients is provided by a buffering system of 6 each T-1 cold tanks at 288°C (550°F) and T-2 hot tanks at 593°C (1100°F). These tanks are each approximately 2.44 m (8 ft) diameter by 6.1 m (20 ft) high and are located in series with the solar receiver as shown in the process diagram of Figure 5-47. The sizing of these tanks is determined by consideration of the response required in the event of (1) failure of the P-1 pump; and (2) passage of a sharp-edged cloud (or loss of sun transient). Sizing of these tanks and performance under the transients described above are discussed in more detail in the following sections.

CONTROL LOOPS — NORMAL OPERATION

The plant is designed for fixed sodium temperatures and variable flow rates to partition the energy flow from the receiver and the fossil-fired sodium heater. The solar insolation sets the ratio between these two energy sources. It is planned to operate the plant primarily in the "base load mode"; however, reduced load operation is allowed at dispatcher option. At summer solstice noon, the receiver supplies 80%, and the sodium heater 20% of full power. Referring to Figure 5-47, the pump, P-1, runs at a constant speed, and the receiver outlet temperature is maintained constant by modulating the control valves, V-301 through V-318. Each receiver-panel outlet header is equipped with a temperature sensor



a. Power vs Time



b. Flow vs Time

Figure 5-48. Flow and Power Match

and control loop for this purpose. For normal operation, the sodium level (Level Control No. 1) in Tank T-2 is fixed by modulating the Control Valve V-105. The signal from the Flowmeter FM-104 sets the furnace heat rate in inverse relation to the flow-through Line 104 at rates of change limited by furnace controls. The heater outlet sodium temperature is fixed by modulating Valve V-112 in accord with the outlet sodium header temperature sensor. For example: incremently, as the receiver power decreases, valves V-301 through V-318, close. The level in T-2 drops signaling V-105 to close restoring the level in T-2. This decreases the flow in FM-104 which signals the heater to increase in heat rate. As the furnace power increases, the furnace outlet temperature increases which opens V-112 restoring the furnace outlet to 1100^{o}F. A reverse sequence takes place on an increase of receiver power.

TRANSIENTS

Loss of P-1 Receiver Pump

In the event the P-1 pump fails and both the receiver control valves and the heliostats fail neutral, the relative motion of the sun will drift the image off the receiver, reducing the input power with time (Figure 5-48a). At the same time, the net head difference between the hot and cold buffer tanks continues the flow through the receiver. The flow decreases with time (Figure 5-48b) and approximately matches the power decrease so that the receiver outlet temperature remains approximately constant without control action. Thus, passive protection against a loss of pump accident is provided for. A more quantitative system performance is discussed in Section 3.1.1 and shown in Figure 5-49.

In the more usual case, the receiver control valves will continue to function, and the heliostat field power will be reversed, thus adding additional margin of protection as well as diversity and redundancy to the system. Backflow through the supply line is prevented by means of the stop check valve, V-100. Following the transient, the heater is shut off, and the plant is tripped and secured for extended shutdown.

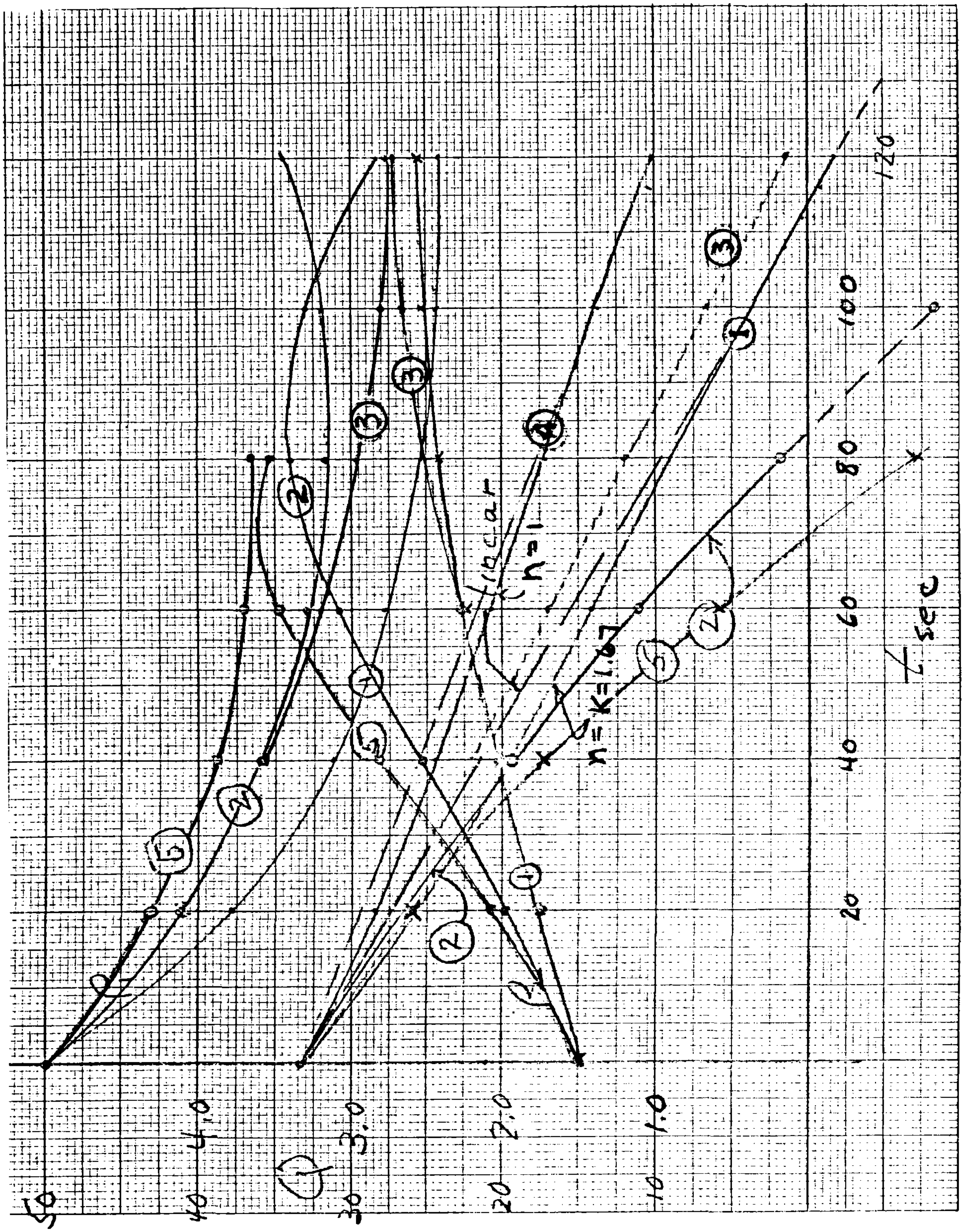
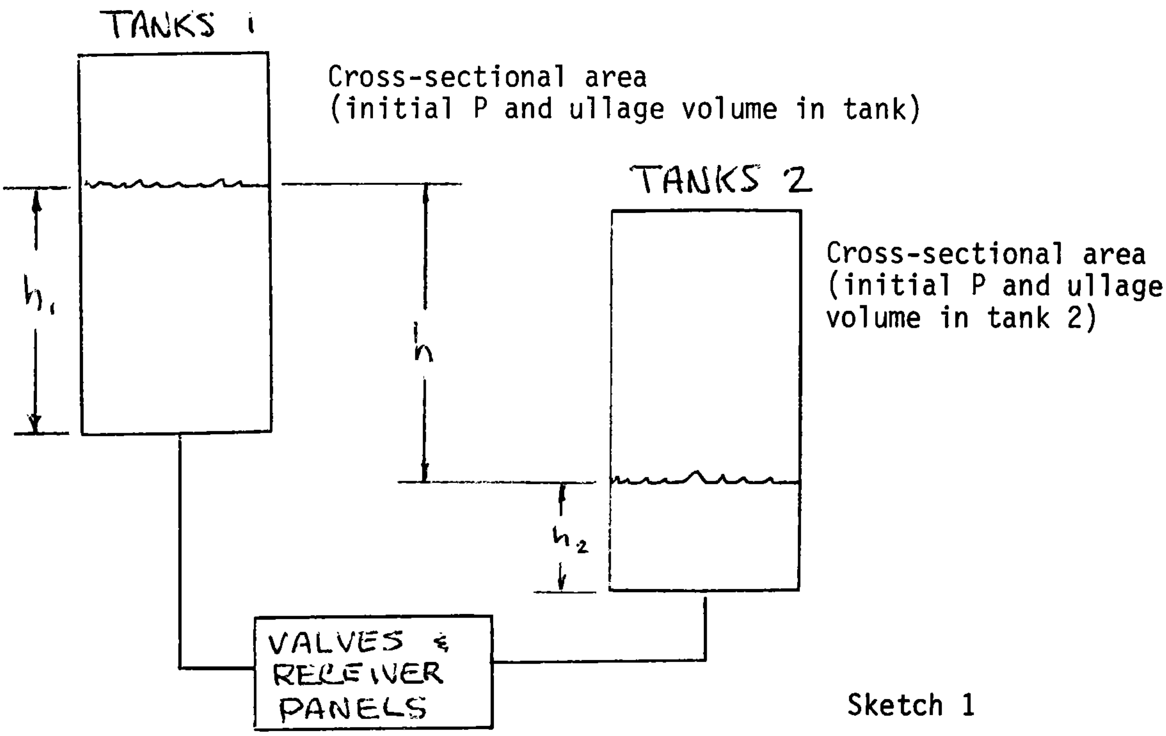


Figure 5-49. Buffer System Response to Loss of P-1 Pump



Sketch 1

Referring to Sketch 1,

$$H = \frac{144}{\gamma_{fluid}} (P_1 - P_2) + h,$$

where H is the net head driving flow through valves and receiver panels.

For mass continuity,

$$-A_1 \frac{dh_1}{dt} = A_2 \frac{dh_2}{dt} = Q$$

$$dh_1 = -\frac{1}{A_1} Q \; dt$$

$$dh = dh_1 - dh_2$$

$$dh = \left(1 + \frac{A_1}{A_2}\right) dh_1$$

Flow velocity through valves and panels:

$$W = \sqrt{2gH}$$

$$Q_{flow} = aw, \quad a = \text{flow area}$$

$$Q^2 = C_1 H, \quad C_1 = 2ga^2 = \frac{Q^2}{H}$$

$$2Q\ dQ = C_1\ dh$$

$$dH = \frac{2Q}{C_1}\ dQ$$

but

$$H = C_2 \left(P_1 - P_2\right) + h, \quad C_2 = \frac{144}{\gamma_{fluid}}$$

$$dH = C_2\ d\left(P_1 - P_2\right) + dh$$

$$\frac{2Q\ dQ}{C_1} = C_2\ d\left(P_1 - P_2\right) + \left(1 + \frac{A_1}{A_2}\ dh_1\right)$$

$$\frac{2Q\ dQ}{C_1} = C_2\ d\left(P_1 - P_2\right) + \left(1 + \frac{A_1}{A_2}\right)\left(- \frac{1}{A_1}\ Q\ dt\right)$$

$$\frac{2\ dQ}{C_1} = \frac{C_2}{Q}\ d\left(P_1 - P_2\right) - \left(\frac{A_1 + A_2}{A_1 A_2}\right) dt \qquad \ldots (1)$$

With tanks not vented, P_1 and P_2 are functions of the initial pressure valves and the changes in ullage volumes, V_1 and V_2.

Assuming adiabatic expansion in Tank 1 and adiabatic compression in Tank 2,

$$PV^K = \text{constant}$$

Differentiating,

$$\frac{dp_1}{dV_1} = -C_3KV_1^{-(K+1)}, \text{ where } C_3 = \left(P_1V_1^{K}\right)_o$$

$$\frac{dp_2}{dV_2} = -C_4KV_2^{-(K+1)}, \text{ where } C_4 = \left(P_2V_2^{K}\right)_o$$

but,

$$V_1 = V_{1_o} - A_1\, dh_1$$

$$V_2 = V_{2_o} - A_2\, dh_2$$

and

$$A_1\, dh_1 = -Q\, dt$$

$$A_2\, dh_2 = Q\, dt$$

Substituting,

$$d\left(P_1 - P_2\right) = -C_3KV_1^{-(K+1)}Q\, dt - C_4KV_2^{-(K+1)}Q\, dt$$

$$\frac{C_2}{Q}\, d\left(P_1 - P_2\right) = -C_2K\left[C_3V_1^{-(K+1)} + C_4V_2^{-(K+1)}\right]dt$$

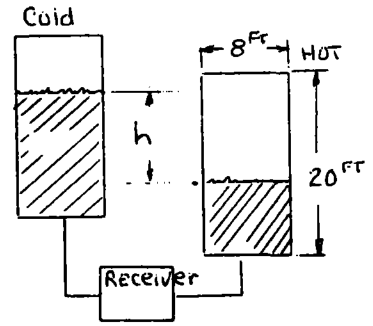
Substituting for $\frac{C_2}{Q}\, d\left(P_1 - P_2\right)$, Equation 1 becomes

$$dQ = -\frac{C_1}{2}\left[C_2K\left\{C_3V_1^{-(K+1)} + C_4V_2^{-(K+1)}\right\} + \frac{A_1 + A_2}{A_1A_2}\right]dt \qquad \ldots (2)$$

With $A_1 = A_2$ = constant with tank height (that is, cylindrical tanks as opposed to shaped tanks), Equation 2 can be integrated as follows,

$$\Delta Q = -\frac{C_1C_2C_3}{2}\, K\left(\overline{V}_1\right)^{-(K+1)} \cdot \Delta t - \frac{C_1C_2C_4K}{2}\left(\overline{V}_2\right)^{-(K+1)} \cdot \Delta t - \frac{C_1}{A_1}\,\Delta t \quad \ldots (3)$$

TABLE 5-9
SYSTEM SIZING PARAMETERS



	Run ①	②	③	④ Isothermal	⑤
$H_0 = \left[\frac{144}{\gamma}(P_1-P_2) + h\right]_0$	101.94	93.28	99.24	101.94	88.60
h_0^{ft} = initial fluid level difference	6.67	-1.99	+3.97	6.67	-6.67
$C_1 = Q_0^2/H_0$	.1096	.120	0.113	.1096	.1261
$C_2 = \frac{144}{\gamma}$	2.722	2.722	2.722	2.722	2.722
$C_3 = (P_1V_1{}^K)_0 \rightarrow$ Ⓒ	8.25×10^5	16.079×10^5	16.079×10^5	1.67×10^4	2.6246×10^6
$C_4 = (P_2V_2{}^K) \rightarrow$ Ⓓ	7.875×10^5	3.323×10^5	8.46×10^5	1.006×10^4	2.4746×10^5
$C_5 = \frac{C_1C_2C_3K}{2}$ argon → ⑤	2.055×10^5	4.082×10^5	4.129×10^5	2.5×10^3	7.52×10^5
$C_6 = \frac{C_1C_2C_4K}{2} \rightarrow$ ⑥	1.9617×10^5	8.436×10^4	2.1728×10^5	1.5×10^3	7.09×10^4
$\bar{\gamma}_{Na}$ = 52.9 16/ft^3	52.9	52.9	52.9	52.9	52.9
$\frac{C_1}{A_1 = A_2} \rightarrow$ ⑦	2.1802×10^{-3}	2.222×10^{-3}	2.248×10^{-3}	2.2×10^{-3}	2.508×10^{-3}
$Q_0 \rightarrow$ ① ft^3/s	3.342	3.342	3.342	3.342	3.342
Q_0 gpm/@, 6 tanks	1500	1500	1500	1500	1500
$V_{1_0} \rightarrow$ ②	335.27	500	500	335.27	670.5
$V_{2_0} \rightarrow$ ③	670.54	400	700	670.54	335.27
K	1.67	1.67	1.67	1	1.67
KH → Ⓑ	2.67	2.67	2.67	2.0	2.67
P_{1_0} psia	50	50	50	50	50
P_{2_0} psia	15	15	15	15	15
Δt increment → ⑧ (s)	4	4	4	4	4

Note that,

$$V_1 = V_{1_{initial}} + \int Q\,dt = V_{1_o} + \int \Delta V$$

$$V_2 = V_{2_{initial}} + \int Q\,dt = V_{2_o} - \int \Delta V$$

and,

$$\underset{\text{for any } t}{\bar{V}_1} = \left(V_{1_t} + V_{1_{t+\Delta t}}\right) \div 2$$

$$\underset{\text{for any } t}{\bar{V}_2} = \left(V_{2_t} + V_{2_{t+t\Delta t}}\right) \div 2$$

$$Q = Q_o - \int dQ = Q_o - \sum \Delta Q$$

Equation 2 can be integrated using the differentials of Equation 3 with small enough time steps, Δt. This integration has been programmed on the Hewlett-Packard HP-97 for several cases of initial conditions and system assumed sizes.

Table 5-9 shows the tabular values describing the cases run. The results are plotted on Figure 5-9.

Although this does not represent the final design, it has been demonstrated that such a system is feasible. Final sizing and performance analysis will more precisely match the power drop off and the actual system when implemented will provide for adequate controls to field adjust the performance.

LOSS OF SUN TRANSIENT

In the loss of sun transient, a sharp-edged cloud is assumed to pass across the field at a velocity of 20 m/s (65 ft/s). This totally shuts off the power to the receiver in about 100 s. To maintain fixed power to the steam generator requires that the sodium heater pick up this load. The maximum ramp rate of the sodium heater is ∿25%/min. The heater alone cannot meet the cloud transient

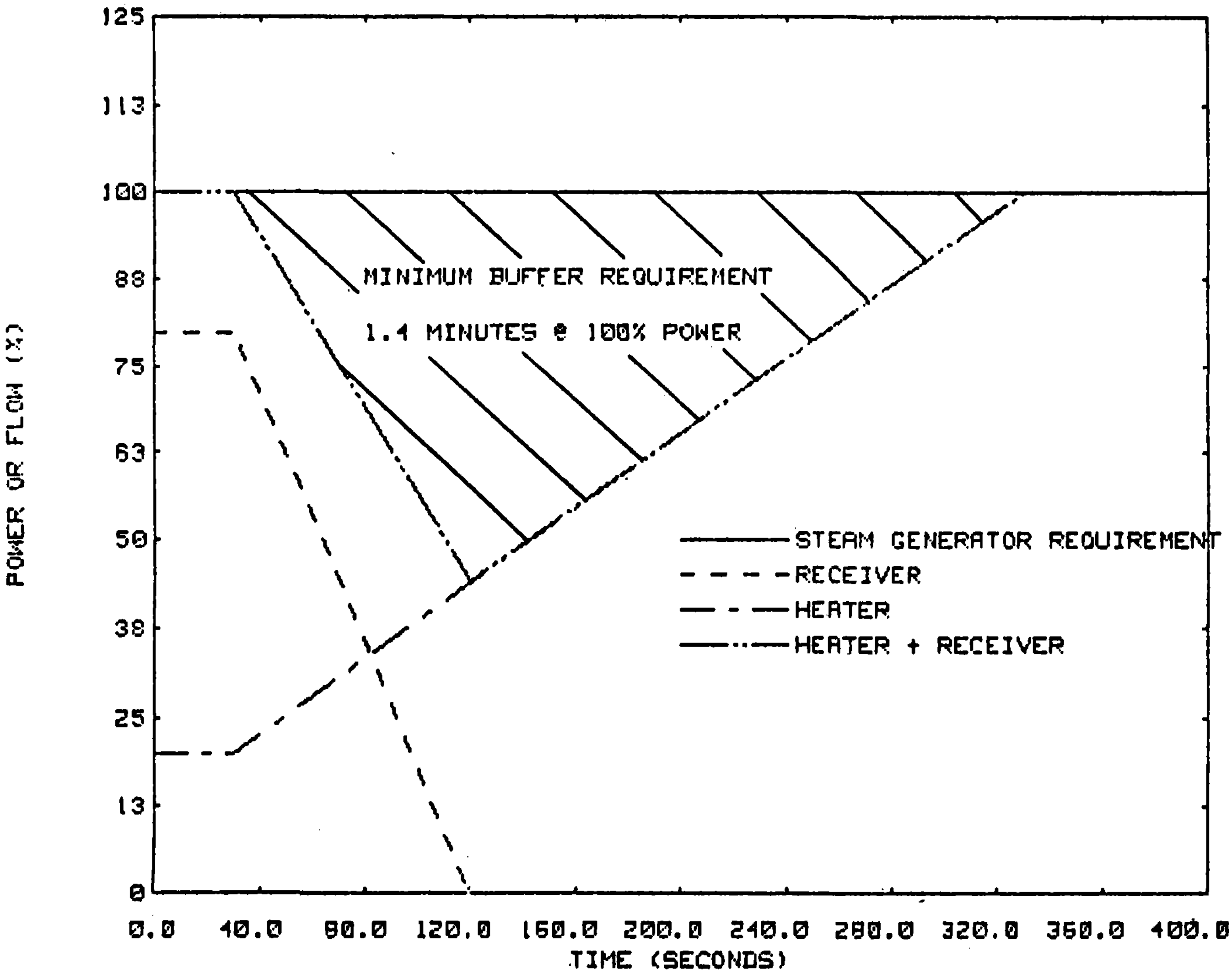


Figure 5-50. 0.8 SM Thermal Buffer Sizing for Loss of Sun Transient

requirements. The difference between the steam generator energy requirement and the ability of the heater to deliver it is made up by flowing sodium from Tank T-2 through the steam generator and into Tank T-1.

Incrementally, as the cloud cover traverses the field at 20 m/s and the power level to the receiver drops at a corresponding rate, the valves, V-301 through V-318, close, tending to lower the sodium level in Tank T-2. As the level drops, Control Valve V-105 closes, the flow in FM-104 decreases, and the heater power ramps up at the maximum rate allowed by its control loop. The maximum closing rate of Valve V-105 is preset to correspond to the maximum allowed heater power ramp. Consequently, this valve is unable to close fast enough to maintain the sodium level in the Tank T-2. When the sodium level in this tank drops about 6 in., the second level device, LIC No. 2, is actuated. When this level device is actuated, it switches the control from FM-104 to FM-100, initiates a pre-programmed heater ramp to full power, and sets the heliostats on the standby. The signal from FM-100 controls V-105 to provide a constant flow through the flowmeter FM-100. As the heater ramps up, Valve V-112 opens to maintain the heater sodium outlet temperature constant. This increases the flow through FM-100 which signals V-105 to close, reducing the flow through FM-100 to normal. This process continues until the sodium heater is up to full power and the receiver is drained and secured. Restart of the receiver is at the discretion of the operator and is done manually, because sequencing of the operations depends on the duration of the cloud cover. The sizing diagram for the Tank T-2 is shown in Figure 5-50.

The shaded area shown in Figure 5-50 and identified as the minimum buffer requirement represents a total volume of 12,600 gal (9,000 gpm for 1.4 min) and translates to a total level change of $\sim$5.6 ft for each of the six T-2 hot tanks. The hot tanks normally operate with about 60 to 70% ullage (corresponding to 8 to 6 ft fluid level) and thus contain sufficient sodium to accommodate the loss of sun transient.

CONCLUSION

The control system as designed provides a constant temperature to the steam generator system under conditions of variable flow (or power) rates.

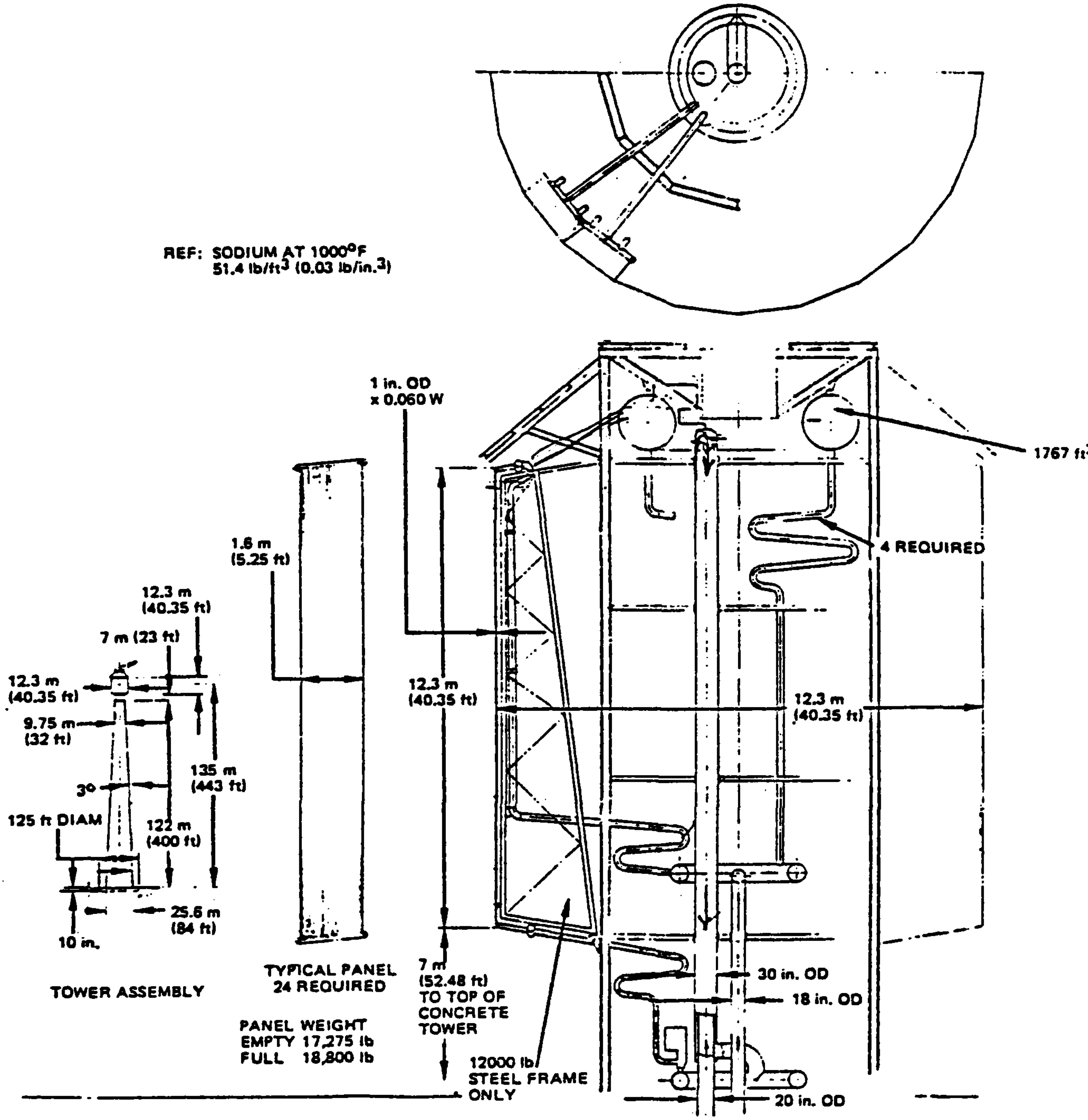


Figure 5-51. Baseline Receiver Design Layout for 0.9 SM Hybrid Concept

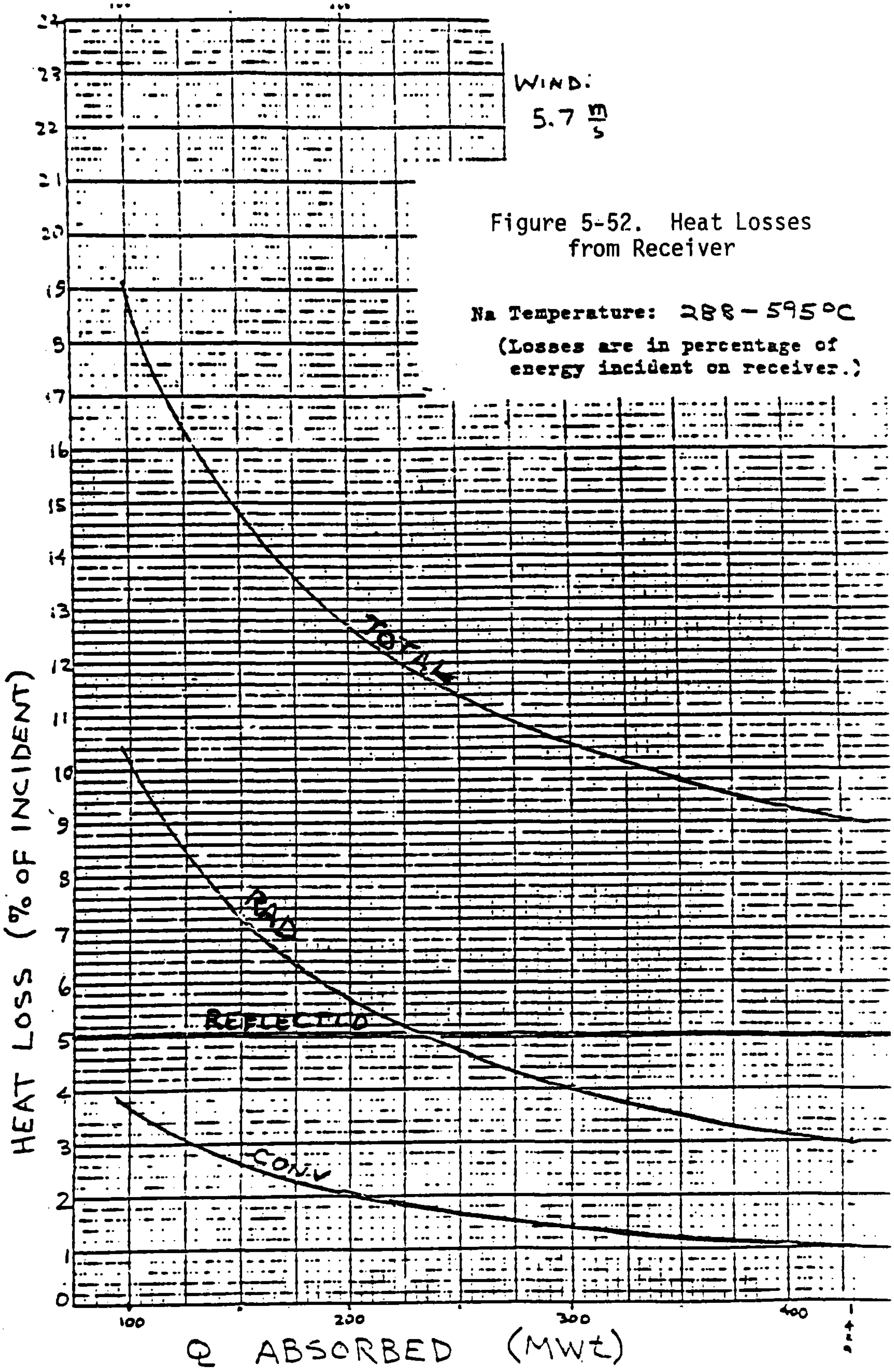
The buffer system of T-1 and T-2 tanks also provides passive protection against (1) loss of P-1 pump and (2) loss of sun (cloud passage) transients. In the P-1 pump failure case where the power is not lost (except for the pump failure itself) the control system provides a measure of redundancy through the continued operation of the receiver control valves and reversal of the heliostat field power.

5.3.2.2 Receiver for 1.4 SM Plant

The conceptual receiver design for the 1.4 SM plant is similar in design to the baseline 0.8 SM design as shown in Figure 5-51 and consists of the following items:

1) Structural steel interface structure
2) Coolant riser and distribution manifold
3) Riser to downcomer crossover piping and control valve
4) Solar panel inlet piping and cooland flow control valves
5) Solar panels with inlet and outlet manifold and panel backup structure
6) Solar panel outlet piping and downcomer
7) Cover gas accumulator and vent lines
8) Heaters, insulation, and instrumentation (temperature and pressure)
9) Miscellaneous equipment and facilities (lights, power, hoists, catwalks, passive shields, lightning protection, water first aid, etc.)

The coolant riser and distribution manifold is 61-cm (24-in.) pipe with 24 outlets, one for each panel. The riser to downcomer crossover is a 15.2-cm (6-in.) pipe which includes the shutoff valve; this is to be used during filling the system and recirculating hot sodium during standby. The inlet piping for each panel, as well as for the control valve, is nominally 15.2 cm (6 in.). Both pipe and valve are free-draining back to the riser. Sodium-cooled panels are the same basic design as those used in the Advanced Central Receiver System. Each panel has 85 tubes 1.9-cm (3/4-in.) OD, 0.127-cm (0.05-in.) wall.


WIND: 5.7 m/s
Figure 5-52. Heat Losses from Receiver
Na Temperature: 288-595°C
(Losses are in percentage of energy incident on receiver.)
TOTAL
RAD
REFLECTED
CONV
HEAT LOSS (% OF INCIDENT)
Q ABSORBED (MWt)
100
200
300
400

The headers are nominally 20.3 cm (8 in.) in diameter, with staggered tubes welded and rolled. The backup structure includes a 15.2 x 15.2 x 1.0 cm (6 x 6 x 38 in.) square tube frame. The tubes slide on clips welded to the frame. Tube bundles and inlet headers are free-draining through the inlet plumbing. The outlet piping is 15.2-cm (6-in.) OD pipe, and the downcomer is a 31-cm (12-in.) OD pipe.

A cover gas accumulator is the high point in the receiver system; it retains the cover gas during receiver operation and fills the void when the sodium level is lowered for standby. Trace heaters heat all hardware with the exception of the panels. The panels will be heated by solar radiation prior to addition of coolant. The back of the panels, as well as all plumbing and valves, will be covered with insulation.

5.3.3 Receiver Losses

Based on the results of the ACR thermal loss analysis as previously discussed in Section 3.3.4, heat losses for the hybrid plant were estimated. Figure 5-52 shows the thermal losses as a percent of the incident power for the design wind condition of 3.5 m/s (11.5 fps) at 10 m (32.8 ft) or 5.7 m/s (18.7 fps) at the receiver elevation. At the yearly average incident thermal power of about 208 MWt for the 0.8 SM plant, the total loss is about 12.5%. The part contributed by the convection process is about 2%. Figure 5-54 shows the thermal losses at a wind velocity of 7 m/s (23 fps) at 10 m (32.8 ft) or 11 m/s (36 fps) at the receiver. The total loss at 208 MWt with this wind velocity is estimated to be 13.4% of which convection is about 3%. For the 1.4 SM design concept, the total loss at 364 MWt with the 11 m/s (36 fps) wind velocity is estimated to be 10.2%, of which convection is about 1.8%.

Figure 5-53 shows the effect of receiver wind velocity on thermal losses for various receiver absorbed thermal power levels. Finally, in Figure 5-54, thermal losses are shown as a function of the wind frequency probability as taken from the ACR program specifications. As can be seen, high wind losses occur only a small fraction of the time. At low wind velicities, ($\sim$4 m/s) which occur almost 50% of the time, the convective heat transfer is very nearly controlled by natural convection processes.

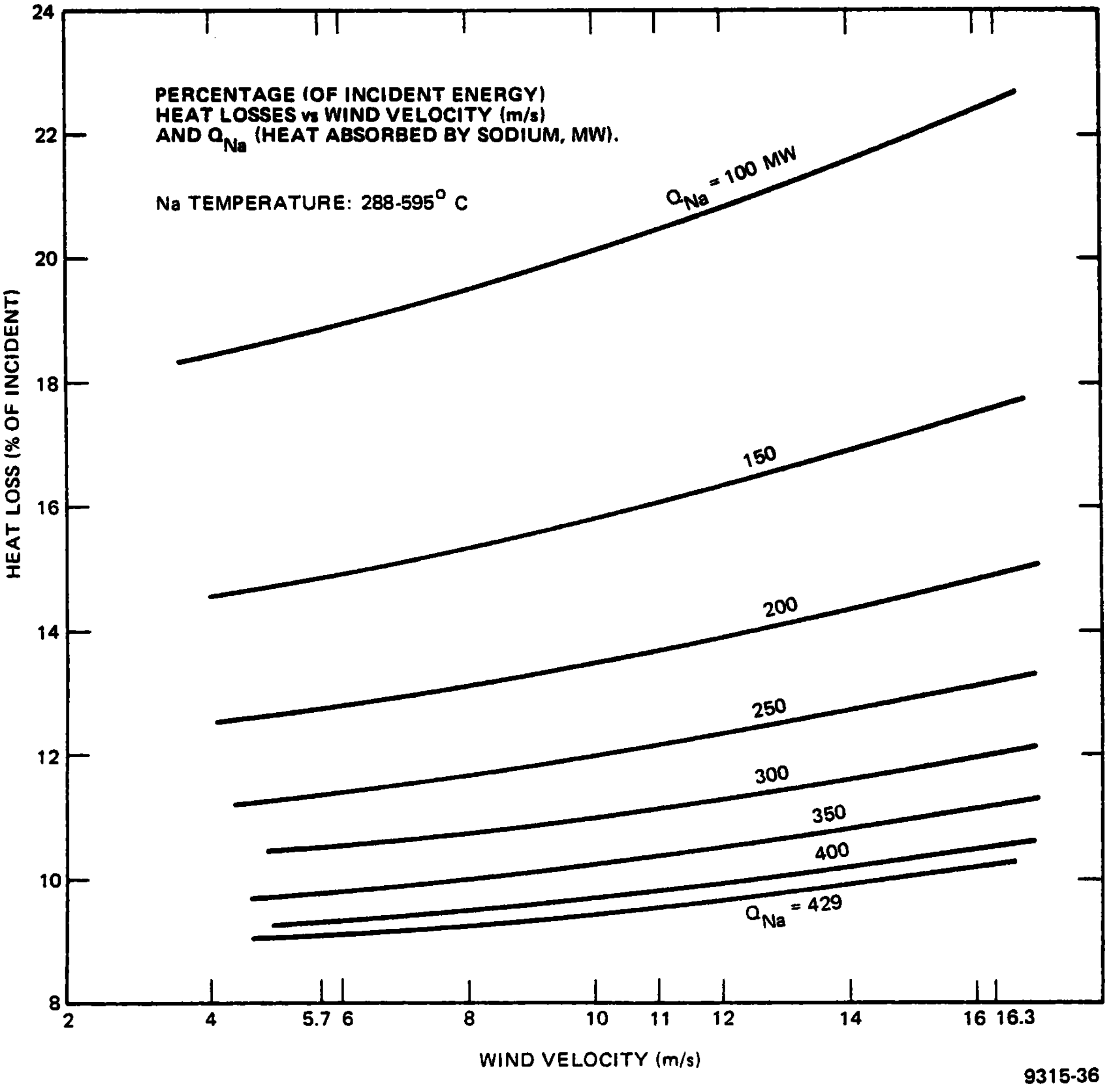


Figure 5-53. Heat Losses from Receiver

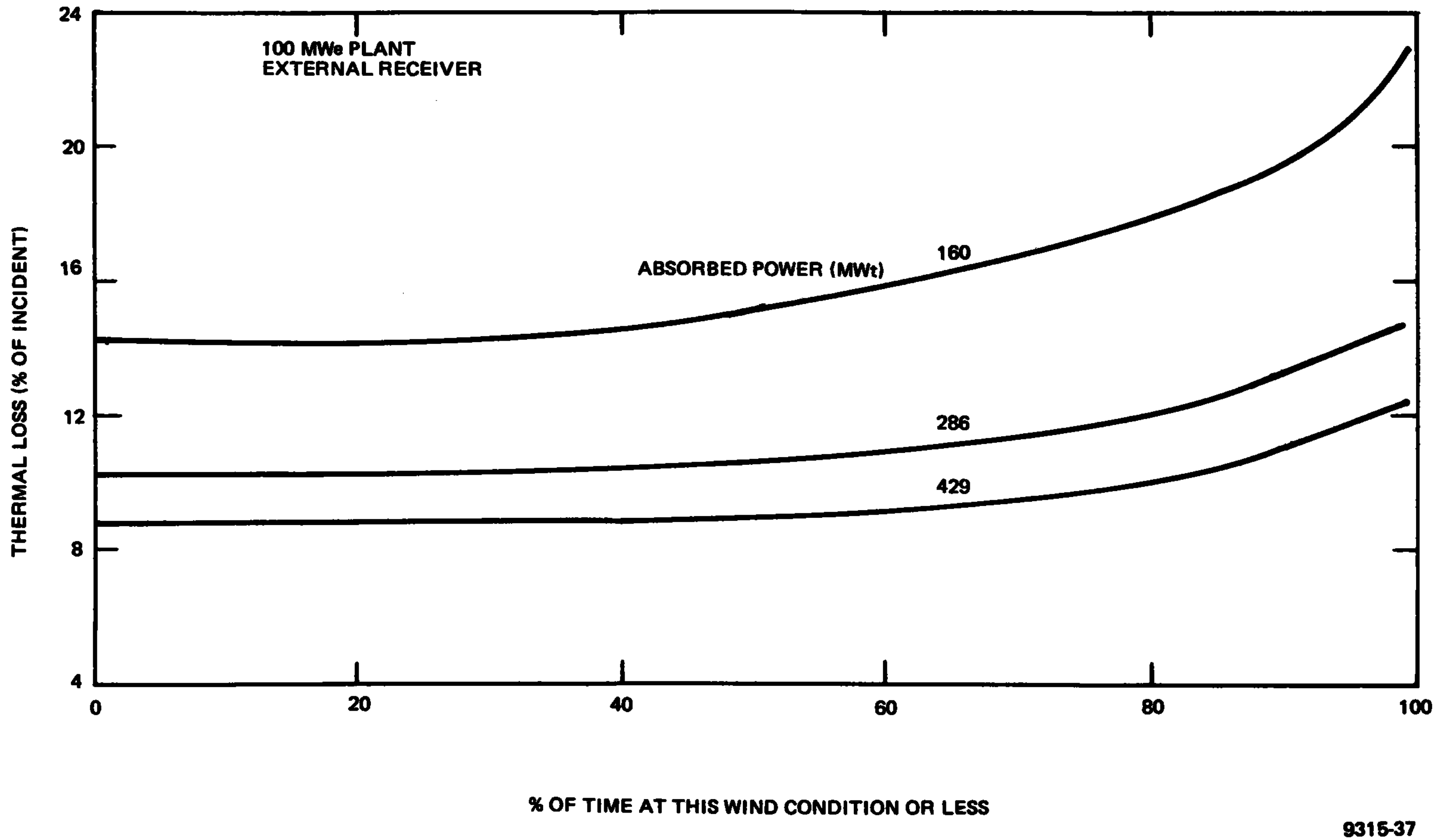


Figure 5-54. Thermal Loss as Affected by Specification Wind Velocity Frequency

5.3.4 Tower and Riser/Downcomer Design

5.3.4.1 Tower Design

The tower is of reinforced, slip-formed concrete design. For the 0.8 SM plant, the concrete tower height is 111.3 m (365 ft) with a base diameter of 15.2 m (50 ft), top diameter of 10.4 m (34 ft). The tower supports a total receiver subsystem weight of 270,000 kg (588,000 lb) and rests on a reinforced concrete mat 3.7 m (12 ft) thick with an outside diameter of 36.6 meters (120 ft). A discussion of the tower design analysis is presented in Section 3.3.7.

5.3.4.2 Riser/Downcomer Design

The trade study for sizing the sodium riser and downcomer piping was previously discussed in Section 3.3.8.2. The optimum pipe size selected for the 0.8 SM hybrid conceptual design study is 51-cm (20-in.) Schedule 30 pipe for both the riser and downcomer. Pipe sizes selected for the 1.4 SM concept are 61 cm (24 in.) for the riser piping and 31 cm (12 in.) piping for the downcomer. The riser piping material is carbon steel, since it contains sodium at 288^{o}C (550^{o}F); whereas, the downcomer piping material is stainless steel, since it contains sodium at 593^{o}C (1100^{o}F).

Based on the thermal expansion study discussed in Sections 3.3.8 and 3.3.9.2, the reference pipe routing design for the hybrid plant is the Type I configuration presented in Appendix K.

This configuration utilizes expansion loops and anchor points on the tower. Each loop contains four 5D pipe bends and 6 m (20 ft) of straight pipe. The pipe hangers are the conventional rigid supports.

5.3.5 Pumps, Piping and Valves

5.3.5.1 Sodium Pump

Receiver Pump for 0.8 SM Plant

The sodium pump selected for the 0.8 SM hybrid plant receiver subsystem is a free surface, centrifugal, fixed speed mixed flow design that handles about 0.76 m^3/s (12,000 gpm), a flow rate that is well within the capability of sodium pumps. Refer to Section 3.3.9.1. Since this pump is operating in a closed loop system, the total pump head is lower than the head required for an open loop system where the pumps must circulate the sodium from the base of the tower to the tank at the top of the tower. The total developed head is 130 m (425 ft).

With the pump installed in the closed loop at the base of the tower, the high suction pressure will allow the pump to operate at the speed for a 2-pole motor (i.e., 3540 rpm). A 1306 kW (1750 hp) motor will be required to drive the pump. The hydraulic characteristics of this pump are given in the "Data Lists" in Appendix E.

Receiver Pump for 1.4 SM Plant

The receiver sodium pump, P-1, for the 1.4 SM plant is a free-surface, centrifugal, variable speed, single-suction design that handles about 1.07 m^3/s (17,000 gpm) with a pump total head of 220 m (722 ft). The total head requirement is higher than the 0.8 SM pump, since this pump operates in an open-loop configuration. This pump circulates the sodium from the cold storage tank up through the receiver to the expansion tank at the receiver. The hydraulic characteristics of this pump are also given in the "Data Lists" in Appendix F.

5.3.5.2 Sodium Piping

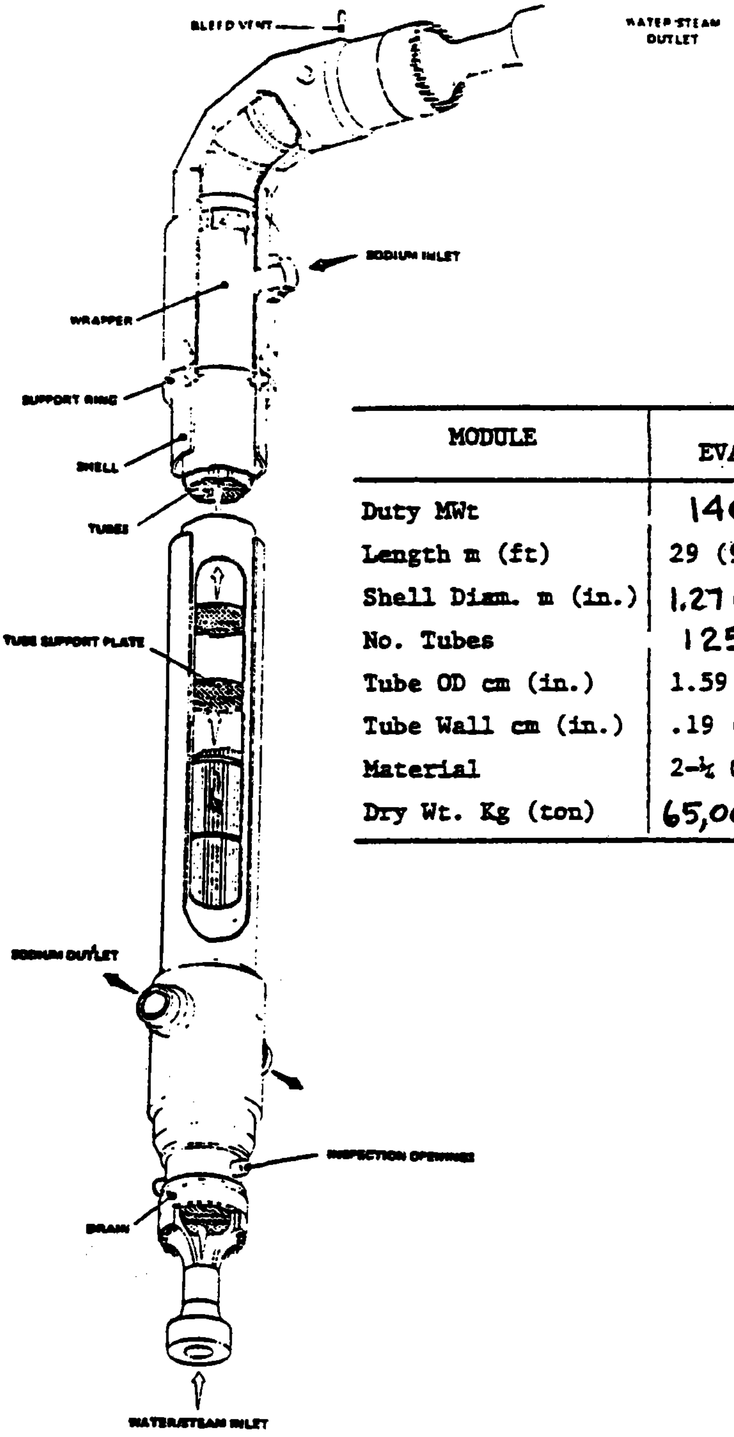
Carbon steel has been specified for all the sodium piping that operates at 288^{o}C (550^{o}F), and stainless steel has been specified for the piping that operates at 593^{o}C (1100^{o}F). Estimates of the piping lengths and weights are given in the Data Lists in Appendix F.

5.3.5.3 Sodium Valves

The sodium valves will be similar to those developed for the Fast Flux Test Facility (FFTF) and the Clinch River Breeder Reactor Plant (CRBRP) project. The small valves will be bellow seal valves, the larger valves may be freeze stem valves.

5.3.6 Steam Generator Design

The reference design utilizes 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



MODULE	EVAP	SH	RH
Duty MWt	146	74	40
Length m (ft)	29 (95)	27.7 (91)	20.1 (66)
Shell Diam. m (in.)	1.27 (50)	.76 (30)	.81 (32)
No. Tubes	1250	269	166
Tube OD cm (in.)	1.59 (5/8)	1.9 (3/4)	3.81 (1.5)
Tube Wall cm (in.)	.19 (.075)	.335 (.132)	.272 (.107)
Material	2-¼ Cr-1 Mo	316	316
Dry Wt. Kg (ton)	65,000 (72)	20,000 (22)	22,000 (24)

Figure 5-55. Steam Generator Modules

units are 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, thus if the bulk liquid is kept out of the stainless steel units, chloride stress corrosion does not become a problem. To accomplish this, a combined steam drum and steam separator and a recirculation pump are installed between the evaporator and the superheater and reheater to assure that no bulk liquid is 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.

The physical features of the evaporator unit are shown in Figure 5-55. 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 plant only in this region, elsewhere the tube support plates suppress any potential tube vibration due to flow. The physical characteristics of the steam generator units for the hybrid plant are given in Figure 5-55 and the data lists in Appendices E and F.

5.3.7 Auxiliary Systems

The auxiliary systems that support the main flow system are: (1) fill and drain, (2) purification, (3) preheat, (4) instrumentation and control, (5) inert gas, and (6) sodium-water reaction relief. In the following discussion, the general characteristics presented are based on common practice with sodium systems.

5.3.7.1 Fill and Drain

The fill and drain system provides for the initial fill of the drain tank with sodium, the fill of the piping system from the drain tank prior to operation, sodium bulk storage, and drain provisions to the drain tank.

Initial fill would be accomplished at a temperature of 204^{o}C (400^{o}F) from railroad-type tank cars each containing 36,400 kg (80,000 lb) of sodium. A melt station is required to melt the sodium in the tank cars; a pressure source of inert gas, such as nitrogen, is required to move the sodium from the tank car to the drain tank.

The riser and downcomer lines are filled from the drain tank using a small pressurized tank. Both lines are filled simultaneously up to the receiver. The receiver is also filled if adequate preheat of the receiver tubes has been attained using the collector field. A filled system is detected by a sodium level in the cold buffer tanks at the top of the receiver.

SUMMARY

Thermal buffer requirements are discussed and presented for the 0.8 SM plant. In the case of the 1.4 SM plant, 3 hours of storage was provided similar to the previously designed ACR plant. Vessel dimensions are presented along with a conceptual design sketch of the large storage tanks. Storage tank heat loss analyses are presented. Ullage and fluid maintenance designs for the storage subsystem are reviewed and sodium monitoring and clean-up system components are described. Sodium piping, valves and pumps are selected from past experience in sodium test and operating systems. A discussion of the drag valve selected for the 1.4 SM plant to dissipate the tower static head is included along with a cut-away drawing of the valve. A description of the leak detection methods proposed for the facility are given.

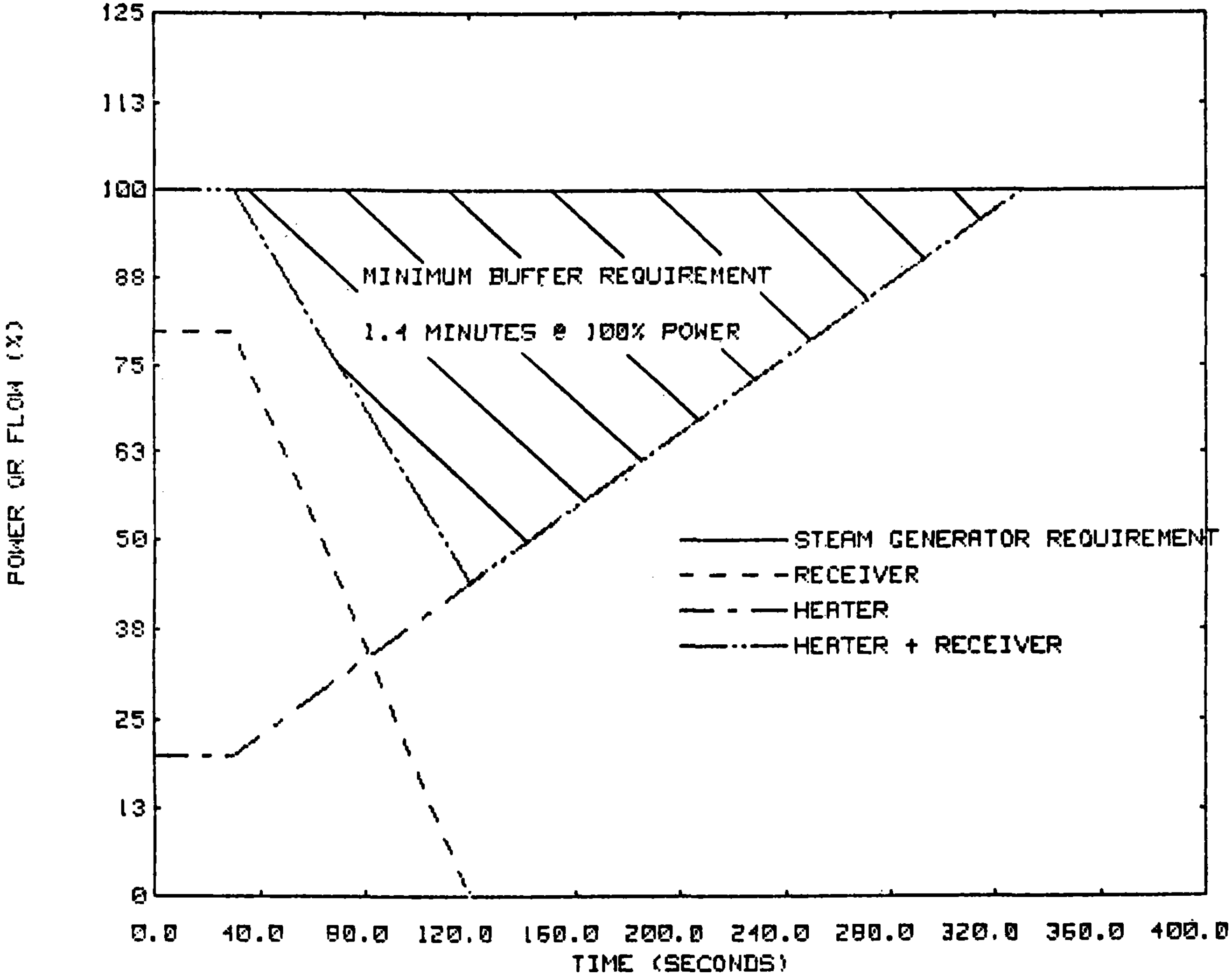


Figure 5-56. 0.8 SM Thermal Buffer Sizing for Loss of Sun Transient

5.4 STORAGE SUBSYSTEM

5.4.1 Storage Subsystem Requirements

5.4.1.1 0.8 Solar Multiple

The storage subsystem selection analysis and trade study described in Sections 4.3 and 3.4, respectively, established that the requirements for thermal storage, or perhaps more accurately thermal buffering, are due only to transient system operation. In the 0.8 solar multiple configuration, the receiver is capable of ramping down much faster than the heater is capable of ramping up. This principle is illustrated in Figure 5-56 for the design cloud cover transient. In this case the cross hatched area represents the integral of the difference between the sum of receiver and heater flow and the required steam generator flow. This integral sets the minimum inventory of hot sodium required to transition from the receiver at full power (80% of steam generator power) to the heater at full power (100% of steam generator power).

The second transient having an impact on the storage subsystem requirements, the plant loss of pump or hotel power accident, sets the requirements for the cold sodium inventory. In this case, the design goal is to provide a passive source of cold sodium for cooling the receiver from the time the receiver pump fails until the time the combined heliostat solar image drifts off the receiver due to the earth's retrograde motion. Previous simulation studies have indicated that the duration of the transient is 90 s and that the required flow decay is approximately linear. This transient also sets the cold and hot sodium inventory head requirements. Table 5-10 summarizes the thermal buffering requirements for the 0.8 solar multiple system configuration.

5.4.1.2 1.4 Solar Multiple

The 1.4 solar multiple system configuration storage subsystem requirements are determined by the desire for a system design which is directly comparable to previously conceptualized central receiver power systems. These systems all had

TABLE 5-10

0.8 SOLAR MULTIPLE THERMAL BUFFER REQUIREMENTS

Hot Sodium Inventory	150 seconds full flow equivalent*
Cold Sodium Inventory	77 seconds full flow equivalent*
Cold-Hot Inventory Steady-State Head Difference	130 ft of sodium

*Includes design margin for assured transient capability

the capability for operating the equivalent of 3 h from storage at full rated plant output. As in the case of the sodium-cooled advanced central receiver program, the gross cycle efficiency of the hybrid system is the same when operating from storage as it is when operating directly from the sun. Consequently, the sodium inventory requirements of the 3-h storage subsystem for the hybrid system simply consists of 3 h of full-flow sodium for the steam generators.

5.4.2 Vessel Design

5.4.2.1 Sodium Buffering Tanks for 0.8 SM Hybrid Plant

For the 0.8 SM plant design concept, the cold and hot buffer tanks are vertical cylindrical tanks ∿2.4 m (8 ft) in diameter by 6.4 m (21 ft) long. There are six cold buffer tanks and six hot buffer tanks, and these tanks are mounted on top of the receiver tower as shown in Figure 3-19. The tanks are designed in accordance with Section VIII Division 1 of the ASME Boiler and Pressure Vessel Code.

The hot tanks are made of stainless steel since they operate at 593°C (1000°F); the cold tanks are made of carbon steel and operate at 288°C (550°F)

5.4.2.2 Sodium Storage Tanks for 1.4 SM Hybrid Plant

The storage subsystem for the 1.4 SM design concept is sized for a minimum net capacity of 3 MWe-hr/MWe. This concept with single hot and cold sodium storage tanks is shown in Figure 5-57. The functional requirements and system design detals for the system are given in the baseline design data sheets of Appendix F, along with a P&I diagram.

The storage tanks are low-pressure tanks with a height of about one-half the diameter. The baseline design 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°C (1100°F) is made of stainless steel; the cold tank at 288°C (550°F) is made of carbon steel. The tanks operate at static head pressures only 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 12-in. drag valve. Details of this drag valve are discussed in Section 5.4.6.

Although no sodium tanks of this size have been built, no particular difficulty is expected in their fabrication, installation, and operation. They will be designed in general compliance with API Standard 620, Recommended Rules for Design and Construction of Large Welded, Low-Pressure Storage Tanks. It should be noted that a major advantage of the all-sodium thermal storage is that the EPGS can operate independently of transient which may occur in the receiver system.

5.4.3 Storage Losses

The hot tank of the thermal storage subsystem stores enough hot sodium - 598°C (1100°F) during the day at equinox to provide ∿3 h of operation at 100% rated power. Both the hot tank and cold tank can store the entire sodium inventory, and for that reason, both tanks are the same capacity and have dimensions - 30 m (100 ft) diameter by ∿15 m (50 ft) high. The hot tank is insulated with 30 cm (12 in.) of calcium silicate; the cold tank operating at 288°C (550°F) has only 15 cm (6 in.) calcium silicate. These insulation thicknesses reduce the outside surface temperature of the insulated tanks to ∿54°C (130°F), which is an acceptable value with respect to personnel safety. The heat loss from thermal storage corresponds to about 0.33 MWt from each tank.

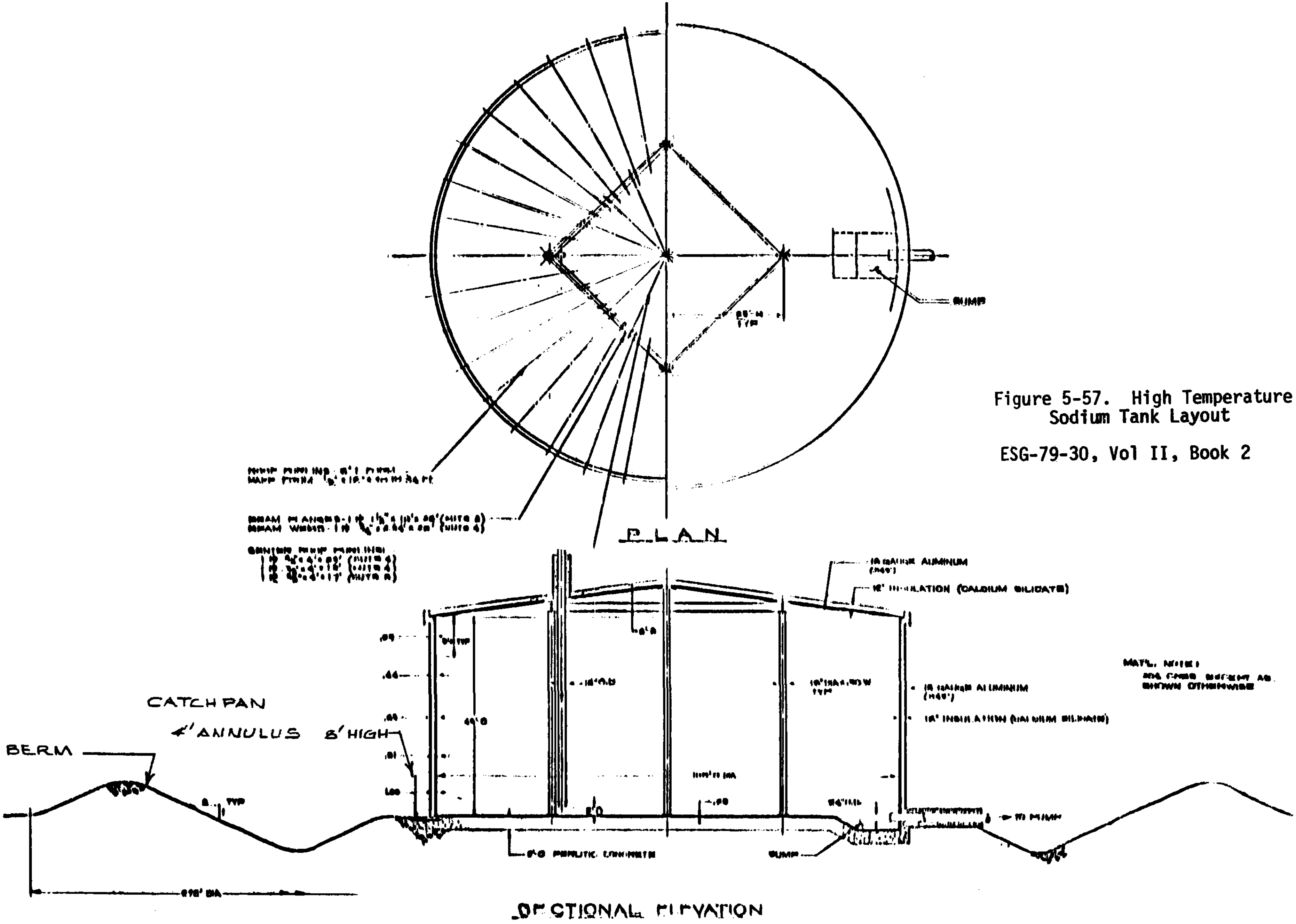


Figure 5-57. High Temperature Sodium Tank Layout

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Figure 5-58 shows the consequences of the thermal losses from storage as related to the resulting sodium temperature decay vs time for the hot tank for various levels of fluid content, i.e., full tank, 1/2 full, and about 1/2 h sodium remaining. The curves indicate that a $10^{o}C$ ($18^{o}F$) fluid temperature drop may be expected over a 24-h period for a full hot tank. This is only about 1-1/2% of the initial temperature value. Figure 5-58 also expresses the thermal loss as a percentage of initial energy content for a full tank, 1/2 full, and 1/2 h sodium remaining condition. For a full hot tank, this percentage loss is only about 4% after a 100-h standby period. This analysis indicates a very high effectiveness for the storage system selected.

5.4.4 <u>Ullage Maintenance Design</u>

See paragraph 3.4.6.

5.4.5 <u>Fluid Maintenance Design</u>

The requirements for fluid maintenance are given in Paragraph 3.4.7. The equipment for maintaining the fluid is described in this section.

The cleanup and measurement techniques for sodium involve mainly the measurement and removal of oxygen. These techniques are based on the fact that oxygen has a positive temperature coefficient of solubility. The saturation solubility curve of oxygen in sodium as a function of temperature is given in Figure 5-59. As can be seen in the curve, as the temperature is reduced, the oxygen precipitates out (as Na_2O). For purposes of measurement, the precipitate plugs a calibrated orifice at a measured temperature. The temperature at which this plugging occurs is referred to as the plugging temperature. Referring to Figure 5-60, to make a "plugging" determination, the plugging orifice is lowered into position by deenergizing the electromagnet. As the sodium flows through the unit, its temperature is slowly lowered until oxides precipitate out and plug the orifice. This begins to decrease the flow which is detected by the flowmeter. At a predetermined flow decrement, the electromagnet is energized opening the orifice, thus flushing it out. As full flow is established, the cycle repeats. The temperature signal from the thermocouple and the signal from the flowmeter are

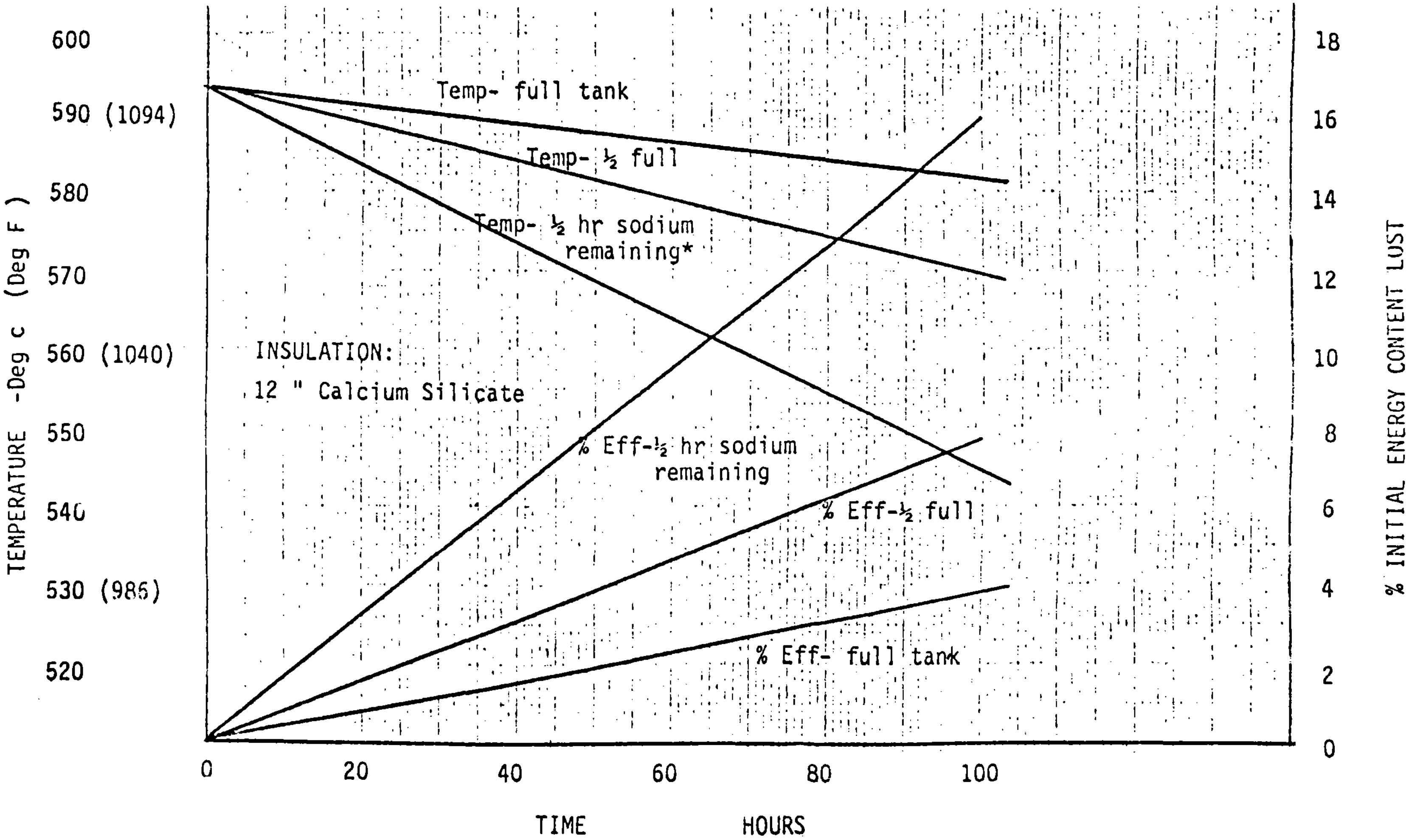


Figure 5-58. Temperature and Percent Heat Loss vs Time-All Sodium Storage

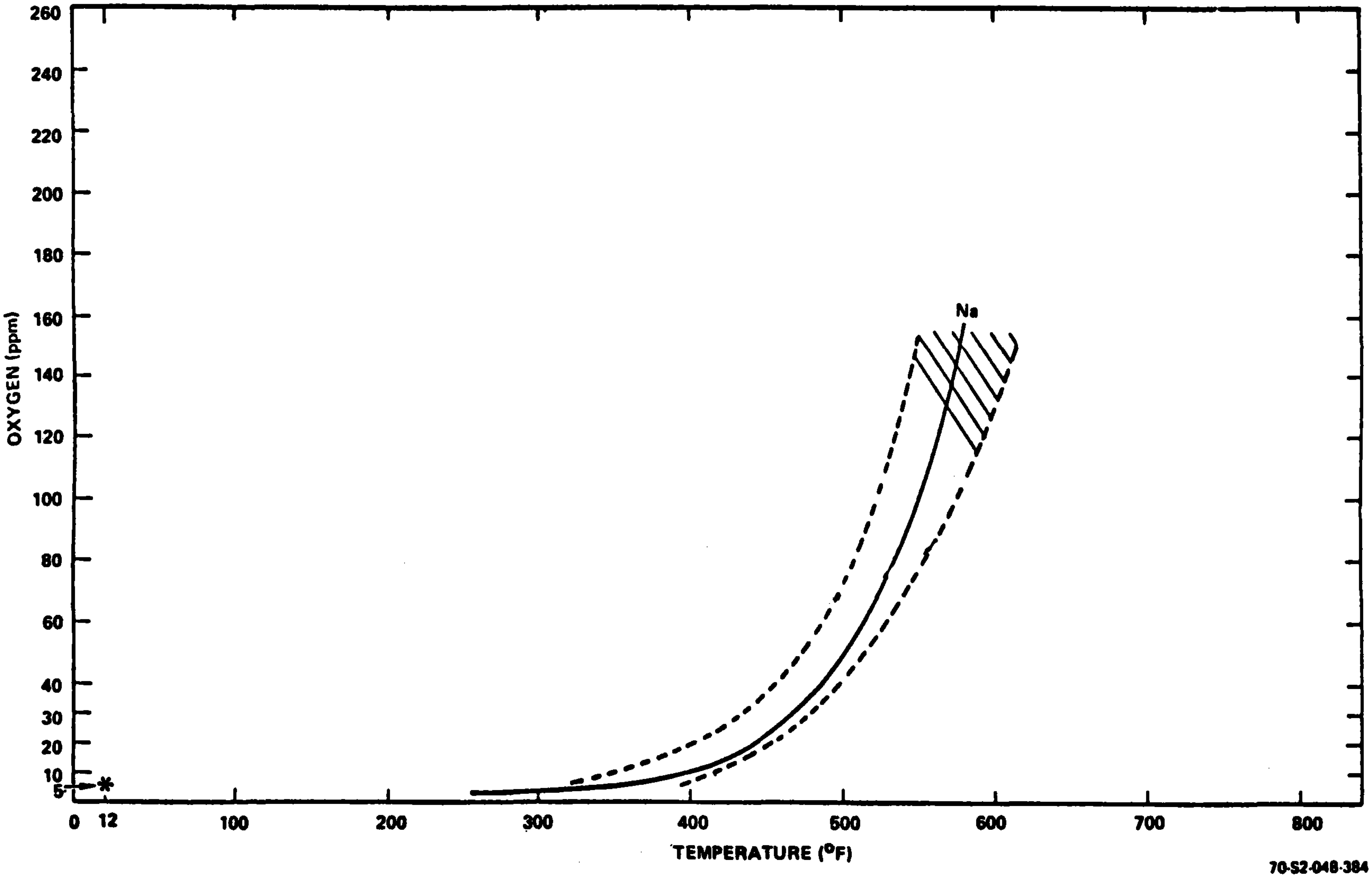


Figure 5-59. Saturation Concentration for Oxygen in Sodium

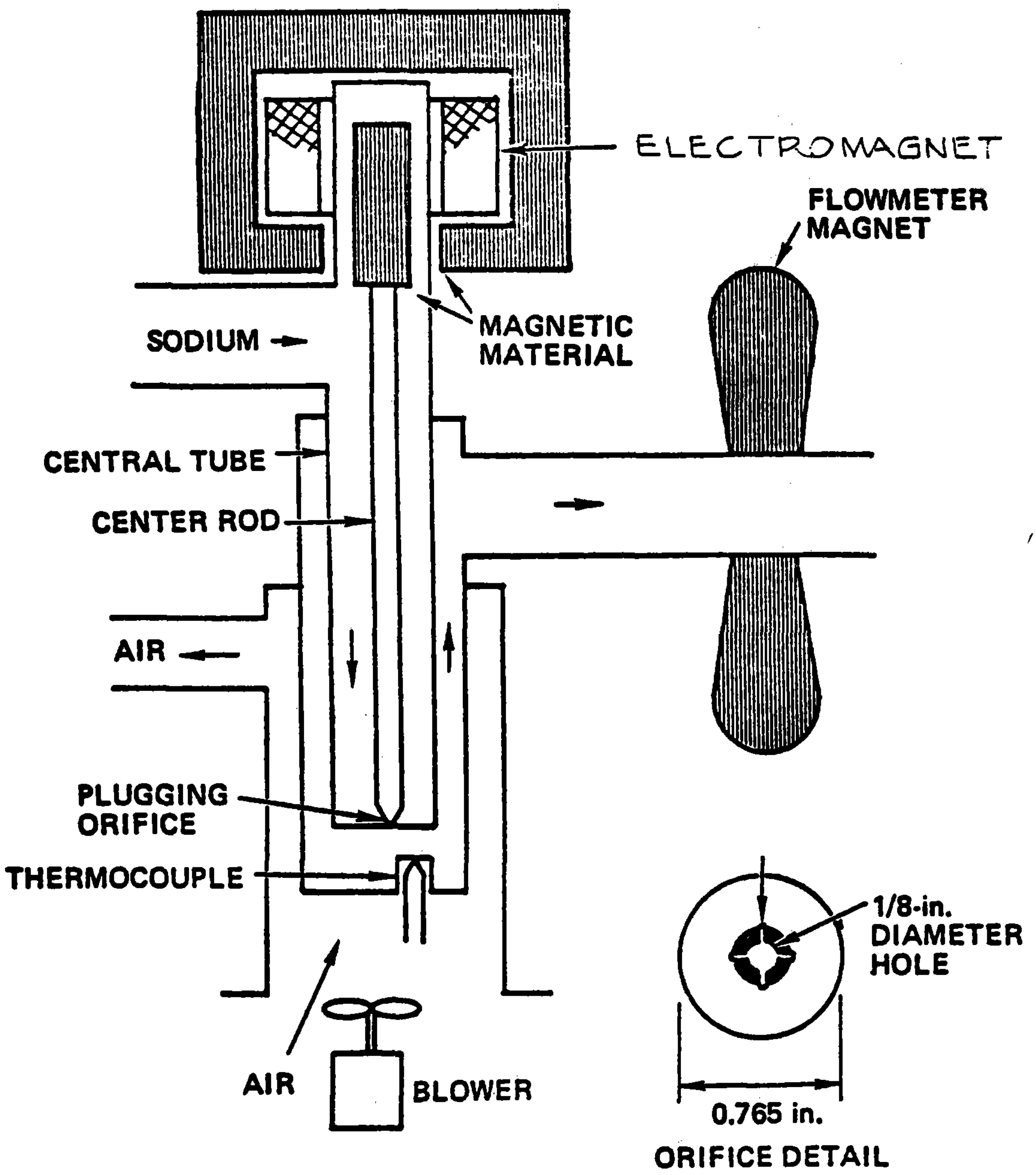


Figure 5-60. Plugging Meter Schematic

recorded on a strip chart. The temperature at which the flow just begins to decrease is referred to as the plugging temperature.

The maintenance of the fluid utilizes the same principle of precipitating the contaminants as the temperature is lowered. This is accomplished by means of a device called a cold trap, depicted in Figure 5-61. In this system, the sodium enters the economizer section of the cold trap vessel and is reduced in temperature to just above the plugging temperature. It then enters the wire mesh section of the cold trap where it is cooled to below the precipitation temperature by the cooling air flowing over the outside of the trap. As the sodium cools, Na_2O precipitates out and is collected in the knitted wire mesh. The sodium ultimately reaches a temperature of about 250^{o}F which corresponds to an oxygen concentration of about 0.75 ppm. The clean sodium then flows up through the center tube, and is heated in the economizer before being returned to the system. Experience has shown that in a system in equilibrium, the plugging temperature and the minimum cold trap temperature are identical.

During the initial filling operation, the sodium passes through a sintered filter at a temperature of about 300^{o}F. The filter takes out the oxide and delivers sodium with an oxide concentration of about 2 ppm.

5.4.6 Pumps, Piping and Valves

5.4.6.1 Sodium Pump P-2

For the 1.4 SM concept, a sodium steam generator pump (P-2) is required to circulate sodium from the hot storage tank through the steam generator components and back to the cold storage tank. The discussion in Section 3.3.9.1 relating to the receiver pump, P-1, is applicable to this steam generator pump which is included in the sodium thermal storage system. The hydraulic characteristics of pump P-2 is given in Appendix E, "Design Data Sheets."

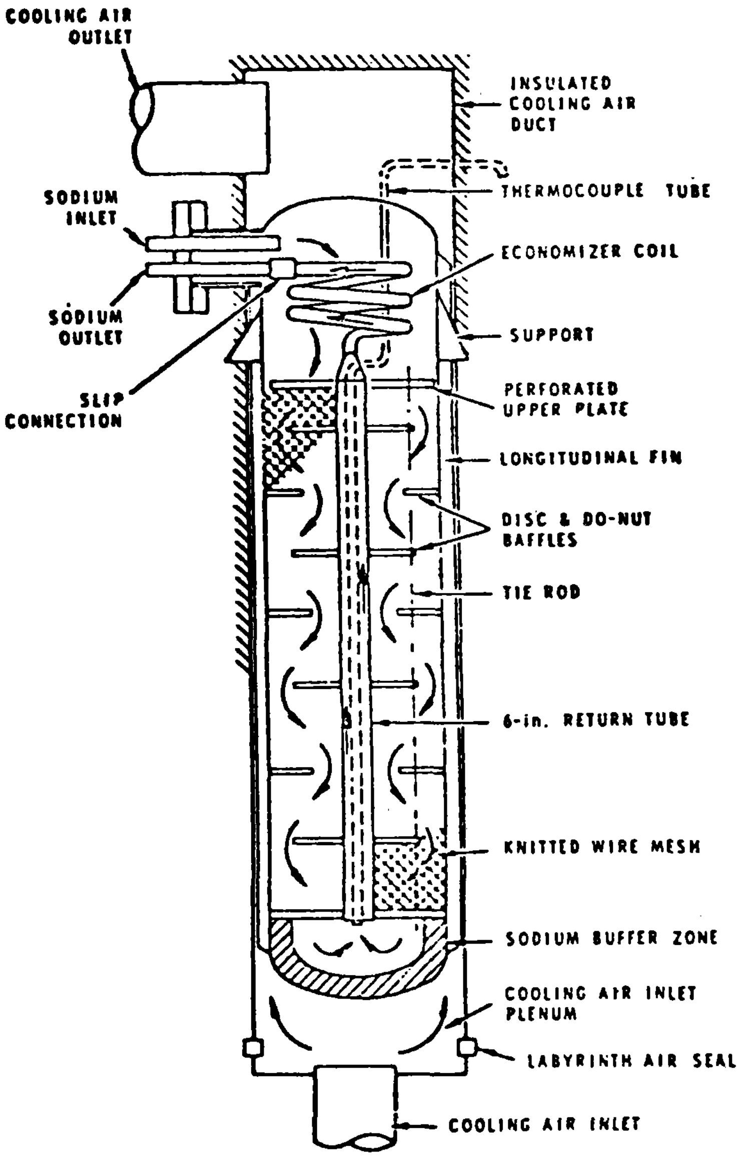


Figure 5-61. Schematic Hallam Cold Trap

5.4.6.2 Sodium Piping

Carbon steel has been specified for all the sodium piping that operates at 288°C (550°F), and stainless steel has been specified for the piping that operates at 593°C (1100°F). Estimates of the piping lengths and weights are given in the Data Lists in Appendix F.

5.4.6.3 Sodium Valves

The sodium valves will be similar to those developed for the Fast Flux Test Facility (FFTF) and the Clinch River Breeder Reactor Plant (CRBRP) project. The small valves will be bellow seal valves, the larger valves may be freeze stem valves.

Drag Valve

In the 1.4 SM sodium thermal storage system, a pressure-reducing device is required to dissipate the tower (receiver) static head. This allows the all-sodium storage tanks to be designed for operation at atmospheric pressure. The argon cover gas pressure is very low (5 psi). Pressurized storage tanks of the large size required would be prohibitively expensive.

A drag valve has been tentatively selected for application as the pressure-reducing device. The drag valve must pass $\sim$20,000 gpm and dissipate the tower static head of 720 ft (maximum receiver elevation). At a sodium density of 50.69 lb/ft^3, this corresponds to a pressure of 253.4 psi.

The valve is sized with 12-in. nominal end connections for a line velocity of 56 ft/s. The drag valve utilizes velocity control elements to provide system pressure and flow control. The valve also incorporates shutoff capability. The valve will be all stainless steel with inconel control elements and can be provided with pneumatic or electrohydraulic control/operator.

The disk stack (Figure 5-62) consists of many disks, integrated together, and fitted with a plug for modulating flow. Each disk has a finite flow capacity which is dependent on the area and number of flow passages between the inside and outside of this disk. The required disk impedance is developed by a series of turns in the flow passages with the number of turns chosed to limit the fluid velocity to an acceptable level regardless of the pressure drop. Since each disk has a specific flow capacity, an appropriate number of them are used to meet the total flow requirement. Typical drag valve construction is shown in Figures 5-63 and 5-64.

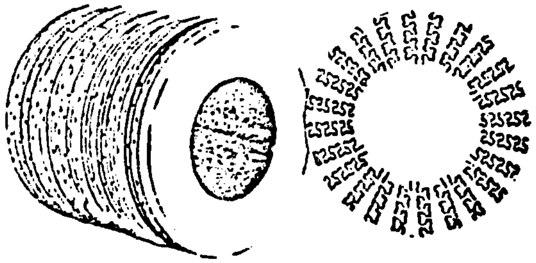


Figure 5-62. Disk Stack with Single Disk

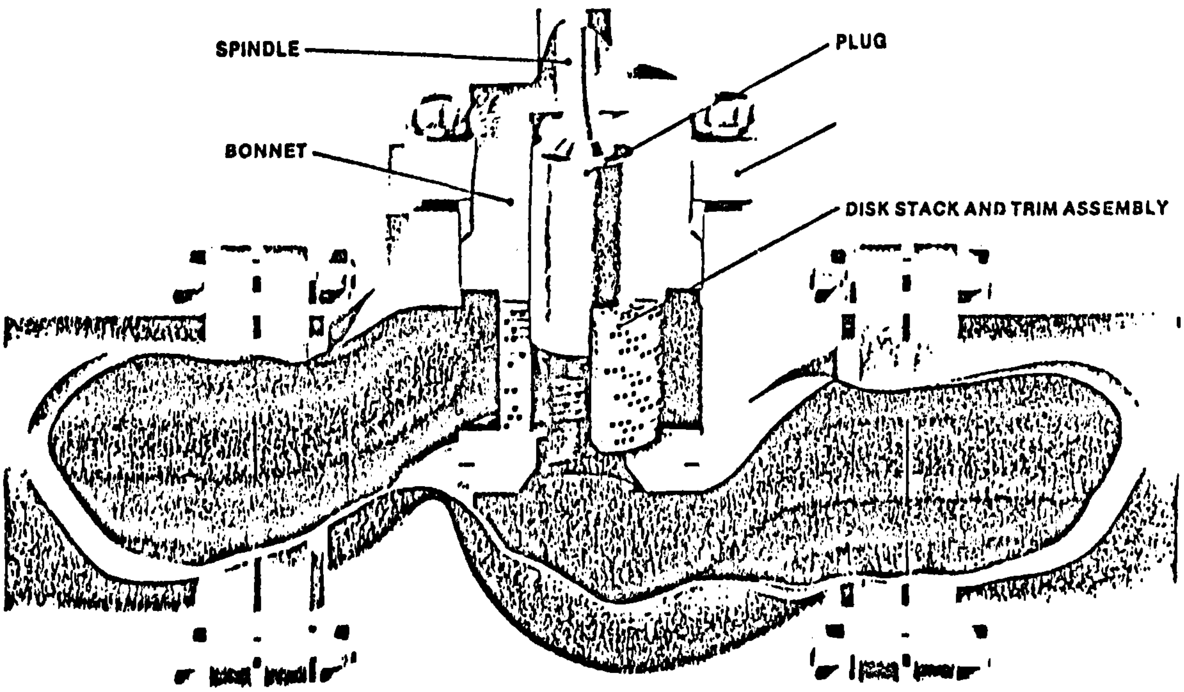


Figure 5-63. The Self Drag Velocity Control Element

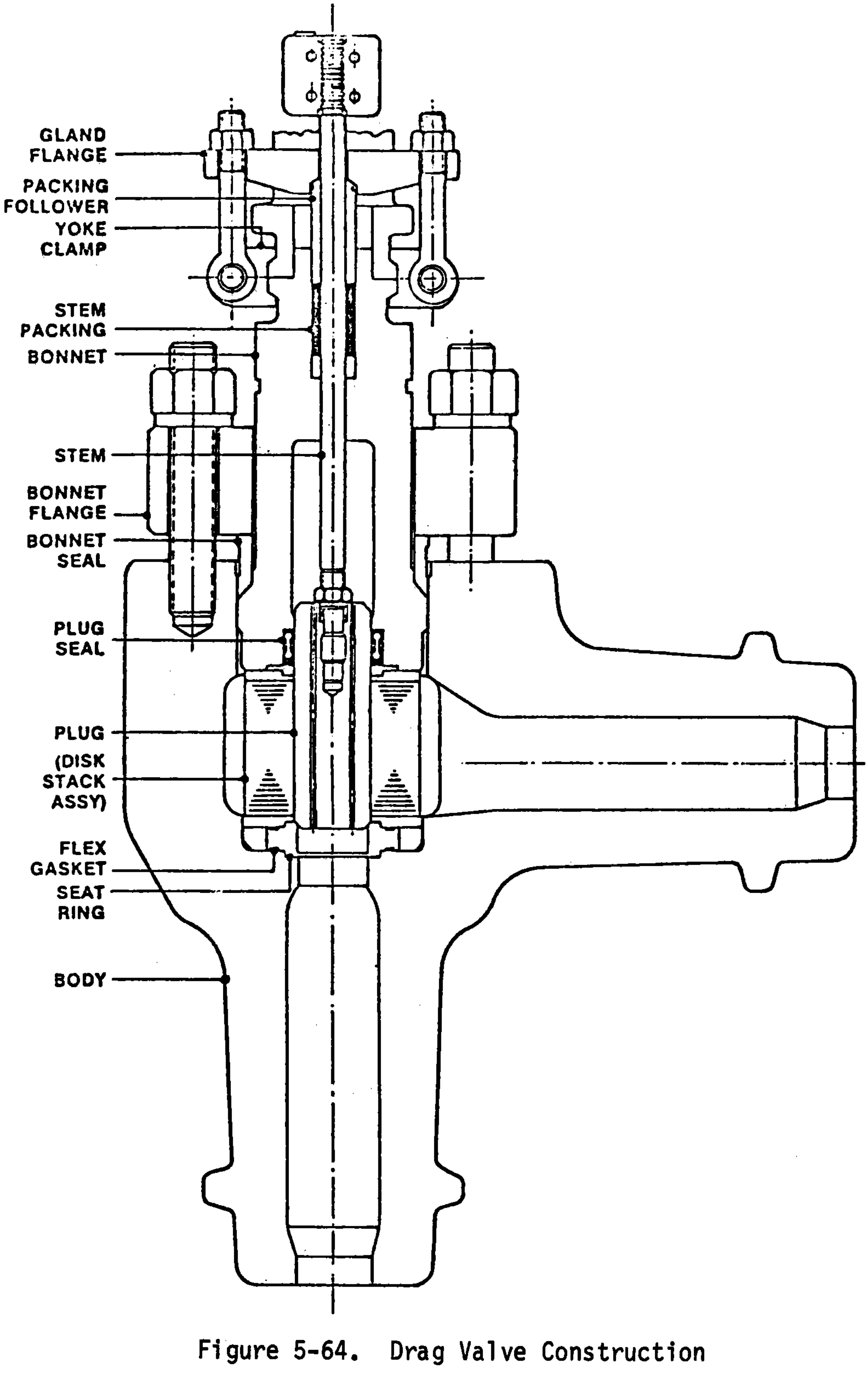


Figure 5-64. Drag Valve Construction

5.4.7 Leak Detection and Fire Protection

Leak detection techniques will vary, depending on the location of the expected leak.

The receiver and other unenclosed areas 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. An alternate plan is to use acoustic emission techniques to detect leaks.

Sodium-sensitive aerosol detectors will be located in enclosed spaces, and in the chimney along with the spacing meter.

Sodium catch pans will be provided under major components to confine the consequences of sodium leaks to a local controlled area until the component can be drained. The steam generator catch pans will be provided with a sump and pump to assure the catch pan remains dry. Nitrogen gas will be supplied for the purpose of flooding the catch pans if sodium combustion is initiated.

Approved fire suppressant extinguishers (Nax) will be placed throughout the facility.

5.5 NON-SOLAR SUBSYSTEM

5.5.1 Non-solar Subsystem Requirements

For both the 0.8 and 1.4 solar multiple system configurations, the fundamental non-solar subsystem requirements are dictated by: (1) the desire for full plant capacity credit, and (2) the results of the fuel selection trade study (see Section 4.3.6). The desire for full capacity credit means that the heater must be capable of supplying the full requirements of the steam generator, 260 MWt. The recommendations of the fuel trade study indicated that the most cost-effective fuel is coal. This then becomes the primary non-solar energy source. However, it is important to remember that the coal-fired furnace is also capable of firing oil or gas. The requirements of the fuel handling system are set up to accommodate coal. But provisions were made for economical transition to the other fuels in the future. A detailed summary of requirements of the coal-fired heater is shown in Table 5-11.

5.5.1.1 0.8 Solar Multiple

In addition to the non-solar subsystem requirements common to the 0.8 and 1.4 solar multiple system configuration, the 0.8 solar multiple has additional requirements relating to the heater ramp rate and minimum power. Since the heater supplements the receiver power, the heater must always be capable of assuming the total plant load on minimum notice. Due to the nature of expected receiver transients and the capacity of the thermal buffer, the requirement for maximum time for the heater to ramp from 20 to 100% power in this configuration is 5 minutes.

Due to the nature of coal combustion, the minimum heater power was set at 20% for the 0.8 solar multiple. This will insure reliable, safe, stable operation at low power and maintain the heater in the optimum condition of readiness for ramping to full power.

TABLE 5-11

NON-SOLAR SUBSYSTEM REQUIREMENTS

	0.8 Solar Multiple	1.4 Solar Multiple
Full Power Output to Sodium	260 MWt	260 MWt
Minimum Power Output to Sodium (Standby)	52 MWt	0
Primary fuel	Pulverized Coal	Pulverized Coal
Backup Fuels	Oil, Gas	Oil, Gas
Coal Handling Capacity	52 Ton/hr	52 Ton/hr
Gas Flow Leaving Air Heater	1×10^6 lb/hr	1×10^6 lb/hr
Maximum Sodium Flow	5.4×10^6 lb/hr	5.4×10^6 lb/hr
Inlet Sodium Temperature	550^oF	550^oF
Outlet Sodium Temperature	1100^oF	1100^oF
Maximum Time to Ramp to Full Power	5 minutes	2 hours
Flue Gas Emissions		
NO_x	0.5 lb/MMBtu	0.5 lb/MMBtu
SO_2	0.6 lb/MMBtu	0.6 lb/MMBtu
Particulates	0.03 lb/MMBtu	0.03 lb/MMBtu

5.5.1.2 1.4 Solar Multiple

In the 1.4 solar multiple configuration, the ramp rate requirement is relaxed due to the size of the thermal storage system, 3 h. Consequently, the ramp time requirements of this heater is set at 0.5 h to allow the heater to come up to full power in a manner which limits the thermal stress magnitudes of the heater components. Also, the 3-h storage system configuration design contains no allowance for storage of heater power. Consequently, heater power is 0 during times of significant solar insolation.

5.5.2 Fuel Storage Design

5.5.2.1 Coal Storage and Handling

The Coal Handling Facility shall supply coal to the 100 MW Solar Central Receiver Hybrid Power Station. The plant will burn ~47.2 tonne/h* (52 tph) of coal at 100% load. The estimated use factor for the coal handling system is 0.58. The proposed coal handling system schematic is shown in Figure 5-65.

Coal Source and Characteristics

The coal will be received from a mining operation by train. For purposes of design, the coal will have a nominal size of 5 cm x 0 cm (2 in. x 0 in.) at the track hopper facility and shall be considered to weigh 800 kg/m^3 (50 lb/ft^3).

5.5.2.2 Coal Receiving Facility

The coal receiving facility shall consist of all components and operations as required for the coal handling from the track hopper to delivery to the crusher building.

1) Coal Delivery

   Coal delivery will be by train in batches of 50 bottom dump 90.9 tonne (100 ton) cars.

2) Coal Unloading

   a) A four-throat track hopper will be provided to receive the coal from the bottom dump cars. The track hopper will be enclosed and dust collection system will be provided to control the fugitive dust generated by the unloading operation.

   b) The rail coal cars shall be unloaded on the track hopper at a rate of 5 cars per hour. Unloading of the track hopper shall

*1 metric tonne = 1,000 kg = 2200 lb = 1.1 ton

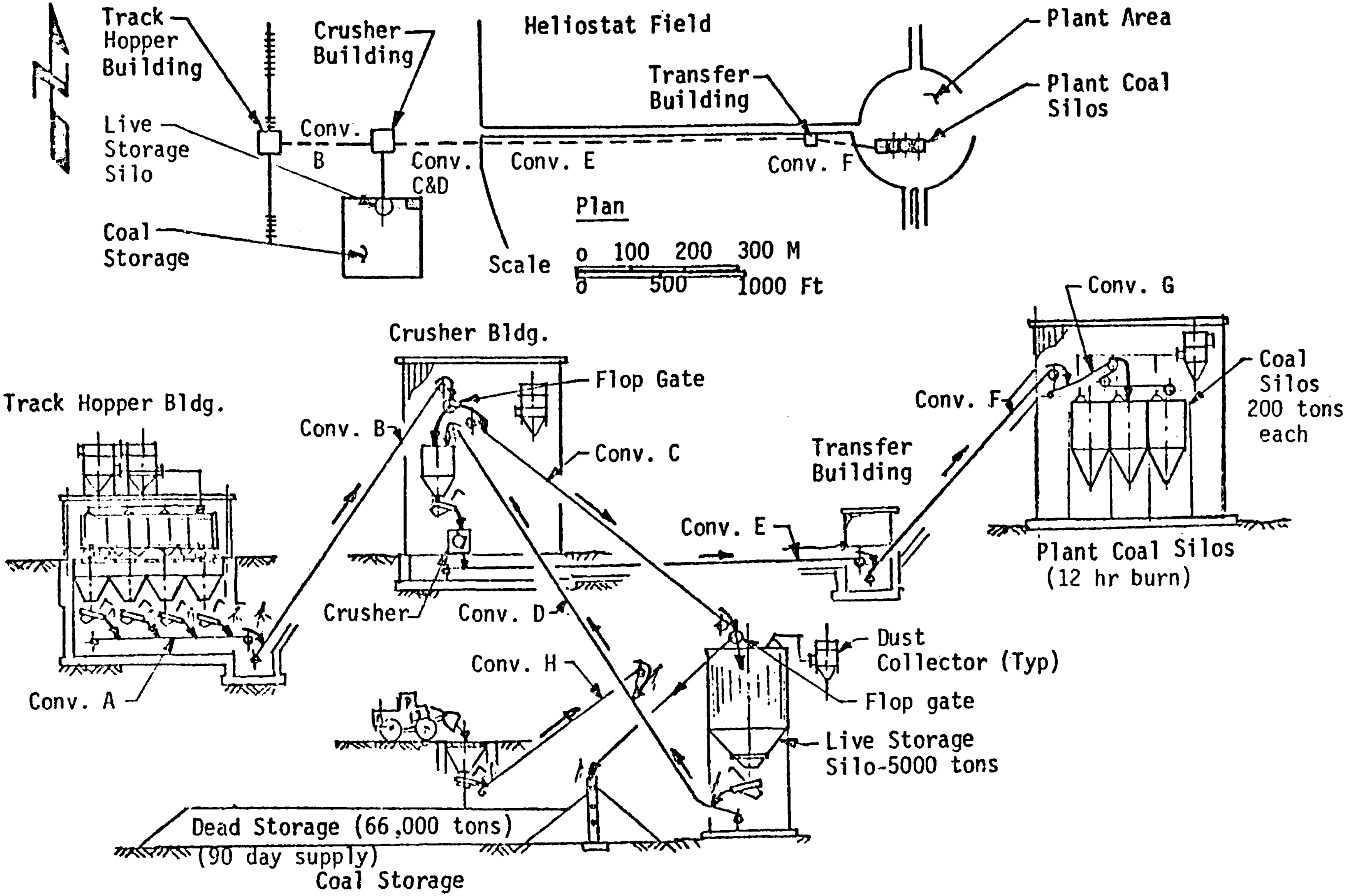


Figure 5-65. Coal Handling Schematic

be accomplished by four vibrating feeders rated at 114 tonne/h (125 thp) each. An 0.9 (36 in.) collecting Conveyer A will be provided to gather the coal from the vibrating feeders and deliver the coal to 0.9 m (36 in.) unloading Conveyer B.

c) The unloading Conveyor B rated at 455 tonne/h (500 thp) shall deliver the coal to the crusher building.

5.5.2.3 Coal Storage

1) Live Storage

a) A 4545 tonne (5,000 ton) live storage silo designed to accept one batch of 50 rail cars shall be provided for the coal handling system to supply the plant silos on demand. A dust collection system shall be provided for the silo to collect the dust generated by the silo filling operation.

b) An 0.9 m (36 in.) stack-out conveyor rated at 455 tonne/h (500 thp) shall be provided to deliver the coal from the discharge end of the unloading Conveyor B to the live storage silo.

c) A vibrating bin bottom and a vibrating feeder rated at 182 tonne/h (200 thp) shall be provided at the bottom of the live storage silo to reclaim the coal. The vibrating feeder shall load the coal onto an 0.6 m (24 in) reclaim Conveyor D. The reclaim Conveyor D shall then deliver the coal to the crusher building.

2) Dead Storage

a) A dead storage pile shall be provided for the coal handling system to provide coal to the plant in cases of mine strikes and the like. The pile will have a capacity of 60,000 tonnes (66,000 tons) which is equivalent to 90 days burn at 58% capacity factor.

b) The dead storage pile shall be built by directing the coal flow at the discharge end of the stack-out Conveyor C by a provided flop gate to a lowering well. The coal shall then be spread and compacted to a 7.6 m (25 ft) high pile.

c) Reclaiming the coal from the dead storage pile shall be accomplished by earth moving equipment. A reclaim hopper, a vibrating feed and an 0.6 m (24 in.) dead storage reclaim Conveyor H shall be provided to receive the coal from the mobile equipment and deliver the coal to the reclaim Conveyor D.

d) A wet dust suppression system shall be provided for the dead storage lowering well and reclaim hopper to control dust generated by handling the coal.

5.5.2.4 Crushing Facility

1) Coal from the track hopper facility and the live storage silo shall be received at the crusher building by a surge hopper. A vibrating feeder located at the bottom of the hopper shall then feed the coal to a crusher at the rate of 182 tonne/h (200 tph).

2) A coal crusher designed to accept 5 cm x 0 cm (2 in. x 0 in.) coal shall be provided to crush the coal to 1.9 cm x 0 cm (3/4 in. x 0 in.) for coal firing. The crusher shall be a ring granulator type. The crusher shall then discharge the coal into an 0.6 m (24 in.) underground transfer conveyor.

3) The crusher building will be provided with a dust collection system to control the dust generated by the crushing operation.

5.5.2.5 Conveying System to Plant

A 0.6 m (24 in.) underground transfer Conveyor E shall be provided to transfer the coal from the crusher discharge to the Transfer Building. A 0.6 m (24 in.) plant Conveyor F shall then accept the coal from Conveyor E and elevate the coal to the silo tripper Conveyor G. The conveying system shall be rated at 182 tonne/hr (200 tph).

5.5.2.6 Silo Filling

1) Three coal silos shall be provided to store 12 h of coal burn or 182 tonnes (200 tons) of coal per silo. The coal silos shall be provided with a dust collection system to control the dust generated by the filling operation.

2) An 0.6 m (24 in.) silo tripper Conveyor G shall be provided to accept the discharge of Conveyor F and load the coal into the silos. A traveling tripper complete with a dust seal system shall be incorporated in Conveyor F to fill the silos.

Fire Protection System

The coal handling system will be protected throughout by fire suppression equipment.

5.5.2.7 Fuel Oil Storage and Handling

The purpose of the fuel oil storage and handling system is to provide a reliable storage and supply of No. 2 fuel oil for the oil ignitors on the sodium heater. The 100 MWe sodium heater rated ignitor oil heat input is 26.4 MWt (90×10^6 Btu/h).

The ignitor oil system diagram for the 100 MWe plant is shown in Figure 5-66.

The fuel oil storage and unloading facility will be designed to handle both rail tank car and tank truck fuel oil deliveries. The ignitor oil will be No. 2 fuel oil meeting the requirements of ASTM D396.

The primary fuel oil storage facility will be located at the rail line outside of the collector field and will consist of a fuel oil unloading pump and an above-ground 946 m^3 (250,000 gal) fuel oil storage tank. A berm will be provided to contain the entire contents of the tank. A fuel oil transfer pump will be used to transfer oil from the primary fuel oil storage tank to the 321 m^3 (84,800 gal) secondary above-ground fuel oil storage tank located within the plant core area.

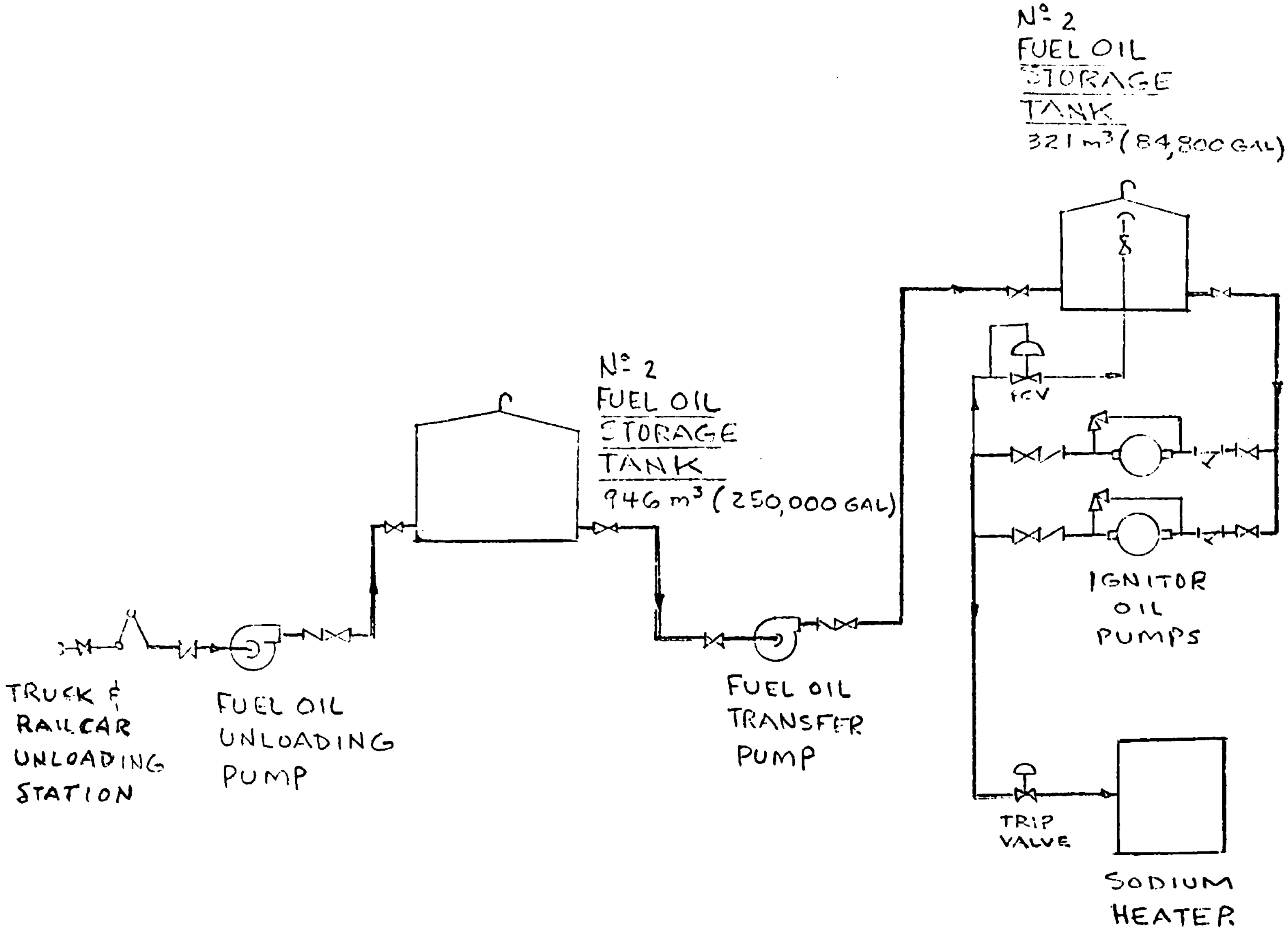


Figure 5-66. Ignitor Oil System Diagram

The ignitor oil pumps (2 full capacity pumps) will be of the horizontal, positive displacement rotary type with electric motor drives. The pumps will be designed to supply 0.045 m^3/min (~12 gpm) of No. 2 fuel oil at 413 kPa (60 psig) to the sodium heater ignitors. The pumps will be controlled remotely from the control room.

Fire protection for the fuel oil storage tanks will be provided by fixed foam extinguishing system. Each tank will be enclosed by a berm designed to contain the entire tank contents. In addition, fire hydrants will be provided as required for area protection.

5.5.3 Fuel Feed Design (0.8 and 1.4 Solar Multiple)

The fuel feed system is required to convey and deliver up to 47,300 kg (52 (tph) of design basis coal to the fuel preparation system and the heater. The components in the fuel feed system include: the coal unloading facility, the raw coal conveying system, raw coal storage silos, coal feeders, and pulverized coal conveying system. Dust suppression and coal weighing and sampling equipment are also included in this system as peripheral components.

A simplified schematic of the final components of this system is shown in Figure 5-67. This system is virtually identical to the standard coal feed and handling equipment being specified and installed in modern conventional coal-fired power plants. A detailed description of the fuel feed design is incorporated in Section 5.5.2.

5.5.4 Fuel Preparation Design (0.8 and 1.4 Solar Multiple)

The fuel preparation system is required to process 47,300 kg/h (52 tph) of the design basis coal (see Appendix F, Electric Power Generation Subsystem). The input coal will be in a raw state and may have more moisture than shown in the design data sheets due to surface moisture. The output coal must be pulverized and dried for use in the dual register burners of the heater.

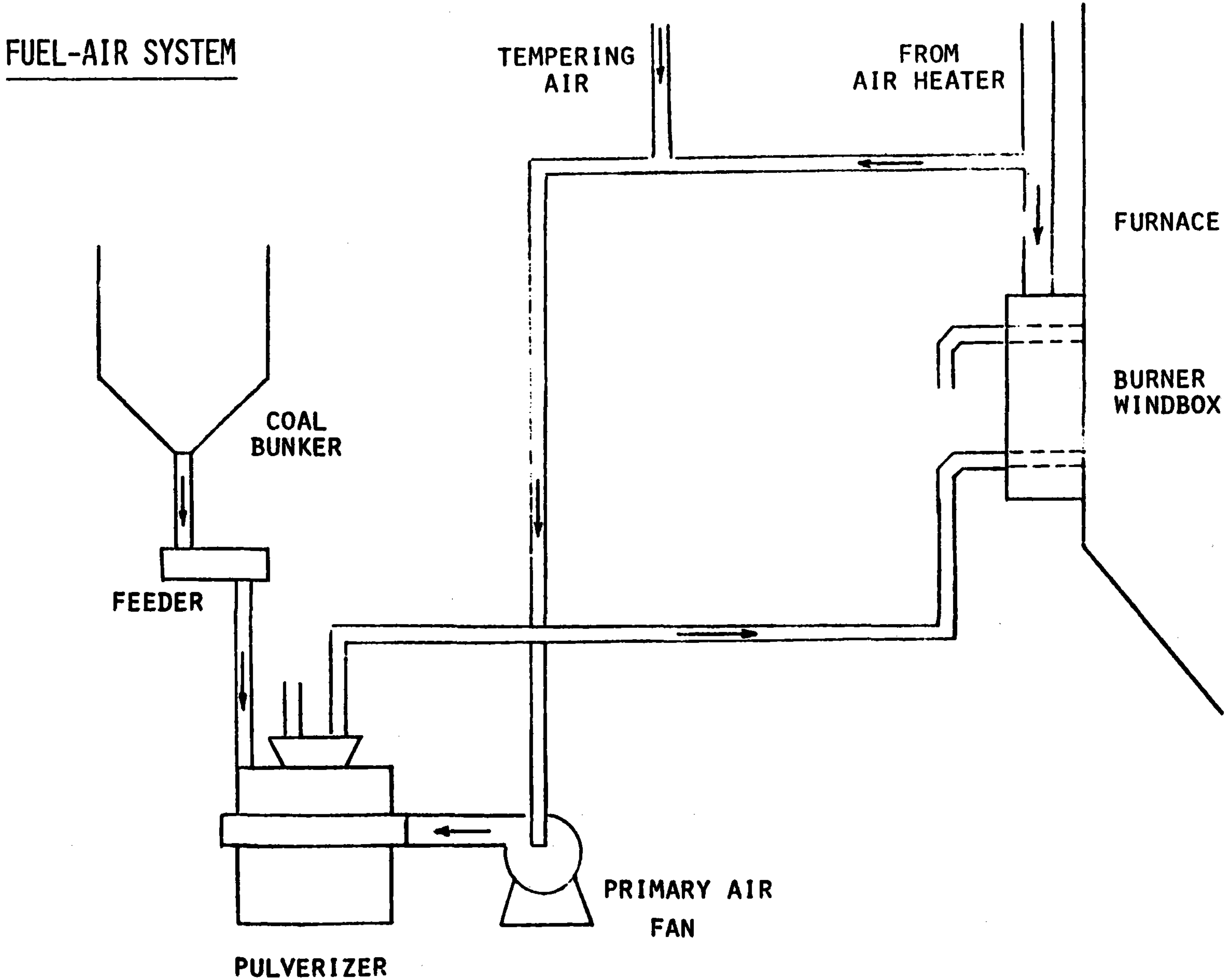


Figure 5-67. Fuel Feed Schematic

There are two components in the fuel preparation system: the crusher and the pulverizer. The crusher is located in the fuel feed system between the raw coal storage pile and the conveying system. The design mean output coal diameter of the crusher is 1.9 cm. The Crushing Facility is described in Section 5.5.2.4.

Three B&W Type EL-76 pulverizers have been selected to supply the 52 ton/h fuel feed rate required at full load. The EL-76 pulverizer is a single-row ball-and-race unit operated under pressure. Its operating characteristics are summarized in Table 5-12. A primary air fan forces hot air through the pulverizer and delivers the resultant coal-air mixture to the burners. Air flow and fuel flow are monitored and controlled to assure that the proper coal-air ratio for stable firing is achieved. Because the system operates under positive pressure, rather than suction, the fan operates entirely on air, and wear of the rotor and housing is minimized.

The pulverizers and burners are operated as sets, with one pulverizer feeding a row of three burners. To eliminate the need for a distributor, each burner is supplied by an individual line direct from the pulverizer. Each pulverizer, at capacity, will process 20 ton/h. Thus the sodium heater can be operated up to ~77% of full load with one of the three units out of service for maintenance.

A tube-mill type pulverizer, which offers storage to facilitate load changes, was considered as a possible alternative to ball-and-race type units. However, because power requirements for these units are essentially independent of load, operating expense at low loads is increased. For this reason, the tube-mill pulverizer is considered unsuitable for this application.

A schematic of the El-type pulverizer is shown in Figure 5-68. Raw coal is fed from the integral coal feeder into a ball and race crusher, pulverizer mechanism. Primary air, from the primary air fan, entrains the pulverized coal and carries it to the classifier. Coal not meeting the required size criteria drops out of the coal/airstreamand is returned to the pulverizer. The coal/air stream splits at the top of the pulverizer and from there travels to the heater burners directly. Pulverizers are switched on or off depending on the heater demand. Each pulverizer is capable of handling 50% of the heater demand at full power.

TABLE 5-12

B&W TYPE EL-76 PULVERIZER OPERATING CHARACTERISTICS

	20% Load (1 unit in service)	Full Load (3 units in service)	Design Value at Rated Capacity	Comments
Sodium Flow Rate (lb/h)	1.08×10^6	5.4×10^6	-	-
Coal Feed Rate per Pulverizer (lb/h)	20800	34700	40000	-
Primary Air Flow per Pulverizer (cfm at 150°F)	12800	16600	18000	-
Primary Air/Coal Ratio (ft^3/lb at 150°F)	36.9	28.7	27.0	76.0 maximum for stable ignition
Air Velocity at Pulverizer Throat (ft/min at 200°F)	6920	8980	9740	4500 minimum to keep coal in suspension

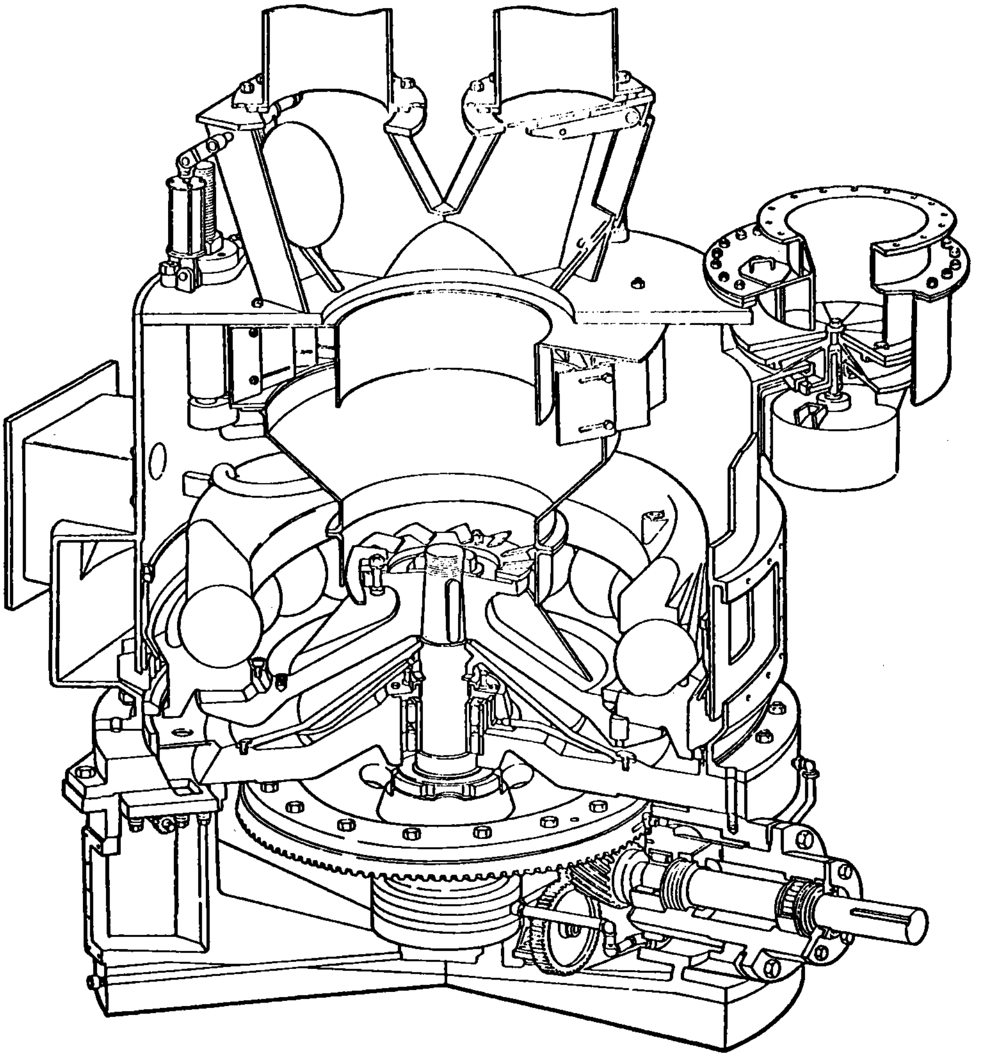


Figure 5-68. B&W's El Pulverizer

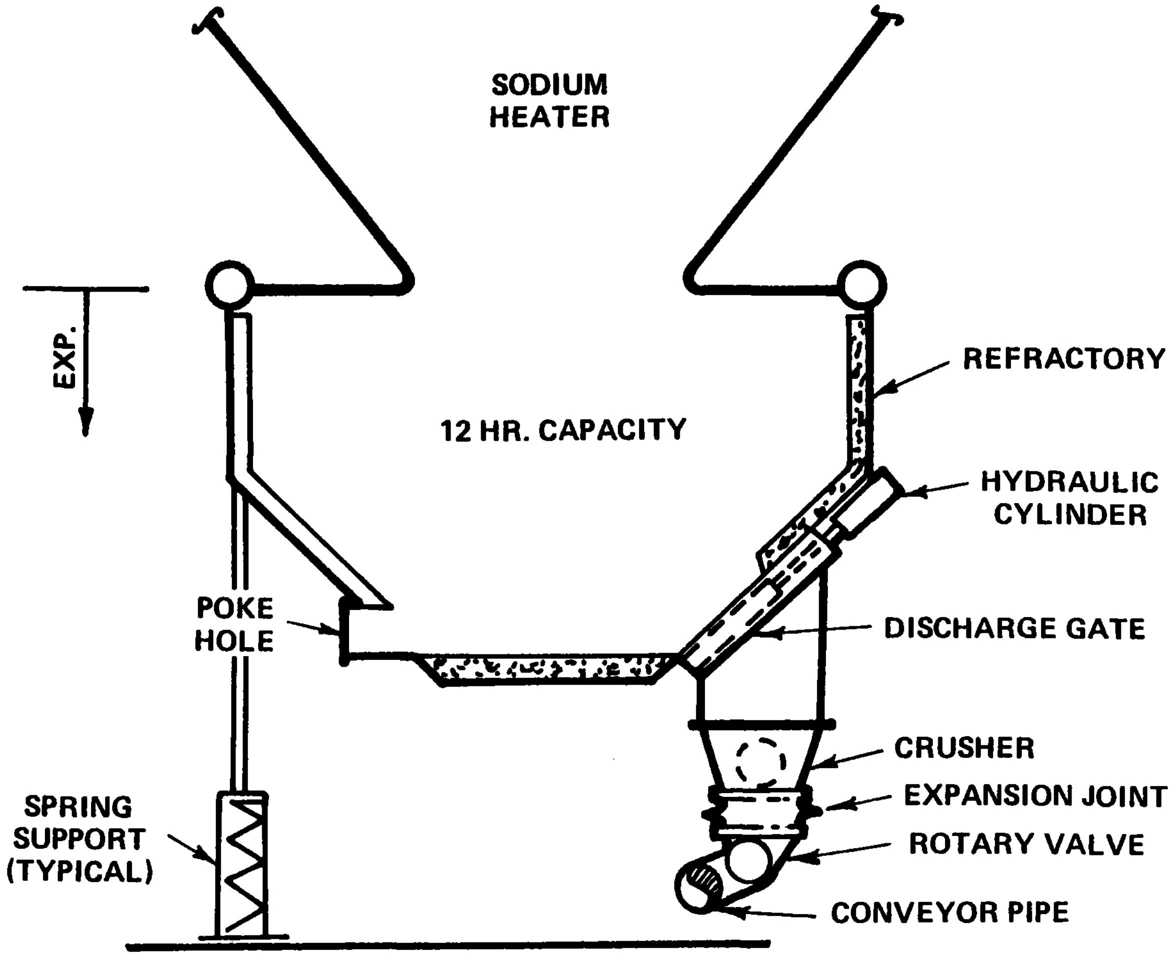


Figure 5-69. Bottom Ash Hopper

Consequently, emergency cross-feeding the pulverizers would allow full heater power output in the event of one pulverizer being unavailable.

5.5.4 Waste Handling

5.5.4.1 Ash Handling System (0.8 and 1.4 Solar Multiple)

The ash handling system design is based on a coal firing rate of 47,300 kg/h (52 tph) with 12-1/2% total ash and a fly ash to bottom ash ratio of 80%/20%. A pneumatic ash conveying system will handle both bottom ash from the sodium heater ash hopper and fly ash from the baghouse ash hoppers. The fly ash system will also remove spent SO_2 absorbent along with the fly ash collected in the ESG dry SO_2 removal system. The conveying scheme, shown in Figure 5-69, consists of a negative pressure pneumatic conveying system powered by a mechanical vacuum producer. The ash storage bin is located in the central core area of the plant.

The bottom ash system will include a three-compartment, dry, refractory-lined ash hopper, suspended from the sodium heater, clinker grinders, and automatic feeding regulation (see Figure 5-69). The bottom ash hopper is sized to provide a minimum of 12 h storage at full load. Bottom ash leaving the crushers will be conveyed by a negative pressure pneumatic conveying system to the ash storage bin where ash is stored prior to removal by truck.

All ash collected in the sodium heater ash hopper and baghouse will be stored in an ash storage bin prior to removal by ash trucks. The ash storage bin is sized to provide a minimum 3-1/2 days storage at rated conditions. Ash is stored in the bin in a dry state. During ash unloading, the dry ash passes through an ash conditioner where it is mixed with the proper proportion of water to prevent dusting and facilitate unloading into ash trucks for disposal. The ash trucks will be provided with covers to minimize dust problems during ash hauling.

5.5.4.2 Flue Gas Exhaust (0.8 Solar Multiple)

The chimney arrangement for the 0.8 solar multiple, 100 MWe, coal-fired sodium heater is shown schematically in Figure 5-70. The chimney is located

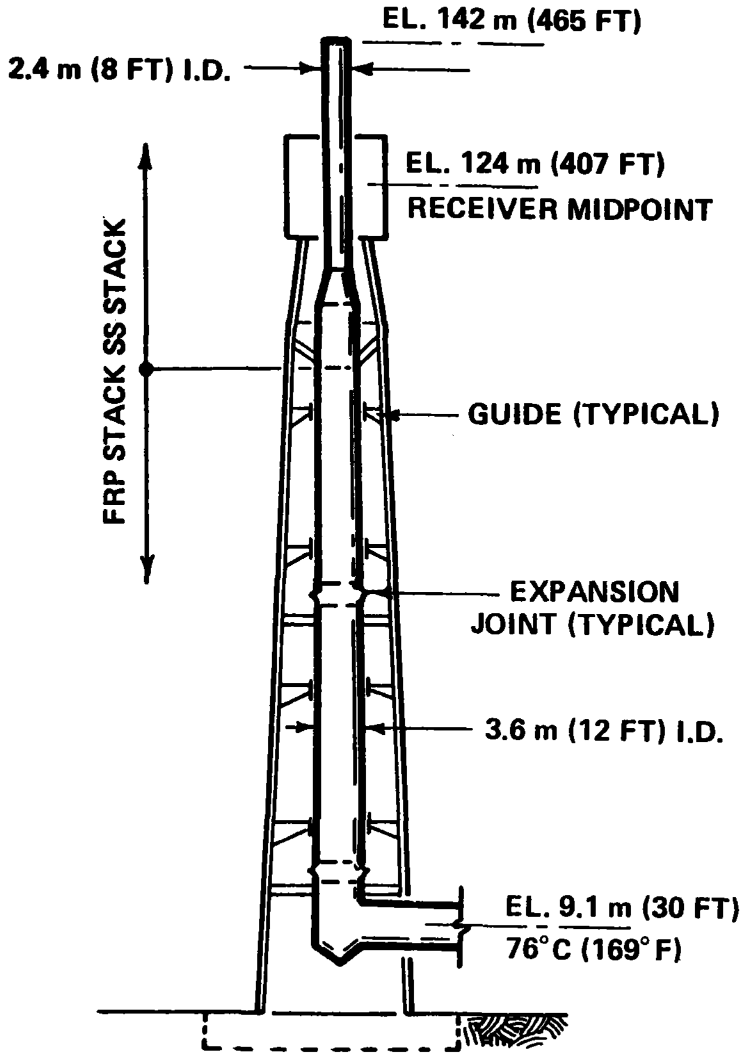


Figure 5-70. Chimney

within the reinforced concrete receiver tower structure which supports the weight of the chimney in addition to the receiver assembly. A detail of the chimney at the tower/receiver interface is shown in Figure 5-71.

The chimney materials were selected to provide the necessary corrosion protection when exposed to the potentially corrosive gases leaving the "dry" SO_2 removal system, in addition to erosion and ambient temperature considerations. The chimney construction below the top of the tower is fiberglass reinforced plastic (FRP), a material which is being used more recently on many conventional fossil-fired plants following wet stack gas scrubbers. Above the interface at the top of the tower, Type 316 stainless steel is used for the chimney material. The transition from FRP to Type 316 stainless steel was due to internal erosion and external temperature considerations in the receiver area. Type 316 stainless steel also provides a high degree of corrosion protection.

The stack plume effects are an important consideration because of the stack's proximity to the receiver surface and heliostat field. Also, insolation can be effected by the stack plume. The estimated plume rise for the 100-MW plant at rated non-solar load and at 20% load for a 142 m (465 ft) stack is shown in Figure 5-72. In the baseline design, the top of the stack was arbitrarily established at 4-1/2 stack diameters or 11 m (36 ft) above the receiver surface in order to minimize any aerodynamic downwash problems due to the proximity of the relatively large receiver surface, particularly at low loads.

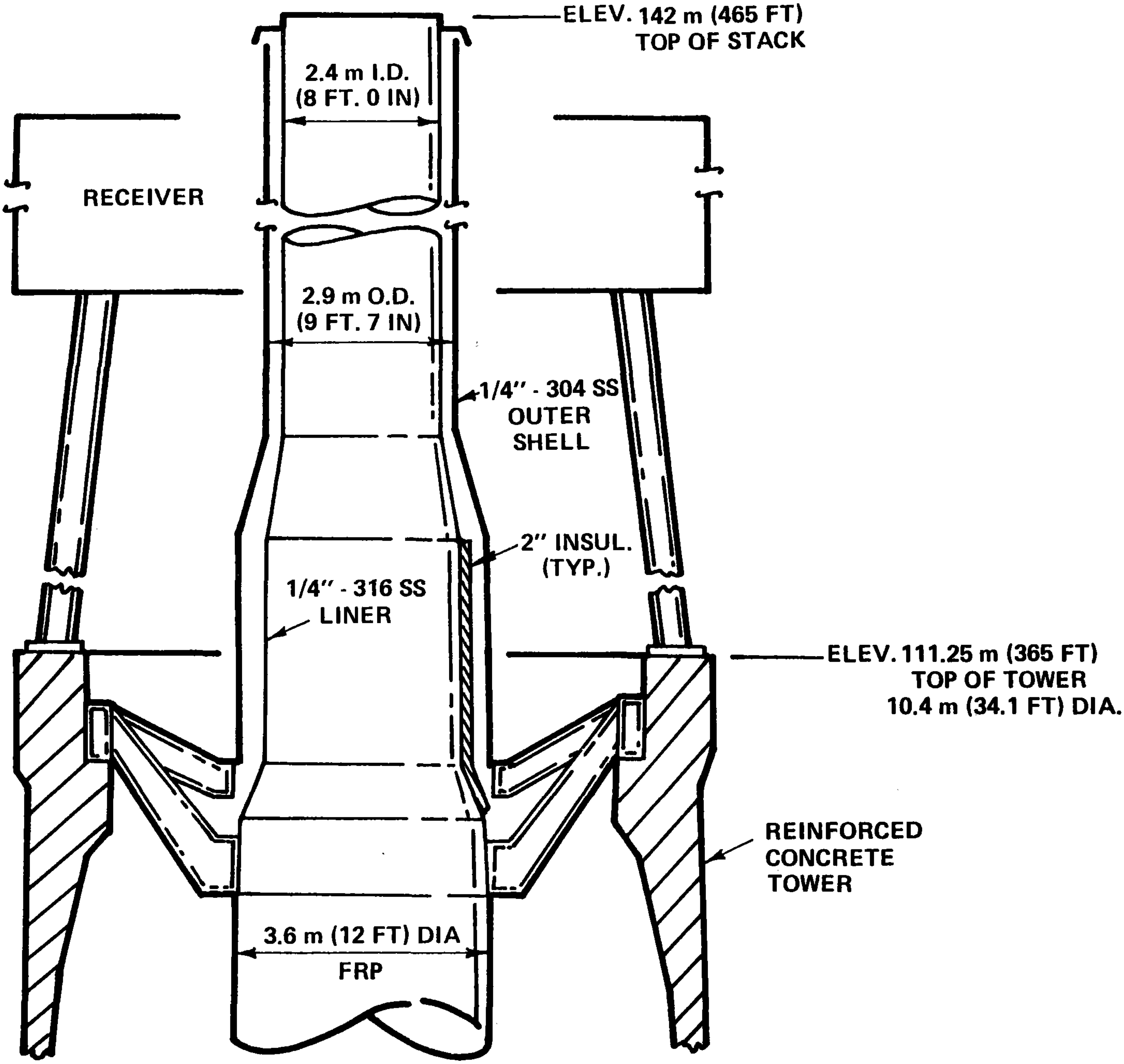


Figure 5-71. Chimney Detail

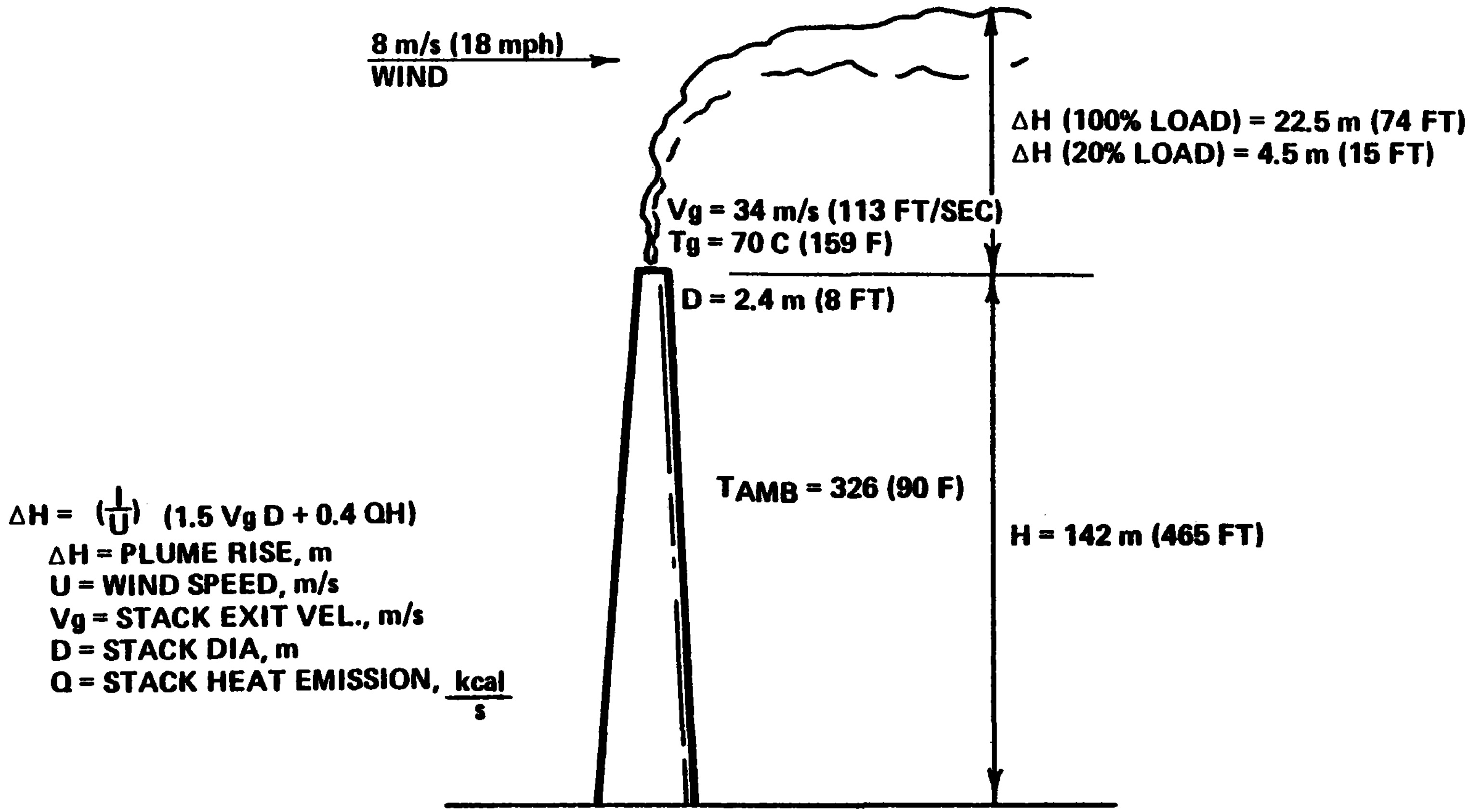


Figure 5-72. Estimated Plume Rise

SUMMARY

The electrical power generating subsystem requirements are discussed and tabulated. The turbine equipment selected is a standard tandum compound, double flow, reheat, condensing turbine rated at 112,000 kw gross. A typical cross-section of the turbine is shown. A detailed description of the fossil-fired sodium heater follows, including sketches of the heater and temperature/power profiles. Next, a description of the feedwater heating and condensing equipment design is given, followed by a discussion of the cooling tower design and makeup water requirements. Heat rejection will be accomplished by utilizing an evaporative (wet), mechanical draft cooling tower. A discussion of a preliminary evaluation of wet vs wet-dry cooling towers is presented. The details of the water treatment and condensate makeup are given and the equipment is specified.

Air quality control equipment for the sodium heater are discussed in some detail and the EPA standards are summarized. The design selected to meet the EPA standards include dual register burners operating in conjunction with 115% theoretical air in the furnace for NO_x formation suppression, an ESG dry flue gas desulfurization (FGD) system for SO_2 removal and a Wheelabrator-Frye fabric filter for particulate removal.

At the end of this section, the details of the main and auxiliary electrical systems are described and a one-line diagram is included. One 150-kw emergency power diesel engine generator was selected to provide ac power for safe shutdown and emergency service. A discussion of the heliostat field feeders and the dc system is also included.

5.6 ELECTRIC POWER GENERATION SUBSYSTEM (EPGS)

5.6.1 Subsystem Requirements

Table 5-13 gives the requirements for the EPG subsystem, based on the Requirements Definition Document, Reference 1, and the preferred system requirements of Section 5.1.1. The gross turbine-generator output was estimated on the basis of preliminary auxiliary power requirements. The EPGS configuration and layout shall be designed to facilitate efficient and safe operation and maintenance. Thermal shocks applied to the turbine loop shall be minimized by appropriate design of the receiver, nonsolar, and energy storage subsystems. The output from the EPGS shall be integrated into existing electric power system networks. IEEE codes will be utilized in the design of the electrical system.

Turbine inlet steam temperature was selected on the basis of the capability of current turbine equipment. While higher steam temperatures have been used in the past, and the sodium system has the capability to provide increased temperatures, the performance record and availability for such units has not been good. The steam throttle pressure was selected by the cycle trade studies of Section 3.6. Wet cooling was specified in Reference 1 of the Requirements Definition Document.

5.6.2 Turbine Equipment Design

The 100 MWe Commercial Plant EPGS conceptual design is based on the use of a standard tandum compound, double flow, reheat, condensing turbine rated at 112,000 kW gross. A typical cross-section of a large reheat turbine of this type is shown in Figure 5-73.

The selected 100 MW Commercial Plant turbine cycle is shown in Figure 5-74 and utilizes single reheat and six stages of feedwater heating with the top heater above the reheat point (HARP cycle). The initial pressure is 12.5 MPa (1815 psia), initial temperature is 538^{o}C (1000^{o}F), and reheat temperature is 538^{o}C (1000^{o}F). Gross turbine cycle efficiency is 43.5%.

TABLE 5-13

ELECTRICAL POWER GENERATION SUBSYSTEM REQUIREMENTS

Gross Turbine-Generator Output (MWe)	112
Net Turbine-Generator Output (MWe)	100
Turbine Inlet Steam Conditions	
High Pressure (Throttle) Steam [°C (°F)]	538 (1000)
[MPa (psia)]	12.51 (1815)
Low Pressure (Reheat) Steam [°C °F)]	538 (1000)
[MPa (psia)]	2.72 (394)
Heat Rejection	
Method	Wet Tower
Wet Bulb Temperature [°C (°F)]	23 (74)
Daytime MWt [(Btu/hr)]	158 (540×10^6)
Nighttime [MWt (Btu/hr)]	150 (511×10^6)
Turbine Exhaust Pressure kPa (in. Hg)	6.77 (2.0)
Generator Output	
Generator Rating (kVA)	135,000
Power Factor	0.90
Voltage (V)	13,800
Frequency (Cycles)	60
Main Transformer	
Rating (kVA)	130,000
Voltage (kV)	13.8/115
Feedwater Conditioning	
Dissolved Solids (ppb)	20-50
pH	9.5

TANDEM COMPOUND DOUBLE FLOW REHEAT STEAM TURBINE

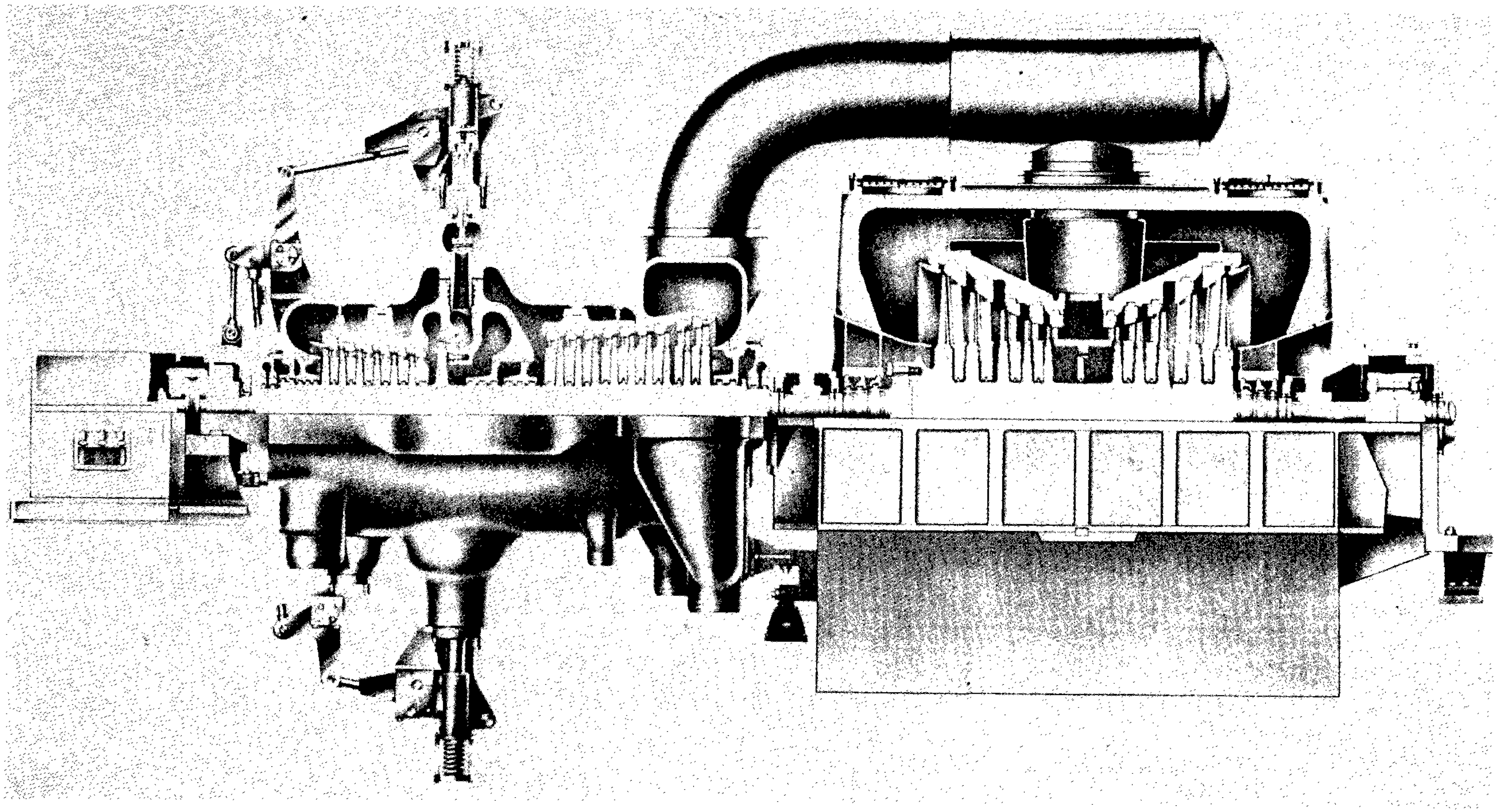


Figure 5-73. Tandem Compound Double Flow Reheat Steam Turbine

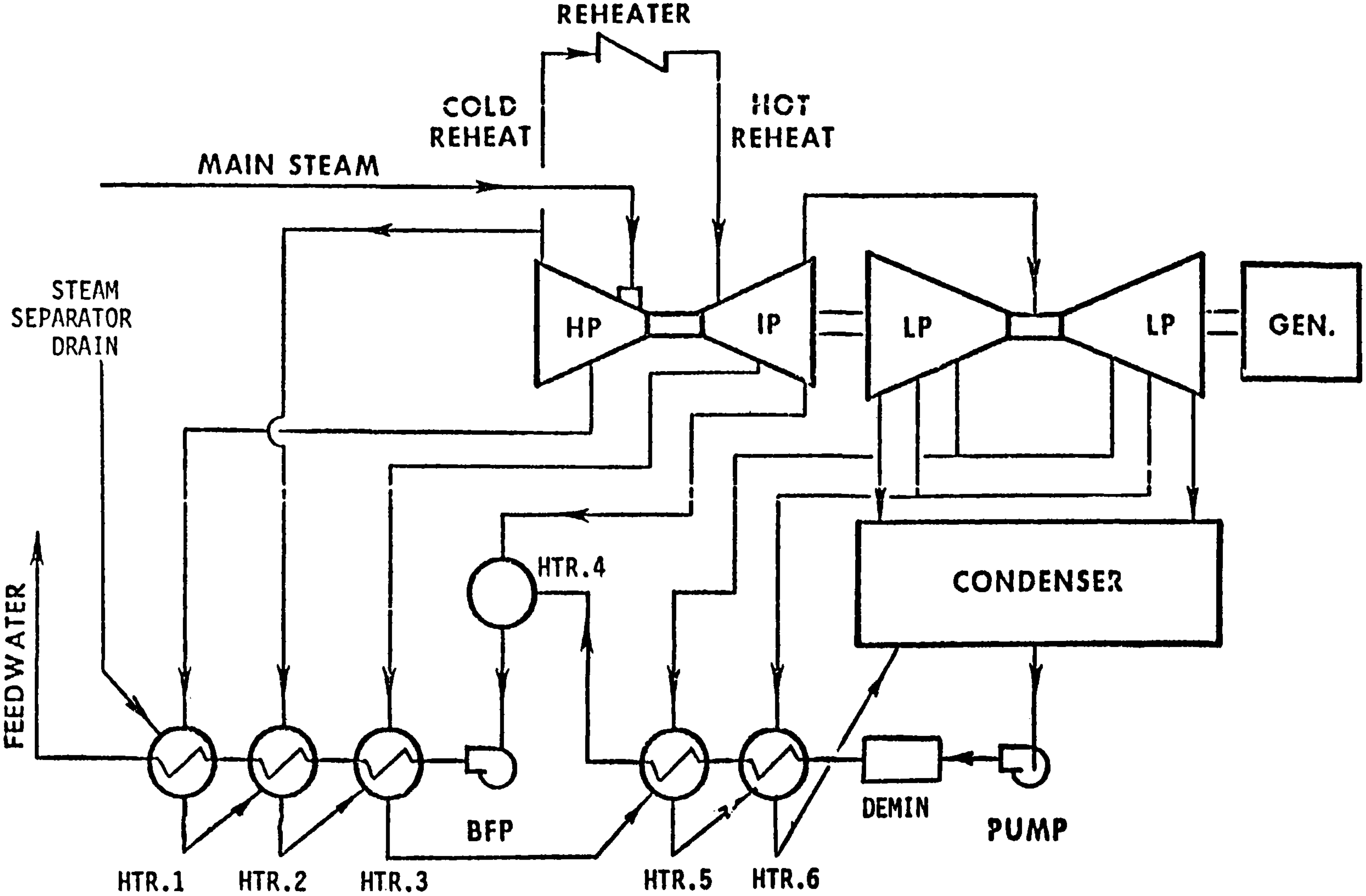


Figure 5-74. Turbine Cycle Configuration

The generator is of the synchronous type rated at 135,000 kVA, 0.90 power factor, 0.58 SCR, 3-phase, 60 Hz, 13,800 V, 3600 rpm, and is hydrogen cooled. A static generator excitation system is provided.

The baseline 100 MW turbine data are summarized in Table 5-14. The preferred commercial turbine data are summarized in Table 5-15.

The design, operation, and performance of the EPGS are independent of the solar/non-solar plant operating modes, except for variations in solar/non-solar plant auxiliary power requirements, since rated steam conditions are provided during either mode of operation.

5.6.3 Energy Generator Equipment Design (Sodium Heater) (0.8 and 1.4 Solar Multiple)

The non-solar subsystem supplies energy to the electric power generation subsystem in the form of pulverized coal. The component which converts this coal to heat energy is the sodium heater. The heater delivers the heat to the primary working fluid, sodium. Finally, sensible heat in the sodium is used to generate steam in the steam generators during times of low or zero insolation. In the case of the 0.8 SM system configuration, the heater is designed to provide at least 20% of the steam generator requirements at all times the plant operates as well as being capable of ramping from 20% to 100% power in < 5 min. For the 1.4 solar multiple configuration, these requirements are relaxed due to the size of the storage subsystem. Otherwise, the heater designs are identical. The designs are summarized below.

The sodium heater is rated at 265 MWt for the required design sodium flow of 5.4×10^6 lb/hr. The heater design sodium inlet temperature is 550°F with the sodium outlet temperature set at 1100°F. The heater is designed to operate in parallel with the receiver. Load apportionment between the heater and receiver is achieved by proportion sodium flow division. The primary heater fuel is pulverized coal supplied by the non-solar subsystem described in Sections 5.5.2, 3, and 4. Gas and oil can be used in the heater by changing out the burners and installing the required fuel handling equipment in the non-solar subsystem.

TABLE 5-14

BASELINE 100 MW TURBINE DATA

Turbine Type	Tandum-compound, double flow, reheat (TCDF)
Last Stage Blade	58.4 cm (23 in.)
Turbine Rating	112,000 kW
Feedwater Heater Extractions	6
Turbine Steam Conditions	
- Inlet (Throttle) Steam	12.4 MPa (1815 psia) 538°C (1000°F)
- Reheat Steam	2.0 MPa (297 psia) 538°C (1000°F)
Turbine Exhaust Pressure	6.8 mPa (2 in. Hg A)
Final Feedwater Temperature	250.8°C (483.5°F)
Gross Cycle Efficiency	43.5%

TABLE 5-15

SELECTED COMMERCIAL TURBINE CHARACTERISTICS

Turbine Rating, MWe (gross)	480
Turbine Type	TC4F-30
Initial Pressure, MPa (psig)	16.5 (2400)
Initial Temperature, °C (°F)	538 (1000)
Reheat Temperature, °C (°F)	538 (1000)
Exhaust Pressure, KPa (in. Hg A)	6.8 (2.0)
Final Feedwater Temperature, °C (°F)	249 (480)
Number Feedwater Heaters	7
Net Turbine Heat Rate, kJ/kWh (Btu/kWh)	8229 (7800)

Heater bottom ash is discharged to a pneumatic conveying system described in Section 5.5.5. Fly ash collection and SO_2 removal are handled by the air quality control equipment described in Section 5.6.7. Clean flue gas from the air quality control system is discharged into the atmosphere via a receiver tower mounted chimney described in Section 5.5.5.

The sodium heater resembles a small B&W "El Paso-type" (see Figure 5-75) boiler arranged for once-through operation. The configuration of the furnace enclosure and convection surface is shown in Figures 5-76 and 5-77. The arrangement of auxiliary equipment, such as the regenerative air heater and fans, is shown in Figure 5-78.

Air is delivered by the forced draft fan to the air heater and distributed to the burner windbox and primary-air fans. The hot flue gas from the furnace is cooled as it crosses, inturn, the high-temperature and low-temperature convection surfaces. The flue gas is further cooled in the air heater and processed to reduce SO_x and particulate emissions. It is finally discharged from the induced draft fan to the stack.

Sodium is heated as it passes sequentially through the low-temperature convection tubing, membrane-wall tubes in the furnace and high-temperature convection tubing. As the sodium exits each heat transfer section, it is collected in a header and transported through downcomers to the next section.

5.6.3.1 Combustion Equipment

Balanced control of fuel and air in the combustion zone is necessary to promote complete combustion with low NO_x generation and with control of furnace and convection surface slagging and fouling. To achieve these objectives, the B&W dual register pulverized coal burner has been selected for the sodium heater. The configuration of the burner is shown in Figure 5-79.

The burner has two registers to proportion air between the fuel rich initial ignition zone and the secondary combustion zone. This arrangement assures efficient and continuous combustion until the fuel is consumed. Proper distribution of the coal-air mixture is accomplished by a venturi in the coal nozzle. An adjustable venturi plug is available to balance coal flow between burners served by the same pulverizer. The burners are compartmented such that groups of burners served by a single pulverizer are provided with a separate windbox. This arrangement enables secondary air flow to be measured and closely controlled.

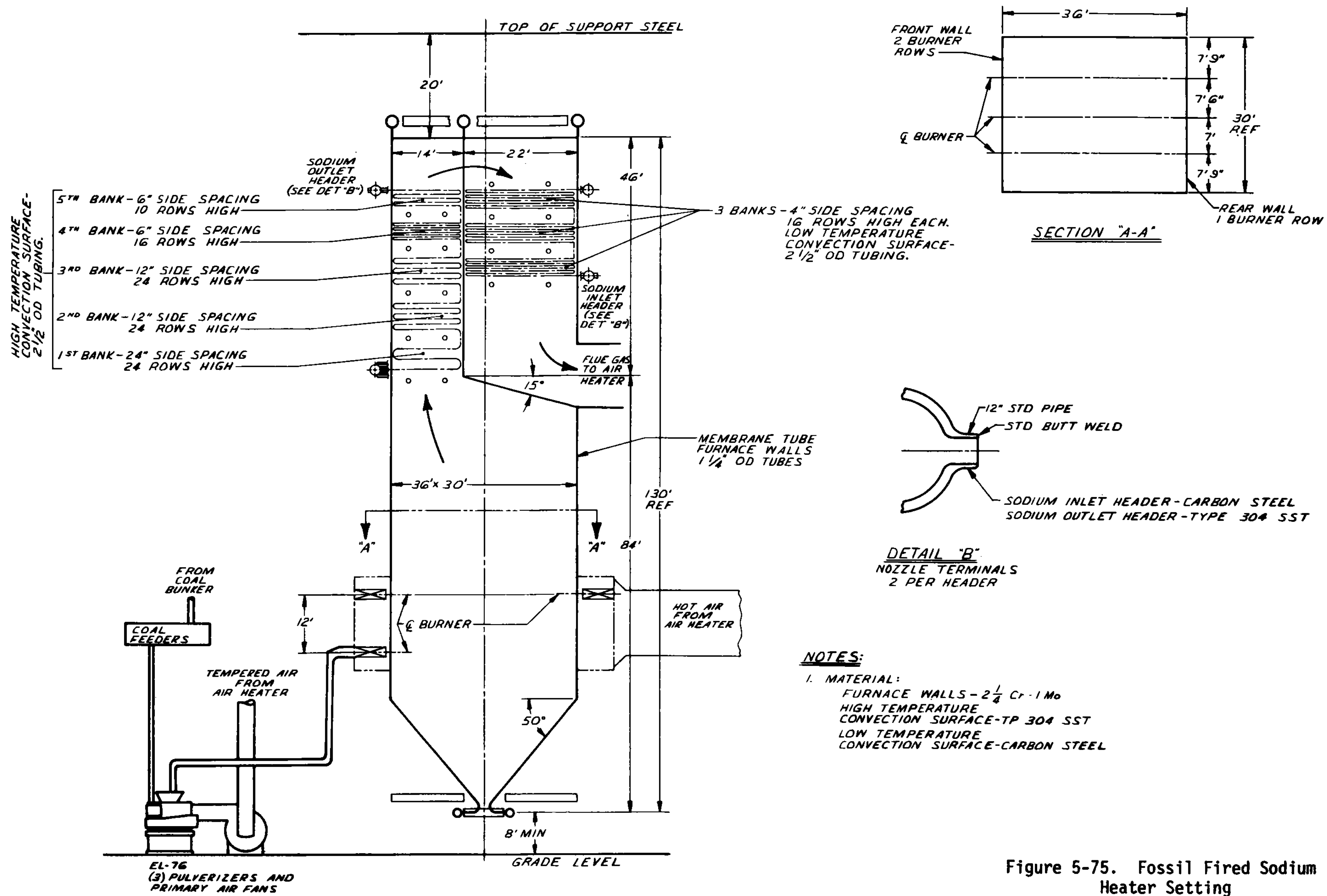


Figure 5-75. Fossil Fired Sodium Heater Setting (Dwg No. 264259E)

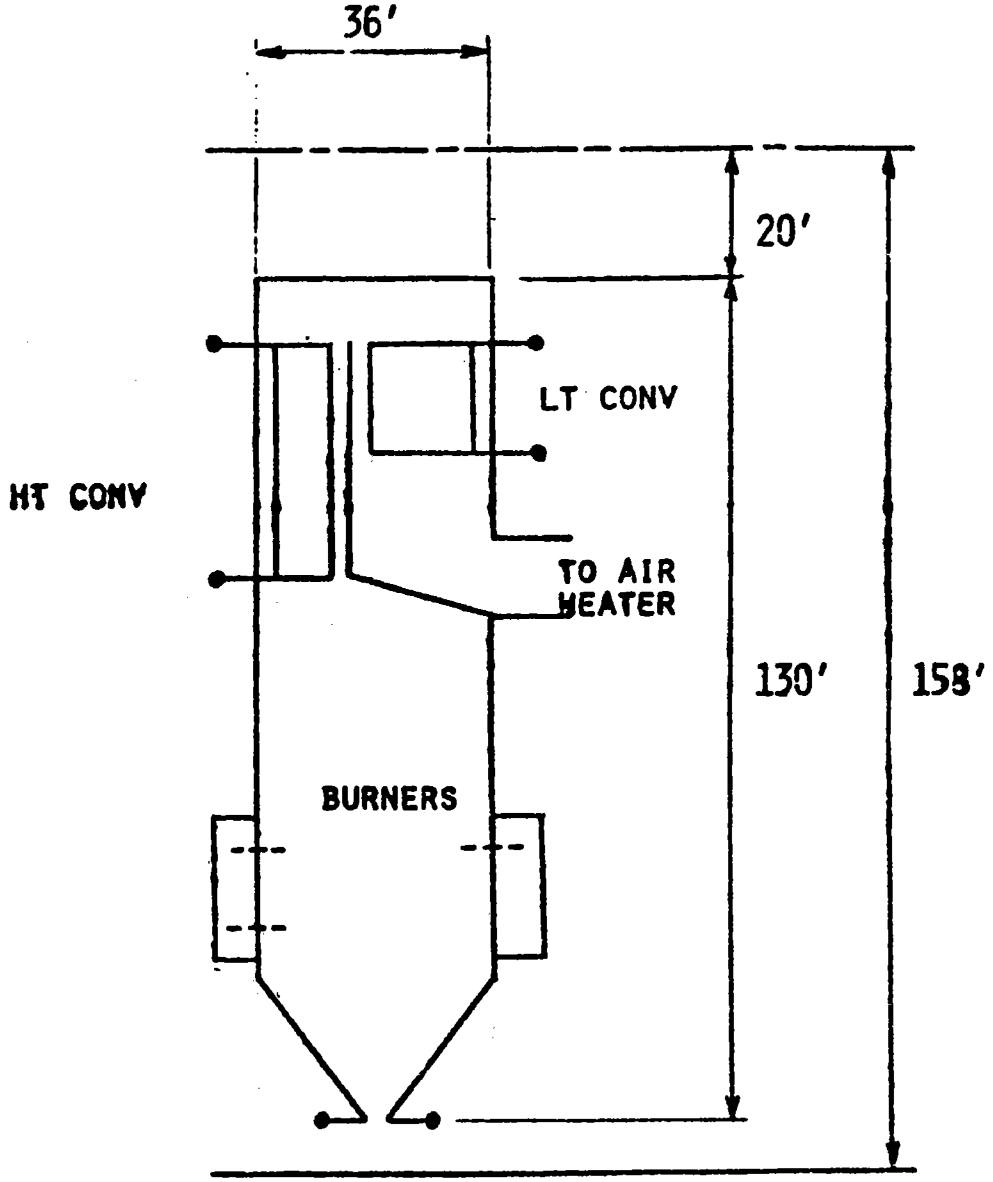


Figure 5-76. Sodium Heater

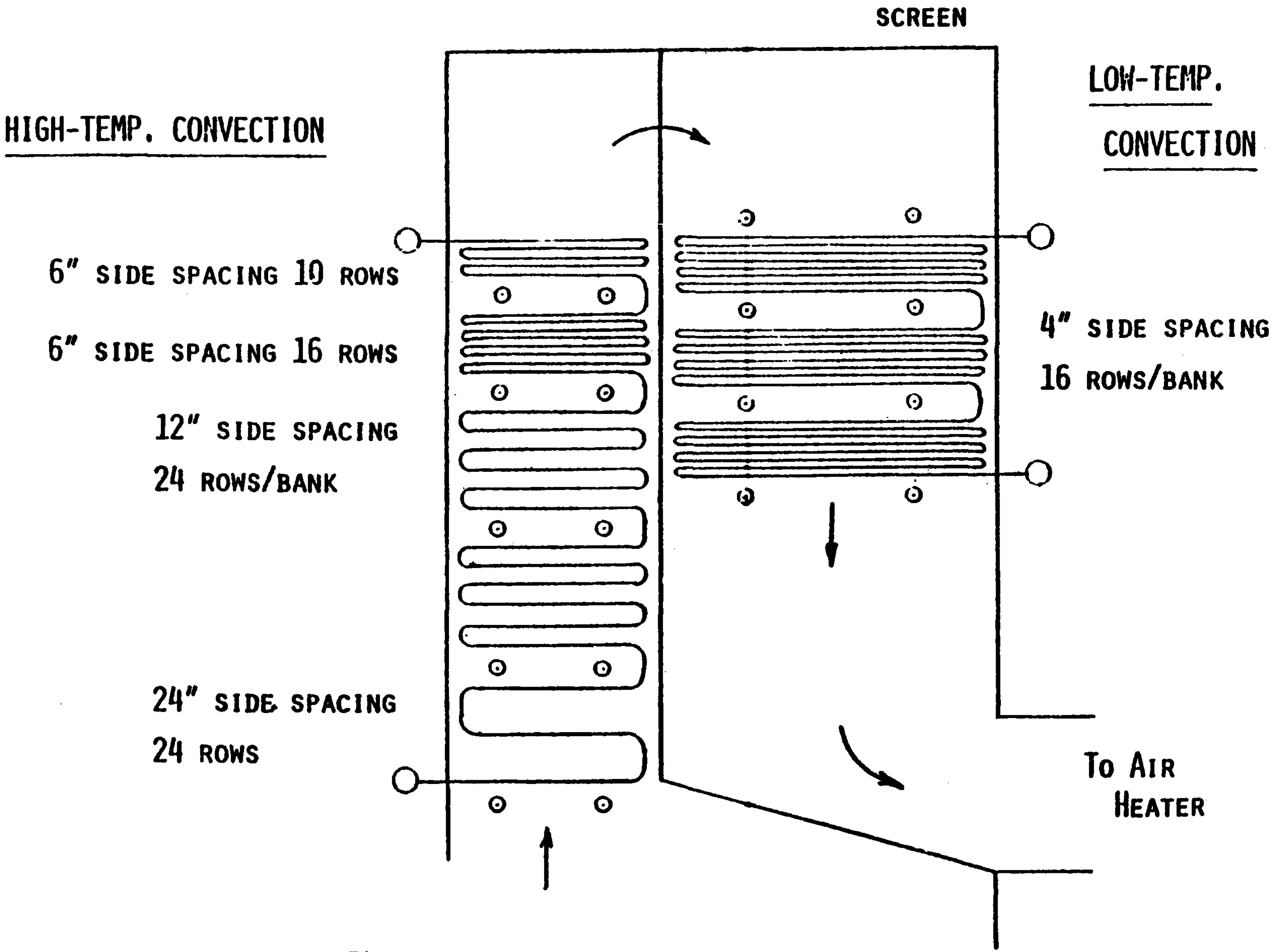
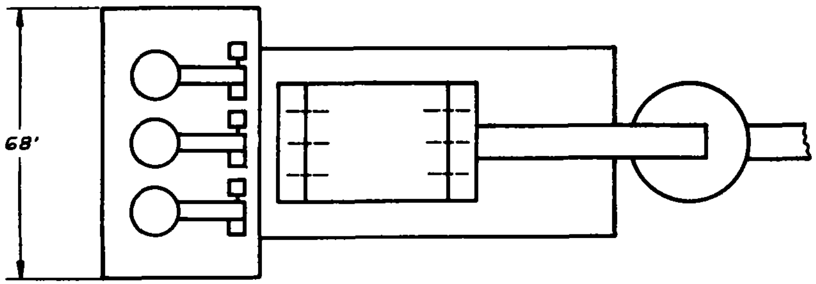


Figure 5-77. Convection Surface Arrangement



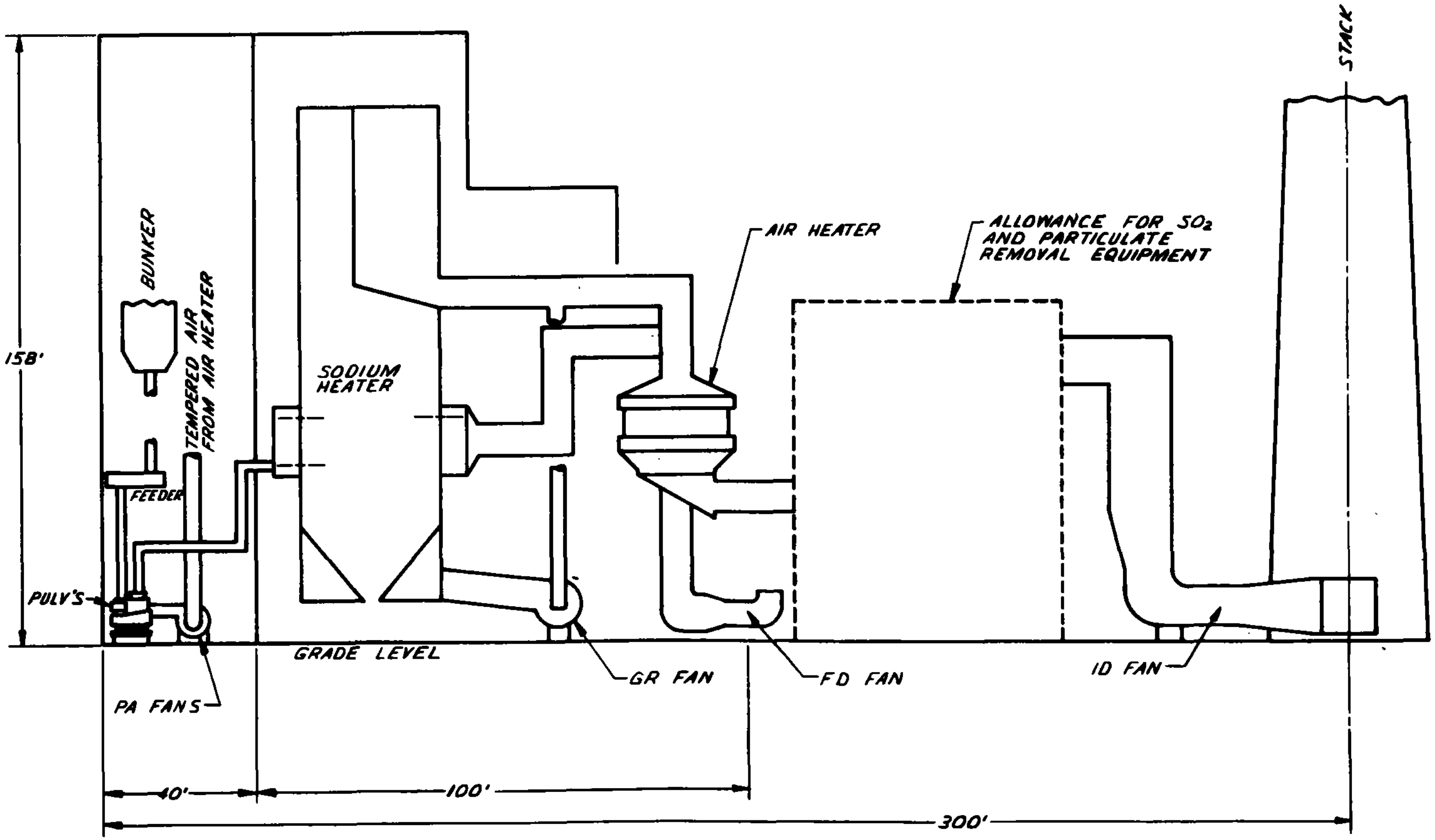


Figure 5-78. Fossil Fired Sodium Heater Arrangement (Dwg No. 264260E)

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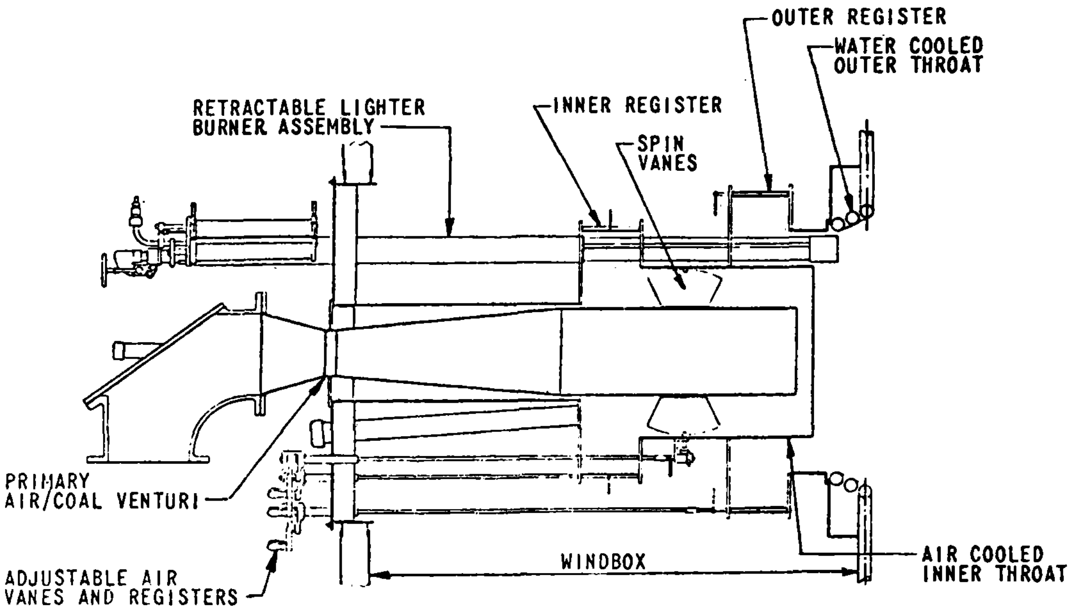


Figure 5-79. Dual Register Pulverized Coal Burner

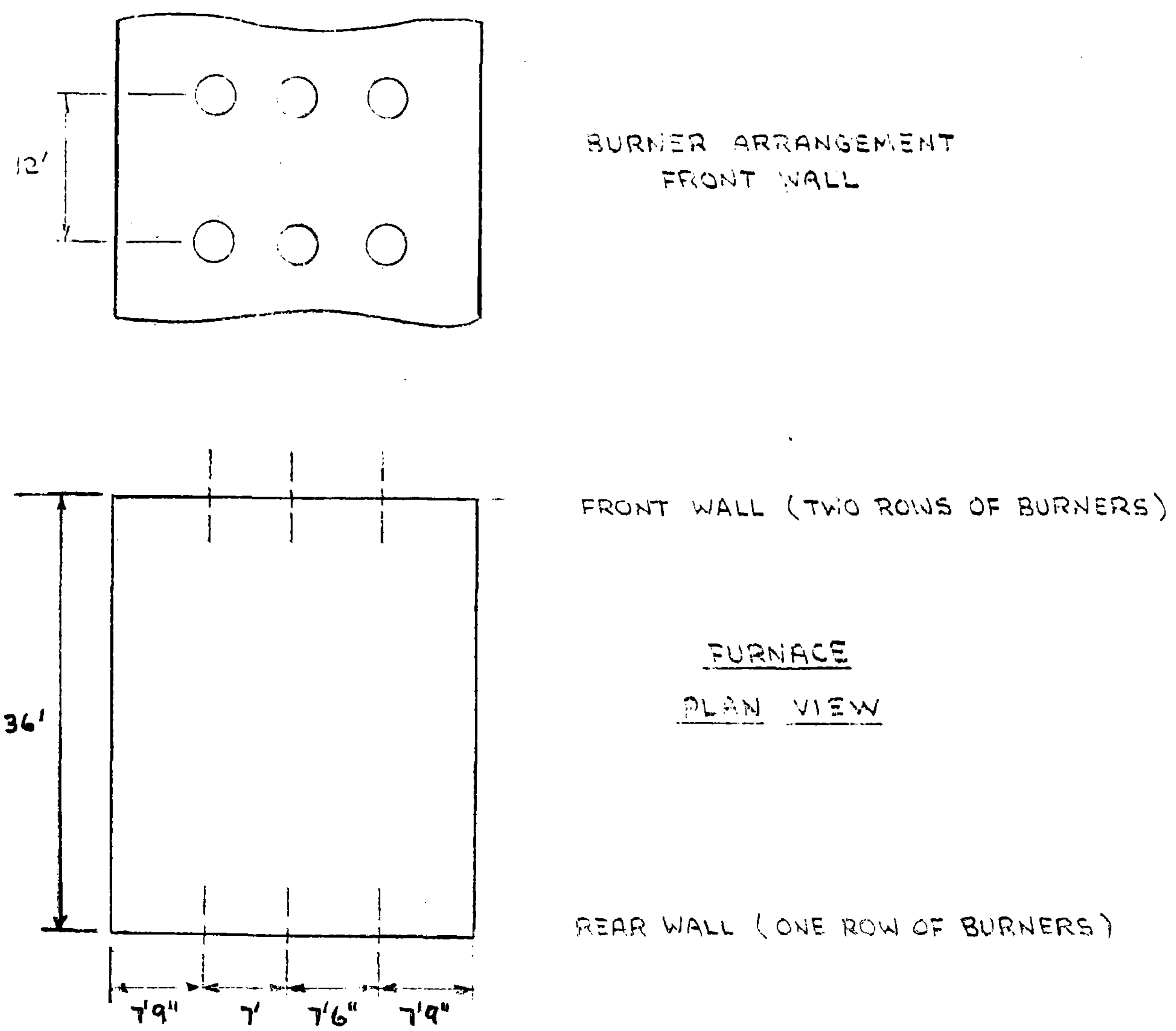


Figure 5-80. Burner Arrangement

Nine burners, arranged in groups of three as shown in Figure 5-80, are used in the sodium heater. The maximum required burner input is 116 x 10^6 Btu/h, or about 70% of the design rating. By using a larger number of smaller burners, the total fuel input is divided into more increments, and any unbalances between fuel and air are more easily reduced and controlled. As shown in Figure 5-81, the burner input selected for the sodium heater is well within the limits of current design practice.[3-5]

The maximum practical turndown ratio for the sodium heater is ∿5:1. As noted in Section 3.5.5, load variations are accomplished by starting up (or shutting down) pulverizer-burner sets. Therefore, minimum load is achieved by operating one of the three burner rows (a top row) at nearly 65% of its full load heat input. An estimated 3 to 5 min is required to make the load ramp from 20% to full load.

By limiting the burner heat input to a minimum of 65% of its full load value, or about 45% of its design rating, burner flame stability is assured. Firing only a top row of burners also serves to reduce furnace absorption at low load by effectively reducing the size of the furnace. In this way, furnace tube metal temperatures are more easily controlled (see Section 5.6.3.3).

5.6.3.2 Furnace Design and Convection Surface Arrangement

The furnace and associated combustion equipment have been designed (a) to promote complete combustion of the fuel before it leaves the furnace, and (b) to control slagging by adequately cooling the flue gases and ash particles before they cross convection surfaces. The design criteria are based on many years of experience with boilers burning a wide range of fuels. Features of the radiant and convective heat transfer surfaces are summarized in Table 5-16.

Furnace exit gas temperature is related to heat release rate and is limited by furnace size. The downward design trend in heat input relative to furnace plan area is shown in Figure 5-82, and is consistent with the ash characteristics of many western coals in current use.[3-5] Similarly, NO_x generation is related to burner zone heat release rate. The recent downward trend in this parameter is

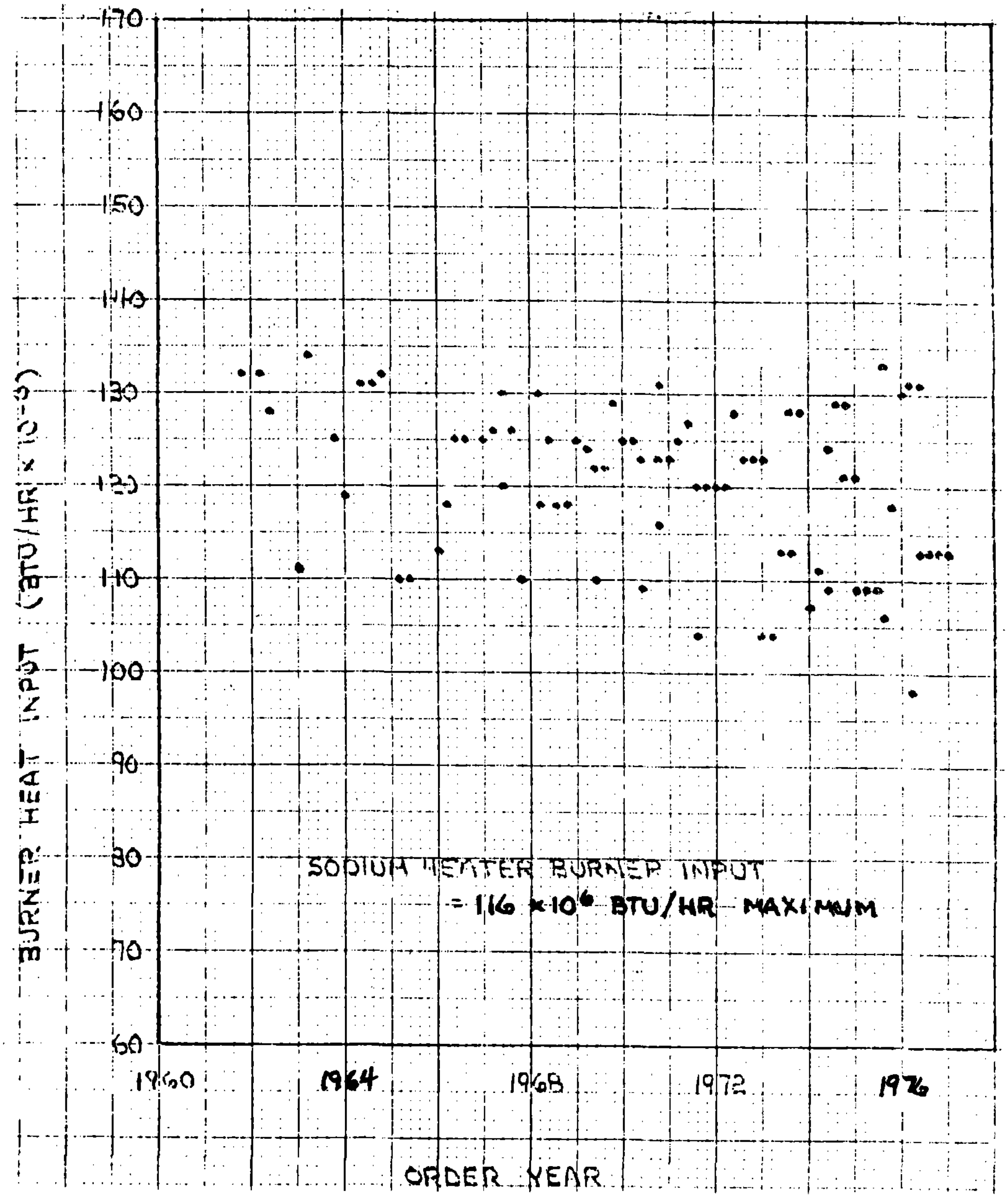


Figure 5-81. Pulverized Coal Fired Boiler Experience — Burner Heat Input

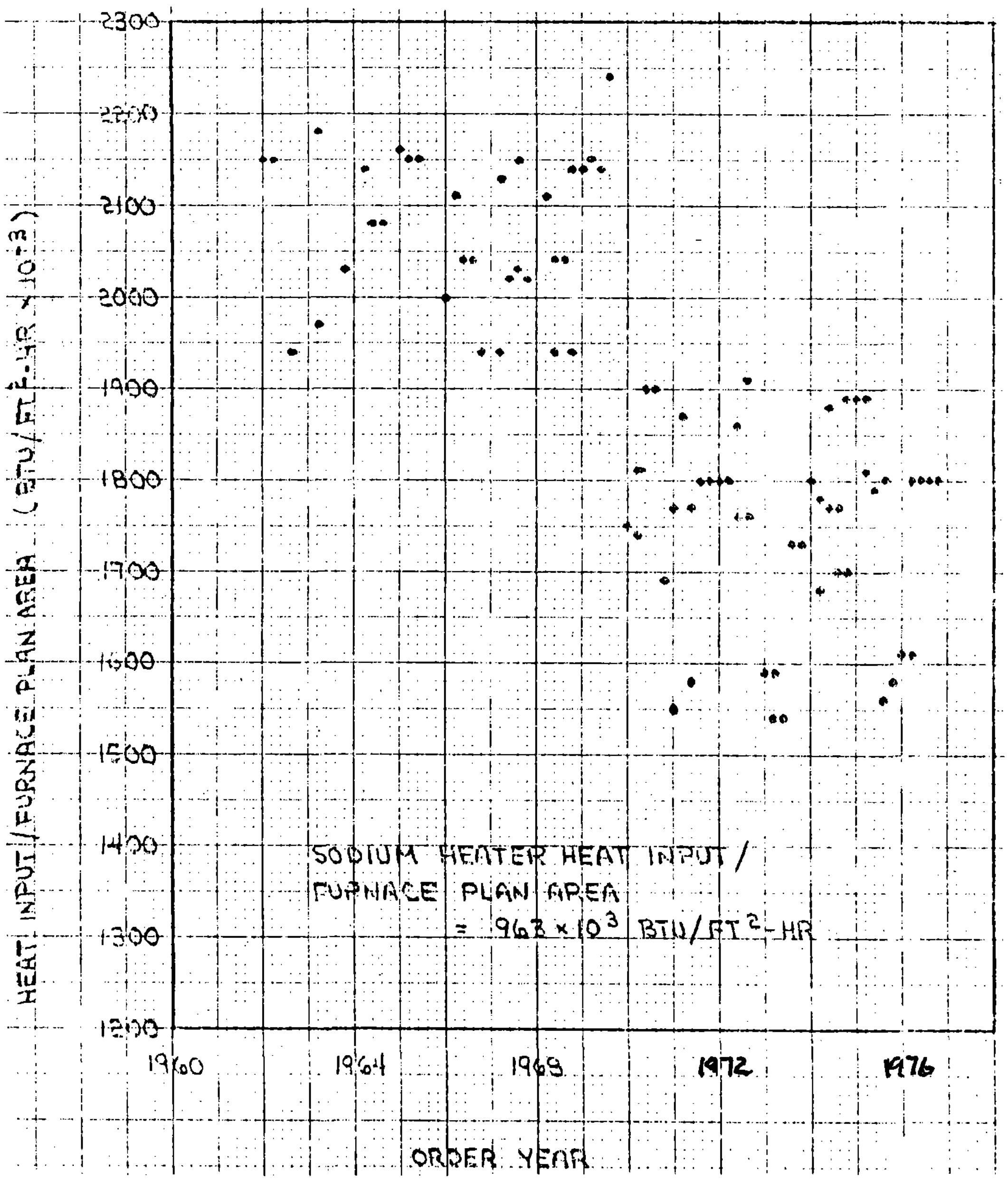


Figure 5-82. Pulverized Coal Fired Boiler Experience — Heat Input/Furnace Plan Area

TABLE 5-16

HEAT TRANSFER SURFACES

	Material	Tube OD (in.)	Surface Area (ft^2)
Low-Temperature Convection Surface	Carbon Steel	2.50	60800
High-Temperature Convection Surface	Type 304 Stainless Steel	2.50	26700
Radiant Surface	2-1/4 Cr - 1 Mo	1.25	9120 (effective at full load) 7460 (effective at 20% load)

shown in Figure 5-83 and reflects the need to comply with government regulations.[3-5] For the sodium heater, both these indices fall within the limits of current design practice. Conventional boilers equipped with dual register burners and operated within the guidelines identified in Figures 5-82 and 5-83, and the burner input limits defined in Section 5.6.3.1, have consistently satisfied EPA limits of 0.7 lb NO_x (measured as NO_2) per 10^6 Btu heat input to the furnace.

The convection surfaces have been divided into tube banks separated by soot blowers. The side spacing of tubes within each bank is arranged to minimize the effects of slagging and erosion by coal ash. This spacing is dependent on predicted flue gas temperatures and on the high fouling characteristics of the design basis coal. The spacing is progressively reduced as the flue gas is cooled. The size of individual tube banks is limited by the effective radius of soot blower penetration.

Tube sizes have been selected to provide adequate cross-sectional flow area to maintain sodium velocities within acceptable limits. The predicted velocities at full load and the corresponding pressure losses through the system at full load and 20% of full load are summarized in Table 5-17. The heat transfer surfaces have been arranged so that the sodium is always heated in up-flow. This arrangement promotes hydraulic stability in the parallel circuits at low load, where the sodium velocity and system pressure losses are quite small.

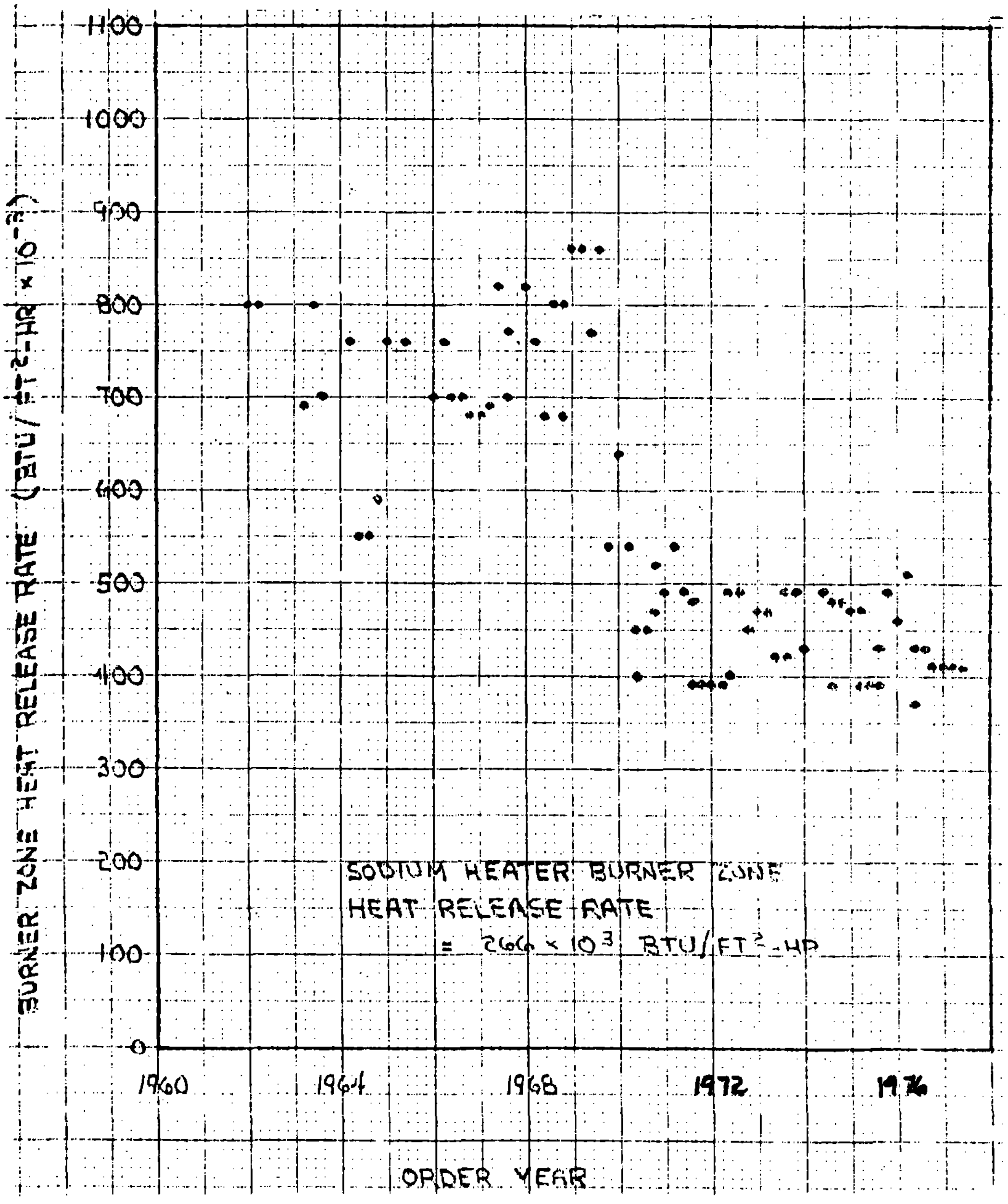


Figure 5-83. Pulverized Coal Fired Boiler Experience — Burner Zone Heat Release Rate

TABLE 5-17

SODIUM VELOCITY AND PRESSURE LOSS

Sodium Velocity (Full Load)		Sodium Pressure Loss	
Low-Temperature Convection Tubes	6 ft/s	at Full Load	70 psi
High-Temperature Convection Tubes	10 ft/s	at 20% Load	3 psi
Furnace Tube	7 ft/s		

Standard membrane-wall panels (Figure 5-84) were selected for the furnace enclosure. Opposed-wall firing of burners was chosen to minimize the overall height of the unit.

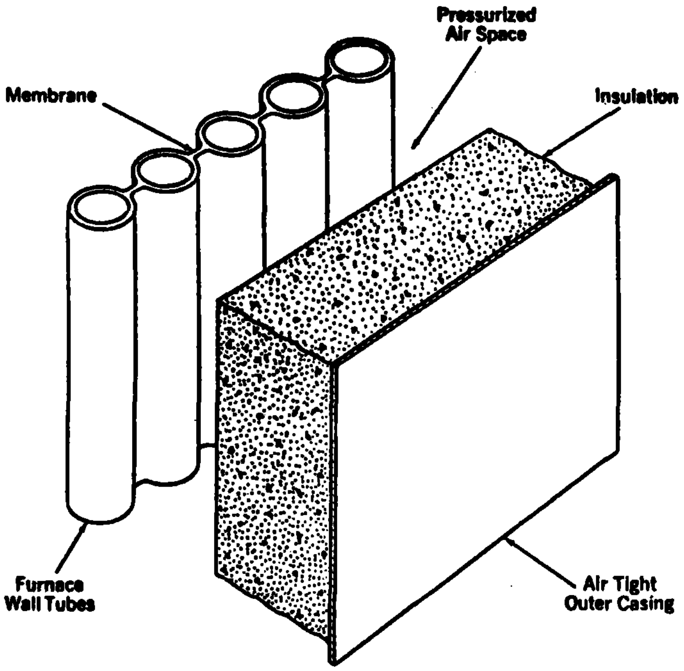


Figure 5-84. Typical Furnace Membrane Wall

5.6.3.3 Performance

The sodium heater has been designed to heat sodium from 550^{o}F to 1100^{o}F over the entire operating load range. Load variations are accomplished by varying the sodium flow rate and fuel firing rate in a nearly linear manner. The predicted sodium and flue gas temperature distributions at full load and 20% of full load (the extremes of the load range) are shown in Figures 5-85 and 5-86.

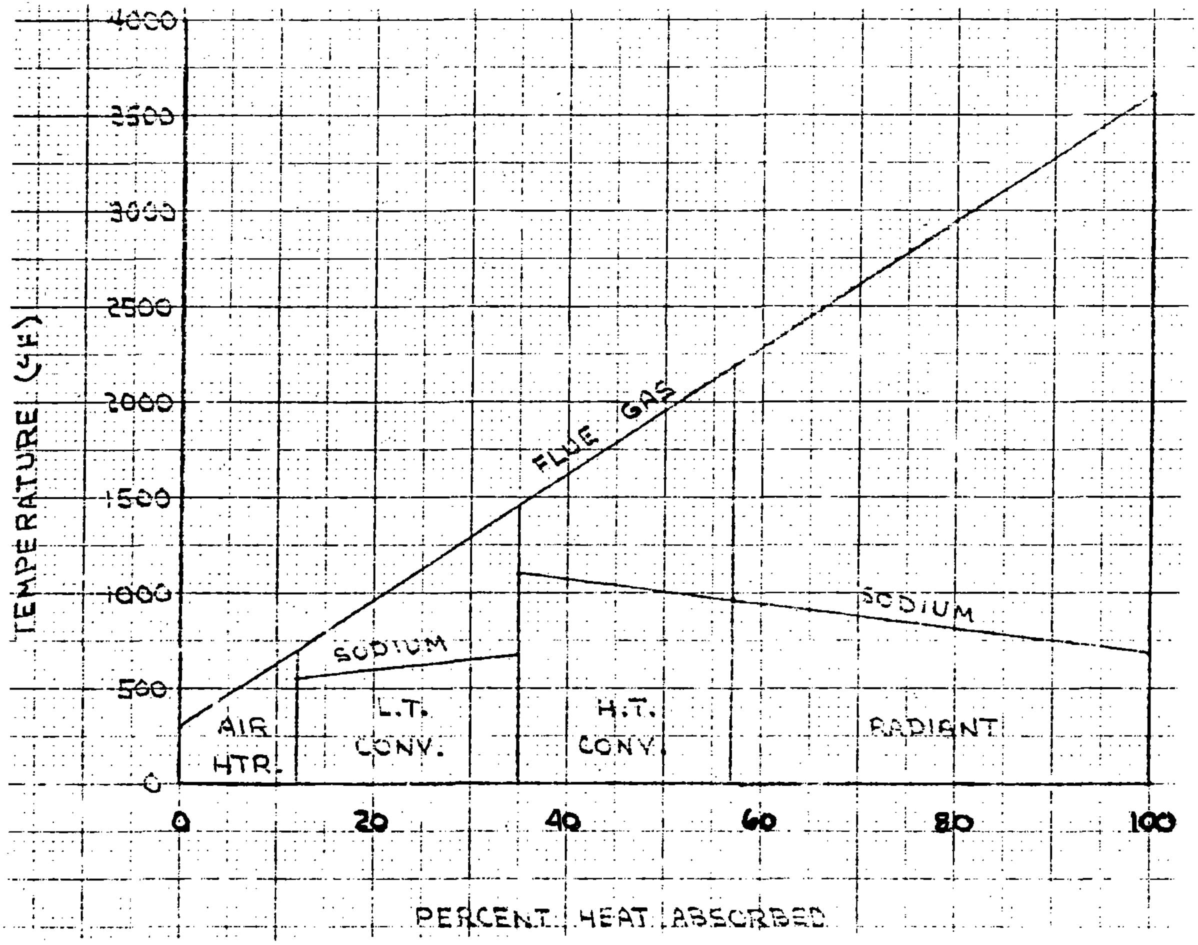


Figure 5-85. Sodium Heater Temperature Distribution, Full Load

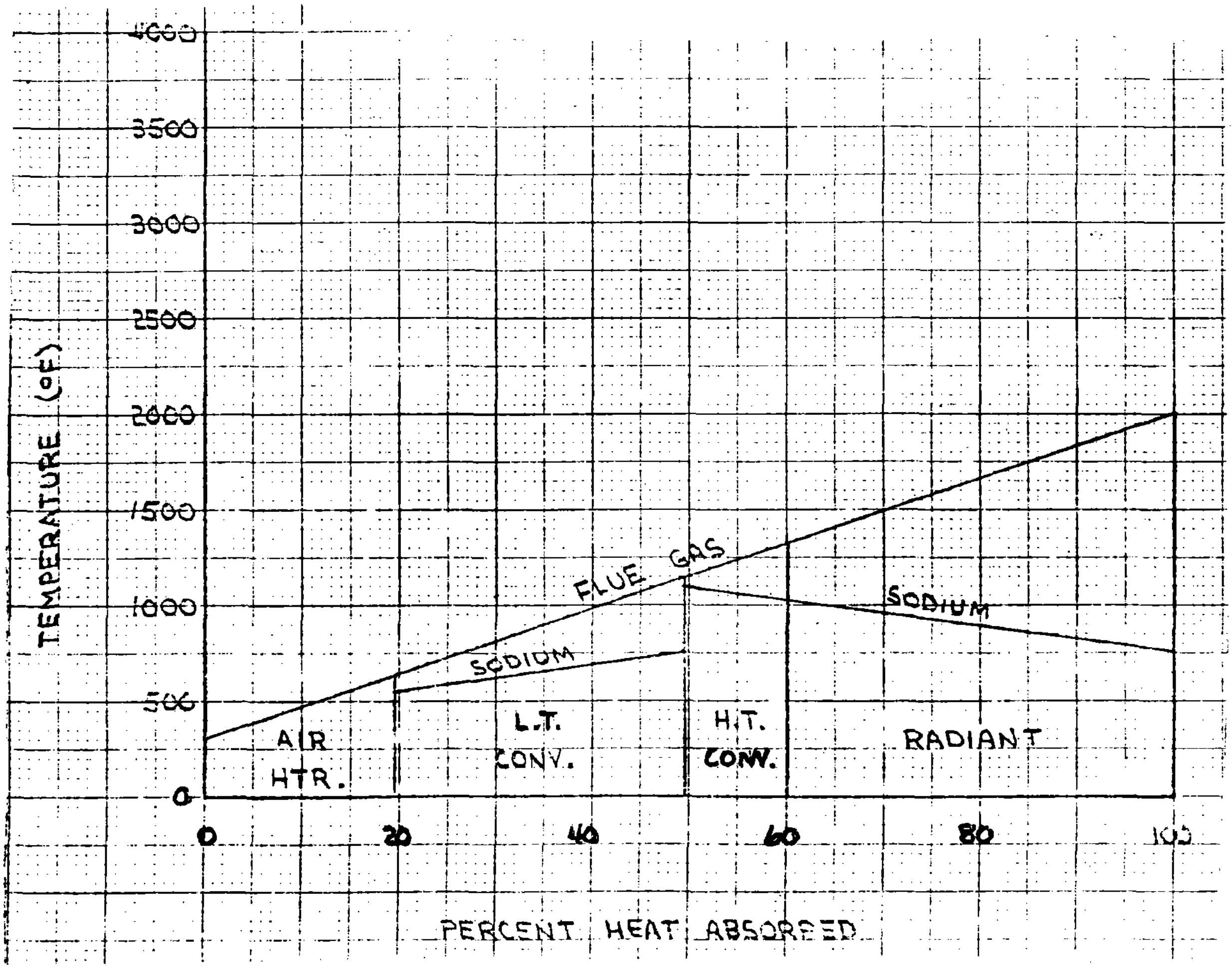


Figure 5-86. Sodium Heater Temperature Distribution, 20% Load
(50% Flue Gas Recirculation)

The design provides for recirculation of approximately 50% of the flue gas from the outlet of the low-temperature convection surface to the furnace hopper during low load operation. This design feature is intended to control furnace tube metal temperature, in order to limit decarburization of the 2-1/4 Cr - 1 Mo alloy in sodium (see Section 3.5.3). The recirculated gas reduces heat absorption in the furnace without significantly influencing the total absorption and efficiency of the heater. As noted in Section 5.6.3.1, only a single top row of burners is fired at low loads. This action also reduces heat absorption in the furnace by effectively reducing furnace size.

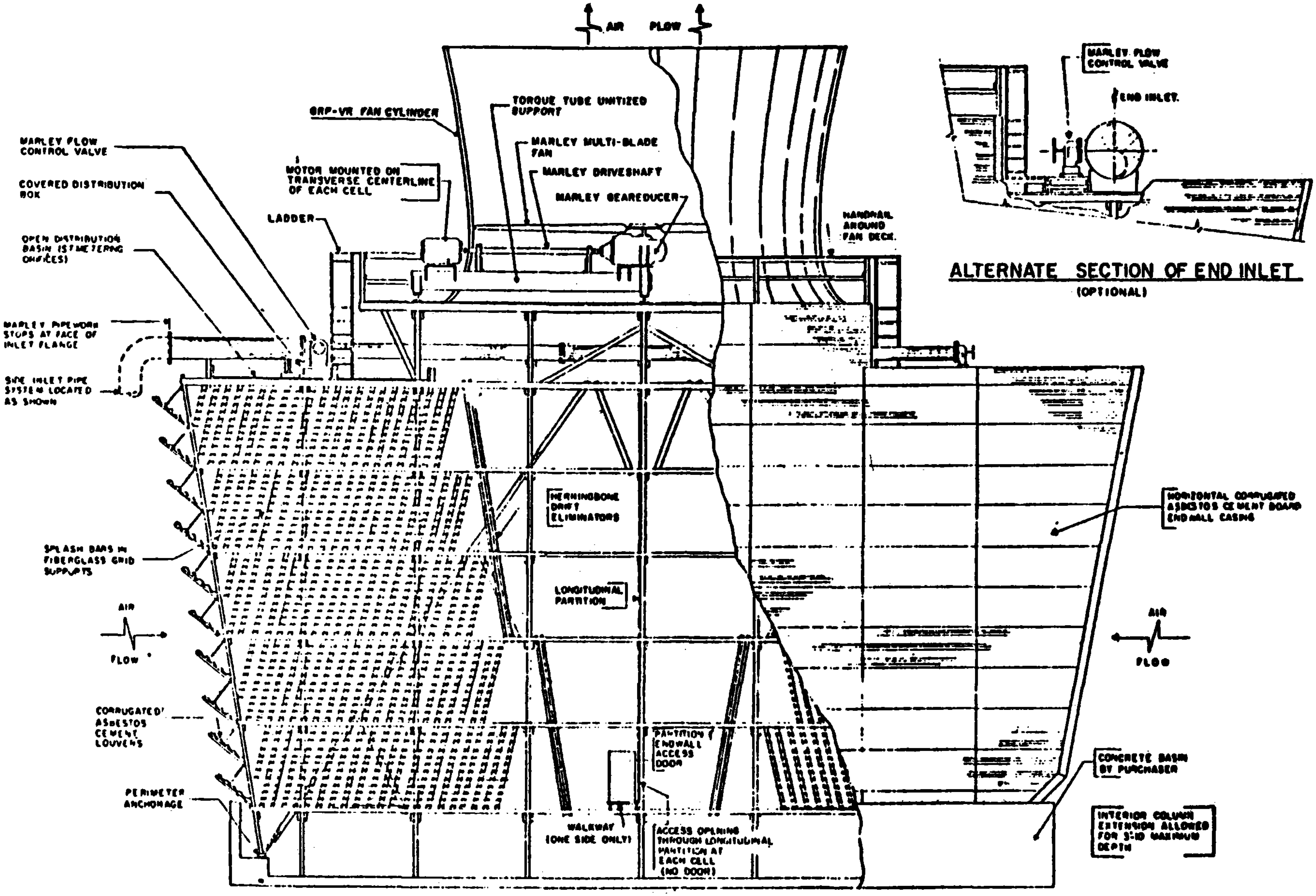
5.6.4 Feedheating and Condensing Equipment Design

Condensing Equipment – The turbine exhaust steam is condensed in a steam surface condenser designed in accordance with the Heat Exchange Institute's "Standards for Steam Surface Condensers." The condenser design characteristics are shown in Table 5-18. Condenser air removal is accomplished by the use of mechanical, electric motor-driven, vacuum pumps. Two full-capacity pumps are provided.

TABLE 5-18

CONDENSER DESIGN CHARACTERISTICS

Type	Steam Surface Condenser, 2-pass, divided water box
Surface	8175 m^2 (88,000 ft^2)
Shell Material	Carbon Steel
Tube Material	90-10 Cu-Ni (ASTM B111, Alloy 706)
Tube Diameter and Wall	2.54 cm (1 in.) OD x 20 BWG (0.035 in.)
Tube Length (Effective)	8.54 m (28 ft)
Duty	154 MWt (525 x 10^6 Btu/h)
Condensing Pressure	6.7 kPa (2.0 in. Hg A)
TTD	3.1^oC (5.54^oF)
Cooling Water Flow	5.7 m^3/s (90,500 gpm)



TRANSVERSE CROSS SECTION

Drawing No. 66-4665A

Figure 5-87. Marley Wet Cooling Tower

Feed Heating - Six stages of feedwater heating are provided in the baseline 100 MW turbine cycle. The heaters are comprised of two horizontal shell-and-tube low-pressure heaters (the lowest pressure heater located within the condenser neck), a direct-contact deaerating heater, and three horizontal shell-and-tube high-pressure heaters.

All heaters are fed turbine extraction steam from various turbine stages in a regenerative turbine cycle. The highest pressure heater is supplied steam from the high-pressure turbine connection preceding the high-pressure turbine exhaust (HARP cycle) in order to improve turbine cycle efficiency as discussed in Section 3.6.3.

The high-pressure heater drains are cascaded to the low-pressure heater (or alternated to the condenser), and the low-pressure heater drains are cascaded to the condenser to accomplish maximum water cleanup via the in-line condensate polishers (demineralizers) and deaeration (oxygen removal).

The materials of construction used in the feedwater heaters are shown in Table 5-19. All heater tube materials are ferrous in order to eliminate copper pickup in the condensate or feedwater system, which would result in copper deposition on the turbine blades. All feedwater heaters are designed in accordance with ASME Boiler and Pressure Vessel Code Section VIII.

5.6.5 Cooling Tower Design

Heat rejection is accomplished by utilizing an evaporative (wet), mechanical draft cooling tower. Figure 5-87 shows a typical transverse cross section of a Marley double flow cooling tower which indicates the principal elements of construction. The primary construction material is treated fir or redwood, although other materials can be employed.

The design characteristics for the 100-MW cooling tower is shown in Table 5-20.

TABLE 5-19

FEEDWATER HEATER MATERIALS

Low-Pressure Heaters	
Shell	Carbon Steel
Tubes	Stainless Steel
High-Pressure Heaters	
Shell	Carbon Steel
Tubes	Carbon Steel
Deaerator	
Shell	Carbon Steel
Trays	Stainless Steel
Vent Condenser	Stainless Steel
Storage Section	Carbon Steel

TABLE 5-20

COOLING TOWER DESIGN CHARACTERISTICS
(100-MW Baseline Plant)

Type	Wet, Mechanical Draft, Crossflow
Number of Cells	5
Fan Size per Cell	150 mW (200 hp)
Duty	158 MWt (540 x 10^6 Btu/h)
Design Wet Bulk Temperature	23.0°C (73.4°F)
Approach to Wet Bulb	5.5°C (10.6°F)
Cooling Range	6.4°C (11.6°F)
Cooling Water Flow	5.9 m^3/s (93,100 gpm)
Overall Dimensions	
Width	22 m (72 ft)
Length	61 m (201 ft)
Height	18 m (59 ft)

Makeup Water Requirements – The makeup water requirements for the 100 MW baseline plant have been estimated as follows:

1)	Evaporation	245 m^3/h	(1080 gpm)
2)	Drift (.01% of water flow)	2 m^3/h	(9 gpm)
3)	Blowdown (assume 6 conc.)	47 m^3/h	(207 gpm)
4)	Total makeup	294 m^3/h	(1296 gpm)

Wet vs Wet-Dry Tower — A combination wet-dry cooling tower, shown schematically in Figure 5-38, can be provided for plume abatement and water conservation. In the wet-dry tower, cooling is accomplished by both sensible cooling (in the dry section) and evaporative cooling (in the wet section) to give the desired results. For solar central receiver power systems, it is very desirable to minimize the cooling tower plume (or fogging) because of optical interference and solids deposition on heliostats or receiver surfaces.

A preliminary evaluation of wet vs wet-dry cooling towers was made for the Barstow reference site, designing the wet-dry tower for plume abatement. A design wet bulb temperature of 23°C (73.4°F) and dry bulb temperature of 42°C (107°F) maximum and -1°C (30°F) minimum for plume abatement were used. Wet and wet-dry cooling tower performance data and costs were provided by the Marley Company. A comparison of the two systems, shown in Table 5-21, indicates that the wet-dry tower requires 40 percent more fan power at approximately double the cost of a wet tower. Since cooling tower drift and fogging problems cannot be completely eliminated, it would appear undesirable to locate the wet-dry cooling tower within the core area (thus eliminating very long circulating water lines required to located the cooling tower outside of the collector field). On the basis of this study, it was decided to baseline a wet cooling tower located outside of the collector field. The actual location of the tower would be determined by the predominant wind conditions at the site. It may also be desirable to provide some degree of wet-dry cooling for plume abatement and water conservation reasons.

5.6.6 Water Treatment and Condensate Makeup

5.6.6.1 Pretreatment

With surface waters, pretreatment is required upstream of the treatment process utilized for the production of electric utility system steam generator makeup water. The principal purposes of such treatment is to remove suspended material and reduce turbidity. Without pretreatment, physical fouling of the ion exchange resins, membranes or cartridge filters preceding the membrane processes could result. In addition, some colloidal material will not be removed by ion

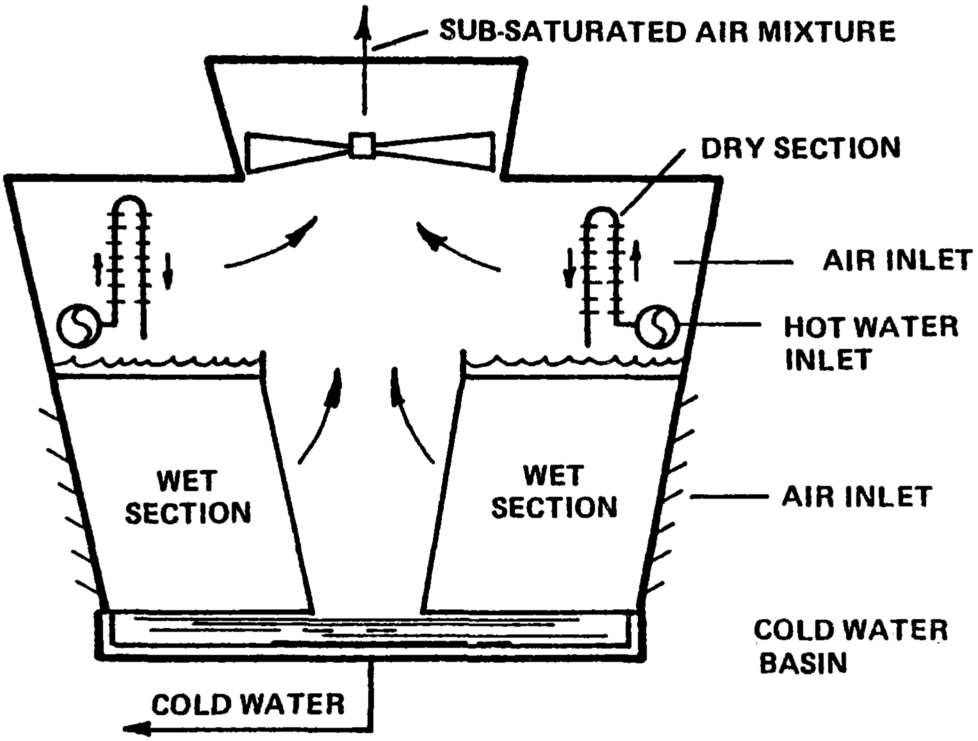


Figure 5-88. Wet/Dry Cooling Tower for Plume Abatement

TABLE 5-21

WET VS WET/DRY COOLING TOWER COMPARISON
(*100% Plume Abatement at 30^{o}F Ambient - Barstow, Calif.)

	WET	WET/DRY *
CIRC WATER FLOW, GPM	96000	96000
HEAT DUTY 10 BTU/HR	555	555
APPROACH °F	10	10
NO. OF CELLS	5	7
HP PER CELL	200	200
LENGTH FT.	201	253
WIDTH FT.	72	70
PUMPING HEAD FT.	41	38
EST. COST $1979 (EXCL. BASIN)	$900,000	$1,750,000

exchange processes. If not removed, it would pass through an ion exchange demineralizer and result in deposit formation in the steam generator and turbine. Colloidal silica, in particular, has been a source of such difficulties. Pretreatment is usually accomplished by clarification equipment, usually followed by filtration.

Pretreatment is occasionally required to reduce the concentrations of suspended solids, ion, manganese, phosphate, calcium, magnesium, alkalinity, silica and/or other constituents of the cooling tower makeup water. Evaporation from the cooling tower system will result in concentration of the various materials introduced into the system with the makeup water. The degree of concentration must be limited to prevent precipitation of the various materials such as calcium carbonate, calcium sulfate, silica (as quartz or amorphous silica), magnesium silicate, which would interfere with heat transfer at the condenser and other heat exchangers utilizing cooling tower water for heat rejection.

5.6.6.2 Final Treatment

Demineralization is required for production of boiler makeup water. The most widely used demineralization process for this purpose is ion exchange. In certain situations, high dissolved solids concentrations, high chemical costs, and/or relatively low water requirements have resulted in reverse osmosis demineralization proving to be the more economical approach. Reverse osmosis does not produce a water sufficiently low in dissolved solids for high pressure boiler makeup purposes. Its effluent must further be treated by ion exchange. Demineralized water would also be the most suitable water in the facility for mirror washing.

The ion exchange demineralizer configuration is subject to many variations. The quantity of the water to be treated will determine the appropriate one.

The final water treatment equipment proposed for the 100-MW solar hybrid plant is as follows:

Two - Makeup water demineralizers, full-size, three-bed trains. Rating 0.38 m^3/min (100 gpm) per train.
Effluent quantity:

Total dissolved solids	50 ppb maximum
Silica	10 ppb maximum

Two - Makeup demineralizer sand filters, each full size, 0.38 m^3/min (100 gpm) each, 1.98 m (6.5 ft) diameter.

One - Demineralizer acid tank, 22.7 m^3 (6,000 gal).

Two - Demineralizer acid pump (1 spare), 0.56 m^3/h (200 gph), 0.75 kW (1 hp), 460 V, ac motor.

One - Demineralizer caustic tank, 22.7 m^3 (6,000 gal).

Two - Demineralizer caustic pump (1 spare), 0.45 m^3/h (120 gph), 1/2 kW (3/4 hp), 460 V, ac motor.

5.6.7 Air Quality Control Equipment Design (0.8 and 1.4 Solar Multiple)

The design requirements of the sodium heater emissions air quality control equipment are set by the latest promulgated EPA standards for new sources. Those standards are summarized in Table 5-22.

TABLE 5-22

CURRENT EPA EMISSIONS STANDARDS FOR NEW FOSSIL EMISSION-SOURCES

NO_x	0.5 lb/MMBtu
SO_2	90% Removal, 0.6-1.2 lb/MMBtu 70% Removal, 0.6 lb/MMBtu
Particulates	0.3 lb/MMBtu

The design selected to meet these standards includes the following equipment: dual register burners operating in conjunction with 115% theoretical air in the furnace for NO_x formation suppression, the ESG dry flue gas desulfurization (FGD) system for SO_2 removal, and a Wheelabrator-Frye fabric filter for particulate removal.

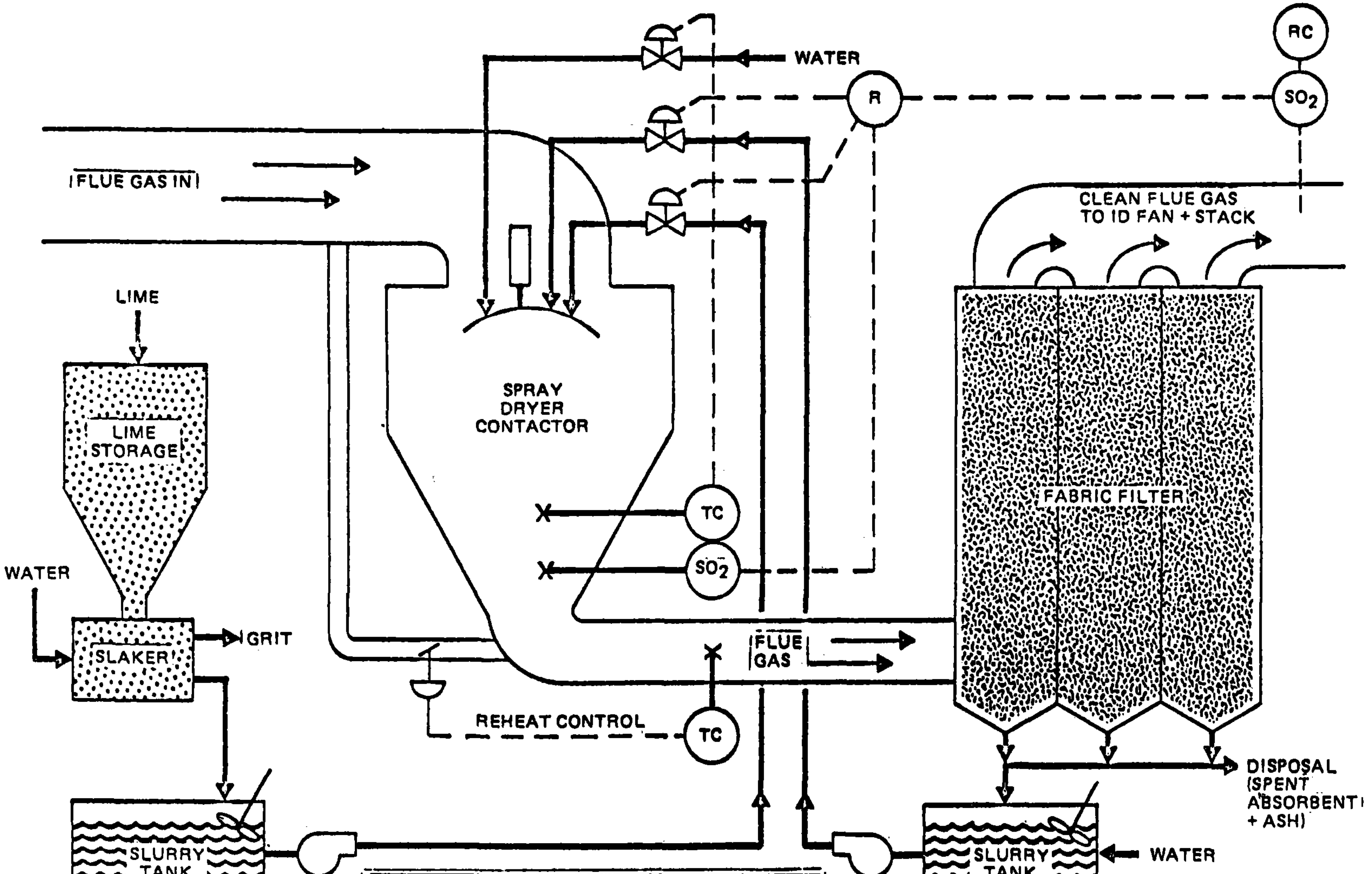


Figure 5-89. Process Flow Diagram — Two-Stage Dry FGD and Particulate Control System

Dual register burners in conjunction with relatively fuel-rich combustion environments are a recognized method of limiting furnace gas temperatures and thereby suppressing NO_x formation. The design NO_x emission for the sodium furnace is estimated to be 0.5 lb/MMBtu. It has been suggested by Babcock & Wilcox that this estimate is conservative and that slight modifications could further reduce these emissions should the EPA requirements become more stringent.

The ESG/Wheelabrator-Frye FGD particulate removal system is shown schematically in Figure 5-89. It consists of a two-stage dry scrubbing system followed by a fabric filter (baghouse). The dry scrubbing system consists of an absorbent solution generation subsystem and a spray dryer. Flue gas from the furnace, after passing through the air heater, is passed through the spray dryer where it reacts with a dilute sodium carbonate solution or calcium hydroxide slurry. Chemical reaction of the absorbent and flue gas removes the SO_2 from the flue gas and the sensible heat of the flue gas evaporates the water and dries the solution to form a powder. A modest spray dryer bypass guarantees that the flue gas never becomes saturated. The flue gas leaving the spray dryer, containing the dry powder and furnace fly ash, enters the fabric filter. As the fly ash and powder are removed from the flue gas in the filter, additional reactions occur and further SO_2 removal occurs.

A schematic diagram of the conceptual design of the spray dryer showing overall dimensions is illustrated in Figure 5-90. A similar schematic of the baghouse is shown in Figure 5-91. The design SO_2 emission rate estimate of this unit is <0.1 lb/MMBtu. The removal associated with this emission is >0.1 lb/MMBtu. The margin in removal efficiency of the design is due to the belief that removal efficiencies of 85% might be required at some time in the future.

The particulate removal estimate is 0.03 lb/MMBtu.

High absorbent utilization is facilitated in this unit by recycling a fraction of the fly ash and powder collected by the fabric filter. Specific air quality control equipment design and performance details are tabulated in the design data sheets for the electric power generation subsystem.

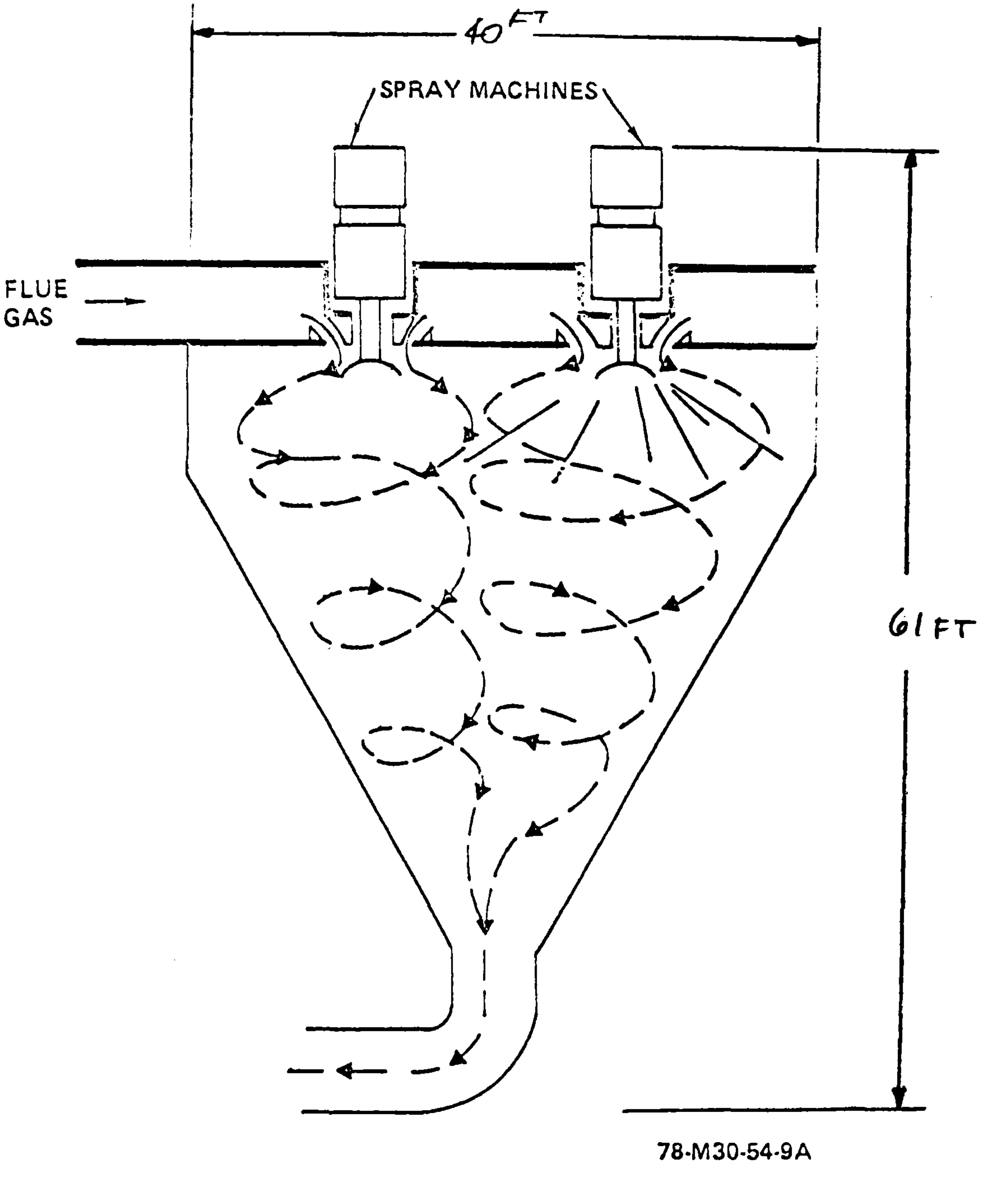


Figure 5-90. Spray Dryer Dimensions

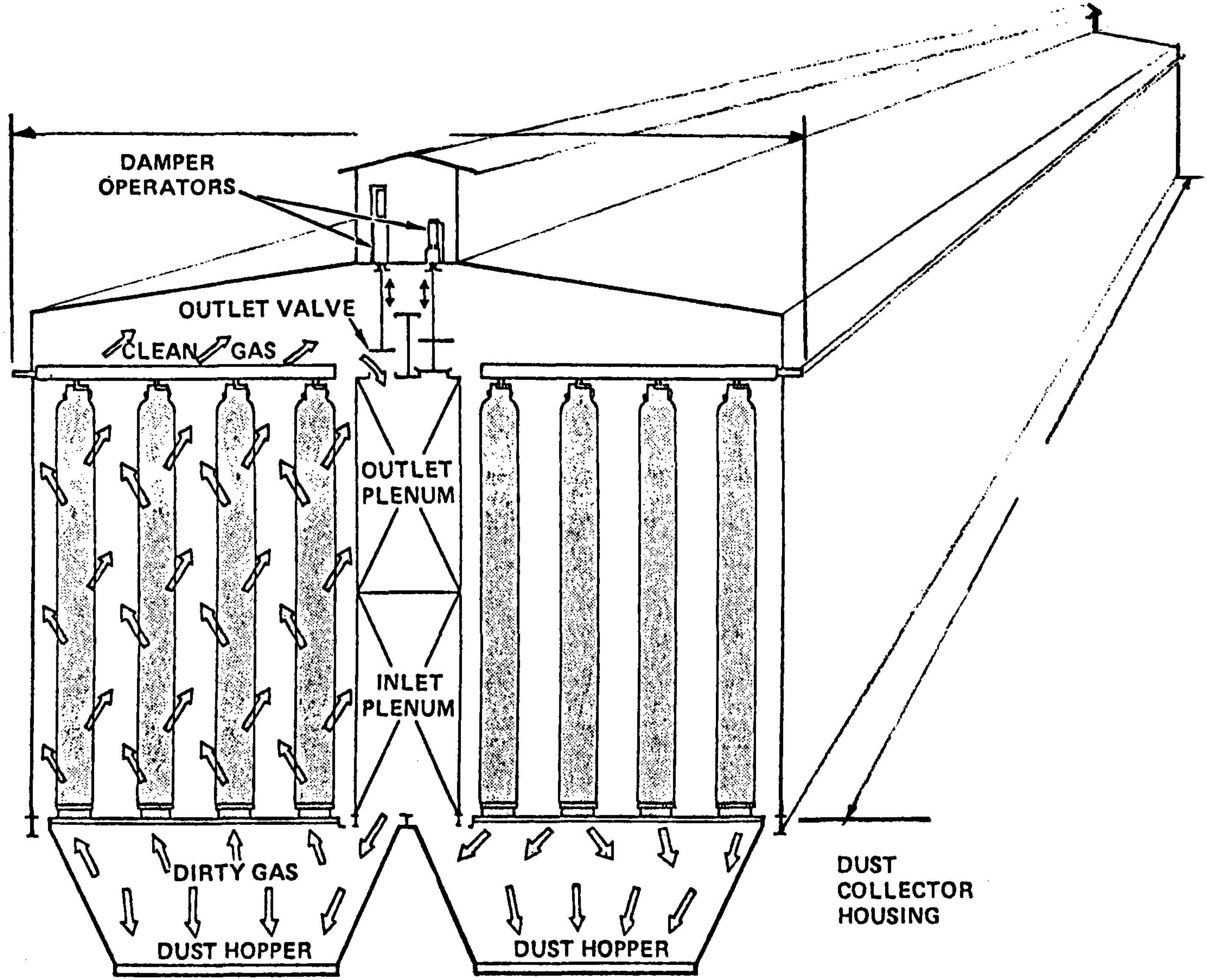


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Figure 5-91. Fabric Filter Dimensions

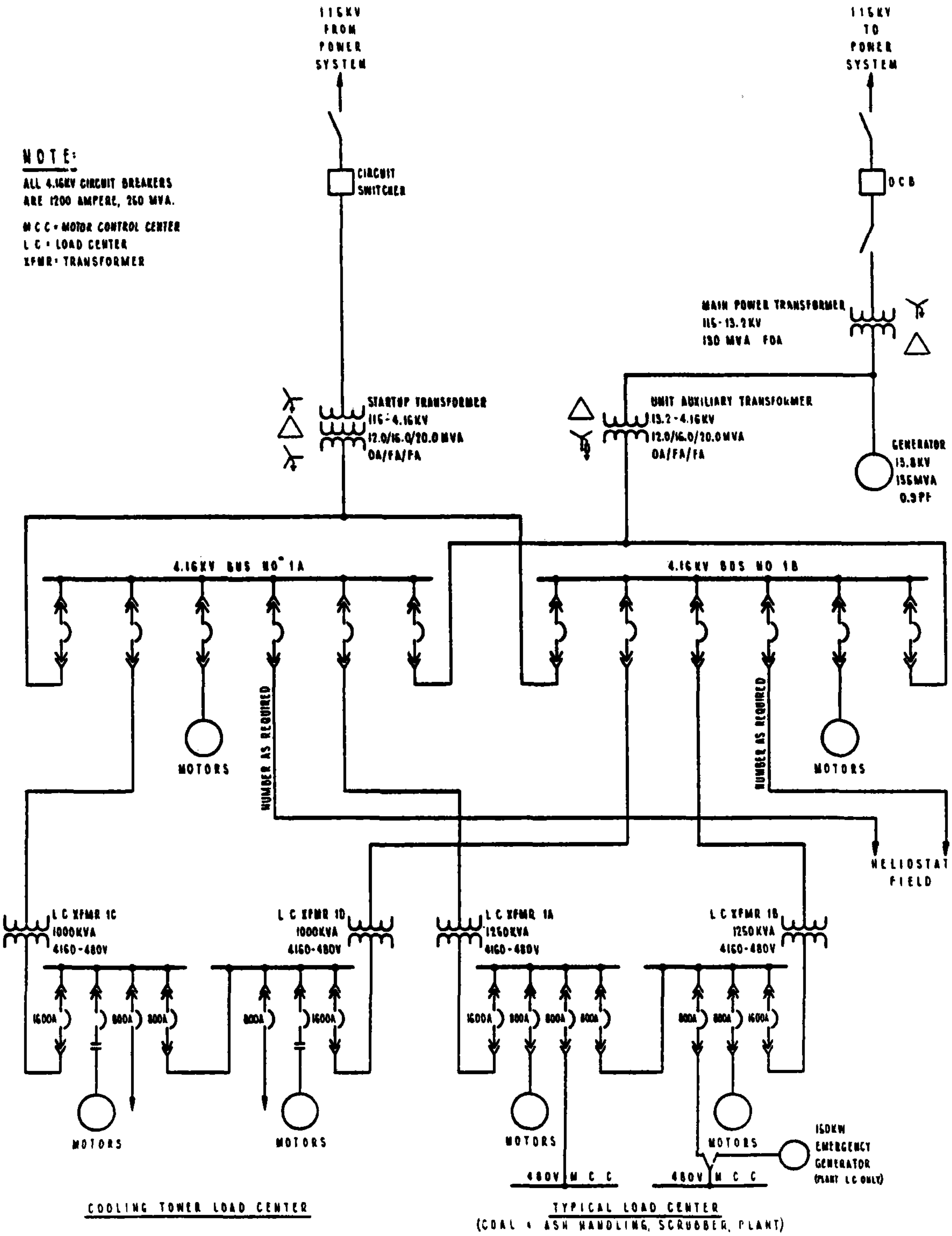


Figure 5-92. 100 MW Solar Hybrid Plant Electrical One-Line Diagram

5.6.8 Electric Plant Equipment

5.6.8.1 Main Electrical System

The generator will be connected by isolated phase bus to the unit auxiliary transformer, surge protection, and voltage transformer cubicle, and the main power transformer, as shown in Figure 5-92, which is the electrical one-line diagram for the baseline 100-MW solar hybrid plant.

The main power transformer will step up generator voltage to the voltage required by the power transmission system. For the purpose of this report, the transmission system was assumed to be 115 kW. The main power transformer will be reduced based on ambient temperature if ambient temperature exceeds 40^{o}C. The 115 kW winding will be wye-grounded; the 13.2 kV winding will be delta.

The main power transformer will be connected to the transmission system by an overhead line or underground cable, oil circuit breaker, and disconnecting switches will be 115 kV, 1,200 amp. The disconnecting switches will be mounted on a steel structure. The 115-kV switching equipment will be as required by the utility.

The startup transformer will be connected to the transmission system by either an overhead line or underground cable and a circuit switcher. The circuit switcher will be rated 115 kV, 1,200 amp. The startup transformer supply and switching equipment will be as required by the utility.

5.6.8.2 Auxiliary Systems

Auxiliary power will normally be supplied by the unit auxiliary transformer which will be rated 13,200-4, 160 V, 12.0/16.0/20.0 MVA, OA/FA/FA. Transformer temperature rise will be reduced based on ambient temperature if it exceeds 40^{o}C. The primary will be connected delta. The secondary will be wye-resistance grounded. The unit auxiliary transformer will be connected to the generator isolated phase bus. The secondary of the transformer will feed two bus sections of metal-clad switchgear operating at 4,160 V. The connection to the 4,160 V bus will be nonsegregated phase bus.

Startup power will be supplied from the transmission system by the startup transformer. The transformer will normally supply all auxiliary power when the generator is not operating. In addition, the transformer will be available, for emergency service, and to supply auxiliary power if the unit auxiliary transformer is not available (due to failure). The startup transformer will be rated 115 kV, 12.0/16.0/20.0 MA, OA/FA/FA. The primary will be grounded wye, the secondary resistance-grounded wye. The transformer will have a tertiary. The final primary voltage will be determined by available transmission voltages. The transformer will be 550 kV BIL, and will be provided with surge arresters. Transformers temperature rise will be reduced based on ambient temperature if ambient exceeds 40°C.

Two bus sections of 4,160-V switchgear were selected to obtain greater reliability and substantially the same cost as a single bus section. The larger breaker required for a single bus section cost about twice as much as the smaller breakers for two bus sections.

All motors larger than 200 hp will be served directly from the 4,160-V buses. Motors larger than 100 hp up to 200 hp will be served from load center circuit breakers. Where reversing motors are required, these will be served by a motor control center. Motors of 100 hp and less will be served by motor control centers.

The plant load center (1A and 1B) will be double ended with two 4,160-480-V, three-phase, 1,250 kVA silicone oil-filled or dry-type transformers. The secondary main breakers will be 600-V, 1,600-amp drawout power circuit breakers. A 600-V, 800-amp drawout circuit breaker will be provided for the bus tie. Feeder circuit breakers will be 600-V, 800-amp drawout power circuit breakers. The plant load center will be located indoors.

The coal and ash handling and scrubber load centers will each be double-ended with two 4,160-480-V, three-phase, 1,250 kVA oil-filled transformers. The secondary main breakers will be 600-V, 1,600-amp drawout power circuit breaker. Feeder circuit breakers will be 600-V, 800-amp drawout power circuit breakers. The coal and ash handling and scrubber load centers will be located outdoors.

The cooling tower load center will be double ended with two 4,160-480-V, three-phase, 1,000 kVA oil-filled transformers. The secondary main breakers will be 600-V, 1,600-amp drawout power circuit breakers. A 600-V, 800-amp drawout power circuit breaker will be provided for the bus tie. The feeder assembly will be a motor control center. The starters for the cooling tower fans will be circuit breaker combination, reversing (if reversing is required). Molded case breakers will supply lighting transformers and miscellaneous services. The cooling tower load center transformers will be located outdoors. The switchgear and motor control center will be located indoors.

Two motor control centers will be served by the plant load centers, one from each bus section. Circuit breaker combination starters will be provided for motors. Molded case breakers will be provided for lighting transformers, battery chargers, and miscellaneous service.

5.6.8.3 Emergency Generator

One 150-kW emergency power diesel engine generator will provide ac power for safe shutdown and emergency service. The generator will be rated 189.5 kVA, 80% power factor, 480 V. The generator will be connected to one of the motor control centers by an automatic transfer switch. If power fails on the motor control center the diesel will automatically start and the motor control center load will transfer to the emergency generator. With the 0.8 solar multiple plant, emergency power for heliostat slewing is not required since cold sodium buffer storage will supply sufficient cooling for safe receiver shutdown on loss of power.

5.6.8.4 Heliostat Field Feeders

The heliostat field will be served by four 4,160-V feeders, pad-mount transformers rated 4,160/240 V will supply the heliostat field. The feeders will be direct burial power cable with concrete cover. The number, size, and location of transformers will be defined under the collector subsystem.

5.6.8.5 DC System

The dc system for the plant will consist of a battery, two battery chargers, distribution panels, and two inverters. The battery will be a 60-cell lead acid, 400 ampere-hour, calcium pasted plate type. The battery chargers will be automatically regulated, 125 V dc equalizing charge, 460 V ac supply. A main distribution panel will supply all loads over 100 amperes.

There will be two small distribution panels. The small distribution panels will supply all loads of less than 100 amperes. All distribution panels will use switches and fuses. Two 15-kVA inverters will provide supply critical control requiring 120 or 208 V ac.

5.7 MASTER CONTROL SUBSYSTEM

5.7.1 Master Control Subsystem Requirements

Modes of Operation The Master Control Subsystem, such as that currently utilized by the utilities, will be configured to sense, detect, monitor and control all system and subsystem parameters necessary to ensure safe and proper operation of the Solar Central Receiver Hybrid Power System. Data recording shall be provided for those parameters considered pertinent in the evaluation of plant performance, safety and operation.

Master Control Design The Master Control Subsystem shall be designed based on the following considerations.

Design simplicity, resembling standard power plant control systems:

- Standard control practices
- Simple, well defined interfaces between the Master Control Subsystem and the other plant subsystem controls

Operational Simplicity, requiring primary operation to be automatic with operator override capability:

- Single console control during both automatic and manual operations
- Easily read displays

Design reliability, requiring:

- Use of proven designs
- Elimination of single point failures through redundant elements whenever it is cost-effective to do so

Operational reliability, requiring:

- Separation of plant operational controls from data acquisition and evaluation peripheral controls within the Master Control Subsystem (thus permitting each control to function independently).
- Manual operation of the plant in the event of failure of the Master Control Subsystem (thus requiring independent controls for the other plant subsystems)

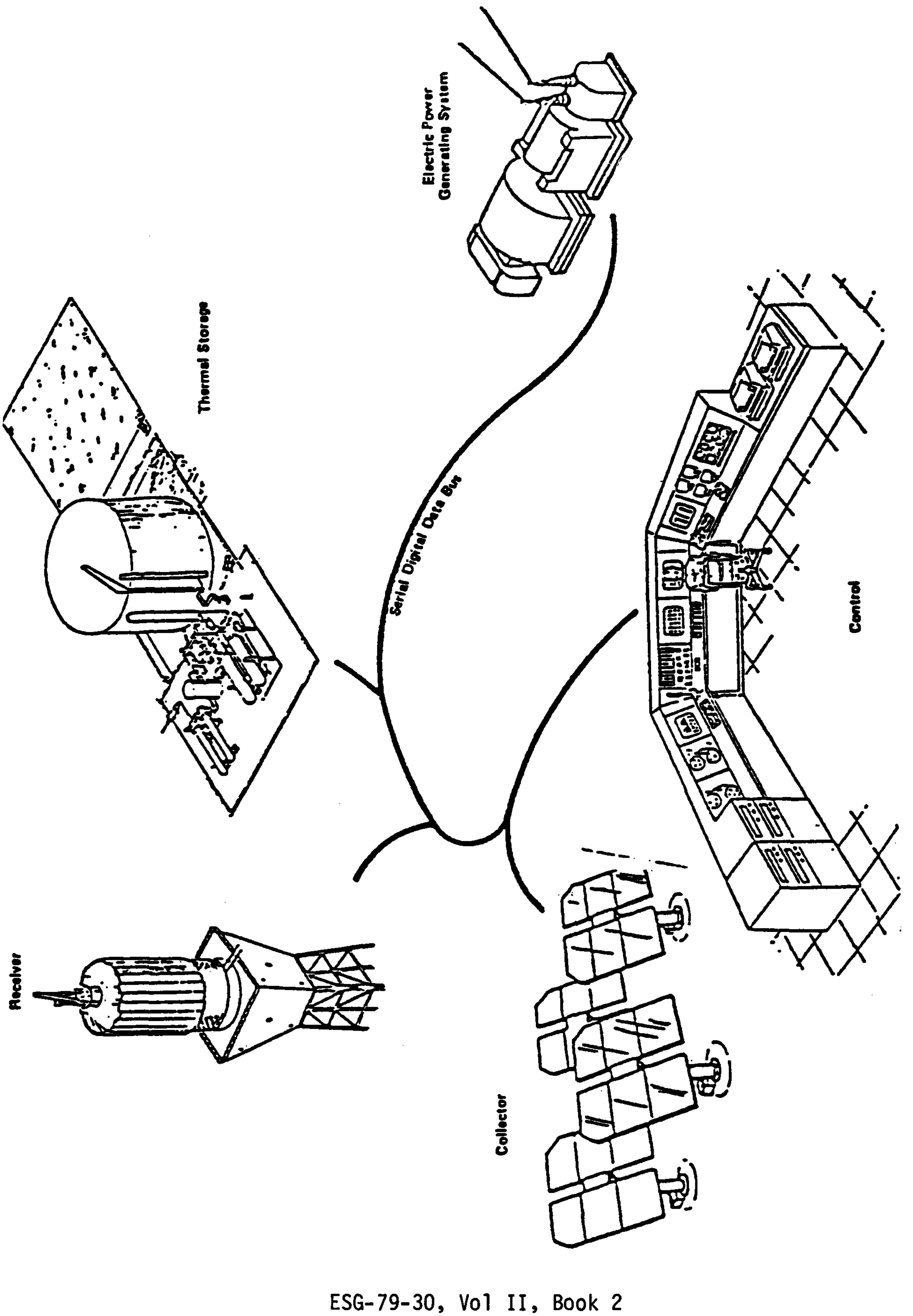


Figure 5-93. Distributed Control Concept

Cost-effective design, requiring:

- Selection of off-the-shelf equipment
- Modularity among the major subsystems of the Master Control Subsystem
- Generically similar equipment in each major Master Control Subsystem
- Multiple analog data channels connected to single high-speed digital channels

Cost-effective operation requiring:

- Flexibility via a comprehensive set of operational modes
- Software driven operational control which is easily changed or expanded

5.7.2 Master Control Subsystem Description

The master control design for the Solar Hybrid Central Receiver System 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 5-93. This design employs a distributed control system 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.

Control/Monitoring System Design

The design of control/monitoring system for the Solar Hybrid Central Receiver System incorporates an integrated plant control center. This center

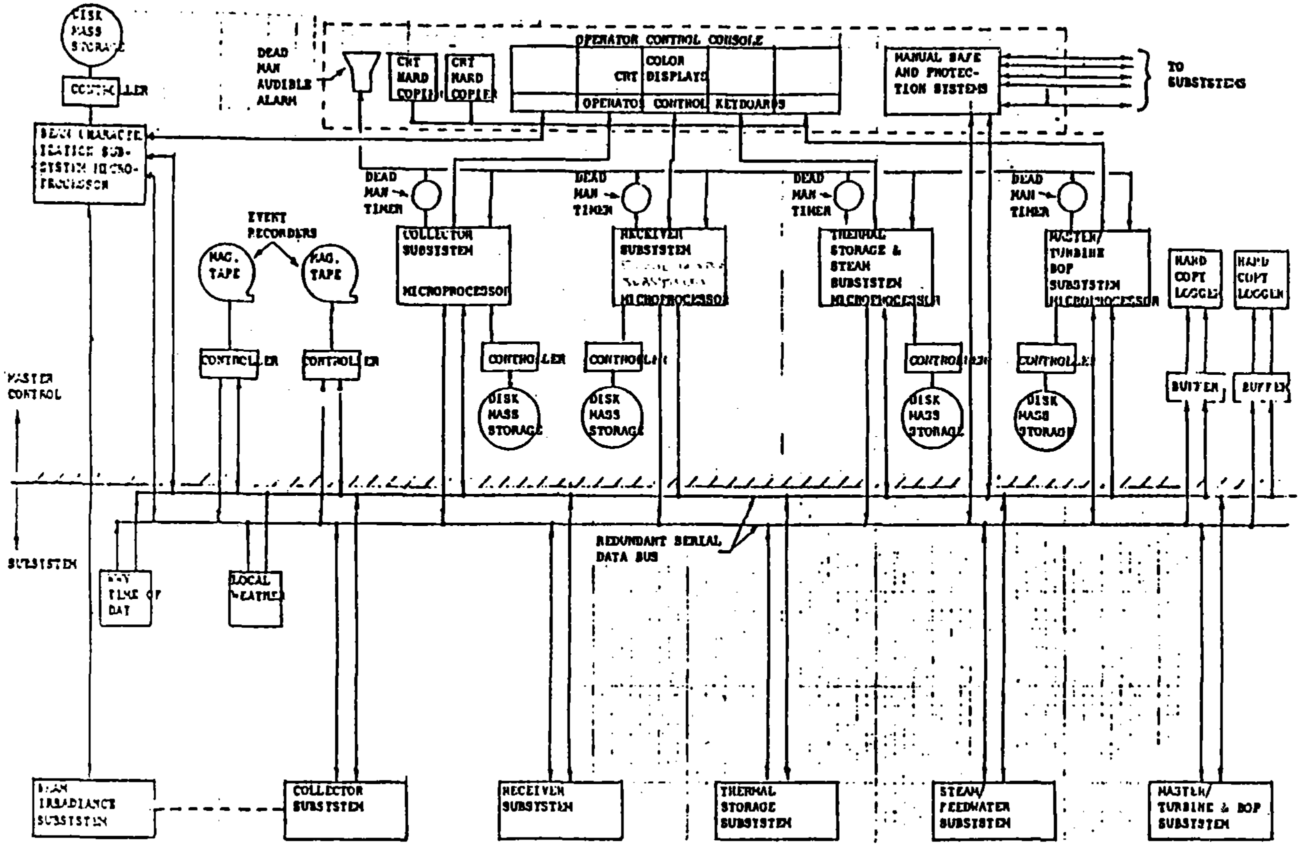


Figure 5-94. Master Control Subsystem — Block Diagram

connects master control and independent subsystem controls to the subsystem controllers, located remotely in the field, by a redundant serial fiber optic transmission scheme.

Features of the plant control center include:

- Distributed control/monitoring functions with redundant fail over capability.
- Single communication bus architecture interfacing all plant control facilities.
- Independent data acquisition and reduction system to accommodate pilot plant experimental instrumentation.
- Automatic and manual safing and protection systems.
- Recording, logging and hard copy capabilities that preserve significant plant operation events.
- Collector and beam characterization subsystems integrated into the plant control concept.
- Time of day, local weather and grid demand coordination connected to the communications bus.

A block diagram of the plant control hardware is shown in Figure 5-94.

The control/monitoring system design employs a combination of hardware and software to achieve plant monitoring and control functions. Specific control/monitoring functions are distributed within six microprocessing systems that provide: 1) independent subsystem control and monitoring that supports automatic, semi-automatic and manual (cascade) modes of plant operation, and 2) a redundant fail over capability for plant control functions to minimize single point failures of computational control hardware and peripherals.

This design approach distributes a common set of interfaces, hardware components and software design disciplines across the subsystems, at the master control level, maintaining system integrity throughout. Significant cost, operational and benefits implementation are obtained through: 1) development of simpler stand-alone software packages for each subsystem processor in difference to development of software packages for a single processor that are complicated by limited single CPU and peripheral resources that each subsystem task must compete for, 2) use of multiprocessors to provide tailored subsystem throughput capacity for control, display and operator interaction without the need for high performance and costly mini or maxi computer systems, and 3) the adoption of the multiprocessor configuration to minimize system monitor/control failures at the control center interface by providing failover to a redundant "look-alike" system rather than a wire-by-wire large control board with a unique combination of manual control and monitoring appliances.

The control center philosophy assigns an independent processing capability to the subsystems with a reserve.capacity to absorb the monitoring and control operations of a companion processor that has failed. Four processors, each configured with memory, arithmetic and mass storage peripherals, will provide the total capacity to monitor and control the plant operating functions exclusive of experimental data acquisition unique to test and development purposes.

Each of the four processor control terminals can communicate with any of the processors. Thus the operator can command and monitor the plant from one CRT/ keyboard or command and monitor each subsystem through an independent CRT keyboard.

Each processor contains the control and monitoring sequences for the entire plant. These programmed sequences are stored in separate secondary storage media and used by the processor as required. A program sequence exists for each subsystem. In addition, a master control program sequence provides overall Plant control and arbitrates the use of peripherals shared by all processor units.

The duplication of processor units, control units and shared peripherals in the central control console provides a high degree of redundancy that minimizes single point failures.

Data Communications Design

The common communications link between the central control console and the subsystem controllers consists of a redundant fiber optics cable, or hardwire.

A hardwire cable at present provides the most cost effective approach to the communications requirements. However, the high speed parallel transmission characteristics and superior electrical noise immunity available using fiber optics techniques are attractive. These techniques should be cost competitive with the hardwired approach in the 1980 and later time period.

The serial hardwired data link will transmit data between the central control console and subsystem controllers in a digital form. This technique is highly immune to external electrical noise perturbations and forms a totally compatible information interface with the central control console processors and the subsystem controllers.

Addressing schemes will be used to direct the data to the appropriate device and word bit patterns will accompany each transmission for the purpose of diagnosing single and multiple bit transmission errors. All information transfers will be sent over both the primary cable and the backup cable. A transmission line monitor continually tests the lines for loss of signal and alarms the central control console if this happens. Each device reads both lines and accepts the primary line if found to be error free. Should an error occur or loss of signal occur on the primary line, the device uses the data from the backup line providing it is error free. Error flags are used to inform the central control that a transmission error has occurred and retransmission of the message is required.

Subsystem Controller Design

Subsystem controllers used by the Solar Hybrid Central Receiver System will consist of the following types of devices:

- Proportional Integral Derivative (PID) Controllers
- Interposing Logic Controllers
- Discrete Controllers (digital output)
- Discrete Monitors (digital input)
- Analog Monitors (analog inputs)
- Analog Controllers (analog outputs)

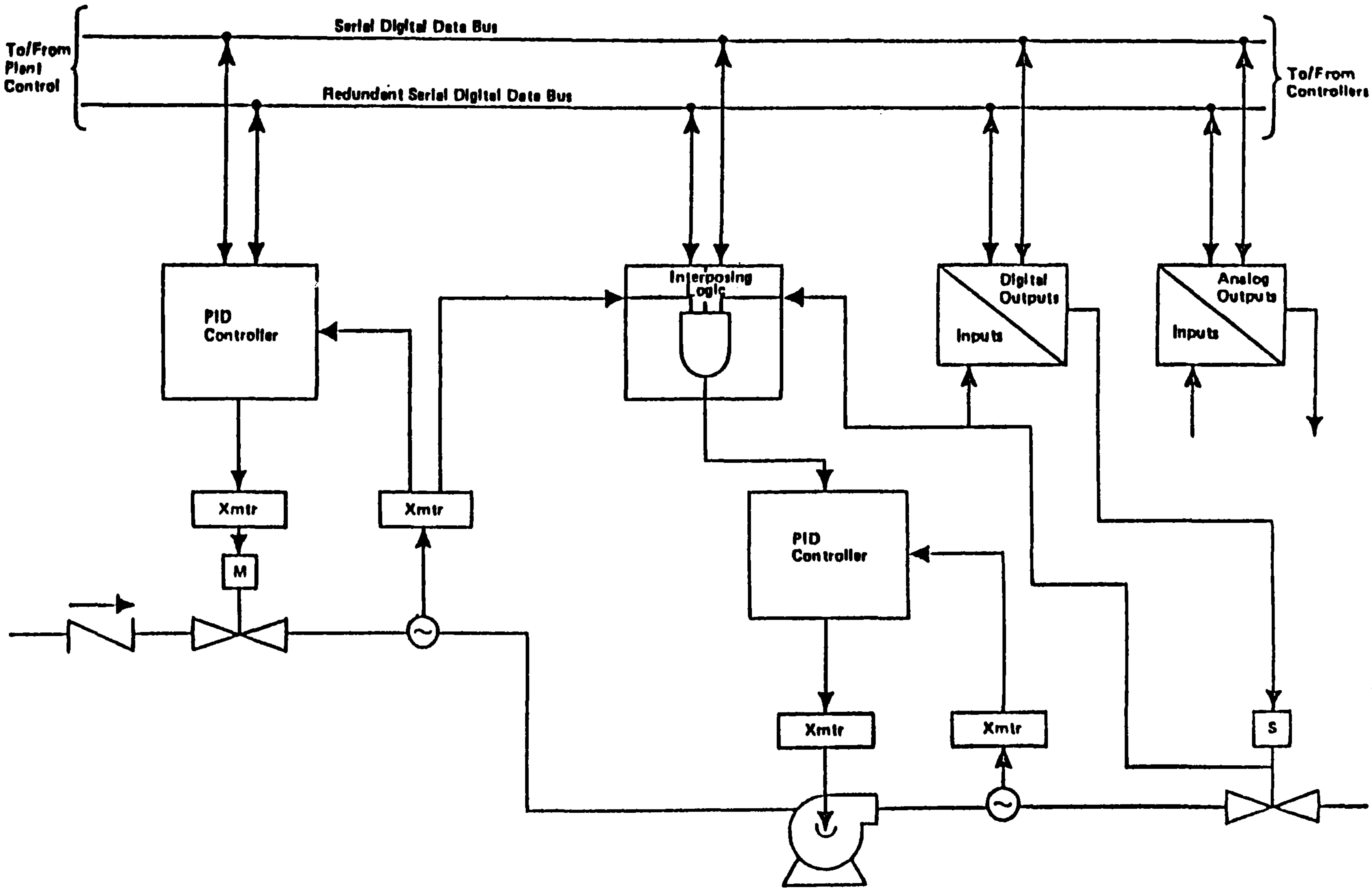


Figure 5-95. Block Diagram Typical Controller Functions

An example showing the use of many of these devices is shown in Figure 5-95. All of these devices connect to the serial data bus for communications with the central control console. In turn, they also link to the process monitor or control functions.

The conceptual design of the control system provides for the distribution of computational and logic functions within each controller device. This is implemented through the integration of microprocessors into the hardware. Consequently, the central control processor functions are not complicated with requirements for complex software and the need for very high performance equipment.

In addition to the computation and logic functions of the subsystem controllers, the microprocessor provides capabilities to diagnose the hardware on a time available basis, store data for use by the central control processors, and communicate with the backup controller to provide automatic fail-over independent of central control.

If a plant upset should occur, this hardware will automatically initiate an emergency monitor mode. At this time monitor and control data will be stored for a selected period of time or until the storage memory is full. Following the upset, central control can immediately interrogate these memories and log the data on a printer for analysis.

5.7.3 Collector Subsystem Control

One of the four processors will be configured with the software modules to control and monitor the operation of the heliostat array. Both 100 MW plants SM 0.8 and SM 1.4 will require this processor, called the Heliostat Array Controller (HAC), to perform the following collector field tasks:

- Heliostat Status - This major module will periodically request information about every heliostat in the field and maintain a status data base on a mass storage device (disk). This module can also be called as a subroutine to either store a status change in the data base or retrieve data about heliostat(s) from the disk for the requesting module. The operating mode will be represented as well as the last known azimuth and elevation angle positions.

- Emergency Slew (if required) - A single command from either the MCS or the operator at the HAC can trigger emergency slew. Emergency slew is a rapid movement of all solar beams focused on the solar receiver away from the solar receiver to a standby position.
- Mode Transition - This module will conduct all mode transitions, except for an emergency slew request, and ensure that they are executed without violating beam safety requirements.
- Aim Point - This module shall calculate a trajectory of aim points across the heliostat field hemisphere to move these heliostats selected for special moves. The beam safety subroutine will be called to advise this module on avoiding areas where beams are not permitted.
- Beam Safety - This module maintains a description of the topography of the heliostat field and surrounding air space where reflected solar beams are permitted and where they are not permitted. It will be necessary for this module to know the heliostat position (x, y, z) and the proposed beam path vector trajectory in order for the module to determine if the reflected beam will pass through a restricted zone.
- Calibrate Heliostats - This module interfaces with the beam calibration/ slignment. This module will calculate gimbal angles which will result in the selected heliostat hitting an active calibration target. After the calibration target has obtained several measurements of image centroid from several mirror positions, the correction algorithms can be executed and new alignment constraints determined.
- Heliostat Reference Locate - If a heliostat or group of heliostats lose their reference points, this module will direct the heliostat(s) to move the shortest distance in order to get a reference update from the absolute encoders on the heliostat. This module will refer to the "status" information for the last known position and the beam safety module for authorization to command the movement.
- Data Collection - This module will collect data from heliostats in accordance with several predetermined data collection formats. The collection module will collect data either from the HAC's global data base or request the required information from the heliostats.

- Start-Up - This module will calculate the heliostat field to be used for cold and hot receiver start-ups. The determination of the requirements for start-up will be obtained from data supplied by the receiver programmed monitor/controller.

5.7.4 Receiver Subsystem Control

A second programmed monitor/controller will be assigned to the receiver subsystem. This monitor/controller will perform the following tasks:

- Startup Management - This module will determine the status of each receiver panel prior to a startup and solve the algorithms for the optimization of cold and hot receiver startups. Optimization data will be presented to the operator and used by the collector monitor/controller for the selection of the heliostats to be used for startup.
- Receiver Shutdown - A module will be required for optimizing shutdown of the receiver to minimize thermal stresses and prevent the solidification of liquid sodium. This module will also provide: 1) SET point command changes to the individual panel controllers initiated by the operator should they be required, 2) monitor tracking of panel status, and 3) formatting status change displays for alarm and operator interpretation.
- Receiver Steady State Operation - The decoupling of the receiver subsystem from the steam/water and power generation subsystems removes interacting subsystem coordination requirements. Consequently, the steady state module provides for the monitoring of receiver operating status and provides alarms and data to the operator. This module provides the capability for commanding controller setting changes if required.
- Receiver Data Collection - This module acquires monitoring/control measurement and status data and formats these data for use by other monitor/control modules of the master control system.
- Receiver Diagnostics - The available time remaining within the programmed controller will continually be filled running diagnostics on programmed controller hardware and interpreting the availability of monitor and control hardware in the field.

5.7.5 Storage/Steam Generators Subsystem Control

A third programmed controller monitors and controls the thermal storage (solar multiple = 1.4) and steam generation subsystems. This element of the power plant is, for the most part, typical of a conventional power plant. The thermal storage and steam generators will use local controllers to maintain steady state operation. The tasks performed by this unit are:

- Energy Management - This module calculates the status for operating the plant based on the available stored energy, the energy requirements to maintain grid demand and operating plan for the day and the available energy storage replenishment. The data from these computations is formatted and displayed to the operator.
- Data Acquisition - Operational data in the form of digitized analog measurements and binary status are collected and formatted for recording, operator display and use by other modules in master control.
- Storage/Steam Control - This module provides the capability for the operator to command changes to control settings for the thermal storage and steam generators if required. Alarm and limit tests and display are performed by this module using data obtained from the data acquisition module.

5.7.6 Nonsolar Subsystem (Fossil Heater)

The control of the fossil heater will be maintained for the second programmed monitor/controller which is also assigned to control of the receiver subsystem. This is because of the close coupling of these two subsystems. In addition to the receiver control tasks, this monitor/controller will perform the following tasks.

- Flow Mixing Between Receiver and Heater - This module will maintain a proper balance between receiver and heater output to assure the proper flow to the steam generation subsystem.

- Heater Ramp Up and Down - This module will control the ramp up and down the heater during major excursion in receiver output. It must also maintain coordination with the thermal buffering (SM 0.8) or thermal storage (S.M. 1.4) to account for lag times in heater and receiver ramp rates.

- Heater Steady State Operation - Provides control of heater during heater only operation, allowing plant operations during extended periods of non-solar collection. Provides capability for thermal storage makeup if deemed necessary and allows checkout of plant prior to turn-on of solar system.

- Heater Data Collection - This module acquires monitoring/control measurements and status data and formats these data for use by the modules of the master control system.

- Heater Diagnostics - Provides hardware status and malfunction report.

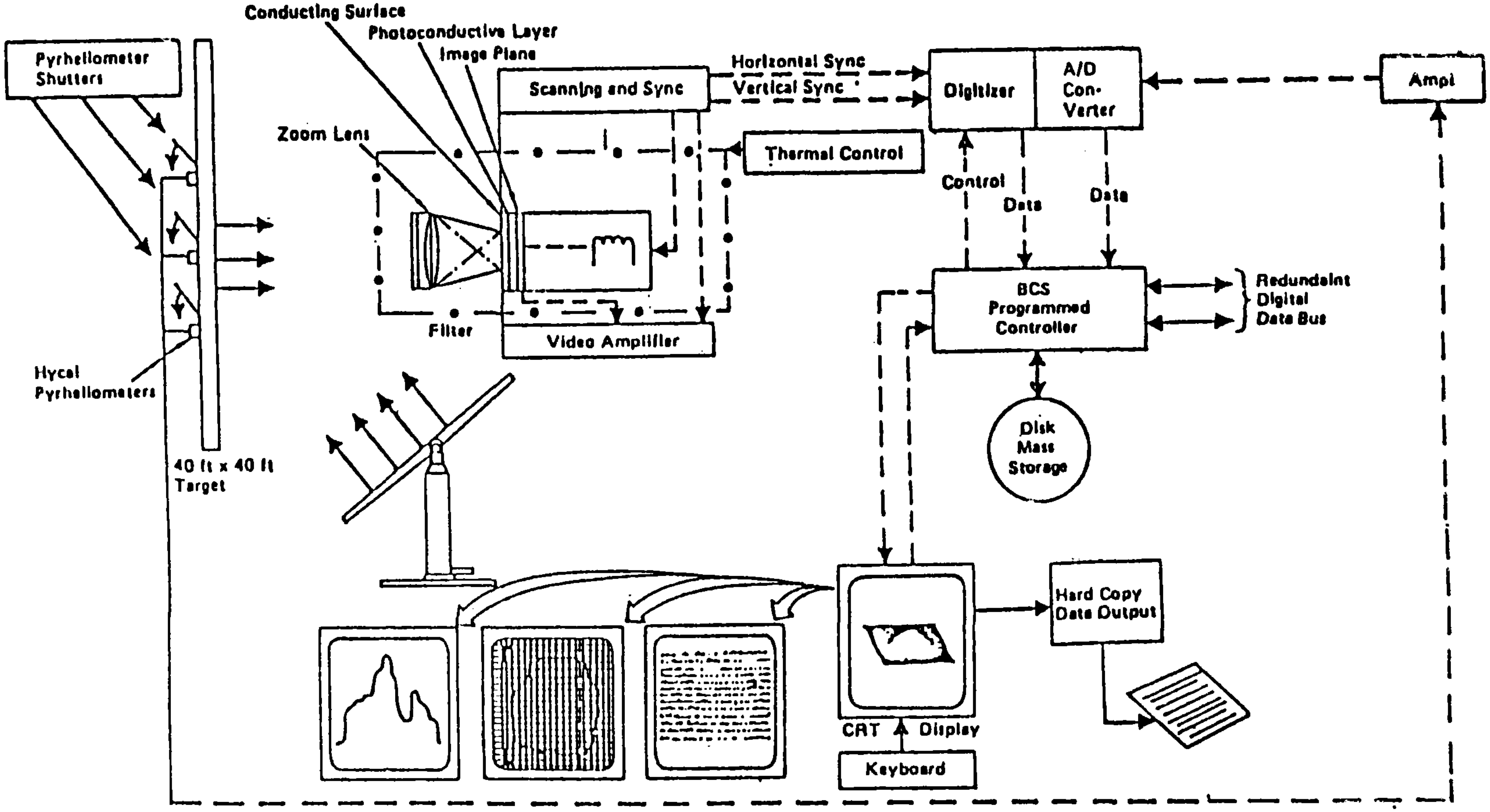
5.7.7 Master Control and Balance of Plant

The fourth program controller contains the modules that will coordinate the activities of all the program controllers as well as monitor and control, if required, specified functions of the balance of plant and turbine generator. Support systems (i.e., N_2 Argon, compressed air, etc.) will be monitored by this unit. Monitor and control modules executed by the master, turbine and BOP controller are:

- Master Control Coordination - This module will manage the input and output traffic of the other programmed controllers when using the redundant serial data bus or the shared peripherals (i.e., event recorders and hard copy loggers). The plant operations sequencing for automatic operation will be provided in this module.

- Master Data Base Manager - A master data base will be stored and updated in the master controller. This data base will be a composite of the other data bases managed in the other three program controllers. The contents of the master data base will be used for the generation of plant reports and the display of graphic and tabular plant data to the operator.

- Plant Report Generator - The generation of plant reports will be accomplished by this module, stored and output on the hardcopy loggers and visual operator display terminals. The report generator will obtain the information for reports from the master data base. Reports will be generated on a time basis or upon demand when requested by the operator.



Beam Characterization System Block Diagram

Figure 5-96. Beam Characterization System Block Diagram

- Redundant Bus Diagnostics - A diagnostic module will be used to test the redundant data bus integrity with the other programmed controllers, shared peripherals and remote subsystem interfaces. This module will automatically assign the programmed controllers to the functioning serial data bus. The failure of a serial data bus will post an alarm to the operation and the programmed controllers.
- Plant Startup - The operator will be required to initiate the master control system startup following a power down incident or when required. A module will be required to initiate the program loading of the other programmed controllers and a functional test of master control when a system startup is required. This module will also report the startup status of master control upon request from the operator.

5.7.8 Beam Characterization Subsystem

An independent fifth programmed controller provides the capability of calibrating the heliostats in the collector field. This controller interfaces to the redundant digital data bus of master control to communicate and transfer information to and from the collector subsystem programmed controller. This controller also interfaces to image digital radiometers remotely located in the field that measure the radiance patterns of the heliostat. A block diagram of this system is shown in Figure 5-96.

The programmed controller in the beam characterization system performs the following tasks:

- Data Collection - This module will collect digitized video scanned irradiation data from a target reflection of a heliostat beam along with heliostat position and available light data. These data will be stored in raw form.
- Data Reduction and Analyses - Beam reflectivity, irradiance, flux density comparisons, flux density distribution and beam centroid data reduction and analysis are performed by this module. Results of these analyses are used to determine the condition and alignment characteristics of each heliostat. These alignment and reflective characteristics are in turn transmitted to the collector subsystem programmed controller where heliostat alignment corrections and maintenance actions are programmed.

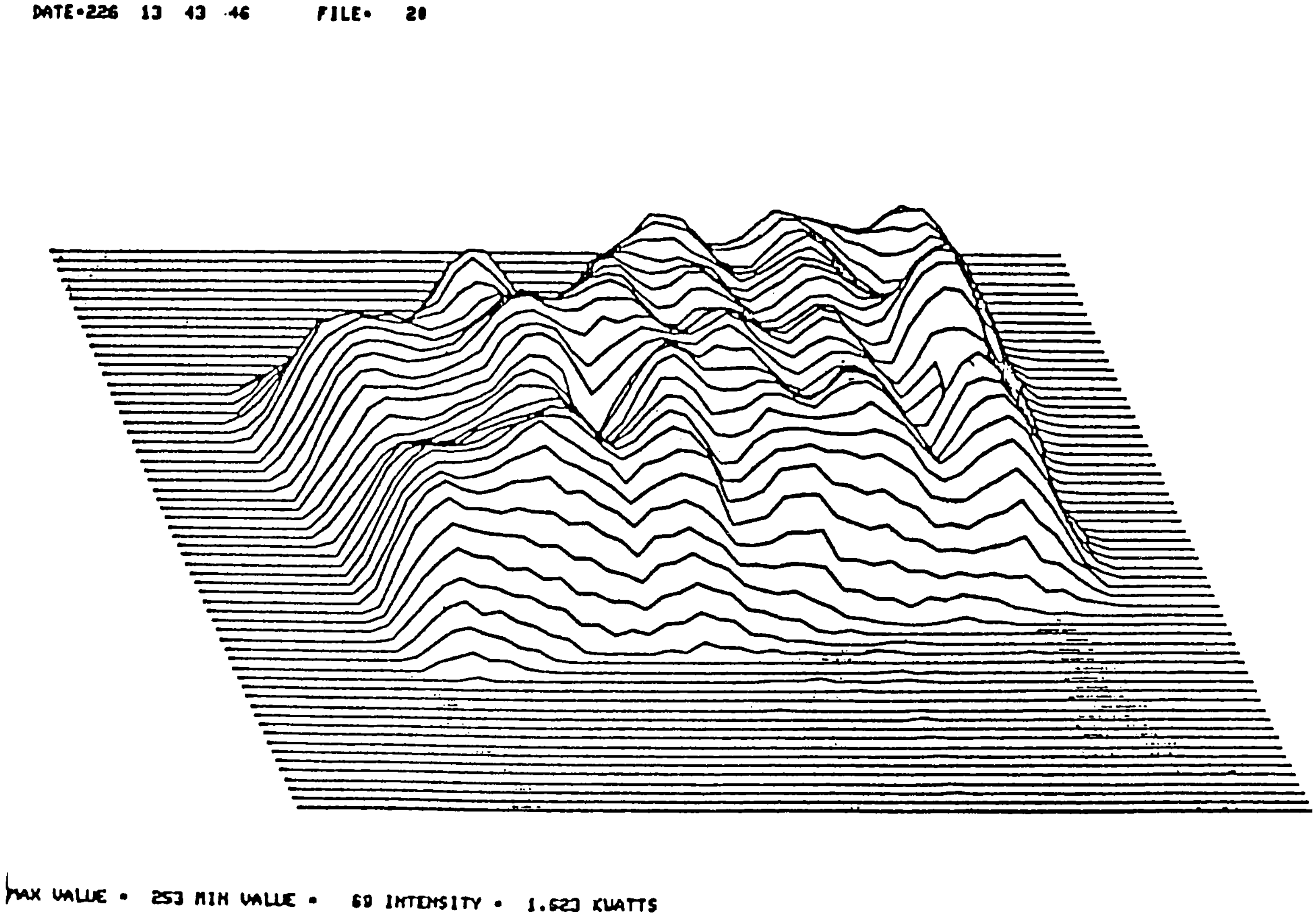


Figure 5-97. Typical Display Information

- Data Display - The display of calibration data for a heliostat will be provided by this module. Tabular and graphical presentations can be commanded from the display terminal. An illustration of the type of display information is shown in Figure 5-97.
- Diagnostics - This module will provide diagnostics that evaluate the programmed controller and irradiance system hardware. Hardware status and malfunction reports will be generated in this module.

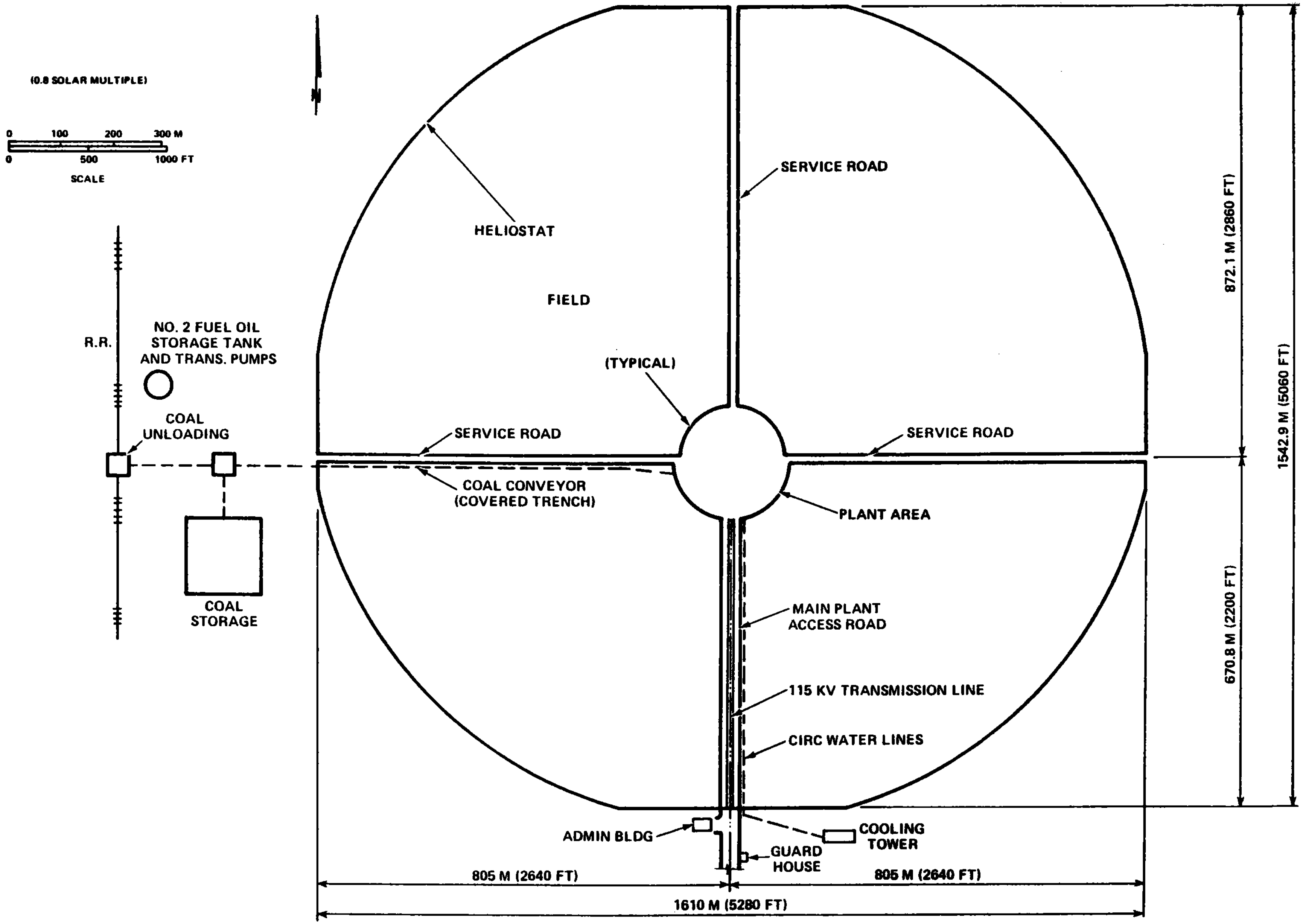


Figure 5-98. 100-MW Key Plan

5.8 BALANCE OF PLANT

5.8.1 Plot Plan

5.8.1.1 100 MWe Baseline Plant

The Plot Plan for the 100 MWe, 0.8 solar multiple baseline plant is shown in Figure 5-98. The plot plan for the 100 MWe, 1.4 solar multiple plant would be similar except for field size. As shown in Figure 5-98, the main plant access road runs north-south below the Central Plant area. Service roads are provided to the east, west, and north of the Central Plant area, as well as a perimeter road (not shown) around the collector field. A 115 kV transmission line parallels the main plant access road.

Coal unloading, crushing, and storage facilities are located to the west of the collector field, along with the primary No. 2 fuel oil storage tank and transfer pumps. Coal is delivered from the crusher building to the Central Plant area by conveyor belt located in a covered trench. Other structures located outside of the mirror field perimeter include the cooling tower, administration building, and guard house.

5.8.1.2 430 MWe Commercial Plant

The preliminary plot plan for the 430 MWe (net), 1.44 solar multiple commercial plant is shown in Figure 5-99. Except for field dimensions, the plot plan of the proposed 430 MWe commercial plant is similar to that for the 100 MWe baseline plant described in Section 5.8.1.1.

5.8.2 Plant Layout

5.8.2.1 100 MWe Baseline Plant Layout

The plant layout for the 100 MWe, 0.8 solar multiple plant is shown in Figure 5-100. The plant layout for the 100 MWe, 1.4 solar multiple plant would be similar, except for the addition of two 30.5 m (100 ft) diameter sodium storage

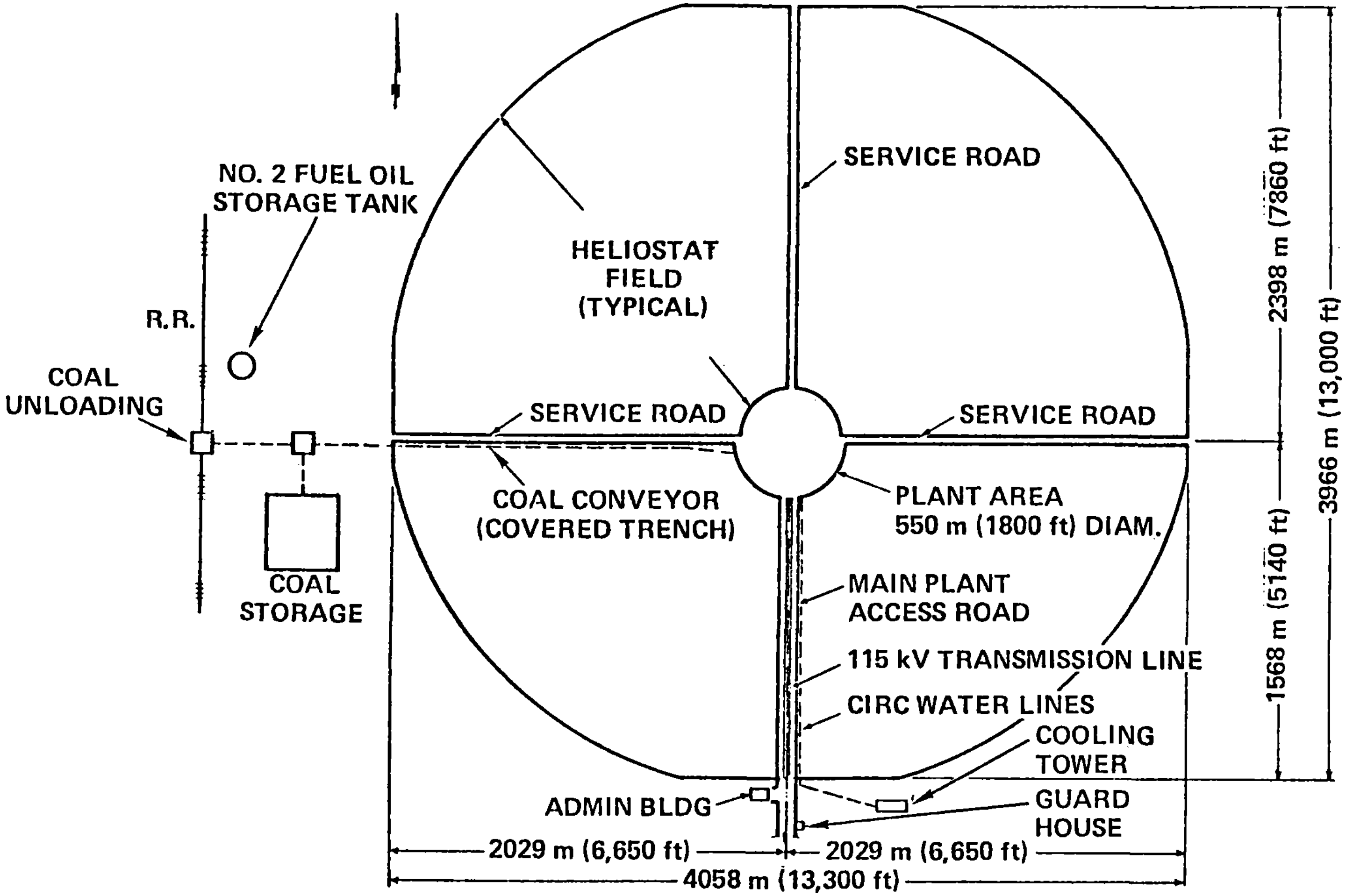


Figure 5-99. Preliminary Plot Plan for 430 MWe, 1.44 Solar Multiple Commercial Plant

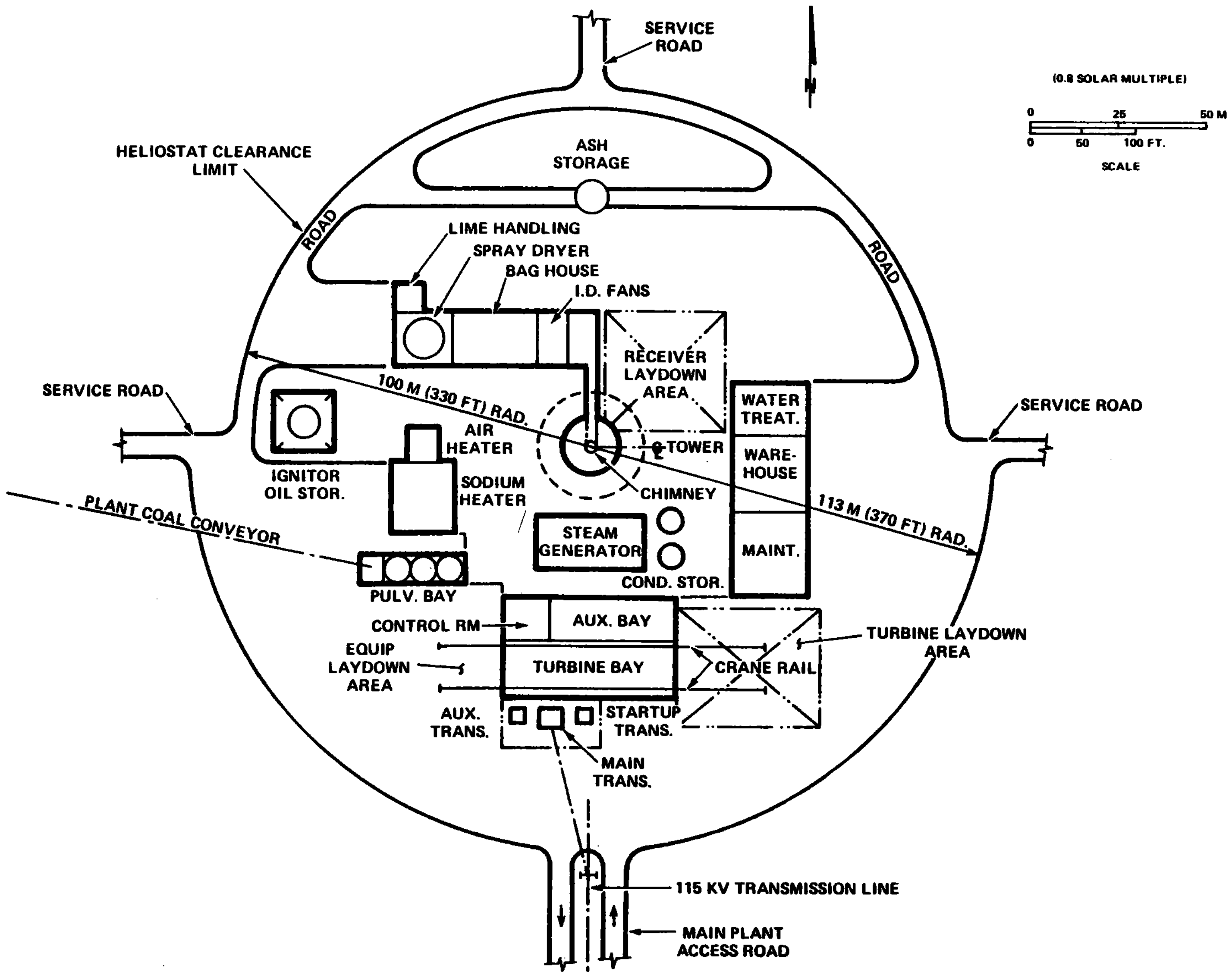


Figure 5-100. 100-MW Plant Layout

tanks. The minimum radius for the central plant area would increase from 100 m (330 ft) to ~125 m (410 ft) for the 1.4 solar multiple plant with 3 h full load storage capacity.

As indicated in Figure 5-100, the turbine building consists of a turbine bay, auxiliary bay, and plant control room. Equipment located within the turbine bay includes the turbine-generator unit, which is an outdoor unit located on the turbine deck, condenser, isolated phase bus, generator protection equipment, condensate hot well pumps, turbine lube oil equipment and low-pressure Heater 6. The auxiliary bay contains the feedwater heaters, boiler feed pumps, air compressors, electrical switchgear and battery room. A gantry crane with extended crane rails is provided over the turbine deck to facilitate turbine-generator and other equipment maintenance.

In addition to the turbine building, other major process equipment located within the central plant area includes the coal silos, pulverizers, sodium heater, air heater, F.D. fan, spray dryer, and baghouse (for SO_2 and particulate removal), ID fan, receiver/tower/chimney, steam generator (evaporator, superheater, reheater) and ash storage tank. Balance-of-Plant buildings located within the central area include a maintenance building, warehouse building, and water treating building.

5.8.2.2 430 MWe Commercial Plant Layout

The 430 MWe commercial plant layout has not been developed; however, the general arrangement for the commercial plant would be similar to the 100 MWe baseline plant layout shown in Figure 5-100.

COST SUMMARY

The capital cost estimate for the first and Nth commercial non-storage 100-MWe solar central receiver hybrid power plants is shown in Tables 5-23 and 5-24, respectively. Tables 5-25 and 5-26 show capital cost estimates for the first and Nth commercial, 100-MWe, 3-h storage systems. The Nth preferred commercial plant, rated at 430 MWe, 5-h storage plant cost estimate is shown in Table 5-27.

The estimates are subdivided by account and subsystem as required by the Requirements Definition Document and subsequent cost accounting guidance provided by Sandia Livermore Laboratories. The total capital cost estimates for the first and Nth commercial, 100-MWe, 0.8 solar multiple plants are $157.9 million and $140.3 million, respectively. The total capital cost estimate for the first commercial 3-h storage, 100-MWe plant is $203.1 million. An Nth commercial plant with the same rating would have an estimated capital cost of $179.3 million. A preferred commercial plant configured for 430-MWe output with 5 h of storage (3 filled by solar energy) has an Nth plant capital cost estimate of $610.6 million. All cost estimates are in 1979 dollars.

Estimated operating and maintenance costs (O&M) for the first commercial, 100-MWe, 1.4 solar multiple plant are shown for various operating years in Appendix T, Volume 3. These costs are broken down by account. The first year O&M costs for this plant are estimated to be $3.0 million.

The busbar cost of electricity, as calculated from estimates of capital, O&M and fuel costs are discussed in detail in Section 4 of this report.

TABLE 5-23

100 MWe, 0.8 SOLAR MULTIPLE, FIRST PLANT CAPITAL COST ESTIMATE — 1979 "000" DOLLARS

Cost Category	5100 Land& Site	5200 Admin.	5300 Coll.	5400 Rec.	5500 Master Control	5600 Non-Solar	5700 Energy Stor.	5800 EPGS
A Excav.& Civil	2,932	14	536	18	1	53	0	71
B Concrete	89	86	4,583	1,882	10	996	0	1,306
C Struc. Steel	0	0		841	0	521	0	0
D Buildings	0	300	0	535	54	1,760	0	490
E Mach.& Equip.	0	1,287	29,121	10,660	1,760	24,330	1,049	28,293
F Piping	96	38	0	8,983	0	45	0	3,165
G Electrical	0	99	1,864	77	5	425	0	4,085
H Instruments	0	0	119	702	145	0	0	500
J Painting	0	8	0	0	2	35	0	250
K Insulation	0	0	0	0	0	0	0	500
Direct Fld. Costs	3,170	1,832	36,223	23,698	1,977	28,165	1,049	38,660
L Temp. Cons. Fac.	0	19	73	136	0	0	0	425
M Cons. Serv.	0	50	55	386	0	0	0	300
N Subs.& Expense	0	46	451	1,039	10	0	0	1,100
P Benifits& Burdens	0	34	611	81	20	0	0	900
Q Equip. Rental	0	0	940	197	0	0	0	1,000
Indir. Fld. Csts.	0	149	2,130	1,839	30	0	0	3,725
Total Fld. Costs	3,170	1,981	38,353	25,537	2,007	28,165	1,049	42,385
R Engineering	190	100	0	1,548	0	0	63	750
S Procurement	0	0	34	16	0	0	0	15
T Management	95	59	1,151	838	60	282	31	1,272
Tot. Fld.& Engr.	3,455	2,149	39,538	27,940	2,067	28,447	1,143	44,422
U Productivity	0	0	896	0	19	0	0	0
V Contingency	0	25	0	298	0	0	0	0
W Fee	173	132	2,022	1,386	103	1,415	57	2,221
Sub-Tot. Cons	3,628	2,296	42,457	29,623	2,189	29,863	1,200	46,643

Total Construction Cost 157,899

TABLE 5-24
100 MWe, 0.8 SOLAR MULTIPLE, Nth PLANT CAPITAL COST ESTIMATE — 1979 "000" DOLLARS

Cost Category	5100 Land& Site	5200 Admin.	5300 Coll.	5400 Rec.	5500 Master Control	5600 Non-Solar	5700 Energy Stor.	5800 EPGS
A Excav.& Civil	2,932	14	420	18	1	53	0	71
B Concrete	89	86	3,618	1,852	10	996	0	1,306
C Struc. Steel	0	0	0	841	0	521	0	0
D Buildings	0	300	0	535	54	1,760	0	490
E Mach.& Equip.	53	1,287	21,782	8013	972	24,330	1,049	28,293
F Piping	96	38	0	8983	0	45	0	3,165
G Electrical	0	99	1,387	77	5	425	0	4,085
H Instruments	0	0	111	682	141	0	0	500
J Painting	0	8	0	0	2	35	0	250
K Insulation	0	0	0	0	0	0	0	500
Direct Fld. Costs	3,170	1,832	27,319	21,001	1,185	28,165	1,049	38,660
L Temp. Cons. Fac.	0	19	57	91	0	0	0	425
M Cons. Serv.	0	50	43	261	0	0	0	300
N Subs.& Expense	0	46	364	930	7	0	0	1,100
P Benifits& Burdens	0	34	483	81	14	0	0	900
Q Equip. Rental	0	0	743	197	0	0	0	1,000
Indir. Fld. Csts.	0	149	1,691	1,560	21	0	0	3,725
Total Fld. Costs	3,170	1,981	29,010	22,561	1,206	28,165	1,049	42,385
R Engineering	0	0	0	0	0	0	0	0
S Procurement	0	0	34	0	0	0	0	15
T Management	95	59	870	677	36	282	31	1,272
Tot. Fld.& Engr.	3,265	2,040	29,914	23,238	1,242	28,447	1,080	43,672
U Productivity	0	0	708	0	13	0	0	0
V Contingency	0	0	0	0	0	0	0	0
W Fee	163	102	1,531	1,162	63	1,415	54	2,184
Sub-Tot. Cons.	3,428	2,142	32,153	24,400	1,318	29,862	1,134	45,856

Total Construction Cost 140,293

TABLE 5-25

100 MWe, 1.4 SOLAR MULTIPLE, FIRST PLANT CAPITAL COST ESTIMATE — 1979 "000" DOLLARS

Cost Category	5100 Land& Site	5200 Admin.	5300 Coll.	5400 Rec.	5500 Master Control	5600 Non-Solar	5700 Energy Stor.	5800 EPGS
A Excav.& Civil	3,718	14	853	20	1	53	0	71
B Concrete	126	86	7,294	2,167	10	996	280	1,306
C Struc. Steel	0	0	0	1,169	0	521	0	0
D Buildings	0	300	0	535	54	1,760	0	490
E Mach.& Equip.	0	1,377	46,344	11,503	1,760	24,330	13,176	28,293
F Piping	53	38	0	13,070	0	45	0	3,165
G Electrical	96	99	2,968	77	5	425	0	4,085
H Instruments	0	0	126	862	145	0	0	500
J Painting	0	8	0	0	2	35	0	250
K Insulation	0	0	0	0	0	0	0	500
Direct Fld. Costs	3,993	1,922	57,585	29,403	1,977	28,165	13,456	38,660
L Temp. Cons. Fac.	0	19	116	176	0	0	0	425
M Cons. Serv.	0	50	87	497	0	0	0	300
N Subs.& Expense	0	46	719	1,069	10	0	0	1,100
P Benifits& Burdens	0	34	973	88	20	0	0	900
Q Equip. Rental	0	0	1,496	197	0	0	0	1,000
Indir. Fld. Csts.	0	149	3,391	2,027	30	0	0	3,725
Total Fld. Costs	3,993	2,071	60,976	31,430	2,007	28,165	13,456	42,385
R Engineering	240	104	0	1,884	0	0	807	750
S Procurement	0	0	59	19	0	0	0	15
T Management	119	62	0	943	60	282	404	1,272
Tot. Fld.& Engr.	4,352	2,237	61,035	34,276	2,067	28,447	14,667	44,422
U Productivity	0	0	1,426	0	19	0	0	0
V Contingency	0	25	0	348	0	0	0	0
W Fee	218	113	3,123	1,936	103	1,415	733	2,221
Sub-Tot. Cons.	4,570	2,375	65,584	36,460	2,189	29,862	15,400	46,643

Total Construction Cost 203,083

TABLE 5-26
100 MWe, 1.4 SOLAR MULTIPLE, Nth PLANT CAPITAL COST ESTIMATE — 1979 "000" DOLLARS

Cost Category	5100 Land& Site	5200 Admin.	5300 Coll.	5400 Rec.	5500 Master Control	5600 Non-Solar	5700 Energy Stor.	5800 EPGS
A Excav.& Civil	3,718	14	669	20	1	83	0	71
B Concrete	126	86	5,758	2110	10	996	280	1,306
C Struc. Steel	0	0	0	1,169	0	521	0	0
D Buildings	0	350	0	535	54	1,760	0	490
E Mach.& Equip.	0	1,377	34,665	8,647	972	24,300	13,176	28,293
F Piping	53	38	0	13,070	0	45	0	3,165
G Electrical	96	49	2,207	77	5	425	0	4,085
H Instruments	0	0	118	702	141	0	0	500
J Painting	0	8	0	0	2	35	0	250
K Insulation	0	0	0	0	0	0	0	500
Direct Fld. Costs	3,993	1922	43,417	26330	1,185	28,165	13,456	38660
L Temp. Cons. Fac.	0	19	91	49	0	0	0	425
M Cons. Serv.	0	50	69	132	0	0	0	300
N Subs.& Expense	0	46	580	970	7	0	0	1,100
P Benifits& Burdens	0	34	769	88	14	0	0	900
Q Equip. Rental	0	0	1,182	197	0	0	0	1,000
Indir. Fld. Csts.	0	149	2,691	1,436	21	0	0	3,725
Total Fld. Costs	3,993	2,071	46,108	27,766	1,206	28,165	13,456	42,385
R Engineering	0	0	0	0	0	0	0	0
S Procurement	0	0	59	0	0	0	0	15
T Management	120	62	1,383	833	36	282	404	1,272
Tot. Fld.& Engr.	4,113	2,133	47,550	28,599	1,242	28,447	13,860	43,672
U Productivity	0	0	1,127	0	13	0	0	0
V Contingency	0	0	0	0	0	0	0	0
W Fee	206	107	2,434	1,430	63	1,415	693	2,184
Sub-Tot. Cons.	4,319	2,240	51,111	30,029	1,318	29,862	14,553	45,856
Total Construction Cost	179,288							

TABLE 5-27

430 MWe, 1.44 SOLAR MULTIPLE, Nth PLANT CAPITAL COST ESTIMATE — 1979 "000" DOLLARS

Cost Category	5100 Land& Site	5200 Admin.	5300 Coll.	5400 Rec.	5500 Master Control	5600 Non-Solar	5700 Energy Stor.	5800 EPGS
A Excav.& Civil	14,838	34	3,002	56	1	149	0	170
B Concrete	187	209	25,841	5,948	10	2,805	0	3,127
C Struc. Steel	0	0	0	338	0	1,469	0	0
D Buildings	0	729	0	550	54	4,962	0	1,173
E Mach.& Equip.	0	3,348	155,557	34,568	1,323	68,175	49,592	67,747
F Piping	106	92	0	37,723	0	127	16,775	7,579
G Electrical	192	241	8,555	217	5	1,198	635	9,782
H Instruments	0	0	275	1,979	277	0	0	1,197
J Painting	0	19	0	2,773	0	99	0	599
K Insulation	0	0	0	3,377	0	0	0	1,197
Direct Fld. Costs	15,323	4,673	193,230	87,480	1,670	78,983	67,002	92,571
L Temp. Cons. Fac.	0	46	410	138	0	0	0	1,018
M Cons. Serv.	0	122	312	372	0	0	0	718
N Subs.& Expense	0	112	2,609	3,101	7	0	0	2,634
P Benifits& Burdens	0	83	3,462	257	13	0	0	2,155
Q Equip. Rental	0	0	5,323	0	0	0	0	2,394
Indir. Fld. Csts.	0	362	12,116	3,868	20	0	0	8,919
Total Fld. Costs	15,323	5,035	205,346	91,348	1,690	78,983	67,002	101,490
R Engineering	919	0	0	0	0	0	0	0
S Procurement	0	0	115	0	0	0	0	0
T Management	460	151	0	2,740	0	790	2,010	3,045
Tot. Fld.& Engr.	16,702	5,186	205,461	94,088	1,690	79,773	69,012	104,535
U Productivity	0	0	5,018	0	5	0	0	0
V Contingency	0	0	0	0	0	0	0	0
W Fee	835	259	10,524	4,104	85	3,989	3,451	5,227
Sub-Tot. Cons.	17,537	5,445	221,003	98,192	1,780	83,765	72,463	109,762

Total Construction Cost 610,547

5.9 COST ESTIMATES

The following description of price estimates for the sodium heater should be included in this section.

Components included in B&W's scope of supply for the coal-fired sodium heater are outlined in Table 5-28. The corresponding price estimate for this equipment is provided in Table 5-29. This estimate includes markup and is current as of June 1, 1979.

In summary, the total price of material, delivered and erected, is $25,500,000. The price for converting the unit from pulverized-coal firing to oil firing, should this action become desirable in the future, is $400,000.

TABLE 5-28

COAL-FIRED SODIUM HEATER — SCOPE OF SUPPLY

Coal Feeders	Soot Blowers
Pulverizers and Drives	Flues, Ducts, and Dampers
Pulverized Coal Conveying System	Regenerative Air Heater
Burners and Combustion Controls	Primary Air and Gas Recirculation Fans and Drives
Sodium Heater	Forced Draft and Induced Draft Fans and Drives
. Furnace	Structural Steel and Platforms Headers and Downcomers
. Convection Surface	

TABLE 5-29

PRICE ESTIMATE — SODIUM HEATER
($)

Pulverizers and Drives	500,000	Service	300,000
Rengenerative Air Heater	500,000	Erection	10,700,000
Fans and Drives	750,000	Total (Material, Delivered and Erected)	25,500,000
Balance (Material and Shop Fabrication	11,750,000	Conversion to Oil Firing (Material, Delivered and Erected)	400,000
Freight	1,000,000		

TABLE 6-1

SODIUM COMPONENT RELIABILITY ASSESSMENT

Component	Operating (h/yr)	Failures/h (λ)	Failure Rate/yr (λ')	MTTR (h)	Outage/Yr Unavailability (h)
Receiver	3,750	49×10^{-6}	1.8×10^{-1}	20	3.6
24 - Receiver Valves	3,750	240×10^{-6}	0.9	10	10
Surge Tank	3,750	Negligible			
Drag Valve	3,750	125×10^{-6}	0.47	20	10
3 - Large Valves	3,750	375×10^{-6}	1.4	20	28
Pipe	3,750	Negligible			
Tanks	8,760	Negligible			
P-1 Pump	3,750	26×10^{-6}	9.75×10^{-2}	100	9.7
P-2 Pump	4,680	46×10^{-6}	0.21	100	21
3 - Large Valves	4,680	375×10^{-6}	1.75	20	35
Evaporator	4,680	1.7×10^{-6}	0.008	200	1.6
Superheater	4,680	0.5×10^{-6}	0.002	200	0.4
Reheater	4,680	0.6×10^{-6}	0.003	200	0.6

TABLE 6-2

TOTAL SYSTEM AVAILABILITY RESULTS (%)

	Forced Outage	Planned Outage
Collector	0.01	
Receiver	2.2	0.6*
Thermal Storage	0.6	
Master Control	0.05	
EPG	2.46	4.5
Total Unavailability	5.32 +	5.1 = 10.42
Total Availability = 89.6		

*The amount which may not coincide with the 4.5% of the EPG outage.

6.0 ASSESSMENT OF COMMERCIAL SCALE SOLAR CENTRAL RECEIVER HYBRID POWER SYSTEM

6.1 POTENTIAL IMPROVEMENTS

6.1.1 Performance

The performance assessment of the sodium system is given in Table 6-1. The summary for the overall system is given in Table 6-2.

The unavailability values for the electric power generation equipment (EPG), the collector, and the master control systems were taken from Reference 6-6.

The values for the receiver and the thermal storage system were calculated using standard methodology. Mean time to repair (MTTR) was estimated from experience with similar equipment and assumes that spares are available. For the MTTR time estimates, credit was taken for the fact that there are approximately 12 h/day for repair at night. No credit was taken for the fact that the sodium loops may be operated independently and, therefore, the unavailabilities of the components are not strictly in series. The actual energy loss should be less than we calculate.

The receiver and steam generator failure rate estimates were based on the observation that tube failures occur primarily in the welds. The failure rate of 4×10^{-10} failures per hour per 2.54 cm (1.0 in.) of weld used in this study is reported in Reference 6-7.

The value of the failure rate used for the receiver control valves is based on experience with valves of a similar type used in the Sodium Pump Test Facility (SPTF) of the Energy Technology Engineering Center (ETEC.[6-8] These values use a free convectively cooled sodium freeze seal blanketed with argon gas. The seal is a rotating seal which has an extremely high success ratio. There is no flow leak-tightness requirements on the valve. The valve body is a cylindrical extension of the pipe, which minimizes valve pipe stress distortions. It is for these reasons, combined with excellent experience with this valve type, that the failure rate used for this valve is lower than that used for the large sodium valves.

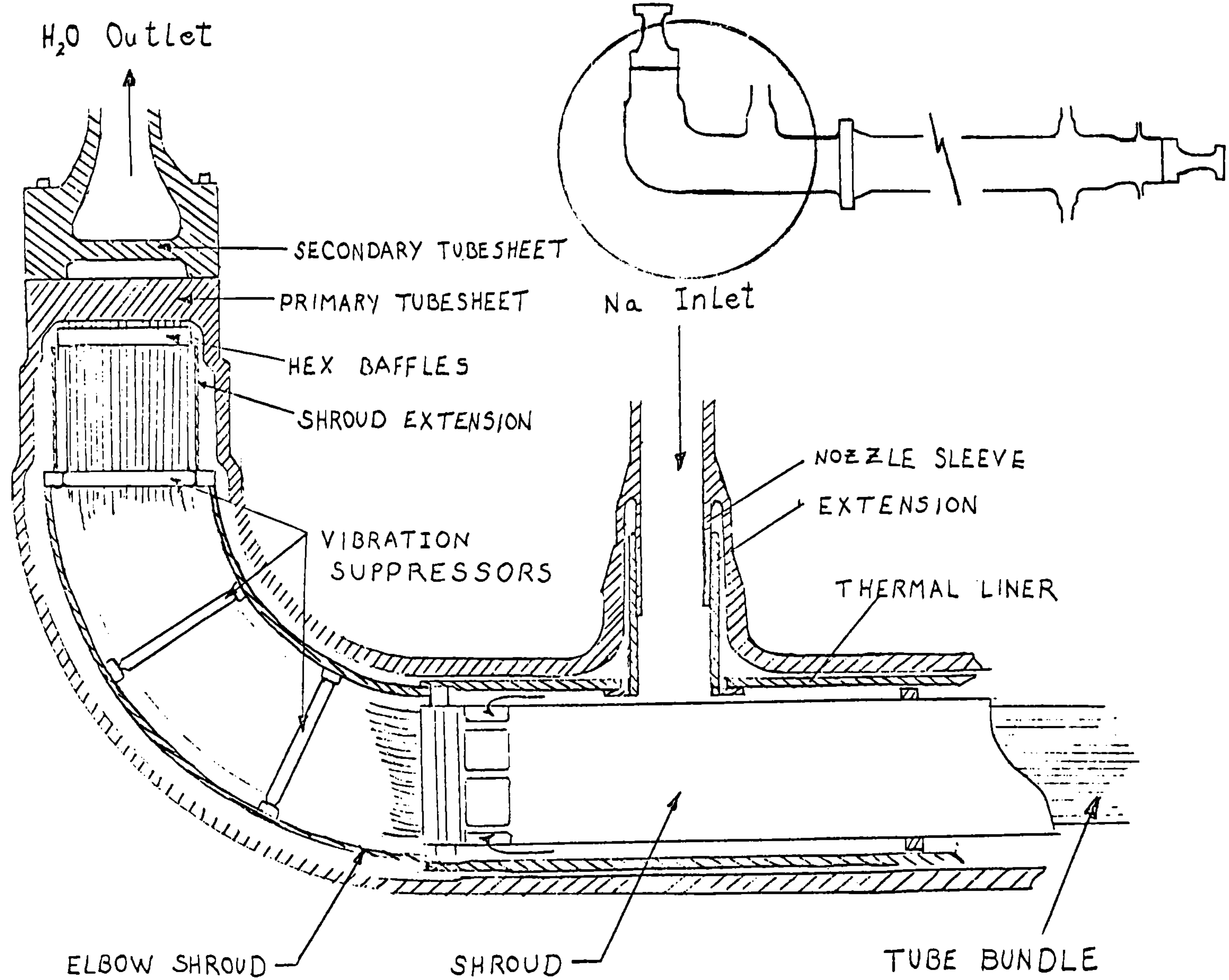


Figure 6-1. Baseline Design for Steam Generator

Large sodium valve failure rates were taken from Reference 6-9.

The pump failure rate data were taken from Reference 6-10, and take into account the fact that the advanced central receiver pumps have bearings which will be pressurized before the pump is started.

Our experience shows that multipass welds made to code welding requirements do not leak. Therefore, the failure rate of the tanks and piping system is considered to be negligible relative to the total of the components.

The plant reliability assessment is consistent with our experience with sodium plants of similar complexity and size [e.g., the sodium reactor equipment,(6-11) and the Hallam Nuclear Power Facility.(6-12)]

6.1.2 Potential Cost Reductions for Steam Generator

The baseline design for the steam generator is based on the CRBRP steam generator (SG) design as shown in Figure 6-1. However, because this design is based on nuclear codes (Section III, Division 1 of the ASME Code), nuclear safety standards, and severe CRBRP thermal transients, many high-cost design features have been incorporated. While the CRBRP design could be used as-is for the solar hybrid except for size and materials, the cost would be prohibitive. For solar applications, care must still be taken to prevent sodium/water leaks which could result in extensive plant downtime; thereby negating any initial capital savings. Costs estimated for the solar hybrid steam generators are a compromise between costs incurred on the CRBRP program and heat exchangers for general industrial use.

In order to reduce the SG costs, some development work for solar applications should be funded. Table 6-3 gives a breakdown of the CRBRP steam generator costs. It is fairly labor intensive with a 3 to 1 labor to material ratio. Two areas of particular concern are the tube bundle of which the major cost is the tube-to-tubesheet weld and the final assembly and closure where alignment problems and welding are complicated by the elbow region (4.25-in. thick shell wall).

Table 6-4 shows studies that could result in potential cost savings. Items 1 and 3 have been initiated and are summarized in the following sections.

TABLE 6-3

BREAKDOWN OF CRBRP SG COSTS

Item	% of Total Cost
Material	25
Tooling	3
Fabrication and Inspection	
Shroud Assembly	6
Shroud/Shell Assembly	13
Tube Bundle	20
Loose Equipment	6
Final Assembly/Closure	20
Pressure Test	2
Material Handling	5
Total	100

TABLE 6-4

POTENTIAL AREAS FOR SG COST REDUCTION

Item	Trade Study	Area of Cost Savings
1	Transient Mitigation	Elimination of thermal liners, baffles, secondary tubesheet, nozzle sleeve, etc.
2	Section VIII, ASME Pressure Vessel Code vs Section III Nuclear Code	Material specifications, weld procedures, QA, weld acceptance criteria, reworks
3	Concept Selection (Comparison of hockeystick with alternate concepts such as straight tube, helical coil, etc.)	Elimination of inaactive surface area in elbow, reduce costs of tube bundling assembly and closure weld

Transient Mitigation

The current CRBRP steam generator (Figure 6-1) includes many design features that enable it to take severe thermal transients. It was felt that SG costs could be reduced if design changes could be implemented by reducing the thermal transients as compared to the CRBRP transients. Cost reductions can be achieved if the following items were eliminated:

- Thermal liner/shrouds
- Nozzle sleeves
- Thermal baffles
- Secondary tubesheets

In order to accomplish this, the following steps must be taken:

1) Identification of the solar plant transients and a qualitative judgment of their severity as compared to the CRBR Plant transients.

2) More detailed evaluation of severe or intermediate transients from Step 1.

3) If Steps 1 and 2 show a reduction in transient severity, assess cost reductions that could be made to the SG design.

The first step has been initiated and the results reported here. The CRBRP transients were reviewed to determine their relevancy and severity for solar applications. In addition, the solar system with storage was examined to determine if there were other transients that should be included.

Table 6-5 is a list of the CRBRP transients. The most serious transients can usually fall under one of two general categories: (1) plant trips and (2) sodium/water leaks. Two typical transients of these types are shown in Figure 6-2. During a plant trip, reactor decay heat must be removed, and therefore, the steam generator must remain in operation after a plant trip in order to dump this excess heat generation and thus sees a large inlet sodium temperature ramp rate. A sodium/water leak can be a large 7-tube guillotine break in which the only interest is to shut the plant down safely (the SG unit is assumed to not be repairable). During a small sodium/water leak, a plant trip is initiated and water expelled from the unit as rapidly as possible by isolation and blowdown

TABLE 6-5
SUMMARY OF CRBRP TRANSIENTS

UMBRELLA TRANSIENT NUMBER	UMBRELLA TRANSIENT DESCRIPTION	TOTAL OCCURRENCES
	NORMAL TRANSIENTS	
SG-01N	DRY SYSTEM HEATUP AND FILL	30
SG-02N	DRAIN AND DRY SYSTEM COOLDOWN	30
SG-03N	STARTUP FROM REFUELING TEMPERATURE	192
SG-04N	SHUTDOWN TO REFUELING TEMPERATURE	60
SG-05N	STARTUP FROM HOT STANDBY	710
SG-06N	SHUTDOWN TO HOT STANDBY	251
SG-07N	LOAD INCREASE	57,118
SG-08N	LOAD DECREASE	56,550
SG-09N	STEADY STATE TEMPERATURE FLUCTUATIONS	30×10^{6}
SG-10N	FLOW INDUCED VIBRATIONS	1.4×10^{11}
	UPSET TRANSIENTS	
SG-01U(A)	REACTOR TRIP FROM FULL POWER	180
(B)(A)	SAME, MINIMUM DECAY HEAT	113
SG-01U(C)	SAME, WITH WATER/STEAM SIDE DRAIN	9
SG-01U(D)	SAME, TO LOWER STATE POINT	64
SG-02U	UNCONTROLLED ROD INSERTION	10
SG-03U(A)(B)	UNCONTROLLED ROD WITHDRAWAL FROM 100% POWER	22
SG-04U	UNCONTROLLED ROD WITHDRAWAL FROM STARTUP, DELAYED TRIP	3
SG-05U	PLANT LOADING AT MAXIMUM ROD RATE	10
SG-06U(A)(C)	WATER SIDE ISOLATION AND BLOWDOWN OF AN EVAPORATOR MODULE	5
(B)	SAME, WITHOUT DRYOUT	2
SG-07U(A)(B)	WATER SIDE ISOLATION AND BLOWDOWN, SUPH AND BOTH EVAPS	6
(C)	SAME, WITH UPSET Na DRAIN	
SG-10U(A)(B)	LOSS OF ALL OFFSITE POWER	21
SG-11U	EVAPORATOR OUTLET RELIEF VALVES OPEN	3
SG-12U	SUPERHEATER OUTLET RELIEF VALVES OPEN	13
SG-13U	TRIP AND COOLDOWN FOR UNAFFECTED LOOPS	12
SG-14U(A)	(ADJACENT EVAPORATOR) WATER SIDE ISOLATION AND BLOWDOWN OF AN EVAPORATOR MODULE	5
SG-14U(B)	SAME, WITHOUT SODIUM DRAIN	2
SG-15U	ADJACENT EVAPORATOR OUTLET RELIEF VALVES OPEN	3
SG-16U	PRIMARY PUMP PONY MOTOR FAILURE	5
SG-17U(A)	SUPERHEATER INLET ISOLATION	
SG-17U(B)	VALVE CLOSURE	5
SG-18U	SUPERHEATER OUTLET ISOLATION VALVE CLOSURE	2
SG-19U	LOSS OF FEEDWATER FLOW TO STEAM DRUM	19
SG-20U	LOSS OF ONE RECIRCULATION PUMP	24
SG-21U	TURBINE TRIP WITHOUT REACTOR TRIP	50
SG-22U(A)	INADVERTENT OPENING OF STEAM DRUM VALVE	3
SG-22U(B)	SAME, UNAFFECTED LOOP	6
SG-23U	UNCONTROLLED ROD WITHDRAWAL FROM STARTUP WITH AUTOMATIC TRIP	17
	EMERGENCY TRANSIENTS	
SG-01E to SG-12E	FIVE OCCURRENCES OF THE MOST SEVERE EMERGENCY TRANSIENT PLUS TWO CONSECUTIVE OCCURRENCES OF MOST SEVERE LIKE OR UNLIKE EVENTS	7

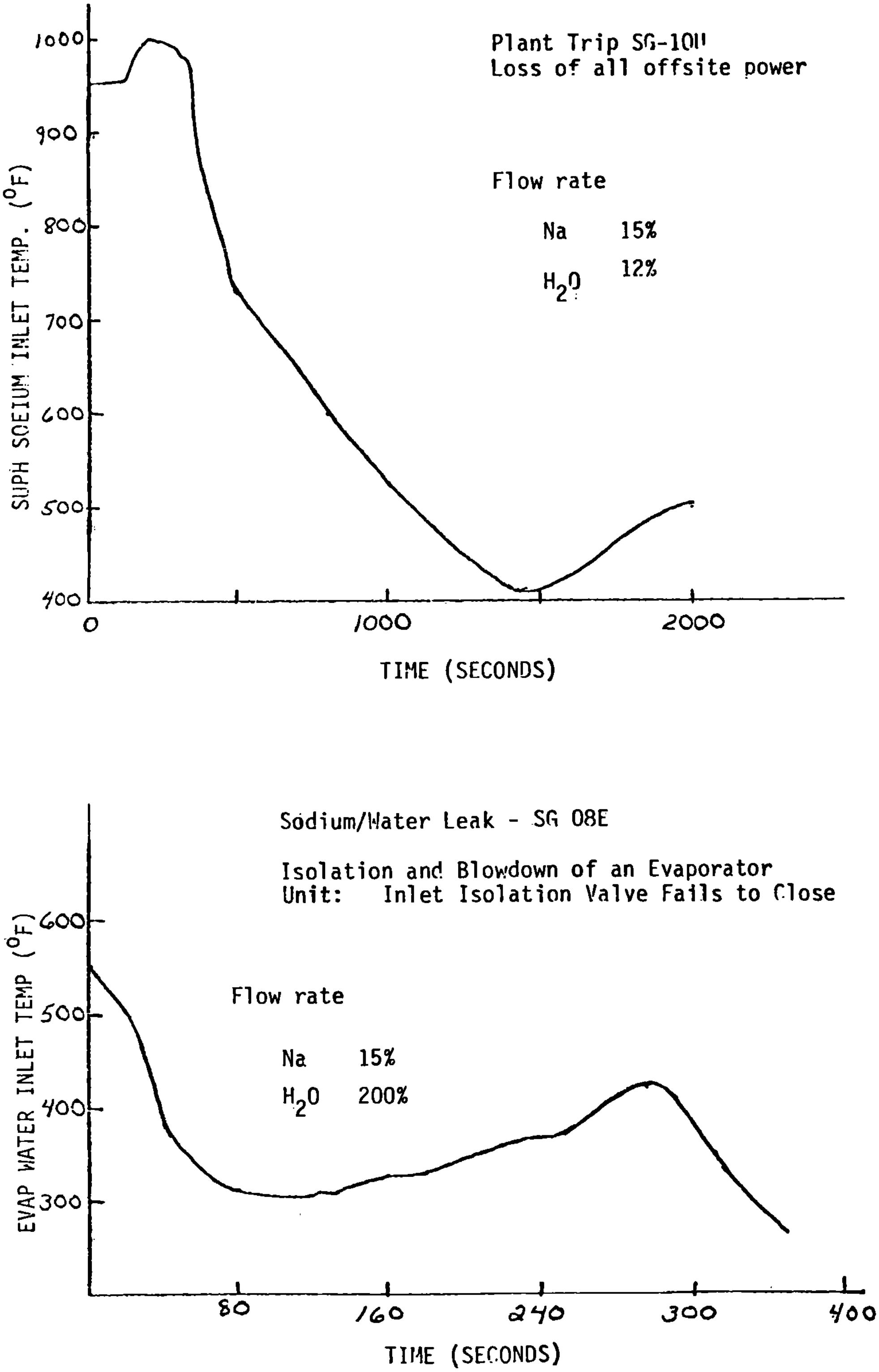


Figure 6-2. Two Typical CRBRP Transients

TABLE 6-6

SOLAR STEAM GENERATOR TRANSIENTS*

Number	Transient Description	Eq. CRBRP Transient	Comments
	Mild Transients		
1.	Load Fluctuations	7N, 8N	No design impact
2.	Pressure and Temperature Fluctuations	9N, 10N	
	Moderate Transients		
3.	Dry System Heatup and Fill	1N	Transients are easily controllable and can be defined at a later date.
4.	Drain and Dry System Cooldown	2N	
5.	Startup/Shutdown	3N, 4N, 5N, 6N	
6.	Loss of Recirculation Pump	20U	
	Severe Transients		
7.	Loss of Sodium Side Flow Without Feedwater Pump Trip		Design System Controls for Fail-safe trip of both pumps
8.	Loss of Steam Side Flow Without P-2 Sodium Pump Trip		
	Indeterminate Transients		
9.	Loss of P-2 Na Pump	1U	These transients can probably be umbrellaed under a single transient "Plant Trip."
10.	Feedwater Pump Trip (or Turbine)	19U	
11.	Loss All Offsite Power	10U	

*Based on solar hybrid with storage

of the SG module in order to keep the damage to a minimum (failed tube will be plugged). The example shown in Figure 6-2 is a case where this procedure has failed to operate as planned, and a large quantity of cold depressurizing water is expelled through the unit.

After reveiewing the CRBRP transients and the solar hybrid plant with storage, eleven solar transients were identified as shown in Table 6-6 as either mild, moderate, severe, or indeterminate. The number of transients is greatly reduced as almost all sodium transients are buffered completely by the sodium storage tanks. Of the mild and moderate transients, no real problem is seen, as most of these transients can easily be controlled to whatever is considered an acceptable level. Transients 7 and 8 (failure of a pump to trip) probably could not be tolerated, and, therefore, a fail-safe trip of both pumps should be incorporated as part of the control system. Transients 9, 10, and 11 may be classified under one event - plant trip where both sodium and feedwater pumps are tripped essentially simultaneously. However, there is a system response time before flow rates will go to zero. To the degree that there is an imbalance of sodium or water flow rates, some transient will be experienced. However, it is expected the flow rates will drop to zero rapidly enough to make the transient either mild or moderate. No transient is shown for sodium/water leaks as currently it is planned to make a normal plant shutdown upon detection of a leak. Evaporator dryout would occur naturally. Evaluation of a plant trip would help determine if the passive approach to achieve dryout is satisfactory.

At this time, the solar transients are seen to be much less severe than the CRBRP transients. Two action items need to be evaluated further:

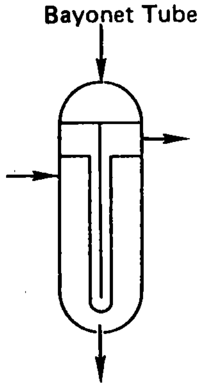
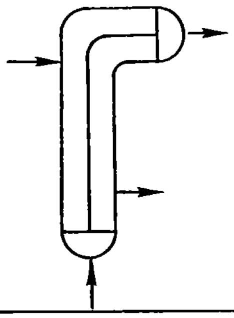
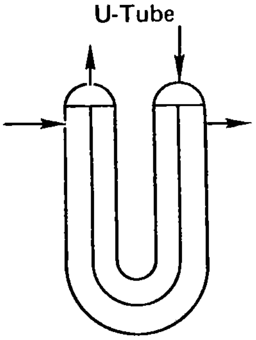
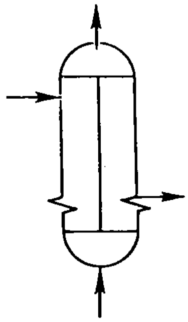
1) System response during a plant trip

2) Tradeoff of active versus passive action to obtain dryout of a SG unit once detection of a sodium-water leak occurs.

Both areas could have significant impact on the severity of transients seen by the SG units.

Concept Selection

The purpose of this study was to determine if there are potential alternate concepts to the hockeystick configuration. The primary objective is reduced cost

Configuration	Bayonet Tube 	Hockey Stick (baseline case) 	U-Tube 	Straight Tube With Bellows 
Where Used	BN-350 (USSR) HNPF (U.S.)	MSG (U.S.) FTTM (U.S.) CRBRP (U.S.)	BN-350 (USSR) PFR (U.K.) SRE (U.S.)	SNR Prototype (NE) SNR-300 (Germany) MAESTRO (France) BR-60 (USSR)
Advantages		1) Good thermal/hydraulic characteristics 2) Straightforward design 3) Good thermal expansion 4) Independent tube expansion 5) Successful test program (MSG)	1) Solves some of the hockey stick tube bundling and closure weld problems	1) Good thermal/hydraulic characteristics 2) Effective use of surface area 3) Easy tube assembly 4) Easier closure weld procedure 5) Good access for tube repair
Disadvantages	1) Poor heat transfer, good for evaporator use only 2) Solar hybrid parameters not compatible	1) Large inactive surface area 2) Costly closure weld due to elbow 3) Costly tube bundling	1) Poor flow distribution, especially at low power. Performance not well predicted 2) Differential thermal expansion between hot and cold leg	1) May have trouble meeting code requirements for bellows 2) Tubes cannot act independently
Cost Assessment	Not compatible with solar hybrid	Moderate in cost with good reliability	Introduces more problems than it solves	Good potential for cost savings if bellows problem is solved

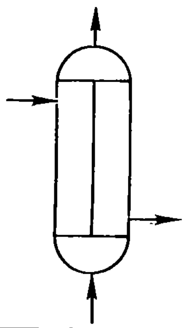
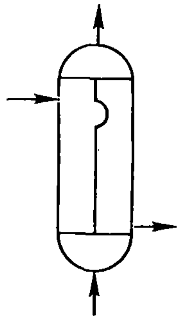
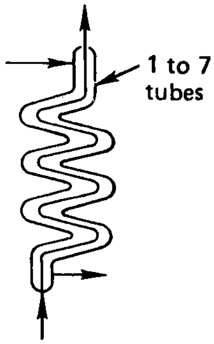
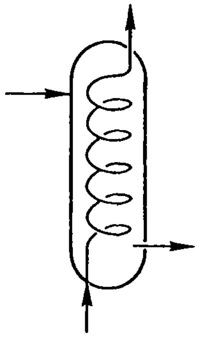
Straight Tube Without Bellows	Short Bend (Sine wave, Z, etc)	Serpentine	Helical Coil
			
EBR-II (U.S.) PGV-1 (Italy)	GVE-45 (France) BN-600 (USSR) BN-600 Prototype	BOR-60-1 (USSR) BA Prototype (France) Phenix (France) Phenix Prototype (France) FBTF (India) CET (France) BOR-60-2 (Czechoslovakia) Micromodule (Czechoslovakia) KNK (Germany) KNK Prototype (Germany) Fermi (U.S.) BN-600 (USSR)	MONJU (Japan) JOYO (Japan) FCB Prototype (France) Super Phenix (France) Super Phenix (Holland) SNR-300 (Germany) SNR Prototype (Germany) SDP-1 (Italy) Zebulon (France) Super Zebulon (France)
1) Good thermal/hydraulic characteristics 2) Straightforward design 3) Effective use of surface area 4) Easy tube assembly and closure weld 5) Good access for tube repair	1) Good thermal/hydraulic characteristics 2) Effective use of surface area 3) Easier closure weld 4) Independent tube expansion	1) Good thermal expansion capabilities 2) Limits damage due to a sodium-water leak 3) Extensive use in foreign designs	1) Excellent thermal expansion capabilities 2) Fewer tubes 3) Shorter, more compact unit 4) Extensive use in foreign designs
1) Poor differential thermal expansion characteristics 2) Tubes cannot act independently	1) Some complications in tube assembly 2) Difficult to support tubes in bend region	1) Ultraconservative design to limit sodium-water leaks 2) Lack of good flow split could hurt performance	1) More complicated fabrication 2) Tube repair and leak detection more difficult
Potential for greatest cost savings	Moderate cost design on a par with the hockey stick	High cost design	Cost difficult to assess due to unique features

Figure 6-3. List of Various Concepts
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without sacrificing good reliability and thermal/hydraulic performance. Figure 6-3 is a list of various concepts, where used, and major pros and cons. The following designs are recommended for further evaluation:

- Hockeystick
- Straight tube with bellows
- Straight tube without bellows
- Helical coil (optional)

The hockeystick design ranks fairly well with the other designs. However, two promising designs are the straight tube with bellows and straight tube without bellows. The former has been adopted by several foreign designs, and four units have been tested in the 5 to 25 MWt power range. Three were tested successfully while one reheater unit developed a leak in the SNR-prototype and was removed from the loop. Twelve new units are being developed for Germany's SNR-300 in the 55-MWt range. Good bellows design and care in installation can give a 30-year life. If higher reliability is required, there is the possibility of double bellows or replaceable bellows. The least cost design is probably a straight-tube with no bellows. While there are reservations, a double-wall tube design has been tested in the FBR-II successfully for 15 years and a single-wall tube is currently being built by the Italians.

The two most common types of steam generators, especially in foreign designs, are the helical coil and the serpentine configurations. The only one that might be cost effective is the helical coil which has been very reliable in testing. The Germans are curently building two units for the SNR-300 of the straight tube with bellows and a helical coil design. So far, their experience indicates that the helical coil design is costing 50% more than the bellows configuration. Currently, it is recommended that this design is not cost effective. However, if the customer feels that a diversity of designs should be evaluated, it does have potential if certain problems can be solved.

A review of factors involved in extending the 265 MWt coal-fired sodium heater design to ∿2000 MWt was made. This assessment indicated that "commercial scale" sodium heaters can be developed using available design standards and established fabrication practices. Considerations to be addressed in developing larger systems include the following:

1) A direct-firing pulverized coal handling system and B&W EL-series pulverizers are employed in the 265 MWt design. Direct-firing is also the preferred method of handling coal in larger systems. However, as the heater rating is increased, it may become economical to replace the small EL pulverizers with higher-capacity B&W type MPS units. The MPS pulverizer is a roll-and-race unit which has been used extensively in larger utility installations. Its load response characteristics are comparable to those of the EL-series.

2) Standard B&W dual register pulverized coal burners are employed in the 265 MWt design. These burners promote efficient combustion of fuel, with low NO_x generation and with control of furnace and convection surface slagging and fouling. For larger systems, the heat input of the individual burners remains the same as for the 265 MWt design. Increases in total heat input are accomplished by adding more burners in accordance with well-established arrangement methods.

3) As the heater is increased, it may be advantageous to control furnace exit gas temperature by "gas tempering." In this scheme, flue gas is recirculated to the furnace outlet, so that the hot combustion gases can be cooled by dilution with the recirculated gas. The required surface area of the furnace is thereby reduced, and a more compact heating unit is possible. Recirculation of flue gas to the furnace hopper remains necessary to limit heat absorption in the furnace, and thus tube metal temperature, during low load operation. With appropriate ductwork and dampers, the same fan can often be used to recirculate gas to both the furnace hopper and outlet.

4) For the 265 MWt design, the furnace tubes are 1-1/4-in. OD. This size has been selected to provide sufficient cross-sectional flow area to maintain sodium velocities within acceptable limits. So

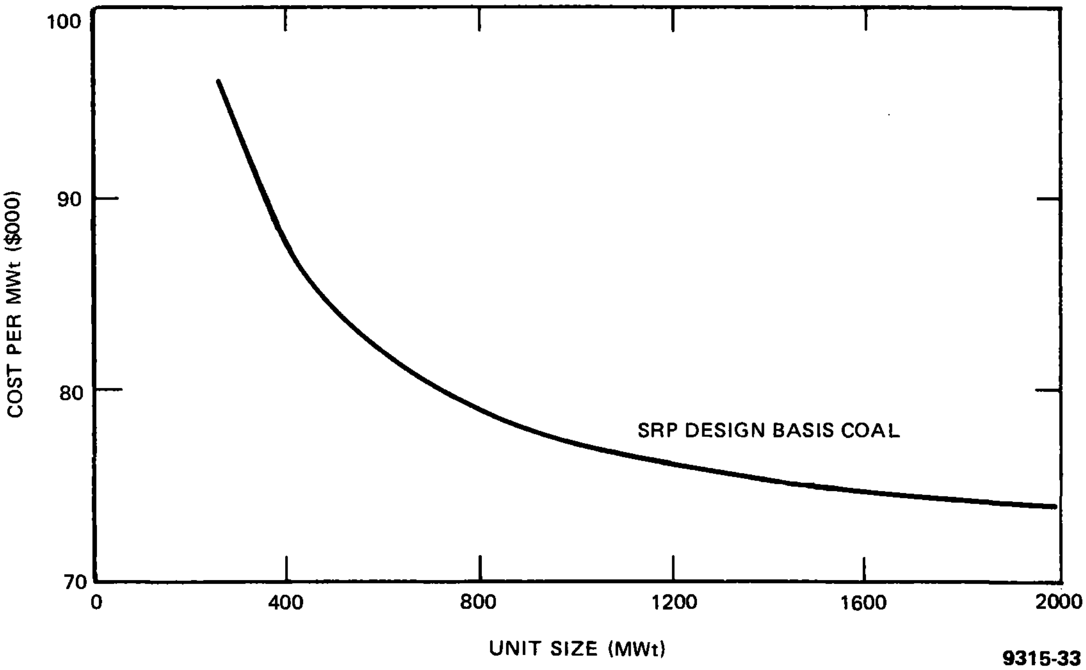


Figure 6-4. Estimated Price for Commercial-Scale Coal-Fired Sodium Heaters

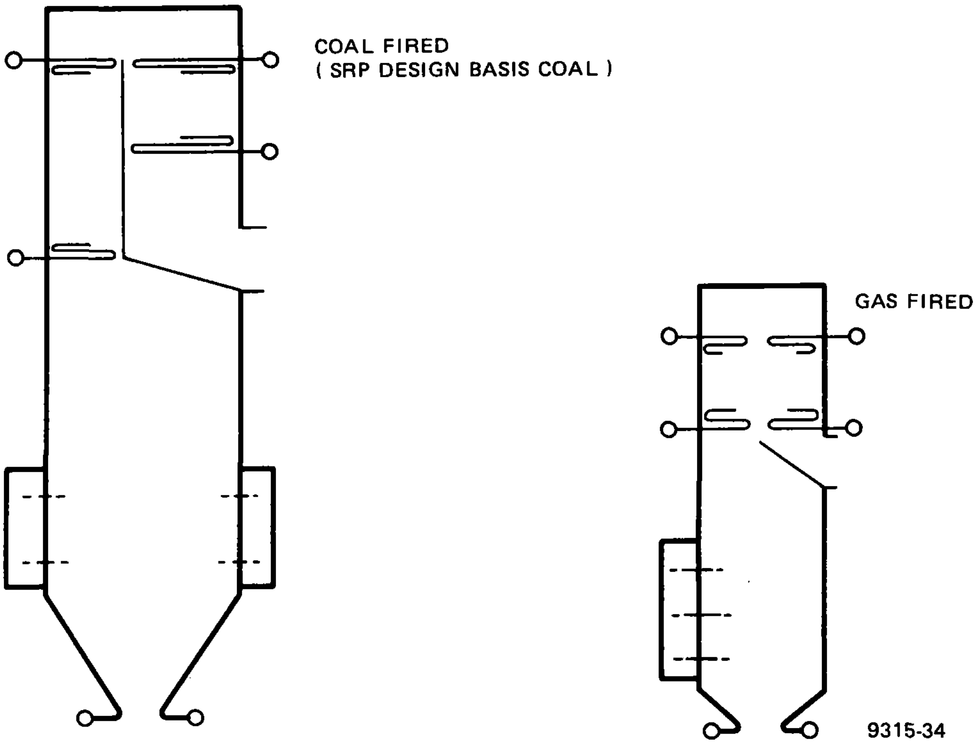


Figure 6-5. Size Comparison Coal and Gas Fired Sodium Heaters

that the plan area of the furnace enclosure can also be limited to a practical maximum, and to permit the use of standard membrane-wall panels, the furnace tube size will have to be increased to accommodate the higher sodium flow rates in larger systems. Preliminary calculations indicate that 2-1/2-in. OD tubes will be adequate for a 2000 MWt unit. Tubes of this size are routinely used in B&W radiant boilers.

5) The furnace and convection heat transfer surfaces will be arranged to maintain similar temperature profiles in sodium heaters of all sizes. Thus, materials selected for the 265 MWt design are also suitable for larger systems.

Estimated prices (as cost per MWt) for coal-fired sodium heaters up to 2000 MWt size are shown in Figure 6-4. These estimates are based on a "size multiplier" correlation developed for application and conventional boilers. They are based on the same scope of supply and performance requirements considered for the 265 MWt design.

The major factor influencing the heater design is fuel selection. With cleaner fuels, the overall size and cost of the heater can be reduced. The relative sizes of coal-fired and gas-fired units of the same thermal rating are shown qualitatively in Figure 6-5. Estimated prices for oil and gas-fired sodium heaters up to 2000 MWt size are provided in Figure 6-6. Note also that equipment for reducing particulate and SO_x emissions is not required with gas-fired heaters, further reducing capital and operating expense.

Design modifications would be necessary to permit the use of poorer quality fuels than the design basis coal. For example, to accommodate lignite, design adjustments must include the following:

1) The furnace surface area must be increased by 25% or more to adequately cool the combustion gases before they cross convection surfaces. As an alternative, gas tempering may be used for this purpose.

2) Additional radiant or convective heat transfer surface area must be provided to compensate for the reduced rate of heat absorption in the furnace.

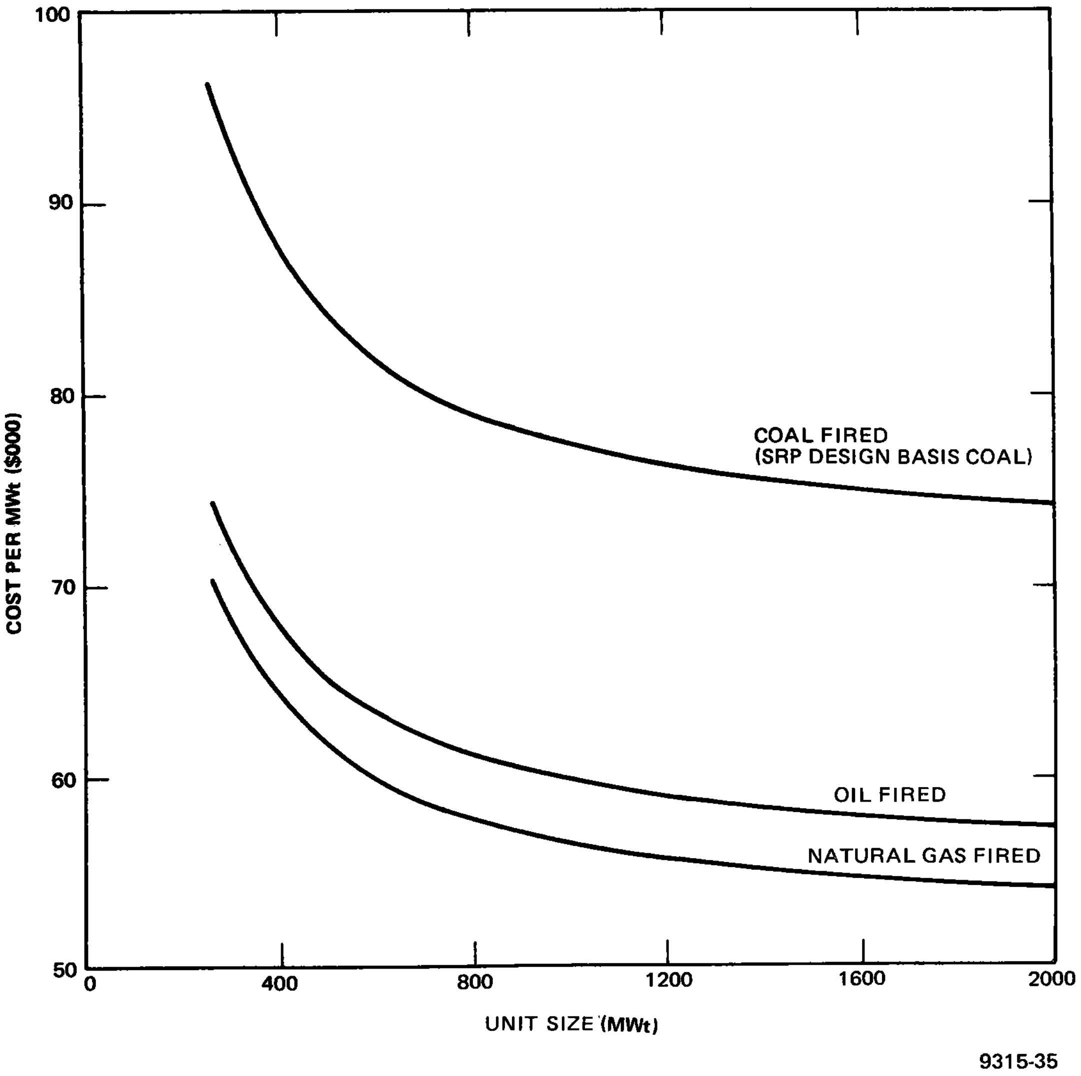


Figure 6-6. Estimated Price for Commercial Scale Sodium Heaters

3) Spacing of the convection surfaces must generally be increased to offset the severe fouling characteristics of the lignite. The size of the individual tube banks must be reduced to permit effective cleaning by the soot blowers.

4) The capacity for pulverizing and conveying coal to the furnace must be nearly doubled. This is necessary because of the poor heating value of the lignite and because the efficiency of the heater is significantly reduced by latent heat losses resulting from the high moisture content of the fuel.

These design modifications would be expected to increase the price of the sodium heater by 25% or more.

Development Plant — Sodium Heater

An important factor in developing the furnace design for the 265 MWt sodium heater has been the need to limit the rate of decarburization of the tube material. For this reason 2-1/4 Cr - 1 Mo alloy has been selected as the furnace material rather than the lower alloys typical of conventional boilers. Other design features intended to promote better temperature control include the following:

1) Provision has been made for recirculation of up to 50% of the flue gas during part load operation. The effect of recirculation is to reduce heat absorption in the furnace without significantly influencing the total absorption and efficiency of the heater.

2) A large number of small burners has been used. In this way, the total fuel input is divided into more increments, and any unbalances between fuel and air are more easily reduced and controlled.

3) Only a single top row of burners is fired at low loads. This action also reduces heat absorption in the furnace by reducing the effective furnace height.

Conservative selection of furnace material and the operational flexibility offered by the features described above provide the basis for a sound design. A detailed development of furnace tube temperature profiles must then be made to confirm design adequacy. Accurate prediction of these profiles involves determination of local heat absorption rates and sodium flow distribution, an effort beyond the scope of this conceptual design study. Brief summaries of the important analytical considerations follow:

Prediction of Local Heat Absorption Rates

The method used to predict local furnace heat absorption rates involves division of the furnace walls into zones of similar absorption and coolant flow characteristics. The average absorption rates for each zone are multiplied by distribution factors to determine local rates at any point along the vertical and peripheral surfaces. The distribution factors have been determined empirically and depend principally on the following variables:

1) Fuel and ash deposition characteristics
2) The type and location of burners
3) Heat release rate
4) Excess air
5) Flue gas recirculation, if applicable

The general shape of the absorption rate pattern is shown in Figure 6-7. This shape will vary with load or firing rate, and its magnitude is a function of heat input. Noncontinuous deviations in the absorption profile are caused by upsets in operational variables, such as:

1) Unbalanced firing
2) Changing slagging conditions
3) Load swings
4) Pulverizer removed from service

The effect of upsets on the absorption profile is also shown qualitatively in Figure 6-7.

Prediction of Sodium Flow Distribution

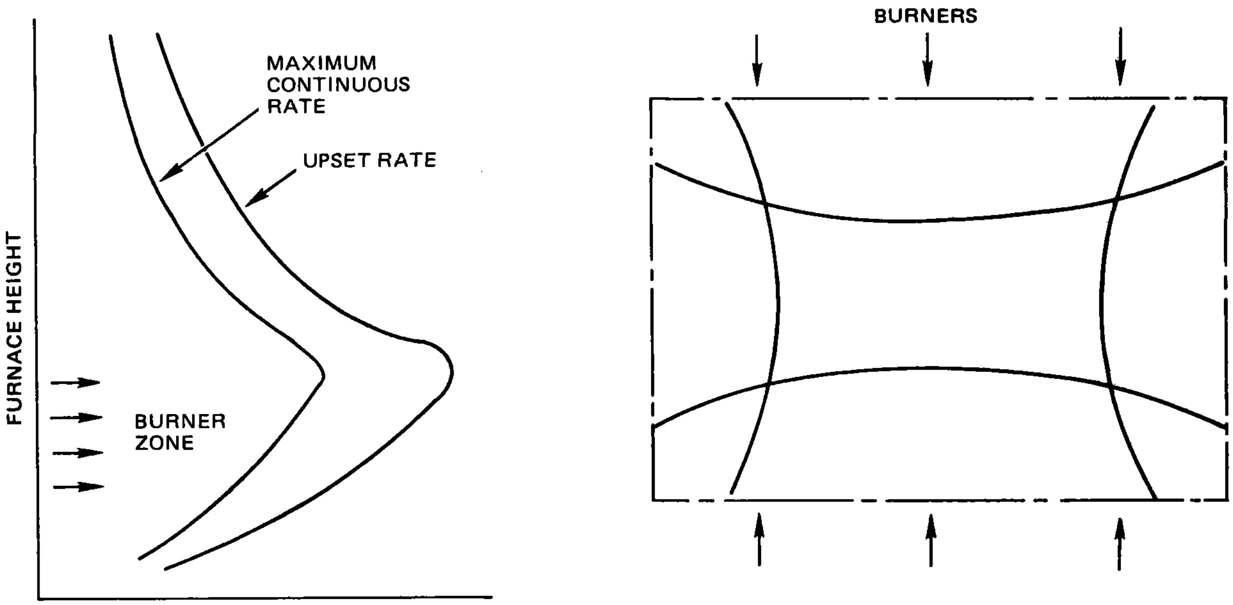
Pressure drop variations in adjacent furnace tubes resulting from variations in fabrication tolerances are small and have little effect on coolant flow distribution. However, some difference in hydraulic resistance can be expected in these parallel flow paths because of variations in their characteristic dynamic loss factors. Flow rates corresponding to each circuit must therefore be determined. If temperature imbalances resulting from flow mal-distribution are significant, adjustment may be accomplished by "intermediate mixing" of the coolant. The simple arrangement shown in Figure 6-8 is usually adequate for this purpose. This method of temperature control is considered preferable to the use of small orifices to achieve a pressure balance.

A second development need involves preparation of operating procedures for startup, shutdown, and normal load swings. The emphasis in this evaluation is on determination of the limiting temperature differentials governing ramp rates. Standard procedures typical for conventional boilers may be used as a basis for this study. However, special considerations required for a sodium-cooled heater must be addressed.

In summary, the following development studies are recommended:

1) Detailed calculation of furnace tube temperature profiles. This work is based on prediction of local heat absorption rates and sodium flow distribution.

2) Preparation of operating procedures for startup, shutdown, and normal load swings.



a. Absorption Rate
(Heat Absorption Rates Along
Furnace Front Wall)

b. Plan View
(Peripheral Distribution of Heat Absorption
in Furnace Walls)

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Figure 6-7. Heat Absorption Pattern

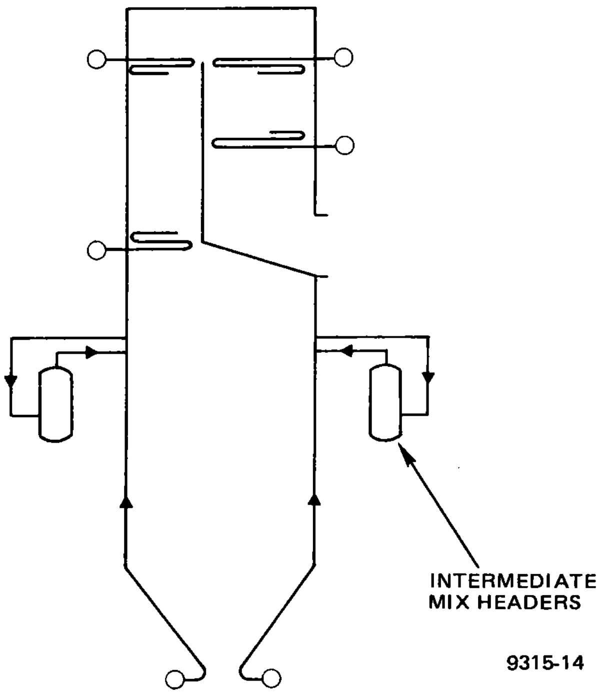

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Figure 6-8. Intermediate Mixing Arrangement

SUMMARY

The several potential impacts of the use of fossil-solar hybrid central station power units discussed above are not particularly severe. Land is definitely available. Water requirements could create siting problems, but these requirements are no greater than those for other power producing units needed (or installed) in the same area. Disturbance of semi-arid ecosystems may cause small impacts, but these are not likely to be extensive or severe. Many of the impacts will be smaller than those for a coal-only unit.

Thus, the environmental impacts including land and water requirements are not likely to prove impediments to selection of fossil-solar hybrid units by electric utilities. It is not necessary to assign economic penalties to the hybrid systems or change market penetration parameters to reflect extraordinary market resistance to the technology.

6.2 POTENTIAL LIMITATIONS TO WIDESPREAD IMPLEMENTATION

6.2.1 Environmental Effects

One of the potential limitations to the implementation of the sodium-cooled, central-receiver, solar-thermal power plant concerns it environmental effects. General environmental impacts have been studied in some detail in the past using water/steam as a baseline concept. Examples of such work are contained in References 6-1 through 6-5, inclusive. Even though the baseline considered was generally water/steam, most of the information is generic in nature, and therefore, applies to all central receiver concepts, including the sodium system.

In reserach for EPRI (the Electric Power Research Institute), Black and Veatch selected candidate sites for Solar Thermal Electric plants. The sites examined were located in southern California, Nevada, Arizona, central and southern New Mexico, the westernmost tip of Texas, and parts of South Dakota, Nebraska, and Kansas. Insolation in the candidate areas ranges from 3 to 7 kWh/m^2 day. The areas considered are shown in Figure 6-9. They are similar to those examined in the market study (see Section 3, 2.5 and 6.5).

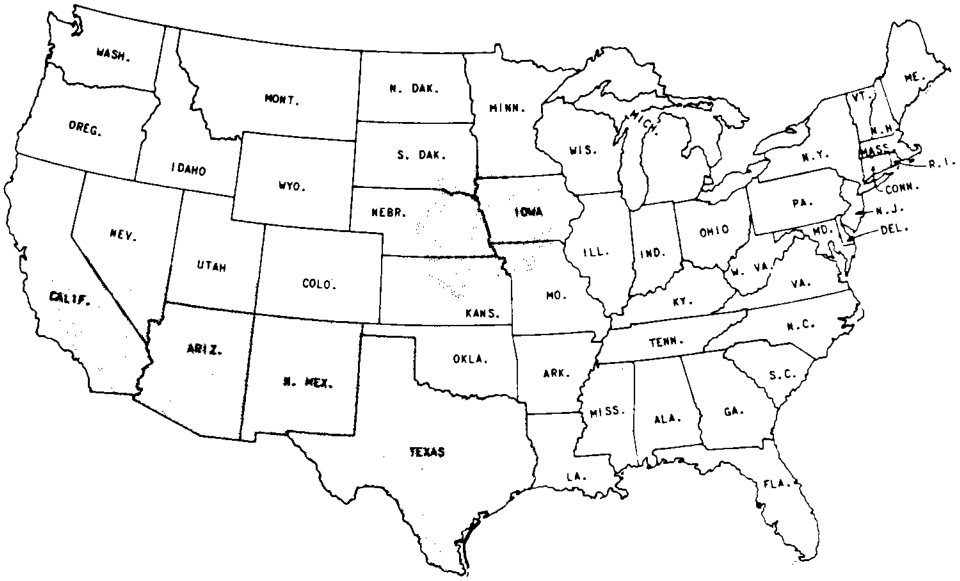

Figure 6-9. Solar Thermal Siting Regions

Most of the sites considered were in dry areas, either desert or steppes. The sites in southern South Dakota, Nebraska, and Kansas, however, are in humid, temperature climates with primarily tall grass prairies. Urban areas, Indian lands, national and state parks, national and state forests, national landmarks, national wildlife refuges, and wilderness areas were categorically excluded from consideration. Military reservations, municipal airports and their control zones, and low altitude federal airways were also excluded.

The principal environmental impacts to be expected from construction and operation of hybrid solar power systems in the areas shown in Figure 6-9 are discussed here. It is important to point out that single impacts will generally be less than those for a coal only or solar only unit. That is, fly ash, SO_x and NO_x emissions will be less for the same power output from a cost-only unit and land requirements will be somewhat less than those for a solar-only unit.

6.2.1.1 Solar Radiation Impacts

Both the solar and coal systems will likely have some impact on the local microclimate, although solar system impacts are expected to predominate. For impacts to affect a large region, there would have to be many or very large scale plants located near to one another. For several reasons, including limits on markets for solar power units and the operational flexibility and stability offered by dispersal, these macroclimate effects are not expected.

A 100 MWe solar hybrid installation would influence the temperature and airflow patterns within its own microclimate. The presence of the heliostat field would be the source of the greatest impact. Waste heat rejection and the evaporative wet cooling to reduce it would also have some impacts. There is, currently, inadequate observational data to quantify these impacts with any certainty. Three studies are planned by DOE which will either monitor actual pilot installations or simulate on-site conditions to achieve a better understanding of these impacts.

Temperature – Albedo

Temperature changes are related to changes in the albedo, the percent of radiation a surface reflects back into the atmosphere.

The table below shows a comparison of albedo for various surfaces.

Surface	Albedo
Deserts	25-30%
Savannah (treeless plain)	
dry season	25-30%
wet season	15-20%
Chapparral (thicket of shrubs or dwarf trees esp. adapted to dry summers and moist winters)	15-20%
Heliostats	56%

Thus, heliostat fields which reflect back to the sky and to receiver surfaces are expected to have about twice the normal albedo of a desert or savannah area and nearly three times that of a chaparral. This would cause an appreciable cooling of air flowing over the mirror field during daytime hours and a decrease in the total energy in the air, including long-wave radiation and convective, conductive, and latent heat. However, there should be no significant difference in nighttime air temperature between the heliostat field and the surrounding environment.

The daytime change could cause an imbalance in delicate semiarid and arid desert ecosystems. Vegetation in the immediate vicinity could be adversely affected. Plant construction will reduce vegetation at the site and also increase albedo.

Airflow Patterns (Velocity and Turbulence)

There will be a reduction of wind speed beneath the tops of the heliostats disrupting low level air flow patterns. Mean winds above the field might be reduced somewhat, and turbulence above the canopy might be increased. However, this turbulence may not penetrate beneath the canopy. These impacts are probably of no great concern.

Waste heat rejection from the power generation complex will cause intense convective updrafts in the immediate vicinity of rejection facilities. It may also cause turbulence and the formation of cumulus plumes above the plant. Wet cooling will cause an amount of water to be evaporated that is directly proportional to the output of the plant. This evaporation might cause local fog or clouds, thus interfering with solar plant performance.

In conclusion, any climatic effects will likely be limited to the microclimate as opposed to the mesoclimate or macroclimate. It is not clear as to whether these impacts will be beneficial, detrimental, or insignificant.

6.2.1.2 Air Pollution Impacts

Fugitive Dust

Construction activities associated with any large scale construction project create air pollutants of a temporary nature. The hybrid solar plants are no exception. Impacts consists mainly of hydrocarbon and carbon monoxide from vehicle and construction equipment operation, and fugitive dust. Fugitive dust can be adequately controlled by wetting or chemically treating the working area. Hydrocarbons and carbon monoxide emissions are not likely to be a serious problem unless the plant is sited in an area which already has air quality problems. This is unlikely to occur in the case of a central receiver solar thermal power plant, given the likely siting locales.

During plant operation, another source of fugitive dust will be the coal located in storage areas and passing through the covered conveyor trench from storage to boiler fuel areas. This could interfere with plant operation by reducing the mirror incident solar radiation and reducing the reflectivity of the mirrors. Soil crusts will be destroyed during construction, and if not reformed, the surfaces will be subject to erosion if they are not paved, chemically treated, or vegitated. These surfaces will be a source of fugitive dust until the flora reestablishes itself.

A paved or chemically treated field on the other hand, creates potentially significant precipitation runoff problems, may interfere with natural water infiltration, and could result in contamination of local water supplies. These types of impacts are common to large paved areas such as shopping centers and parking lots and can be controlled through careful planning. Impacts of a paved heliostat field on flora and fauna will be discussed in the section on ecosystem impacts.

Plant Emissions

As the coal and the solar components operate in parallel, both will use evaporative wet cooling towers. Cooling tower impacts will vary according to the chemical/mineral content of the water used in the cooling process and the meteorological conditions of the plant site. Impacts, if any, will result from cooling tower drift — evporated water and any dissolved or suspended solids it contains. At the least, some moisture, and possibly fog or rain, could be expected downwind of the cooling tower. Impacts on the rest of the surrounding area would be minimal, due to the rural nature of prospective sites and the lack of other stationary sources in the vicinity.

The coal burning component of the plant would be the primary source of air pollutant emissions, having the usual combustion-related emissions associated with any fossil fuel burning plant: particulates, NO_x, SO_2, and trace elements (arsenic, barium, beryllium, etc.) depending on the trace elements contained in the coal being utilized.

The plant will utilize a fabric filter for fly ash removal. These are 99.5% effective. Modified combustion could reduce NO_x emissions by 50 to 63%, and a scrubber will remove 85 to 95% of sulfur oxide emissions. The design emission goals for the plant will comply with applicable new source standards.

Due to the relatively remote siting, these emissions are unlikely to pose any general threat to human welfare. However, a few individuals could be affected. There might be acute, chronic, or long-term effects on local flora and fauna. Biota are most likely to be unfavorably impacted by high, short-term concentrations of SO_2 and NO_x located within a few kilometers of the plant during adverse meteorological conditions. For example, acute injury might occur if an inversion were to result in a plume fumigation, causing stack gas effluents to mix downward rapidly, and thus subjecting organisms in the path of the plume to high concentrations of all the plume constituents. Whereas a high concentration of one of the plume constituents may have little or no adverse effect on an organism, the mixture may cause a synergistic response resulting in serious injury. While injuries from short-term, high concentrated exposures are more easily recognized and quantified than those due to long term, low concentration chronic exposure, they are also less likely to occur. Situations in which pollutants reach levels associated with chronic injury occur more frequently than those which result in acute injury, but studies dealing with these effects are limited and any judgments are speculation.

In the long term, there could be abnormal changes in ecosystems and subtle physiological alterations in organisms which may result from the coexistence of air contaminants and living systems for decades or longer. Studies of such long-term effects of pollutants are virtually non-existant.

One Study calculates near worst case, short-term ground level concentrations of the major pollutants for a coal-fired plant (no solar component) as shown in Table 6-7. It should be borne in mind that these concentration apply to a plant

TABLE 6-7
MAXIMUM* SHORT-TERM GROUND-LEVEL CONCENTRATIONS
(100 MWe Plant - Using Western Coal)

$\mu g/m^3$	3-hour	24-hour
SO_2	967	267
NO_x	316	92
Particulates†	24	7

*Distance to maximum is 600 m
†Assumes use of particulate removal equipment with 99.5% efficiency

which is probably operating between 70 to 100% capacity, 24 h a day. The hybrid plant would be burning coal at 20% capacity for substantial periods of time, decreasing the likelihood of such conditions occurring. Of the two primary gaseous pollutants, SO_2 is likely to have a greater impact on ecosystems than NO_x. Hill et al (1974(exposed 87 species of plants, native to the American desert in their natural habitat, to from 1,300 to 26,000 $\mu g/m^3$ SO_2 for two years and found that 5,200 $\mu g/m^3$ was needed to damage all but a few of the species. Only one species was damaged by 1,300 $\mu g/m^3$. The dosages required for observed damage are far heavier than postulated in the worst case above.

Exposure of 10 native Montana grassland species to four levels of SO_2 [$\sim$10 (ambient), 52, 130, and 260 $\mu g/m^3$] continuously through one growing season (early June through late October), revealed abnormal effects.

SO_2 concentrations are not expected to reach levels likely to cause either acute or chronic deleterious effects to wildlife as long as the scrubber system is operating properly. Should the scrubber system fail, SO_2 may reach concentrations which have proven harmful to laboratory animals, but this is unlikely. Even if such a failure did occur, it would be unlikely to persist for more than one hour.

At the levels indicated in Table 6-7, nitrous oxide levels may remain high enough to adversely affect the lower respiratory tract of some animals.* Chronic exposure to $\sim 100\ \mu g/m^3$ may be deleterious to humans.

Loss or change of even the most sensitive ecosystem component could, eventually, change the whole ecosystem because of the delicate balance that exists among the components.

Precipitation

Due to the natural alkalinity of solids in arid regions, and the relative lack of other sources, acid precipitation, if it occurs, is not likely to be a serious problem. Acid compounds arising from NO_x will also be neutralized. The resulting nitrates and nitrites may induce toxic reaction in animals and man.

Particulates will be produced as a result of the coal combustion. While the overall efficiency of the fabric filters in removing particulates from combustion stack emissions can be above 99%, they are less effective in removing the smallest particulates, those in the range of 0 to 5 μm. Efficiency for these may be as low as 90%. Possible impacts on plant life include interference with heat exchange and photosynthesis, and greater susceptibility to disease. Depending upon the toxicity of the trace elements contained in the particulates, effects on animals and humans may range from respiratory irritation, to chronic bronchitis, bronchial asthma, pulmonary edema, silicosis, and cancer. Since solar hybrid plants will most likely be located in rural areas with few or no other stationary sources, actual impacts are not likely to be significant.

6.2.1.3 Water Impacts

Both the solar and the coal components of the plant may potentially impact water supply or water quality or both. Problems may arise from a variety of

*Effects at these levels have been observed in the laboratory.

causes from the simple presence of the plant, to consumptive use of water in an area where it is already in short supply, to actual release of pollutants which contaminate surface or groundwater.

<u>Water Pollution</u>

In a desert siting, the likelihood that there will be a problem with potable water contamination is remote. Generally, arid areas have fewer surface bodies of water, groundwater is usually at a depth of 100 ft (30 m) or more, minimizing change of contamination. Stream and groundwater contamination could occur as a result of systems flushing, heliostat cleaning, wastewater disposal, accidental release of working/storage fluid and disposal of ash and sludge from coal combustion. In reality, systems flushing should not prove a serious hazard to surface water quality, because proper handling of such industrial chemical wastes is well understood, and presently available disposal methods are adequate.

Leakage or spillage of the liquid sodium working fluid would not be a serious occurrence. In the case of a small leak in the system, the sodium would form sodium oxide smoke; if the rupture were large, the sodium would leak as a liquid stream. When exposed to air at high temperature sodium will ignite forming sodium oxides. The sodium flame temperature is low ($<1600^{\circ}F$) and the "flame" height is <1 in. high, similar to a charcoal fire. Thus secondary damage to metal structure does not occur. Sodium in contact with water reacts violently. Such contacts should be designed for. Sodium will react vigorously with concrete. Thus concrete is normally protected from sodium spills.

A reasonably detailed series of calculations was performed to predict the aerosol concentration and fallout within and outside the plant boundary. The calculations have shown that the threshold limit value for 24-h/day inhalation [2 mg/m^3 of $Na(OH)_2$] by human beings would be reached at the plant perimeter (assumed to be 1600 m from the base of the tower) if a continuous jet of sodium at 0.5 kg/s (1 lb/s) were released to the environment at the 174 m elevation. This release rate corresponds to a release through about 0.95 cm diameter hole in the receiver, a hole which is considered to be due to a large-caliber bullet. Moreover, the calculated concentration values correspond to the most adverse weather types, neglect such naturally occurring phenomena as agglomeration, and disregard the conversion of the hydroxide to carbonate. For short-term releases, where 80 mg/m^3 is allowed, release rates can be substantially greater (20 kg/s). Thus, assuming that human inhalation limits are the most sensitive environmental criterion, the presence of sodium does not appear to present an unreasonable risk to the environment outside of the plant perimeter. It is also to be noted that, although the oxide and hydroxide forms of sodium are of concern insofar as their effects on humans, flora, and fauna are concerned, these compounds are not toxic and readily convert to carbonates after exposure to air for a few minutes or hours, depending upon the amount of water in the air in the vicinity of the release. The carbonate is generally considered to be reasonably innocuous. One other mitigating circumstance is the fact that the release and subsequent burning of a jet of sodium is readily visible; consequently, action can be initiated to drain sodium away from the failed area. This procedure will further limit the amount of sodium released in an accident situation.

Additional caclualtions were performed to predict the aerosol concentration values and the deposition in the vicinity of a ground-level, pool-type fire that could be postulated to occur as a result of a sodium spill. Under the most adverse weather circumstances, the long-term, threshold-limit value is reached at the outer boundary of the plant if the burning area of the pool is about 15 m^2. For short-term releases, which are the more likely events since corrective action can be taken,* a pool fire area of 160 m^2 can occur without the aerosol concentration exceeding the 80 mg/m^3 criterion. Fallout rates and concentrations just downwind from the pool fire but within the plant boundary are, however, high. A deleterious effect on plant life, if there is any, within this boundary could be anticipated. Outside the boundary, however, there does not appear to be a serious environmental concern.

Althouth the calculations, which are reasonably conservative, predict an acceptable environmental effect if a release of hot sodium should occur, the liklihood of such an event is very small insofar as large quantities are concerned. Since the early 1950's when sodium and NaK loops of significant sizes were first put into operation, no major release or spill above several hundred pounds has

*Sodium can be drained from all parts of the loop into either or both of the large storage tanks.

occurred; yet millions of hours of operating time have been accumulated in both sodium loops and operating nuclear power plants in the U.S. and abroad.

6.2.2 Land Use Constraints

6.2.2.1 Land Use

Solar thermal electric plants are land intensive. Aerospace Corporation estimates for land requirements range from 1 to 2 mi^2 (2.6×10^6 m^2 to 5.2×10^6 m^2) for each 100-MWe capacity. LBL estimates about 3 km^2 per 100 MWe, not including access roads and transmission line right of ways. The less optimal the location the greater the amount of land area required for the same MWE capacity. For the reference plant, Rockwell estimates a requirement of $\sim$1 mi^2.

Rights/Availability

According to the Aerospace siting analysis, even when the most stringent criteria are applied, there are 55,000 km^2 of land suitable for central receiver power plants in the southwest. Total United States electrical demand in 1975 is about 1.9×10^6 GWh annually. This would require about 54,000 100-MWe central receiver plants or about 16,000 km^2 land area. As actual demand for solar units will be less than current totals, Aerospace concluded that there is sufficient land that is suitable for central receiver power plants. Much of the suitable land is either state or U.S. government property. Southwestern utility companies have already designated lands for future power plant construction.

Agriculture, Grazing, Recreation Displacement

In some instances, prospective sites may be in agricultural use. As most prospective sites are in arid areas, agricultural placement should not prove to be a serious problem. Grazing rights are also a consideration, although here too grazing lands suitable for solar total energy (STE) are probably marginal as rangeland.

Some vocal opposition may be raised to the extent that recreational activities (camping and recreational vehicles such as trail bikes, jeeps, and dune buggies) are curtailed. This opposition may be overcome by drawing attention to the benefits derived, and is not expected to be a serious barrier.

Plant Site Physical Disturbance

Since the desert ecosystem is so finely balanced, physical disturbances during construction and operation are potentially of greater importance than the shading or wind deflection caused by the in-place heliostat field. Locally, construction impacts on the desert ecosystem will be severe. Large areas will be cleared of their natural vegetation during construction. Any desert pavement that may have formed on the site will be destroyed, increasing susceptibility to wind erosion. Off-road construction vehicle tracks may become gullies, increasing water runoff.

During both construction and operation of the plant, walkers and vehicles may compact the soil causing substantial increases in its bulk density and penetration resistance and decreases in its micropore space. This will adversely affect water availability, root growth, and aeration. Intense compaction, even over a short term required for construction, can be reversed; however, long-term compaction can cause more serious changes in soil structure. To reduce the potential for soil compaction, heavy maintenance should be scheduled during dry periods, since dry soil is less susceptible to compaction than moist or wet soil. Vehicles should be confined to specific roads in the collector field to minimize their compaction impact.

Since dust can reduce the efficiency of a solar unit, some form of control is needed. From an environmental standpoint, the most desirable method of erosion control would be to develop ways of strengthening the desert crust and encouraging it to form more quickly or to encourage rapid revegetation with some low height plants. This could prove less costly than paving.

Transmission Lines

A 115 kV transmission line is planned for the facility. This is the smallest of the lines requiring supporting towers. It would require a 50 to 100-ft right-of-way, but a line of that size is amenable to multiple uses along its path, including farming, grazing, and recreational uses in locales where these would normally take place. Its major impact is its intrusion on the visual quality of landscape. Transmission lines are difficult to mask in a desert or grassland. Energized conductors can be a danger to birds of prey unless insulated or strung in such a way that a bird perching on the tower will not contact the conductor either directly or through its dangling prey. Waterflowl may also be killed by collision with high voltage transmission lines near watering places.

Construction of the lines can cause some of the same impacts as the construction of the plant – soil erosion from clearing, ruts and gullies from construction equipment. These impacts can be mitigated by proper construction procedures. Cleaning should not occur until tower construction is ready to begin. Any vegetative cover should be replaced once the placement of the tower is complete, and rigorous construction specifications should be stipulated and followed.

Access Roads

Access roads will most likely follow the transmission line right-of-way since easy access to the lines is necessary to repair purposes.

6.2.2.2 Ecosystem Impacts

Likely sites for plants utilizing solar thermal electric central receivers are arid and semi-arid regions – desert, steppe, prairie, or chaparral – where there is either little rainfall or the evaporation rate is higher than the precipitation rate. Because of the scarcity of water, the ecosystem is extremely delicate. Actions which allow the soil to retain moisture, may also allow it to support larger populations. Actions which further decrease the water supply, whether by direct use, contamination, or removal of access, will almost certainly decrease the size of the plant and animal population the area can support.

There is inadequate observational data, but because of the fine balance in desert communities, it is likely that once modified or destroyed, it would be difficult to regenerate. Regeneration, if possible, could take many years.

Siting

In an area with sparse vegetaion, removing any substantial amount of vegetation will have an impact. Similarly, a plant sited close to a watering hole and interfering with its use, either by contamination or proximity, will have a serious adverse impact on the native population. Much of the surface water found in desert areas is periodic, of short duration, and occurs in well-defined wash areas called playas. Siting a power unit on a playa would destroy the playa as a source of water. The fauna displaced will move to nearby watering holes, causing overcrowding and perhaps ultimately reducing the faunal population.

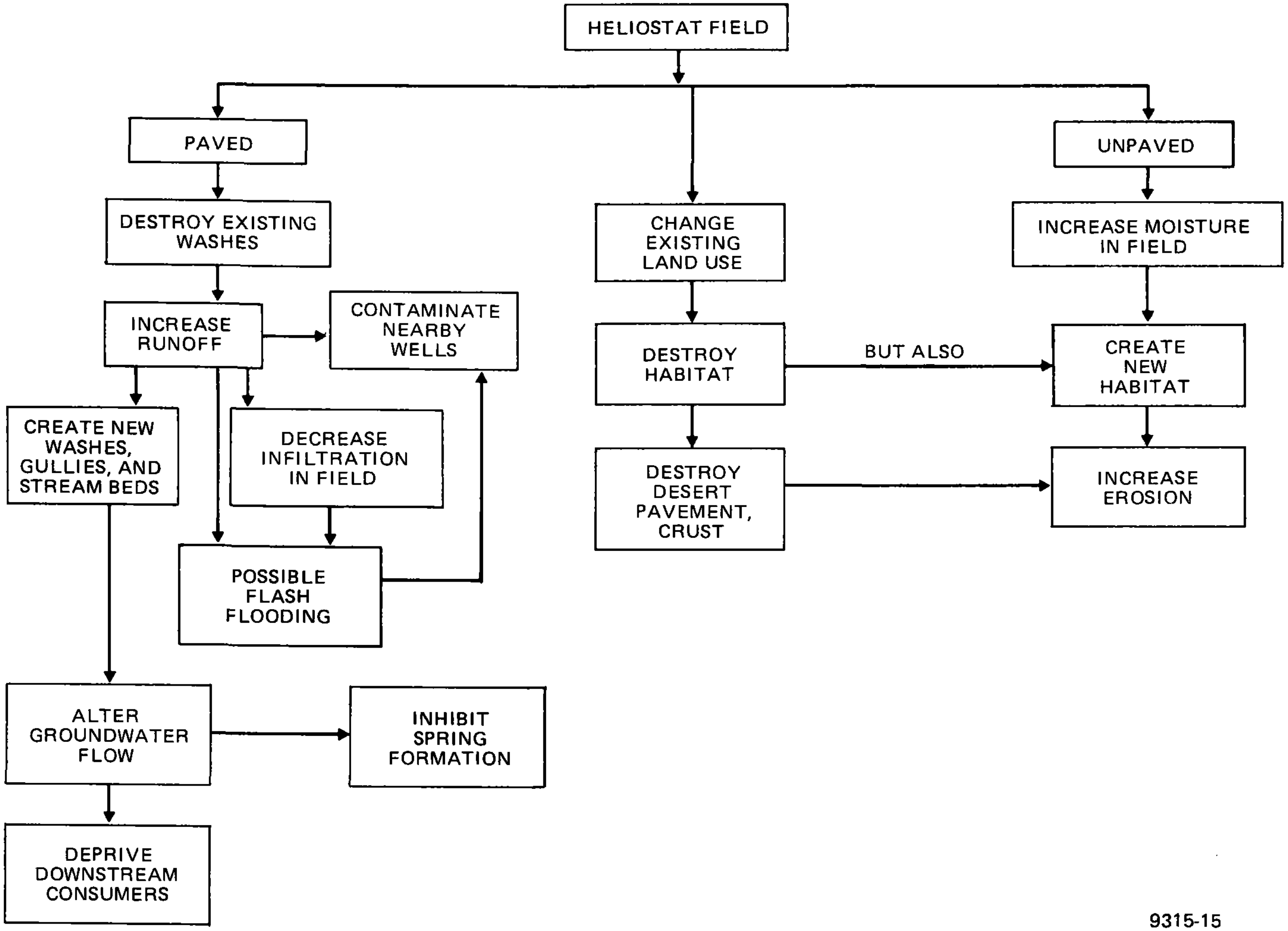

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Figure 6-10. Potential Effects of Heliostat Fields on Environment

To minimize impacts, the importance to the native communities of the site itself, its vicinity, and the presence of the plant in that vicinity should be assessed.

Construction

Construction impacts could be severe, at least in the near term. Habitat on those portions of the site where structures are placed will be destroyed, whether for the coal or for the solar component. At least part of the heliostat field may be restored as native habitat after construction. The extent of restoration depends upon whether the field is paved or unpaved, fenced or unfenced, treated or untreated. During construction, the site will be denuded of vegetation and species dependent upon that vegetation will be displaced, perhaps permanently. If the species involved are wide-ranging, the problem is less serious, although they will stress the food and water resources of the area to which they emigrate. The existing food chain will be broken, affecting the species reliant on it. This could include such threatened or endangered species as the gila monster, the spotted bat, and the spot-tailed, earless lizard.

Off-road vehicles may crush burrowing animals who spend most of the hot, daylight hours underground. This is a potentially serious impact, depending upon the population of animals near the plant site, their burrowing habits, the tonnage of trucks used, the width of roads, and the amount of off-road driving that is necessary or permitted.

Heliostat Field

Heliostat field impacts may be critical to the local ecosystem. Consequently, impacts of the various field options should be considered carefully before actual plant construction begins. These effects are illustrated in Figure 6-10. If the heliostat field is paved, the lack of vegetation combined with the presence of maintenance personnel will combine to make the area inhospitable to wildlife. The two species which are not put off by such conditions are rodents and coyotes. Paving also renders the field susceptible to flash flooding in the event of a large storm, and the runoff may create new gullies while destroying old ones, and also alter stream beds affecting water availability to wildlife.

If the field is unpaved, but fenced to exclude wildlife, plant communities may be reestablished, including some that were not previously native to the site. Vegetation may experience faster than normal growth, creating maintenance problems unless herbicides are used. Any deficiency in ground cover would increase wind erosion. Presence of dust in the air decreases the amount of direct solar radiation reaching the heliostats, and dust on the reflective surfaces of the heliostats decreases their efficiency. Thus, dust suppressant may be used. Application of these chemicals could contaminate groundwater and ultimately drinking water supplies.

Unpaved, untreated, and unfenced, the heliostat field may well be reclaimed by plant and wildlife, perhaps in greater numbers than before. Returning animal species may adapt to the presence of man and also aid in regulating the standing vegetation, resulting in a thriving microcommunity. This could be a positive impact, but it might also create ecosystem imbalances.

Working/Storage Fluid (release and disposal)

Impacts of working and storage fluids on the ecosystem should be insignificant if proper management and system maintenance are employed to prevent leakage or spillage, and there is proper containment, removal, and disposal of intentionally flushed fluids.

Coal Transportation

Average coal requirements would for the reference plant involve no more than one delivery a week, assuming a 40-car train, with each car carrying 100 tons of coal. The primary effect, besides fugitive dust which influences unit performance is one caused by noise. This is minimal as effects of intermittent noise are less severe than effects of continuous noise.

Storage Piles

The major problems, associated with storage of coal and reagents coal scrubbling, are dust and runoff. Windblown deposits of coal dust landing on vegetation may interfere with photosynthesis and lead to leaf necrosis. Soot from coal combustion would have the same impacts. Reagent dust should not be much of a problem in the arid and semi-arid areas most suitable for central receiver solar power plants. Where humidity is high and there is dew formation throughout the growing season, the dust may form a crust on leak surfaces causing lowered photosynthetic activity and even leak mortality.

Runoff from coal storage contains coal fines and various trace minerals including heavy metals. There is little surface water near the most likely sites, and the natural alkalinity of the native soil, plus the increased alkalinity of the limestone runoff will mitigate the impacts of the coal runoff, by serving as a buffer for acid inputs from both coal storage and stack emissions, and decreasing the solubility of the trace minerals. Impacts would be site-specific.

Coal Combustion

Most of the impacts from coal combustion emissions (SO_2, NO_x, particulates) are discussed in Paragraph 6.2.1.2 (Plant Emissions). As vegetation is more susceptible to these emissions, they would be impacted first. Herbivores would in turn impact the carnivores, and so on up the food chain.

Chronic SO_2 plant injury can be light to severe and is characterized by leaf yellowing (chlorosis) which begins on the margins of the leaf and moves to the intercostal areas. This can eventually result in the death of the plant. However, if exposures are intermittent, the plant may recover between exposures. Tolerance levels are lowered by high light intensity before and/or during fumigation, high temperature, daylight, morning hours, high relative humidity, water on the leaves, high soil moisture, old plants, young (but not expanding) leaves, developing conifer needles, high physiological activity (flowering, seed set), low vigor due to insects or disease, and low nutrition levels. Several of these are unlikely to apply in the case of the proposed physical plant. First, the plant will run at higher than 20% capacity only during hours of low insolation or darkness. At those times, the temperature in the region will be in its low range, and there will be low light intensity before and during possible fumigation episodes. It is unlikely in the type of arid or semi-arid region suitable for a central receiver plant that there would be high relative humidity. Thus, most exacerbating factors are minimized or eliminated. Except for any vegetation growing under the heliostat canopy, there is unlikely to be water on the leaves, and only the ground within the field is likely to have high soil moisture. Conifers are not likely to be growing in prospective central receiver sites. The likelihood of plant injury occurring during a fumigation in a power plant of this size is unlikely.

Concentrations projected for a 100-MWe plant using western coal (316 $\mu g/m^3$ - 3-h maximum, and 92 $\mu g/m^3$ - 24-h maximum) are not likely in and of themselves to prove harmful to animals or man. Animals are more likely to be affected indirectly through impacts on vegetation causing modification of habitat or loss of important food.

The major concern with particulates is the impact of the trace elements absorbed to them. Their impact on plants depends upon their natural concentrations in the soil, the soil's exchange capabilities, and the uptake mechanism of the individual element. The last is not totally understood and varies according to plant species and environmental conditions from simple diffusion to active uptake. Environmental conditions in likely sites are favorable to diffusion of trace elements. Light sandy soils have lower trace element exchange capabilities than do heavier clay soils. Short grass prairies or deserts, being more susceptible to wind and water erosion, may lose larger quantities of deposited trace elements than more densely covered tall or mixed grass prairies and forests.

Animals are exposed to trace elements through inhalation of combustion vapors and airborne particulates, and through ingestion of drinking water and vegetation. At least 14 trace elements are essential to animals, but become toxic at levels only slightly higher than their level of essentiality.

Results of analyses of Dvorak et al, 1977, and Dvorak and Penecost et al, 1977, indicate that trace-element emissions from a single conventional model power plant may have relatively little impact on terrestrial ecosystems provided that new source performance standards for particulates (0.1 $lb/10^6$ Btu heat input) are met and that tall stacks are used. Add to this the probable lack of other stationary sources in the region, the modest size of the planned facility, and the probable average percent capacity at which it will run, and overall impacts will be small.

To determine impacts with any degree of accuracy, site specific information is needed: background information on the soil, endogenous levels of trace elements in those soils, native vegetation and animals, characteristics of the site which may increase or decrease the possibility of impacts, meteorological factors and topography.

Assessment of the impacts of radioactive particulates (arising from coal combustion) on wildlife requires characterization of the ecosystem, identifying the more important or more sensitive species and analyzing effects to those species of radiation from ingestion, inhalation and external exposure. The most likely effect would be an increase in the cancer rate after a long latent period extending into decades.

Coal Solids Wastes

Disposal of the solid wastes, fly ash, bottom ash and scrubber wastes, is expected to take place off-site. Impacts will depend upon the characteristics of that site. Wastes may be returned to the mine site on the return trip of the coal delivery train. It may also be deposited nearby. In either case, the primary impacts arise from the preemption of land from other uses, water fowl use of active disposal sites, and runoff and seepage from disposal sites.

Disposal in a mined out pit, if followed by reclamation, allows future use of the surfaces. Reclamation efforts, however, are not always successful. Success depends upon the properties of the disposed material, availability of good earth cover materials, and the climate of the region.

As the wastwater from cleaning the heliostats is to be cleaned and recycled, this should pose no significant problem. Waste from coal combustion, ash and sludge, is somewhat more of a problem. Disposal will be off-site, and impacts will be determined largely by the place chosen and the method used. Wastes may be placed in nearby ash and sludge disposal ponds, or transported back to the mine site on the coal train's return trip. Ash may also be utilized in cement mixture asphalt mixes, road surfacing, and other products. If not properly disposed of, these wastes containing the sulfur and trace metals removed in the treatment processes, could contaminate streams and groundwater and prove injurious to both land and aquatic organisms. Such impacts are more easily prevented than corrected.

6.2.3 Natural Resource Constraints

6.2.3.1 Water Requirements

This is perhaps, the most critical environmental concern when dealing with any power facility. Some arid areas, with the requisite insolation, are short on water. Water requirements will act to limit the areas available for siting. However, they should not limit hybrid solar unit use.

The plant will need water to be converted to steam to run the turbines that produce the electricity, it will use water to mix with the limestone for use in the scrubber, and to wash the heliostats. Although this last use will recycle the water, some new water will be needed periodically to replace whatever water is consumed or evaporated in the process. The largest water use will go into the evaporative wet cooling process. Rockwell projects their water needs as follows:

PLANT WATER CONSUMPTION
(gal/yr)

Cooling Tower	4.43×10^8
Flue Gas Desulfurization	2.33×10^8
Heliostat Cleaning	847,000

In addition to these requirements, central solar facilities are labor-intensive. Estimates for construction manpower needed for a 100-MWe STE are as high as 10,000 man-year; and, for a 100-MWe coal plant, 3,900 man-years. Peak employment might be one-half of the total man-years or 2,000-5,000 MW. Influxes of personnel during construction will represent substantial increases in local population, especially since sites are likely to be in regions that are fairly sparsely populated. This will create increased need for water for life, irrigation, and recreation. During operation of the units, staff would not exceed 50 to 100 persons, and the water demands would be much more modest.

Water Cycle

More important than potential contamination but less important than water demand are potential changes in water movement. The water cycle in arid regions is extremely important to all forms of wildlife, and any modification of this cycle could affect the local ecosystem. Likely sites for solar hybrid units include playas and desert bajadas. Playas are low lying saline flats which are subject to flooding and may be the remnants of ancient lakes. Bajadas are alluvial fans with gentle slopes which are formed by runoff from nearby mountains or slopes. Siting a power plant on a playa would destroy its water collection function. A plant sited on bajada would be subject to heavy runoff and erosion (if the heliostat field were not paved).

In contrast to most other central station solar power systems, the Rockwell concept uses large amounts of sodium as a heat transfer medium. The cost and, particularly the availability of sodium, are thus items that require separate analysis. Cursory examination of other materials requirements shows that solar system reqirements are only a small fraction of current national production.

6.2.3.2 Current Procduction and Utilization of Sodium

In the United States, all sodium is produced by the electrolysis of a mixture of sodium chloride, alkali fluorides, and calcium chloride in a Downs cell. Material and energy requirements per ton of metallic sodium are: sodium chloride — 6,300 lb; calcium chloride — 12 lb; and electricity — 15,000 kWh, The fluorides are not consumed in signifcant quantity. Commercial sodium is 99.95% pure, and available in two grades — regular grade (containing a maximum of 0.040% calcium and 0.005% chloride) and reactor grade (with maximum of 0.001% calcium and 0.005% chloride). Some oxide, hydroxide, or carbonate may also be present as a surface coating.

Production of metallic sodium since 1960 is shown on Table 6-8 along with reported plant capacities for several years. The current producers and their plant capacities are shown in Table 6-9.

The installed plant capacity is about 70-90% of current demand. The dominant use for sodium is the manufacture of lead alkyls used in gasoline as octane improvers and antiknock agents. The consumption pattern for sodium in recent years is shown in Table 6-10.

Over the years from 77% up to almost 90% of the sodium consumed was used to make lead alkyls. The second phase of an EPA mandated reduction in the use of lead alkyls in motor gasolines was implemented in January of 1978. The reduction in production of sodium from 144,000 metric tons in 1977 to an estimated 125,000 tons in 1978 indicates the magnitude of the impact EPA regulations have on the use of sodium. Another reduction in the use of lead alkyls is scheduled for January 1980. The current gasoline shortage has prompted President Carter and others to call for a postponement in the implementation of the next reduction.

TABLE 6-8

METALLIC SODIUM STATISTICS
(thousands of metric tons)

	Capacity	Production
1960		(103)
1961		99
1962	n.a.	108
1963	157	114
1964	n.a.	126
1965	n.a.	138
1966	163	150
1967	n.a.	149
1968	n.a.	141
1969	172	150
1970	n.a.	155
1971	n.a.	139
1972	173	145
1973	173	161
1974	173	157
1975	173	131
1976	--	132
1977	--	144
1978	173	125*

*Based on first nine months data. Source: Current Industrial Reports M28A, Department of Commerce.

TABLE 6-9

U.S. PRODUCERS OF METALLIC SODIUM

Company and Plant Location	Estimated Capacity as of January 1, 1978 (thousands of metric tons)
E. I. Du Pont de Nemours & Company, Inc.	
Industrial Chemicals Department	
Memphis, Tennessee	20
Niagara Falls, New York	51
Ethyl Corporation	
Baton Rouge, Louisiana	41
Houston, Texas	27
RMI Company	
Ashtabula, Ohio	34
Total	173

TABLE 6-10

ESTIMATED CONSUMPTION OF METALLIC SODIUM
(thousands of metric tons)

<table>
<tr><th>Uses</th><th>1963</th><th>1967</th><th>1969</th><th>1972</th><th>1974</th><th>1977</th></tr>
<tr><td>Lead alkyls</td><td>93.5</td><td>123.7</td><td>130</td><td>130.7</td><td>120.5</td><td>110.6</td></tr>
<tr><td>Metal reduction</td><td>4.6</td><td>11.9</td><td>9.0</td><td>5.8</td><td>11.0</td><td rowspan="3">33.4</td></tr>
<tr><td>Sodium peroxide</td><td>6.8</td><td>3.0</td><td rowspan="2">11</td><td rowspan="2">8.5</td><td rowspan="2">25.5</td></tr>
<tr><td>Miscellaneous*</td><td>9.1</td><td>10.4</td></tr>
<tr><td>Total</td><td>114</td><td>149</td><td>150</td><td>145</td><td>157</td><td>144</td></tr>
</table>

*Including exports

Source: SRI Chemical Economics Handbook, adjusted.

While EPA has not yet acted, the chances seem good that the next reduction in use of lead alkyls will be delayed.

The longer range outlook for lead alkyls, however, is for its removal from motor gasolines. As smaller cars replace the current models, gasoline consumption in the United States is expected to decline. The lowered consumption should reduce the need to improve gasoline mileage through the use of the alkyls. SRI,. in another analysis, has estimated that by 1990, 90% of the gasoline produced in the United States will contain no lead. In addition, overall gasoline use will be reduced. Thus, lead alkyl demand may be 10% or less of current demand. While the timing may not be just right, the trend is correct.

None of the other current markets for sodium is likely to grow sufficiently in the mid-term to offset the loss of this large market. (The production of reactive metals via sodium reduction is the next largest use, but this is 10% or less of the total.) RMI (formerly Reactive Metals Incorporated) is the largest user. It makes titanium metal (and sodium perioxide) by reacting titanium tetrachloride with sodium. RMI is one of three titanium producers. The other two, TMCA (Titanium Metals Corporation of America) and Oremet (Oregon Metallurgical) use magnesium instead of sodium as the reductant.

In recent years, 4 to 7% of the sodium production has gone to titanium manufacture. In these years, from 25 to 35% of U.S. titanium has been produced by sodium reduction.

Titanium metallurgy and markets are complicated and hard to assess. Large increases in use of titanium have been predicted off and on since the mid-1950s. Except for use in military aircraft, a minimal use on commercial jets, and some use in chemical equipment exposed to extremely corrosive conditions, titanium has been too expensive to use. Markets will probably grow, but the impact on sodium consumption will be marginal unless new technologies appear.

One potential major use of titanium is in heat exchangers for salt water environments. Ocean thermal gradient power plants may be introduced after the year 2000. The very large heat exchangers required would be made from aluminum or titanium. These 21st century plants would required 15,000 to 16,000 tons of titanium for each 1,000-MWe unit, or potentially 33,000 to 35,000 tons of sodium.

Aluminum heat exchangers are likely to be used instead. While corrosion and biofouling may be more difficult to control, they will cost considerably less. If titanium-using, ocean-based power plants were chosen despite their higher cost, expanded titanium production capacity would be required. If sodium were used for the reduction, it is obvious that new sodium metal production capacity would be required.

Sodium might be used in commercial nuclear breeder reactors by the year 2000. A single 1,200-MWe nuclear (similar to the French Super Phenix) unit would require 4,700 metric tons or 2.7% of current capacity. This market, if it exists, would be small in the early years of the 21st century.

If nuclear reactor or ocean gradient power plants are commercialized, some new sodium manufacturing cacity will be required. There is no fundamental restriction on this additional capacity, since the basic raw material sodium chloride is in abundant supply. Costs of sodium might increase slightly, however.

Sodium perioxide is only made by one producer in the United States. New uses have not been developed for sodium perioxide so large amounts of sodium metal will not be required for that market.

One of the largest miscellaneous markets for sodium is for export. From 10,000 to as much as 20,000 tons have been exported. This market could grow as the third world countries become more industrialized.

Barring any major changes in the uses for sodium, the demand in future years is expected to be as shown on Table 6-11.

6.2.3.3 System Requirements

The amounts of additional metallic sodium required for the solar hybrid systems are estimated in Table 6-12 (calculated on basis of 870,000 #/100 MWe, SM = 0.8) in thousands of metric tons per year. Based on this rate of sodium consumption, the existing capacity should be capable of supplying all needs until well past the year 2000, provided none of the existing sodium production capacity is shut down permanently prior to the 1990s for lack of markets. However, the probability that some of these facilities will be closed down appears quite high. Again, they could be restarted.

TABLE 6-11

PROJECTED USE OF SODIUM*
(Thousands of Metric Tons)

Uses	1982	1985	1990	1995	2000
Lead alkyls	66	50	38	38	48
Metal reduction	12	13	15	18	21
Sodium peroxide	4	4	5	5	6
Miscellaneous	13	15	20	25	30
Total Use	95	82	78	86	105
Capacity†	173	173	173	173	173
Unused capacity	78	91	95	87	68

*Assumes little or no use in nuclear systems.
†Assumes none of the existing capacity will be shut down permanently.

Source: SRI International

TABLE 6-12

SUMMARY OF PROJECTED SODIUM DEMAND

	Annual Additional Sodium Requirement	Forecast Surplus with Solar Requirements
1990	0	95
1991	0.9	
1992	0.9	
1993	2.6	
1994	5.2	
1995	8.7	79
1996	13.9	
1997	14.8	
1998	15.7	
1999	20.9	
2000	27.8	50

6.2.3.4 Sodium Prices

The list prices and F.O.B. values for sodium metal are shown on Table 6-13.

TABLE 6-13

SODIUM METAL PRICES
($/lb)

	F.O.B. Shipment Values	List Prices
1963	0.165	0.170
1967	0.154	0.178
1969	0.158	0.178
1972	0.170	0.188
1974	0.179	0.188
1975	0.207	0.225
1976	n.a.	0.225
1977	0.288	0.33
1978	n.a.	0.41
1979 (March)		0.41

Sources: Current Industrial Reports M-28-A
U.S. Department of Commerce (values)
Chemical Market Reporter (prices)

No data were found that would allow any comparison among values, prices, and production costs.

Sodium production requires considerable electricity, 15,000 kWh per ton of sodium. The cost of electricity has increased as follows since 1967:

	Electricity Cost Index* 1967=100	Sodium Value Index 1967=100
1967	100	100
1969	102.7	102.6
1972	121.5	110.4
1974	163.1	116.2
1977	232.9	187.0

*Source Survey of Current Business, U.S. Department of Commerce

TABLE 6-14

NON-NUCLEAR SODIUM TEST RIGS IN U.S.

Site	Test Rig	Temperature	Inventory	Flow	Status
LMEC	SCTI (70 MWt)	1050°F	25,000 gal	8,700 gpm	Design
	SCTL	1200°F	13,000 gal	3,500 gpm	Operating
	SPTF	1100°F	20,000 gal	20,000 gpm	Operating
	LLTR	900°F	2,000 gal	-	Construction
	B/057-2	1300°F	500 gal	-	Operating
	B/006-2	1350°F	200 gal	-	Operating
	B/032-9	1200°F	6,000 gal	-	Operating
HEDL	CRCTA	1200°F	39,000 gal	500 gpm	Operating
	TTL	1200°F	850 gal	600 gpm	Operating
GE	SGTR	1000°F	3,000 gal	200 gpm	Operating
	DNB Loop	1000°F	2,000 gal	100 gpm	Operating
	3-Sodium Pots	1300°F	1,000 gal	-	Operating
W	GPL-1	1200°F	500 gal	200 gpm	Operating
	GPL-2	1200°F	2,000 gal	2,000 gpm	Operating
	3-Sweater	1200°F	20 gal	3 gpm	Operating
ABL	CCTL	1200°F	1,000 gal	800 gpm	Operating
	SFSCF	800°F	100 gal	100 gpm	Operating
	CAMEL	1200°F	30 gal	200 gpm	Operating
	FFDL	1200°F	30.2 gal	30 gpm	Operating

The cost of electricity between 1967 and 1977 increased greater than the general rate of inflation. Consumer price index for 1977 (1967=100) was 181.5. The cost of electricity continues to increase faster than the general rate of inflation. It appears, however, that sodium values are not rising as fast as electricity cost so sodium values would appear to be increasing at about the same rate as inflation. The price of sodium then in 1990 is likely to be:

In current dollars	\$ 0.70/pound*
In constant (1977) dollars	\$ 0.29/pound

6.2.3.5 Summary

Sodium availability and price are not factors in limiting fossil-solar hybrid unit use.

6.2.4 Status of Materials Technology

About 127 sodium and NaK test loops, with thermal power levels up to 70 MW, have been designed, built, and operated over the last 20 to 25 years. A representative listing of these is shown in Table 6-14. Many hundreds of thousands of hours of operating time have been successfully accumulated. Over one-half of these loops are still in operation, and additional ones are being built. In addition to a large number of sodium loops, about 21 liquid-metal-cooled (sodium and NaK) nuclear reactors have been designed, constructed, and operated. Some of these systems (see Figure 6-11) have or had power levels as low as 100 kWT, others as high as 1000 MWt. The first of these reactors was built in 1951, and seven of them are still operating. About 14 new sodium-cooled power reactors, with power levels up to 1300 MWe (3500 MWt), are under construction or in design in the U.S. and abroad. In the process of building the liquid metal loops, and particularly in the development and operation of sodium-cooled nuclear power plants, components such as pumps, valves, tanks, heat exchangers, and steam generators have been designed, fabricated, extensively tested, and operated. For example, in the U.S. alone, over 322,000 h of successful operation have been accumulated to date on various types of sodium pumps with capacities in the range

*Assumes 7% year inflation.

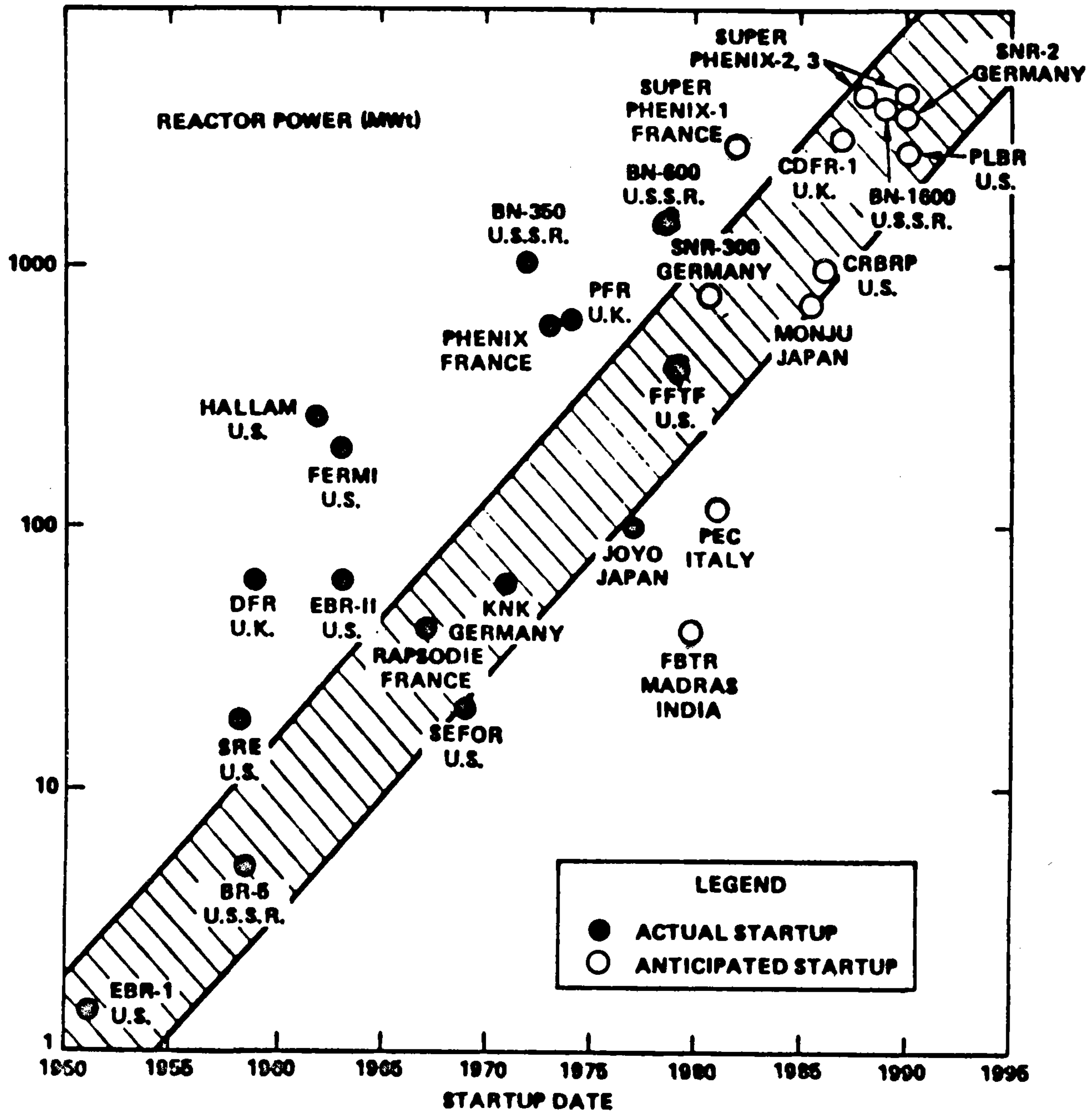

Figure 6-11. World LMFBR Plants (Progress Growth)

of 2,700 to 14,500 gpm (0.17 to 0.9 m^3/s). Thus, the current state of sodium technology is more than adequate to justify its application to solar electric systems. Furthermore, sodium components in the size range for solar pilot plants (i.e., 20 to 100 MWe) have already been developed and tested and are essentially available in terms of required pressure, temperature, and capacity ranges. Components of the sizes that would be applicable to full-scale commercial solar plants (i.e., 100 MWe) are currently in the design and test stage for use in liquid-metal-cooled, nuclear power plants in the U.S. and are expected to be available within the time frame projected for solar electric commercialization. Components of the size needed in the optimized (∿300 MWe) solar plant have already been built, tested, and operated in other countries.

6.2.5 Power Conversion Equipment Availability

The Central Receiver Hybrid Power System uses standard equipment at modern temperatures and sizes; therefore, there should be no availability problems with the equipment.

6.2.6 Manufacturing and Marketing Capacity Constraints

The only mass-production type item required in the sodium-cooled concept is the heliostat. This production capability and capacity is very limited at the present time, but the problems associated with meeting the forecasted demand have been dealt with in detail on a number of other programs. The assumption has been made on this program that heliostat production capability will grow to meet the power production requirements for the solar central receiver plant. Since the number of heliostats per plant of the same capacity is less in the sodium system than in the water/steam plant, the production capability could be expected to be met more easily or sooner in time. The production capability for the steam side of the sodium-cooled concept (i.e., steam turbines, generators, cooling towers, condensers, etc.) already exists, since the sodium-cooled system utilizes "off-the-shelf," modern-steam-plant, turbine technology and systems. No specialized turbine types would be required over and above those normally ordered by utilities who procure new Rankine cycle steam plants. The assumption is made that, as the solar central receiver becomes economically viable, steam turbines for the solar plant would be procurred in place of steam turbines for fossil-fuel plants. Thus, the demand would only follow the projected demand for new capacity in the most economical mode of operation (i.e., peaking plants or intermediate-load plants), and, therefore, the required capacity has probably already been accounted for by current manufacturers. This hypothesis is valid as long as the solar plant penetration does not require a significant increase in backup capacity.

The production capacity and capability for sodium has been discussed above. At the present time, the capacity is more than adequate, and the capability probably exceeded the actual production during 1977. The production of sodium in 1977 was 177,000 T, but capacity was 190,500. As the demand for sodium decreases in the area of the production of antiknock compounds (tetra ethyl lead, etc.), the need for sodium in the central receiver system might be expected to rise in such a way as to match production capability, depending upon the economical viability of the concept and the timing for its introduction.

Although virtually every sodium component, except the receiver, has been built on a large scale both in the U.S. and worldwide, these components are not being produced in large quantities at the present time. Large quantities in the sense of mass production are, however, not required. The sodium-component manufacturing requirements would be similar to those for steam turbines and generators. Assuming, for example, that the annual growth rate in the demand for electrical energy in the U.S. is 5.5% and that ∿25% of that new capacity is in the intermediate-load demand category, one finds that, on the average, about 15 GWe per year would be required between 1985 and 1995.* If all of this demand were optimistically to be met by solar central receivers of the 300-MWe size, a total of 50 plants a year would have to be installed. In terms of U.S. heavy machining manufacturing capability, this market does not represent a large number of components, although the components are of large size. Atomics International has already made preparations, for example, to produce 10 steam generators each in the 100-MWt-size category for the Clinch River Breeder Reactor. Within the time frame postulated for economic viability for solar central receivers, it is anticipated that the production requirements for sodium components could readily be met.

*1975 total capacity is taken to be 500 GWe

6.2.7 Safety Considerations

The specific safety requirements for the Central Receiver Hybrid Power System - Sodium-Cooled Concept, include the conventional occupational safety requirements and requirements peculiar to a sodium-cooled solar power plant. The conventional safety requirements include the applicable Occupational Safety and Health Administration (OSHA) regulations of the Federal Government (Title 29 Chapter XVII, Part 1910 for operations and Part 1926 for construction) and/or the OSHA regulations for the state in which the site is located. Other specific requirements will include the American National Standards Institute (ANSI) requirements (ANSI C1-1973 National Electrical Safety Code); the National Fire Protection Association (NEMA) requirements (NFPA 70-1978 National Electrical Code, National Fire Codes, Vol. 1-15); standards of the National Electrical Manufacturers Association (NEMA); ASME Boiler and Pressure Vessel Code, Sections I, II, V, VIII, Division 1 and IX; Standards of the American Institute of Steel Construction and the American Concrete Institute; applicable liquid metal safety criteria; and the building codes, air pollution and water quality regulations of the local governmental agency. The System Safety Program Requirements Specification for Solar Thermal Power Systems[6-13] and System Safety Design Criteria for the Central Receiver Solar Thermal Power System[6-14] will be used as guidelines.

6.2.7.1 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 around the field.[6-15]

The third concern, sodium combustion products dispersed to the site boundary from leaks in the receiver or from pool fires at ground level, has been examined in detail both analytically[6-16] and experimentally.[6-17]

The largest leak expected to occur in the receiver is postulated to be caused by a rifle bullet piercing one of the receiver tubes. The resulting 1 cm (3/8 in.) hole releases a jet of sodium which catches fire and forms a plume of sodium, and sodium combustion products. The plume develops into a white cloud of

TABLE 6-15

SODIUM RELEASES WHICH PRODUCE LIMITING AEROSOL CONCENTRATION
AT A PLANT BOUNDARY OF 1600 m (1 mile)

Type of Release	Amount of Release [kg/sec (lb/sec)]	Pasquill Weather Type	Reference Wind Speed [m/s (mi/h)]	Aerosol Particle Size [(μm) AED]	Aerosol Concentration Limit (mg/m^3)
Jet from 174 in (570 ft^2) Elevation	0.5 (1)	B*	1 (2)	20	2†
Pool on Ground	15 m^2 (150 ft^2)	F*	2 (4-1/2)	1	2
Jet from 174 m (570 ft) Elevation	20 (40)	B*	1 (2)	20	80§
Pool on Ground	160 m^2 (1600 ft^2)	F*	2 (4-1/2)	1	80

*Weather conditions which maximize the delivery of aerosols downwind
†Long-term limit (continuous exposure)
§Short-term limit (1/2 hr to 1 hr)

Na, Na_2O_2, $N_2(OH)$, and Na_2CO_3 aerosols and is carried toward the site boundary by the wind. A computer code[6-18] based on test data, has been developed which calculates the sodium and sodium combustion product distribution as a function of time and distance from the sodium release. A summary of the significant results of these calculations is given in Tables 6-15 and -16.

Table 6-15 gives the maximum allowed release rates to produce acceptable long-term and emergency aerosol concentrations at the site boundary, assuming that meteorological conditions exist which maximize the aerosol concentrations downwind. The concentration limit for long-term exposure is 2 mg/m^3. The limit for emergency release is 80 mg/m^3.

The estimated release rate from the postulated accident at the top of the tower is $\sim$1 kg/s (2 lb/s) or factor of 20 below the limiting value.

The exposed surface area of a burning sodium pool at ground level which will give the emergency limit at the side boundary is 160 m^2 (1600 ft^2). The free surface area for combustion in the catch pans (described under Plant Protection) will be limited to less than 1/20 this value by compartmentalization and by the use of vented covers on the pans.

It may be concluded from these results that the combustion of sodium at the installation will not represent a hazard to the public. 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. An alternate plan is to use accoustic emission techniques to detect leaks.

Table 6-16 gives the maximum concentration and the location where it occurs. It is seen that the maximum occurs well within the site boundary.

The maximum surface concentration corresponding to the postulated leak rate continuing for 25 min is expected to be $\sim$40 mg/m^2. Preliminary studies indicate that this concentration is not deleterious to the mirror surfaces.

TABLE 6-16

CALCULATED MAXIMUM SODIUM AEROSOL CONCENTRATIONS

Type of Release	Downwind Distance [m (miles)]	Concentration (mg/m^3)	Pasquill Weather Type	Reference Wind Speed [m/s (mi/h)]	Aerosol Particle Size [(μm) AED]
Jet from 174 m (570 ft) Elevation	700 (0.4)	3.5	A*	1 (2)	20
Pool on Ground	<100 (0.06)	<50	F*	2 (4.5)	1

Note: Maximum concentrations inside plant boundary for releases which produced limiting concentrations at assumed plant boundary of 1600 m (1 mile)

*Weather condition which maximizes the delivery of aerosols downwind

6.2.7.2 Personnel Safety

Personnel safety is adequately covered by the Occupational Safety and Health Administration (OSHA). For design purposes, the provisions of Title 8, California Administrative Code, will also be invoked (assuming a California site). In case of conflict between the two, the Federal Standards will govern.

Particular emphasis will be placed on preventing coincident multiple beam irradiance anywhere but at the receiver. In addition, personnel will wear flame-proof clothing, appropriate hard hats, PVC gloves, and eye protection when they are outside of the protection of the buildings or when they are working on open sodium systems.

Plant features which enhance plant safety aspects are:

1) Location of the elevator inside of the tower.

2) Railed catwalks at the elevations of the horizontal pipe runs and caged ladders for the vertical runs of the raiser and downcomer will be provided.

3) Exit doors at the catwalk levels every 30 m (100 ft) will lead to a protected exterior ladder. (Personnel will be excluded from the upper one-half of the tower during operation.)

4) At least two exits will be provided at the tower base.

5) Oxygen meters will be installed in all pits subject to potential argon flooding.

6) Sodium-sensitive aerosol detectors will be located in enclosed spaces.

7) Emergency safety showers and eyewash fountains will be placed at strategic locations.

8) Approved fire suppressant extinguishers (NaX) will be placed throughout the facility.

9) Provision will be made for the programmed draining of systems or components which are suspected of leaking.

10) Sodium catch pans will be provided under major components to confine the consequences of sodium leaks to a local controlled area until the component can be drained. The steam generator catch pans will be provided with a sump and pump to assure the catch pan remains dry.

11) Nitrogen gas will be supplied for the purpose of flooding the catch pans if Na combustion is initiated.

6.2.7.3 Plant Protection Features

Protecting the plant integrity is considered to be an important first step in protecting the public and operating personnel. The identified events which can potentially damage the plant are given in Table 6-17 together with plant features and actions planned to prevent or mitigate the damage. There are two independently operating sodium loops, the Energy Absorption Loop (EAL), consisting of the cold tank, the receiver pump (P-1), the receiver and the drag valve, and the Power Generation Loop (PGL), consisting of the hot tank, the steam generator pump (P-2), and the steam generator. The plant protective features respond in accordance with which loop is affected.

6.2.7.4 Conclusions

The plant safety features incorporated in the design provide a wide margin of safety for the public, personnel, and the plant.

6.3 MARKET ANALYSIS

6.3.1 Introduction

The adoption of hybrid solar central station power systems will be determined by (1) the market needs, (2) the comparative economics of commercial and other near commercial systems for producing electric power and (3) other less tangible factors including consumer preference, materials constraints, and social and political pressures. In the following analysis, the influence of comparative economics on market share will be discussed. Also discussed will be the influence of less tangible factors on market share and rates of market penetration. Finally, the impact of these factors on markets for hybrid power systems will be evaluated and market projections presented.

TABLE 6-17

PLANT PROTECTION - SUMMARY FEATURES
(Sheet 1 of 2)

Initiating Event	Plant Protective Features To Limit Consequences	Action Taken
Loss of Load	Alarm and P-2 pump speed reduction to condenser power capacity	Steam dumped to condenser
Turbine and Steam Equipment Failure	Turbine trip circuits	Turbine trip PGL* shutdown
Steam Generator to Sodium Leak	Rupture disk in steam generator shell Reaction products tank Isolation valves Antisyphon on T-1 inlet	Turbine trip and PGL tripped and secured
Faulting in PGL	PGL trip circuits	Turbine and PGL trip
Sodium-to-Air Leak in PGL Components	Sodium aerosol detectors Catch pans N_2 supply for catch pans	PGL shutdown N_2 flood-affected pan
Leak in T-2 Tank	Sodium aerosol detectors Catch pans Pump connection to the T-1 tank	Plant shutdown
Leak in T-1 Tank	Sodium aerosol detector Catch pans Pump connection to T-2 tank	Plant shutdown
Loss of Flow in the EAL	Check valve Syphon break in riser and downcomer lines Emergency slew circuits	Emergency slew mirror field. Shut down and secure the EAL loop.

TABLE 6-17

PLANT PROTECTION - SUMMARY FEATURES
(Sheet 2 of 2)

Initiating Event	Plant Protective Features To Limit Consequences	Action Taken
Sodium Leak in Riser or Downcomer Lines	Na aerosol detectors Catch pans with N_2 Drain lines	Defocus mirror field Shut down EAL Drain the affected lines
Sodium Leak in the Receiver Headers	Na aerosol detectors Catch pans Receiver drain line Steel cover on top of tower	Defocus mirror field Shut down EAL Drain receiver
Sodium Leak in Receiver	Television surveillance loop (or acoustic emission monitor) Receiver drain line Top 30 meters (100 ft) of tower insulated and steel capped Receiver support structure insulated	Slew mirror field Shut down EAL loop Drain Receiver
Focusing Error at Tower	Temperature sensors on structures Receiver structure insulated	Slew mirror field

*Power generation loop - hot tank, P-2 pump, and steam generator
**Energy absorption loop - cold tank, P-1 pump, and receiver assembly.

6.3.2 Equilibrium Market Share

Economists believe that the need for goods or services will be fulfilled by competing suppliers. Unless the market is very restricted or one supplier has an overwhelming advantage in price, many suppliers will have a share. As new goods are introduced into the marketplace, they will also gain a share, thus the total available market, e.g., for base load electric generating capacity, is currently shared between various nuclear, coal, oil, or gas fueled steam generating electric power units and hydropower units.

As an idealization, the share of a particular market that a single new technology or product can attain in competion with one other technology at any particular time under steady-state conditions can be represented by the curve shown in Figure 6-12 and is given by:

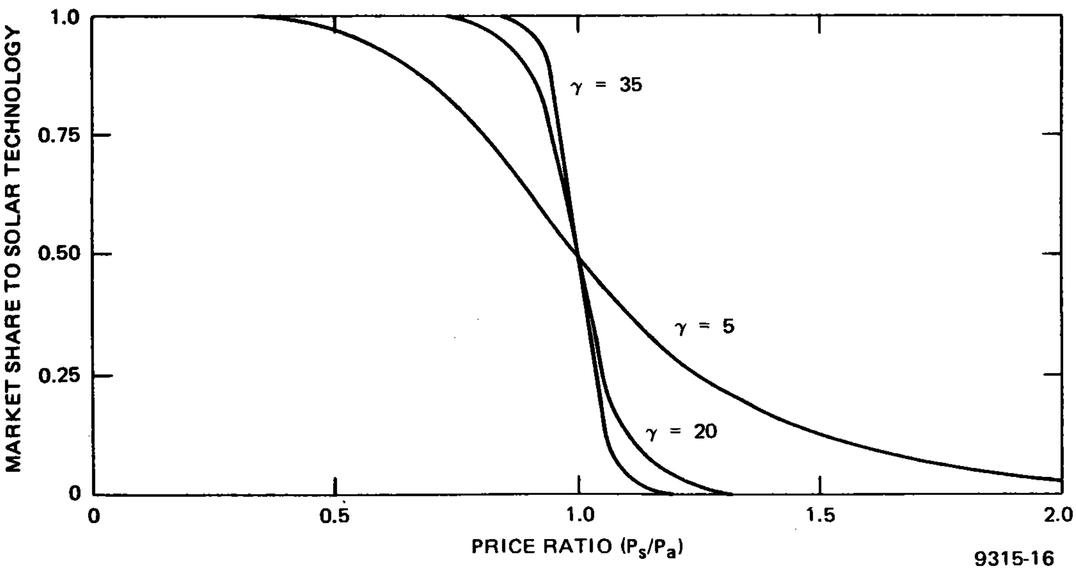

Figure 6-12. Steady-State Market Share

Steady-state market share to solar technology =

$$\frac{1}{1 + \left(\frac{P_s}{P_a}\right)^{\gamma}}$$

where P_s and P_a are the marginal prices of the solar energy product (such as solar-derived electricity) and the alternative (competing) energy product (such as coal-derived electricity), respectively. This static representation indicates that when P_s and P_a are equal and under steady-state conditions, the market will be shared equally. The market share parameter (γ) is a measure of market imperfections, price variations, and consumer preferences.

When two or more products are competing for a share of the same market as is the solar-derived product, a more general market share formula is used. For example, if N different competing technologies all produce the same product, then the solar market share is represented by the following equation:

$$\text{Steady-state solar market share} = \frac{1}{1 + \left(\frac{P_s}{P_{a1}}\right)^{\gamma} + \left(\frac{P_s}{P_{a2}}\right)^{\gamma} + \left(\frac{P_s}{P_{a3}}\right)^{\gamma} + \ldots + \left(\frac{P_s}{P_{aN}}\right)^{\gamma}}$$

where P_{a1} through P_{aN} represent the prices of the first through the Nth alternative (competing) products. If all of the prices P_{a1} through P_{aN} and P_s were equal, each product would receive 1/(N + 1) of the market.

In the static economic analysis, peformed here, representative prices for electricity generated by the hybrid solar system under different assumed conditions are compared to those from alternative energy sources. Actually, significant individual variations from these representative prices do exist. The market share parameter compensates for the fact that the analysis uses representative prices instead of price ranges.

The noneconomic behavior of marketplace decision-makers is another factor considered by the market share parameter. Even if a new technology is somewhat more expensive than the alternative, some fraction of purchasers will choose it, perhaps because of novelty, environmental reasons, or "energy independence" considerations. Alternatively, some fraction of purchasers will continue to use their familiar energy source even if economic considerations dictate a change to a new one. Imperfect price information is an additional factor that may cause a decision-maker to act in a noneconomic fashion.

In a perfect market with a high level of price sensitivity and none of these real world effects, γ would be infinite, and the energy product with even a very slight economic advantage would obtain a 100% steady-state market share. Such conditions do not describe real energy markets; instead, more realistic response patterns of various markets can be modeled by a suitable choice of γ. For example, large utility systems, such as those that might purchase a hybrid power plant, would generally be modeled with high γ values. These values reflect the strong response to price variations characteristically displayed by utility consumers who deal with large quantities of energy and are acutely aware of economic considerations. Much lower gamma values would be used to model smaller scale energy consumers who typically are influenced as much by personal values as by economics. Factors such as esthetics, convenience, and novelty may weigh more heavily with a residential than an industrial consumer.

Observations of utility purchase behavior indicate that within a single utility many choices such as coal purchase are highly responsive to price, i.e., the low bidder almost always wins even though his marginal advantage is very small. In this case, γ approaches infinity. Choices between different electric generating methods, other factors such as familiarity with equipment supliers, desire to have alternate fuels, and perceived attitudes of regulatory bodies may influence choices. The response parameter, γ, will decline from infinity to a high value of, say, 35. Finally, individual utility systems have different load demand patterns, mixes of existing generating capacity, and different regulatory bodies to which they must respond. Under these circumstances, the response is still broader. Since all utilities are strongly influenced by requirements to provide service at low cost, the demand parameter must still reflect this fact. As a practical matter, we have used a γ of 20 for this and other studies. With a γ of 20, a and a single competitive product, the hybrid fossil-solar unit would obtain a 90% equilibrium market share if the ratio of levelized bushbar costs P_s/P_a equalled 0.8959. Similarly, the hybrid fossil-solar plant would gain only 10% of the equilibrium market if the ratio, P_s/P_a, equalled 1.1162.

Typical equilibrium market shares for hybrids starting up in 1990 are presented in Table 6-18 under a number of assumptions. Included are variations in hybrid capital costs, insolation levels, and coal price escalation rates. The prices of electricity from hybrid and competing systems used to derive the values in Table 6-18 are shown in Table 2-3.

TABLE 6-18

PROJECTED EQUILIBRIUM MARKET SHARES FOR FOSSIL-SOLAR HYBRIDS
(No "Behavioral Lag" is Considered; 1990 Start-Up)

Intermediate Load (40% Capacity Factor)	Plant Capacity (MWe)	Equilibrium Market Share (% Captured in 1990)							
		8%/Yr coal price escalation				10%/Yr coal price escalation			
		Solar Insolation (kWh/m^2 day)				Solar Insolation (kWh/m^2 day)			
		4.5	5.5	6.5	7.5	4.5	5.5	6.5	7.5
Solar-Oil Hybrid, 1st plant cost	430	0.0	0.0	0.3	0.3	0.0	0.4	2.6	2.6
Solar-Oil Hybrid, Nth plant cost	430	0.3	3.7	29.9	29.9	2.3	23.0	76.9	76.9
Base Load (70% Capacity Factor)*									
Solar-Coal Hybrid, 1st plant cost	615	0.1	0.1	0.2	0.3	0.6	1.3	2.6	5.3
Solar-Coal Hybrid, Nth plant cost	615	1.4	2.7	5.4	10.6	9.0	17.9	33.2	54.1

NOTE: See Table 2-3 for the levelized busbar power costs used in deriving these equilibrium market shares.

* Nuclear power plants are not considered among the competing plant types.

The market shares associated with Nth plant hybrid capital costs do not represent realistic values for the 1990 time frame. The real competition in 1990 will be between a 1st hybrid unit and several more conventional types of electric generating systems. Unless the manufacturer or the government provides a discount or subsidy, the 1st hybrid unit will produce electricity at higher cost than the Nth plant and will consequently receive a lower equilibrium market share, as shown in Table 6-18. As HTLF units are installed, the price of electricity produced from them will fall in constant dollar terms, until Nth plant conditions are reached, and the equilibrium market share will increase until that time.

At the introduction of the hybrid system, and perhaps for some time thereafter, customer unfamiliarity and other market restraints will inhibit purchase of the "new" hybrid system. These factors influence the rate at which actual sales approach the equilibrium market condition (market penetration). Full delineation of markets as a function of time will be based on successive steps from the 1st to the Nth plant costs and on other market factors.

6.4 MARKET PENETRATION

6.4.1 Introduction

The adoption of hybrid solar central station power systems will be influenced by both real and perceived impediments. These impediments can require plant modification leading to higher capital and/or operating costs which reduce the market share. Such real impediments are reflected in the calculations discussed in the previous section. Alternately, they can result in institutional adjustments required by siting, regulatory or other difficulties that affect the purchasing utility's willingness to buy. This change in willingness would be reflected in the rate at which the market is penetrated.

While newness of the technology, siting problems, etc. may be viewed as impediments, other aspects of solar plant use may be viewed as incentives. For example, at present, a utility adapting solar technology is likely to gain in image among its customers — it is using what is popularly identified as a renewable and benign technology. Such positive factors will create a willingness to purchase that which will also be reflected in the rate of market penetration.

TABLE 6-19
SOLAR THERMAL POWER POWER SYSTEM ENVIRONMENTAL ISSUES
AND RESPECTIVE IMPACT AREAS

ISSUE		AIR QUALITY	WATER QUALITY	LAND USE / SOLID WASTE	ECOLOGICAL IMPACTS	HEALTH & SAFETY	ESTHETICS	SOCIAL / INSTITUTIONAL	RESOURCES
HANDLING AND DISPOSAL OF SYSTEM FLUIDS AND WASTES	(U)	X	X	X	X	X			
COOLING TOWER IMPACTS	(U)	X			X		X		X
COLLECTOR GLASS BREAKAGE	(U,M)					X			
ECOLOGICAL IMPACTS OF THE HELIOSTAT FIELD	(U)		X	X	X		X		
AUXILARY UNIT EMISSIONS/RESIDUALS	(U)	X	X	X	X				
POTABLE WATER CONTAMINATION	(U)		X			X			
SYSTEM MAINTENANCE	(U)		X		X	X			
HELIOSTAT REFLECTION	(U)				X	X	X		
WATER USE	(U)				X				X
ALTERATION OF THE MICROCLIMATE	(U)	X			X		X	X	
SYSTEM COMPONENTS MANUFACTURE	(M)					X			X
RECEIVER TOWER IMPACTS	(U)				X	X	X		
BOOM TOWN EFFECTS	(U)	X	X	X				X	X
LAND DISPLACEMENT	(U)			X	X		X	X	X
CONSUMER-UTILITY INTERFACE	(U)							X	
ZONING/BUILDING CODES	(U)						X	X	
SITE RECOVERY AFTER PLANT SHUTDOWN	(U)			X	X		X	X	
COMPONENT QUALITY ASSURANCE AND REGULATION	(U,M)					X		X	
NOISE (TURBINES - COOLING TOWERS)	(U)						X		

KEY

X = DENOTES IMPACT AREA
M = IMPACT ARISING FROM MANUFACTURING PROCESS
U = IMPACT OCCURRING AS A RESULT OF SYSTEM USE

Some market share and market penetration are estimated in other parts of this study. A brief examination of some of the factors that could influence share and/or penetration is in order.

6.4.2 Environmental Impacts

Among the more important of these factors are those dealing with the environment. In the following pages a discussion of potential environmental impacts is presented to provide background to judgments made regarding the parameters chosen for market share or penetration rate calculations. A second purpose of this discussion is to alert developers to potential problem areas.

Even though there are potential environmental impacts expected from installation of hybrid solar power units, these impacts are expected to be tolerable. In many cases they will be less than impacts from other power producing units. It is only in land use that hybrid solar units exceed the impacts of other power producers. Studies have shown that there is ample land and so this effect should not impair the use of the hybrid solar concept.

6.4.2.1 Objective – General Impacts

Since the effects of a solar hybrid power plant have never been tested in actual operation, it is not possible to quantify impacts with any certainty. Therefore, the following discussion treats impacts generically.

Factors normally considered include: siting (land, water, vegetation, proximity to urban areas, rail lines, power lines), impacts on micro-climate, air and water quality, impacts on local ecosystems, health and safety implications for employees and the public, and social and institutional impacts (federal, state, and local). Because of time and cost constraints this report considers only environmental impacts, excluding health and safety and social and institutional impacts. These latter will be much the same whatever power plant is built.

Impacts, for the most part, are related to desert environments, as these are the most likely sites in the near term. In areas with less than optimum amount of direct solar insolation, much larger land areas would be required to accommodate many more heliostats to produce the same amount of energy. In different environments, the impacts and their magnitude would be somewhat different. These factors are shown in an expanded but schematic form in Table 6-19.

6.4.2.2 Description of Plant

The basic unit considered here will be capable of producing 100 MW net electrical output from the solar system alone, from the fossil fuel component alone, or from the combined output of the solar and fossil fuel components.*

The system will meet all applicable codes and regulations. It is expected that the fossil fuel component will be run at a minimum 20% capacity even during period of high insolation. During the night, and those daylight hours with insufficient insolation to generate the required amount of solar energy, the coal component would run to as much as 100% of capacity. The output from the plant will be fed directly into an electric utility power grid.

Solar Thermal Electric (STE) System

The basic STE components (0.8 SM) will cover a square mile $2.59 \times 10^6 m^2$ of land at a minimum. It will have a field of 8460(3-3) heliostats with a field receiver power ratio (FRPR) of 1.05. The total mirror area will be 414,540 m^2 or 23% of the total field area. These heliostats will reflect incident solar radiation to the surface of a receiver, atop a 450 ft (137 m) tower located south of the field's midpoint. Liquid sodium will circulate in a closed cycle through receiver panels, and by absorbing heat from the receiver surface, will reach a temperature of 1100^oF (593^oC). This heat will convert water into steam to operate Rankine cycle turbines. These will in turn supply electric power generators with steam at 1000^oF (538^oC) to produce electricity at 43.4% cycle efficiency. The electricity will then be fed directly into a utility power grid. Heat rejection will be accomplished by evaporating wet cooling. The solar system will have minimal (3 h) storage, using the liquid sodium working fluid as the storage medium.

Fossil Fuel System

The fossil fuel system will be operated in parallel with the solar system. It is assumed that typical sub-bituminous coal would be the feedstock. Coal

*The analysis reported here was conducted early in the project. It focused on the requirements of a 100 MW coal-solar hybrid. The conclusions drawn are generally valid for the larger fossil-solar systems described in other sections.

would be pulverized and fed directly into the boiler from the pulverizer at a rate of 46 tons per hour at full power for coal only operation. [Heat input will be 10^9 Btu/h, yearly coal requirements for base (70% CF) and intermediate coal plants (40% CF) would be 190,000 and 69,000 tons, when the solar contributions available at the Barstow site are included.]

(In the least favorable solar insolation locations, the plant will burn ∿300,000 tons of coal each year, or about 820 tons of coal per day.) The fossil fuel stack will be located inside the receiver tower (to ensure that it does not interfere with the optical path between heliostats and the receiver tower). The combustion gases will travel through a heat exchange system to transfer heat to the liquid sodium.

Most of the coal system will be located within the plant area immediately surrounding the receiver tower. Thus, much of the coal subsystem will not require additional land. However, some facilities including the railroad spur for coal delivery, the coal unloading and storage area, fuel oil storage,* — evaporative ponds, and cooling towers will be outside the perimeter of the heliostat field. (Additional land also will be required in the plant vicinity for power transmission lines and access roads.)

The "design basis coal" recommended by the Salt River project personnel has the characteristics shown in Table 6-20. Any emissions estimates will be based upon these figures.

The plant will utilize a regenerative scrubbing system with an SO_x removal efficiency of 85 to 95%. A fabric filter (99.5% of removal efficiency) will be used to control fly ash.

If ∿90% of the sulfur is emitted from coal and 75% of ash is released to the stacks, the reference plant would emit a maximum of 150 tons SO_x and 90 tons of ash to the atmosphere annually. The exact scrubbing process has not been specified, but raw material requirements and waste streams are expected to be low. Fly and bottom ash combined would be the largest solid waste stream at 25,000 tons per year.

*Oil igniters are used to initiate combustion of the produced coal.

TABLE 6-20

DESIGN BASIS COAL[(3-3)]

(Sheet 1 of 2)

		Average	Range
Proximate Analysis			
Moisture		14.5	9.5 - 18.0
Volatile Matter		36.3	34.0 - 38.0
Fixed Carbon		36.7	32.0 - 41.5
Ash		12.5	9.0 - 18.0
Btu		10,000	9,000 - 10,800
Ultimate Analysis			
Moisture		14.5	9.5 - 18.0
Carbon		55.8	50.5 - 60.5
Hydrogen		4.2	3.9 - 4.8
Oxygen		11.5	10.0 - 13.5
Nitrogen		0.9	0.7 - 1.0
Sulfur		0.6	0.4 - 1.0
Ash		12.5	9.0 - 18.0
Chlorine		0.03	0.01 - 0.04
Ash Analysis			
Phosphorous Pentoxide	P_2O_5	0.08	0.05 - 0.12
Silica	SiO_2	57.78	47.50 -63.00
Ferric Oxide	Fe_2O_3	6.21	3.90 - 7.90
Alumina	Al_2O_3	21.64	19.00 -14.30
Titania	TiO_2	1.19	0.70 - 1.30
Lime	CaO	4.39	4.10 - 8.10
Magnesia	MgO	1.14	1.00 - 1.60
Sulfur Trioxide	SO_3	4.33	3.90 - 7.20
Potassium Oxide	K_2O	0.52	0.30 - 0.60
Sodium Oxide	Na_2O	1.78	0.40 - 2.10
Undetermined		0.34	

TABLE 6-20

DESIGN BASIS COAL(3-3)

(Sheet 2 of 2)

	Average	Range
Sulfur Forms		
Pyritic	0.2	0.1 - 0.7
Sulfate	0.0	0.0 - 0.2
Organic	0.4	0.2 - 0.8
Water Soluble Alkalies		
Na_2O_4	0.036	0.016-0.079
K_2O	0.003	0.000-0.007
Silica Value	82.4	74.0-92.4

Interface

The system will be run in a parallel configuration and be controlled through a master control unit, using a central computer, in combination with the required peripheral equipment and software, to monitor and control the subsystem interfaces and overall system operation during normal operating modes and transient conditions.

6.5 MARKET PENETRATION METHODOLOGY

The market share curve in Figure 6-12 is only a static representation of a market. To assess the dynamics of market penetration, a "dynamic market response curve" can be used to describe how fast the current market will move toward the static price-determined market share curve as a result of real world behavioral response. This is called the behavioral lag effect.

The dynamic market response curve, given by:

$$\frac{1}{1 + \left(\frac{h}{n}\right)^{\alpha}}$$

is shown in Figure 6-13 where

h = behavioral lag half-life (time required for one-half of the market to respond to the entrance of a new technology)

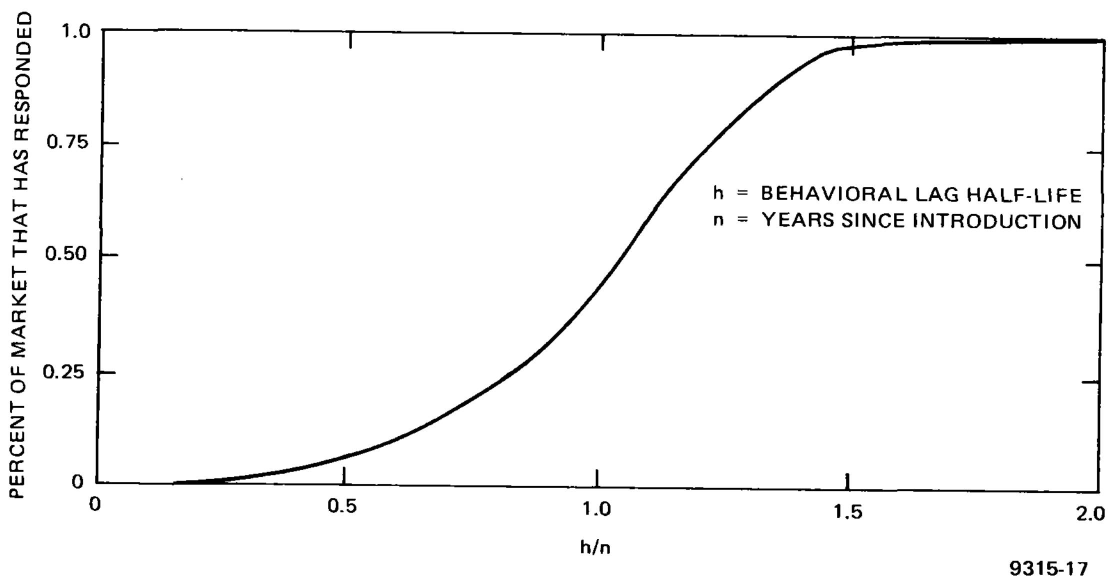

Figure 6-13. Dynamic Market Response

n = years since introduction of new technology

α = behavioral lag response parameter.

This curve tends to slow the introduction of a new technology based on the time that it takes for decision-makers to accept and switch to new energy sources, especially those that are based on unfamiliar technologies.

The behavioral lag parameters, h and α, provide a means of quantifying the dynamic market response. The half-life, h, defines the number of years that it would take for 50% of the market to respond to the introduction of the new technology. The second behavioral lag parameter, α, fixes the relative shape (curvature) of the dynamic market response curve once the half-life parameter has been chosen.

The parameters chosen should be representative of past actions of specific industries, in this case the electric utility industry. Modifications of parameters to reflect system differences of impediments should not be necessary for investigations of hybrid systems. As discussed above, the environmental and materials impediments are minimal. The system can be operated at all times regardless of weather and no capacity loss penalty need be imposed. The values of h and α used, namely 10 and 4 are those used in previous studies of solar central-station electric markets.*

To find the share of the open market captured by the solar technology in any particular year, the equilibrium market share and dynamic market response curves are multiplied. This results in a dynamic market share for the solar technology that varies with time. This response is depicted by Figure 6-14. For given price ratios such as shown by A or B on the curve to the left, there is an associated equilibrium market share as denoted by the dotted lines. These depict the ultimate market shares that would eventually be achieved if the price ratios were to remain constant. Curves A and B on the right in Figure 6-14 demonstrate the behavioral lag effect that delays the introduction of new technologies. Curve A, for example, presents the dynamic market share as a function of the time following commercial introduction. It rises from zero to a maximum of about 28% as the new technology becomes known to larger portions of the market.

*J. Witwer et al., "A Comparative Evaluation of Solar Technologies: Implications for Federal R&D," SRI Project 6375, January 1978.

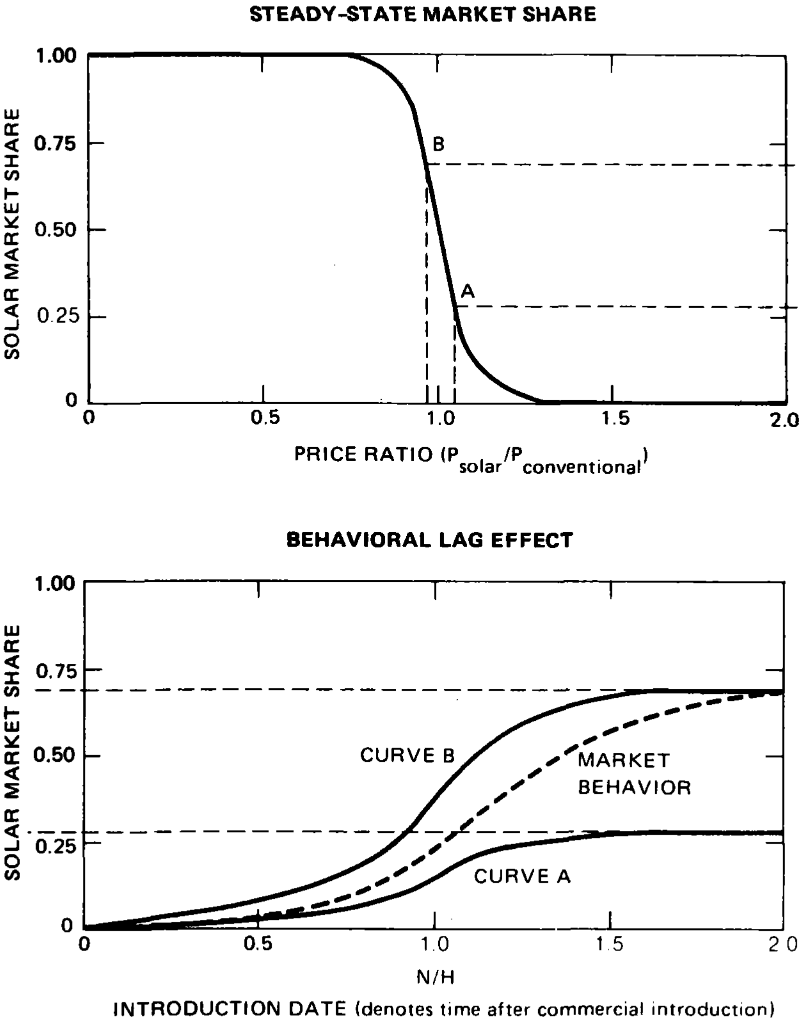

Figure 6-14. Calculation of Dynamic Market Share

In general, the price ratio, P solar/P conventional, does not remain constant. It can be expected that this ratio will decline as fossil-fuel prices increase and as learning effects decrease solar costs. This learning effect is taken into account by assuming that the hybrid plant capital costs vary as a function of the number of plants constructed. As shown in Table 2-2, decreases of ∿21% are assumed to occur between the 1st and Nth plants constructed. In our market penetration analysis, we have assumed that a smooth transition from 1st to Nth plant costs takes place as a function of time according to the following equation:

$$\text{Cost }(t) = \text{cost }(1\text{st}) \left[TCL + (1 - TCL)e^{-(t \cdot TCR)}\right]$$

where

Cost (t) is the hybrid capital cost at time t (t is measured in years following year of first plant construction).

Cost (1st) is the capital cost of the 1st hybrid plant.

TCL is the ratio of the ultimately achievable (lowest) capital cost to the 1st plant cost.

TCR denotes the rate at which the ultimately achievable cost is approached.

Due to the fact that the price ratio of P solar/P conventional will decrease with time, a movement from point A to point B on the curve to the left in Figure 6-14 could represent a real situation. In this case, the actual dynamic market share curve would be between curves A and B on the right in this figure. This curve, labelled "market behavior" starts out identically to curve A and then rises to meet curve B with time.

Once the dynamic market share (or "market behavior") curve has been determined, the hybrid system demand is found by applying this curve, in time steps, to estimates of the market size that open up to capture.

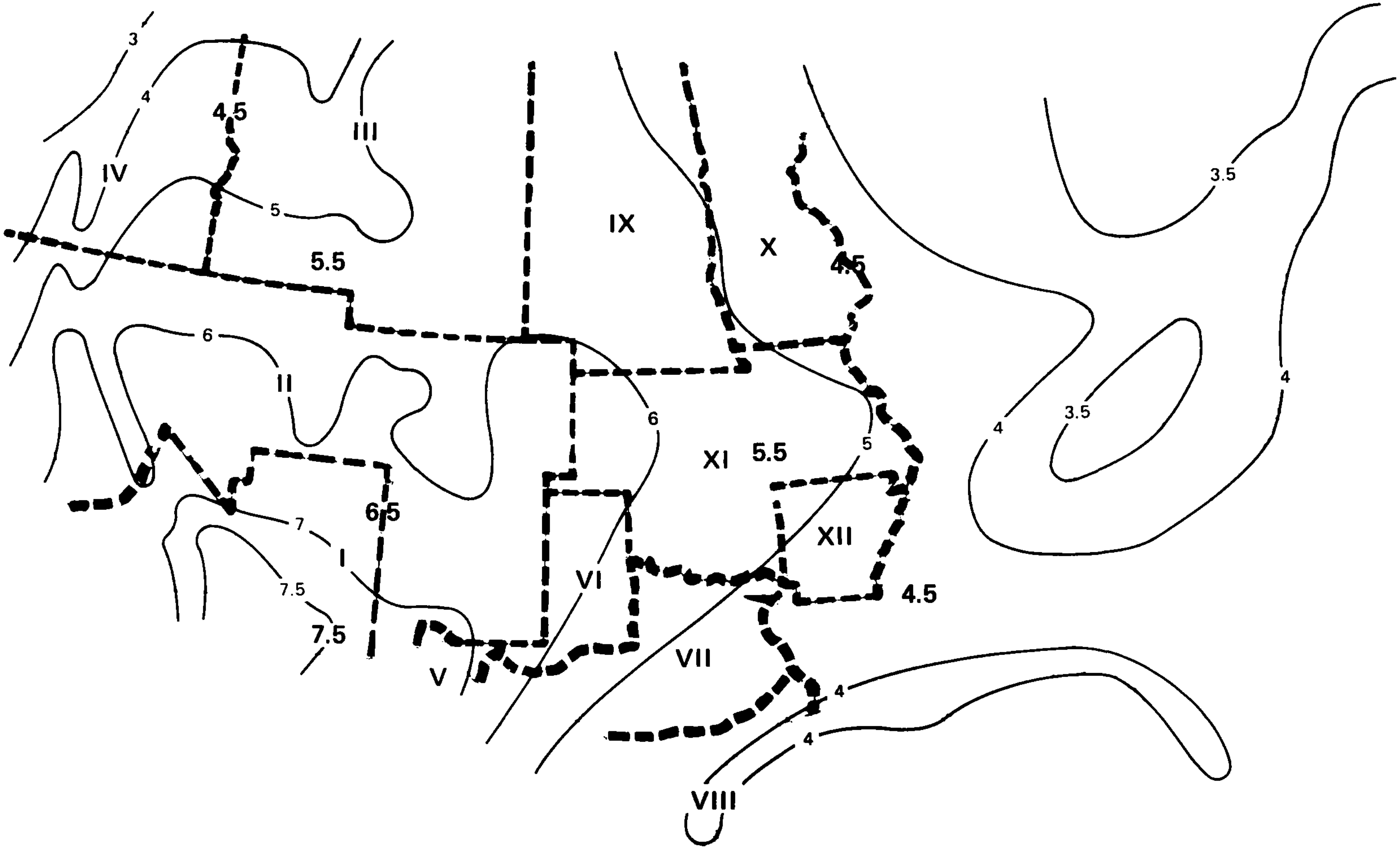

Figure 6-15. U.S. Solar Insolation Regions (Direct Normal Insolation in kWh/m^2 day)

6.6 MARKET PENETRATION ASSUMPTIONS AND RESULTS

In performing long-term assessments for the marketability of power generation equipment, it is impossible to escape the conclusion that penetration results are highly sensitive to a number of important parameters. This is clearly demonstrated by the wide variations in the equilibrium market share shown in Table 6-18. Those shares ranged from zero to more than 75%, depending upon solar insolation levels and the assumptions made about hybrid capital costs and the future fuel costs for hybrid's major competitor, coal-fired power generation. Since a large degree of uncertainty surrounds almost any long-term cost projection, market penetration results based upon such projections are necessarily speculative. As a result, sensitivity analyses were performed to measure the response of the market to variations in coal price escalation rates.

This section presents the results of the hybrid market penetration analysis as a function of five time periods (1990, 1995, 2000, 2005, and 2010) and twelve regions that were developed by roughly grouping utilities according to solar insolation level. (These regions are depicted by Figure 6-15.)

The hybrid unit sizes and costs used in the analysis were selected by Rockwell. Rockwell also suggested some of the combinations of presumably competive systems used in the final comparisons. The interpretation of results is that of SRI.

Three separate cases have been considered in the final market penetration analyses (see Table 6-21). The first deals with the marketability of the 430 MW solar-oil hybrid with storage in intermediate load service. It has been assumed that the major competition this hybrid will face consists of coal and oil-fired steam-cycle power plants of $\sim$400 MW capacity, and smaller oil-fired combined cycle facilities in the size range of 200 to 250 MW.*

The second and third cases consider the market penetration of the 615 MW solar-coal hybrid into the base load power market. The differences between these cases are based on the competion that the hybrid is assumed to face. The major

*The economic parameters assumed for these facilities are presented in Table 2-2.

TABLE 6-21

SUMMARY OF CASES EMPLOYED IN THE HYBRID MARKET PENETRATION ANALYSIS

Case	Load Category	Hybrid Plant Considered	Major Non-Solar Competition	Hybrid Capital Cost Assumptions
I	Intermediate	430 MW Solar-Oil Hybrid	400 MW Coal/Steam 400 MW Oil/Steam 250 MW Oil/Combined - Cycle	A) 1st plant costs in 1990 decreasing to Nth plant costs
II	Base	615 MW Solar-Coal Hybrid	1000 MW Coal/Steam 1000 MW Coal/Combined-Cycle	A) 1st plant costs in 1990 decreasing to Nth plant costs B) Nth plant costs throughout study period C) Average of 1st and Nth plant costs in 1990 decreasing to Nth plant costs
III	Base	615 MW Solar-Coal Hybrid	400 MW Coal/Steam	A), B), and C) Same as above

competition in case II consists of large coal-fired power plants. Specifically, 1000 MW steam-cycle and combined-cyle systems were assumed to be representative.*

In case III, it is assumed that the historical trend toward larger coal fired plants is reversed in favor of smaller units. As a result, the major competitor in this case is a 400 MW coal fired steam cycle facility, identical to the one that forms a part of the competition in case I.

Nuclear power plants were not included as competitors in any of the three cases considered. Based on current economic comparisons, these systems could be very important competitors in the base load market because they provide power less expensively than do the large coal-fired plants or solar hybrids in many regions of the country.

We wish to note that although most analyses over the past years, including ours, have indicated a notable cost advantage to the large nuclear fueled units, the rate of actual market penetration has lagged behind theoretical projections. As the future of nuclear power remains uncertain, it is necessary to consider what might happen in its absence. Also, it is possible that substantive charges will be required in the design and operation of nuclear power and fuel cycle plants in order to meet new safety requirements. Such changes could negatively affect both the economics of nuclear energy and the utility outlook for the purchase of nuclear plants during the 1990 to 2010 time frame of this analysis.

As discussed previously, a basic assumption employed in this assessment is that hybrid capital costs are reduced as the number of installed units increases. A prototype facility is assumed to demonstrate the feasibility of the hybrid concept around 1990 and in the basic analyses 1st plant costs are considered for this time frame. As more plants are completed, the hybrid capital costs eventually decrease to Nth plant costs, assuming sufficient market penetration is achieved within the time frame of the analysis. This assumption has been modified for two sensitivity calculations that were applied to both cases II and III. The details of these analyses are discussed in Section 6.6.

*The economic parameters assumed for these facilities are presented in Table 2-2.

TABLE 6-22

SOLAR-OIL HYBRID UNITS IN INTERMEDIATE LOAD SERVICE AS FUNCTION OF TIME

CASE I COMPETITION. COAL BASE COST $1.40/MM BTU, ESCALATION AT 10%

Region	1990	1995	2000	2005	2010
1	0	0	4	11	20
2	0	0	4	9	17
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	1	2
6	0	0	1	4	8
7	0	0	0	0	1
8	0	0	0	0	0
9	0	0	0	0	1
10	0	0	0	0	0
11	0	0	0	2	4
12	0	0	0	0	0
Total in Service	0	0	9	27	53
Installed in Interval	0	0	9	18	36

The Case I (intermediate load) analysis indicates no penetration of markets by 2010 if the coal costs are $1.40 per million Btu and the coal price escalation rate is 8%. At a 10% escalation rate, 9 units are in place in 2000; the Nth unit is placed on line about 2007; and 53 units are in service by 2010. This is indicated in Table 6-22.

Base load markets for the hybrid system considered are more or less favorable than the intermediate load application depending on the competition assumed. If the fossil only competition includes large coal units as in Case II, the results are not favorable. For Case II and at an assumed 8% coal price escalation, no units would be placed in service. At 10% ($1.40 per million Btu 1979 base price), one unit would be in operation by 2000, 3 units by 2005 and a maximum of 8 units by 2010 (see Table 6-23). Nth plant conditions would not be reached until some time after 2020.

If new coal only units were restricted to 400 MW size and if an 8% annual coal price escalation rate prevails, then only a very few 615 MW (SM = 1.0) units without storage would be purchased by 2010. (The first commercial unit would come on line after 2000 and no more than 5 would be in service by 2010.) At a 10% coal price escalation rate, the situation improves as shown in Table 6-24. The first commercial unit would go on line in 1996. Nth plant costs would apply for units installed in 2006 and 13 and 57 units would be on line in 2000 and 2010, respectively.

The demand for electricity and thus the market for hybrid units in Texas (Regions 6, 7, and 8) is potentially very large. The actual penetration of this market will depend on the areas in which units are sited. Demand is heaviest in eastern Texas, but that area's poor insolation will negatively affect the economics of using solar energy. Siting in western Texas will improve generation economics but complicate the transmission problems. Without consideration of this transmission possibility, the analysis shows that the large potential market of eastern Texas (Region 8) has smaller numbers of installed hybrid units than does western Texas (Region 6) with a smaller overall demand.

Actual markets for solar hybrid systems in the eastern United States are expected to be small because of the generally poorer insolation conditions and thus higher costs of solar electric power. Only extremely high coal prices would result in significant market penetration in these areas.

TABLE 6-23

SOLAR COAL HYBRID UNITS IN BASE LOAD SERVICE AS A FUNCTION OF TIME

Case II Competition. Coal Base Cost $1.40/MMBtu, Escalation at 10%

Region	1990	1995	2000	2005	2010
1	0	0	1	2	5
2	0	0	0	1	1
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	1
7	0	0	0	0	0
8	0	0	0	0	1
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
Total in Service	0	0	1	3	8
Installed in Interval					

TABLE 6-24

SOLAR COAL HYBRID UNITS IN BASE LOAD SERVICE AS A FUNCTION OF TIME

Case III Competition. Coal Base Cost $1.40/MMBtu, Escalation at 10%

Region	1990	1995	2000	2005	2010
1	0	0	4	9	14
2	0	0	2	5	7
3	0	0	0	0	1
4	0	0	0	0	0
5	0	0	0	0	1
6	0	0	2	4	7
7	0	0	0	1	2
8	0	0	5	11	19
9	0	0	0	0	1
10	0	0	0	0	0
11	0	0	0	1	2
12	0	0	0	2	3
Total in Service	0	0	13	33	57
Installed in Interval					

TABLE 6-25

IMPACT OF CHANGE IN EFFECTIVE COST OF EARLY UNITS FOR SOLAR HYBRID BASE LOAD MARKETS

1st unit Case II competition costs reduced. Nth unit costs unchanged. Coal price $1.40. Coal escalation 10%.

	Installed Units								
	Full 1st to Nth			Reduced 1st to Nth			Nth Only		
Region	2000	2005	2010	2000	2005	2010	2000	2005	2010
1	1	2	5	2	4	7	3	6	9
2	0	0	1	0	1	3	1	2	3
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	1	0	1	2	1	1	3
7	0	0	0	0	0	0	0	0	0
8	0	0	1	0	1	2	1	2	3
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
	1	2	8	2	7	14	6	11	18

6.7 EFFECT OF MARKET ASSISTANCE PROGRAMS

Under several assumed combinations of fossil fuel prices and coal price escalations, the hybrid solar systems do not compete well with more conventional forms of electric generation. In some of these instances the dominant factor seems to be the high capital cost of the 1st commercial unit. With its high cost (21% above Nth unit cost), it does not gain a significant market share and thus the capital cost moves too slowly toward Nth unit conditions.

This condition could be overcome if special market assistance were available. For example, suppliers could offer special price incentives (as was done in the use of fixed price contracts for early nuclear units). Also, the government could subsidize the unit in ways that would effectively place the first unit costs at or near those for the Nth unit.

The effect of subsidy that makes Nth unit costs available to the 1st unit is shown in Table 6-25 which compares expected penetration under non-subsidy conditions with those involving subsidy. The section headed Nth only describes the condition in which the effective subsidy, from manufacturers or government, reduces the cost of 1st and subsequent units to the Nth unit cost. The markets under partial subsidy, i.e. one that reduces the normal capital cost differential between the 1st and Nth units by 50% for the first unit followed by similar adjustments for each successive unit sale are described under the heading "Reduced 1st to Nth." Markets for normal conditions are indicated under the heading "Full 1st to Nth."

As Table 6-25 indicates a situation which apparently offers no opportunity to coal solar hybrid systems in base load applications is changed, and from 14 to 18 units, instead of 8, would enter service by 2010. An important market (and perhaps policy) factor is the prediction of a relatively rapid move into the market in the period before 2005. With assistance, 7 to 11 units could be operating instead of the 2 units projected under normal conditions.

Similar effects are shown in Tables 6-26 and 6-27. In these tables, the impact of effective capital costs reduction (subsidy) is shown for Case III (small coal only) competition at 8% and 10% coal price escalations. The influence of subsidy is shown in the much more rapid introduction of solar units under the 8% escalation assumption. At 10% coal price escalation, the unit is already competetive at an early date and the subsidy has little influence.

TABLE 6-26

IMPACT OF CHANGE IN EFFECTIVE COST OF EARLY UNITS ON SOLAR HYBRID BASE LOAD MARKETS

1st Unit Costs Reduced. Nth unit costs unchanged. Case III Competition. Coal price $1.40. Coal price escalation 8%.

Region	Installed Units								
	Full 1st to Nth			Reduced 1st to Nth			Nth only		
	2000	2005	2010	2000	2005	2010	2000	2005	2010
1	1	2	3	2	3	5	3	5	8
2	0	0	1	0	1	3	1	2	3
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	1	0	1	2	1	2	3
7	0	0	0	0	0	0	0	0	0
8	0	0	2	0	1	3	2	4	5
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
Total	1	2	7	2	6	13	7	13	19

IMPACT OF CHANGE IN EFFECTIVE COST OF EARLY UNITS ON SOLAR HYBRID BASE LOAD MARKETS

1st unit costs reduced. Nth unit costs unchanged. Case III Competition. Coal price $1.40. Coal price escalation 10%.

	Installed Units								
	Full 1st to Nth			Reduced 1st to Nth			Nth Only		
Region	2000	2005	2010	2000	2005	2010	2000	2005	2010
1	4	9	14	5	9	14	5	9	14
2	2	5	7	2	5	8	3	5	8
3	0	0	1	0	0	1	0	0	1
4	0	0	0	0	0	0	0	0	0
5	0	0	1	0	0	1	0	0	1
6	2	4	7	2	4	7	2	4	7
7	0	1	2	0	1	2	0	1	2
8	5	11	19	6	12	21	7	14	22
9	0	0	1	0	0	1	0	0	1
10	0	0	0	0	0	0	0	0	0
11	0	1	2	0	1	2	0	1	2
12	0	2	3	1	2	3	1	2	3
Total	13	33	57	16	34	60	18	36	61

In the intermediate load market, changes similar to those shown in Table 6-26 are expected. There will be some acceleration in the number of units in service.

Market assistance could be an important factor in solar system use and energy savings.

6.8 SUMMARY OF SOLAR HYBRID MARKETS

The prospective markets for fossil-solar hybrid systems are speculative. In practice, they will depend on reduced capital costs achieved through design and manufacturing but also, and perhaps more heavily, on the prices of competitive fuels. Nuclear fuels and nuclear-based electricity are currently much less costly and effectively exclude higher priced fossil fuels and solar units from baseload markets. If the nuclear units are excluded, the coal-solar hybrid unit would be very competitive with smaller coal units at nominal prices ($1.40 per million Btu and 8% coal price escalation). If the coal-Solar hybrid is forced to compete with large coal only units, higher coal prices or initial manufacturer or government subsidy could be required before the units will effectively reach the market early in the 21st century.

In intermediate load markets, nuclear power is not a factor. Instead, the major competition facing hybrid units would consists of moderate size (250 to 400 MW) fossil-fired units. At the expected coal and oil price 8% and 10% per year, the 430 MW coal-oil hybrid would not be likely to compete well against these plants. In particular, 400 MW coal-fired units present a less expensive alternative. At the higher coal price escalation rate of 10% per year, however, significant market penetration is projected to occur, with as many as 53 intermediate load hybrid units being installed by 2010.

Under all assumed conditions, the earliest and largest hybrid market penetration occurs in the Southwestern U.S. which has the highest solar insolation levels in the nation. In particular, it appears very likely that the large electricity demands of Southern California, fed by commercial solar-fossil hybrids located near the Arizona-California border, will be the first to be served.

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