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Acurex Project 6176

MODULAR SOLAR THERMAL COLLECTOR FIELD SYSTEM

Prepared by
M. Matteo, M. Ordona, B. Villanueva, and K. Yasuda
Acurex Corporation
Alternate Energy Division
485 Clyde Avenue
Mountain View, California 94042

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ACUREX FINAL REPORT FR-80-15/AE

Prepared for
Sandia Laboratories
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ABSTRACT

Acurex Corporation, under contract to Sandia Laboratories, has developed a preliminary design of a modular solar thermal collector field system to generate saturated steam at 827 kPa (120 psia) and 172°C (342°F). The collector field consists of 4818 m^2 (51840 ft^2) of parabolic trough line focusing modules with FEK reflective surfaces. Modular features have been introduced throughout the system in the form of standardized components, skid-mounted assemblies, prefabricated and preassembled items, and a simple field layout. These features will reduce system costs by reducing engineering, hardware, and construction costs and also improve reliability.

System performance has been determined for three site locations for both north-south and east-west collector field orientations. In addition, costs were estimated for various numbers of systems.

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ABSTRACT

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SECTION 1

EXECUTIVE SUMMARY

1.1 INTRODUCTION

Modularity in solar thermal systems has the potential to reduce system costs by reducing or eliminating much of the engineering cost, to reduce component cost by increasing production, and to improve reliability by having standardized systems.

To promote the modularity concept Acurex was awarded a contract by Sandia Laboratories, Albuquerque, to develop a preliminary design of a solar thermal system that would consist of parabolic trough collectors with a nominal field aperture area of 5,000 m^2 (~54,000 ft^2) and would generate saturated steam at 827 kPa (120 psia) and 172°C (342°F). Emphasis was to be placed on making the system modular while still satisfying the design characteristics and considerations outlined in the Statement of Work. In addition, estimates of performance were to be made for three site locations (Albuquerque, New Mexico; Bismarck, North Dakota; and Charleston, South Carolina) for both north-south and east-west field orientations. Finally, estimates of cost were to be made for systems in lots of 1 to 10, 10 to 100, and 100 to 1,000.

The remainder of this Executive Summary will describe the selected system, discuss the more salient trade-offs, identify the major modular features, and summarize the performance and cost estimates.

1.2 SYSTEM DESCRIPTION

The system selected comprises a collector field made up of 4818 m^2 (51,840 ft^2) of Acurex parabolic trough line focusing modules with FEK reflective surfaces, packaged unfired steam generator, a feedwater pump, a collector field pump, and a small expansion tank. Heat transfer oil is used as the working fluid. The relationship of these components and the principle of system operation are illustrated in the schematic of Figure 1.

The collector field consists of 18 rows of collectors. Each row contains four groups of 12 10-ft long modules, and each group is equipped with a drive unit and tracker. The supply manifold borders one edge of the field and the return manifold the other. The heat transfer oil is Therminol 55, a Monsanto product having the required thermal stability and viscosity properties. A centrifugal pump circulates the oil through the field and steam generator at a constant rate. The expansion tank is vented to the atmosphere and accommodates the thermal expansion of the oil. A centrifugal feedwater pump provides makeup water as steam is generated. A summary of the major equipment is given in Table 1.

The control system includes only that instrumentation required to operate the system unmanned and protect it against damage from high winds or equipment malfunction. Control functions are discussed in Section 2.2.3. As allowed by the Statement of Work, a data acquisition system has not been included, except as necessary for control and operations.

1.3 SYSTEM TRADE-OFFS

The system selected was arrived at after comparing performance, simplicity, safety, and cost of various options. The major alternatives were: (1) water or oil as the working fluid, (2) a flash boiler or an

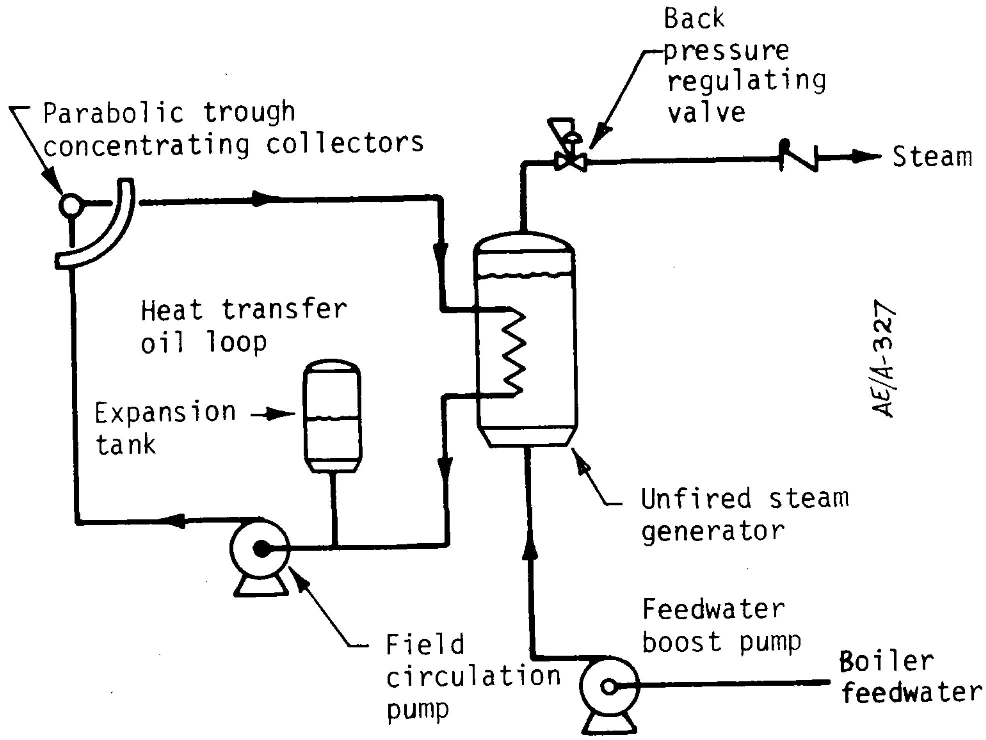


Figure 1. Modular Solar Thermal Collector Field System Schematic

Table 1. Major Equipment Summary

Collectors	
Type	Line focusing parabolic trough
Reflective surface	FEK
Total aperture area	4,818 m^2 (51,840 ft^2)
Unfired Steam Generator	
Capacity	2,900 kW
Heat transfer area	110 m^2 (1,180 ft^2)
Expansion Tank	
Type	Atmospherically vented
Volume	5.7 m^3 (1,500 gal)
Field Pump	
Type	Centrifugal
Capacity	0.017 m^3/sec (270 gpm)
Motor size	18.7 kW (25 hp)
Feedwater Pump	
Type	Centrifugal
Capacity	0.001 m^3/sec (19 gpm)
Motor size	1.1 kW (1.5 hp)
Emergency Generator	
Size	45 kW (480 volt/three phase/60 Hz)
Type	Natural gas

unfired steam generator, (3) constant flow (variable outlet temperature) or variable flow (constant outlet temperature) through the collector field. Details of these trade-offs are discussed in Section 2.3, but the principal advantages of the chosen system are:

- Low pressure in the collector field
- Low parasitic power consumption

- Simplicity -- freeze protection not required
- Commercially available components

These factors make for a simple, reliable, and cost effective system that is readily adaptable to modularity.

In locations where freeze protection is not required water could easily be substituted for oil without changing the fundamental design, but the operating pressure would increase markedly.

Perhaps the greatest concern with an oil system is the potential for fire. Safety was stressed in choosing the working fluid. Much has been learned about the design and operation of oil systems from the Willard and Coolidge solar facilities, and these lessons (use welded fittings, keep pump bearings cool, have extinguishers standing by, and others) have been incorporated into the design.

1.4 MODULARITY

With the baseline design established emphasis was placed on making the system modular. The approach was to examine all of the system components and determine which could be procured as standard items, where prefabrication or preassembly could be used, and how the design could be altered to more readily accept modular components. Some examples of modularity are: (1) off-the-shelf and skid-mounted pumps, (2) a packaged steam generator, (3) pipe spools with integral instrumentation, and (4) a prefabricated weather tower. These and other modular features are discussed in Section 2.4

1.5 PERFORMANCE ESTIMATES

Estimates of performance (power output) for the system were made for three site locations, each with the collector field oriented in both a north-south and east-west direction. Collector field performance was determined by a computer model that used insolation data from tapes of a typical meteorological year and collector efficiency data as measured by Sandia for Acurex collectors with FEK reflective surfaces. Heat losses and parasitic power were estimated manually and combined with field performance to obtain net power output. The results are summarized in Table 2 and show that the best site is clearly Albuquerque, followed by Bismarck, then Charleston. On the basis of daily average power output a north-south field is superior to an east-west field. Conversely, considering only peak power output, an east-west field is better. Additional discussions of performance results, including plots of daily average power output versus time of year, and parasitic power requirements are given in Section 3.

1.6 COST ESTIMATES

The largest cost element of the system is the collector field. Acurex would supply the parabolic trough line focusing collectors with FEK reflectors and has priced them depending on quantity. Prices for standard items are based on vendor quotes. Prices for construction and installation, engineering, and management are Acurex estimates based on experience with similar systems. System costs will vary depending on the specific site, owing to differences in shipping costs and local labor costs. For Albuquerque, installed system costs are shown in Table 3 for various lot sizes. These costs are burdened with overhead and G&A, but are without fee. A more detailed cost breakdown is given in Section 4.

Table 2. Summary of Performance Estimates

	Daily Average[1] Power Output, GJ/Day		Peak Power Output			
			kW_{th}		Steam Rate, kg/sec	
	N-S	E-W	N-S	E-W	N-S	E-W
Albuquerque, New Mexico	44.2	39.1	2,727	2,789	1.16	1.18
Bismarck, North Dakota	19.9	19.0	2,326	2,626	0.99	1.11
Charleston, South Carolina	17.6	16.8	2,272	2,274	0.96	0.96

[1]Based on the integrated annual system output

Table 3. Summary of Estimated Installed System Costs (Albuquerque)

Number of Systems	System Cost, $000	$/ft2
1	2,529	48.79
10	1,878	36.23
100	1,441	27.08
1,000	1,307	25.21

SECTION 2

SYSTEM DESIGN

This section summarizes the design of the 5,000 m^2 system. Section 2.1 outlines the design requirements and other considerations which influenced the design. Section 2.2 describes the system, its components, and how it operates. The mechanical, control, and electrical subsystems are all discussed in detail. The trade-off studies which led to the final system configuration are described in Section 2.3. Section 2.4 discusses the modular features of the design.

2.1 DESIGN REQUIREMENTS

A set of design requirements for the system was given in the Statement of Work. Briefly, the system was required to generate saturated steam at 827 kPa (120 psia) and 172°C (342°F) from 95°C (203°F) feedwater using a nominal collector field aperture area of 5,000 m^2 (53,800 ft^2). A complete list of the design specifications appears in Table 4.

In addition to these specifications, the system design was also to incorporate considerations such as modularity, safety (as defined by applicable codes), and reliability.

Further, the system must be capable of unmanned operation and automatically correct for unsafe or out of limit operation.

Table 4. System Design Specifications

Collector field area (nominal)	5000 m^2
System output	Saturated steam (827 kPa, 172°C)
Feedwater temperature	95°C
Design life	20 years 15,000 cycles
Environmental conditions	
• Ambient temperature	-30°C to 50°C
• Wind velocity	50 kph operational 150 kph survival
• Hail	19.1 mm diameter
Utilities available	
• Electric	440 VAC, 60 Hz, 3 phase
• Water	18°C
• Fossil fuel	Natural gas
System availability	75 percent

Other conditions, specified by the Statement of Work, that influenced the design were: the land area required was level and graded; all steam output of the system was used, and no thermal storage was required; data acquisition and instrumentation were limited to that required for system control and operation. Further assumptions were made to complete the system costing and are discussed in Section 4.

2.2 SYSTEM DESCRIPTION

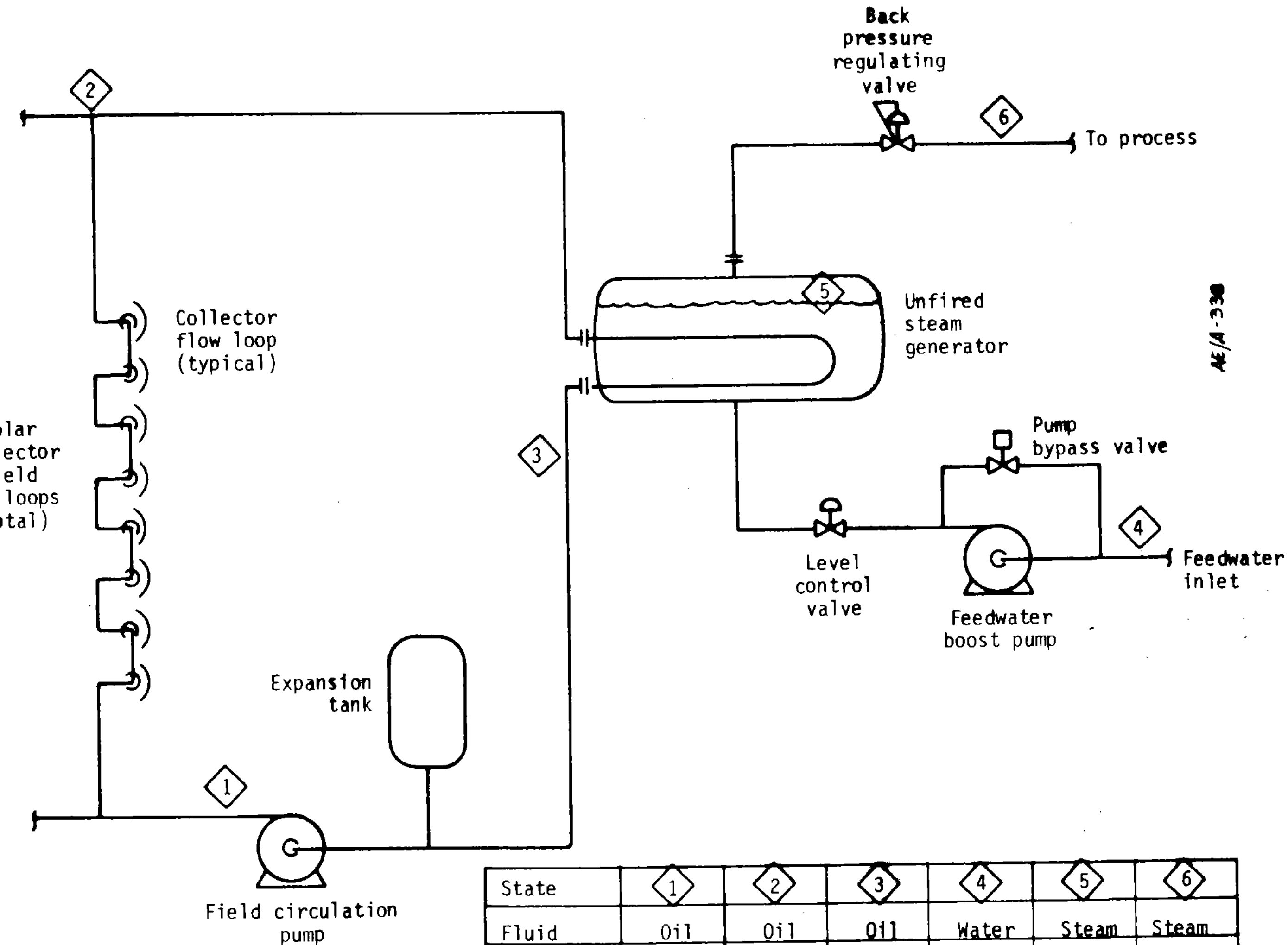
The concept of system modularity was maintained throughout the system design. The overall design philosophy was to develop a system design which was generic, and could be used at any location, in any orientation. Since the system design is a complete modular package, several systems could be arranged at the same site with their outputs manifolded together. The system design can also be used for different applications with slightly varying steam temperatures and loads by changing the component specifications and by adding or deleting the modular flow loops. Standardized modular components were also used wherever possible.

Results of the conceptual analysis and trade-off studies indicated that the best approach for generating steam is to use an unfired steam generator, with a heat transfer oil circulating in the collector field. This system was selected taking into consideration performance, simplicity, reliability, and cost-effectiveness. The trade-off studies are discussed at length in Section 2.3.

The solar system consists of four major subsystems: (1) collector field and foundation, (2) piping/distribution, (3) control, and (4) electrical. The process flow diagram, Figure 2, indicates the schematic arrangement of components and the predicted state points of the system.

A heat transfer oil is circulated through a distributed collector field at a constant flowrate of 17 liters/sec (270 gpm). Proper manifolding will maintain flow constant through each ΔT string to within ± 2 percent. The oil is heated to a maximum temperature of 252^{o}C (486^{o}F) by the collector field. The oil is then circulated through the tube bundle immersed in the feedwater of the unfired steam generator to produce steam. Under peak insolation conditions, the system will generate 1.2 Kg/s of steam. The heat transfer oil is then returned to the collector field to be reheated.

The oil is circulated by a centrifugal pump. An expansion tank just upstream of the pump accommodates thermal expansion of the oil,



State	1	2	3	4	5	6
Fluid	Oil	Oil	Oil	Water	Steam	Steam
Temp (^oC)	181	250 max	181	95	174	172
Press (kPa)	662	296	172	703	872	827
Flow (Kg/3)	13.1	13.1	13.1	1.1 max	--	1.1 max

Figure 2. Process Flow Diagram

provides the pump with sufficient net positive suction head (NPSH), and provides a convenient location for monitoring the oil level in the system and adding makeup oil if required. A feedwater boost pump is required to provide feedwater to the steam generator at the required flowrate and pressure. The following sections describe the system and its components in further detail.

2.2.1 Collector Subsystem

Collector Field

The collector field consists of 864 Acurex Model 3001 parabolic trough line focusing modules equipped with FEK reflective surfaces. These collectors represent three generations of engineering refinement combining high performance with reliability, modularity, simplicity, and compatibility with mass production fabrication.

A standard group of collectors consists of 12 collector modules connected to a common tracking drive. A flow loop, or ΔT string, consists of four collector groups connected in series. The entire field consists of 18 flow loops arranged in 18 rows. The plot plan, Figure 3, illustrates the collector field layout.

This field layout balances performance considerations (i.e., field pressure drop, manifold heat loss, manifold, and insulation costs) with practical considerations such as field access for periodic reflector cleaning, and simplified manifolding for ease of installation. A collector row spacing of 6.1m (20 ft) from center to center provides a layout which minimizes the effects of shading and manifold heat loss on overall performance. This layout also provides adequate space between collectors so that vehicles can be brought in to clean and maintain the collectors.

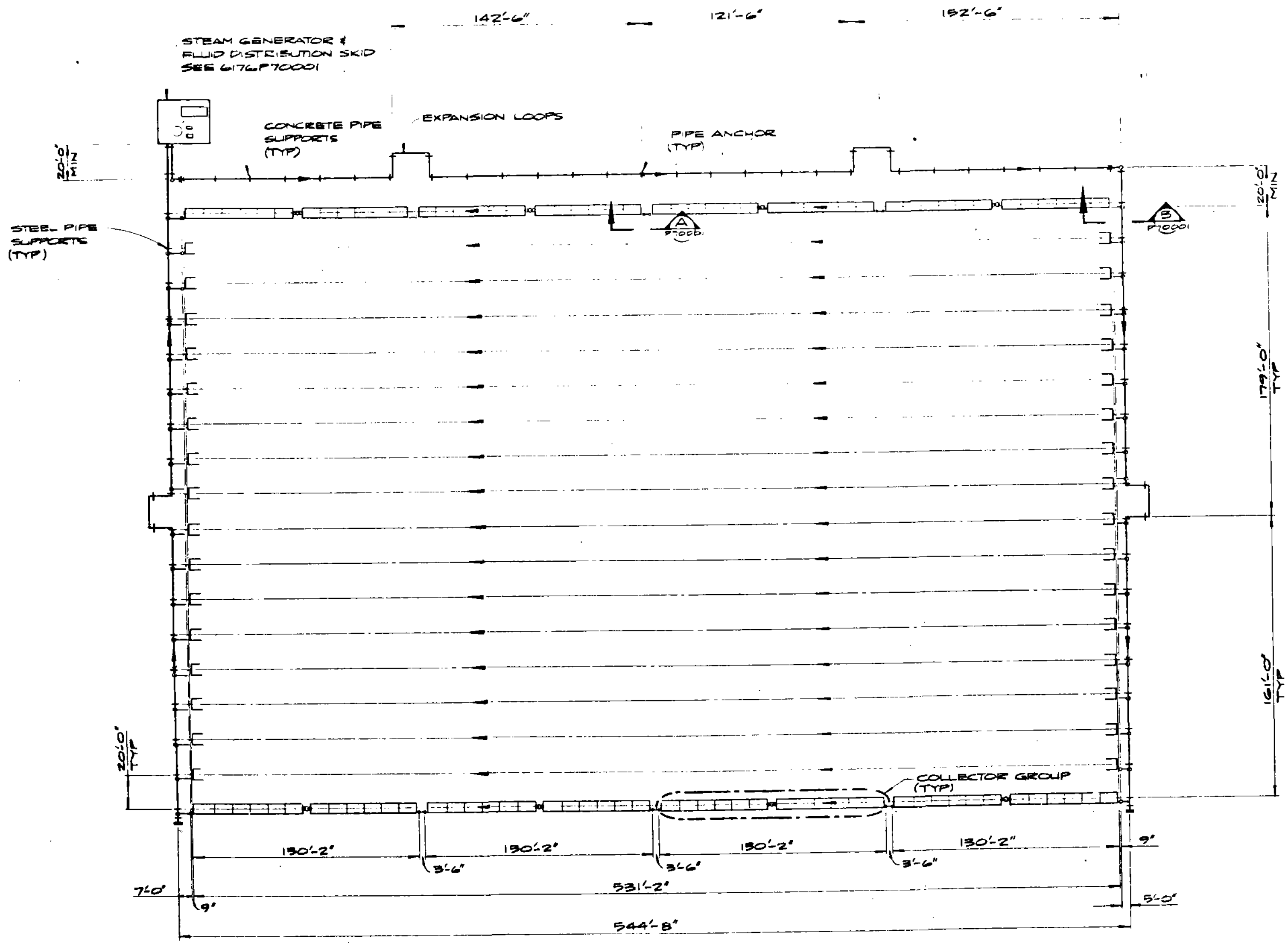


Figure 3. Plot Plan

Collector Foundations

Each collector group is supported by 13 support posts. The foundations for the support posts are designed based on the following loads and collector group tolerances:

- 150 kph wind load in the stow position
- 6.4 mm of permanent soil deformation under maximum loads
- 6.4 mm of differential settlement between any two foundations within a collector group

Foundation design is site specific, and must be evaluated for each installation. A soils analysis must be conducted before a foundation design can be selected. The options include driven pile, poured caisson, and spread footing foundations. The poured concrete caisson has been selected at most of the Acurex solar installations as the most cost effective design. Therefore, for purposes of this generic study, the poured caisson will be used as the baseline design and for costing.

2.2.2 Piping/Distribution Subsystem

Piping and Insulation

The process flow diagram (Figure 2) and the plot plan (Figure 3) illustrate the simplicity of the system and collector field piping. The collectors are arranged in 18 parallel rows with a manifold at each end. Process piping is only required to pipe the heated oil to the steam generator, and return it to the field. All collector manifolds and system piping are above grade, insulated, aluminum jacketed, and laid out with proper supports, guides, anchors, and expansion loops. All piping is designed per ANSI B31.3 to withstand daily thermal cycling over a 20 year life span.

The design presented in Figure 3 assumes the plant is adjacent to the collector field. For collector installations remote from the plant, the steam generator would still be located adjacent to the field, and the steam piped to the process. This is because cost and heat loss are greater for the higher temperature, larger diameter oil pipes than the steam and feedwater lines.

Pipe supports will consist of channels constructed from steel set on poured concrete foundations. The channels will limit extreme movements of the pipe, yet allow it to slide axially and laterally.

To minimize thermal losses from the system, all pipes and components will be well insulated. Previous studies at Acurex have shown the optimum insulation thickness to be approximately 3, 4, and 5 in for 2, 3, and 4-in diameter pipe, respectively. All pumps, valves, flanges, and fittings will also be insulated.

Standard fiberglass insulation will be used for most piping runs. A closed-cell cellular glass will be used around all areas with potential for leaks; i.e., flanges, valves, fittings, etc. to reduce fire hazard.

Expansion Tank

The solar system contains about 5.7 m^3 (1,500 gallons) of heat transfer oil, and an expansion tank is required to accommodate the thermal expansion of as much as 1.32 m^3 (350 gallons). The tank, situated at the high point of the system and tied into the system piping at the suction side of the field circulation pump serves several functions:

- Vents entire system through a flame arrestor
- Acts as system fill point
- Provides for particulate and water collection at the tank bottom

- Serves as system leak detection point with low and high level switches
- Ensures adequate pump NPSH

The expansion tank is of standard size and construction, and will be fabricated per API 650 "Welded Steel Tanks for Oil Storage." It will be supported by four legs above the field pump, connected to the system piping by a small diameter, stainless steel, insulated pipe to minimize heat loss. The tank itself will be uninsulated. A "cold" tank is desirable to minimize oil degradation at high temperatures. A flame arrestor at the tank vent/overflow allows the tank vapors to be vented directly to the atmosphere.

Pumps

The system has two pumps; a collector field circulation pump and a feedwater boost pump. The heat transfer oil is circulated through the field at a constant flowrate by a high performance (pump efficiency 63 percent), low maintenance, self-cooled centrifugal pump with a mechanical seal. Pressure drop calculations based on the piping design show the required pump motor size to be 18.7 kW (25 hp). A strainer is mounted in the line at the suction side of the pump to protect the system against foreign debris. An air separator removes entrained air and hydrocarbon vapors from the circulating oil and routes them through the expansion tank to be vented to the atmosphere.

The feedwater boost pump is required to supply feedwater to the unfired steam generator at the desired flowrate and pressure. This pump will also be centrifugal, high performance, and low maintenance. It will have a slightly lower pump efficiency (about 45 percent) due to its smaller size.

The feedwater boost pump will be on continuously while the solar field is operating. Flow will be modulated with a level control valve controlled by the level controller in the steam generator. A bypass line is provided to maintain a minimum flowrate to avoid stalling the pump.

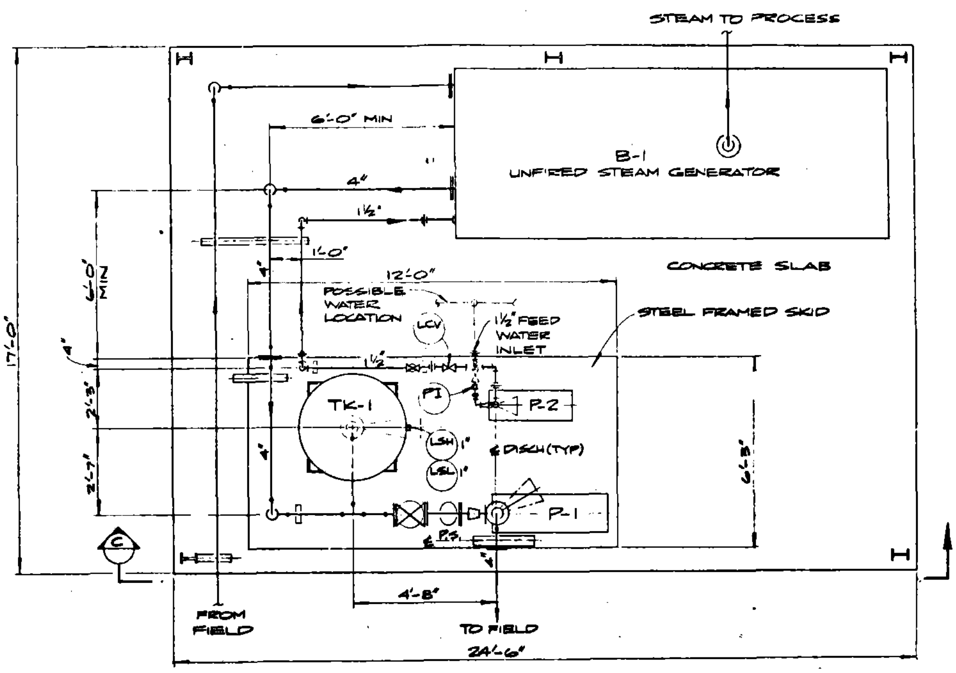
Both pumps, the expansion tank, and the associated piping and fittings will be mounted on a welded steel skid. The purpose of the skid is to eliminate many of the costly field welds by assembling these components in a shop. The skid simplifies transportation and installation of the preassembled components. Figure 4 shows the arrangement of the components on the skid.

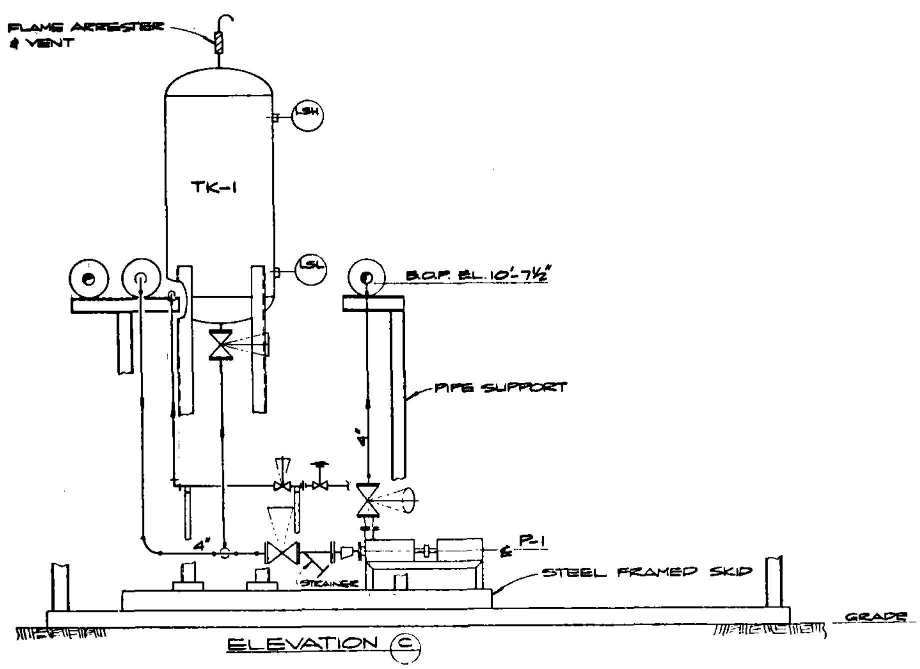
Unfired Steam Generator

The unfired steam generator converts the thermal energy collected by the heat transfer oil into process steam. This unit is a standard commercial item manufactured by a number of companies. Figure 5 shows a typical packaged unfired steam generator.

The steam generator shell will be designed. constructed, and stamped to the requirements of the ASME Code, Section VIII, for Unfired Pressure Vessels. Reinforced manholes are standard design practice for these units. The shell will be designed for 150 psig internal pressure. Welds will be fully X-rayed and stress relieved after fabrication. The generator will be equipped with safety valves installed per ASME Section I Boiler Code. Approximate shell dimensions for the unit are 1.5m (4.9 ft) diameter and 4.3m (14.1 ft) long. The heat exchanger will be fabricated from carbon steel with approximately 110 m^2 (1,180 ft^2) of surface area.

The water level controls will be packaged as part of the steam generator unit. The liquid level control system also contains an ASME





Major Components

B-1 Unfired steam generator
P-1 Field circulation pump
P-2 Feedwater boost pump
TK-1 Expansion tank

Figure 4. Fluid Distribution Skid

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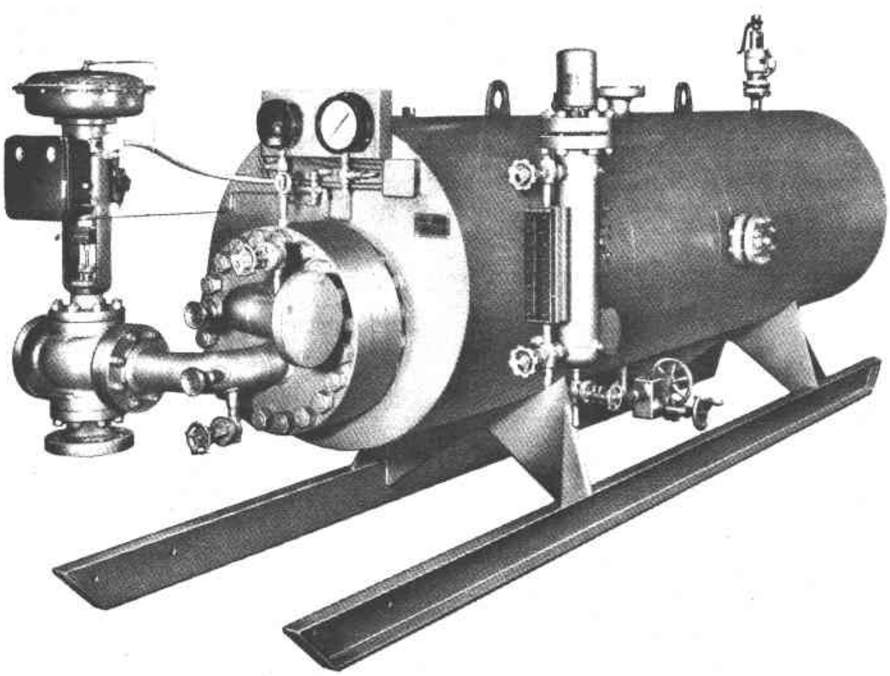

Figure 5. Typical Packaged Unfired Steam Generator

gage glass assembly to permit visual inspection of water level. Thermal insulation is also an integral part of the generator assembly. The generator shown in Figure 5 contains 5 cm (2 in) of fiberglass insulation under the outer skin.

Heat Transfer Oil

The heat transfer oil used in the solar collector field must have good thermal performance, low cost, and a lifetime exceeding 20 years. Previous studies at Acurex have shown several oils to have the required thermal properties (density, heat capacity, conductivity). However, like all oils, they "crack" at high temperatures, reducing to lower molecular weight compounds, noncondensable vapors, and olefins. This leads to the formation of deposits or coking in the solar collectors and field piping which reduces system performance. There are heat transfer oils manufactured for high temperature applications that exhibit little cracking, but these oils do cost more. For this application, the bulk oil temperature will be about 200°C (390°F) with peak temperatures of 260°C (500°F). At this temperature, the two best candidates are Therminol 55 and Humbletherm 500 (Caloria HT-43). Both oils cost about the same, but Therminol 55 has a slightly better life, is more readily available, and therefore was selected. The properties of Therminol 55 were used to compute system performance.

2.2.3 Control Subsystem

The instrumentation employed, as well as its functional use, is illustrated in Figure 6. As called for in the Statement of Work, the control system includes only those instruments required to operate the solar system unmanned and to protect it against damage from high wind, over temperature or equipment malfunction. Also, as allowed by the

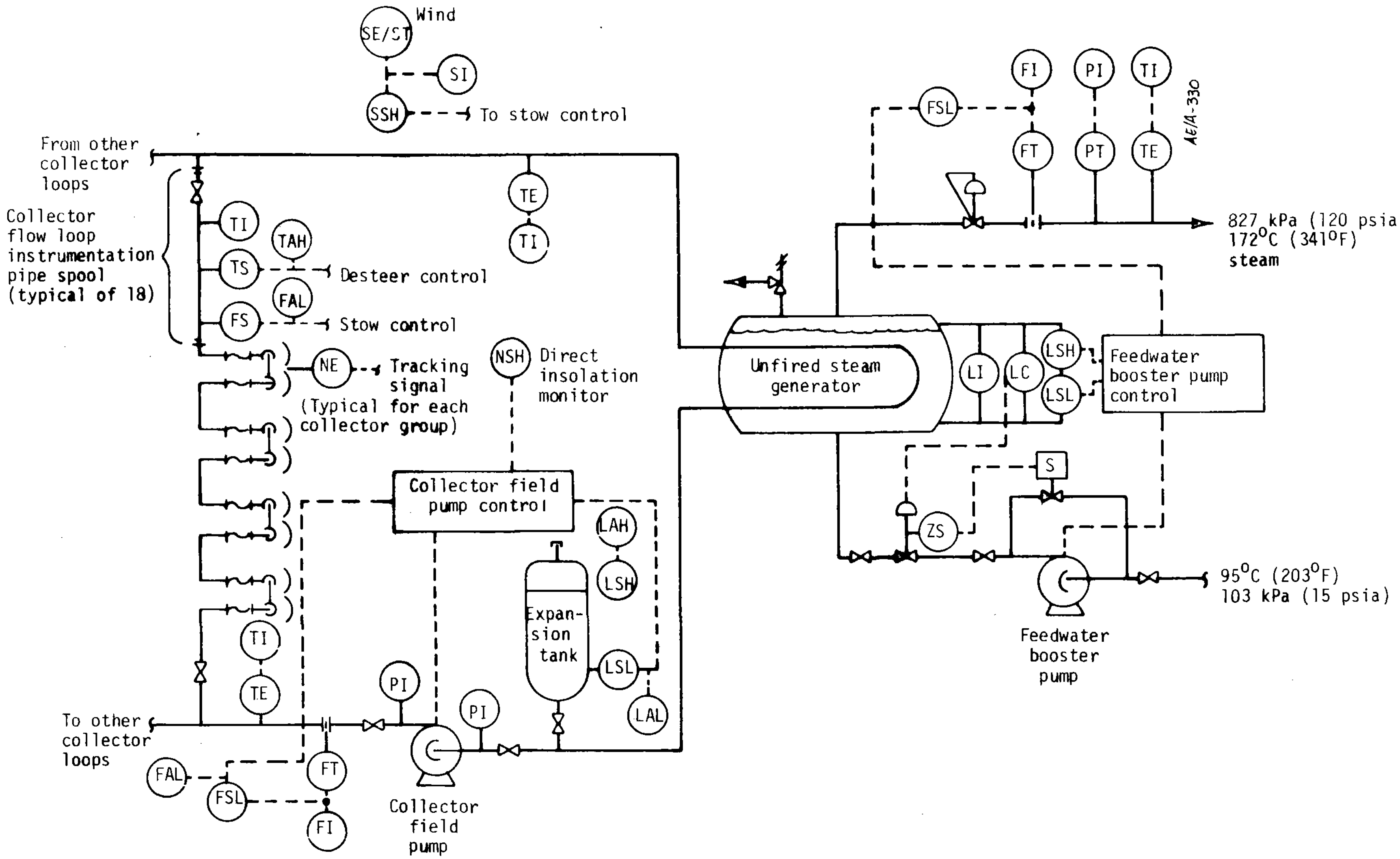

Figure 6. Instrumentation and Control Diagram

Statement of Work, a data acquisition system has not been included except as necessary for system control and operation.

The control system is based on the logic and principles used successfully with existing systems. The control modes for the various system elements are described below.

Collector Field

System Wake-Up

The collector system, if placed in the automatic mode, will receive signals from the direct insolation monitor (DIM) for the system to operate. If protective functions (sensed automatically) such as wind speed or fluid inventory are satisfied, the collector field pump will start automatically, and the collector tracking system will track the sun upon adequate direct insolation.

Collector Tracking

The DIM automatically initiates tracking when sunlight is adequate for efficient operation of the solar system. Responding to the orders of the DIM, one shadow-band-sensor (SBS) at each collector drive motor tracks the sun. Each SBS is supplied with tracker motor control (TMC) to provide an easily connected interface with other system controls.

Collector Desteer

If a high fluid temperature develops in the absorber tube, temperature switches interrupt signals to the tracker, and the tracking system will desteer the collector by 5 degrees to prevent receiver coating and collector fluid damage. By desteering only 5 degrees, the collectors can quickly and efficiently be returned to tracking position once the fluid temperature returns to normal.

Collector Stow

The stow control provides a fail-safe system where collectors are stowed toward the ground upon conditions of (1) high wind, (2) inadequate insolation, (3) loss of flow to the collectors, or (4) collector field pump motor overload.

Unfired Steam Generator

Heat transfer oil flows through the tube side of the unfired steam generator at a constant rate. In contrast, the feedwater flow through the shell side of the boiler is controlled by a single element (water level) control system.

A booster pump which can be controlled automatically or manually is used to increase the feedwater pressure to the boiler. In the automatic mode, the pump will start when a low level exists in the boiler. It will stop on either of two conditions (1) when a high level exists in the boiler, or (2) when no steam is flowing from the boiler.

A solenoid valve is installed at the bypass line of the pump and is controlled by a position switch mounted at the stem of the level control valve. The switch will cause the solenoid valve to open when the level control valve is at a near-closed position. The solenoid valve is designed for a fail open position.

A self-contained back pressure regulator valve mounted at the steam generator outlet controls and sets the steam condition to the desired pressure (827 kPa). Instrumentation furnished with the boiler is shown in Figure 6 and includes pressure gage, temperature gages, level gage, level controller, and level switches.

System Operation

To monitor the operation of the system, the following process indicators are provided in the main control room: (1) wind speed, (2) fluid flow in the collector field, (3) collector header outlet temperature, (4) steam flow, (5) steam pressure, and (6) steam temperature. In addition, all process control equipment will fail to a safe state if there is a system malfunction.

System "Kill" Switch

A system "kill" switch for system emergency shutdown is provided at the main control panel. When this switch is activated, the collectors will go to the stow position and the pumps tripped for a total system shutdown. The switch will be labeled to ensure that uninformed personnel know what switch to activate in case of emergency.

2.2.4 Electrical Subsystem

Electricity will be supplied by an existing 480 volt, three phase, 60 Hz line, and will be distributed throughout the system as shown in Figure 7. A fused disconnect switch is provided as the main feeder line over-current protection and system isolation switch and feeds the field circulation pump motor, the feedwater boost pump motor, and the collector field system.

Power within the collector field comes from a 45 KVA Scott-connected transformer, which steps down the 480 volt, three phase primary to a 120-volt, two phase, three wire secondary. The transformer feeds a distribution panel, containing four two-pole and 12 single-pole breakers. The two-pole breakers feed the loop connection boxes, which in turn supply the collector drive motors with 120-volt, two phase, three wire power.

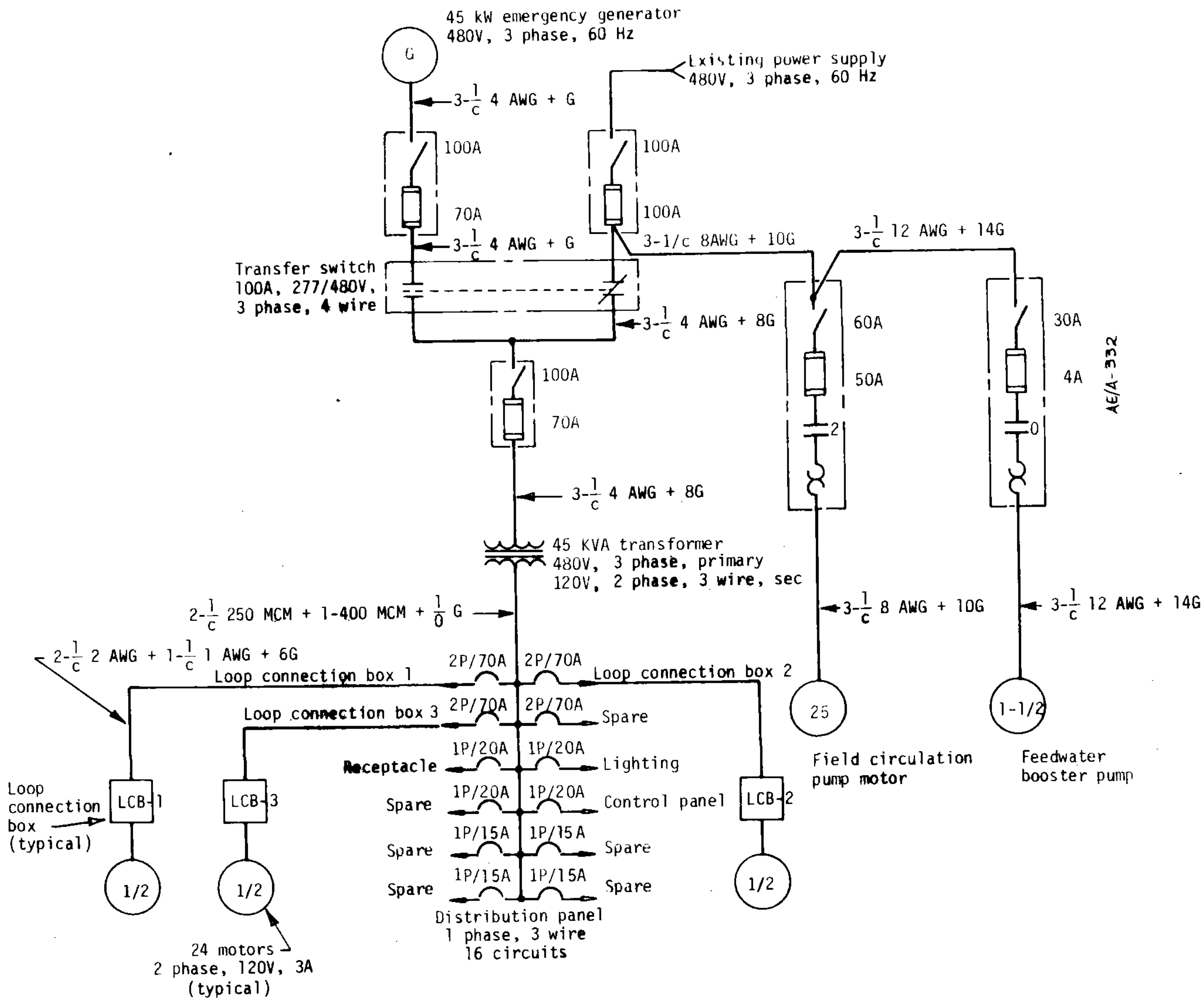

Figure 7. Single Line Diagram

All other 120 volt power requirements for lighting, receptacle outlets, control and instrumentation are fed from single-pole breakers.

The collector field is served by three loop connection boxes (LCB), one for each six loops. Each LCB consists of a disconnect-switch to turn off incoming power and terminal blocks for all power, control, and instrumentation cables.

Emergency power will be supplied by a 45 kW natural gas powered generator (480 volt, three phase, 60 Hz) to automatically stow the collector field when the transfer switch senses loss of grid power. This will protect the collector from wind damage and receiver tube over-temperature. To prevent the collectors from stowing on momentary fluctuation of normal power, a pneumatic relay, adjustable from 1-1/2 to 15-sec, is used to delay the transfer of standby power. A synchronous timer, adjustable from 2 to 60 min, avoids retransfer on short term normal power restoration. Both the relay and timer are standard equipment on the transfer switch. The transfer switch and generator are off-the-shelf items.

The field circulation and feedwater boost pump motors are started by individual full voltage nonreversing combination fused disconnect magnetic starters. Each starter is provided with three overload relays for over-current protection of the motors.

The electrical equipment and conduit layout of the collector field system are shown in Figure 8. Each loop connection box is located in the middle of the six loops that it serves. Experience has shown that this location is best for this kind of installation to optimize the use of wires and cables.

Pull boxes are used and placed strategically to reduce the cost of trenching and to minimize the number of conduit runs by using bigger conduit.

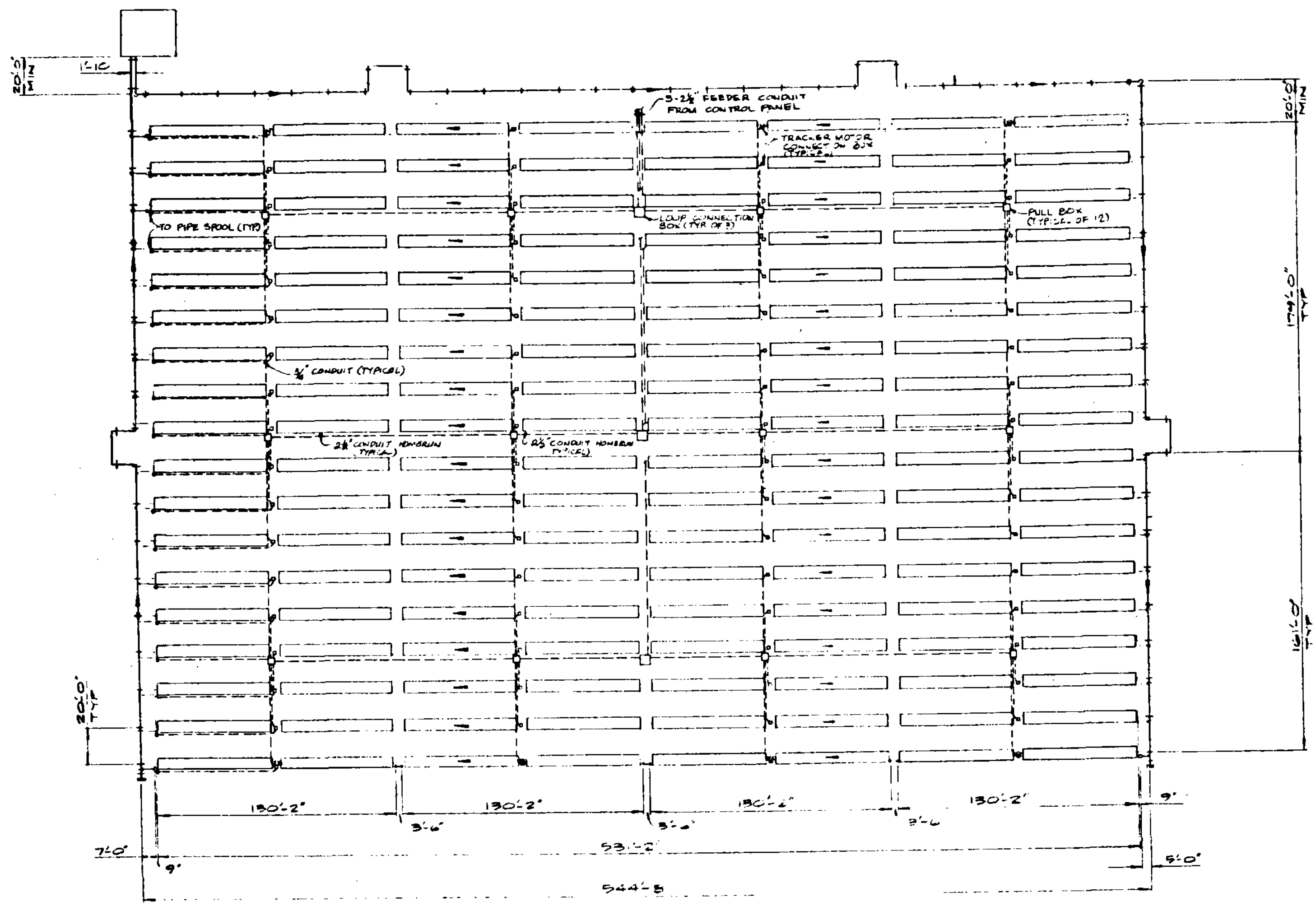

Figure 8. Electrical Equipment and Conduit Layout

Underground installation was selected because it is less expensive and conduits are concealed. Shadowing could occur if above ground installation is employed.

The location of the transformer, distribution panel, and other electrical equipment has not been established as it will depend on the location of the process building.

Lightning protection for the collector field will be provided by a lightning rod connected to the ground system of the field. The system grounding will interconnect each collector drive post together to ground wells.

2.3 SYSTEM TRADE-OFFS

The system design described in Section 2.2 was selected after carefully considering several alternative system configurations. The fundamental trade-offs involved the method of steam generation, working fluid, and system control which led to the system configuration shown in the process flow diagram. Further trade-offs were conducted to determine the best collector field and manifolding arrangement. Results of previous studies were also used for determining insulation thicknesses, system flowrate, expansion tank design, and pipe support design. The system trade-offs are described in greater detail in the following sections.

2.3.1 System Configuration

Alternative System Configurations

Three potential system configurations were evaluated:

- Pressurized water with flash boiler
- Pressurized water with unfired steam generator
- Heat transfer oil with unfired steam generator

The first alternative circulates pressurized water through the collector field. The high pressure water is throttled through a valve, producing a mixture of flashing water and steam. The steam is separated from the water and routed to the process. The water not flashed to steam is recirculated through a flash tank and back to the collector field. Makeup feedwater is supplied to the flash tank. The principal advantage of the flash boiler system is that no secondary heat exchanger is required; therefore the collectors can operate at a lower temperature and higher efficiency.

There are two system options for generating steam with an unfired steam generator. Both systems circulate the working fluid in a closed loop through the collector field and unfired steam generator. The difference is in the working fluid, one using pressurized water, the other a heat transfer oil. The advantages of using an unfired steam generator are:

- Low parasitic power due to lower pump heads
- Commercially available, modular, steam generator

The lower pump head represents a significant performance advantage. The flash boiler system must pressurize the feedwater by as much as 1,379 kPa (200 psi) only to have it throttled at the steam separator. The resulting parasitic power consumption is about four times greater for the flash boiler system.

Selection of different working fluids affects performance, cost, and reliability. The decision to select water or heat transfer oil involves the following considerations:

- Water has better thermal transport properties
- Water requires freeze protection
- Water would be at high pressure

- Oil does not create corrosion problems
- Oil presents a fire hazard
- Oil costs ~$400/m^3$ ($1.50/gallon)

Rationale for Configuration Selection

The criteria used for system selection are modularity and cost effectiveness, which is system cost divided by energy delivered to the load. Cost effectiveness is influenced by system capital cost, collector thermal performance, piping heat losses, warmup losses, and parasitic power consumption. All these factors were computed for the three candidate systems.

The results of the comparison, shown in Table 5, indicate that the unfired steam generator is more cost effective than the flash boiler concept by 5 percent. Despite the slightly higher collector efficiency for the flash boiler, the higher parasitic power consumption associated with the pressurized water system gives it the lowest net energy delivered. Costs for the flash boiler are also slightly higher because of the high pump head and the freeze protection system. Thus, the flash boiler was eliminated from further consideration.

The decision to select a collector working fluid is not as clear cut. Both cost and performance differentials are small, with the water system having a slight edge of 0.3 percent. Differences in fluid transport properties and cost were included in this comparison. With such a small difference, other qualitative factors were considered. The oil system presents a potential fire hazard, yet there are many industrial applications (including solar systems) which are currently using heat transfer oils. When proper safety precautions are taken, there is no appreciable increase in risk.

Table 5. Cost and Performance Comparison of Three Candidate System Configurations

	Pressurized Water/ Flash Boiler	Pressurized Water/ Steam Generator	Oil/Steam Generator
Annual collected energy	1.000	0.989	0.960
Thermal energy delivered to load	0.937	0.926	0.920
Thermal energy to load net parasitics	0.874	0.913	0.902
Capital cost	1.0	0.998	0.989
Cost effectiveness index	1.144	1.093	1.096

Water systems, however, require freeze protection which adds complexity to the system control, and requires energy. The complexity results in a mild increase in cost, but more importantly impacts the system reliability. Freeze protection also requires thermal energy to maintain the system piping above freezing (simple anti-freeze solutions decompose at the high collector operating temperatures and cannot be used). In an area such as Bismarck, North Dakota, the thermal requirement for freeze protection can reduce the net thermal energy delivered by an additional 10 percent.

Another consideration is operating pressure of the system. The collectors have a maximum operating pressure of 400 psig. This corresponds to a maximum operating temperature with pressurized water of about 224°C (435°F). For a typical system flowrate and steam generator operating condition, this means the maximum process steam conditions are about 190° (375°F) and 1,303 kPa (189 psia). Although this presents no problem for this system design, it limits the overall applicability of this generic system design.

The final selection was to use heat transfer oil in the collector field with an unfired steam generator. This system will exhibit the best performance over most of the country, especially those areas with subfreezing temperatures. Precautions for fire hazard will be taken by adhering to all applicable codes and ordinances.

Collector Field Layout

The collector field layout illustrated in Figure 3 was designed to balance collector performance against thermal losses, pumping power, and capital cost. An important consideration in selecting a manifold arrangement is the location of the process equipment (steam generator and pumps). The equipment was located at one corner of the field for better system modularity. This arrangement permits up to four modular 5,000 m^2 systems to be installed at a central process area. The length of the steam manifold, feedwater and electric power conduit will be shortest with this central process location.

The two common manifold arrangements were considered; manifolds at both ends of a collector row for a ladder type arrangement, or center manifolds which require an extra length of pipe for the flow to loop back at the edge of the field. The end manifold design was selected, primarily because it requires 23 percent less manifolding than the other arrangement resulting in lower cost and thermal loss. A reverse return piping arrangement was also considered to balance the flow through each row. Calculations, however, indicate that the small head loss in the manifold header will result in an acceptable flow imbalance of only ±2 percent between the rows at either end.

The flow loop or ΔT string length of four collector groups (268 m^2) results from a trade-off between a greater number of shorter rows with longer manifolds or a fewer number of longer rows with higher pressure drop.

The collector row spacing is influenced by mutual shading of adjacent collectors, land and site preparation costs, and length of manifolding. A performance analysis showed that the performance gain with increasing row spacing was significant up to 6.1m (20 ft). Beyond this point, the increase in land costs, manifold costs, and heat loss exceeded the performance gain.

System Control

Two types of system control options were considered: (1) constant flowrate and (2) variable flowrate. Since the unfired steam generator imposes no fixed outlet temperature for the solar system, a constant flowrate system can be employed. A constant flowrate allows the outlet temperature of the heat transfer oils to vary according to the available insolation and ambient conditions. This "floating" outlet temperature means energy is transferred to the process load at a lower average fluid temperature. A primary advantage of the constant flowrate is its simplicity and its inexpensive controls.

In general, the advantage of a variable flowrate over a constant flowrate is that it requires less pumping power. The estimated annual pumping requirement, however, is less than 1 percent of the estimated annual thermal output. In addition, variable flowrate requires somewhat more complicated controls than a constant flowrate.

All factors considered, the collectors will operate with approximately the same net output with either constant or variable flow. However, since the constant flowrate scheme offers simplicity and lower cost it was selected.

2.4 MODULARITY

Design of modular subsystems and components was investigated as a means to reduce the installed system cost. The potential for cost reductions in three areas was examined:

- Component costs
- Installation cost
- Engineering design cost

Component costs can be reduced by high volume purchases. This not only results in vendor discounts, but encourages mass production which lowers the manufacturing costs. High volume purchases are accomplished by standardizing those components which are repeated throughout the system. Furthermore, components were selected which could be used in other systems at different sites, orientations, and even different process conditions. The best example of this is the collector field. Since the solar collectors are by far the largest single cost component, there is tremendous potential for reducing the system cost by using a standard solar collector. Significant discounts for other components will also be realized, but the impact on installed system cost will be much less. Thus, the system design emphasized standardization of components within the system, which are also applicable in other similar systems.

Another area with much potential for cost reduction is installation. To minimize expensive field labor, preassembly of components at Acurex or by shop fabricators was evaluated. This approach encourages the use of subsystem modules which combine many individual components into a single module which can be shipped to the site. Those areas in which modular preassembly will be done are:

- Collector group
- Fluid distribution skid
- Unfired steam generator
- Collector loop pipe supports
- Instrument pipe spool
- Weather tower
- Main control panel
- Two-phase power
- Loop connection box

Other areas were considered for modularity and preassembly, but were not considered cost effective. These included manifold piping and headers, flow loop interconnections, and manifold pipe supports. The primary reason why these areas were not conducive to modularity was their simplicity. Shop welding the few fittings on each item does not compensate for the cost of shipping and an additional subcontractor. Furthermore, these items do not represent a significant part of the total installed cost.

Installation costs are also reduced by standardization of design. This permits the subcontractor to gain experience with installation procedures and increase his efficiency. The best example of this is the collector rows which have been modularized into a standard flow loop.

Each flow loop is exactly the same, which benefits installation of the foundations, collectors, piping, insulation, instrumentation, and electrical power. This same concept extends to the entire field if the same set of contractors were used.

The third area which benefits from modularity is engineering design costs. Much of the engineering labor and many drawings can be eliminated if the same design can be used for several systems. This concept of modularity in system design was emphasized throughout the design process. The simplest example is to use the system as-designed in different locations or orientations. Of the entire detailed design drawing package, approximately 75 percent of the drawings would require little or no change. The other 25 percent of the drawings are site specific, and deal primarily with the process interface and soil conditions at the site. The major drawings most affected by the site are:

- Plot plan
- Foundations (collector, process, and pipe supports)
- Interface drawings

The net result is a reduction in the engineering costs (including drafting and project management) by about 55 percent.

Another aspect of modularity is the ability to assemble the system modular components for various applications. Differences between systems could involve land availability, process load or process temperatures. Land availability could negate many of the cost advantages of modular, pre-engineered systems. Fortunately, the proposed field layout has the flexibility to accommodate different land constraints.

The field width can be changed by reducing the row spacing to as little as 4.6m (15 ft). Field length can be reduced by eliminating one or two groups from each collector row. Total field area could be maintained by adding more rows. Both these changes would only reduce net thermal performance slightly, and could be made with minor drawing revisions.

A small variation in process load can be met with additions or deletions to the number of flow loops. Specifications for the size of pumps, expansion tank, and steam generator would also vary, but their arrangement and generic type would remain the same. Both these changes could easily be made to the existing drawing package. For much larger process loads, the current design can be replicated with the steam from each modular field manifolded together and piped to the process.

Variations in process (steam) conditions are more easily accommodated. For higher or lower temperature steam conditions, the back pressure regulating valve needs to be adjusted and the steam generator specified for the proper operating pressure. No changes in the collector field layout, manifolding, or control system are required. The only precaution is to verify that the operating temperatures in the collector field do not exceed the maximum allowable temperature (600°F).

In summary, the concept of modularity was applied to the system design at several levels from component selections to system installations to engineering. Modularity is exhibited in the system by the use of standardized, preassembled modular components in a standardized system design which can be replicated or modified in modular increments. The next three sections describe in detail the preassembled modular components.

2.4.1 Mechanical

Efforts to modularize the collector field have already taken place. The individual reflector modules are combined in groups of 12 with a common drive system and solar tracker. This modular collector group design has been standardized and is applicable to a wide range of process temperatures and fluids. Significant cost savings are anticipated at high volume production and will be reflected in total systems cost.

A flow loop is simply four collector groups arranged in series. The additional hardware required to form a flow loop is the interconnecting pipe between the groups and from the end groups to the manifold. This piping has few fittings and can easily and inexpensively be fabricated at the site. The pipe supports, however, have been specially designed to bolt onto the last collector post and support the pipe with minimum heat loss. These supports have been standardized, and are shop fabricated then shipped to the site.

The flow loops are arranged in parallel, and are connected by a common manifold. The manifold is simply a long pipe of varying diameter (2, 3, and 4 in diameter) with an expansion loop and a fitting every 6.1m (20 ft) to connect it with the flow loops. The simplicity and uniqueness of the manifold (two manifolds per field) make the cost benefit of prefabricating the manifold and shipping it to the field insignificant.

The piping around the pumps and expansion tank is not so simple, and significant cost savings could be achieved with a modular, skid mounted fluid distribution assembly. This assembly, shown in Figure 4, contains the field circulation pump, expansion tank, feedwater boost pump, and associated valves and fittings. All components will be installed on the skid with interconnecting piping at a shop near the site, pressure tested, then shipped to the job site. This arrangement cuts installation costs by reducing the number of field interfaces to four (two oil, two water).

The unfired steam generator comes from the factory as a modular unit complete with controls and instrumentation. All that is required is a concrete foundation, power for instrumentation, and the four interface connections for oil, feedwater, and steam. The modular aspects of the unfired steam generator make it well suited to this modular system design.

2.4.2 Control Subsystem

Preassembled Instrument Pipe Spool

Figure 9 details the preassembled pipe spool that would house all instrumentation and outlet valving for each collector row. It contains (1) a flow switch used for stowing the collector row when no flow exists in the absorber tube, (2) a temperature switch used to desteer the collectors when high temperature exists in the absorber tube, (3) a temperature indicator for local indication of fluid temperature, and (4) a manual valve for isolating the collector row. All of the protective functions for the collector loop parameters are satisfied with the above standard off-the-shelf instrumentation.

The instrument pipe spool is assembled by the system supplier. As shown in the figure, the flow switch body, the tee's which hold the thermowells for the temperature switch and indicators, and the manual valve are all welded to the piping. Welding of the flow switch body and the manual valve body does not affect the maintainability of this equipment since the flow switch and the valve internals could be easily unscrewed and removed when servicing is required. As for the temperature switch and indicator, this equipment is easily unscrewed from their respective thermowells.

The overall length of the pipe spool is 4 ft making field handling and installation easy and fast. To minimize field wiring, the instruments

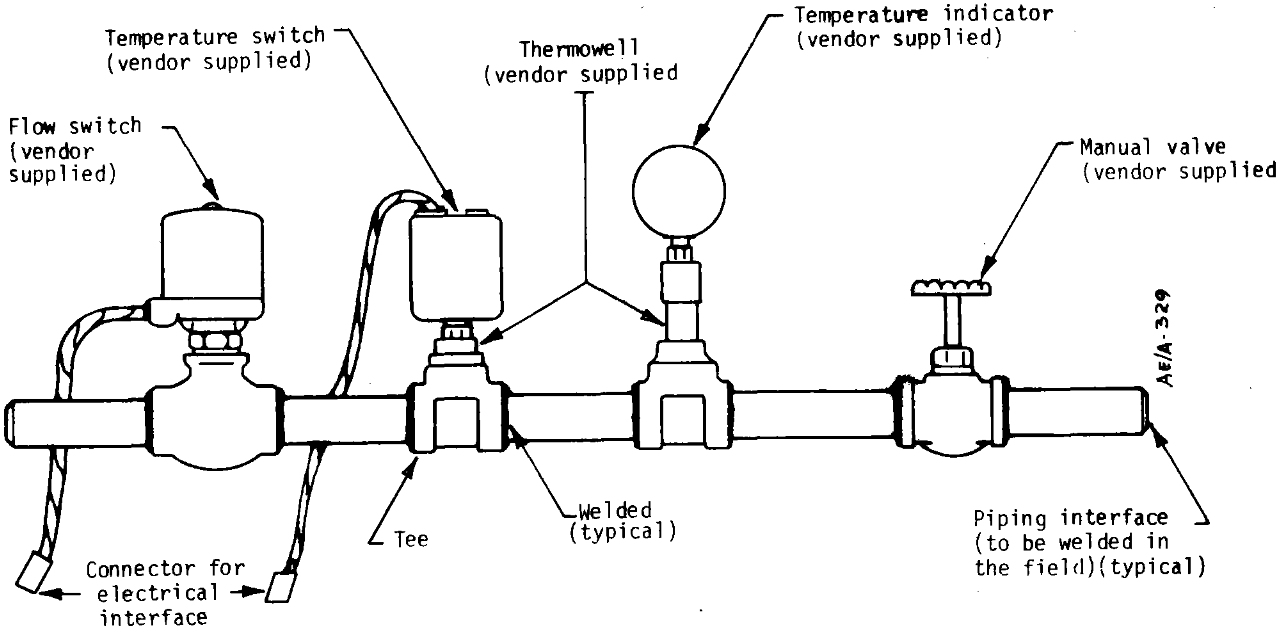

Figure 9. Modular Instrumented Pipe Spool

are wired in the shop and provided with weatherproof self-locking connectors for ease of field electrical interface.

Preassembly of the instrument pipe spool definitely speeds up assembly in the field and saves cost of field welding (160 welds) installation, and checkout since shop labor is approximately half the price of the field labor.

Preassembled Weather Tower

Figure 10 details the preassembled weather tower for the direct insolation monitor (DIM) and wind speed sensor. The DIM is used to (1) "wake up" the system upon adequate direct insolation and (2) stow the collectors and shut down the system at night. The wind speed sensor is used to protect the collector against high wind velocity by stowing the collector when velocity reaches 30 mph. The DIM will be supplied by Acurex, whereas the wind speed sensor is a standard off-the-shelf item. The weather tower will be located at the edge of the collector field nearest the main control panel to minimize signal voltage drop of the wind speed sensor to the panels.

The preassembled weather tower is made of weatherproof steel and will be assembled by the system supplier. The height of the tower will be approximately 7 ft to ensure that the collectors do not shadow the DIM. A base plate will be provided with the tower for mounting in the foundation provided by field personnel. To minimize field wiring, the instruments will be wired in the shop and provided with weatherproof self-locking connectors for ease of electrical interface.

The preassembled weather tower would reduce field installation and field checkout costs by using less expensive, more productive shop labor instead of field labor.

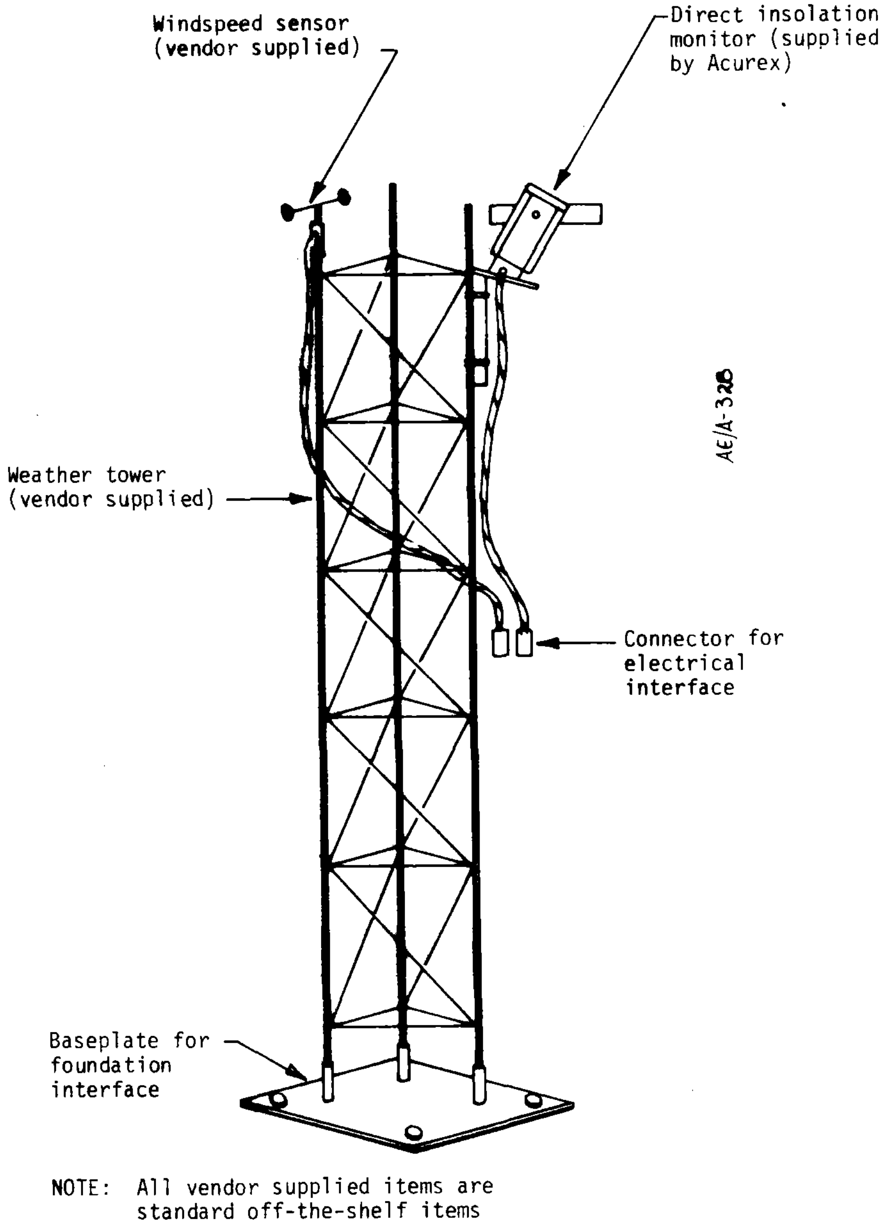

Figure 10. Preassembled Weather Tower

Main Control Panel

Figure 11 shows a modular main control panel which will be assembled and checked out in the shop by the system supplier. The control panel is a NEMA 12 freestanding enclosure with nominal dimensions of 90 in high by 36 in wide by 36 in deep. It will contain the following standard off-the-shelf components:

1. Annunciators. Alarms for abnormal system operating conditions such as expansion tank high and low levels, pump trip or lockout, common alarm for collector row low flow, and common alarm for collector row high fluid temperature.
2. Process indicators. To monitor system operation process indicators such as wind speed, collector inlet and outlet temperatures, header flow, steam flow, steam temperature, and steam pressure are provided.
3. Control switches. The control switches used for the operation of the system, e.g. pump, pump lockout, tracking selector switch, and systems emergency shutdown "kill" switch, are located in the main control panel. Also located in this panel are pushbutton switches to acknowledge and silence the annunciators.
4. Bistables. These switches are used to convert analog signals to contact closure signals and are located inside the cabinet.
5. Control relays and timers. These components are located inside the cabinet and are used for electrical system operation.

The main control panel will be located in an existing building. To save costs on electrical wiring, conduit, and field installation, it should be located close to the collector field. Savings in cost of field

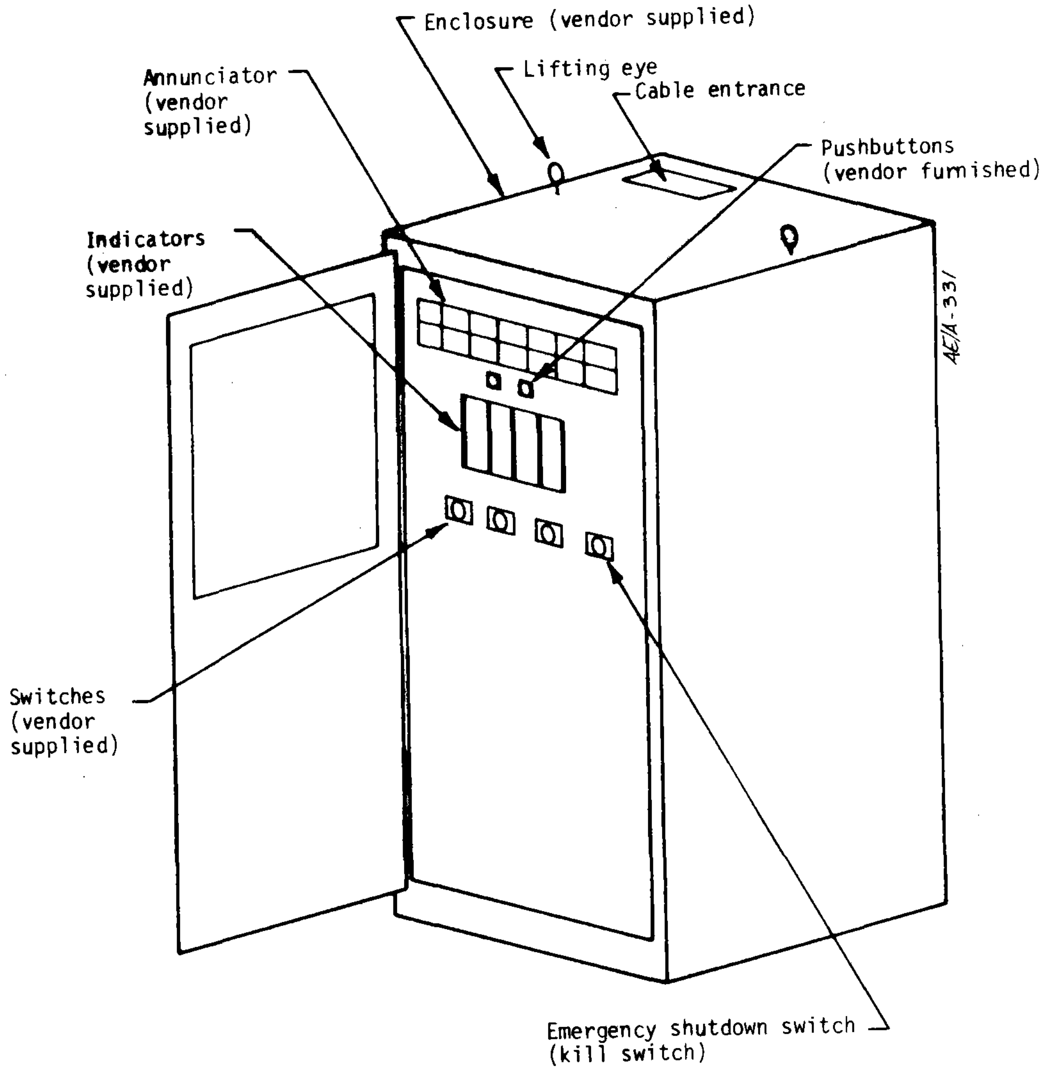

Figure 11. Main Control Panel

installation can also be realized by routing the incoming electrical cable to a top entrance to the panel. This will avoid breaking through the concrete flooring of an existing building to bring in electrical conduit. The panel is provided with lifting eyes for easy handling both in the shop and in the field. The electrical interface in the panel will consist of terminal blocks for terminating field wiring.

Preassembly of the control panel by the system supplier will speed up work in the field, since only simple connections of field wiring to the designated terminals need be made. Savings in cost will be realized during installation and checkout since shop labor is approximately half the price of field labor.

2.4.3 Electrical Subsystem

Two-Phase Power

A Scott-connected transformer, 45 KVA, 480 volt, three phase primary and 120 volt, two phase, three wire secondary will provide two-phase power to the collector field.

Previous designs used three-phase, four wire power systems. However, the collector drive motors which are essentially two phase motors require single phase power, three position selector switches, and an RC network to operate the motor clockwise or counterclockwise.

The two phase, three wire system provides the necessary power to run the drive motor clockwise or counterclockwise and eliminates the power conversion from three phase to single phase to two phase and the use of the RC network and selector switch. Installed costs of all equipment including wiring between two phase and three phase systems show that the two phase system is less expensive owing to the elimination of the RC network and its box.

Loop Connection Box (LCB)

The loop connection box consists of one disconnect switch to turn off the incoming power, and terminal blocks for power, control, and instrumentation cables. Each loop connection box will house all the incoming and outgoing signals for six loops of collector modules to track, desteer, stow or unstow, and stop the collector modules. Each loop of collector modules consists of four drive motors, four tracker sensors, one temperature switch, and one flow switch.

Using the conventional design, the signals from the direct insolation monitor (DIM) and wind speed, which come from the control panel to the loop connection boxes, were usually multiplied by using relays (54 total for this field) to track and stow or unstow the collector system. These relays were also used to multiply the signals coming from temperature switches, to desteer collectors, and from flow switches, to stow or unstow collectors. To operate each loop of collector modules manually, six selector switches were used. For servicing and cleaning of each group of collectors (four groups per loop), one toggle switch was provided.

Modular designs employ terminals for signal multiplication. The incoming signals to each loop connection box will be converted to multiple outgoing signals by shorting the terminals. This eliminates the cost of incorporating relays, thus reducing labor and engineering costs. Instead of having a toggle switch to run one group of collectors for servicing and cleaning, two switches, installed on one of the tracker motor connection boxes (each loop has four tracker connection boxes) will be utilized to operate each loop of collector modules.

Using terminals instead of relays for signal multiplication decreases not only checkout, shop labor, and engineering cost, but also the maintenance cost.

SECTION 3

PERFORMANCE ESTIMATES

3.1 SYSTEM MODELING

A computer model was developed to compute the energy supplied by the collector field. The computer code performs an energy balance of the system for each hourly timestep and sums them to obtain a daily, monthly, and yearly output. Thermal losses associated with the manifold piping, equipment, and warmup losses were estimated outside the code and subtracted from the collector field output to obtain net thermal output delivered to load. Steam flowrates were computed from the thermal output, and the known steam conditions and feedwater temperature.

The code first inputs the data required to specify the system. This includes solar collector and steam generator characteristics, fluid properties, system flowrate, desired steam conditions, and details of the collector field layout. Then the code begins to step through each hour of a simulation year. The hourly insolation and ambient temperatures are obtained from the typical meteorological year (TMY) weather tape obtained from the National Weather Service (NOAA). The information on the weather tape is the same as that used to formulate the graphs of insolation data presented in the Statement of Work. Since hourly simulations would give the most accurate results, and the data base was the same, the weather tapes were used in place of the furnished graphs.

The first computational step is to determine the position of the sun, and then compute the incidence factor (cosine loss), shading, and end losses for the collectors. This gives the energy incident upon the collector aperture. Next, an iterative process is required to determine the operating temperatures of the system and the collector efficiency. Finally, the system output for the timestep is computed, the results summed, and the code moves to the next timestep.

The thermal piping losses were computed from the average system temperature, average ambient temperature, and insulation characteristics of the piping. Warmup losses were obtained in a similar fashion, and verified by previous, more detailed computer simulations. The thermal losses varied from 7 percent (in Albuquerque) to 13 percent (in Charleston) of the gross thermal collected energy.

3.2 PERFORMANCE RESULTS

Monthly net thermal outputs for the three sites are shown in Figures 12, 13, and 14. As expected, the better insolation areas have greater energy outputs, and the north-south axis collectors show a much wider swing in useful energy between winter and summer. In fact, a north-south axis field in Bismarck, North Dakota will generate no useful net energy in the month of December. The other interesting result is that the insolation and useful energy output in Charleston, South Carolina is so poor, even in the summer months.

The annual performance results as well as the maximum system outputs are shown in Table 6 with the insolation levels at the three sites. Depending on site and orientation, this system with its 4,818 m^2 of collectors will collect from 17.45 x 10^6 MJ/yr in Albuquerque to 7.45 x 10^6 MJ/yr in Charleston. The peak output for the system is

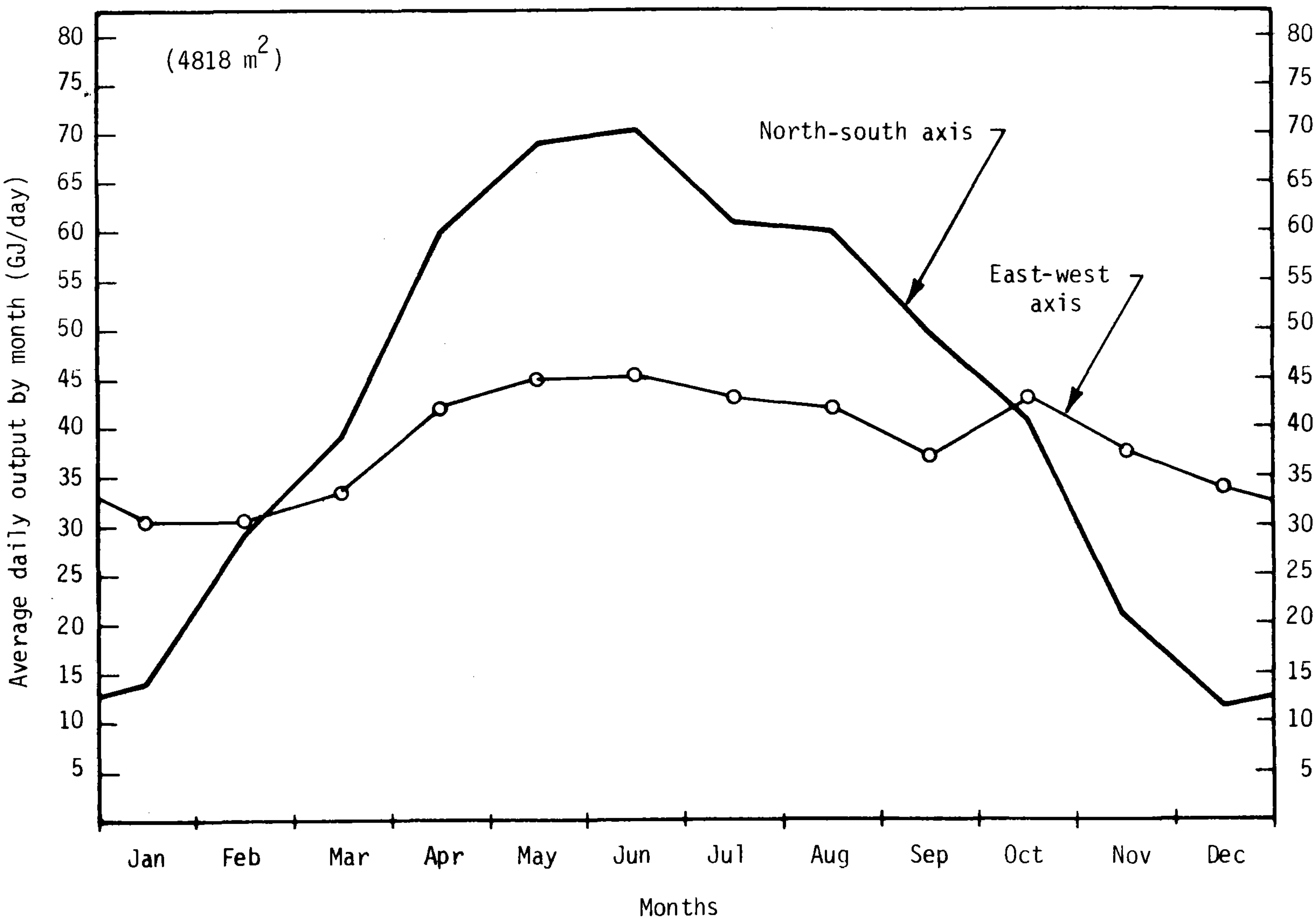

Figure 12. Average Daily Net Power Output by Month (Albuquerque)

AE/A-333

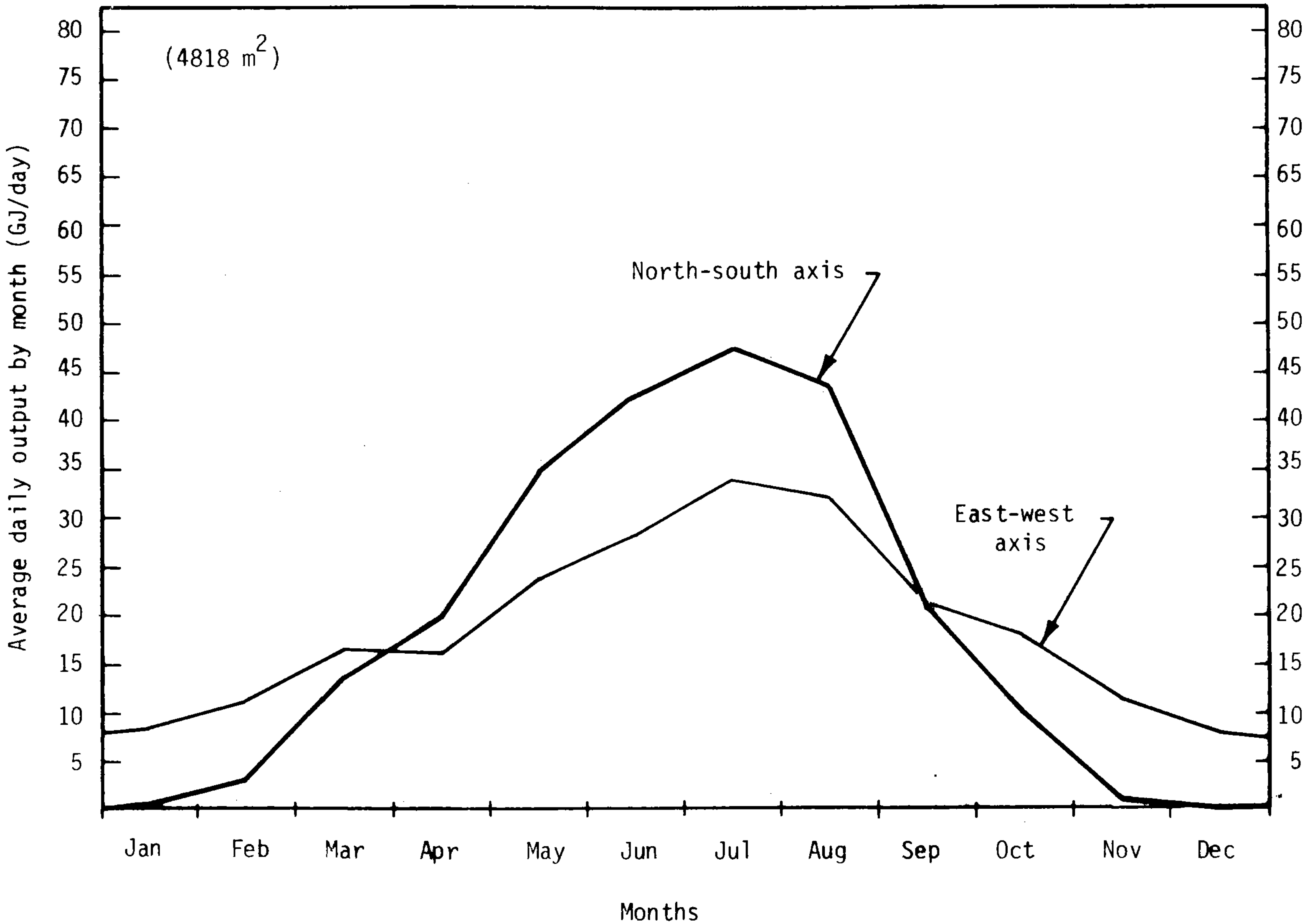

Figure 13. Average Daily Net Power Output by Month (Bismarck)

AE/A-334

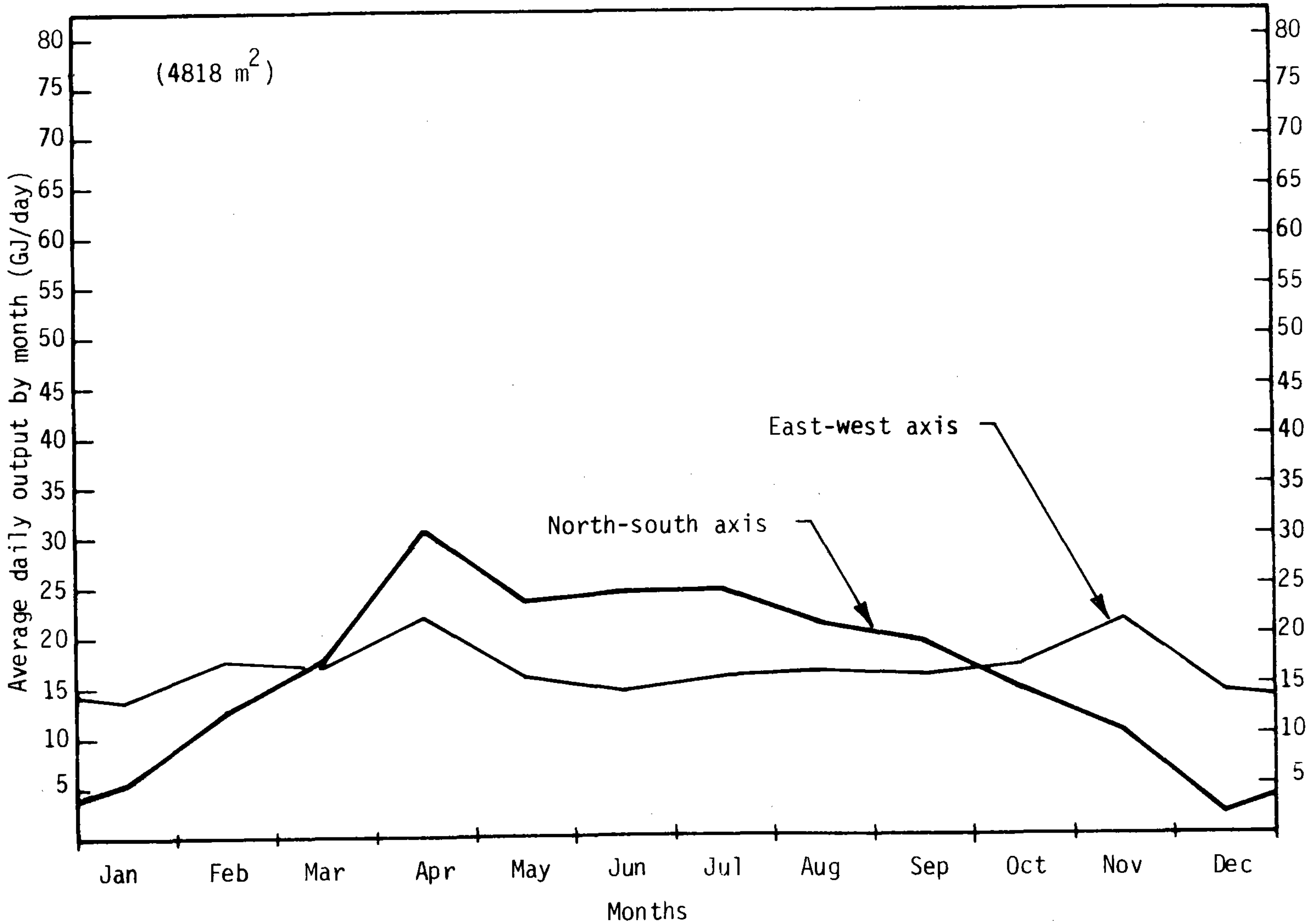

Figure 14. Average Daily Net Power Output by Month (Charleston)

AE/A-335

Table 6. Annual Performance and Peak Power Summary

Site		Annual Direct Normal Insolation (10^6 MJ)	Annual Insolation to Aperture (10^6 MJ)	Total Useful Energy -- Annual (10^6 MJ)	Average Daily Energy (GJ/day)	Peak Power, (kW_{th})	Peak Power Steam Rate (kg/s)
Albuquerque, New Mexico	N-S	45.4	37.1	17.45	44.2	2,727	1.16
	E-W		34.1	15.58	39.1	2,789	1.18
Bismarck, North Dakota	N-S	27.9	21.8	8.64	19.9	2,326	0.99
	E-W		20.8	8.10	19.0	2,626	1.11
Charleston, South Carolina	N-S	23.5	19.8	7.63	17.6	2,272	0.96
	E-W		18.8	7.45	16.8	2,274	0.96

2,789 kW_{th} at Albuquerque, or the equivalent of 1.2 kg/s of steam to the process.

The system is a module which would be installed as designed at any site. Depending upon process needs or site constraints, the field can be oriented with a north-south or east-west axis or even in between. The maximum performance variation with orientation is 13.0 percent at Albuquerque, and 4.7 and 4.8 percent at Bismarck and Charleston, respectively.

3.3 PARASITIC POWER ESTIMATES

Parasitic power is consumed by the collector drive motors, the field circulation pump, the feedwater pump, and the control subsystem. The amount of power drawn depends on the system operating mode and field orientation. During normal daily tracking, the pumps and control subsystem operate continuously, but the drive motors run only a small portion of the system operating time. During system startup and shutdown, the collectors are raised and lowered in unison and all drive motors operate simultaneously.

Measurements of parasitics made at the 150 kW field at Coolidge, Arizona show that a continuously operating drive motor (as in stowing) draws about 0.2 kW and that when tracking, the average motor running time was only 2.6 percent of the system operating time. The field at Coolidge has a north-south orientation; for an east-west field tracking parasitics become negligible. In addition, the control console power demand was found to be 0.5 kW.

Based on these data and the power drawn by the pump motors, estimates of parasitic power were made for normal operation, startup/shutdown, and emergency shutdown. The results are summarized in Table 7.

Table 7. Parasitic Power Estimates

	Startup/ Shutdown, kW	Normal Operation, kW	Emergency Shutdown, kW
Drive motors	15.3	0.4	15.3
Field circulation pump	13.5	13.5	0
Feedwater pump	0.9	0.9	0
Controls	0.5	0.5	0.5
Total	30.2	15.3	15.8

SECTION 4

COST ESTIMATES

Estimates were made of the cost to install the system described in Section 2.2. Variations in cost with the number of systems built and site were also investigated. Prices for major equipment were based on vendor quotes. Current solar collector prices and projections for large volumes were obtained from the collector manufacturing group at Acurex. Engineering, management, construction supervision, and subcontracts administration will all be performed by Acurex personnel, and were costed based on experience with similar systems. The construction and installation work will be subcontracted to local labor. Cost estimates for these tasks were made from standard cost estimating references (Means Cost Data, Richardson Process Plant Construction Estimating Std, and Dodge Manual) and historical cost files at Acurex based on actual field experience.

Several assumptions went into the costs presented in this section. The time required to construct and install the system was assumed to be 1 year in all cases. The land was assumed to be available at no cost, with the site graded sufficiently as to require no additional grading for foundations or access roads. The collector field and process areas were surrounded by a chain link fence. The process equipment (steam generator, pumps) were provided with a foundation, but no mechanical building.

Painting was also assumed to be not required. All equipment was costed FOB point of origin. Shipping costs for the solar collectors being a major cost item, however, were included. Finally, all subcontract negotiations were to be done at Acurex in Mountain View, California.

Albuquerque was chosen as the baseline site which affected labor, shipping, and foundation costs. For the system costs in lots of 10, 100, and 1,000, all systems were assumed to be constructed at the same location by the same set of contractors. This assumption was made to indicate the reduction in installation and construction costs as the contractor becomes more familiar with the installation procedure. Multiple systems built at different locations would reduce component costs, engineering labor, and any assembly of modular components at Acurex but not necessarily installation costs.

A summary of the cost analysis broken down by discipline is shown in Table 8. The collector costs are by far the major cost component with 44 percent of the total installed cost of one system. The mechanical components and installation accounts for 13 percent of the system cost, with the civil, insulation, instrumentation and control, and electrical areas equivalent to another 17.8 percent.

Of interest in Table 8 are the vast reductions in cost at high volumes. Most dramatic are the solar collector costs which are anticipated to reduce in cost to just 41 percent of the cost of the first collector field. Further reductions in the collector cost are possible if demand merits another manufacturing facility closer to construction sites, thereby eliminating the shipping costs. Large reductions in cost are also anticipated in the mechanical installation costs and engineering.

Table 8. Estimated Installed System Costs (Albuquerque)

(1980 Dollars)

	Number of Systems			
	1	10	100	1,000
Civil All foundations Chain link fence	188,200	165,600	159,970	135,980
Mechanical Pipe supports Piping and valves Pumps Expansion tank Steam generator Collectors (installation only)	368,700	324,460	320,770	272,650
Insulation Piping and valves Vessels (included	81,900	72,100	69,620	59,170
I&C Pipe spools Control panel Weather tower Instruments	69,800	61,420	56,340	49,410
Electrical Power Loop control boxes Conduit Cable Terminations Emergency generator complete Transformer	153,500	143,520	138,150	124,340
Collectors Includes shipping to Albuquerque, New Mexico	1,124,900	855,360	440,640	409,540
Subcontracts	138,400	85,000	85,000	85,000
Engineering Design Drafting	114,200*	114,200	114,200	114,200
Construction Supervision	289,800	56,800	56,800	56,800
Total	2,529,400	1,878,460	1,441,490	1,307,090
Cost per ft^2	48.79	36.23	27.08	25.21

*Does not include nonrecurring engineering costs

Also of interest is the sensitivity of cost to jobsite. Estimates for shipping, and varying local labor rates were made for the other sites mentioned, namely Bismarck, North Dakota and Charleston, South Carolina. The cost variances in both cases are less than 5 percent. Variations in soil conditions and weather, affecting foundation costs and construction schedule were not included.