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DESIGN, CONSTRUCTION, AND OPERATION OF A 150 kW SOLAR-POWERED IRRIGATION FACILITY

Phase II

MASTER

Final Report, September 30, 1977–September 30, 1979

By
D. Duffy
M. Matteo
D. Rafinejad

May 1980

Work Performed Under Contract No. EG-77-C-04-4159

Acurex Corporation
Alternate Energy Division
Mountain View, California

U.S. Department of Energy

Solar Energy

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for period
September 30, 1977 through September 30, 1979

D. Duffy, M. Matteo, D. Rafinejad

May 1980

Acurex Corporation
Alternate Energy Division
485 Clyde Avenue
Mountain View, Califoria 94042

Prepared for
U.S. Department of Energy
Albuquerque Operations Office

Under Contract DE-AC04-77-ET20227

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ABSTRACT

Acurex Corporation was contracted to design, construct and startup a solar powered experimental facility to provide 150 kW of electric power for the operation of deep-well irrigation pumps. Acurex also supplied its Model 3001 Solar Collector. This facility is located on the Dalton Cole Farm near Coolidge, Arizona.

The facility is presently the largest operating solar thermal powerplant in the world. Experience gained on this plant will pave the way for many future power generation facilities. The present International Energy Agency (IEA) project in Spain is utilizing technology learned on the 150 kW project.

The project was operated and completed by September 30, 1979 and was turned over to the DOE technical advisor, Sandia Laboratories, and the University of Arizona on October 1, 1979.

The dedication of the project occurred on November 9, 1979. The solar collectors were tracking on full automatic, and the power conversion system started up and operated on automatic control for full demonstration to the public and many honored guests.

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SECTION 1

EXECUTIVE SUMMARY

1.1 INTRODUCTION

Acurex's involvement in the 150 kW Solar-Powered Deep-Well Irrigation Facility began in February 1977 when the Department of Energy (DOE) awarded a 7-month contract to Acurex for the conceptual and preliminary design of the solar thermal irrigation system. This Phase I effort resulted in the selection of an optimum system to meet the design goals and operational objectives, and preliminary design drawings and specifications of components and subsystems were prepared. Two alternative design concepts were studied in parallel under two other DOE contracts. These concepts were the central receiver and the paraboidal dish. The Acurex system based on the parabolic trough concentrator was chosen for Phase II construction as a result of this competitive study. The basis for selection was technological readiness, and short term and long term cost-effectiveness of such systems in the 200 kW power range.

In September 1977 Acurex was given prime responsibility for conducting Phase II; a 2-year period during which detailed designs were prepared, material and equipment procured, the facility was erected, started-up, and operated successfully.

The balance of this report will address only the activities performed during Phase II. The Phase I final report was issued in August 1977.

1.2 PROJECT DESCRIPTION

The completed solar facility, shown in Figure 1-1, occupies approximately eight acres on the Dalton Cole cotton farm four miles south of Coolidge, Arizona (Figure 1-2). The purpose of the plant is to demonstrate the feasibility of providing cost-effective and reliable solar-thermal generated electricity. In this particular application 150 kW of electrical power are supplied to operate irrigation pumps. This is accomplished by delivering metered electrical energy directly to the utility grid and receiving credit for its value. The pumps are operated by drawing electricity directly from the grid. In providing this power, solar energy is collected by 23,040 square feet of Acurex-supplied line-focusing parabolic trough collectors arranged in eight loops having a north-south orientation.

The system is designed around three heat transfer loops. One loop extracts warm heat transfer oil from the bottom of a thermal storage tank, circulates it through the collector field and returns it hot to the top of the thermal storage tank. The second loop extracts hot oil from the top of the storage tank, circulates it through a vaporizer heat exchange unit and returns it to the bottom of the storage tank (or directly to the collector field inlet). The third loop circulates toluene through the vaporizer heat exchange unit to vaporize it and then expands the vapor through the turbine in the power conversion module to extract the energy for electrical power generation. The cycle is completed by condensing the

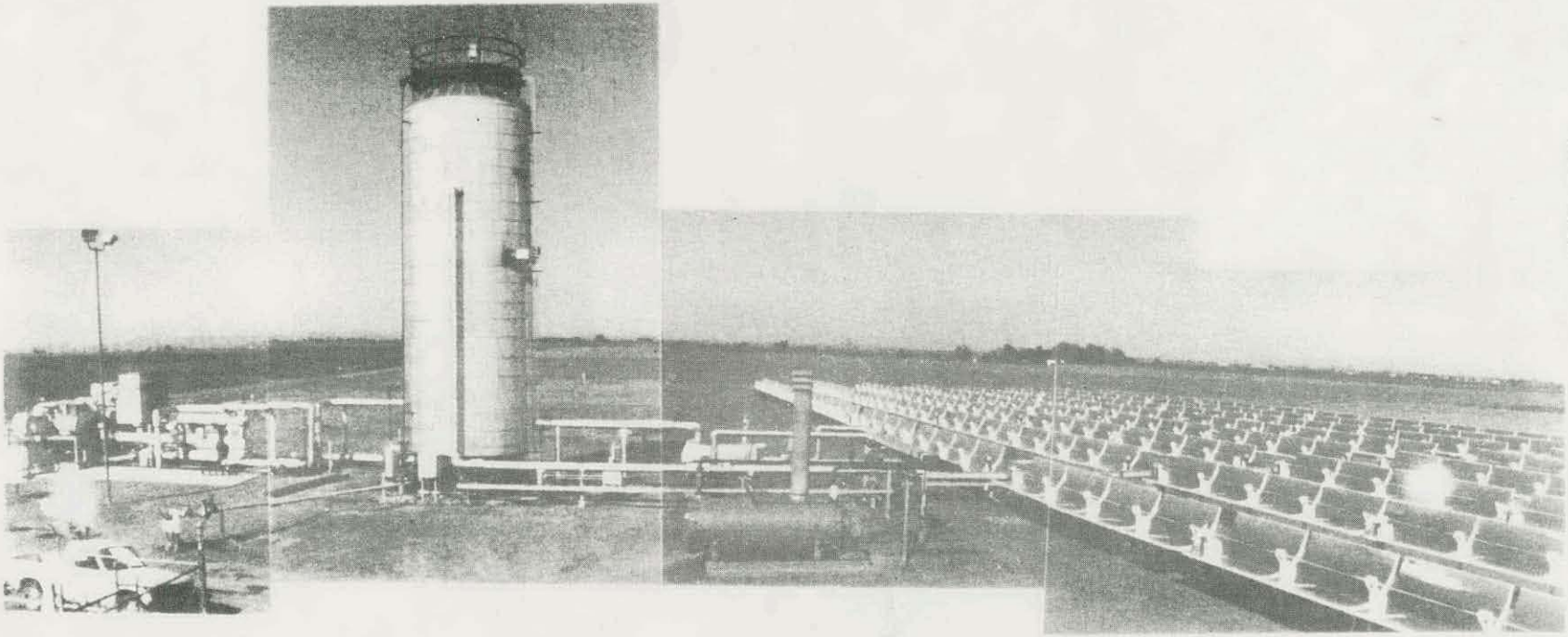

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Figure 1-1. View of completed 150 kW installation.

Figure 1-2. Site location.

expanded low-enthalpy vapor and pumping the condensate back to the vaporizer. The system flow diagram is shown in Figure 1-3.

The solar energy is converted to electrical energy by means of an organic Rankine cycle (ORC) power conversion module, using toluene as the working fluid. The unit is complete with gear reduction and a 440 VAC 60 Hz high-efficiency generator. Supporting equipment includes a vapor condenser for condensing the toluene and a vaporizer assembly consisting of a preheater, evaporator, and a superheater for vaporizing the toluene.

Energy is stored in a 30,000 gallon insulated tank 13.67 feet in inside diameter and 49 feet high. Various pumps, valves and auxiliary tanks are included, and an underground tank is provided for the makeup heat transfer oil.

The control subsystem monitors and controls the collection and storage of solar energy, the supply of hot fluid to the power generation subsystem, and the generation and supply of electric power. In addition, it protects against system-related anomalies such as high temperatures in the collector field, as well as natural events such as high gusty winds.

The main control functions are:

- Collector tracking
- Field flow
- Collector loop flow
- Thermal storage
- Vaporizer loop
- ORC system

These control functions are largely independent (not cascaded), have built-in fail-safe action or directly acting limiting devices, and are based primarily on closed loop control and analog signal transmission.

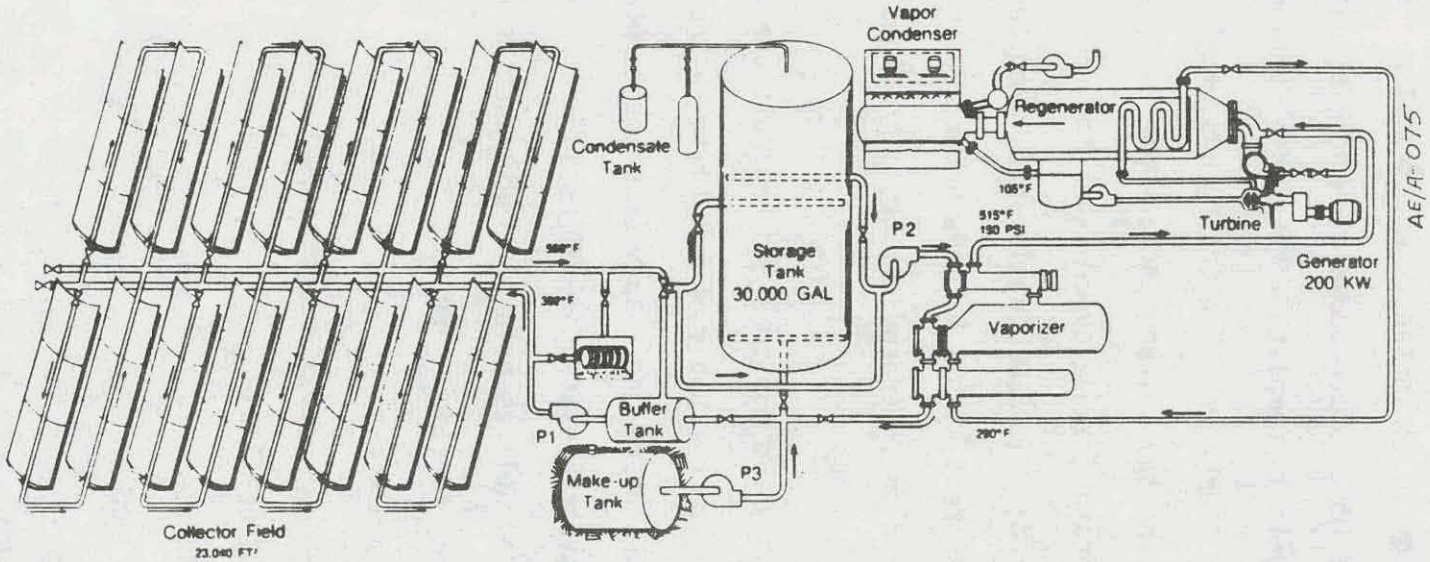

Figure 1-3. 150 kW solar-powered irrigation facility flow diagram.

The data acquisition subsystem monitors the performance of the system and measures the auxiliary power consumed by the system.

The data acquired are used for plant control and for the performance analysis of main plant components. Data are derived from:

- Weather conditions
- Collector fields
- Storage tank
- ORC unit
- Plant electrical output

Most of the data collected consist of conventional temperature, pressure, flowrate, and power measurements. Because of the large quantity of information gathered and processed, an Acurex Autodata 9 Data Acquisition System is used. This system processes raw data and determines the performance of each of the plant subsystems.

A summary of the major system elements is given in Table 1-1.

1.3 PROJECT ORGANIZATION

Acurex, as prime contractor to DOE, was supported by several major subcontractors. Table 1-2 lists the participating firms along with their areas of responsibility.

1.4 DEDICATION

Formal dedication of the system occurred on November 9, 1979. Representatives of DOE, state and local governments, Sandia, the University of Arizona, Acurex, and subcontractors were present. A photograph of the dedication event is shown in Figure 1-4. All system components operated successfully as designed. Up to the time of dedication, the collectors had operated for 260 hours, the ORC for 31.8 hours, and 2826 kWh of electrical energy were produced. The system

TABLE 1-1. SUBSYSTEM DESCRIPTION

Collector Field:	
Size	48 Acurex collector groups with N-S axis orientation = 23,040 ft^2
Fluid	Caloria HT-43
Temperatures	Inlet 392°F, outlet 550°F
Design conditions	q_i = 190 Btu/ft^2-hr
	$\dot{m}$ = 15,800 lb/hr
	System efficiency = 38.6 percent
Thermal Storage:	
Type	Stratified liquid (thermocline)
Tank size	50,000 gal -- 13.67 ft diameter x 49 ft length (30,000 gal usable storage)
Storage temperature	392°F to 550°F
Storage medium	Caloria HT-43
Insulation	12-inch thick fiberglass
Cooling System:	
Type	Vapor condenser
Water (makeup)	10 gal/min
Condensing temperature	105°F
Power Generation:	
Type	Organic Rankine Cycle
Working fluid	Toluene
Gross efficiency	20 percent

TABLE 1-1. Concluded

Vaporizer:	
Type	3-stage counterflow shell and tube
Flowrates	Caloria HT-43: 34,700 lb/hr
	Toluene: 13,900 lb/hr
Turbine:	
Type	Axial flow, single stage, impulse
Inlet conditions	515°F, 150 psia
Outlet conditions	105°F, 1.46 psia
Electrical Generator:	
Power rating	250 kVA
Gross power production	203 kW
Controls:	
Collector control	Shadow band tracker with automatic/ manual supervisory control at control console
Fluid temperature	Variable flowrate through the field for constant outlet temperature
Power generation subsystem control	Speed control using toluene flow control
Auxiliary Oil Heater:	
Type	Natural gas burner
Flowrate	35,000 lb/hr
Inlet temperature	392°F
Outlet temperature	550°F

TABLE 1-2. PARTICIPANTS AND ROLES

Participant	Roles
Acurex	Prime Contractor System Engineering and Design Thermal Storage Design Manufacturer of Concentrating Collectors Manufacturer of Major Data Acquistion Equipment: Autodata 9, Central Control Console, Weather Station
Sundstrand Energy Systems	ORC System (ORC, vaporizer, vapor condenser, generator, control cabinets)
Sullivan & Masson	Civil and Electrical Design
Marathon Steel	Thermal Storage Tank Fabrication
Tierra West	Civil and Foundation Installation
Gallo & Sgrignoli	ORC Foundation
Newbery Energy	Electrical Installation
Wismer & Becker	Mechanical Installation
Thorpe Insulation	Insulation Installation
Landauer	Control Building
Steel Engineering	Material and Equipment for Startup Support

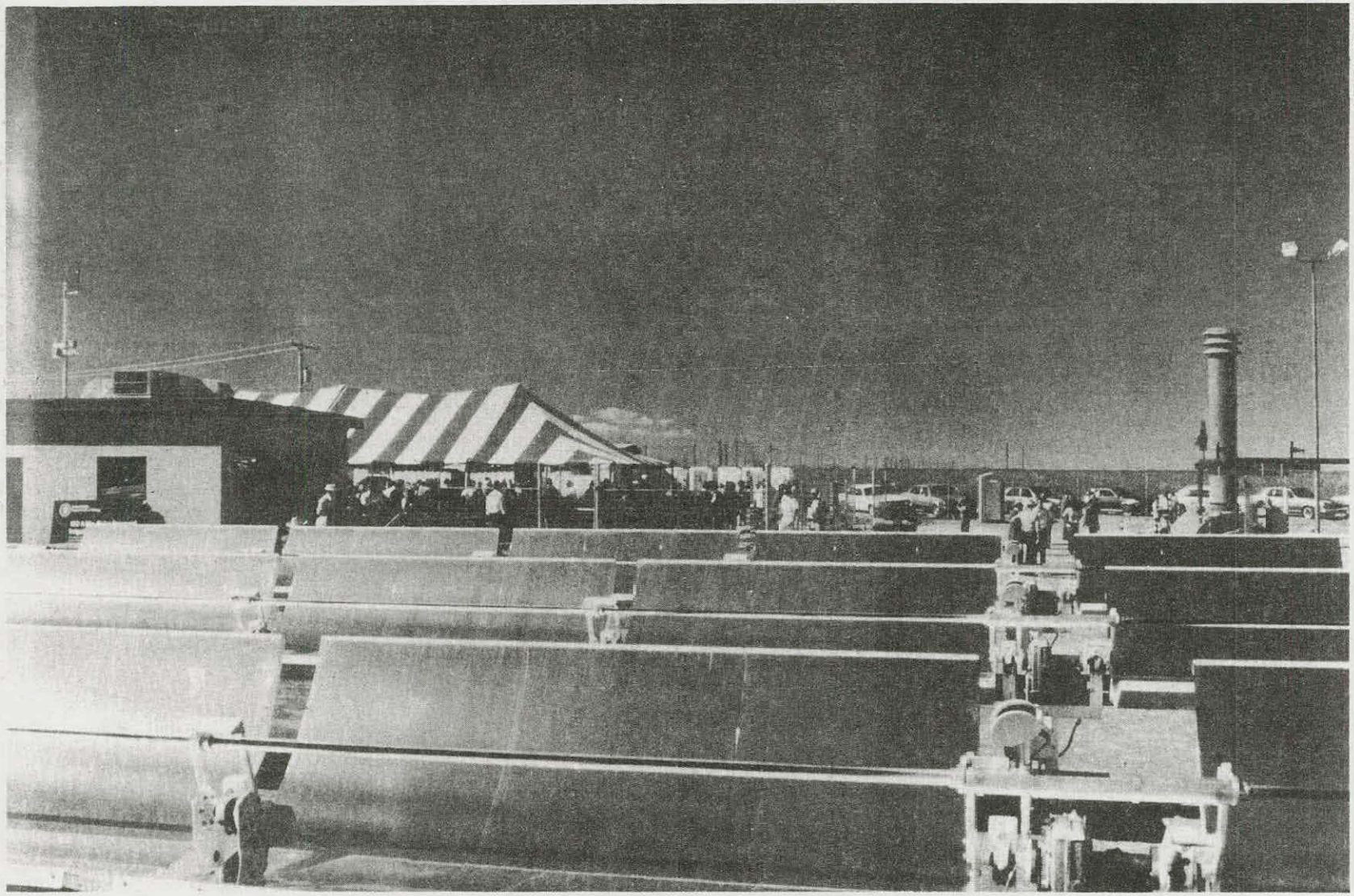

Figure 1-4. Dedication of 150 kW solar-powered irrigation facility.

was turned over to the DOE technical advisor, Sandia, and the University of Arizona on October 1, 1979, but Acurex continues to provide support to ensure successful operation and furnish feedback on system performance.

1.5 CONCLUSIONS

The successful completion of Phase II has demonstrated that reliable electrical power can be generated from solar-thermal energy. The objectives to design, construct, and operate the solar system were achieved. Limited funds allowed only half of the original collector field to be installed, but performance of the various subsystems and successful plant operation was not compromised as a result.

The balance of this report explains in detail the system, subsystem, major components and their functions. Detailed design drawings and specifications and equipment operating and maintenance manuals have been submitted under separate cover.

SECTION 2

SYSTEM DESCRIPTION

The 150 kW solar-powered deep well irrigation system is presented in schematic form in Figure 2-1. Five major subsystems are noted; solar collector field, thermal storage, power generation, heat rejection, and power distribution. Subsystems of importance not noted in the schematic, but to be discussed here are piping, control, data acquistion, and auxiliary gas-fired heater.

An aerial photograph of the entire 150 kW installation is presented in Figure 2-2 to provide an overview of the site. Features of the site clearly visible are the collector field, thermal storage tank, control building, and the power generation equipment. The power generation equipment is located on the north-west side of the storage tank. Note the open area on the east side of the site which has been prepared for expansion of the collector field. Collector foundations and pipe support piers are in place for the expanded field. Cotton crops surround the site.

Three different working fluids are utilized in the various subsytems; Caloria HT-43, toluene, and water. HT-43 is a heat transfer oil refined from petroleum by Exxon Corporation which has an operating temperature range of 30 to 600°F. This is used in the collector field and the thermal storage subsystem. Toluene is the working fluid of the power generation subsystem. Thermal energy is transferred to the toluene

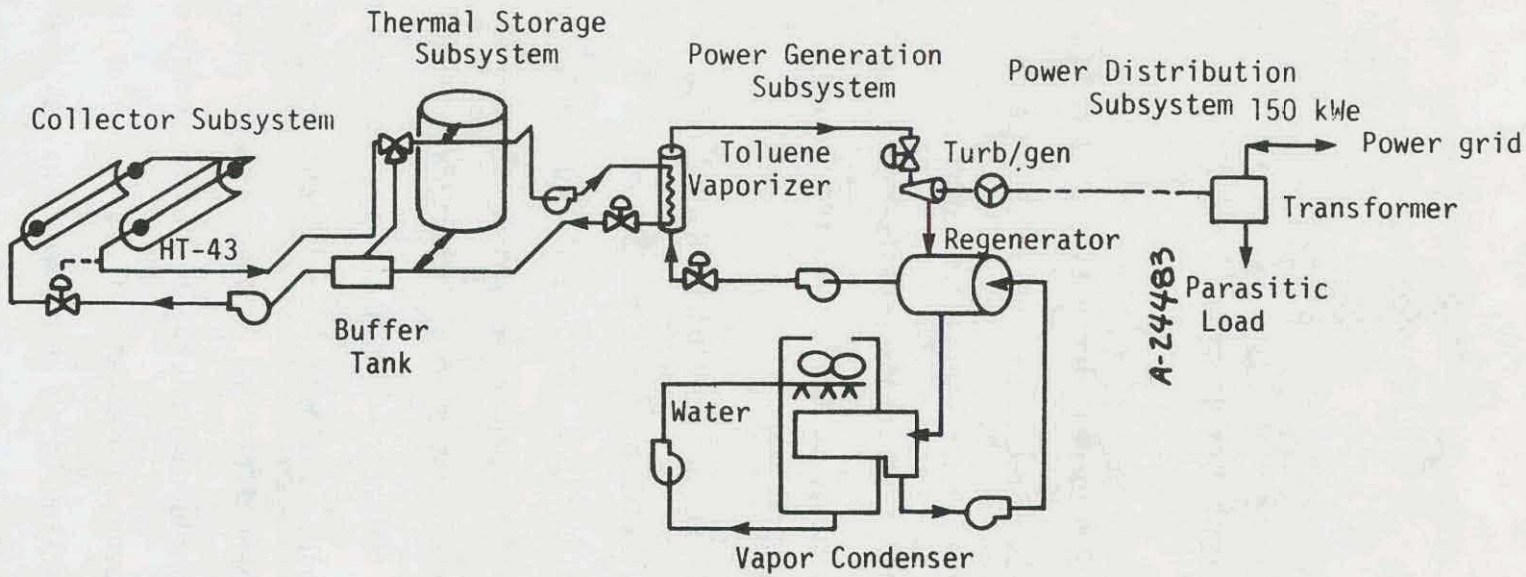

Figure 2-1. 150 kW solar-powered deep-well irrigation system schematic.

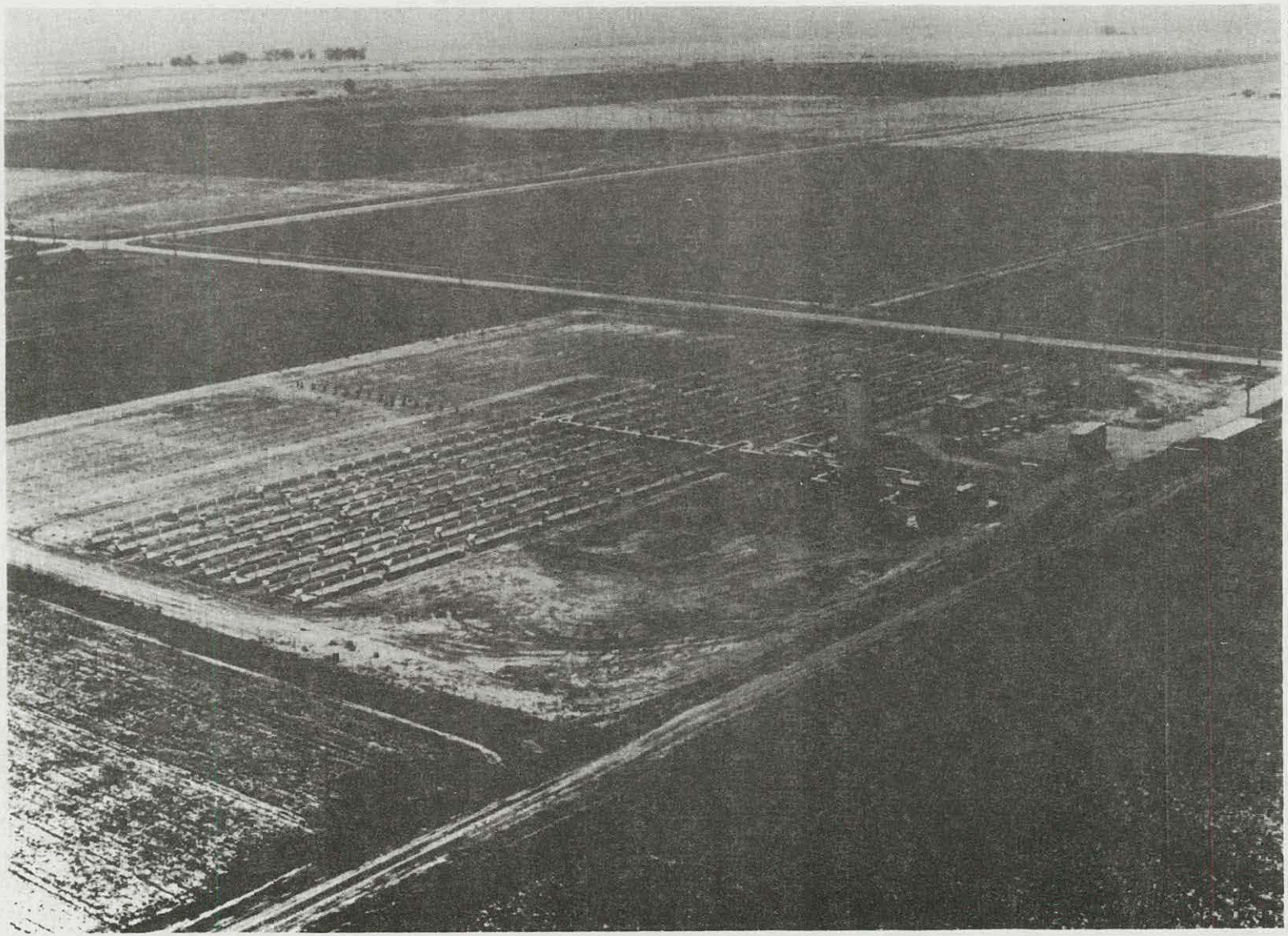

Figure 2-2. 150 kW solar-powered installation facility, Coolidge, Arizona.

from the HT-43 in the vaporizer. Toluene is an organic solvent with low toxicity which provides excellent performance in the Rankine cycle at design temperatures. Toluene was selected as the working fluid for the ORC because it is relatively inexpensive, widely used, and its properties are well documented. In addition, toluene has a high molecular weight and gains superheat when expanded from high- to low- pressure vapor, These properties allow it to be used to drive a single-stage impulse turbine more efficiently than other fluids. Subsequent to expansion of toluene through the turbine, toluene is condensed in the heat removal subsystem. The heat removal system utilizes evaporation of water to the atmosphere as the heat removal mechanism.

General operating conditions of the various subsystems are summarized in Table 2-1. Conditions listed are for the insolation of 275 Btu/hr-ft^2 and net electrical output of 150 kW.

TABLE 2-1. GENERAL OPERATING CONDITIONS

	Collector field	Storage	Power Generation	Heat Removal
Fluid	HT-43	HT-43	Toluene	Water
Operating temperature (^oF)	550	550	515	90
Max. pressure (psia)	77	25	150	35
Nominal flowrate (lb/hr)	30,500	--	13,900	100,000

System operation is constrained by several environmental conditions. By far, the most important condition is the solar insolation level. The collector field will operate (track and collect energy) when the insolation is at or above 100 Btu/ft^2-hr. There is no upper limit within physical realities. When the wind speed, as measured by the anemometer on the control building, reaches 30 mph, the collector field will stow itself for structural protection. The collector field will not be activated in automatic control if the ambient temperature is below 30°F. The final environmental constraint is the wet bulb temperature. If the temperature exceeds 74°F the heat rejection subsystem will loose some capacity, resulting in decreased performance of the power generation subsytem.

The collector field consists of 23,040 square feet of gross aperture area arranged in eight parallel flow loops. Main piping manifolds run through the center of the field on an east-west axis. A flow loop consists of a row of collectors from the manifold to field edge and a second row returning flow to the field center. Collectors are Acurex Model 3001 with polished anodized aluminum reflectors.

Thermal storage for the system is contained in the large vertical tank on the west side of the collector field. The tank is 49 feet tall and 13.67 feet in diameter and contains 30,000 gallons of fluid useful in thermal storage. The working fluid is Caloria HT-43.

The main equipment items contained in the power generation subsystem are the vaporizer, turbine/generator set, regenerator, and related pumps. Equipment in the power generation and heat rejection subsystems were provided by Sundstrand Energy Systems.

The heat rejection subsystem consists mainly of the vapor condenser which condenses toluene vapor after it exits the turbine. Heat rejection is accomplished by a water spray over the condensing coils. A fan provides air flow through the unit to increase heat transfer and the cooling water is recirculated. Makeup water is continuously added to offset evaporative and blowdown losses.

The power distribution subsystem is composed of electrical equipment and cables which route and process the generated electrical power from the generator to the public utility grid.

The control subsystems serve two primary areas; collector field operation and power generation subsystem operation. The control philosophy provides capability for totally automatic operation of the plant. Manual overrides are provided for all phases of operation so that various experiments may be performed on subsystems.

A data acquisition subsystem has been included in the plant to enable performance evaluations of the various equipment and subsystems, as well as the entire plant. A large number of sensors have been built into the plant to monitor various parameters of interest. Data signals from these sensors are transmitted to the control room where they are recorded on magnetic tape.

An auxiliary natural gas-fired heater has been installed in the HT-43 piping to provide additional experimental flexibility. This heater has a temperature and heating capability approximately equal to the solar collector field at maximum insolation levels. The heater allows tests to be performed in the storage and power generations subsystems during periods of low solar insolation.

CAUTION

The collector field and the heater should not be operated at the same time. Too many parameters must be monitored, and the chance for a flow upset and overtemperature problems is too great.

The major subsystems of the plant are interconnected with the piping subsystem. Included in this subsystem are piping, insulation, and minor inline equipment such as various small tanks, pumps, valves and strainers.

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SECTION 3

SUBSYSTEM DESCRIPTION

The following section describes the various subsystems in greater detail and present numerous pictures of the completed installation of equipment.

3.1 COLLECTOR FIELD

The collector field installed at the site is approximately one-half the size for which the system design was optimized. The optimum design specified 17 parallel loops of collectors for a total field size of 48,960 square feet of aperture area. The installed field consists of 8 loops for a total of 23,040 square feet. The field reduction was necessitated by rising collector and construction costs. Before the field reduction decision was made, the site had been prepared for the full-size field. This preparation included foundations for collectors and pipe supports. These foundations are visible in the aerial photographs of the site. These foundations were left in place with the intention that the remainder of the field would be eventually installed. The HT-43 piping and field circulation pump are sized to service the full-size field.

The predicted performance of the installed collector field is presented in Table 3-1. The flowrate through the field is controlled so that the outlet temperature remains nearly constant at 550°F. At maximum insolation, the rate of energy collection is approximately

TABLE 3-1. COLLECTOR FIELD PERFORMANCE

Insolation (Btu/ft^2-hr)	Field outlet temp (^oF)	Field flowrate (lb/hr)	Collected energy (mBtu/hr)
100 (min)	550	5,080	0.51
190 (nom)	550	16,700	1.69
275 (max)	550	30,500	3.08

90 percent of that required by the power generation subsystem to produce a net output of 150 kW. The effect of the reduced collector field is that the thermal storage subsystem must be charged to a large degree prior to initiating the power generation subsystem. Once started, the power generation subsystem depletes storage at a greater rate than it can be replaced. Thus, the plant may still produce a net 150 kW output, but the operating time is reduced.

The schematic presented in Figure 3-1 represents the equipment contained in a collector flow loop. The entire field consists of eight such flow loops, and each one is made up of six collector groups. A group consists of six single 6- by 10-foot collector modules for a total of 480 ft^2 of aperture area. The groups are connected to each other by flexible hoses and interconnecting piping. Each group has its own tracker and drive mechanism. The flow loop may be isolated from the system piping by manual valves near the interfaces with the supply and return headers. The loop may also be isolated from the system by the air operated shutoff valve and the check valve. The air operated valve may be actuated from the control room. The flow control valve regulates the HT-43 flowrate through the loop. Resistance temperature detectors (RTD's) are located at

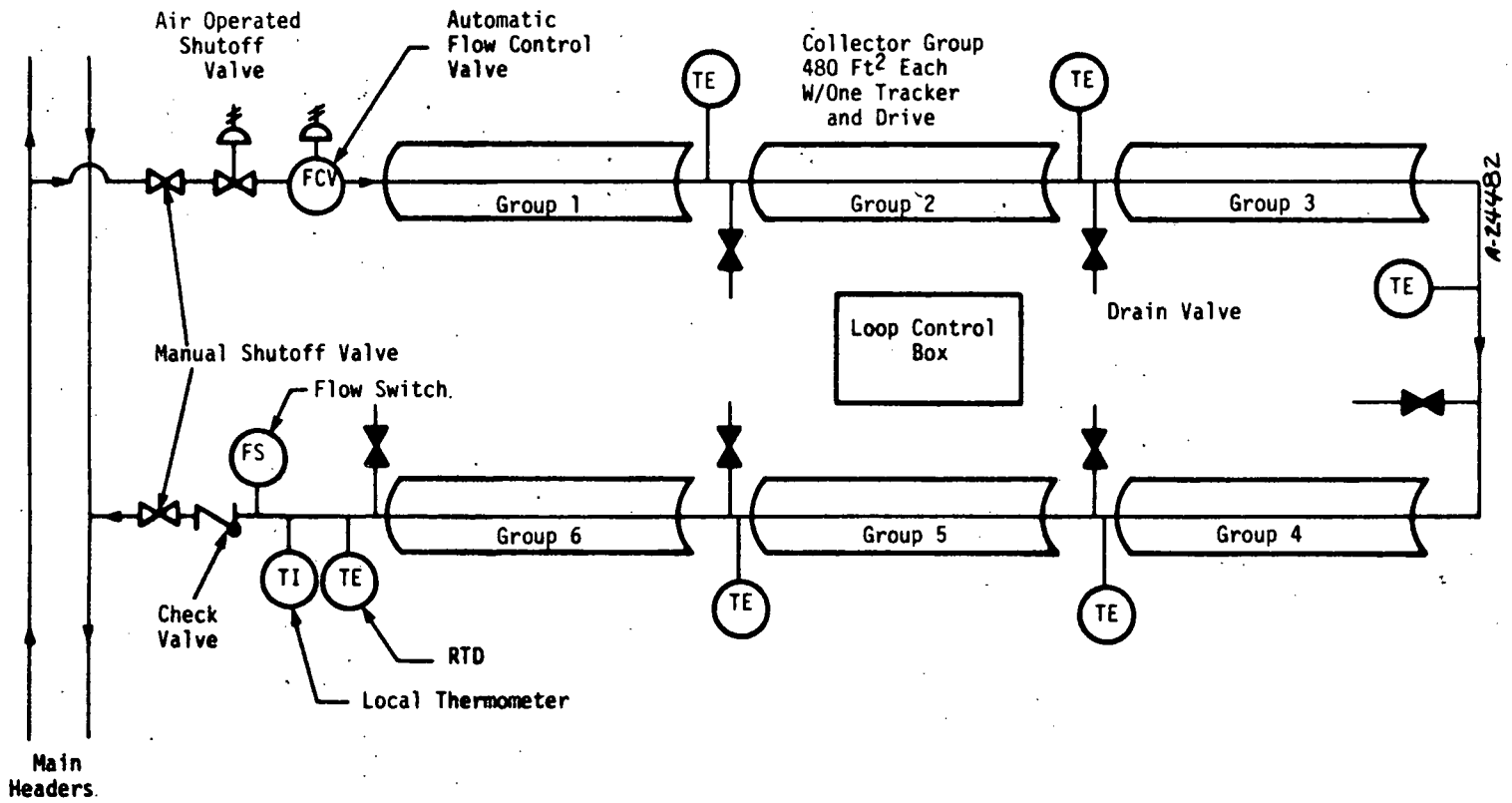

Figure 3-1. Collector field control.

the outlet of each collector group to sense any overtemperature condition. These temperatures may be viewed in digital form in the loop control box. The outlet temperature of the last collector in the loop is transmitted to the control room for data recording. The flow switch is a safety interlock in the control system which prohibits tracking of the collectors until flow has been established in the loop.

Figure 3-2 presents an overall picture of the installed collector field from the south edge of the field. The collectors are tracking as indicated by the bright receiver tubes. The insulated piping in the foreground connects the third and fourth collector groups in the flow loop. Note the thermal storage tank and the control room in the background.

A view down a collector row from the south edge of the field is shown in Figure 3-3. Note the main piping headers traversing the center of the field.

Figure 3-4 shows a close view of the end of a collector group with the flex hose and the receiver tube in view. This picture is taken from the center of the field looking south at the last collector row. Note the illumination of the receiver.

The insulated piping between inline collector groups is illustrated in Figure 3-5. This view is looking north at the last group in a row.

The piping interface with the return header is visible in Figure 3-6. Details of the collector post/foundation interface are also shown clearly. The horizontal structure parallel to and just below the return header is a cable tray which contains instrument air lines.

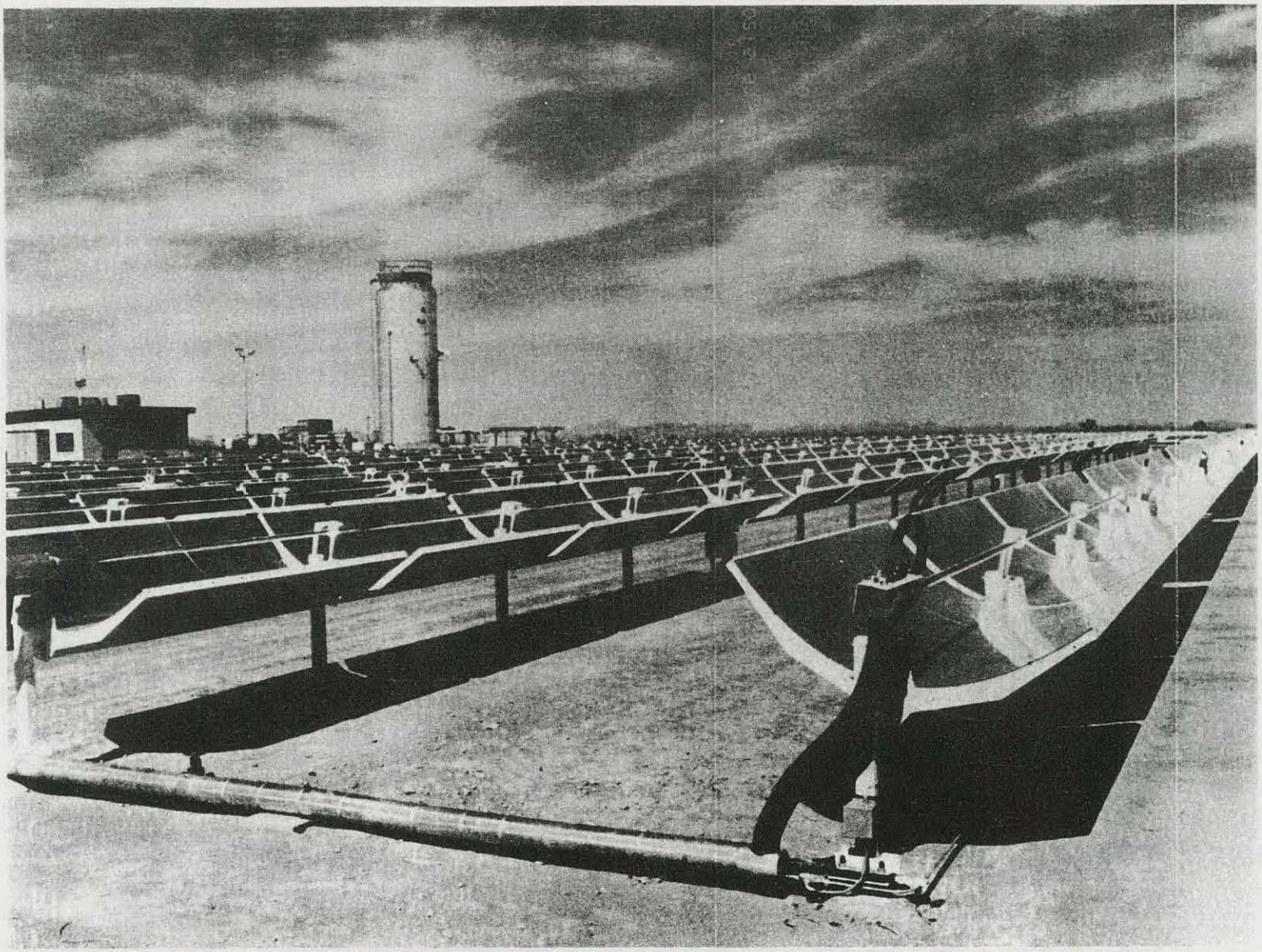

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Figure 3-2. Collector field viewed from south side.

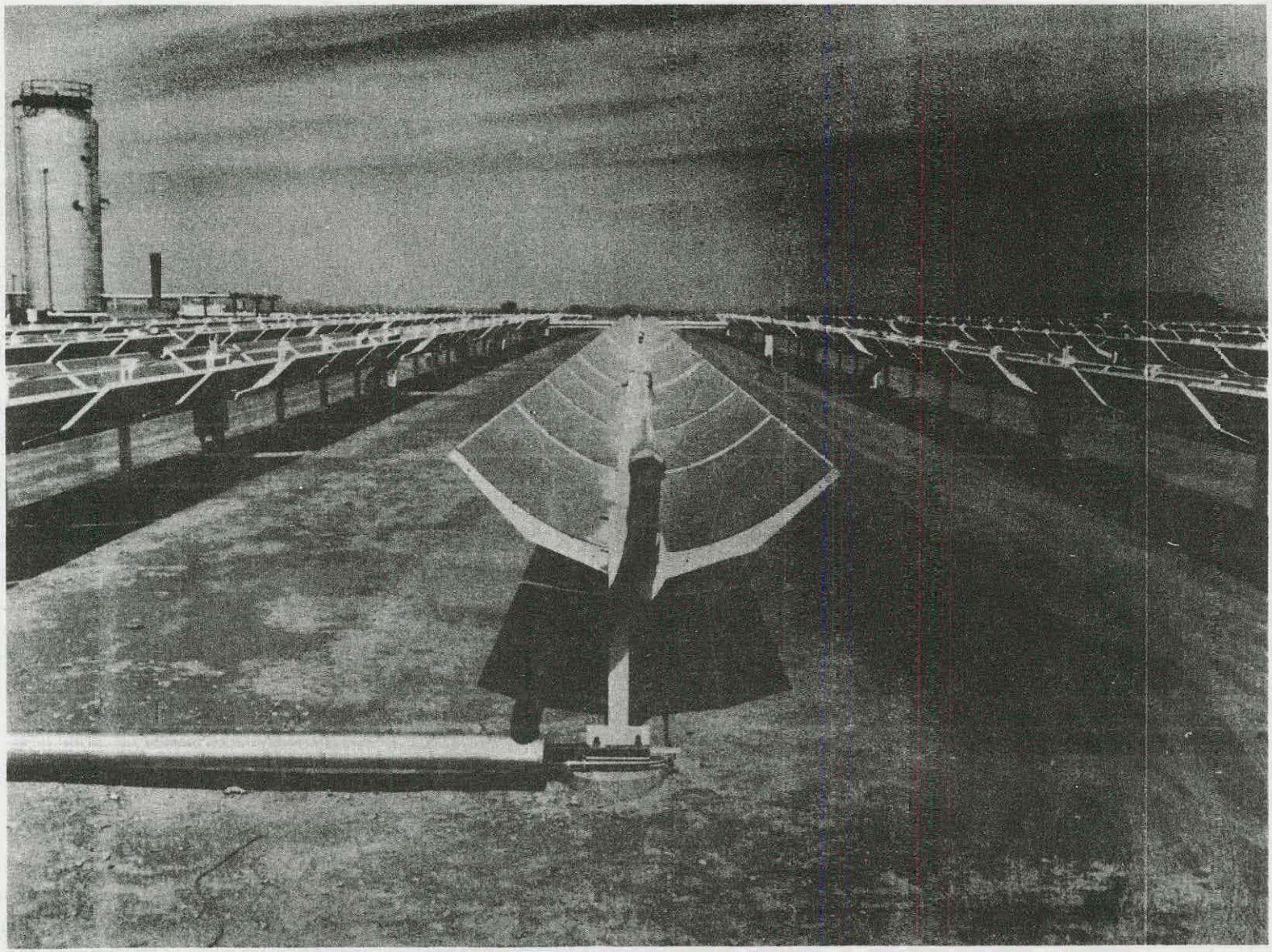

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Figure 3-3. View down a collector row.

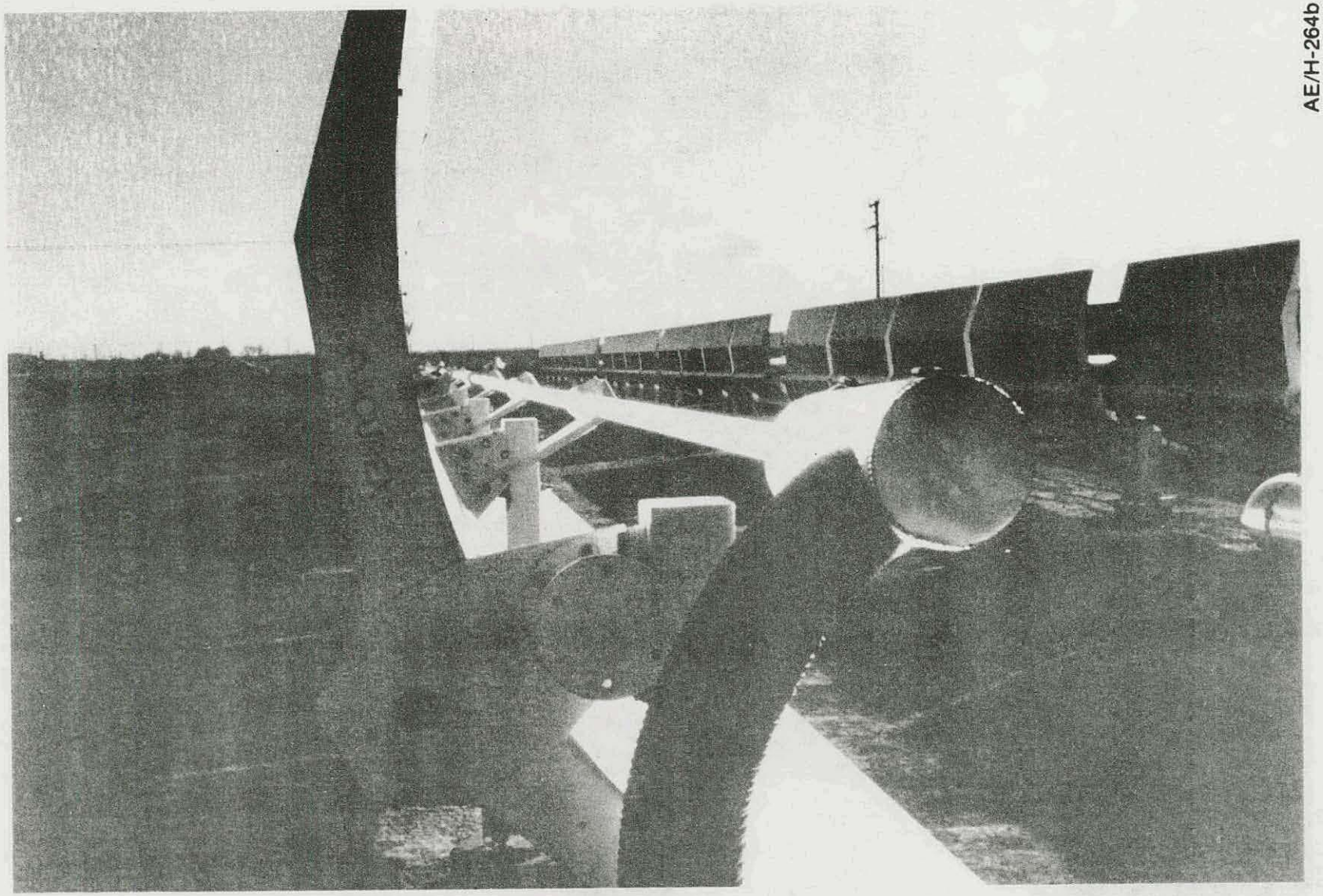

Figure 3-4. View of collector looking south.

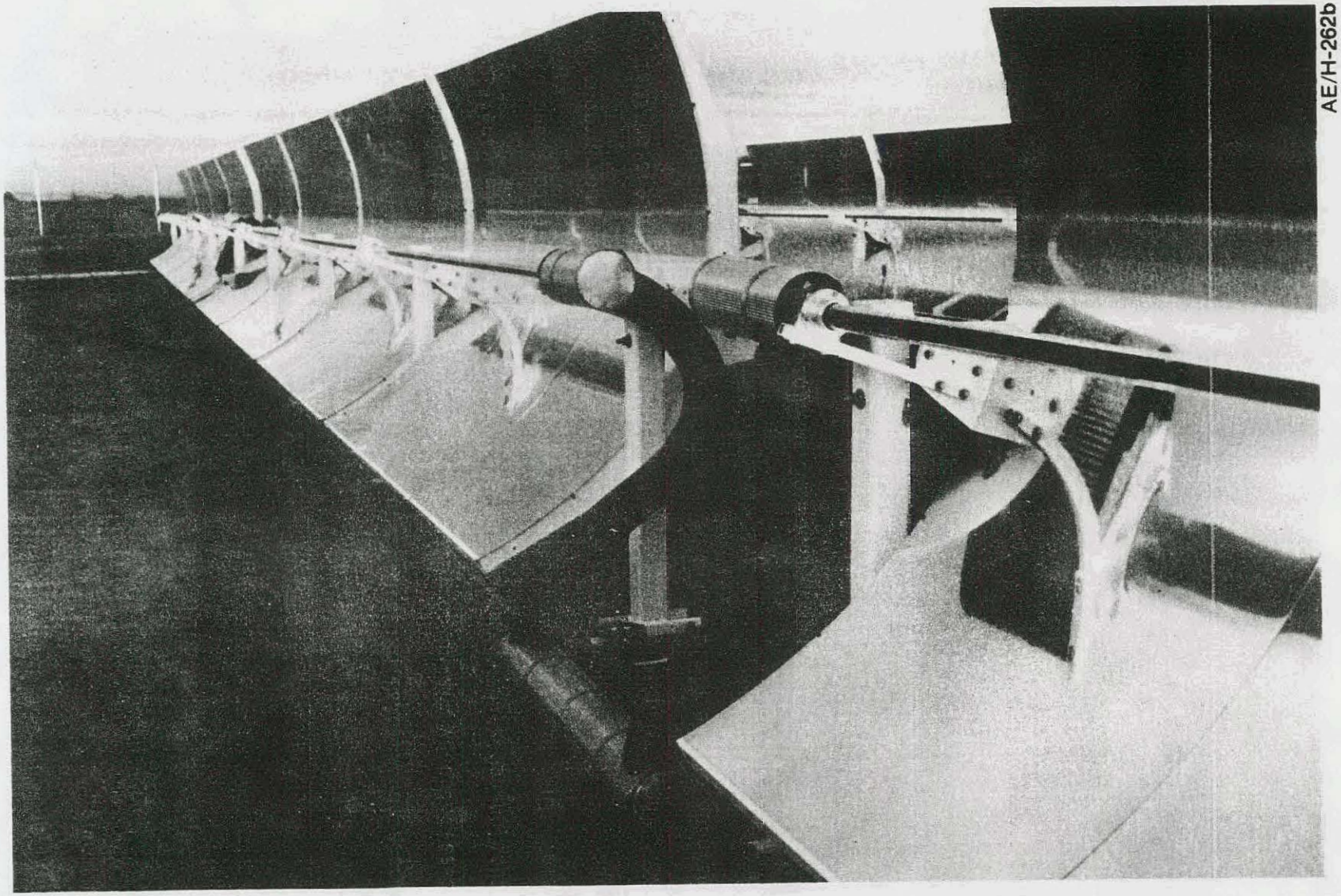

Figure 3-5. Interface between collector groups.

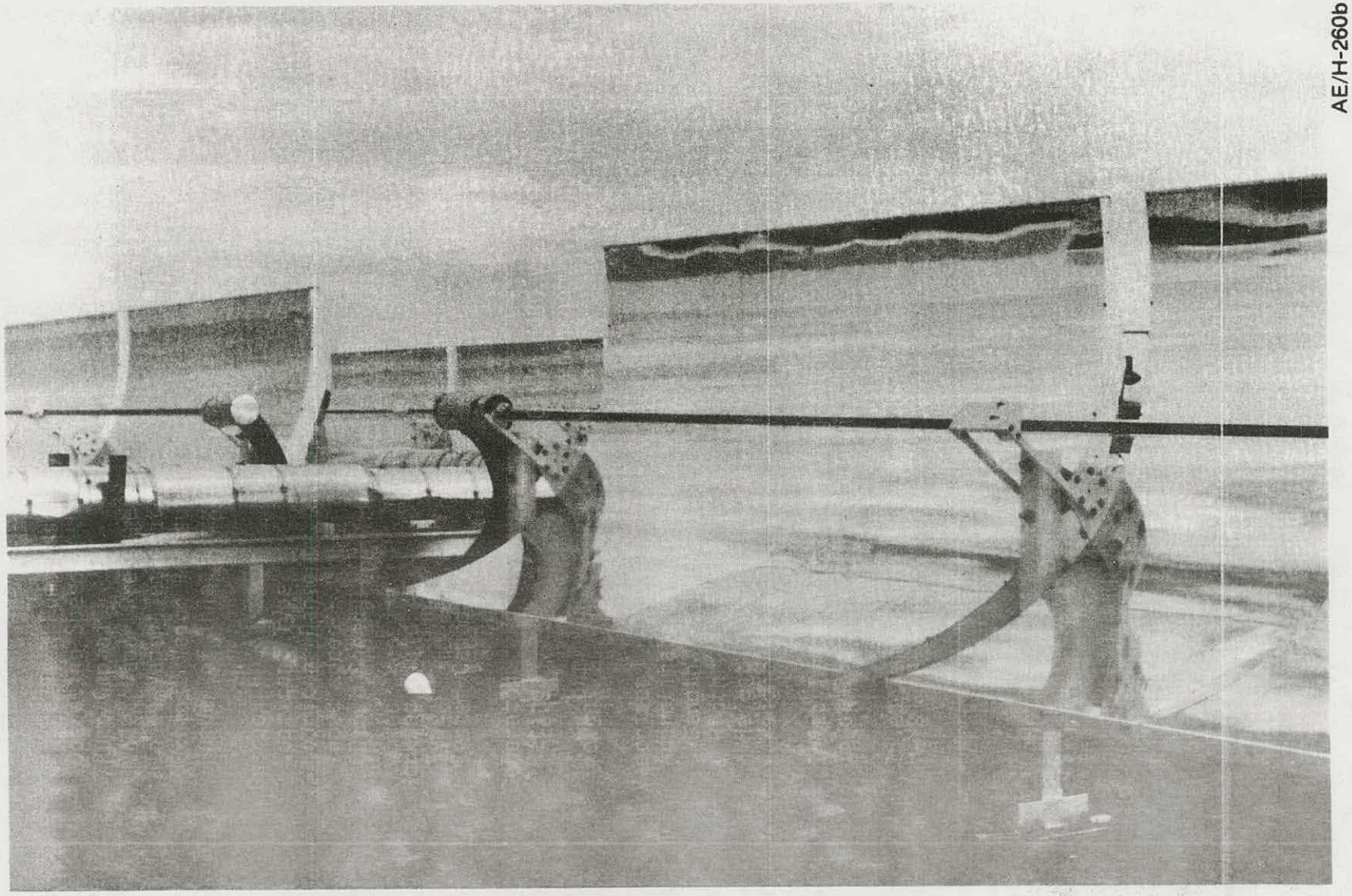

Figure 3-6. Collector/return header interface.

Figure 3-7 illustrates the collector field at sunset when the insolation is too poor to operate. The collectors have gone to the stow position facing east, awaiting sunrise. The box in the foreground is the loop control box.

3.2 THERMAL STORAGE

The thermal storage subsystem serves the function of decoupling the power generation subsystem from the collector field. Since the most severe operating conditions of the turbine are startup and shutdown, minimizing the number of operating cycles will result in maximum equipment life. The rate of energy collection by the collector field is constantly varying and is generally unpredictable at any given time of day due to clouds and other atmospheric conditions. Thus, it is desirable to have a means of storing a quantity of energy prior to starting the power generation subsystem to avoid numerous shutdowns during the day.

The thermal storage subsystem consists mainly of a large vessel containing Caloria HT-43. The vessel is sized to store thermal energy for 6 hours of operation of the power generation subsystem. This is equivalent to 30,000 gallons of usable fluid. Manifolds for injecting and extracting the fluid of the tank are designed for very low turbulence and to distribute fluid over the entire cross section of the vessel. With these manifolds, mixing of hot fluid and cooler fluid is avoided. This allows the development of a thermocline, or a narrow transition thickness between hot fluid and cooler fluid.

A vapor space is maintained in the top of the tank to allow for expansion of the fluid as it is heated. This space is filled with pressurized nitrogen to avoid oxidation of the fluid. The pressure in the vapor area is maintained in the range of 1 to 10 psig.

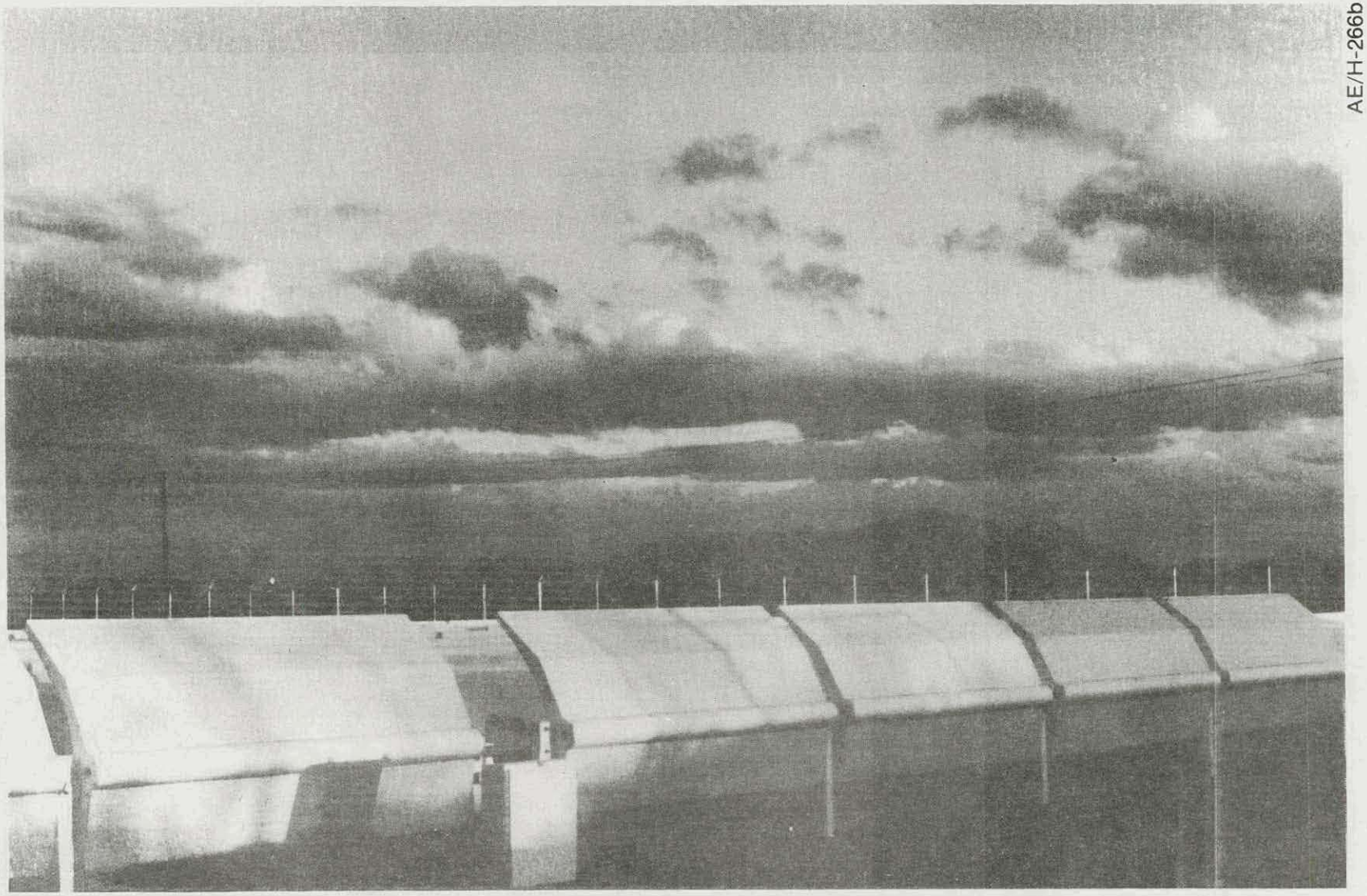

Figure 3-7. Collector field at sunset.

The normal operating temperature of the thermal storage vessel is $550^{o}F$ for hot fluid and $392^{o}F$ for cooler fluid returned from the power generation subsystem.

The vessel is fabricated of steel and stamped with the ASME code. The pressure rating is 30 psig.

The vessel is instrumented internally with temperature elements for study of the temperature profile within the fluid. A vertical instrument tree near the center of the vessel provides measurements at 1-foot intervals near the top fluid level and 2-foot intervals over the remainder of the fluid column. Two horizontal instrument trees oriented at right angles provide measurements at 1-foot intervals across the vessel section at approximately the two-thirds level of the fluid column.

The vessel is insulated with 12 inches of fiberglass insulation on the shell and both heads. The top and sides are protected from moisture by corrugated aluminum sheet. The support skirt is thermally isolated from the vessel and is left uninsulated to avoid high temperatures in contact with the concrete foundation.

An overall view of the thermal storage vessel is presented in Figure 3-8. This view is looking north. The external insulated vertical pipe entering the tank at the three-fourths level is the hot oil input to the tank from the collector field. Fluid level in the tank is maintained at just above this entry point. The horizontal insulated pipe interfacing with the right side of the vessel near the bottom is the cool fluid supply to the collector field. The active thermal storage volume is between these two nozzles.

Figure 3-9 shows the base of the thermal storage vessel and some of the other equipment of the thermal storage subsystem. The small vertical

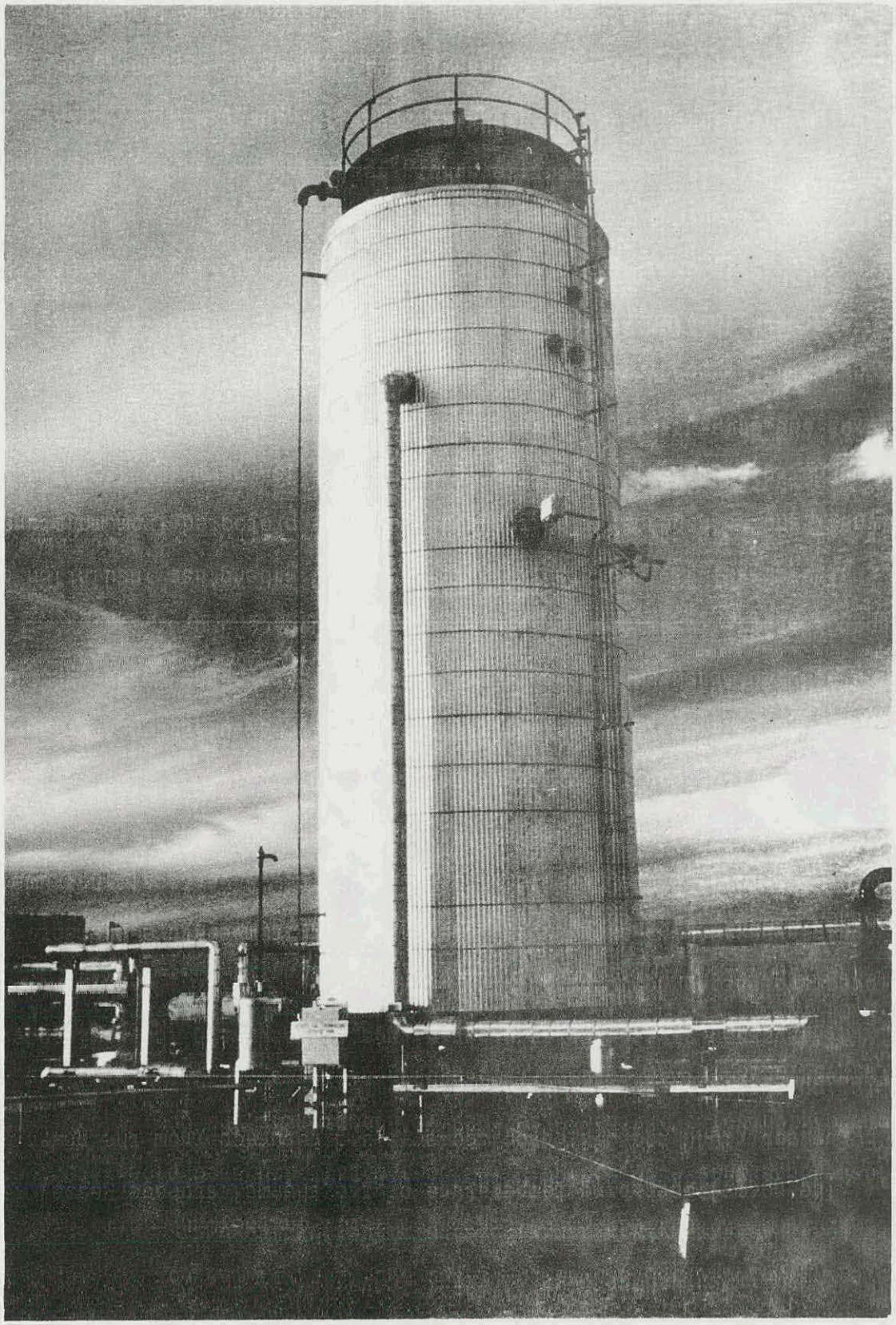

Figure 3-8. Thermal storage vessel.

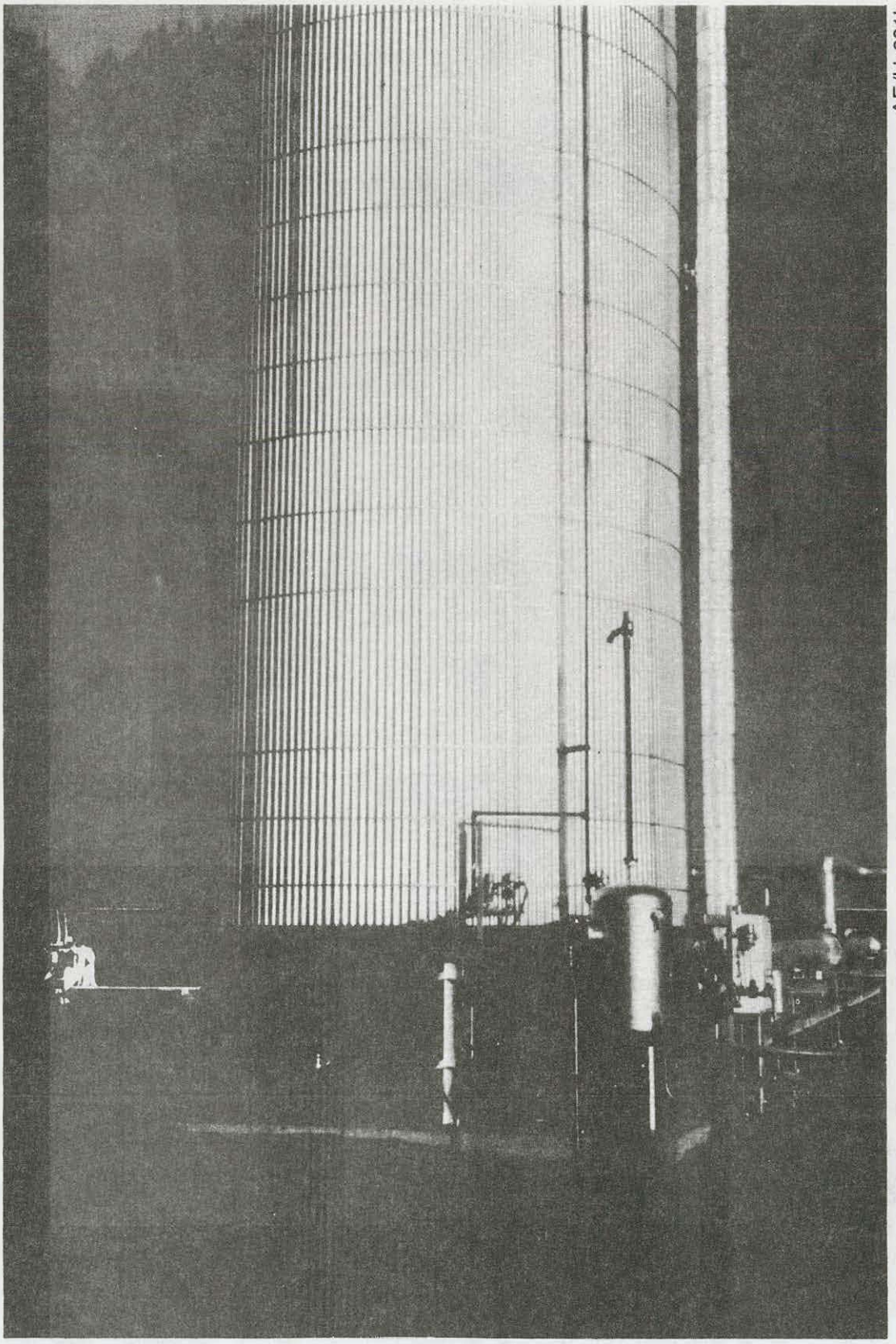

Figure 3-9. Thermal storage subsystem.

vessel is the condensate tank which cools any gas released to the atmosphere due to high internal pressure in the thermal storage vessel. This gas may contain condensable hydrocarbons produced by thermal breakdown of the HT-43. These hydrocarbons are collected in the condensate tank and periodically drained.

The nitrogen bottles used to pressurize the thermal storage vessel are visible on the foundation at the center of the vessel in this view. This view is looking east.

3.3 POWER GENERATION SUBSYSTEM

The principal components of the power generation subsystem are the vaporizer assembly, power conversion module, and the generator. The solar generated thermal energy of the HT-43 from the storage tank is transferred to toluene in the vaporizer. The toluene is expanded through the turbine to drive the generator producing electrical power.

Selected particulars describing size, weight, capacity and operating conditions for the major components of the subystem are listed in Table 3-2.

An overall view of the installed subsystem is presented in Figure 3-10. From right to left the major items in view are the storage vessel, piping run to vaporizer, vaporizer, generator, turbine, regenerator housing, and vapor condenser.

The vaporizer assembly consists of three sections; the preheater, vaporizer, and superheater. The assembly is a fluid-to-fluid heat exchanger. A sketch of the equipment (Figure 3-11) identifies major items in the assembly.

Caloria that has been heated by the solar collectors is pumped through the superheater section, the vaporizer section, the preheater

TABLE 3-2. POWER GENERATION SUBSYSTEM PARTICULARS

Model Number		ORC200S01
System Part Number		725559
Power Conversion Module		
Approximate Dimensions		
Length		24 ft
Width		8 ft
Height		10 ft
Weight (Dry)		28,000 lb
Turbine/Feed Pump Assembly		
Operating Speed		9,300 rpm
Pump Capacity		35 gpm
Inlet Vapor Pressure		150 psia
Inlet Vapor Temperature		515°F
Exhaust Vapor Pressure		1.46 psia
Number of Inlet Nozzles		5
Gearbox		
Lubricant Type		MIL-L-23699
Lubricant Capacity		7-9 gal
Input speed		9,300 rpm
OUtput Speed		1,800 rpm
Working Fluid		
Type		Reagent Grade Toluene
System Capacity		1,100 gal
Generator		
Ratings		250 kVA, 480 Vac, 60 Hz, Synchronous, 3-phase
Weight		6,000 lb
Vaporizer		
Approximate Dimensions		
Length		23 ft
Width		5 ft
Height		8 ft
Weight (Dry)		9,600 lb
Inlet Temperature	Working fluid (toluene)	290°F
Inlet Pressure	Working fluid (toluene)	165 psia
Inlet Temperature	Caloria	550°F
Inlet Pressure	Caloria	20 psia

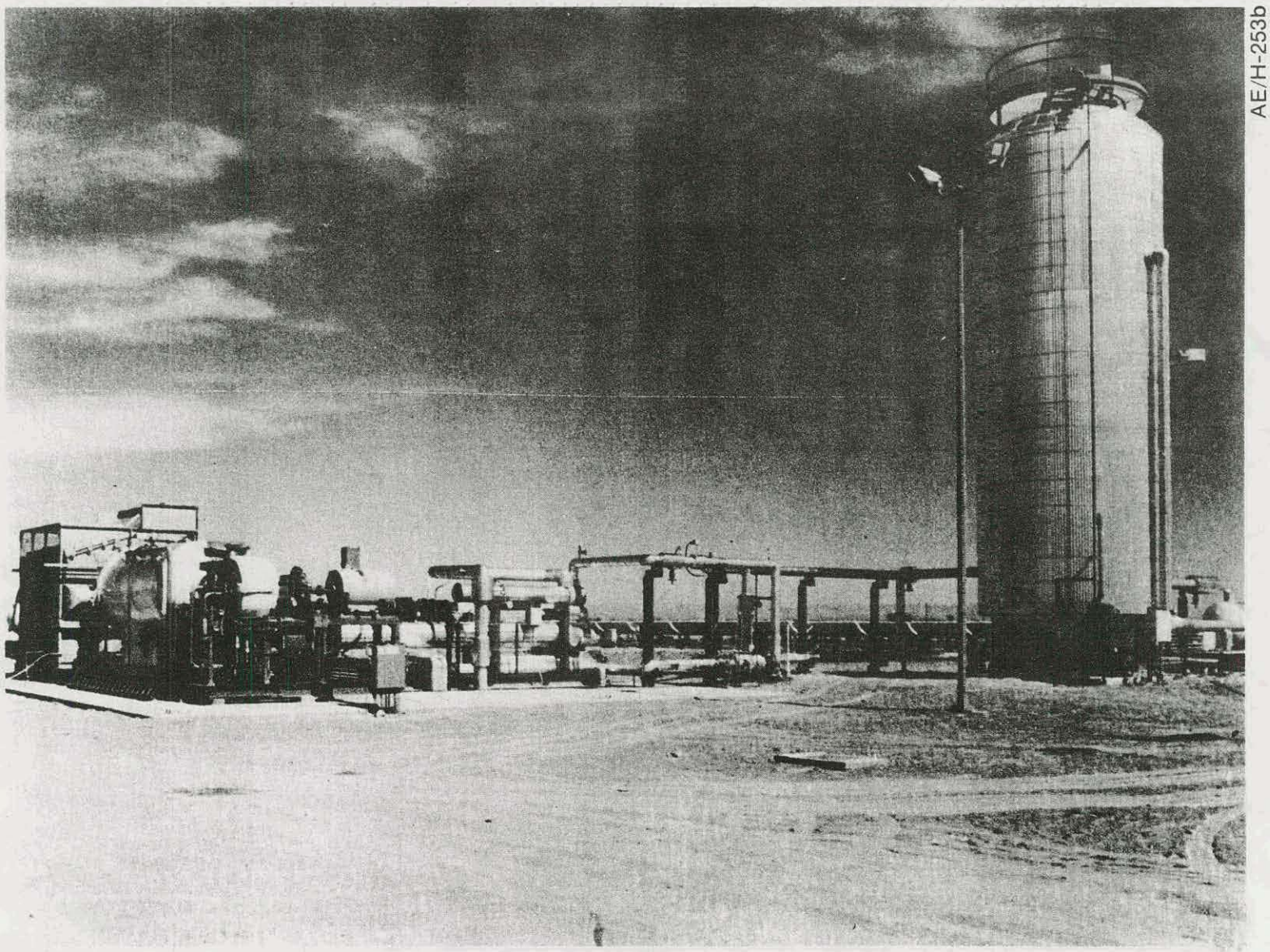

Figure 3-10. Power generation subsystem.

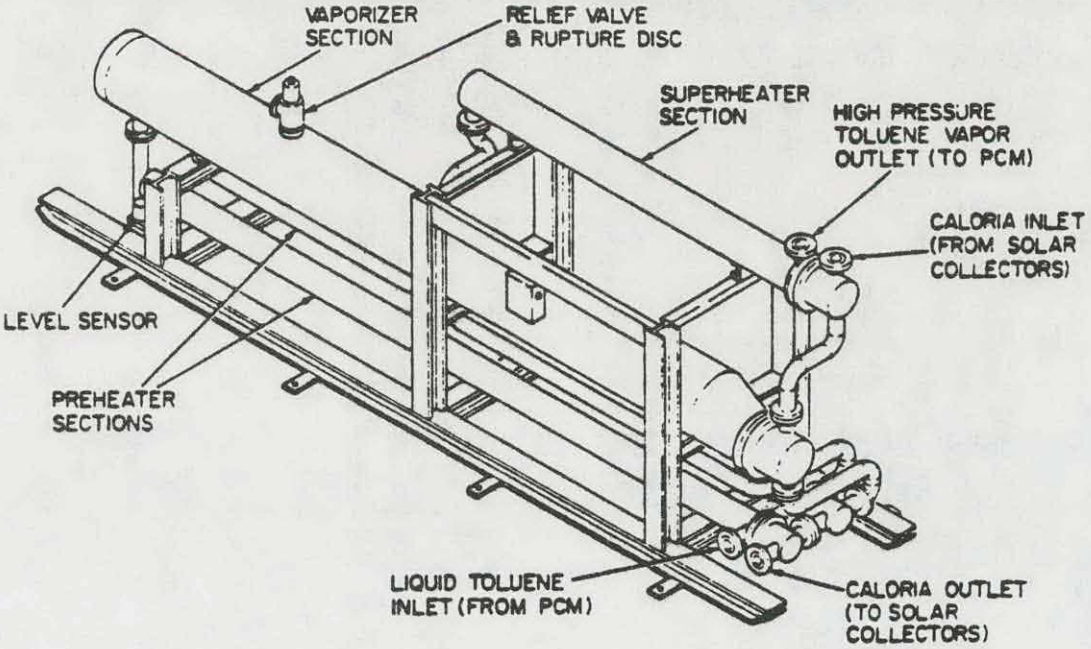

Figure 3-11. Vaporizer assembly.

sections; and then pumped back through the solar collectors. At the same time, toluene is pumped into the preheater, through the vaporizer and superheater sections, transferring the heat from the caloria to the toluene. This heat transfer vaporizes the toluene which is then piped to the turbine on the Power Conversion Module (PCM). A level sensor in the vaporizer section is provided to signal the level control valve on the PCM to open or close as needed to regulate the amount of toluene entering the vaporizer assembly. This ensures that there is the correct amount of toluene in the vaporizer assembly to meet the vapor needs of the system.

Figure 3-12 presents a view of the installed vaporizer. Here, the vaporizer as well as piping has been insulated. Toluene piping to and from the PCM runs in an underground, covered trench.

The PCM components include the turbine/feed pump assembly, gearbox, regenerator assembly, noncondensable removal system, and liquid/vapor toluene plumbing with related filters and pumps. These components are identified in Figure 3-13. A description of the components follows.

1. Turbine/Feed Pump Assembly

   The turbine/feed pump assembly is mounted on a welded framework at one end of the PCM frame. The turbine exhaust outlet is connected to the regenerator by a bellows. The output shaft is connected to the gearbox by a flexible steel coupling. the two-stage main feed pump is mounted on the other end of the turbine shaft. The turbine bearings are lubricated with the working fluid (toluene). Normal operating speed of the turbine is 9,300 revolutions per minute.

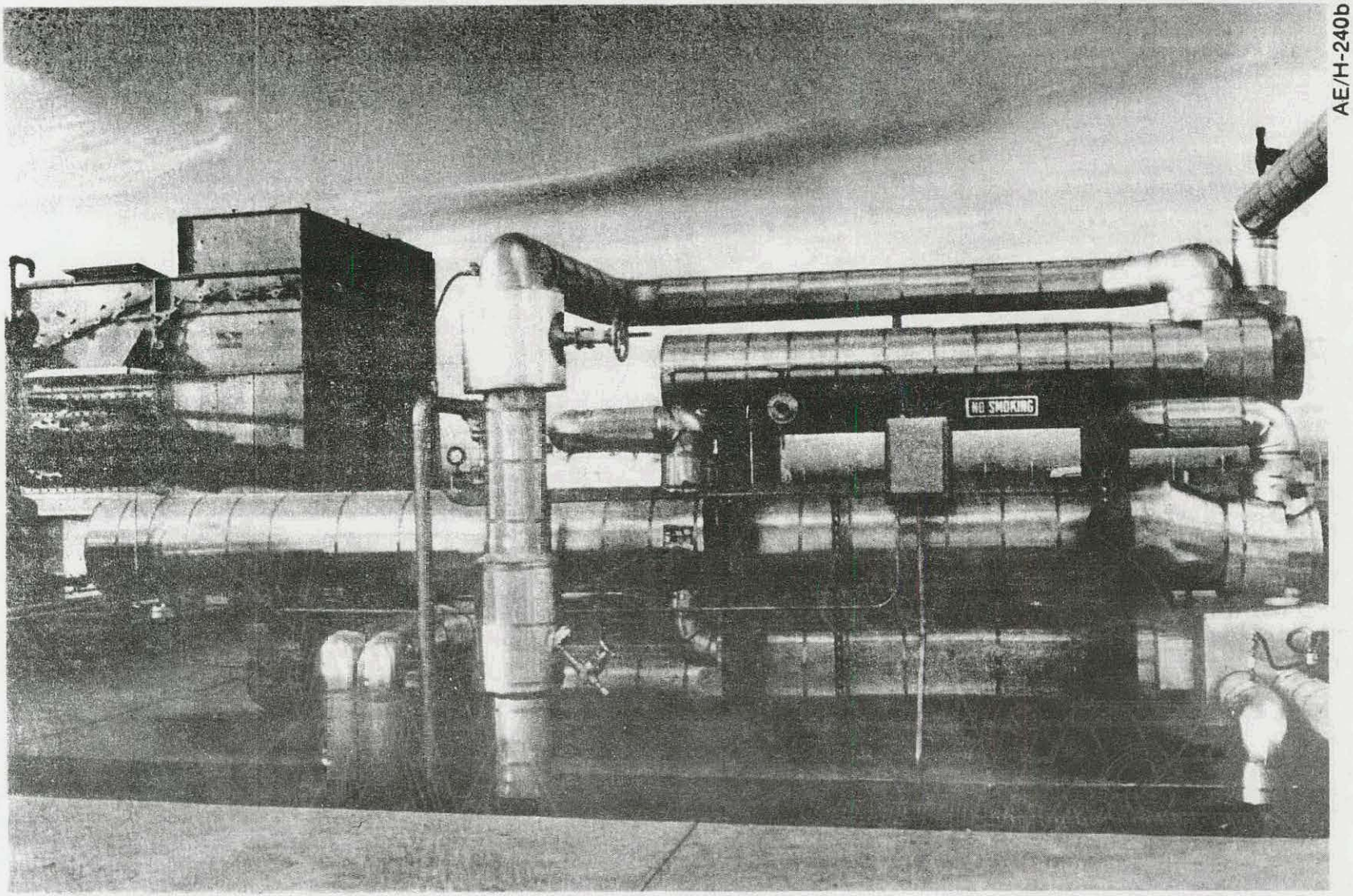

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Figure 3-12. View of vaporizer assembly.

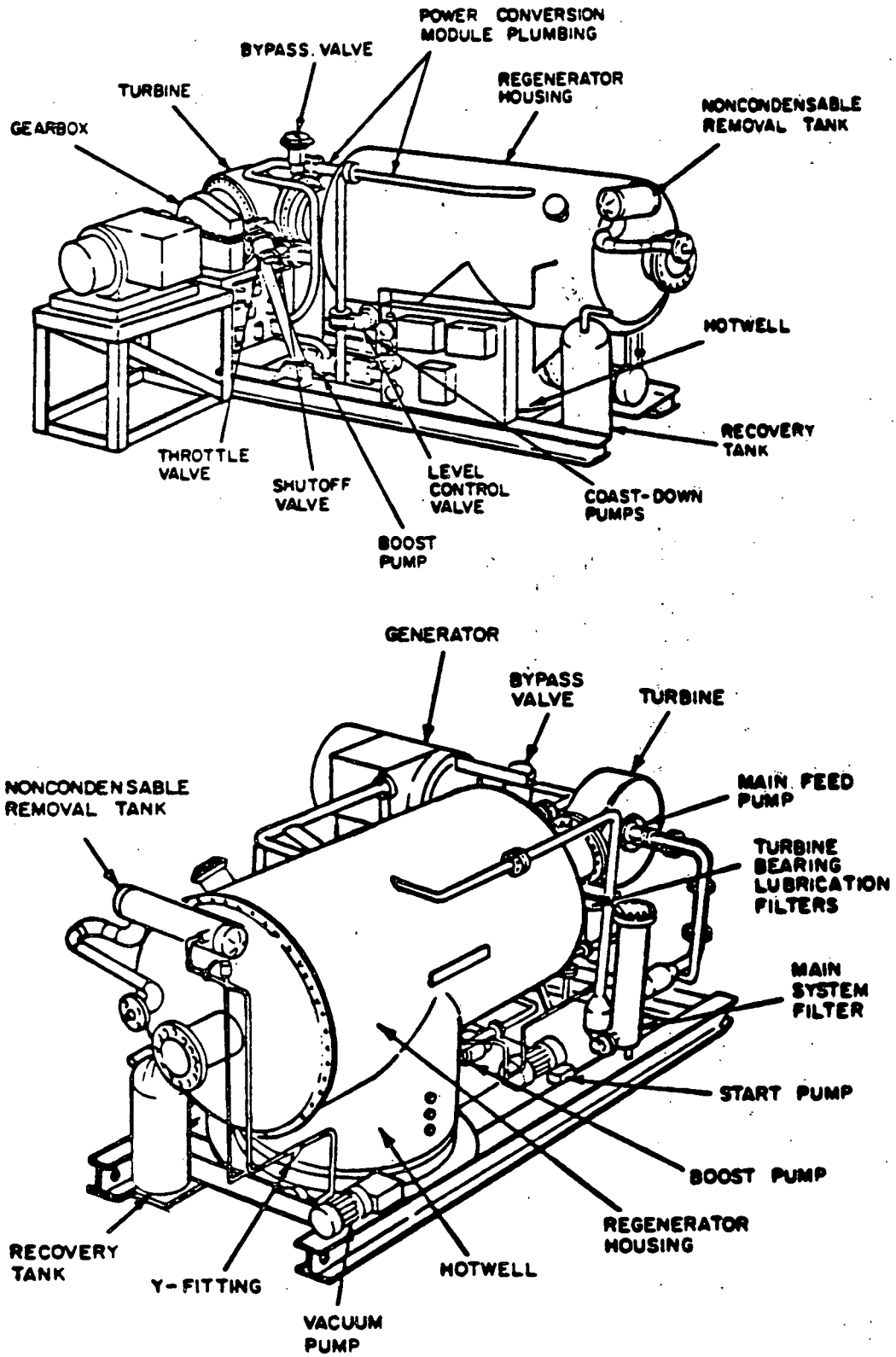

Figure 3-13. Power conversion module.

2. Gearbox

The gearbox and turbine are mounted on opposite ends of a common support framework. This eases shaft alignment and eliminates relative motion of the shafts due to thermal expansion of the framework. The gearbox has an oil pump, sight glass, drain and fill plugs, and an oil filter. The oil is maintained at 200 degrees Fahrenheit by an external finned-tube oil cooler. The gearbox output speed is maintained at 1,800 revolutions per minute.

3. Regenerator Assembly

The regenerator assembly houses the regenerator core. As high temperature toluene vapor enters the housing from the turbine, some of its heat is absorbed by the liquid toluene flowing through the regenerator core toward the vaporizer assembly (this preheats the liquid). As a result, less heat is needed at the vaporizer assembly to vaporize the toluene.

The cooled vapor in the regenerator housing is then piped to the vapor condenser assembly where it is liquified and the condensate returned to the hotwell. The system toluene level can be checked at three sight glasses on the side of the hotwell.

4. Noncondensable Removal System

The noncondensable removal system draws noncondensable gases (mostly nitrogen) from the vapor condenser core. Before system startup, a vacuum pump in the system lowers the pressure in the regenerator assembly to 3.0 pounds per square inch absolute. (During steady-state operation, the pressure is

maintained at 1.18 pounds per square inch absolute.) As the system is running, the noncondensables are drawn from the core through a heat exchanger (to condense remaining toluene vapor). The condensed toluene flows from the heat exchanger to the vapor condenser before flowing to the hotwell. The remaining gases are drawn through a strainer before being pumped to the atmosphere by the vacuum pump. The system is activated as needed when a temperature differential between toluene vapor in the condenser and gas in the removal system indicates a buildup of nitrogen in the vapor condenser.

5. Liquid/Vapor Toluene Plumbing

The PCM toluene plumbing includes piping, valves, filters, and pumps as indicated in Figure 3-13.

6. Control Valves

The air-actuated valves that control system operation are the throttle, shutoff, bypass, and level control valves.

The shutoff valve is located at the turbine inlet and is an emergency shutoff valve used to rapidly shut off all vapor flow to the turbine. It is held open during operation, and is tripped by a solenoid valve to protect against turbine overspeeds.

The throttle valve regulates the amount of vapor entering the turbine during startup and paralleling to keep it running at 9,300 revolutions per minute. Its position is determined by a speed sensor on the turbine. During steady-state operation, the valve remains open.

The bypass valve is used only during startup. It is a normally closed valve that opens to allow toluene to flow from the vaporizer assembly through the regenerator assembly during startup to drain liquid toluene from the turbine inlet line.

The level control valve regulates the amount of toluene that flows to the vaporizer assembly. When the turbine needs more vapor to maintain operating speed, the liquid level in the vaporizer sections drops. The level sensor signals the level control valve to open to supply more toluene to the vaporizer assembly.

Various views of the power generation module are shown in Figures 3-14 through 3-16. Various components may be identified by comparison to the notations in Figure 3-13. The dark colored structure on the north side of the regenerator housing is the vapor condenser.

3.4 HEAT REJECTION SUBSYSTEM

The primary piece of equipment in the heat rejection subsystem is the vapor condenser. It uses outside air and cascading waterflow to cool and condense toluene vapor passing through tube bundles.

After leaving the regenerator housing, the toluene vapor enters the vapor condenser tubes. Two fans force air over the tubes while a spray of water keeps the tubes wet. The resulting evaporation process cools and condenses the toluene vapor. The condensed liquid flows back to the hotwell on the PCM. The cooling water is recirculated, and additional water is automatically added to replace water lost in the evaporation process.

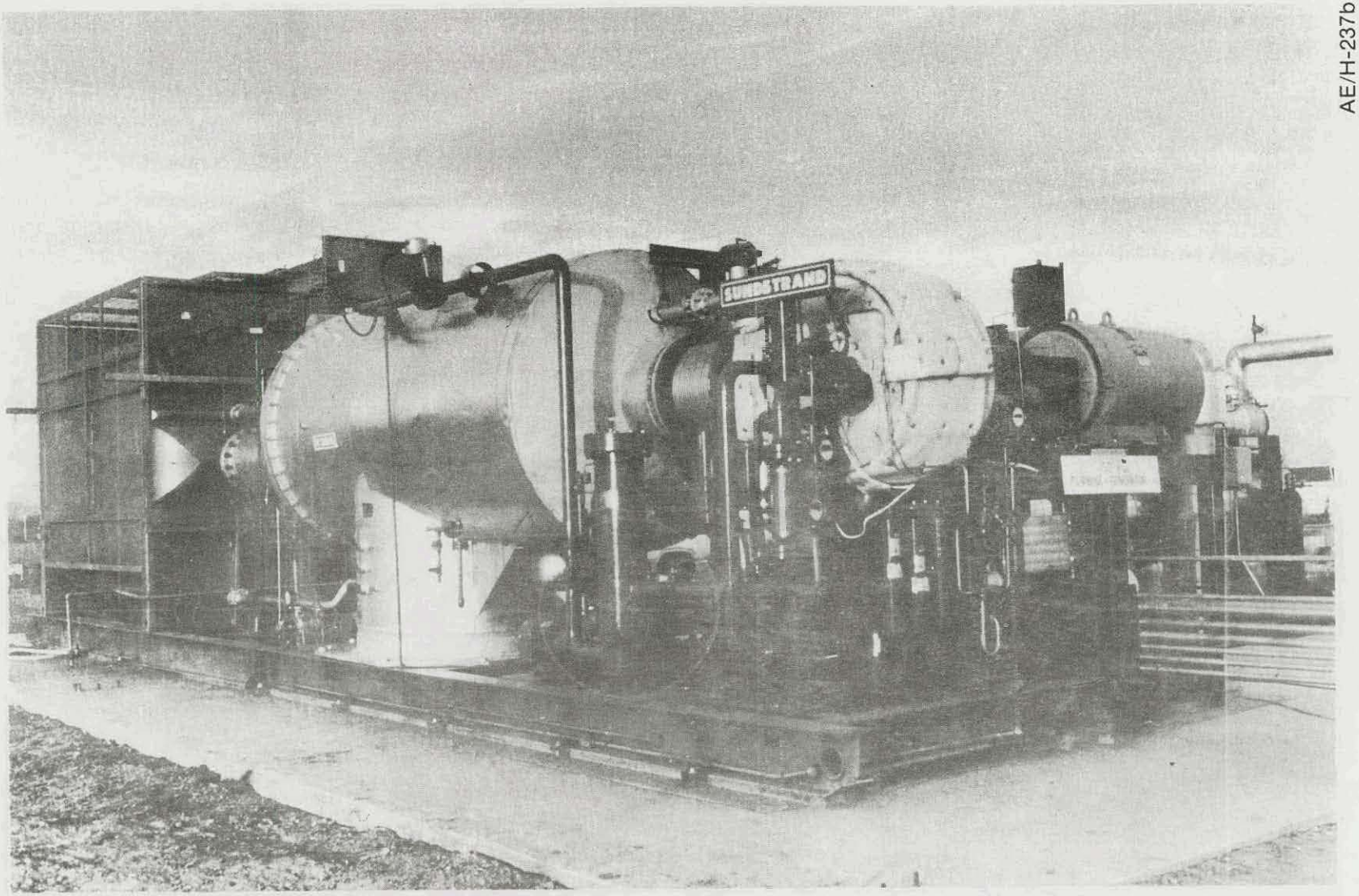

Figure 3-14. View of power generation module (looking north-east).

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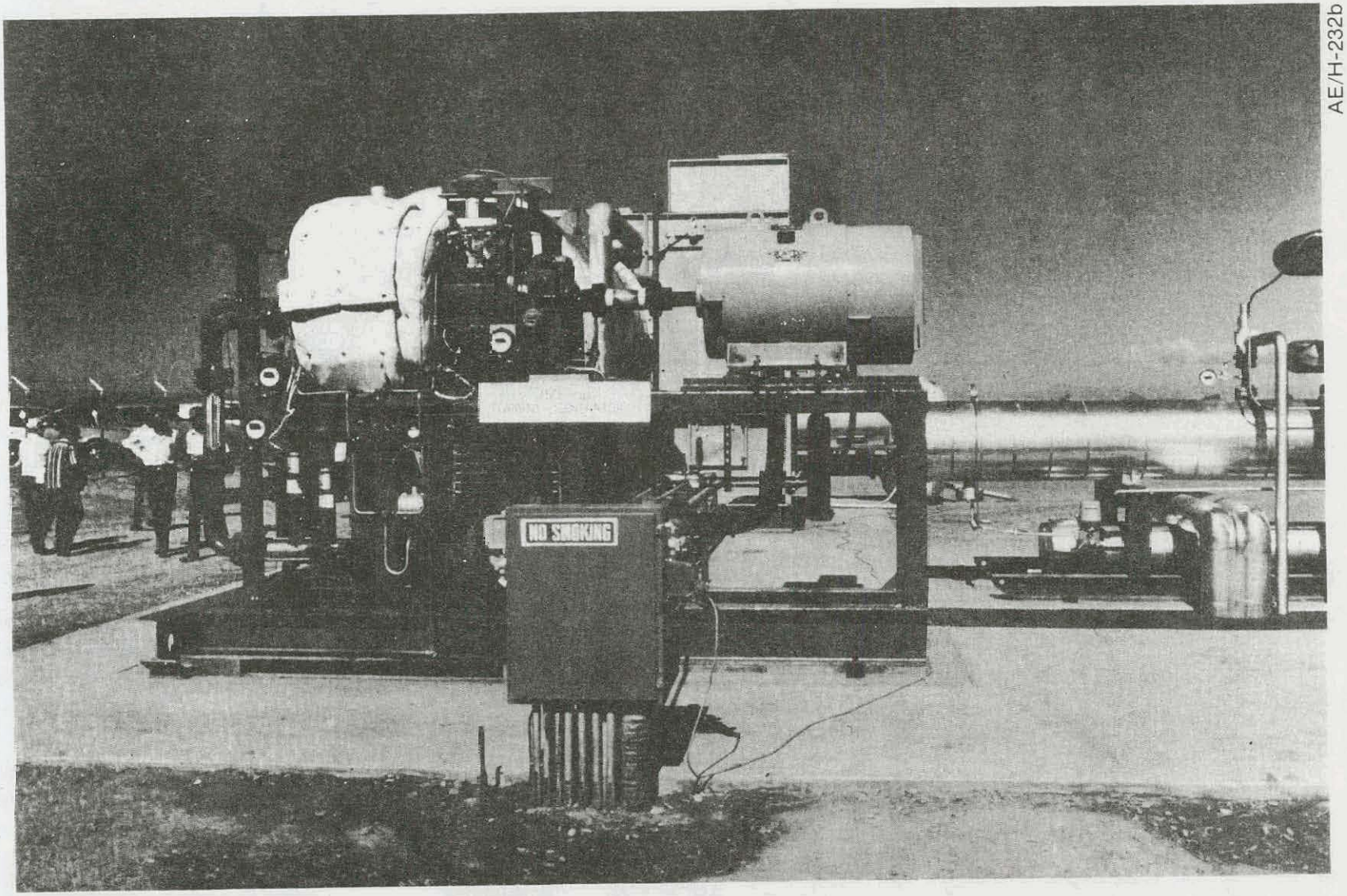

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Figure 3-15. View of power generation module (lookirg north).

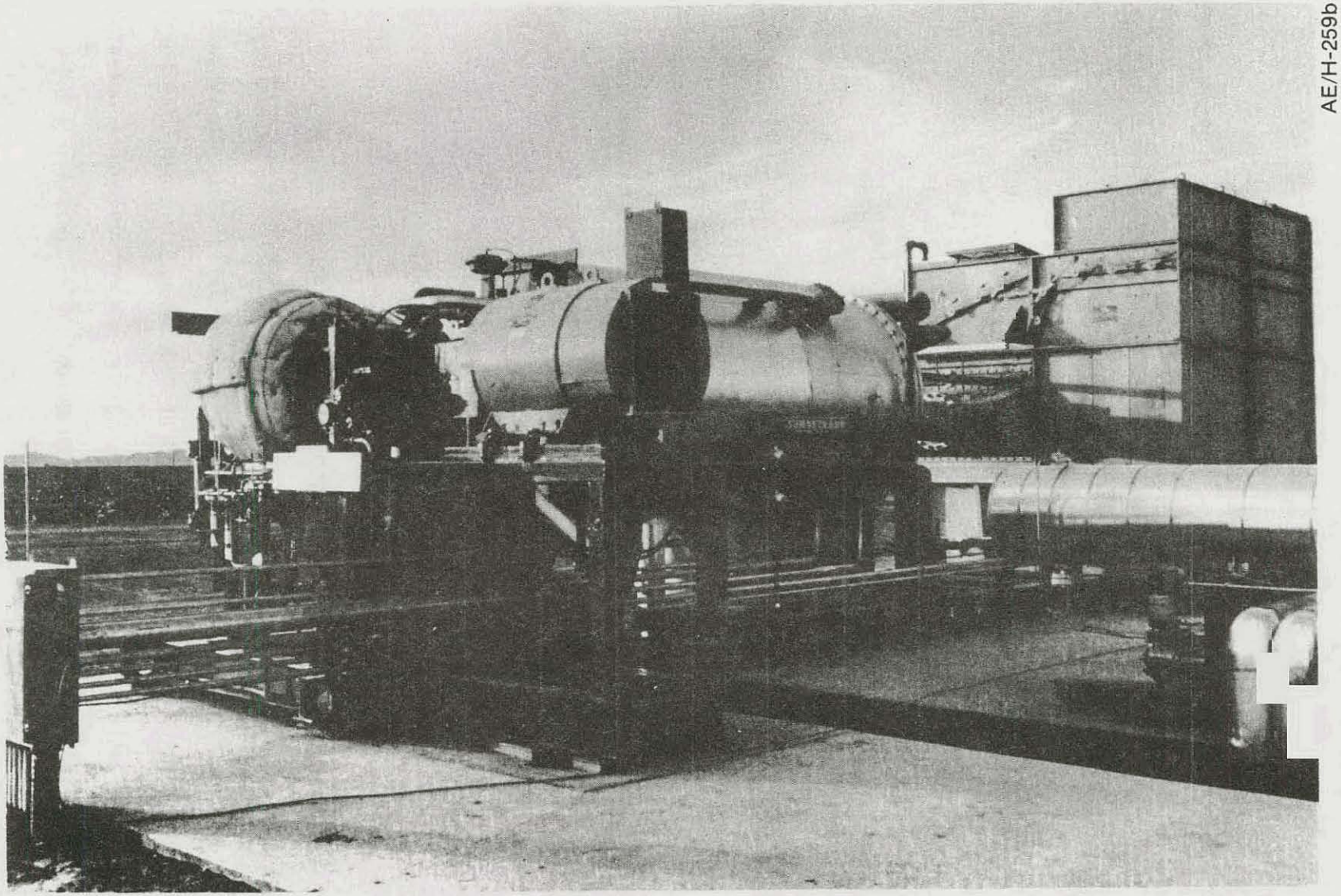

Figure 3-16. View of power generation module (looking north-west).

The vapor condenser was manufactured by Niagara Blower Company as part of its standard line of cooling equipment. Specifics on this vapor condenser are given in Table 3-3.

TABLE 3-3. VAPOR CONDENSER SPECIFICS

Approximate Dimensions	
Length	22 ft
Width	11 ft
Height	14 ft
Weight (Dry)	16,700 lb
Water Capacity	300 gal
Cooling Capacity	2.5 MBtu/hr
Condensing Temperature	105°F
Maximum Wet Bulb Temperature	74°F

Figure 3-17 shows the installed vapor condenser. The tank on the trailer in the background was used as a water supply during system startup prior to hookup to the public water system. This hookup has now been completed and all underground water supply lines on the site are operational.

3.5 POWER DISTRIBUTION SUBSYSTEM

The function of the power distribution subsystem is to connect the generated power to the public distribution grid as well as supply power to onsite equipment. The primary equipment and arrangement are shown in the block diagram of Figure 3-18.

The main piece of equipment in the power distribution subsystem is the electrical generator. It is rated at 250 kilovolt-amperes, 60 hertz and is a three-phase, synchronous alternating current unit that operates at 1,800 revolutions per minute with an output of 480 volts.

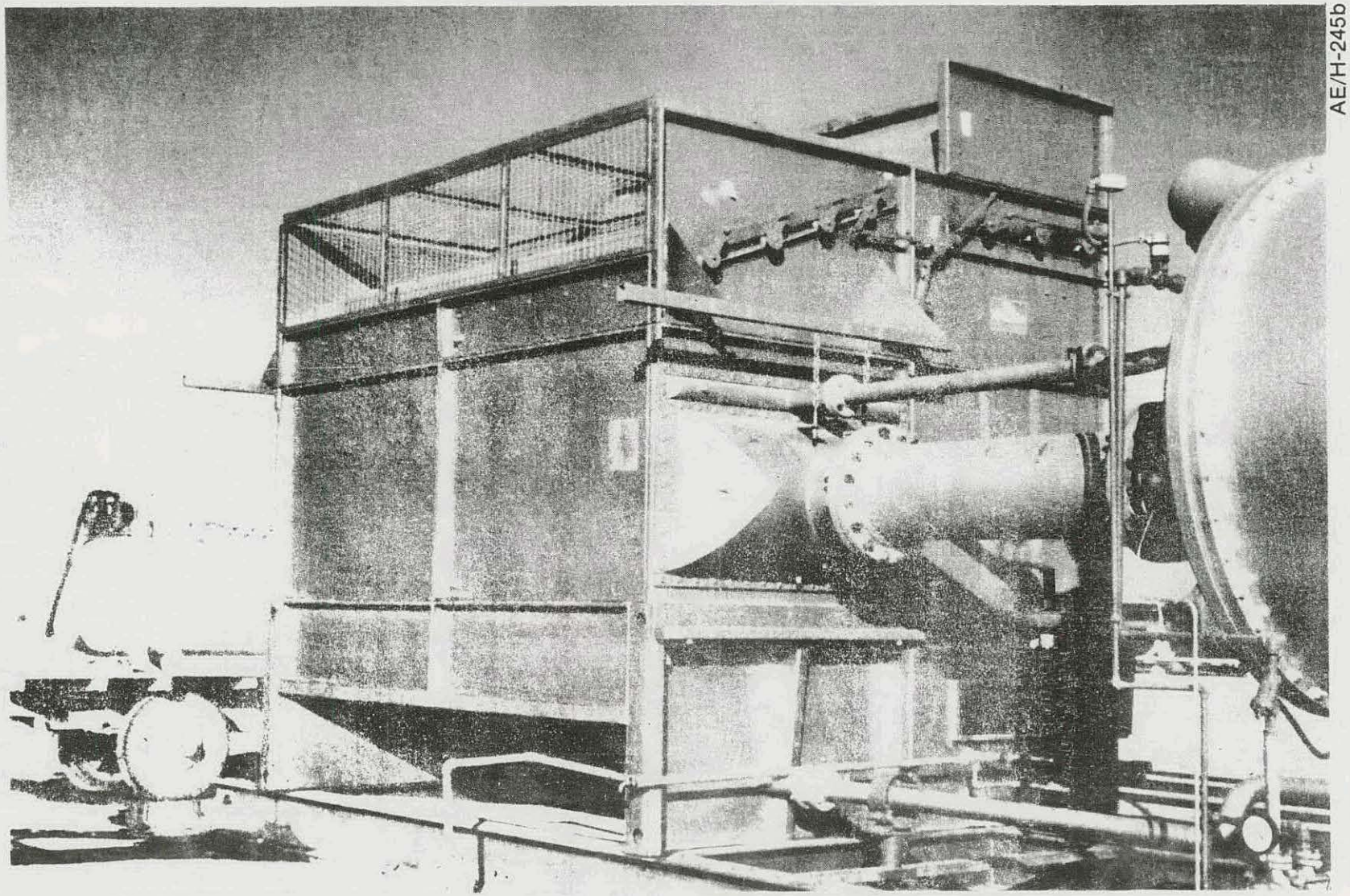

Figure 3-17. Vapor condenser.

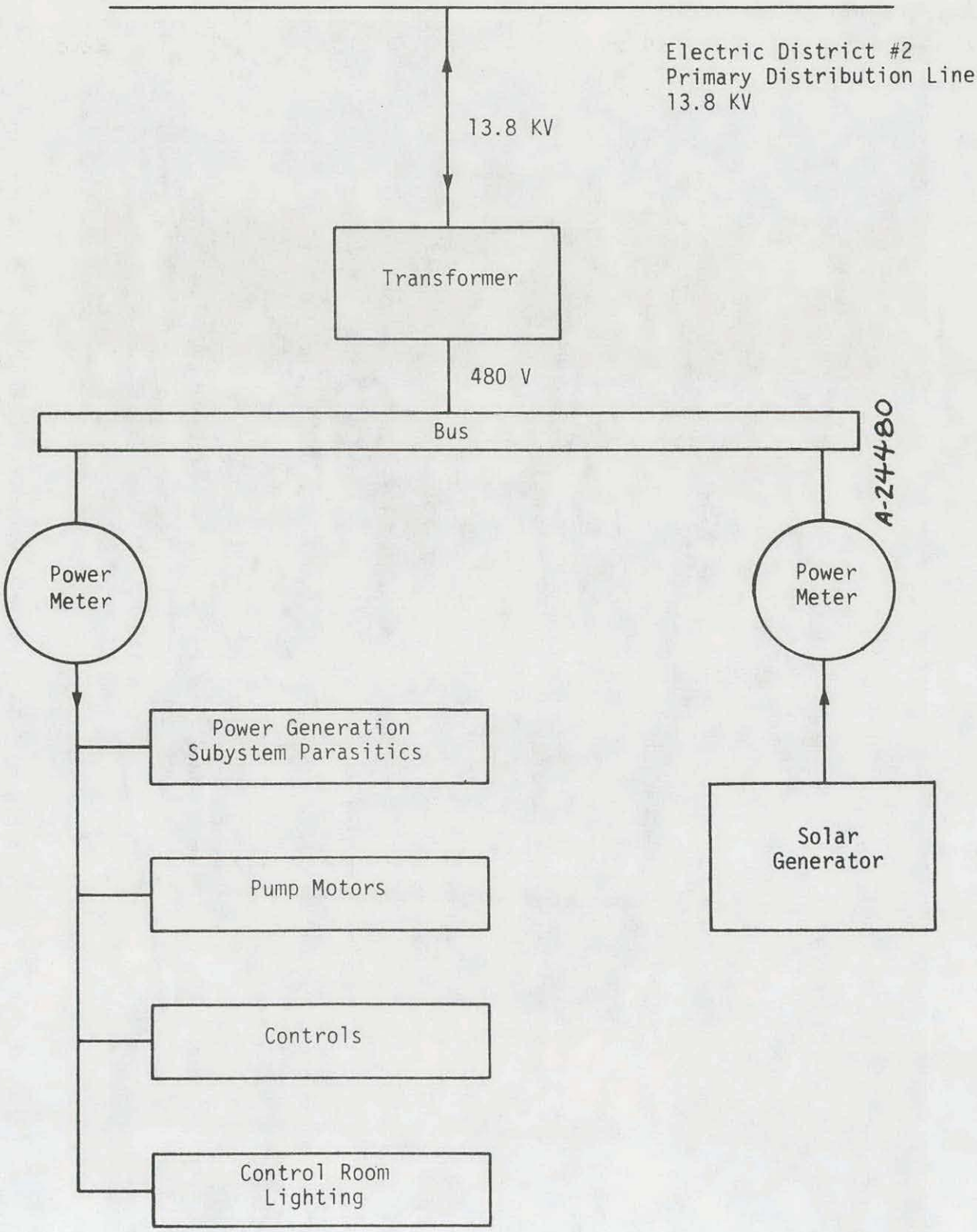

Figure 3-18. Electrical power block diagram.

The efficiency of the generator is 95.6 percent at 0.8 power factor and was especially designed and manufactured for this solar system by Kato.

The generator is mounted on a welded framework that is bolted to the PCM framework. It is linked to the gearbox output shaft by a flexible steel coupling. The generator and its framework are visible in Figures 3-15 and 3-16.

3.6 CONTROL

The 150 kw solar powerplant has been provided with the capability for fully automatic operation. The collector field is automatically started when sufficient solar insolation is present, and automatically stows itself after a set period of low insolation. The power generation subsystem automatically starts when sufficient hot fluid is available in the storage tank, and shuts itself down when the energy has been depleted. The power distribution subsystem automatically parallels with the public utility grid when producing electrical power. The control system is equipped with appropriate safety interlocks which monitor critical parameters and automatically shut the system down and prohibit automatic restart if these parameters are beyond safety limits. The control system is also equipped with manual override options for all control functions to enable greater flexibility for tests and experiments.

A simplified schematic of the collector field fluid flow control is presented in Figure 3-19. The control scheme varies the fluid flowrate through the collectors to maintain a constant outlet temperature. Upon startup of the field, fluid is recirculated through the buffer tank at minimum flowrate until the outlet temperature rises to a set value.

The flowrate is set by the flow control valve (FCV). This valve is a constant flowrate controller with variable setpoint. The control signal

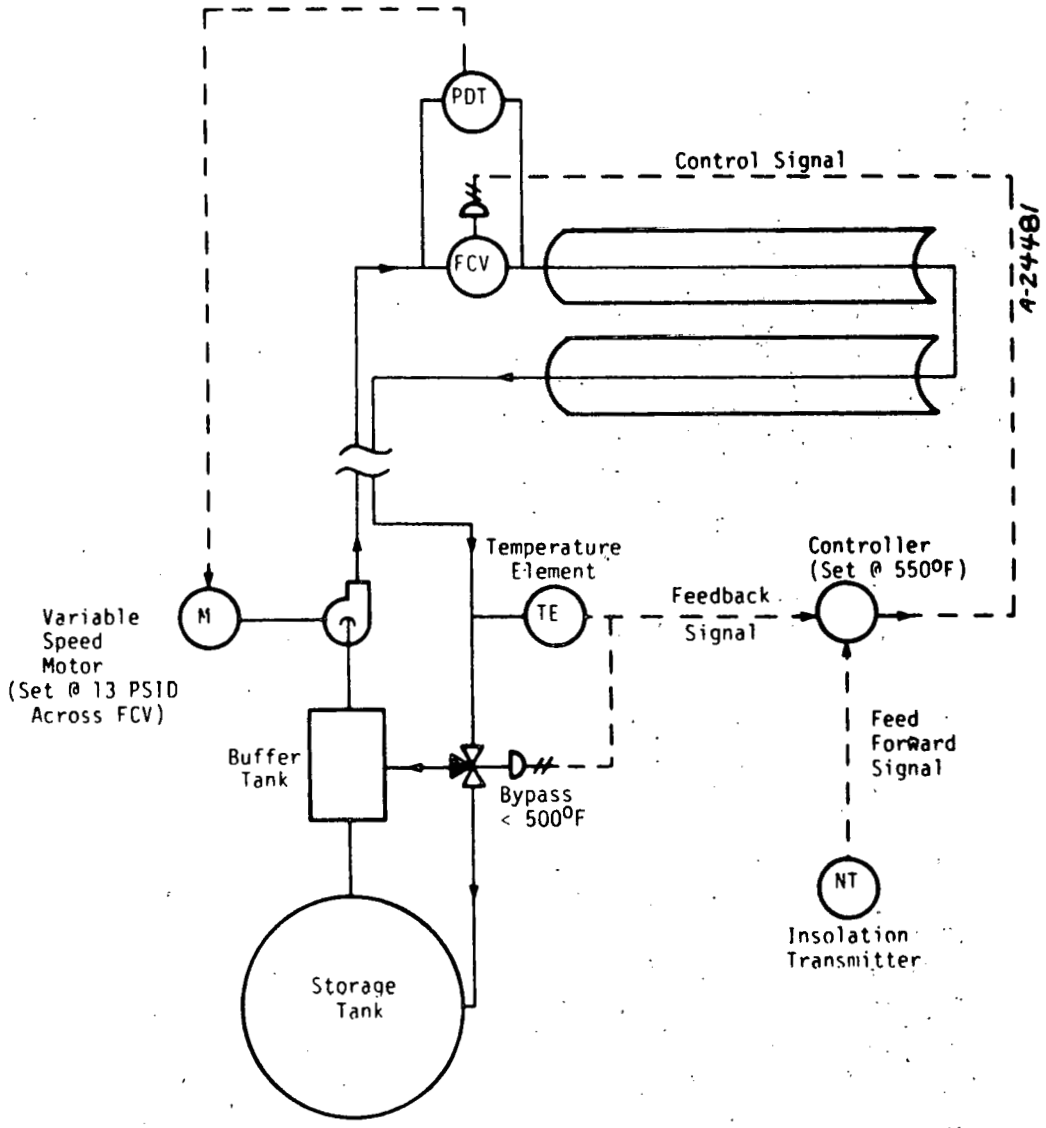

Figure 3-19. Collector field control.

for the FCV is composed of a feed forward component and a feedback component. The feed forward component is based on instantaneous direct insolation and the feedback component is dictated by outlet temperature of the field. Each of the eight parallel collector loops contains an FCV. All these valves are controlled by the same signal.

Fluid is supplied to the collectors by a variable speed pump. The pump speed is controlled to provide a constant pressure drop across the FCV in the last collector loop.

An alternate control scheme is possible with only minor alterations. In this scheme the FCV's are fixed fully open and fluid flow is controlled by the variable speed pump. The feed forward and feedback control signals are used to set a pump speed which yields a constant outlet temperature from the field.

Collector tracking of the sun is a closed loop control system within each collector loop. Each of the six groups of collectors within a flow loop has its own tracker. A temperature sensor is located at the outlet of each group to detect overtemperature conditions. When this is sensed, only the affected group of collectors is desteered. A flow switch at the end of the collector loop senses loss of fluid flow and desteers all collectors in the loops.

When the collector field control is in the automatic startup and operation mode, the following conditions must be satisfied before the field pump will be started:

- Wind speed less than 30 mph
- Ambient temperature greater than 30°F
- Solar insolation greater than the minimum set point

With these conditions satisfied, the pump will start circulating fluid at the minimum flowrate. The outlet temperature from the field will initially be less than 500°F, thus the fluid will be recirculated through the buffer tank. Once flow through the collectors has been verified by the flow switches, the collectors come up out of the stow position and track the sun. When the fluid temperature rises above 500°F flow is diverted to the storage tank and the control mode switches to constant outlet temperature control.

Three of the devices which are part of the collector field control system are shown in their installed positions in Figures 3-20, 3-21, and 3-22. The Direct Insolation Monitor (DIM) shown in Figure 3-20 serves two functions in the control system. First, it determines when the insolation is coming from a point in the sky (as opposed to strong diffuse light reflected from a cloud which confuses optical trackers), and second, signals the trackers that the point source is supplying radiation levels above the minimum setpoint. The DIM is installed on the roof of the control building, as shown in the figure.

The tracker sensor shown in Figure 3-21, is located above the drive mechanism for each collector group. The electronic logic part of the tracker is contained in the closed box attached to the collector drive post at the bottom of the figure.

The device which supplies the insolation feed forward signal to the control system is shown in Figure 3-22. This device is a pair of pyranometers, one shaded to measure diffuse radiation and one exposed to measure total radiation. Direct insolation (the component useful to the collectors) is the difference between the two measurements. The device is mounted at the end of a collector row and moves with the collector as it

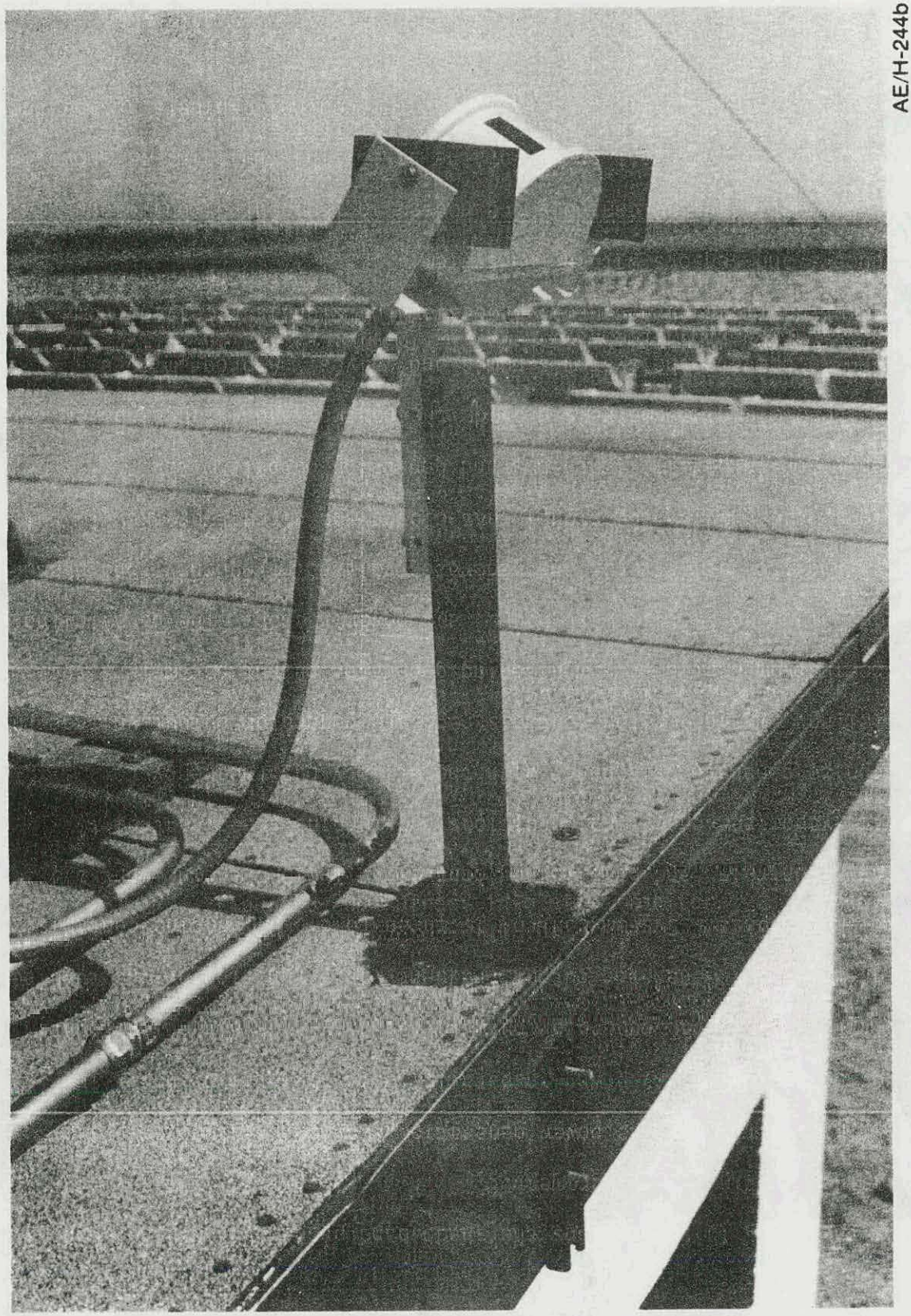

Figure 3-20. Direct insolation monitor.

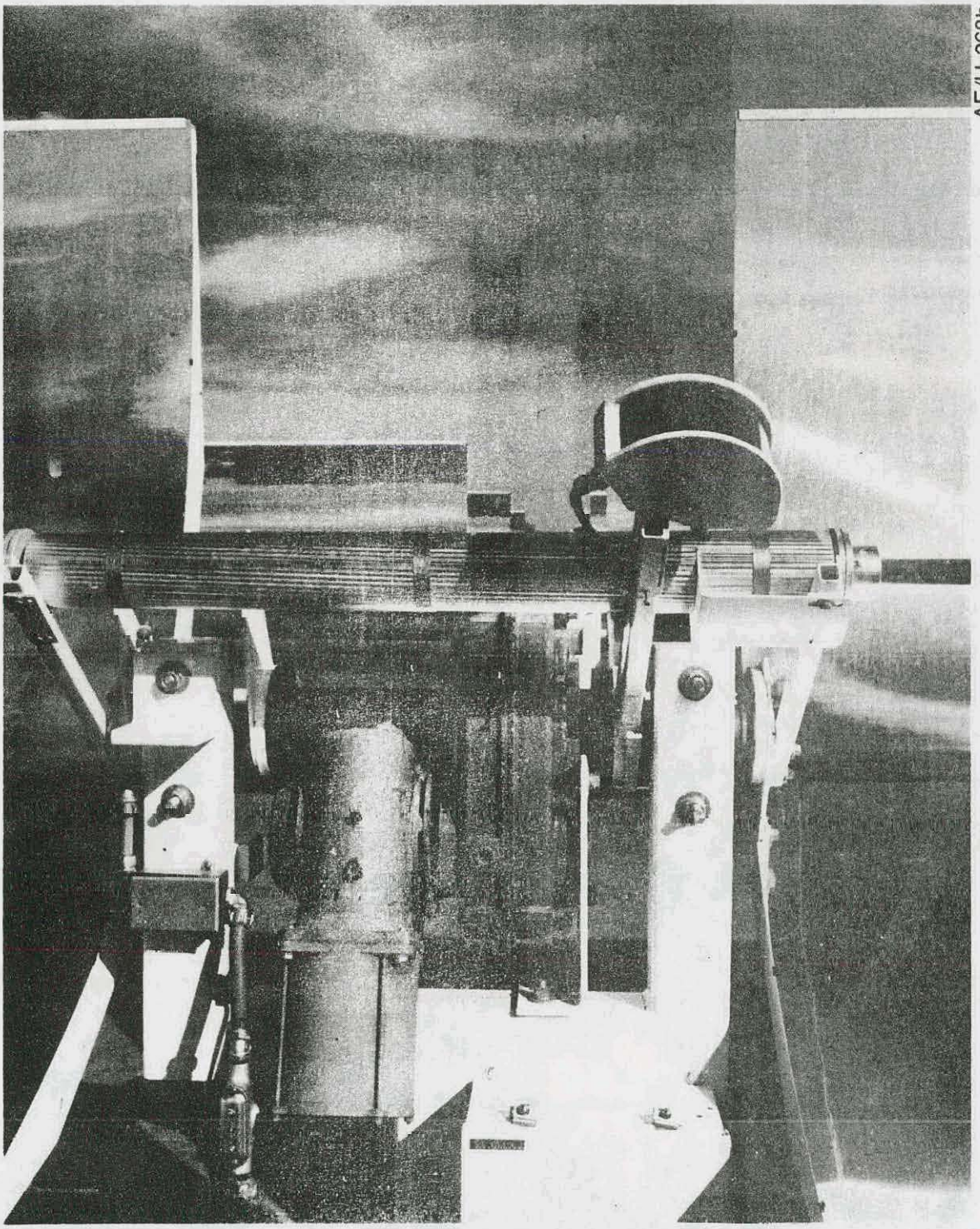

Figure 3-21. Tracker sensor and drive mechanism.

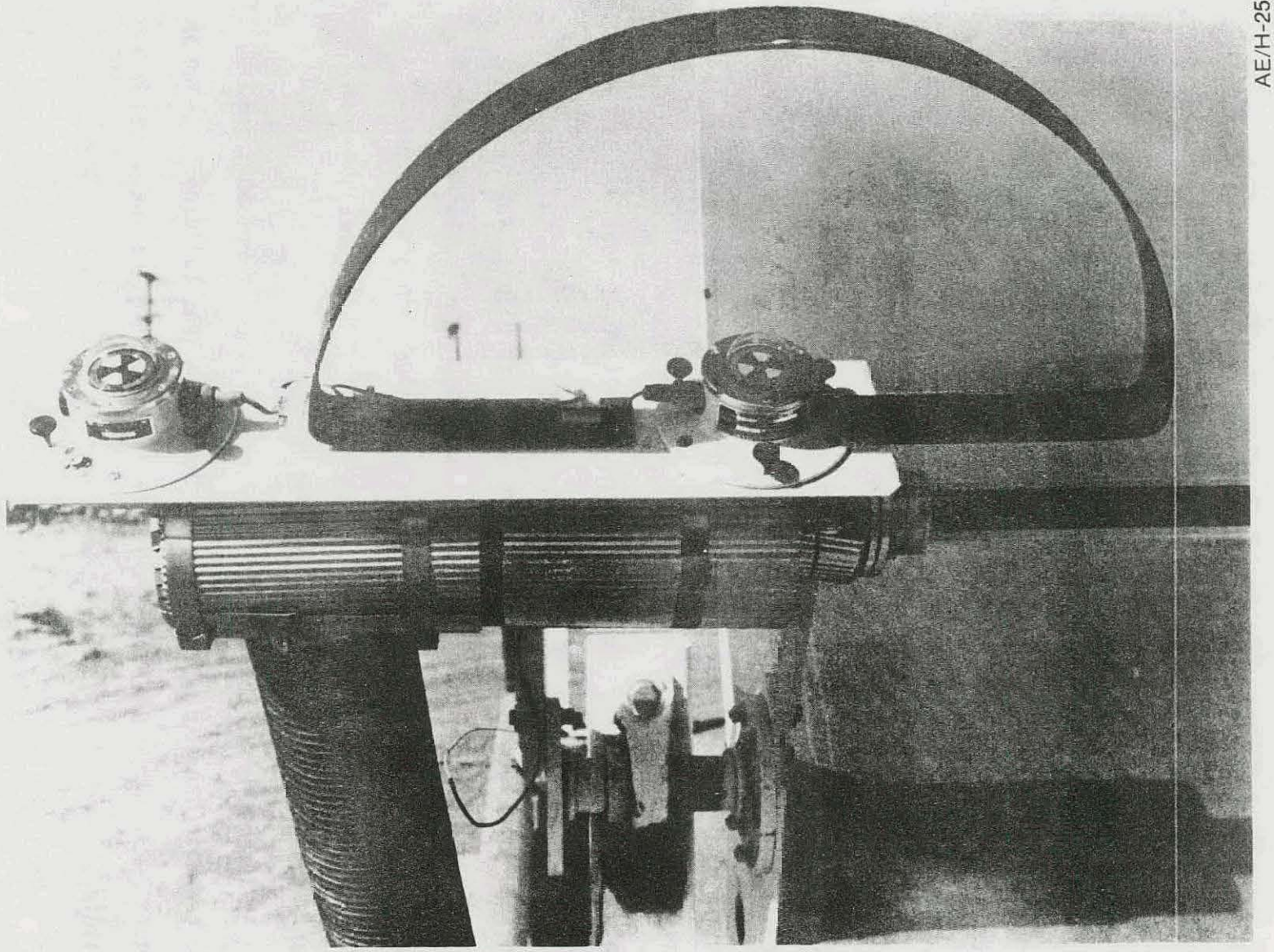

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Figure 3-22. Pyranometer.

tracks the sun. This positions the shadowband properly and also induces the cosine loss in the measurement.

The function of the power generation and distribution subsystems is to provide supplementary power in parallel with the utility bus. To perform that task, the generator output frequency and voltage must match that of the bus. Generator output frequency is a function of the turbine output shaft speed. System control is three fold: ORC engine controls, generator controls, and paralleling controls. The ORC engine controls maintain vaporizer operating conditions and turbine speed control to synchronize generator frequency with the utility bus frequency for paralleling. The generator controls regulate generator output voltage and provide instrumentation for monitoring generator output parameters such as voltage, amperage, watts, watt-hours, and power factor. The paralleling controls monitor utility bus and generator voltage, frequency, and phase relations, and provide the signal that closes the circuit breaker to put the generator in parallel when bus and generator outputs match.

The ORC engine controls provide the control and external power required to operate the system's pumps and valves. A programmable sequencer functions as a central processor for signals received from transducers and sensors within the system.

Automatic system controls are housed in the control building located near the southwest corner of the site. This building is shown in Figure 3-23. Figure 3-24 gives a view of the control cabinets inside the building.

3.7 DATA ACQUISITION

The data acquisition subsystem is a fully automatic scanning and recording system which measures all parameters of interest and stores the

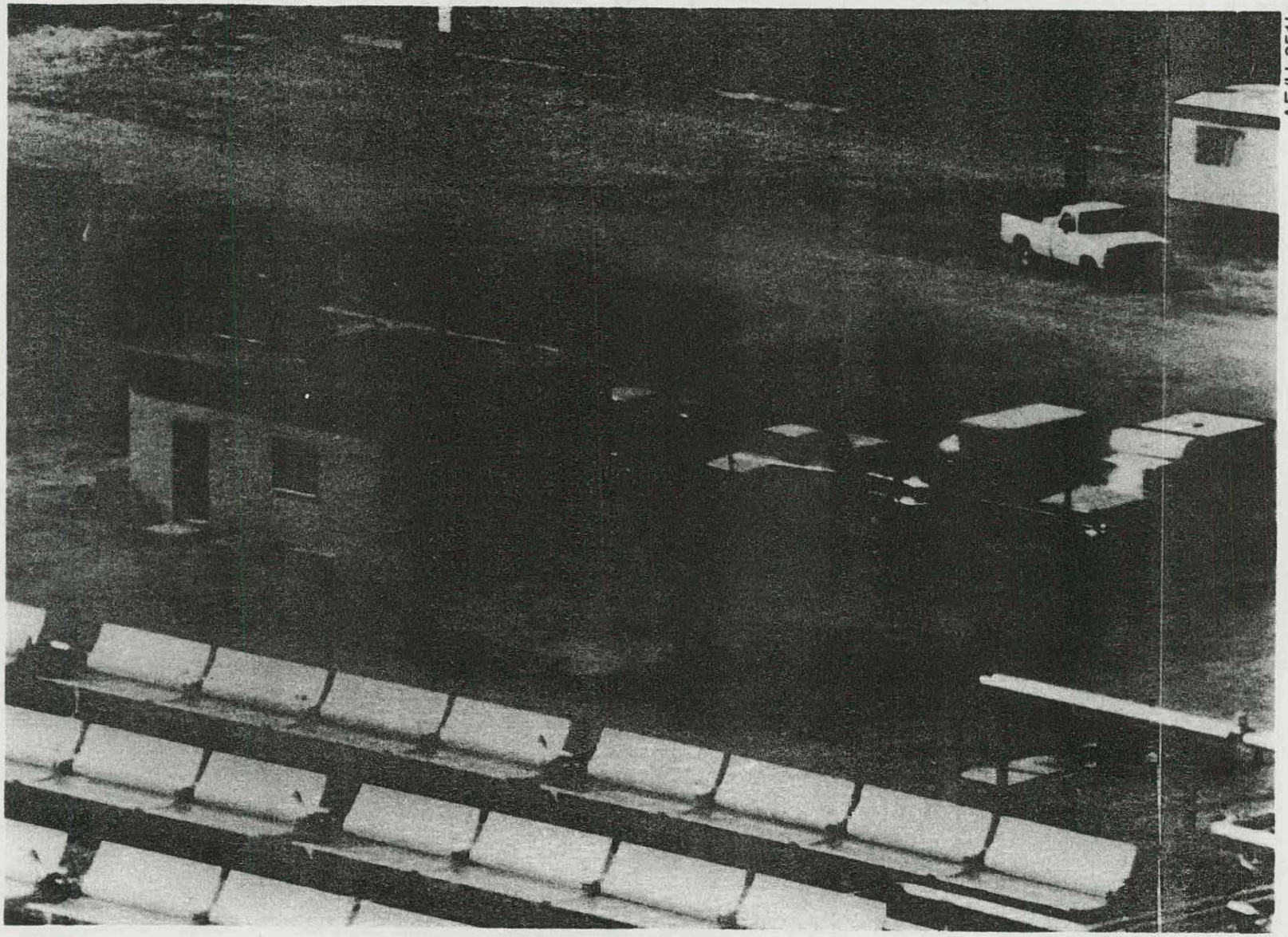

Figure 3-23. Control building.

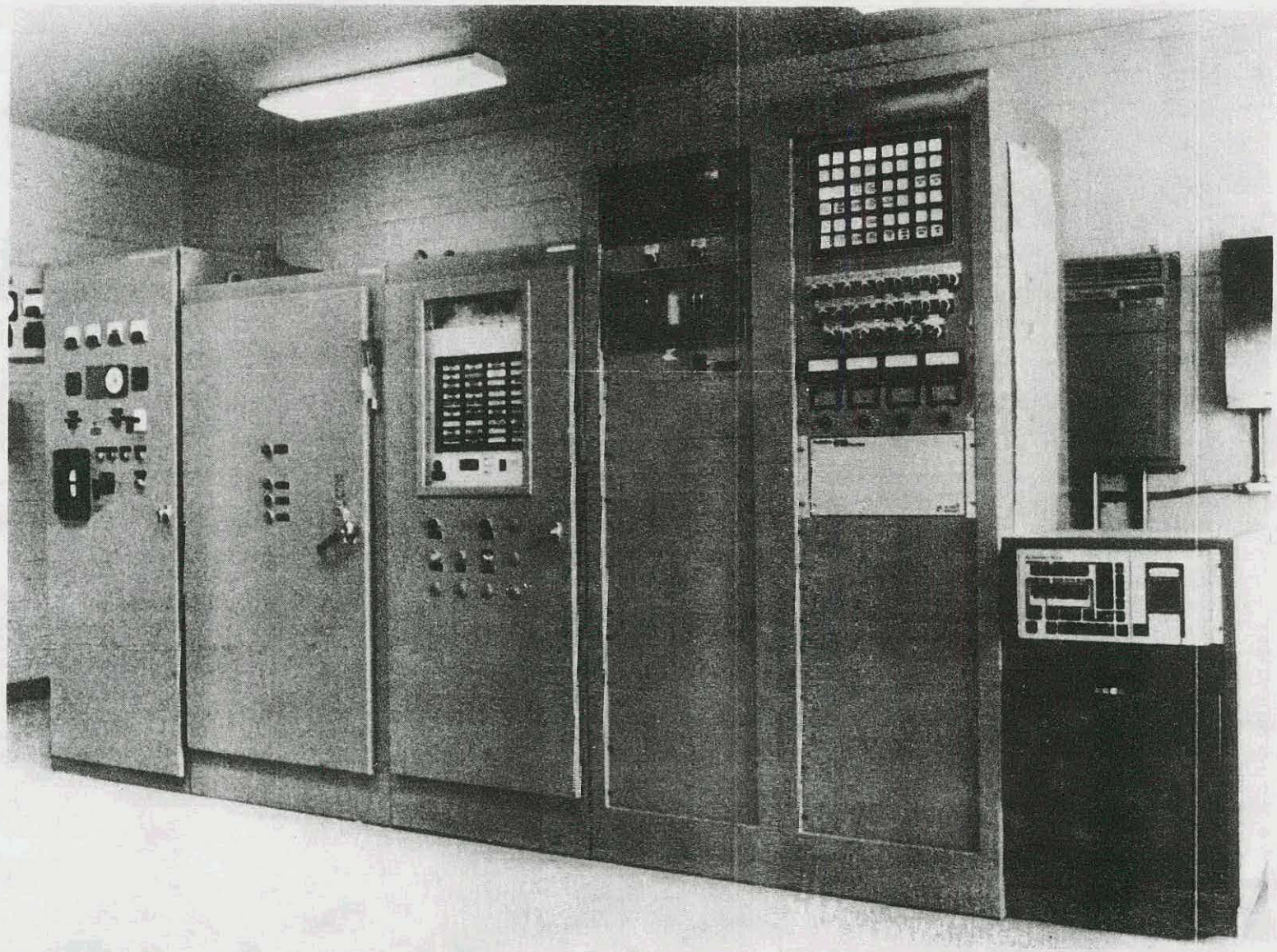

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Figure 3-24. System control and data acquisition equipment.

data for evaluation of system performance. This subsystem consists of field sensors, signal transmitters, a signal scanner, the autodata-nine digital voltmeter/processor, a paper tape printer, and a magnetic tape recorder. All equipment is housed in the control building except for the field sensors and some signal transmitters.

Figure 3-24 shows the control and data acquisition consoles within the control building. The short console at the right houses the autodata nine, paper printer, and magnetic tape recorder. The next two consoles to the left, house the remaining signal transmitters and the 616 signal scanner.

The Autodata Nine automatically scans all sensors at 15-minute intervals and records all data on magnetic and paper tape. A digital display on the Autodata Nine also allows continuous monitoring of any single sensor output.

In addition to the Autodata Nine and tape outputs, the two control consoles which house the 616 scanner and signal transmitters contain a three-pen chart recorder and four voltmeters. The chart recorder continuously monitors and records the collector field flowrate, field outlet temperature, and the pressure differential across the collector flow control values. The four voltmeters are 0 to 5 VDC switchable input indicators of collector loop output temperature, field differential pressure, vaporizer flowrate, and many other system parameters. Table 3-4 lists the selector switch position parameter being measured and the conversion factor for each of the four meters.

Sensors are located at key points throughout the solar system to allow evaluation of both overall system and subsystem performance.

TABLE 3-4. CONTROL CONSOLE METER READOUT SUMMARY

Meter Number	Switch Position	Parameter Measured, VDC	Conversion Factor	P&ID Number
UJI-401	1	Loop 100 outlet temperature	1-5 VDC = 0-600°F	TE-106
UJI-401	2	Loop 110 outlet temperature	1-5 VDC = 0-600°F	TE-116
UJI-401	3	Loop 120 outlet temperature	1-5 VDC = 0-600°F	TE-126
UJI-401	4	Loop 130 outlet temperature	1-5 VDC = 0-600°F	TE-136
UJI-401	5	Loop 140 outlet temperature	1-5 VDC = 0-600°F	TE-146
UJI-401	6	Loop 150 outlet temperature	1-5 VDC = 0-600°F	TE-156
UJI-401	7	Loop 160 outlet temperature	1-5 VDC = 0-600°F	TE-166
UJI-401	8	Loop 170 outlet temperature	1-5 VDC = 0-600°F	TE-176
UJI-402	6	Caloria top temp. in Tank T-1	1-5 VDC = 0-600°F	TE-400B
UJI-402	7	Field inlet temperature	1-5 VDC = 0-600°F	TE-15
UJI-402	8	Field outlet temperature	1-5 VDC = 300-600°F	TE-10
UJI-403	1	Total horizontal insolation	1-5 VDC = 0-350 Btu/hr-ft^2	NE-10
UJI-403	2	Direct insolation at collector aperture loop 100	1-5 VDC = 0-350 Btu/hr-ft^2	NE-11A&B
UJI-403	3	Direct insolation at collector aperture loop 130	1-5 VDC = 0-350 Btu/hr-ft^2	NE-12A&B

TABLE 3-4 (Concluded)

Meter Number	Switch Position	Parameter Measured, VDC	Conversion Factor	P&ID Number
UJI-403	4	Direct insolation at collector aperture loop 160	1-5 VDC = 0-350 Btu/hr-ft^2	NE-13A&B
UJI-403	5	Differential pressure at loop 170 FCV	1-5 VDC = 0-40 psid	PDT-250
UJI-403	6	Differential pressure at loop 160 FCV	1-5 VDC = 0-40 psid	PDT-260
UJI-403	7	Field flowrate	1-5 VDC = 30-200 gpm	FT-15
UJI-403	8	Vaporizer caloria flowrate	1-5 VDC = 30-200 gpm	FT-300
UJI-403	9	Field mass flowrate	1-5 VDC	FY-15
UJI-403	10	Ambient temperature	1-5 VDC = 0-150°F	TE-11
UJI-403	11	Regenerator toluene flowrate	1-5 VDC = 11-50 gpm	FT-330
UJI-403	12	Turbine inlet pressure	1-5 VDC = 0-200 psia	PT-354
UJI-404	1	Turbine outlet pressure	1-5 VDC = 0-2 psia	PT-355
UJI-404	2	Flow control valves control signal	1-5 VDC	FY-10
UJI-404	3	Pump P-1 speed control signal	1-5 VDC	PDIC-1
UJI-404	4	Field return temp. flowrate control signal	1-5 VDC	TIC-10
UJI-404	5	Field differential pressure	1-5 VDC = 0-75 psid	PDT-16
UJI-404	6	Wind velocity	1-5 VDC = 0-100 mph	SE-20

Typical evaluations would include such factors as: Energy collected in the field, collector array efficiency, collector field efficiency, field piping heat losses, storage tank performance, power generation subsystem performance, etc.

Typical parameters which are measured and recorded by the data acquisition subsystem are: fluid temperatures, insolation, fluid pressures and flowrates, and ambient conditions. These are measured with standard grade industrial instruments with high accuracy and reliability. Table 3-5 lists the parameter being measured, the conversion factor (if applicable), the sensor number from the P&ID, and the overall measurement accuracy for each parameter. Each measurement accuracy figure is a compilation of accuracy for the sensor, lead wires, transmitter, Autodata Nine and calibration procedure.

The Autodata Nine is the heart of the data acquisition system and is shown in closeup in Figure 3-25. Together with the 616 scanner, the Autodata Nine is capable of handling 100 channels of data. It performs many conversions automatically to engineering units and acts as the D.A. subsystem clock. Scan features are fully programmable allowing the operator to record data from any combination of channels at any rate desired.

The magnetic tape recorder is a Cipher nine-track machine capable of storing several weeks of data on each tape at the 15-minute scan rate. The nine-track format was chosen to be compatible with standard data reduction and analysis sytems.

3.8 AUXILIARY HEATER

An auxiliary heater fired by natural gas was added to the system design shortly after the decision was made to reduce the original

TABLE 3-5. DATA ACQUISITION SYSTEM MEASUREMENT SUMMARY

Autodata 9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
00	Wind velocity	VDC	1-5 VDC = 0-100 mph	±5.01% of reading	SE-20
01	Field mass flowrate	VDC	1-5 VDC = 30-200 gpm	±0.46% FS	FY-15B
02	Field outlet temperature	VDC	1-5 VDC = 300-600°F	±1.31% of span	TE-10
03	Field return temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-15
04	Maximum direct insolation at collector aperture	VDC	1-5 VDC = 0-350 Btu/hr-ft^2	±1.47% FS	NY-10
05	Ambient temperature	VDC	1-5 VDC = 0-150°F	±0.75% FS	TE-11
06	Field flow control signal	VDC	1-5 VDC = 0-100% flow	±2.03% FS	FY-10
07	Vaporizer caloria flowrate	VDC	1-5 VDC = 30-200 gpm	±0.46% FS	FT-300
08	Loop 170 differential pressure	VDC	1-5 VDC = 0-40 PSID	±0.21% FS	PDT-250
09	Loop 160 differential pressure	VDC	1-5 VDC = 0-40 PSID	±0.21% FS	PDT-260
10	Caloria temp. in T-1 vertical tree	°F	--	±0.56% FS	TE-400A

TABLE 3-5. Continued

Autodata 9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
11	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-401A
12	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-402A
13	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-403A
14	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-404A
15	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-405A
16	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-406
17	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-407
18	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-408
19	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-409
20	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-410

TABLE 3-5. Continued

Autodata-9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
21	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-411
22	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-412
23	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-413
24	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-414
25	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-415
26	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-416
27	Caloria temperature in T-1 vertical tree	°F	--	±0.56% FS	TE-417
28	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-418
29	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-419
30	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-420

TABLE 3-5. Continued

Autodata-9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
31	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-421
32	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-422
33	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-423
34	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-424
35	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-425
36	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-426
37	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-427
38	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-428
39	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-429

TABLE 3-5. Continued

Autodata-9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
40	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-430
41	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-431
42	Caloria temperature in T-1 horizontal tree at N-4	°F	--	±0.56% FS	TE-432
43	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-433
44	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-434
45	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-435
46	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-436
47	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-437

TABLE 3-5. Continued

Autodata-9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
48	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-438
49	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-439
50	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-440
51	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-441
52	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-442
53	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-443
54	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-444
55	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-445
56	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-446

TABLE 3-5. Continued

Autodata-9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
57	Caloria temperature in T-1 horizontal tree at N-5	°F	--	±0.56% FS	TE-447
58	Not used	--	--	--	--
59	Dew point	°F	--	±1.81% FS	MT-12
60	Not used	--	--	--	--
61	ORC turbine inlet temperature	°F	--	±5°F	TE-333
62	ORC turbine outlet temperature	°F	--	±5°F	TE-356
63	Regenerator inlet temperature	°F	--	±5°F	TE-330
64	Regenerator hotwell temperature	°F	--	±5°F	TE-331
65	Vapor condenser inlet temperature	°F	--	±5°F	TE-361
66	Vaporizer toluene outlet temperature	°F	--	±5°F	TE-303
67	Vaporizer caloria inlet temperature	°F	--	±5°F	TE-305
68	Vaporizer caloria outlet temperature	°F	--	±5°F	TE-304

TABLE 3-5. Continued

Autodata-9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
69	Vaporizer caloria inlet temperature	°F	--	±5°F	TE-302
70	Turbine inlet pressure	VDC	1-5 VDC = 0-200 PSIA	±0.36% FS	PT-354
71	Turbine outlet pressure	VDC	1-5 VDC = 0-2 PSIA	±0.36% FS	PT-355
72	Regenerator inlet flowrate	VDC	1-5 VDC = 11-50 gpm	±0.46%	FT-330
73	Field differential pressure	VDC	1-5 VDC = 0-75 PSID	±0.21%	PDT-16
74	Not used	--	--	--	--
75	Not used	--	--	--	--
76	Not used	--	--	--	--
77	Not used	--	--	--	--
78	Generator output voltage	VDC	--	--	ET-395
79	Generator current output	VDC	--	--	IT-395
80	Not used	--	--	--	--
81	Loop 100 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-106
82	Loop 110 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-116
83	Loop 120 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-126

TABLE 3-5. Concluded

Autodata-9 Channel Number	Parameter Measured	Units Recorded	Conversion Factor	Overall[a] Accuracy	P&ID Number
84	Loop 130 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-136
85	Loop 140 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-146
86	Loop 150 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-156
87	Loop 160 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-166
88	Loop 170 outlet temperature	VDC	1-5 VDC = 0-600°F	±0.76% FS	TE-176
89	Not used	--	--	--	--
90	Not used	--	--	--	--
91	Not used	--	--	--	--
92	Not used	--	--	--	--
93	Not used	--	--	--	--
94	Not used	--	--	--	--
95	Not used	--	--	--	--
96	Not used	--	--	--	--
97	Not used	--	--	--	--
98	Total horizontal insolation	VDC	1-5 VDC = 0-350 Btu/hr-ft^2	±1.06% FS	NE-10
99	Direct insolation	VDC	--	--	--

[a]All RTD's must be calibrated using ice and boiling water reference points to achieve rated accuracy.
Pressure transducers must be calibrated to achieve rated accuracy.

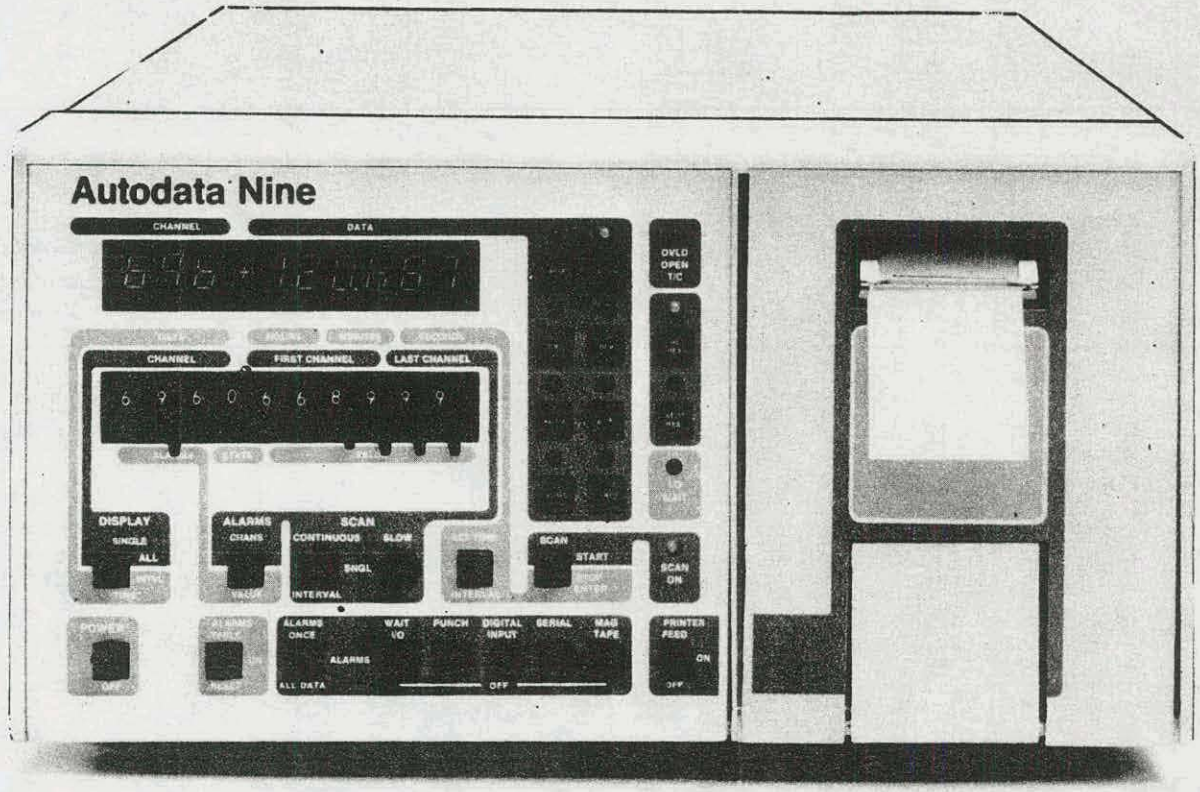

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Figure 3-25.
Acurex Autodata 9 data acquisition and control system.

collector field size. The heater was specified and furnished by DOE. The purpose of the heater in the system is to allow experiments to be performed in the storage and power generation subsystems which require thermal input equivalent to the output of the original collector field. The heater is sized to match the maximum output of the portion of the field which was deleted. The heater also enables tests and experiments to be performed in the storage and power generation subsystems at times when the insolation level is inadequate for operation of the collector field.

The auxiliary heater is shown in the foreground of Figure 3-26. The heater is located in the storage tank area to the southeast of the tank.

3.9 INTERCONNECTING PIPING

The major equipment items of the collector, storage, and power generation subsystems are interconnected with piping which was designed, constructed, and tested in accordance with the ANSI B31.3 Code for petroleum refinery piping. Piping material is carbon steel. Design conditions are 550°F and 150 psig for toluene piping and 75 psig for HT-43 piping.

Thermal insulation on piping and equipment is generally fiberglass. Foamglass has been used in areas around joints and flanges. Insulation thicknesses are shown in Table 3-6.

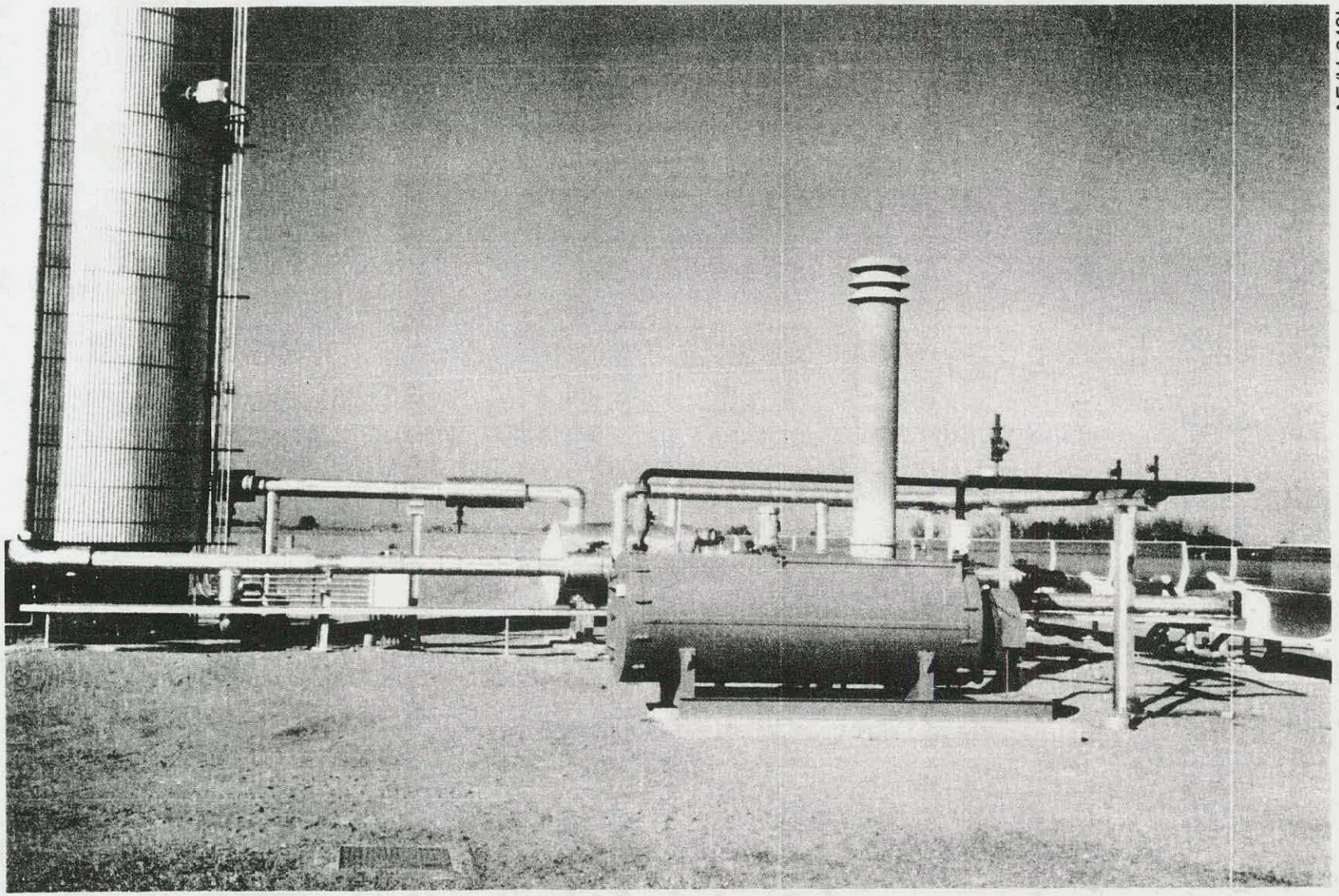

Figure 3-26. Auxiliary heater.

TABLE 3-6. INSULATION SCHEDULE

Item	Insulation Thickness (inch)
4 inch pipe	3.5
3 inch pipe	3
2 inch pipe	2.5
1 inch pipe	2.5
Equipment under 3 feet dia.	4
Equipment over 3 feet dia.	12

SECTION 4

CONSTRUCTION

The designs and specifications prepared during the detailed design period formed the basis for the procurement and construction activities that followed later. Vendors for material and equipment were selected and subcontracts for construction were let. A brief discussion of the construction events is presented below.

4.1 CIVIL WORK

The site was graded to provide a 0.5 percent slope in the collector field to facilitate drainage. Additional drainage provisions included five drywells ranging in depth from 30 to 60 feet located around the perimeter of the field. An earthen dike was formed around the thermal storage tank to serve as a catch basin for potential oil spills. A chain link fence was constructed around the site perimeter, and the site entrance and parking areas were paved with asphalt.

4.2 FOUNDATIONS

Reinforced concrete foundations were laid to support the various pieces of equipment and control building.

Collector foundations were poured-in-place 18-inch diameter caissons with protruding anchor bolts. Since positioning of these bolts throughout a collector group is important to module alignment, a fixture

(Figure 4-1) was used to ensure their proper placement. Smaller caissons, 9 to 12 inches in diameter were used to support piping.

Slabs were used to support the remaining equipment (tanks and ORC unit) and the control building.

4.3 EQUIPMENT INSTALLATION

4.3.1 Mechanical

The thermal storage, buffer, makeup, and condensate tanks arrived from the fabricator preassembled and were merely hoisted onto their foundations by a crane. This is shown in Figure 4-2 for the thermal storage tank.

The ORC equipment was delivered as skid-mounted subassemblies consisting of the vaporizer, power conversion module, generator, and condenser. Placement of these units on the common foundation and interconnection with each other proved to be straightforward. Particular care was given to aligning the generator to the turbine. The completed ORC unit is shown in Figure 4-3.

The gas-fired auxiliary heater was installed under Sandia direction.

4.3.2 Piping

Piping associated with the collector field, thermal storage, and ORC was installed in accordance with design. Deviations from the system piping design were limited to addition of a bypass to the gas-fired heater.

4.3.3 Electrical and Instrumentation

Electrical and instrumentation installation was a longterm effort that overlapped with other ongoing site work. Major electrical subassemblies and instrumentation components were fabricated and tested prior to delivery to the site. Figure 4-4 illustrates electrical conduit being laid coincident with collector installation.

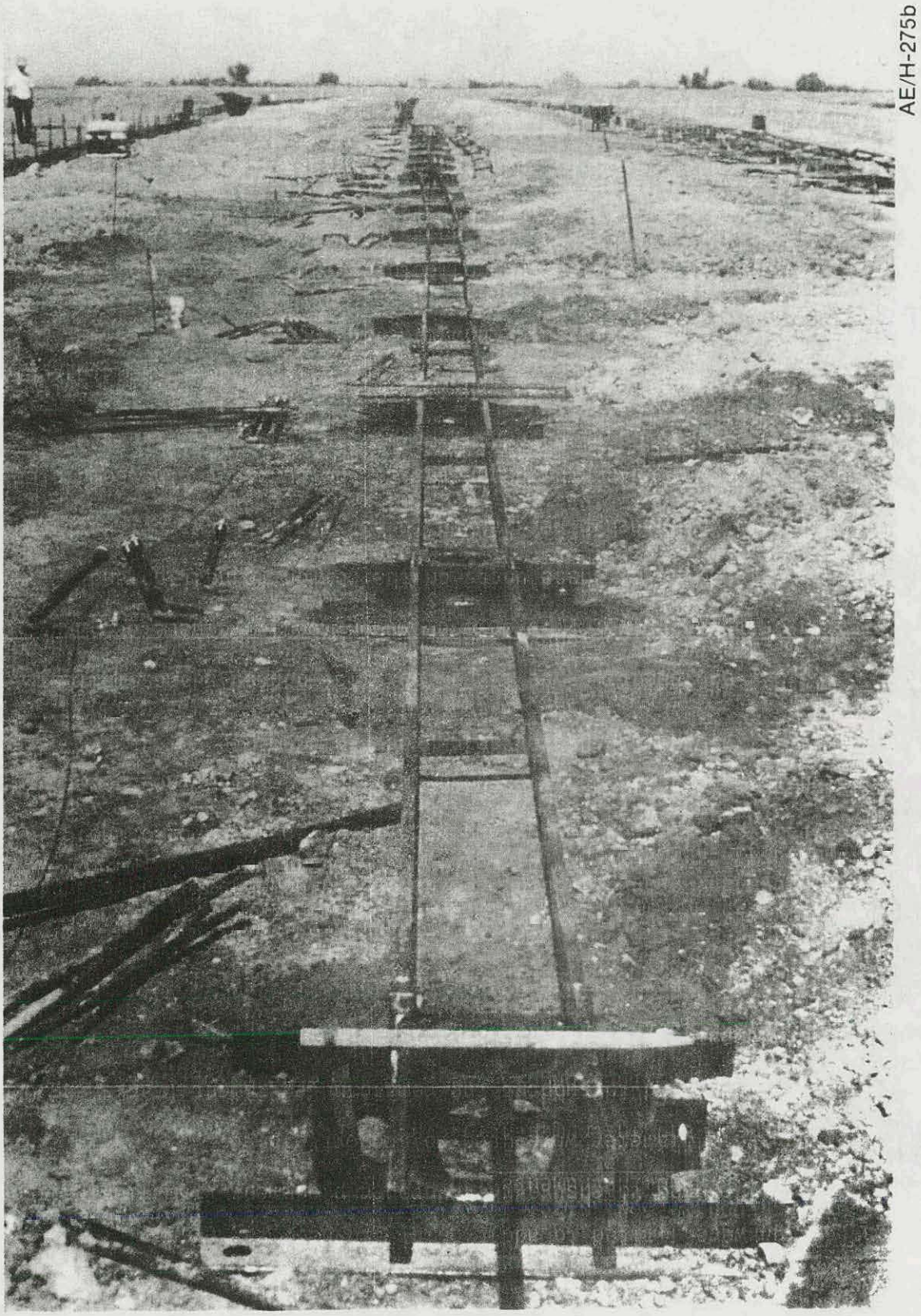

Figure 4-1. Collector foundation alignment.

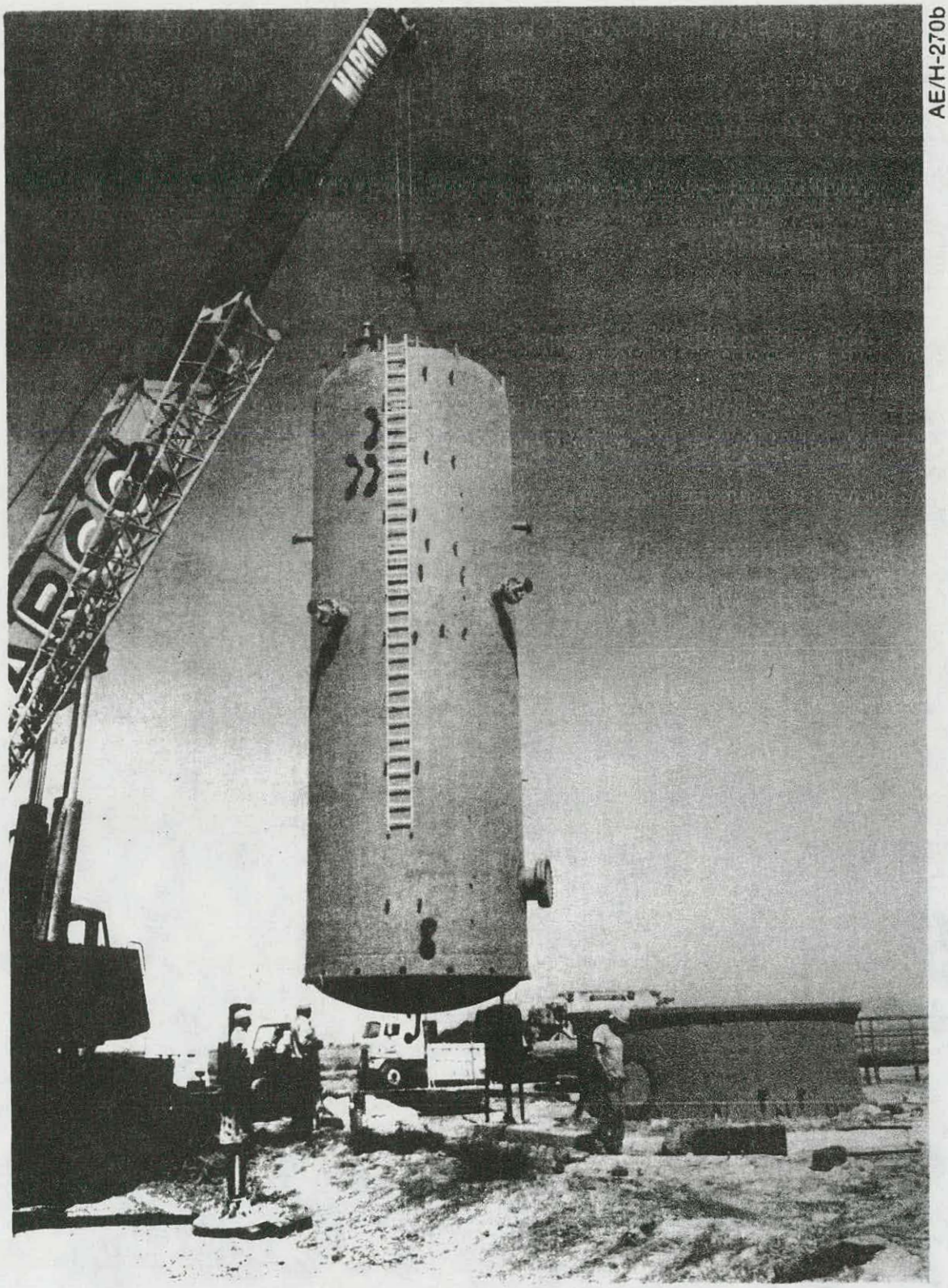

Figure 4-2. Thermal storage tank installation.

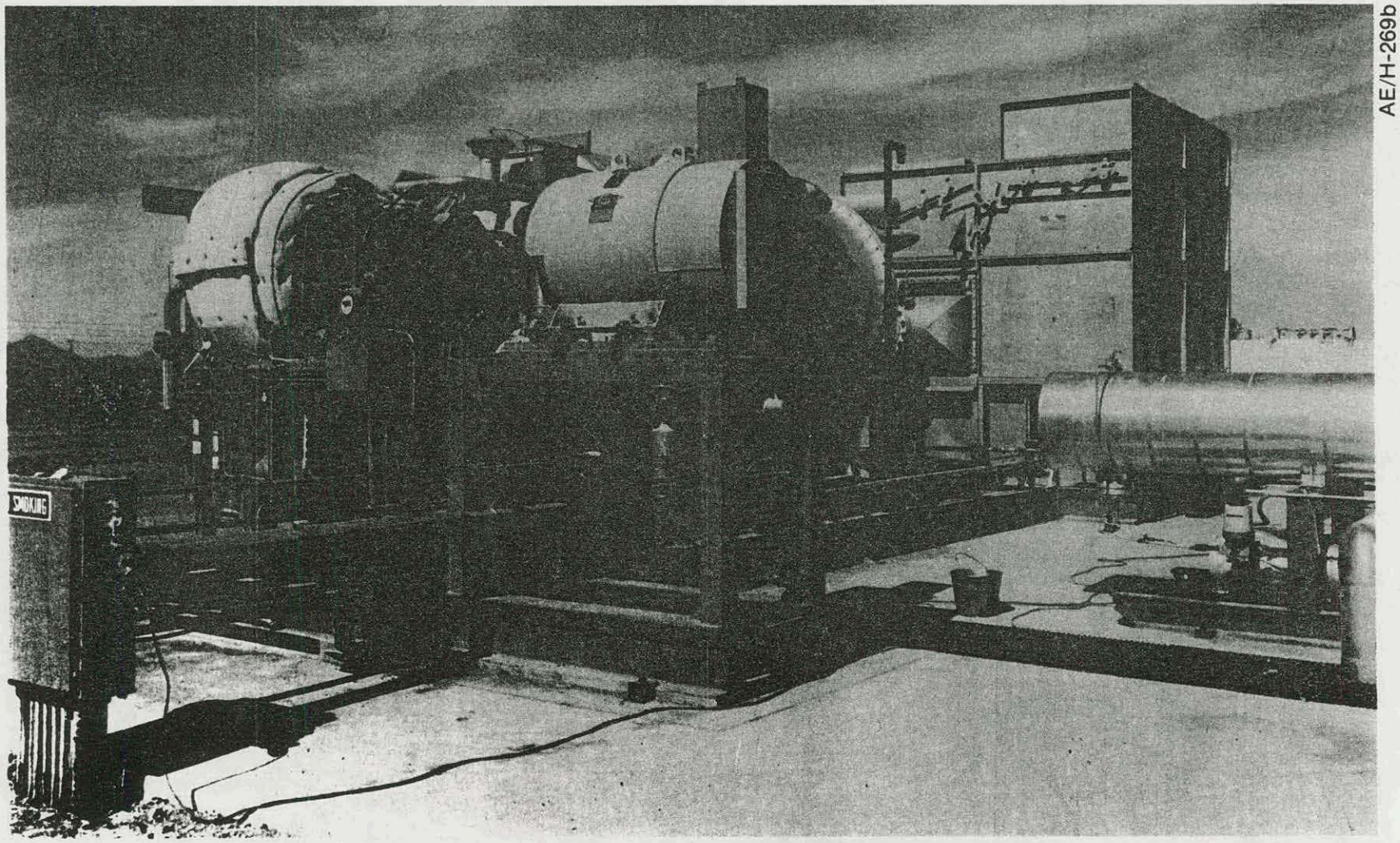

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Figure 4-3. Power generation unit.

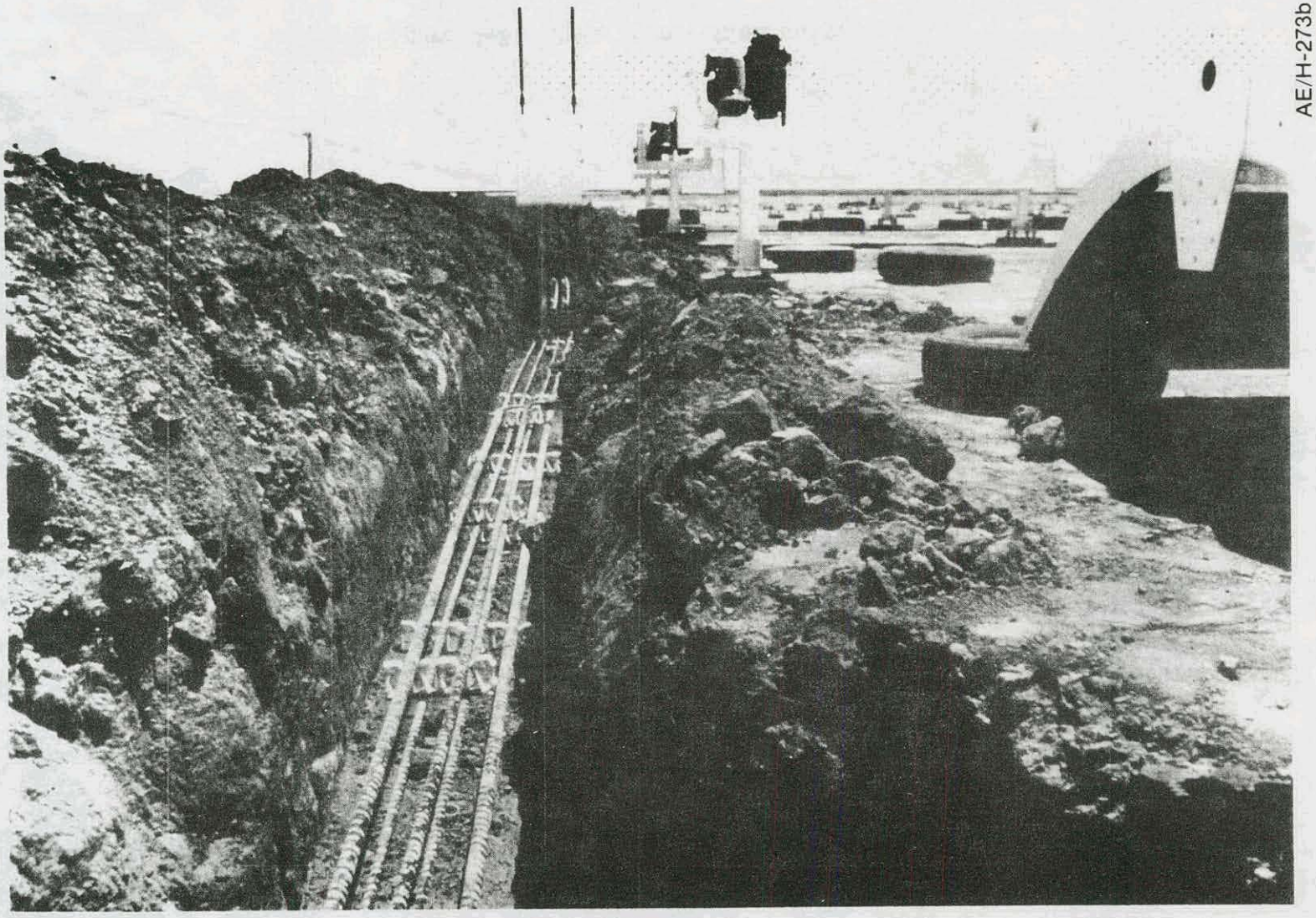

Figure 4-4. Electrical conduit installation.

4.3.4 Collectors

The Acurex-supplied collector components were easily assembled into a completed collector field by a subcontractor. The sequence of assembly followed the well-established pattern developed by Acurex, namely:

- Drive post and support post installation and alignment
- Module installation and alignment
- Receiver assembly installation and alignment
- Hose assembly installation
- Interface wiring terminations
- Tracker sensor assembly installation
- Static pressure leak test
- Insulate receiver assembly interconnections

Some typical photographs of collector installation are shown in Figures 4-5 and 4-6.

4.3.5 Insulation

Insulation was applied to vessels and piping carrying hot oil or toluene to reduce heat losses. The thermal storage tank and buffer tank were insulated with 12-inch thick fiberglass with an aluminum jacket. Piping in the collector field, thermal storage and ORC areas used 2-1/2 to 3-inch thick fiberglass insulation. Closed cell foamglass was used in regions of potential oil leakage. A picture of the thermal storage tank being insulated is shown in Figure 4-7.

4.4 BUILDING

The facility contains only one building. It is constructed of concrete blocks and serves as an office and houses the control and data acquisition equipment.

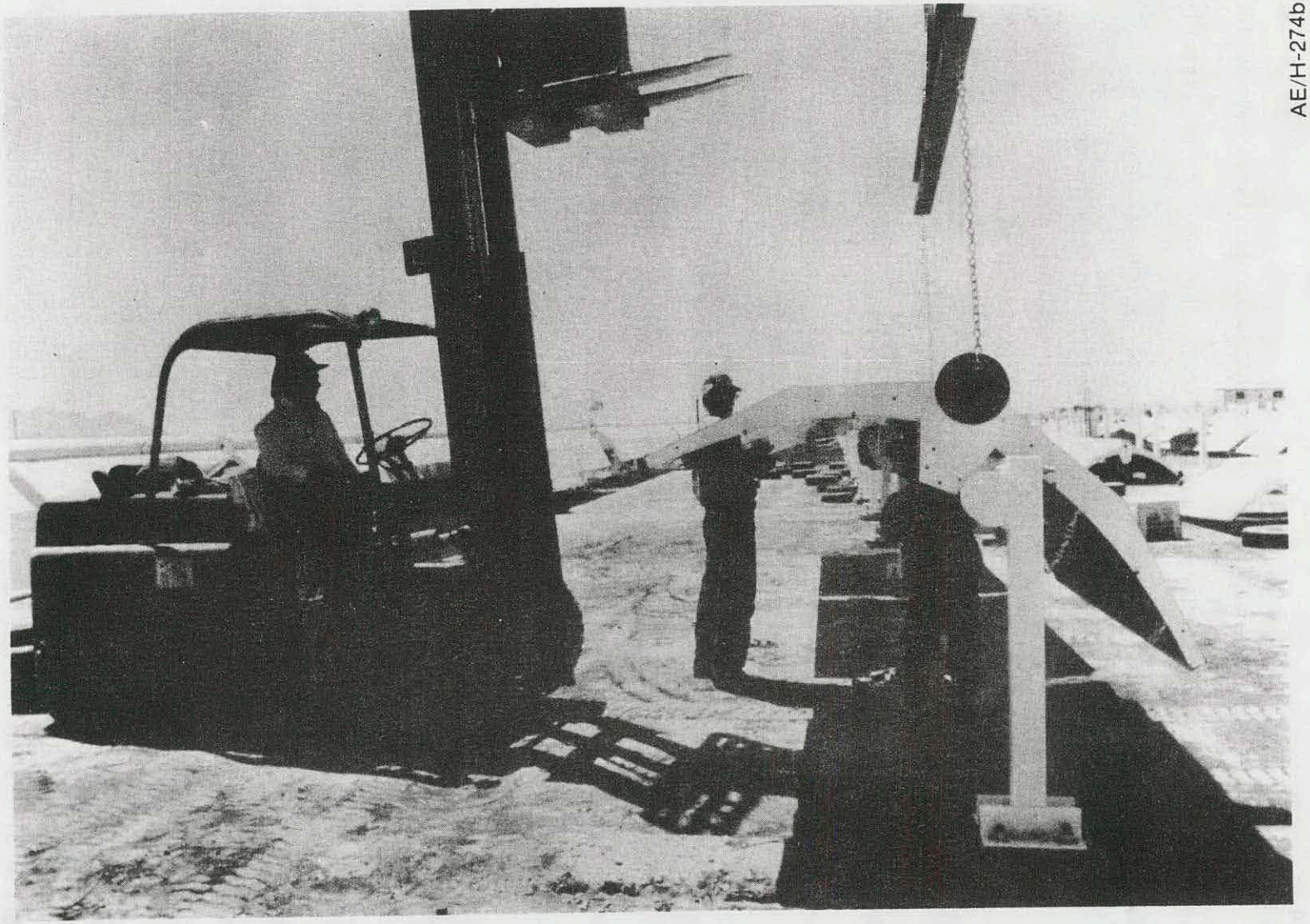

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Figure 4-5. Collector module installation.

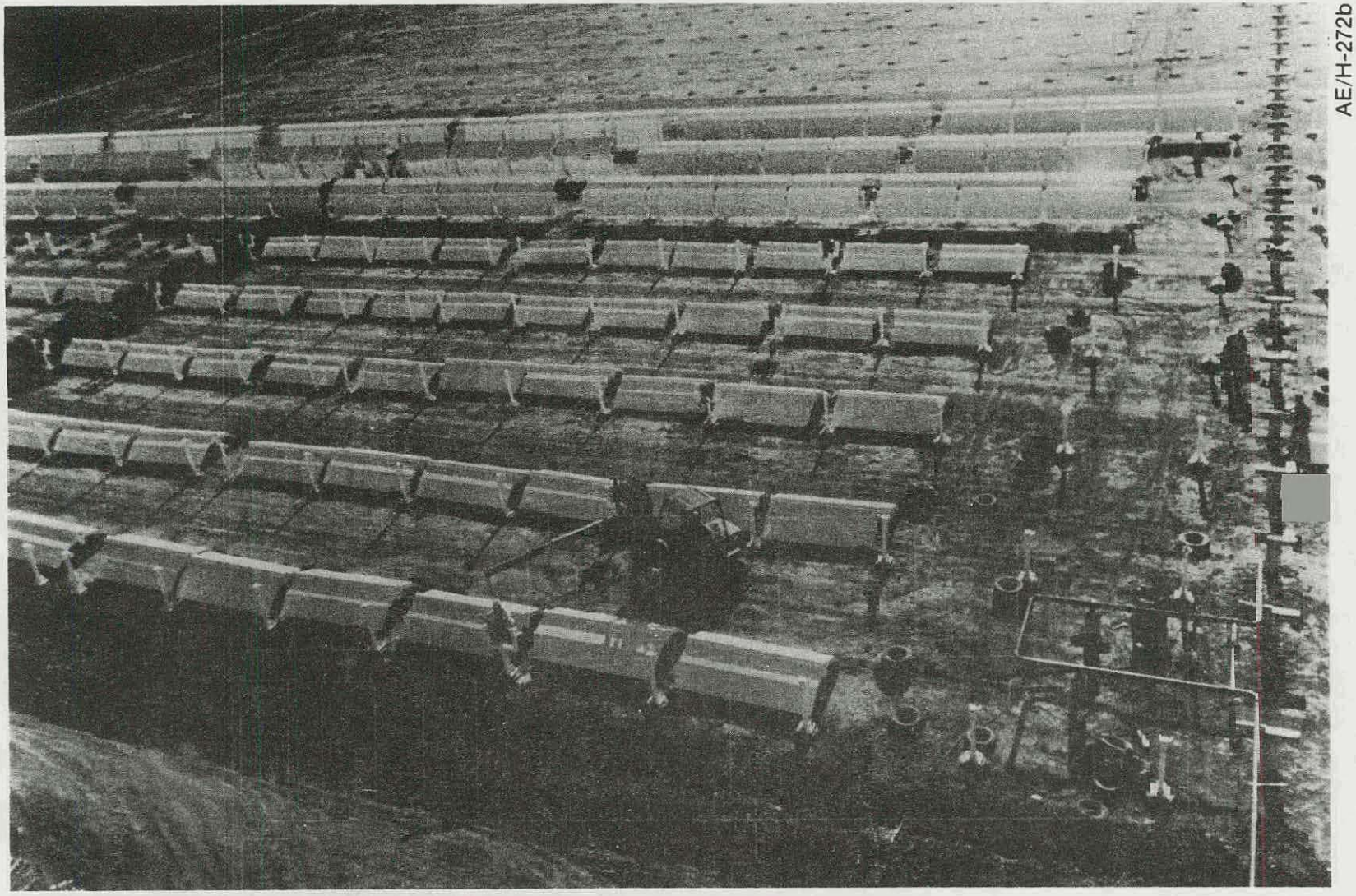

Figure 4-6. Collector field partially completed.

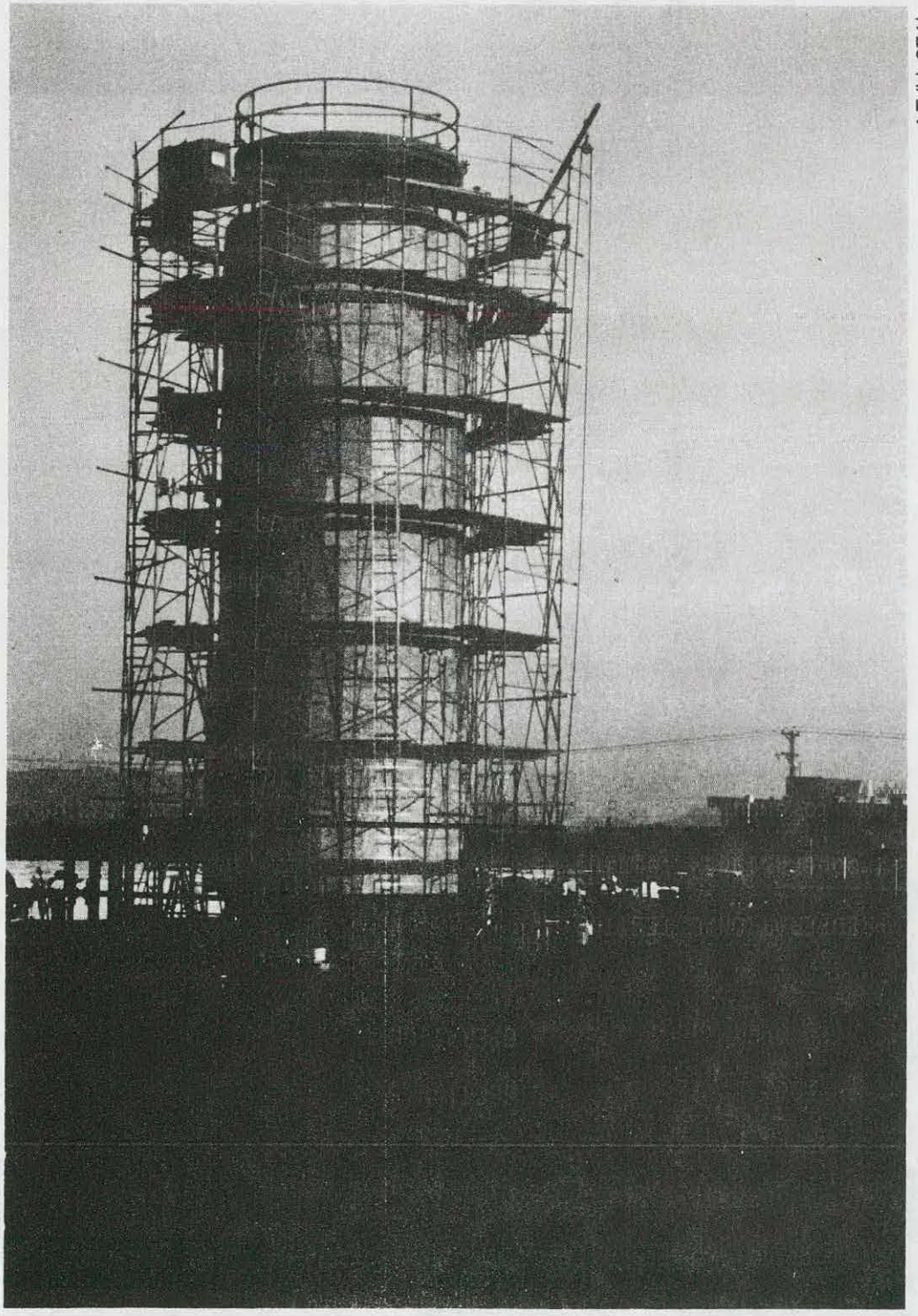

Figure 4-7. Insulation of thermal storage tank.

SECTION 5

OPERATION

5.1 PREOPERATIONAL TESTING

Preoperational testing was performed on the various components and subsystems to ensure that the final plant would function as designed. Two types of testing were performed: preinstallation tests, and checkout and startup tests. Preinstallation tests were performed on equipment prior to site installation to verify compliance with design requirements. Checkout and startup tests were made after installation of components and subsystems and consisted of acceptance tests, subsystem tests, and integrated system tests. A schematic sequence of the many preoperational tests performed is listed in Table 5-1.

5.2 SYSTEM OPERATION

The initial paralleling of the generator to the electric grid was on September 21, 1979 at 3:15 pm. This was the major milestone to prove all major mechanical and electrical equipment was operational. Since the initial paralleling of the generator, various adjustments were made to the system and some minor debugging of the control system have occurred. The collectors have been tracking on full automatic control. They "wakeup" on automatic control in the morning, come out of the stow position and go into the tracking mode. At the end of the day when the sun is low in the sky, the direct insolation monitor sees low insolation and gives the stow

TABLE 5-1. PREOPERATIONAL TESTING

- Preinstallation tests
  - Manufacturing tests
    - Certification tests of vessels, equipment, and heat exchangers
    - ORC operation tests
    - Acurex collector first article tests
    - Control console and storage tank instrument tree
  - Quality control
    - Collector production random sampling
    - Vaporizer acceptance tests
    - Vapor condenser acceptance tests
    - Equipment and instrument acceptance tests
    - Generator acceptance tests
- Checkout and startup tests
  - Installation acceptance
    - Check instrument loops
    - Pressure-test piping
    - Check power wiring
    - Check eletric motor rotation
    - Check collectors
  - Subsystem tests
    - Startup utilities
      - Plant air compressor
        - -- Instrument air dryer
        - -- Service pressure test piping
      - Plant water system (temporary supply)
    - Fill-up system
      - Caloria fill
        - -- Check tans level controls
        - -- Commission makeup pump
        - -- Fill up the main tank and buffer tank
      - Toluene fill (fill up the hot well)
    - Cold flow tests
      - Field circulation
        - -- Commission field pumps
        - -- Flush field loops
        - -- Functional test plant shutdown
      - Vaporizer Caloria circulation loop
        - -- Commission the pump
        - -- Flush vaporizer loop
        - -- Functional test safety shutdown
      - Functional check instruments
    - Safety tests
      - Test collector safety
        - -- Central desteer and stow functions
        - -- Local overheat
      - Emergency shutdown tests
    - Hot flow tests
      - Collectors in tracking mode
      - Check piping thermal expansion
      - Check vaporizer thermal expansion
      - Collector mechanical and instrumentation checkout
      - Charge the storage tank
      - Check the nitrogen ullage and tank instrsumentation readings
      - Startup ORC
      - Check for leaks
  - Insulate the system
  - Integrated system tests
    - Set the controls in automatic start mode
    - Test all safety lockout and alarm functions
    - Demonstrate grid operation
    - Adjust the controller program and set points
    - Record data and check against field readouts

command. The collectors have been operating on full automatic control since September 30, 1979.

The Sundstrand power conversion system has been operating on the automatic startup and automatic electrical system parallel. The controls have all been tuned and various adjustments made so that the system can operate on the full automatic mode.

One set of operation and maintenance manuals is at the project site to be used as the operational copy. Another set has been sent to the Department of Energy to serve as the record copy. In addition, Acurex and Sundstrand, the major vendors, have supplied listings of recommended spare parts. The vaporizer and the field pump presently have spare mechanical seals and wear rings at the site. The operation and maintenance manuals list the recommended spare parts associated with their respective supplied equipment.

A general procedure for plant startup and operation was developed during Phase II and is included in Appendix A.

The operation of the plant was turned over to DOE technical advisor, Sandia Laboratories and the University of Arizona on October 1, 1979.

APPENDIX A

150 KW PROJECT

OPERATING PROCEDURE

GENERAL

Wind and Dirt Protection

The collectors should be in the stow position any time there is no maintenance or operational activity. This is to protect the collectors from wind daamage and limit dust buildup on the reflective surfaces.

Focus Protection

Establish flow through the collector loop any time the collectors are brought out of the stow position. Two speed wrenches are to be ready and available in the event of a power outage and manual desteer is required.

Pump Minimum Flow Protection

Ensure there is a flow path established whenever the pumps are operated. This is to protect the pumps and provide the minimum flow required.

System Pressure Protection

Isolation of any part of the system may cause an excessive pressure buildup. Caloria HT-43 has a large thermal expansion coefficient. Any time a valve is closed ensure that there is room for fluid expansion or a vent or drain valve is open.

Manual Start of the Collector Field

1. Check the manual valve lineup, thermal storage tank, T-1 suction valve open and on through the supply and return manifolds and back to the storage tank and the buffer tank.
2. Check the 3 way valve open to the buffer tank at the console and locally at the valve.
3. Check the air compressor operating with a minimum receiver pressure of 50 psi.
4. Open all loop isolation air operated valves (AOV's) at the console by switching to "Manual."
5. Start the field pump, P-1 by closing the breaker at Panel HA, switching P-1 to manual at the console and switching on locally at the tank area terminal cabinet.
6. Check all loop flow lights at the console are "ON" indicating individual loop flow has been established.
7. Switch the AOV's to automatic at the console. Check the flow indicator lights "ON". If the 70 percent loops flow light is "ON" the collector will track if there is sufficient direct insolation.
8. After the field return temperature is 500°F or above, transfer the three-way valve from the buffer tank to the storage tank.
9. Individual collector loops or groups can be hand operated locally at the respective loop control boxes. Ensure flow has been established before placing collectors into focus.

Manual Shutdown of the Collector Field

1. At the console transfer the three-way valve from the storage tank to the buffer tank.
2. Switch the AOV's from automatic to hand. The interlock relays will give the collectors a stow command. Check all the collectors going to the stow position.
3. Switch the field pump, P-1 to "OFF" at the console.
4. Switch the P-1 breaker at Panel HA to "OFF".
5. Check all loop flow lights "OFF".
6. Close the storage tank main feed supply valve.
7. In an emergency the entire system can be shutdown by pushing the emergency stop button on the console, any of the four emergency stop buttons out in the field, or the emergency stop button in the ORC area.

Startup of the Power Conversion Module

1. Check valve lineup open from the ORC manifold in the storage tank, vaporizer pump, vaporizer and on back returning to the storage tank lower manifold.
2. Start P-2 the vaporizer pump by switching P-2 to manual at the console and by switching on locally at the tank area terminal cabinet.
3. If the vaporizer is below 200°F it should be heated up slowly. This can be accomplished by bumping the pump, i.e., running the pump for 15 seconds and shutting it down for several minutes and allowing the vaporizer to heat soak and then repeating the pump run and shutdown sequence.

4. The vaporizer shell pressure should not be allowed to reach 180 psig since this is the burst disc setpoint. At 150 psig either the ORC should be started or P-2 should be shut down.
5. The step by step startup procedure for the ORC is in the Sundstrand operation and maintenance manual.

Shutdown of the Power Conversion Module

1. For emergency shutdown any of the six emergency push buttons can be pressed.
2. For normal shutdown stop P-2, the vaporizer pump.
3. Allow the ORC to "coast down" utilizing the thermal energy in the vaporizer.
4. When the generator is no longer producing power the generator will trip on the reverse power relay.
5. The shutdown of the auxiliaries should be performed following the step by step procedure in the Sundstrand operating and maintenance manual.

Auxiliary Gas Fired Heater Operation

1. Valve lineup to the heater is established by opening tank suction valve and heater isolation valves.
2. Close the header suppply valve to solar collector field.
3. Position the three-way valve to the buffer tank.
4. Start P-1 to circulate fluid through the gas fired heater.
5. Light off and start up the gas fired heater per the manufacturers operating and maintenance manual.
6. When the outlet temperature reaches 500°F, operate the three-way valve so that the return flow goes to the storage tank.

7. Adjust firing rate and or pump speed to obtain desired outlet temperature. Do not exceed 550°F outlet temperature from the gas fired heater.

CAUTION

Do not try to operate the collector field and the gas-fired heater at the same time. There are too many parameters to monitor, and there is too much chance for a flow upset and over temperature problems.

Automatic Operation of System

The collector and storage tank systems have all the required controls and safeguards necessary to operate from startup in the morning to shutdown in the late afternoon. The various functions and steps can be monitored as they are sequenced. Switching from automatic to manual and back again can be done on a system basis while monitoring all subsystems. Care should be taken when performing these operations.

150 KW PROJECT

SYSTEM INTERLOCKS AND SAFETIES SET POINT LIST

Device	Location	Pressure Range	Setpoint
PSH-36	P-1	1-8 psig	5 psig
PSH-37	P-2	1-8 psig	5 psig
PSH-30	T-1	1-14 psig	10 psig
PSL-31	T-1	1-30 in. WC	10 in. WC
PSL-270	Air System	1.5-36 psig	2 psig
PSH-271	Air system	1.5-36 psig	2 psig
PSL-80	Air system	3-100 psig	80 psig
PSV-12	T-3	--	9 psig
PSV-12A	N_2 bottle	--	100 psig
PSV-12B	N_2 bottle	--	1 psig
PSV-34	T-1	--	12 psig
PSV-35	T-1	--	2 in Hg Vac
PSE-30	T-1	--	15 psig
PSE-32	T-1	--	4 in. Hg Vac

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