JIM FISH 2452

DOE/SF/10738-1/2

SOLAR REPOWERING FOR ELECTRIC GENERATION, NORTHEASTERN STATION UNIT 1, PUBLIC SERVICE COMPANY OF OKLAHOMA

Final Report

July 15, 1980

Work Performed Under Contract No. AC03-79SF10738

Black & Veatch, Consulting Engineers
Kansas City, Missouri

U.S. Department of Energy

Solar Energy

35-0112 VOL 2

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additions to existing site facilities are required. Solar system performance is characterized by the generation of 29.1 MW_e of the 145 MW_e net plant output at the design point (noon, March 21) and 48 GHw_e on an annual basis. The construction cost estimate for repowering NES I is $55.1 million (1980 dollars), and annual operations and maintenance cost is estimated to be $244,000. The plant was designed giving appropriate consideration for construction, operational and public safety. Principal environmental impacts (positive and negative) and institutional/ regulatory considerations were factored into the design process.

Key characteristics of the five major systems were established in the design. The collector system consists of 2,255 heliostats, their associated controllers and a power distribution network; these heliostats are in circular arcs centered on and located north of the receiver tower in a 5.1 x $10^5 m^2$ (126 acres) area. The external water/steam receiver, which uses a novel arrangement of screen tubes that increase its efficiency to almost that of a cavity receiver, employs economizer panels, boiler screen tubes, superheater membrane panels, a circulating pump, and closure doors; it is 9.45 m (31 ft) in diameter by 15.2 m (50 ft) high and supported by a 109.5 m (359 ft) high concrete tower. The receiver loop system provides interface piping of feedwater, steam, and condensate between the receiver and fossil energy systems. The digital master control system coordinates the operations of all plant systems and ensures the safe and proper operation of the integrated repowered plant; it provides data logging and plant simulation for operator training. The fossil energy system contains the existing power plant equipment and the fossil fuel which is used during hybrid operation and normal plant operation.

The economic evaluation focused on the value of the repowered unit to PSO. It is calculated from fuel displacement savings and the deferral of capital investment due to the extension of the usable life for NES I. Two analytical techniques were employed in the evaluation. The first calculates the energy contribution throughout the year by system performance simulation. The second computes the economic impacts of the repowered unit on the entire PSO system's fuel consumption and capital investment schedules;

ABSTRACT

The Department of Energy contracted for Black & Veatch to develop a conceptual design for solar repowering Northeastern Station Unit I (NES I) of the Public Service Company of Oklahoma (PSO). Subcontractors were PSO and Babcock & Wilcox Company (B&W). The objective of the effort was to develop the best site specific design which would satisfy the following requirements.

- Provide practical and effective use of solar energy for repowering.
- Have the potential for construction and operation by 1985.
- Maximize use of existing solar thermal central receiver technology.

NES I is located about 50 km (30 miles) northeast of Tulsa, Oklahoma. This plant was selected because it is representative of candidate plants for repowering and for solar-fossil hybrid operation; it is located in a moderate insolation region, utilizes an efficient reheat cycle with steam conditions characteristic of modern power plants, and has sufficient land for repowering. NES I has a subcritical, single reheat turbine-generator and a gas-fired steam generator. Although the unit is currently base loaded, PSO plans to substantially reduce its use due to projected fuel restrictions and costs unless the unit is repowered.

The basic repowering configuration was established through a series of trade studies and the criterion that proven technology be used. The system selected has a water/steam receiver which supplies superheated steam to the turbine at a design point flow rate sufficient to displace 20 per cent of the unit's fossil fuel consumption. The hybrid nature of the plant's operation eliminates the need for costly thermal storage. The collector system maximizes the annual energy delivered to the receiver per unit cost, consistent with solar flux distribution requirements of the receiver.

The conceptual design of the repowered plant consists of four solar systems (collector, receiver, receiver loop and master control) which are fully integrated with the existing fossil energy system for hybrid operation in both automatic and manual modes; the existing fossil energy system will not be altered for repowering. Minimal site preparation and

PREFACE

This report describes the conceptual design and evaluation of solar repowering an electric generation plant as part of the Department of Energy (DOE) Solar Repowering/Industrial Retrofit Program. The DOE San Francisco Operations Office issued Contract Number DE-AC03-79SF 10738 to Black & Veatch (B&V) for this effort, which was performed during the period September 24, 1979 to July 15, 1980 on B&V Project 8734. Significant contributions to the project were made by B&V's subcontractors, Public Service Company of Oklahoma, the utility and site owner, and the Babcock & Wilcox Company, designer of the solar receiver. B&V expresses appreciation for the guidance provided by Mr. Fred Corona, Contract Manager for the DOE San Francisco Operations Office, and Mr. Jim Gibson, Technical Manager for Sandia National Laboratories, Livermore, California.

The report is contained in three volumes: Executive Summary, Final Report, and Appendix. The Executive Summary provides a brief overview of the conceptual design, a synopsis of the performance and economic evaluation, and an assessment of the concept from the site owner's perspective. The Final Report contains a more comprehensive description of the work performed on the project; this volume presents the trade studies, conceptual design, system performance, economic analysis, and development plan as well as a description of a test program carried out on the project. The Appendix volume consists of the System Requirements Specification and insolation data obtained in the test program.

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SOLAR REPOWERING FOR ELECTRIC GENERATION

NORTHEASTERN STATION UNIT 1

PUBLIC SERVICE COMPANY OF OKLAHOMA

FINAL REPORT

July 15, 1980

Black & Veatch, Consulting Engineers
Public Service Company of Oklahoma
Babcock & Wilcox Company

Department of Energy
Contract No. DE-AC 0379SF 10738

it is determined by PSO's modeling their power production and expansion plans through the year 2024. Results of the economic evalution led to three key conclusions.

- The value of repowering is about 25 per cent of construction cost.
- The most cost effective size for solar repowering NES I is 30 MW_e.
- Fossil fuel displacement is not sensitive to operating strategy.

Based on the conceptual design, performance, and economic analyses, a development plan was created. To provide for the timely and efficient implementation of repowering at NES I, a detailed Critical Path Method Schedule was prepared, premised on initial operation by September 1984. This plan leads to commercial operation of the repowered unit through an overlapped sequence of five phases: design, construction, system checkout/start-up, system performance evaluation, and joint user/DOE operations. An important factor of the design which benefits the development plan is the absence of need for a Subsystem Research Experiment. Integration of the schedule and the construction cost estimate identified the cash flow requirements (1980 dollars).

Fiscal Year	1981	1982	1983	1984	1985
Cash Flow (000)	$114	$6,245	$19,036	$24,262	$5,442

The development plan concluded with PSO's comments on repowering at NES I and its role in implementing solar thermal central receiver system for utilities.

In support of current and future design activities for repowering NES I, a test program was conducted at the site to measure direct normal insolation and the accumulation of dust on heliostat mirrors. The following conclusions were reached as a result of the test program.

- The test data agree with the 5.4 kWh/m^2 day annual average direct normal insolation as interpolated from published isopleth maps.
- The average degradation of mirror reflectivity due to dust accumulation was about 5 per cent; the peak value was about 10 per cent.
- The cooling tower effluent, not the coal pile for Units 3 and 4, are the predominant source of mirror surface contamination.
- The dust accumulations on the mirrors are easily washed away by rainfall, restoring the optical performance of the mirrors.

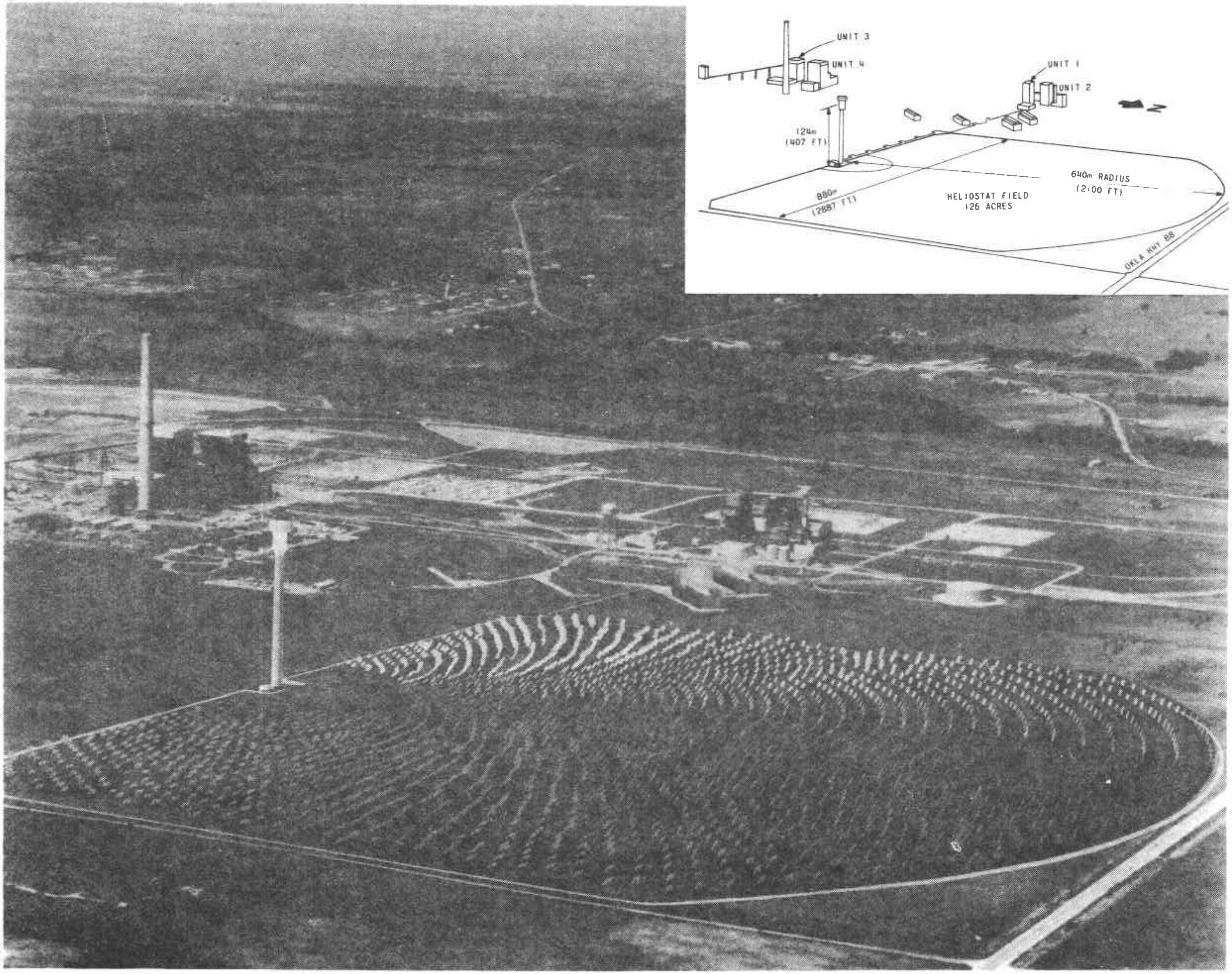

FIGURE I-1. PHOTO RENDERING OF SOLAR REPOWERED NES I

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1.0 EXECUTIVE SUMMARY

The conceptual design and evaluation of solar repowering an electric generating unit of Public Service Company of Oklahoma (PSO) is described in this report. The solar addition would permit, at the design point, a 20 per cent reduction of the fossil fuel consumed by PSO's 150 MW_e Northeastern Station Unit 1 (NES 1). The work was performed as part of the Department of Energy's Solar Repowering/Industrial Retrofit Program. Black & Veatch, Consulting Engineers, was the prime contractor, with PSO and Babcock & Wilcox Company (B&W) as subcontractors.

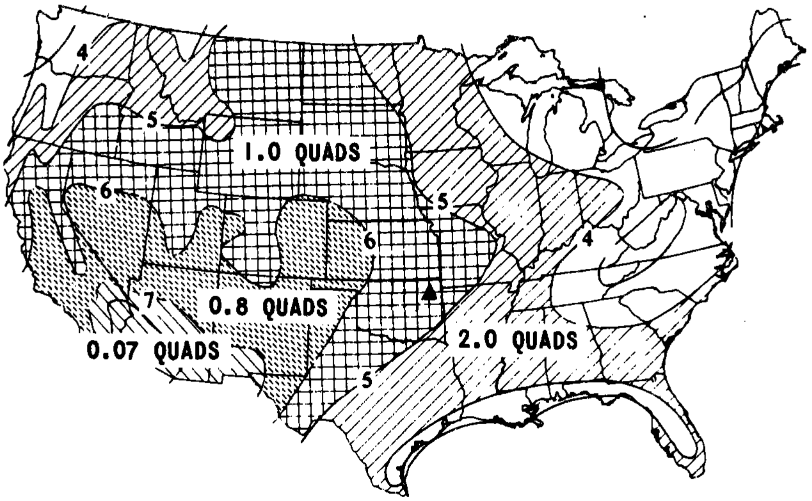
The project objective was to develop the best site-specific solar repowering design that would fulfill the following requirements.

- Provide practical and effective use of solar energy.
- Have the potential for construction and operation by 1985.
- Make maximum use of existing solar energy technology.

Project tasks included appraisal of the technical viability, identification of the economic value of solar repowering for NES 1, and preparation of a development plan to implement the solar repowered plant. Figure 1-1 is an artist's rendering of the conceptual design.

1.1 BACKGROUND AND APPROACH

Solar energy has the potential to serve the nation's need to achieve energy independence. An opportunity to displace significant amounts of fossil fuel is to use solar central receiver systems for the generation of electric power. The implementation of such systems in the near term requires that proven technology be combined into a new system with performance and economic requirements that meet the needs of specific electric utility systems. Initial studies of solar power plants emphasized sites in the high insolation areas of the southwestern United States. However, oil and gas consumed in this region represent but a small portion of the fluid fossil energy consumed annually to produce electricity. An order-of-magnitude more fluid fossil energy is consumed for electric generation in those portions of the United States where the sun's energy is more modest. Figure 1-2 shows the annual consumption of oil and gas in various insolation zones of the United States and emphasizes the nation's need to develop, evaluate, and learn how to operate central receiver designs for these important, but less sunny, regions.



▲ LOCATION OF NORTHEASTERN STATION
PUBLIC SERVICE COMPANY OF OKLAHOMA

QUAD = 10^{15} Btu
= 1.72×10^{8} BBLS OIL

FIGURE 1-2. OIL AND GAS (QUADS) USED TO PRODUCE ELECTRICITY (1976) IN ZONES BETWEEN DIRECT INSOLATION ISOPLETHS (kWh/m^2)

The technical approach taken to meet the project goals utilizes the established practices for design, construction, and operation of electric generating stations. To meet the 1985 operational date, all aspects of the design use presently available technology. The receiver fluid is water/steam whose design criteria are well understood by B&W, a company that has been designing and building steam generators for 113 years. Furthermore, water chemistry and materials compatibility at the operating conditions of the solar receiver are known, and the risks associated with combining materials to perform in uncertain operating regimes are eliminated. The use of solar-fossil hybrid operation in lieu of storage eliminates the need to derate the turbine performance at lower steam temperature from storage, or to risk possible failures by combining and using materials in new, unproven higher temperature operating regimes. A common thread throughout the technical approach is to eliminate problem areas by simplicity of the design, instead of adding complex features to "fix" or "patch" potential design risks.

The project was organized with Black & Veatch providing overall management responsibility, engineering design responsibility, and integration of project effort. PSO, as the site owner, provided utility guidance for the technical design and operating procedures, economic criteria and analysis for evaluation of the repowered unit, and information to guide the development plan. B&W used its expertise in the design of the receiver, tested and evaluated the fossil steam generator for solar-hybrid operation, and specified equipment for the control system. This team, including several of the present project staff members, was involved in the design and construction of NES 1 in 1959-1961.

1.2 SITE DESCRIPTION

The proposed repowering site and the existing fossil power plant are described in the following subsections.

1.2.1 Location and Characteristics

PSO Northeastern Station is located 51 km (30 miles) northeast of Tulsa, adjacent to Oologah Reservoir (Verdigris River) in northeastern Oklahoma at 36°26' north latitude and 95°42' west longitude (Figure 1-3). The site occupies 5,340,000 m^2 (1,320 acres), is almost square in shape, and abuts US Highway 169 on the west and Oklahoma Highway 88 on the north. The access road to the station is 350 m (1,100 ft) east of the intersection of these two highways. A thin silty clay soil mantle, generally 0.3 to 0.9 m (1 to 3 feet) thick, overlays weathered limestone which, in turn, overlays competent limestone bedrock. The land is flat and slopes gently toward the southwest; the heliostat field area drops from an elevation of 210 m (690 feet) above mean sea level to 198 m (650 feet). The site area, other than that which is used for the generating units and their ancillary facilities, resembles pastureland with little brush and essentially no trees.

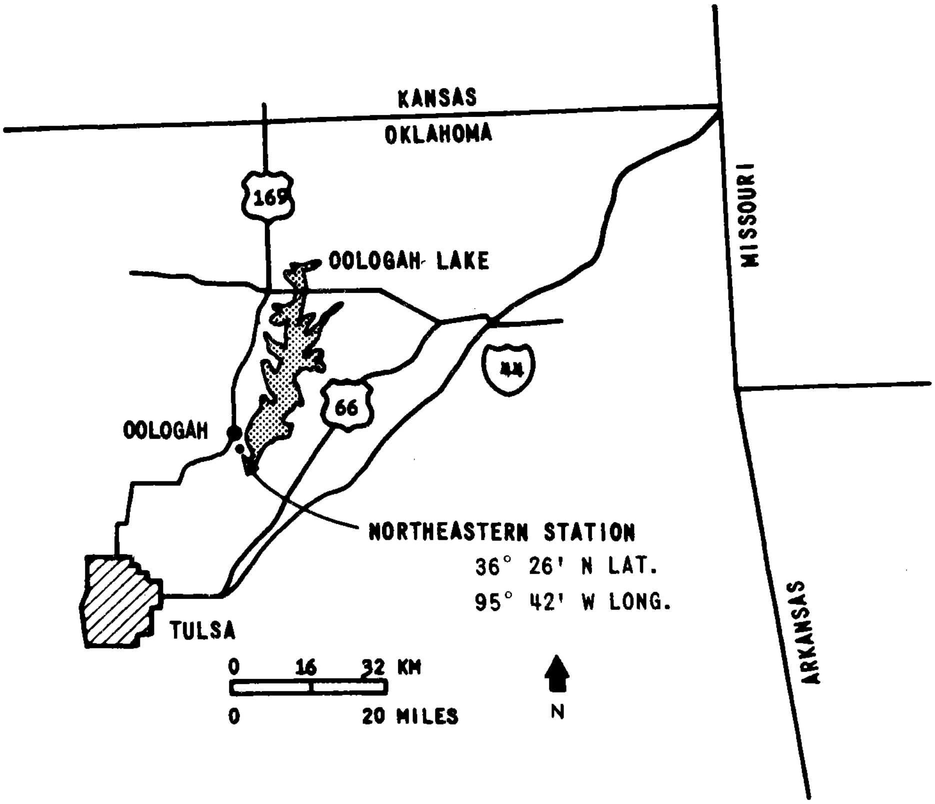


FIGURE I-3. LOCATION OF NORTHEASTERN STATION, PUBLIC SERVICE COMPANY OF OKLAHOMA

The climate is characterized by highly variable precipitation and temperature. During summer, southerly winds bring warm, moist, tropical air from the Gulf of Mexico. Cold, dry air from polar regions predominates in winter. There are often sudden and severe weather changes when polar and tropical air masses meet over the area. Occasionally, drought conditions are produced by dry air from the plateaus of Mexico.

The region has a moist, humid to subhumid climate. Spring and autumn are characterized by warm days and cool nights; summers are long, but not unusually hot; and winters are comparatively mild. Daytime summer temperatures above 38 C (100 F) are frequently experienced; in winter, surges of cold Arctic air traveling southward across the central states occasionally cause subzero temperatures.

Thunderstorms are common and are the major source of precipitation. Snowfall is distributed evenly over the 3 winter months. Average monthly precipitation is characterized by a maximum in May and June and a secondary maximum in September and October.

Prevailing winds are southerly. Wind speeds are generally light to moderate. Strong gusty winds associated with thunderstorms and cold fronts are common. The area is subject to severe windstorms, including tornadoes.

1.2.2 Plant Description

Northeastern Station consists of four generating units.

	Capacity	Fuel	Commercial Date
Unit 1	150 MW_e	gas/oil	1961
Unit 2	470 MW_e	gas/oil	1970
Unit 3	450 MW_e	coal	1979
Unit 4	450 MW_e	coal	1980

The location of Units 1, 2, 3, and 4, key plant equipment, other features, and the location of the conceptual design heliostat field are shown in the site arrangement, Figure 1-4.

NES 1, the unit proposed for the solar repowering, is currently a base load unit used to feed power into the system network. The unit is kept on the line at all times except for scheduled and emergency outages. As the availability of the base load fuel gas declines and its cost in relation to coal and lignite increases, this unit will be relegated to an intermediate type unit. PSO has plans to modify this unit for weekly and daily start-up cycling. These modifications will permit cycling without overstressing and damaging equipment parts, fortuitous for Solar Repowering. The fossil fuel heat rate on this unit, which includes fossil steam generator losses, is currently 3.08 MW_t/MW_e (10,500 Btu/kWh).

NES 1 utilizes a subcritical steam Rankine cycle to generate 150 MW of electricity. The fossil steam generator is a radiant, drum-type unit designed and built by B&W, is rated at 522,000 kg (1,150,000 pounds) steam per hour, produces superheated steam at the turbine throttle of

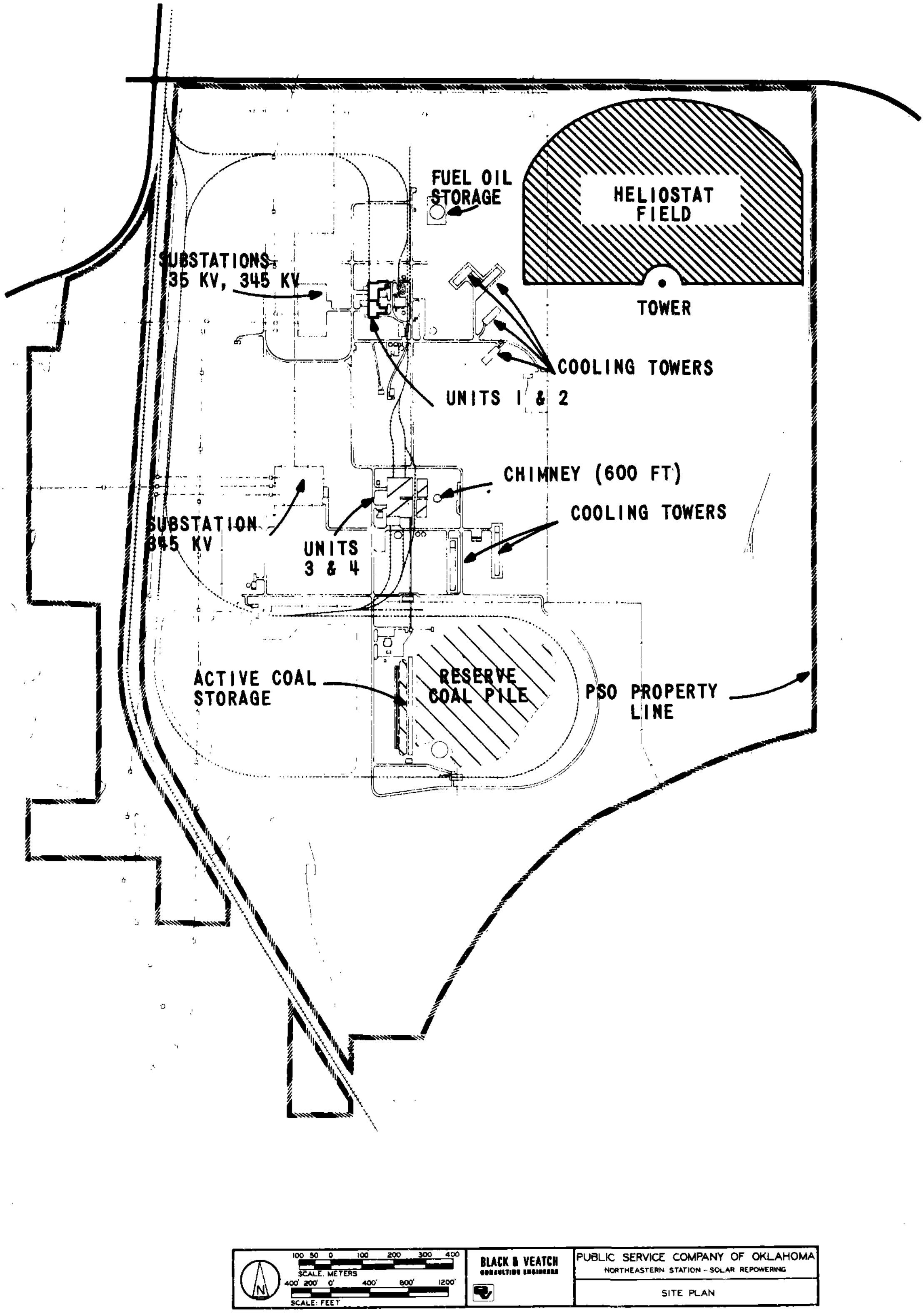


FIGURE I-4. SITE ARRANGEMENT OF NORTHEASTERN STATION SHOWING HELIOSTAT FIELD

12.5 MPa (1,800 psi) and 538 C (1,000 F), and reheats the steam to 538 C (1,000 F). The Westinghouse turbine is a tandem compound, double flow, reheat, condensing machine with extractions for five regenerative feedwater heaters. The system also employs a horizontal, two pass, surface condenser manufactured by Westinghouse, and two Marley induced draft wet cooling towers. Bailey Meter Company (now Bailey Controls Company of B&W) supplied the plant control system, which interfaces with the pneumatic boiler control system and the mechanical/hydraulic turbine control system. The use of redundant condensate and feedwater pumps is typical of the Black & Veatch design approach which has made NES I a very reliable unit, averaging 91.8 per cent availability.

1.3 PROJECT SUMMARY

The solar repowered NES I is a hybrid central receiver solar-fossil power plant that eliminates the need for costly storage systems. This conceptual design study addresses the repowering of a current highly efficient reheat cycle, 12.5 MPa/538 C/538 C (1,800 psi/1,000 F/1,000 F), which represents the class of candidates likely to be beneficially repowered.

Solar repowering offers the potential to extend the contribution which NES I will make to PSO's electric power grid by increasing NES I's projected load factor and extending its operating life. The repowering system generates superheated steam by conversion of solar energy to steam thermal energy. The steam fraction produced in the solar receiver is merged with that from the fossil steam generator before continuing to the turbine. Thus, the solar steam displaces fossil steam and reduces the amount of fossil fuel consumed in the generation of electricity. The 30 MW_e rated solar repowered unit would provide sufficient energy derived from the sun to displace the equivalent of 88,000 barrels of oil per year.

The NES I repowering conceptual design is based on the most widely used and proven electric generating technology--the direct conversion of thermal energy into high energy steam, the steam into mechanical energy, and the mechanical into electrical energy. This approach reduces the risk and provides the greatest opportunity to evaluate central receiver systems performance in an actual utility operating environment. From a technical standpoint, there will be no need to extend the range of use for materials, no potentially catastrophic safety hazards from salts or sodium, and no need to retrain plant operators for an alien technology.

Primarily, solar repowering is attractive because it provides the most effective R&D opportunity to introduce central receiver technology to the electric utilities. The economic evaluation confirms the fact that \$260/m^2 heliostat costs will not permit solar-generated electricity to be cost competitive with today's alternatives. Repowering provides the necessary first steps in the development of demand for heliostats, leading to their large volume production and attainment of cost goals which permit competitively generated electricity.

The importance of timeliness to the economic value of repowering is clearly illustrated in the case of NES I. During the first 10 years, 1985 to 1995, solar repowering displaces natural gas valued at \$14.9 million. During the last 5 years of the 15-year plant lifetime, solar electricity displaces lower cost coal and nuclear-generated electricity and not higher-priced gas or oil. In fact, the continued use of NES I after 1995 increases the gas consumed and the annual fuel costs after 1995. This is due to the transition from gas to coal and nuclear fuels forced by the National Energy Act, and by the high oil and gas prices. The economic benefit in these last years is created by the extended use of the solar repowered unit which, in turn, allows a delay in generation expansion and deferral of capital investment.

The repowering of NES I also provides an opportunity and the incentives to introduce central receiver technology into utilities on a cost-sharing basis. This introduction is a necessary step toward valid appraisal of solar thermal powered central stations for the production of electricity.

Stated concisely, the reasons for implementing the conceptual design for solar repowering of NES I are the following.

- Commercial technology exists.
- Subsystem Research Experiments are not required.
- Operationally, the solar unit is feasible.
- Economic shortfall of about 75 per cent is within the Solar Repowering Program Plan Criteria.
- PSO Northeastern Station Unit 1 offers significant size, representative steam cycle temperature and pressure, minimum complexity, and a project team/staff with 20 years of proven working relationships.

1.4 CONCEPTUAL DESIGN DESCRIPTION

Trade studies identified preferred key design characteristics which were then used as design specifications for the conceptual design. The solar repowered system is designed to generate superheated steam by conversion of solar radiant energy. A schematic of this repowered system is shown in Figure 1-5.

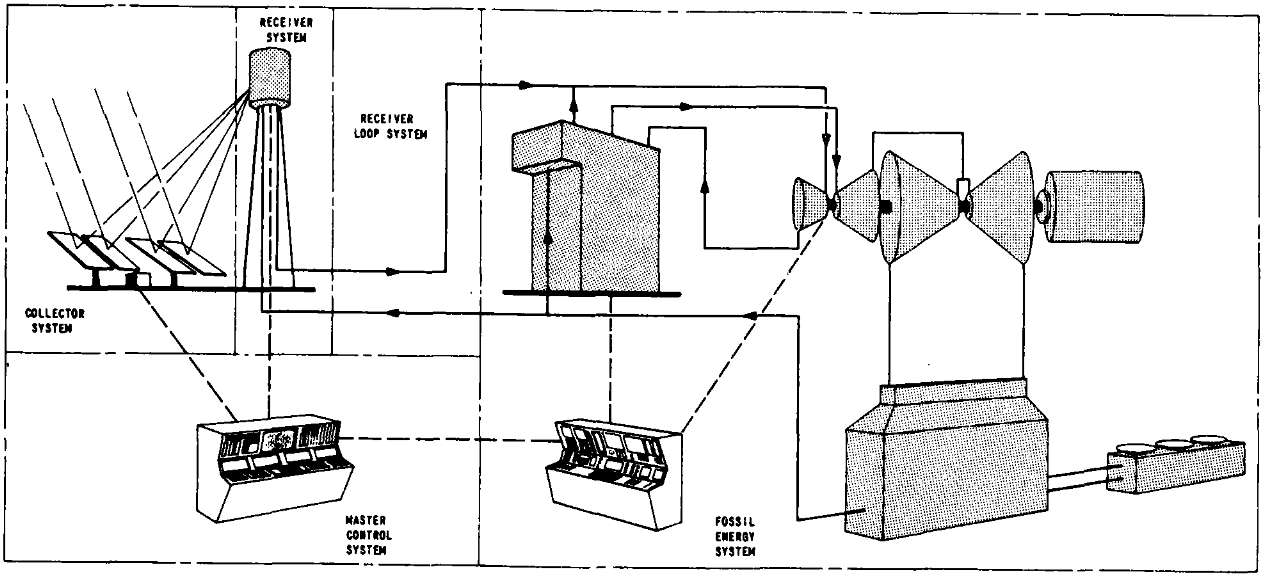


FIGURE 1-5. SOLAR REPOWERING SYSTEM SCHEMATIC

The major systems of the repowered plant are the collector system, receiver system, receiver loop system, master control system, and, of course, the existing fossil energy system and its associated facilities. The four solar systems are fully integrated with the fossil energy system to provide:

- Maximum use of solar energy.
- High system reliability.
- System safety for personnel and equipment.
- Simple operation.

The solar repowered plant operates in a hybrid mode; the solar and fossil generated steam flows are merged before entering the turbine. At the design point of noon, March 21, the solar repowered plant supplies a net power of 73.3 MW_t with a reference insolation of 950 W/m^2; this represents 20 per cent of the thermal input to the cycle at the plant rated output. The plant is designed to operate under environmental conditions specified by the DOE system requirements. Functional requirements, design and operating characteristics, site requirements, and performance of each system are described below.

The collector system, based on DOE second generation heliostat specifications, consists of 2,255 heliostats, optimally located in 48 circular arcs centered on and north of the receiver support tower. They occupy 510,000 m^2 (126 acres), in an area 880 m (2,887 ft) wide (east-west), and the radius of the outer row of heliostats is 640 m (2,100 ft). The heliostats are located in a staggered radial array, which allows close packing with minimum optical interference. Their location is shown in the site rendering, Figure 1-1. Each heliostat has a unique, fixed aim point selected so as to provide uniform flux on the receiver.

The receiver system converts solar energy into main steam thermal energy; it consists of an external receiver and its support tower. The external design, closure doors, and pumped circulation features of the receiver offer a simpler design, smaller size, and lighter weight than a cavity receiver, with only slight loss in performance. Pumped circulation was selected to permit the maximum freedom for transitions between operating modes. The receiver design includes extensive thermohydraulic analyses which show excellent performance under upset conditions. The use of commercial materials and fabrication procedures further assures reliability, low maintenance, and safety. The heat absorbing surface is configured as a 16 panel, 240° sector of a right circular cylinder centered at 124 m (407 ft) above grade level, 9.45 m (31 ft) in diameter by 15.24 m (50 ft) high, with two concentric heat absorbing surfaces, Figure 1-6. The inner surface has 12 panels which compose the superheater surface; the outer surface forms a protective screen in front of the superheater and composes the evaporator (boiler) surface; the economizer has 4 panels, 2 located at either end of the superheater panels. The south 120-degree sector of the receiver cylinder, which does not contain heat transfer surface, provides the storage region for two 120-degree closure doors, which are used to reduce heat loss during shutdown. Superheater temperature control is accomplished through spray attemperation. The receiver has its own control system which interfaces with the master control system.

The receiver tower is a reinforced concrete shell, rising 109.5 m (359 ft) above grade, and tapering from 9.15 m (30 ft) in diameter at the base to 6.40 m (21 ft) in diameter at the top. It has uniform wall thickness of 250 mm (10 in) and is founded to the competent limestone with rock anchors (see Figure 1-7). Eight structural steel columns affixed to the top of the tower carry the solar receiver loads. Reinforced concrete platforms provide a room at the top for auxiliary equipment. Tower accessories include an elevator, aircraft obstruction lighting, caged ladder, polar crane, and communication and ventilation systems.

The receiver loop system provides the piping interface between the solar receiver and the existing fossil energy system. The system transports high energy steam from the receiver to its interface on the fossil system, feedwater to the receiver from the fossil system, and condensate drains from the receiver and main steam piping to the fossil system. It also provides blowdown and drain tanks for the receiver. The system consists of piping, filters, pumps, tanks, vents, valves, water chemistry equipment, and control elements.

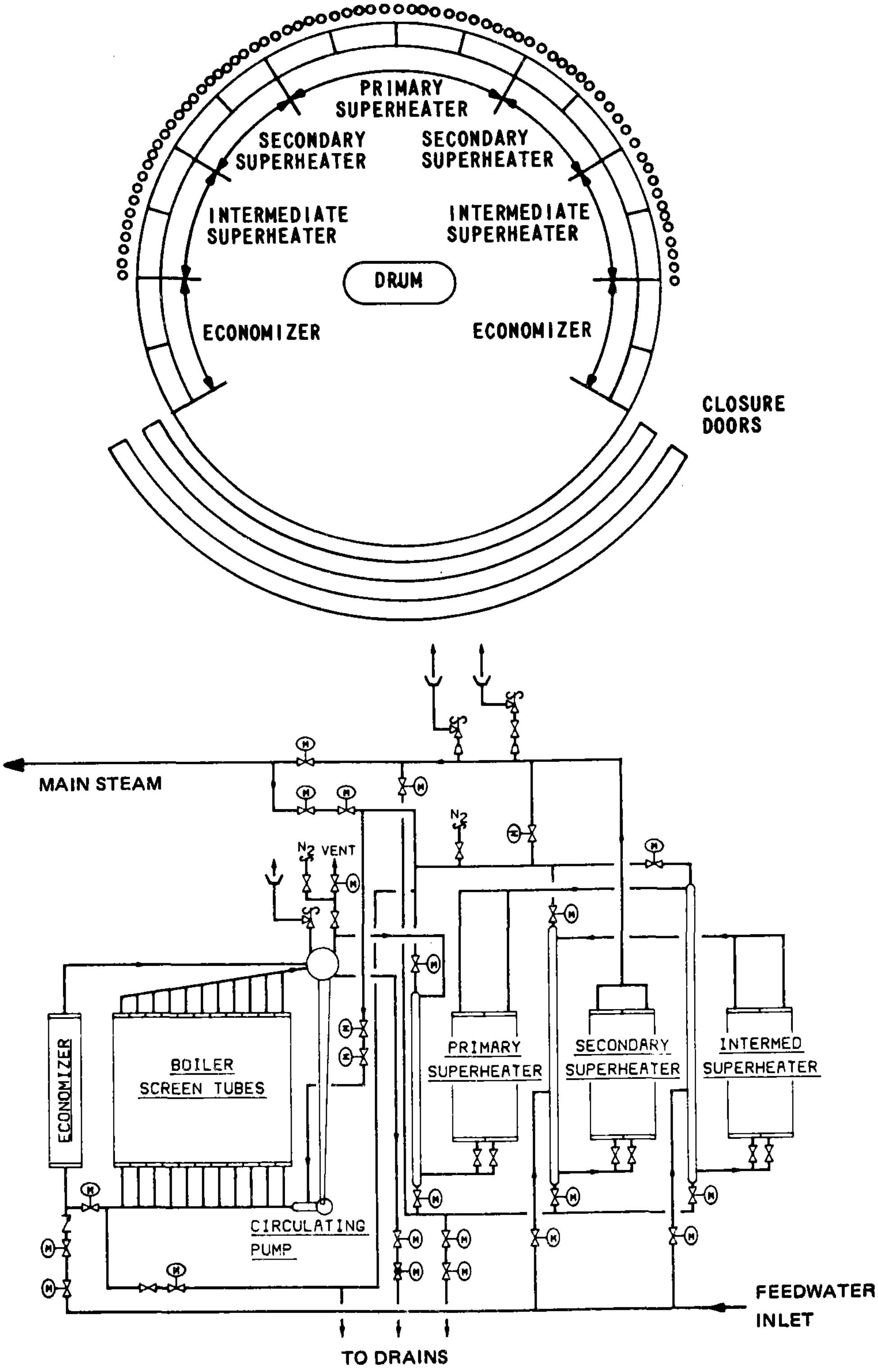


FIGURE I-6. EXTERNAL RECEIVER SCHEMATIC

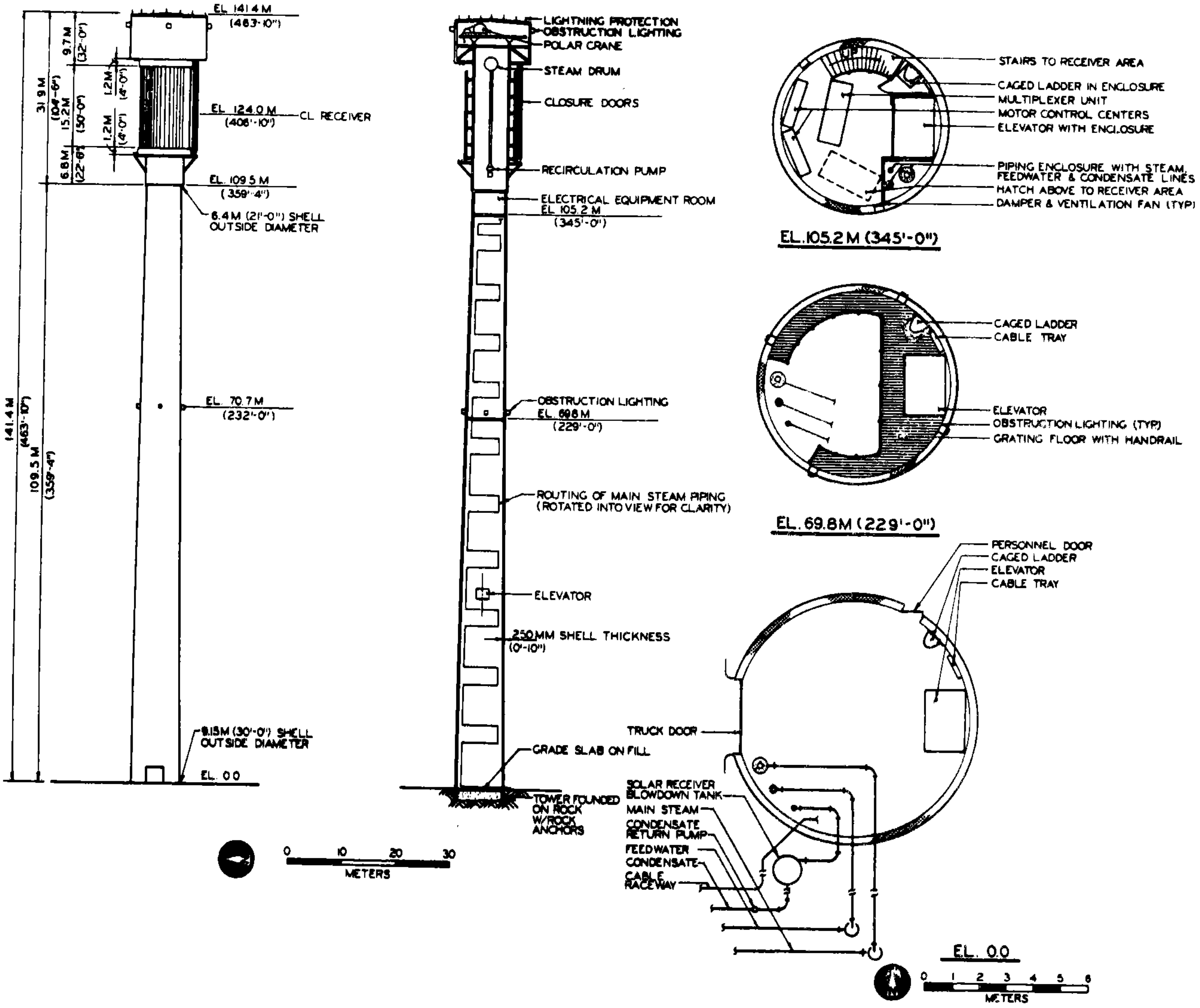


FIGURE 1-7. RECEIVER TOWER

Key features of the conceptual design are presented in Table 1-1. Construction cost estimates of this conceptual design are given in Section 1.6.

1.5 SYSTEM PERFORMANCE

The performance of the conceptual design was determined through simulation modeling of the hybrid solar repowered system. Individual characteristics and performances of the collector, receiver, receiver loop, master control, and auxiliary systems provided the inputs to the

TABLE I-I. CONCEPTUAL DESIGN SUMMARY

Key Feature	Description
(1) Prime Contractor	Black & Veatch, Consulting Engineers, Kansas City, Missouri.
(2) Major Subcontractors	Public Service Company of Oklahoma, Tulsa, Oklahoma. Babcock & Wilcox Company, Alliance, Ohio.
(3) Site Process	Electric Repowering. Westinghouse tandem compound, double flow, simple reheat condensing turbine rated at 150 MW_e with steam conditions of 12.5 MPa (1,800 psi)/ 538 C (1,000 F)/538 C (1,000 F).
(4) Site Location	PSO Northeastern Station, Oologah, Oklahoma.
(5) Design Point	Noon, March 21.
(6) Receiver System	Receiver Fluid: Water/Steam. Configuration: External, absorber 240-degree sector of 9.45 m (31') diameter by 15.24 m (50') high cylinder with closure doors. Type: Drum with pumped circulation. Elements: Economizer, boiler, superheater. Output Fluid Temperature: 544 C (1,012 F). Output Fluid Pressure: 14.97 MPa (2,155 psi). Tower: Concrete shell 109.5 m (359') high.
(7) Collector System	Heliostats: 2,255. Individual Mirror Area: 49 m^2 (528 ft^2) Cost: $260/$m^2$. Type: Second generation. Field Configuration: North.
(8) Storage	None.
(9) Total Project Construction Cost: (excluding land costs, 1980 dollars)	(a) $55,099,000 for heliostats installed at $260/$m^2$. (b) $51,767,000 for heliostats installed at $230/$m^2$.
(10) Construction Time	2.0 years.
(11) Solar Plant Contribution at Design Point	30 MW_e, 73.3 MW_t.
(12) Solar Fraction, Design Point: Annual:	20 per cent. 8.3 per cent.
(13) Annual Fossil Energy Saved	88,000 barrels of crude oil.
(14) Type of Fuel Displaced	Natural gas.
(15) Net Annual Energy Produced	48 GWh_e.
(16) Ratio of $\frac{\text{Annual Energy Produced}}{\text{Total Heliostat Mirror Area}}$	434 kWh_e/m^2.
(17) Ratio of $\frac{\text{Capital Cost}}{\text{Annual Fuel Displaced}}$	$368/$MWh_t$.
(18) Site Insolation (direct normal)	5.4 kWh/m^2 day, annual average. Source: "On the Nature and Distribution of Solar Radiation", March 1978, HCP/72552-01. Site Measurements: Started Feb. 20, 1980; See Section 8.0.

Solar Thermal Electric Plant Performance Evaluator (STEPPE) simulation program. The collector system performance model is part of OPTICS, Black & Veatch proprietary software, developed for central receiver collector/receiver systems. This engineer/computer interactive set of programs is used for design optimization. These simulations were used with a modified ASHRAE clear air model of the direct insolation to calculate net annual thermal energy available to the turbine. The net energy accounts for the energy deficit associated with receiver system and receiver loop system diurnal thermal cycles.

The design point and annual average energy efficiency stair steps are shown in Figure I-8. At the design point, the thermal collection efficiency is 69.3 per cent, and the overall solar to electric efficiency is 27.7 per cent, producing 29.1 MW_e. The annual performance of the repowered system has a solar-to-thermal efficiency of 55.6 per cent and an overall efficiency of 22.1 per cent, producing 48 GWh_e per year.

I.6 ECONOMIC ANALYSIS

The economic evaluation of solar repowering NES I included the following considerations.

- Construction cost estimate.
- Operating and maintenance cost estimate.
- Fuel cost factors.
- Economic factors.
- Methodology for evaluation.
- Value of the repowered plant to PSO.

These six considerations are presented in the following paragraphs.

The construction cost estimate is based on the conceptual design. The cost of each major system and its fraction of the total cost are given in Figure I-9 when heliostats are costed at $\$260/m^2$ of mirror area. The estimate of the annual operating and maintenance costs of \$247,720 is allocated to four major accounts as shown in Figure I-10. The fuel cost and escalation rates, as currently used by PSO in their planning and as specified by DOE/Sandia Laboratories for economic analyses in this project, are given in Table I-2. Table I-3 presents the economic factors used by PSO in their planning studies.

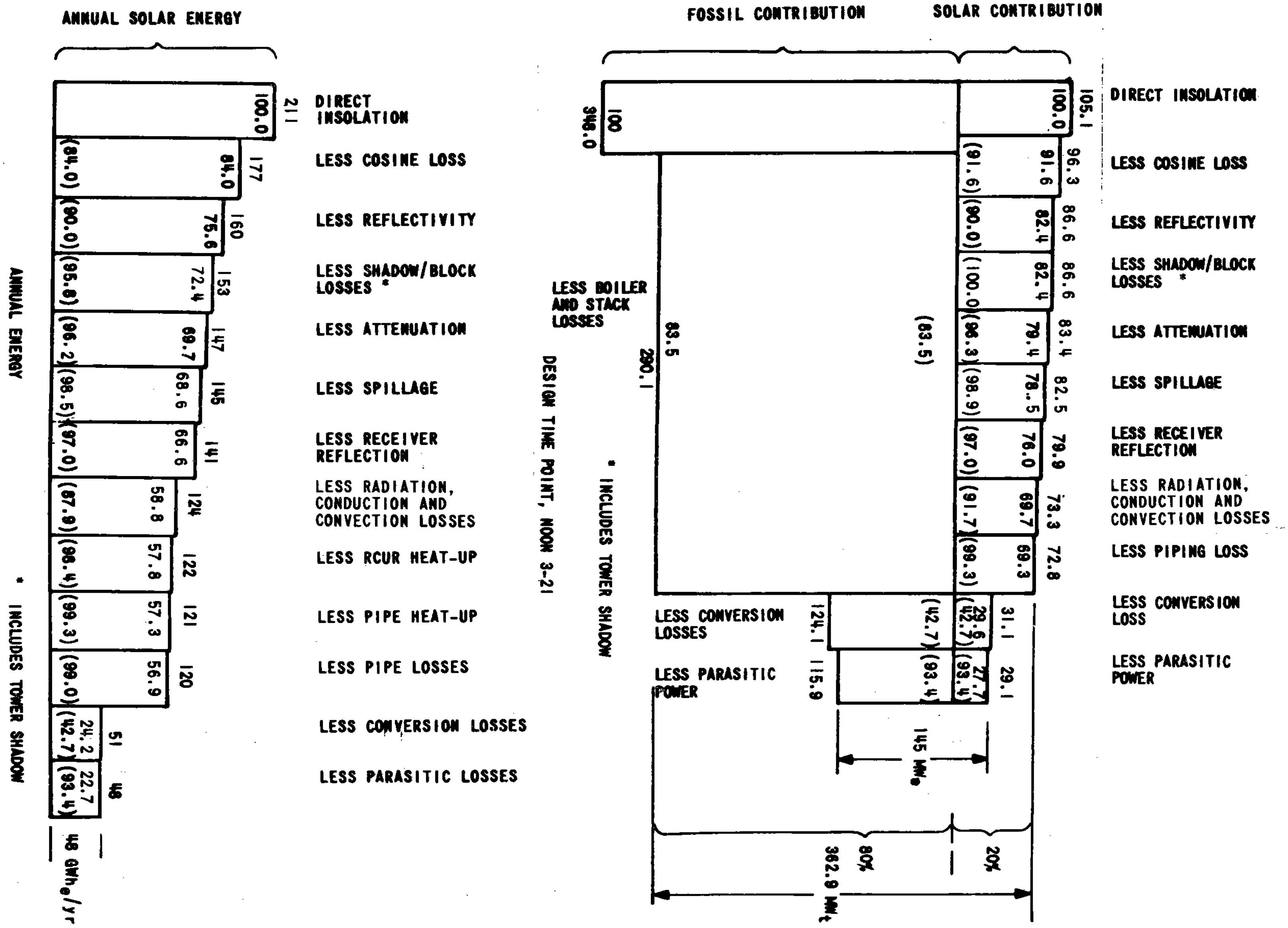


FIGURE I-8. DESIGN TIME POINT AND ANNUAL SYSTEM EFFICIENCY STAIRSTEPS

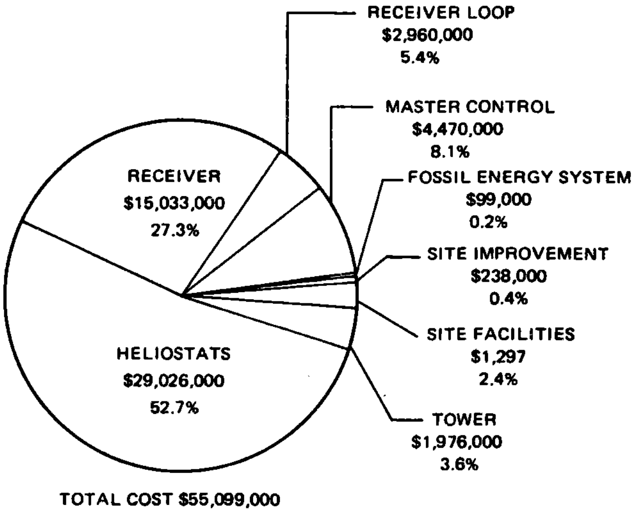


FIGURE I-9. CONSTRUCTION COST ESTIMATE

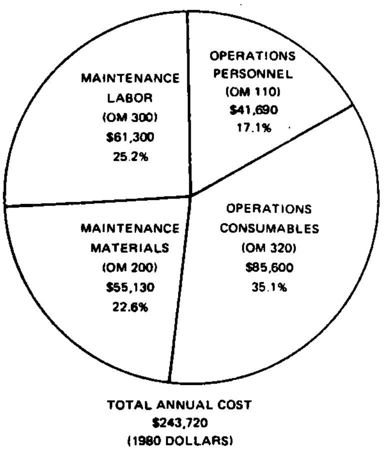


FIGURE I-10. OPERATING AND MAINTENANCE COST ESTIMATE

TABLE I-2. FUEL COSTS AND ANNUAL ESCALATION (1980 $)

Fuel Type	PSO Projection	DOE Projection
Natural Gas	$2.80/MBtu - 8 per cent	$2.50/MBtu - 11 per cent
Coal	$1.41/MBtu - 8 per cent	$1.25/MBtu - 10 per cent
Lignite	$0.99/MBtu - 8 per cent	$0.95/MBtu - 10 per cent
Nuclear	$0.58/MBtu - 8 per cent (Equilibrium Cycle)	$0.85/MBtu - 9 per cent

TABLE I-3. ECONOMIC FACTORS (PSO)

Discount Rate	13 per cent
Investment Tax Credit	10 per cent
Property Tax Rate	2 per cent
State and Federal Tax Rate	50 per cent
Insurance Rate	0.1 per cent
Solar Plant Lifetime	15 years
Fossil Plant Lifetime	24 years
Investment Cost	$588/kW (1980 $)

The methodology for calculating the value of the solar repowered facility to PSO was based upon the standard procedure and criteria used by PSO to evaluate generation options. It involves analyzing revenue requirements of the investment, the investment related costs, and the operating costs. The analysis develops levelized revenue requirements and compares alternate plans for solar repowering. The value of the facility is due to the lower operating costs, primarily fuel savings, and the deferral of capacity additions. With repowering, the economic lifetime of NES I can be extended from December 1994 to December 1999. The 5-year extension could allow the deferral of 150 MW of new capacity to the PSO system.

Benefit evaluation was done by establishing alternate generation expansion plans, then simulating each plan using a utility industry accepted computer model, PROCOS, adapted to the PSO system. The simulation produced annual production costs which, together with the annual revenues required for the return on capital investment, were combined to yield the total annual revenue requirement. Comparison of the levelized revenue requirement at the end of a 40-year evaluation period, ending 2024, allows the explicit determination of the value to PSO of the repowered facility. These comparisons were made using PSO economic factors and DOE economic factors.

The results of the value determination are summarized in Table I-4. The six cases tabulated are described below. The tabulation provides a direct comparison between pairs of plans.

- Case I. Using PSO fuel and capital cost projections, compares the plan that has solar repowering and deferral of 150 MW of coal-fired capacity addition from 1995 to 2000 with the present PSO baseline plan.
- Case II. Identical comparison as Case I, except that there was no deferral of planned expansion.
- Case III. Same as Case I, except DOE fuel and capital cost projections were used.

- Case IV. Same as Case II, except DOE fuel and capital cost projections were used.
- Case V. Same as Case I, except that solar repowering of the hybrid facility was assumed to be 50 MW.
- Case VI. Same as Case III, except that solar contribution was assumed to be 50 MW.

Table I-4 shows for each case the value due to operating savings and capacity deferral in 1980 present-worth dollars. For all cases, the solar unit reduced fuel requirements, but the solar unit can cause increased fuel costs. This increase is due to the delayed installation of 150 MW of coal capacity having low energy cost, thus causing an increased consumption of high cost gas. The increase in operating costs for those cases is more than recovered by the capacity credit associated with deferral of the high capital costs required for that coal capacity.

Total value to PSO is the sum of the operating savings and the capacity credit. This value, shown in Table I-4, is in 1980 present-worth value and in equivalent $/kW. The $/kW comparison shows that there is no apparent economic incentive associated with increasing the

TABLE I-4. VALUE TO PSO OF SOLAR REPOWERING

Case	I	II	III	IV	V	VI
Solar Component Capacity, MW	30	30	30	30	50	50
Cost Projection Parameters	PSO	PSO	DOE	DOE	PSO	DOE
Capacity Deferred	Yes	No	Yes	No	Yes	Yes
Value Due to Operating (Fuel Cost) Savings*	(4.7)	4.0	(10.8)	6.9	(0.3)	(0.2)
Value Due to Capacity Deferral*	17.1	0.0	27.7	0.0	17.1	27.7
Total Present-Worth Value*	12.4	4.0	16.9	6.9	16.8	27.5
Present-Worth $/kW Solar	403	133	563	230	336	550
Value to PSO, per cent of cost estimate**	28.2	8.9	38.9	15.4	--	--

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*Expressed in millions of 1980 dollars.

**As-built investment including AFUDC in 1985 is $65.00 M.

amount of solar repowering to 50 MW. This lack of incentive is due to the fact that the capacity credit is dependent on the 150 MW_e deferred capacity and independent of the fraction of solar repowering.

The amounts shown on Table 1-4 depend on the calculated solar unit performance. The value to PSO is rather independent of the repowering construction cost and derives from the operating costs and capacity credit factors.

The value to PSO does not include any debit for increased risk associated with a first-of-a-kind facility nor the risk of extending the lifetime of NES 1. Retaining operation of NES 1 past 1995 increases the dependence of PSO on possible supply constraints and the system's vulnerability to regulated usage restrictions on natural gas. This risk is eliminated by installing the 150 MW replacement capacity in 1995. By not deferring capacity installation, the value of the solar facility will be limited to the associated fuel costs savings, $4.0 million.

1.7 DEVELOPMENT PLAN

The development plan addresses the technical, economic, and organizational issues in making the transition from a conceptual design study to an operating facility. PSO, the site owner, would be the prime contractor for implementing the engineering, construction, and performance validation phases. No requirement for Subsystem Research Experiments (SRE) was identified; the development plan activities are the preliminary design, detailed design, procurement, construction, checkout and start-up, performance validation, and the required appropriate PSO/DOE authorizations and approvals.

For the design and construction phases, Black & Veatch as a subcontractor to PSO, will provide engineering services commensurate with current PSO/B&V relationships for power plant construction. In this role, Black & Veatch would provide Project Management Services to PSO. The role of other industry members (equipment suppliers, construction contractors, etc.) will follow the normal procedures of PSO under an established quality assurance program for large capital investments.

For activities during the system performance and validation phases, PSO will provide operating personnel and materials. Black & Veatch and appropriate equipment suppliers will provide operator training and technical support. This support will include operator indoctrination in personnel and equipment safety procedures as part of a safety assurance program.

The Major Milestones Schedule, Figure I-11, highlights the PSO/DOE milestones, engineering activities, major procurements, and construction packages. This schedule is derived from a Critical Path Method precedence diagram; the symbols follow the DOE uniform reporting guidelines with "circles" highlighting those milestones which are on the critical path.

Preparation of the precedence diagram for the implementation of the solar repowered NES I was based on the conceptual design; Black & Veatch's engineering design, procurement, and construction management experience; and B&W's determination of the requirements for design, materials procurement, fabrication, and erection of the solar receiver. This plan was premised on completion of the solar repowering facility by September 30, 1984. The schedule, milestones, and critical dates shown for PSO/DOE approval/authorization are compatible with those presented in the Solar Repowering/Industrial Retrofit Program Element Plan, January 1980.

The plan illustrated in Figure I-11 would be reviewed and updated as part of a mangement plan and work breakdown structure (WBS) prepared in the initial effort of the preliminary engineering phase contract. No reasons have been identified to prohibit solar repowering NES I by September 30, 1984.

The implementation phase cash flow requirements given below, expressed in thousands of 1980 dollars, are based on the CPM schedule and the construction cost estimate.

Year	1981	1982	1983	1984	1985
Calendar Year Cash	471	11,212	16,065	23,819	3,532
Fiscal Year Cash	114	6,245	19,036	24,262	5,442

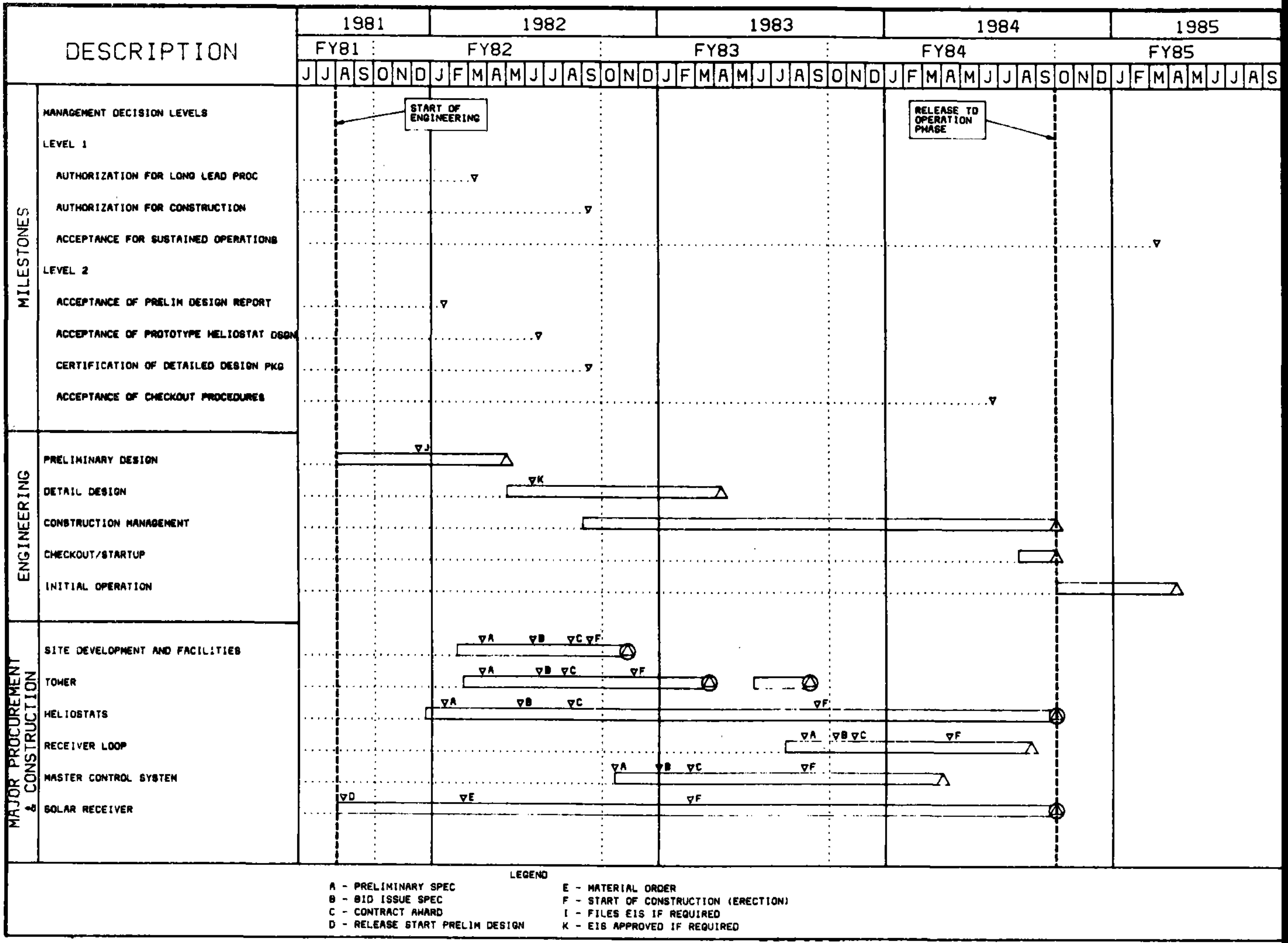

FIGURE I-11. MAJOR MILESTONES SCHEDULE

1.8 SITE OWNERS ASSESSMENT

To date, the conceptual designs for central receiver solar thermal systems have not been validated by performance and cost data obtained in utility operating environments. Although the electric utility industry believes that Solar Central Receiver technology has the potential for beneficial energy production, a successful central receiver demonstration in an operational setting, such as Northeastern Station, is necessary to establish confidence in the performance, cost and reliability of these systems.

PSO believes industry must demonstrate this technology at its basic level before progressing to advanced generation designs. Northeastern Station provides a flexible test and demonstration facility for all basic central receiver systems. The NES I repowering conceptual design has significant size, temperature and pressure level without added complexity. The conceptual design for repowering Northeastern Station presents no radical or severe safety or operational requirements and can be adapted at other stations where land is available.

If a potential for a reasonable return on the capital required for applications of hybrid solar-fossil steam supply systems in electric generation can be demonstrated, there will be no reason for utilities not to consider them in planning for new stations. Once an operating hybrid central receiver system, such as Northeastern Station Unit I, is working, the electric utility industry will be quick to identify and evaluate central receiver hybrid applications and will support advanced concept developments.

The immediate need is to demonstrate repowering. Then industry will identify applications for central receiver technology, whether they be new or repowered. PSO's Comanche Station is just such a a potential one-of-a-kind application which could be a cost effective solar hybrid application. Undoubtably, other unique applications will be identified when operating utilities see the technology demonstrated. It may be counterproductive to tie the demonstration evaluation of solar central receiver technology to repowering for existing fossil units as there may not be many such applications that are economical.

The development plan is technically sound with a feasible schedule and does not present any special problems for its implementation. PSO suggests that the follow-on project be funded using cost sharing and rapid tax depreciation. This arrangement would permit private industry to take the lead in the program with government helping by underwriting the risk of this new and promising technology.

The repowering demonstration should follow the KIS adage, KEEP IT SIMPLE. The unknowns are the solar aspects; their evaluation should not be confounded by including complexities associated with unnecessary features such as solar reheat receivers, storage systems, and unconventional fluids with their steam generators. Such complexities may cause the demonstration to fail. The failure would be remembered long after the fact that the solar portion was not at fault is forgotten.

A suggested cost-sharing plan is for government research agencies to fund engineering and equipment, with the utility funding erection, project management, and operation. Following a successful demonstration period, the utility would purchase the government's interest at the fair market value, giving consideration to construction funds previously expended. In the event of unsuccessful operation, the government would be responsible for removal and restoration of the utility's site.

2.0 INTRODUCTION

This document describes the site specific conceptual design for solar repowering Public Service Company of Oklahoma's (PSO) Northeastern Station Unit 1. The work performed for the Department of Energy was under Contract No. DE-AC03-79SF10738, entitled, "Solar Repowering for Electric Generation, Northeastern Station Unit 1, Public Service Company of Oklahoma." The contract amount was $387,127 for the period of September 24, 1979 to July 15, 1980. The prime contractor was Black & Veatch, Consulting Engineers. Sheldon L. Levy was the Project Manager; he fulfilled the role of principal investigator. Public Service Company of Oklahoma and the Babcock & Wilcox Company were subcontractors. The mailing address of the prime contractor is as follows.

Black & Veatch, Consulting Engineers
P.O. Box 8405
Kansas City, MO 64114

2.1 STUDY OBJECTIVE

The project objective is to develop the best site specific conceptual design that will fulfill the following requirements.

- Provide practical and effective use of solar energy for repowering an electric power plant.
- Have the potential for construction and operation by 1985.
- Make maximum use of existing solar thermal technology.

In more general terms, the goal of this effort is to demonstrate the technical viability and identify the economic potential of solar repowering for commercial electric power generation.

2.2 TECHNICAL APPROACH AND UNIT SELECTION

Important criteria for the technical approach and unit selection were the use of proven and accepted technology, a plant whose physical condition and age is compatible with repowering and a utility whose management would provide the leadership required for introducing a new technology. The technical approach selected is a water/steam receiver supplying superheated main steam to the turbine in parallel with steam supplied by the fossil steam generator. This hybrid operation provides flexibility for operations and simplifies control of the repowered plant; further, the hybrid system eliminates the need for thermal storage and its inherent expense and thermal losses. The use of a water/steam receiver permits generation of steam whose pressure and temperature conditions, 13.8 MPa (2,000 psia) 538 C (1,000 F), match those currently used with highly efficient turbines in electricity generation, using materials that have a historically proven compatibility and safe operation. These factors in toto, combined with the very high reliability of the proposed unit, mean that solar repowering of NES I would permit a straightforward test of a solar central receiver in utility operation; that is, this implementation of solar repowering features a system in which the main solar components are being evaluated unplagued by malfunctions of extraneous components which are new to power plant operations.

There are two additional factors favoring NES I for repowering. The moderate daily average direct insolation of 5.4 kWh/m^2 at the site is more representative of insolation levels found at other plants where gas and oil displacement by repowering is possible than in the high insolation areas of the southwestern United States; 10^{15} Btu/year of oil and gas are consumed for electricity generation in the area having this insolation compared to the 7 x 10^{13} Btu/year consumed in highly intense sun belt area (see Figure 1-1). Therefore, this site presents to DOE the opportunity to evaluate repowering with more comprehensive applicability, i.e., greater market penetration potential. Offsetting the lower insolation at NES I is the improved efficiency of the unit's reheat cycle. Second, the project team consists of the same firms (including several key individuals) who participated in the original design and construction of NES I. The relationships and trust between team members is well established, and the organization is consistent with common industry practice.

2.3 SITE LOCATION

PSO's Northeastern Station is located about 50 kilometres (30 miles) northeast of Tulsa, Oklahoma, adjacent to the Oologah Reservoir, as shown in Figure 2-1. The town of Oologah is located about 1,600 metres (1 mile) north of the site. Primary access to the site is by US Highway 169; Oklahoma Highway 88 borders the site to the north.

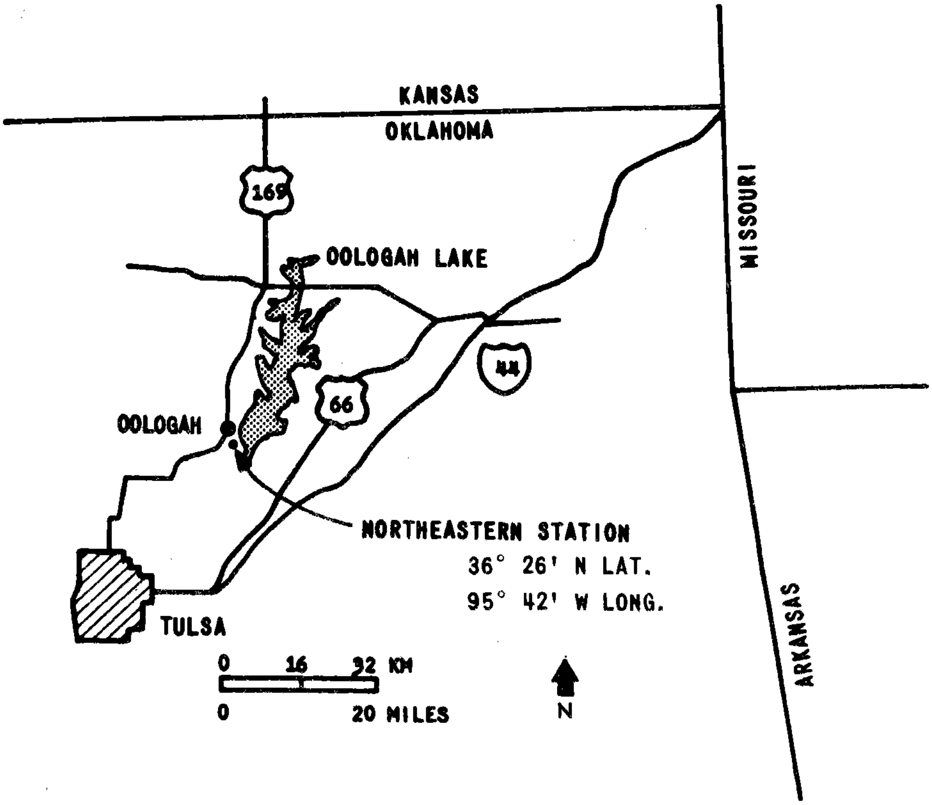

FIGURE 2-1. LOCATION OF NORTHEASTERN STATION
PUBLIC SERVICE COMPANY OF OKLAHOMA

2.4 SITE GEOGRAPHY

Four generating units are located on the $5.34 \times 10^6 m^2$ (1,320 acres) site of the Northeastern Station of this area, about 2×10^6 m^2 (500 acres) are presently used by the four units and about 0.8×10^6 m^2 (200 acres) are needed for repowering. Thus, PSO has ownership of all land required for the proposed repowering operation. The majority of the repowering land is needed for the heliostat field; however, a few acres are required for the receiver tower, receiver loop piping, and vehicle access to the repowering system. As shown in Figure 2-2, the solar site is located northeast of Unit I; the receiver tower is about 920 metres (3,020 feet) east of Unit I, and the heliostat field extends 640 metres (2,100 feet) north of the tower.

The topography of the proposed heliostat field consists of a gently rising slope (less than 2 per cent grade) to the east and north. A shallow layer of silty clay topsoil covers the limestone; bedrock outcroppings of rock are visible at several locations throughout the field. The area, which is currently used as a pasture for cattle, contains a small farm pond and no trees. The site is located at 36° 26' north latitude and 95° 42' west longitude. The ground elevation of the heliostat field is about 204 metres (670 feet) above sea level.

Northeastern Station is situated in a region of minor to moderate seismic risk. The site area is classified by the Uniform Building Code (UBC) as Zone I of seismic risk for the contiguous United States. In this zone, minor damage from earthquake activity may be expected. Zone I indicates the possibility of an earthquake with a maximum intensity of VI on the Modified Mercalli Scale occurring in this area, or minor damage resulting from a major distant disturbance.

2.5 CLIMATE

The Tulsa region has a pronounced continental-type climate characterized by highly variable precipitation and temperature. During summer, southerly winds bring warm, moist, tropical air from the Gulf of Mexico. Cold, dry air from polar regions predominate in winter. There are often sudden and severe weather changes when polar and tropical air masses meet over the area. Occasionally, drought conditions are produced by dry air from the plateaus of Mexico.

The region has a moist, humid to subhumid climate. Spring and autumn are characterized by warm days and cool nights; summers are long, but not unusually hot, and winters are comparatively mild. Brief periods of extremely cold weather occur in some years.

The region is far enough north to usually avoid long periods of hot weather. However, daytime summer temperatures above 100 F are frequently

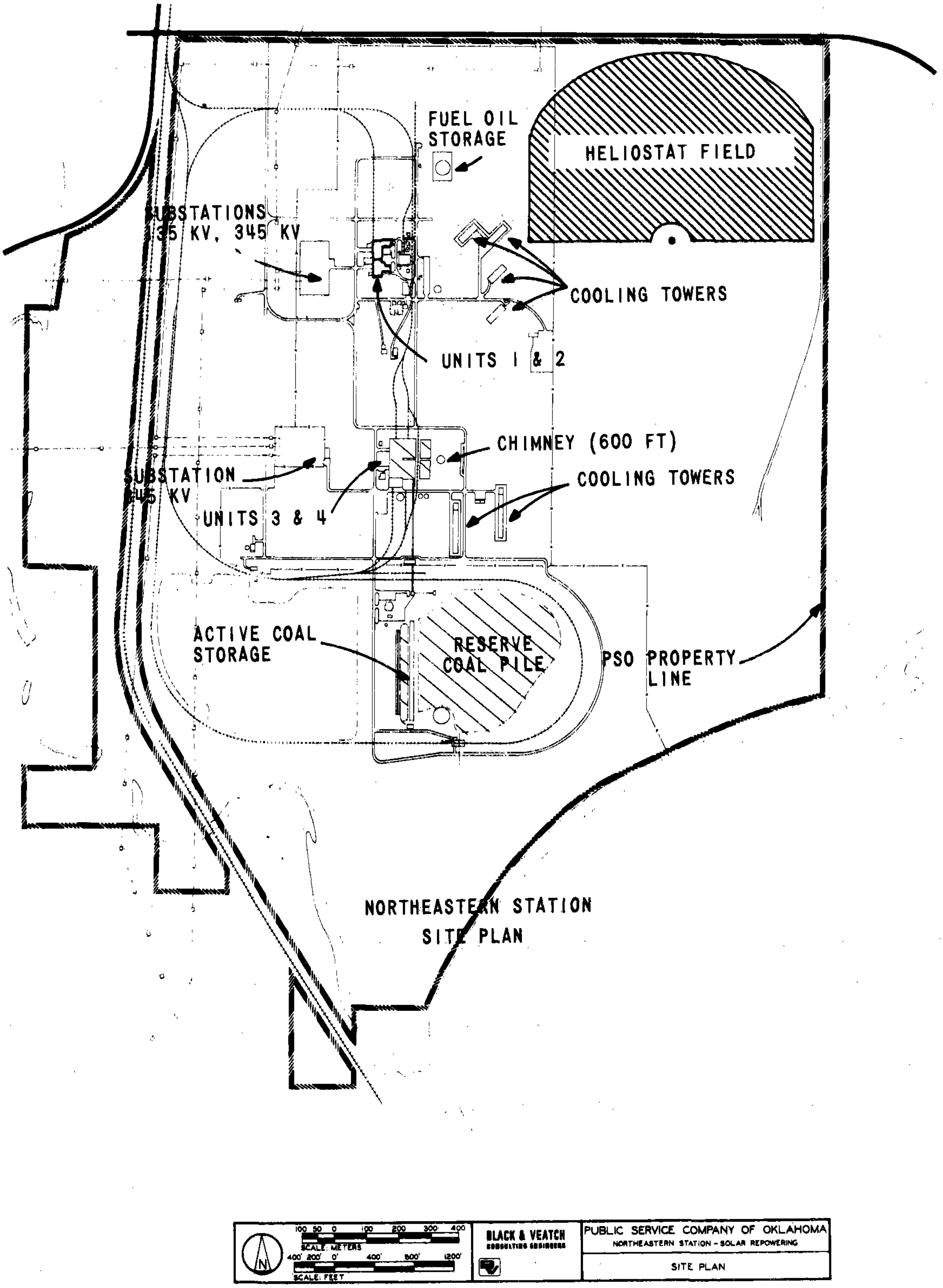

FIGURE 2-2. SITE ARRANGEMENT OF NORTHEASTERN STATION SHOWING HELIOSTAT FIELD

experienced, and the nights are fairly cool. Surges of cold Arctic air traveling southward across the central states occasionally cause subzero temperatures.

Thunderstorms are common and provide the source of most precipitation. Snowfall is distributed evenly over the three winter months. Average monthly precipitation is characterized by a maximum in May and June and a secondary maximum in September and October.

Prevailing winds are southerly. Wind speeds are generally light to moderate. However, strong gusty winds associated with thunderstorms and cold fronts are common. Further, the area is subject to severe windstorms, including tornadoes.

Although large bodies of water can modify weather extremes, the water area within the state of Oklahoma is too small to have a significant effect on generalized weather patterns.

Considerable data are available from various weather stations in the northeastern section of Oklahoma; however, the first order station of the National Weather Service at Tulsa is utilized as the base line reference source for the establishment of the climatology for the plant site.

The average summer dry bulb temperature is approximately 27 C, with an average daily minimum temperature of 21 C and an average daily maximum temperature of 33 C; extreme temperatures for the summer months are 9 C and 44 C. Spring-fall temperatures average about 16 C, with an average daily minimum of 10 C and an average daily maximum of 22 C; there is a 62 C range of extreme temperatures during the spring-fall months. There is also a wide range of extreme temperatures for the winter months, -22 C to 30 C; average winter temperatures are about 3 C.

The average annual precipitation for the area is 966 mm (38.03 in). May is the wettest month with an average of 132 mm (5.21 in) of precipitation. The average annual snowfall is 236 mm (9.3 in).

The average wind speed in all months ranges between 4.1 m/s (9.1 mph) and 5.7 m/s (12.7 mph). The maximum wind recorded was 33.5 m/s (75 mph) in May 1949. Wind roses for the four seasons are presented in

Section 8. The Tulsa region is subject to violent windstorms and tornadoes which occur mostly during spring and early summer, although occurrences have been noted throughout the year.

Site insolation is characterized by 62 per cent annual sunshine and an average daily direct normal insolation of 5.35 kWh/m^2. These data for the site were obtained from three sources: National Climatic Center,[1] and two DOE reports, one prepared by Watt Engineering Ltd,[2] and the other by the Jet Propulsion Laboratory.[3] In addition, the results of the test program conducted as a part of the conceptual design project, described in Section 8, support these data.

2.6 EXISTING PLANT DESCRIPTION

The existing site contains four generating units as shown in Figure 2-2.

	Capacity	Fuel	Commercial Date
Unit 1	150 MW$_e$	gas/oil	1961
Unit 2	470 MW$_e$	gas/oil	1970
Unit 3	450 MW$_e$	coal	1979
Unit 4	450 MW$_e$	coal	1980

Unit 1 consists of a subcritical, single reheat turbine generator and a conventional steam cycle with five stages of regenerative feedwater heating. The initial steam conditions for the turbine are 12.5 MPa (1,800 psi) pressure and 538 C (1,000 F) temperature with 538 C (1,000 F) temperature reheat. The turbine generator unit operates at 3,600 rpm.

The gas- or oil-fired steam generator is rated at 522,000 kg/h (1,150,000 lb/h) of steam at main steam pressure and temperature of

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[1] "Local Climatological Data, 1978, Tulsa, Oklahoma," National Climatic Center, Ashville, NC.

[2] "On the Nature and Contribution of Solar Radiation," DOE Report HCP/T2552-01, Watt Engineering Ltd., (March 1978), p. 202.

[3] "The Effects of Regional Insolation Differences Upon Advanced Solar Thermal Electric Power Plant Performance and Energy Costs," DOE Report DOE/JPL-1060-17 Jet Propulsion Laboratory, Pasadena, California, (March 15, 1979), p. 19-31.

14.4 MPa (2,070 psi) and 540 C (1,005 F), respectively, with 540 C (1,005 F) reheat temperature. The steam generator is supplied with feedwater from three 295,000 kg/h (650,000 lb/h) motor-driven, constant-speed feedwater pumps; these are 3,600 rpm pumps driven by 2,240 MW (3,000 horsepower), 4,160 volt motors.

The condenser has 11,200 m^2 (120,000 ft^2) of tube surface. Cooling water is supplied to the condenser at the rate of 7.5 m^3/s (119,000 gpm) from two induced draft, cross-flow mechanical cooling towers by two constant-speed circulating water pumps.

The water treatment system consists of a pretreatment plant and a deionization system. The pretreatment plant utilizes a cold lime process. Makeup water for the steam generator is treated in a 0.013 m^3/s (200 gpm), six-bed deionization system consisting of primary, secondary, and polishing cation and anion exchangers in series.

2.7 EXISTING PLANT PERFORMANCE SUMMARY

Unit 1 at Northeastern Station is currently a base load unit feeding power into the system network at all times; the overall heat rate of this unit including fossil steam generator losses is currently 3.07 kWt/kWe (10,500 Btu/kWh); this heat rate is sufficiently low to keep the unit on the line at all times except for scheduled and emergency outages. However, as the availability of natural gas declines and its cost in relation to that of coal (and lignite to be used in future plants) increases, this unit will be relegated to an intermediate type unit unless it is repowered with solar-generated steam. Without repowering, the annual output of NES 1 is projected to drop to about 28 per cent of capacity in 1985 and to about 1 per cent in 1989, and remain at that level until its retirement in 1994. However, PSO believes the load factor for this unit will be significantly increased with the addition of the solar energy supplementing the present fossil fuel.

2.8 PROJECT ORGANIZATION

The team that prepared the conceptual design consisted of Public Service Company of Oklahoma (PSO), Black & Veatch, Consulting Engineers, and Babcock & Wilcox Company (B&W). The organization chart, Figure 2-3, shows the team member relations and responsibilities, and the key personnel involved in the project.

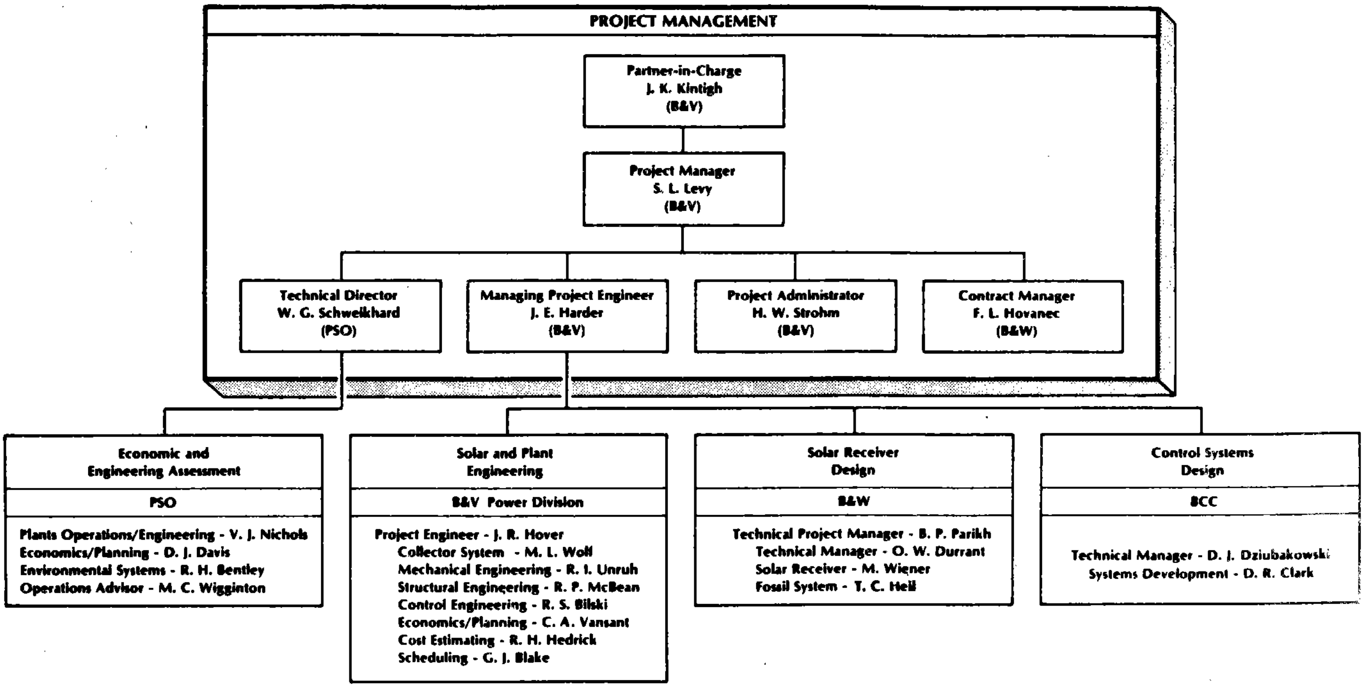


FIGURE 2-3. PROJECT ORGANIZATION CHART

Black & Veatch, the prime contractor, provided overall project management and coordinated all technical and reporting efforts. Black & Veatch also provided the design engineering, analysis, and cost estimating for the collector system, receiver loop system, master control system, plant integration, receiver tower, and site facilities; Black & Veatch also had responsibility for the performance analysis of the integrated system. PSO, as the owner and operator of NES I, provided utility direction and performed economic analysis pertinent to the fuel displacement and value of the solar repowered unit. PSO also reviewed and provided engineering criteria for the design and operation of the solar repowered NES I. B&W's Fossil Power Generation Division had responsibility for providing data used in trade studies, design, cost estimate and implementation procedures for the receiver system, as well as for testing and evaluating the existing fossil steam generator for its use in a hybrid mode. B&W's Bailey Controls Company provided consultation on the master control system and a cost estimate for that system.

2.9 FINAL REPORT ORGANIZATION

The organization of the final report basically follows the flow of effort on the project. That is, as the project began with system trade studies aimed at identifying major system characteristics, the body of the report begins (Section 3.0) with a description of the process used to select the preferred repowering system. The next major task was to develop the conceptual design; correspondingly, that design is presented in the next two sections: Section 4.0 deals with the overall system design requirements and features, and Section 5.0 describes the individual system characteristics. The value of the design was then assessed on the project; likewise, Section 6.0 presents the economic analysis. The final major project task was the preparation of a development plan to identify the sequence of activities necessary to transform the conceptual design into a successfully operating repowered unit; this plan is discussed in Section 7.0. In addition to the previous project tasks and report sections, Black & Veatch conducted a test program at the PSO Northeastern Station site; that program is described in Section 8.0.

Two appendices are included in the final report. One consists of the System Requirements Specification, in accordance with project contractual obligations. The other contains data collected in test program.

3.0 SELECTION OF PREFERRED SYSTEM

Prior to the development of specific conceptual designs for repowering NES I, a series of broadly based assessments and analyses were performed. These scoping studies address fundamental issues relating to system configuration, resulting in the selection of site-specific design concepts for subsequent development and refinement into a conceptual design. The studies conducted can be organized into three broad topics; they are as follows.

- Overview considerations, such as the means of repowering (steam generation versus feedwater heating) and operating strategies.
- Collector system considerations, such as 360 degree versus sector field designs.
- Receiver system considerations, such as steam conditions and cavity versus external designs.

This section of the report describes the trade studies conducted to identify the system design. In addition, it outlines the factors considered in specifying the repowering capacity, reviews the current status of solar technologies and assesses their compatibility with the 1985 repowering schedule, and briefly summarizes the proposed system configuration. Emphasis is given to defining the requirements applicable to the system selection, to defining decision criteria, and to describing the selected design option. The trade studies are reported first.

3.1 TRADE STUDIES

Trade studies are intended to provide a basis for selecting specific design concepts for further design attention. The trade studies conducted for repowering NES I included the following.

- Solar Interface Study.
- Preferred Operating Strategy.
- Collector System.
- Cavity Versus External Receivers.

- Solar Versus Fossil Reheat.
- Steam Conditions.
- Flux Distributions.

3.1.1 Solar Interface Study

Two basic means exist for solar repowering a fossil-fueled Rankine cycle power plant; they are the generation of steam for use in the turbine and the heating of feedwater, either method reduces the fossil fuel heat impacts to the cycle. Although these two general options have been considered in numerous other studies, a review of the options for the specific NES I situation was appropriate, with the study results determining the points of interface of the solar system with the existing NES I fossil power plant.

In general, the feedwater heating option offers lower capital costs for piping and for the solar receiver because feedwater conditions are moderate compared to steam, permitting the use of less expensive materials. Alternatively, the steam generation option is more straightforward to interface with the existing plant piping and operational networks; it can displace up to 100 per cent of the fossil fuel input and can be applied to virtually any power plant. In addition to those considerations, the overall effects on net plant heat rate are also important.

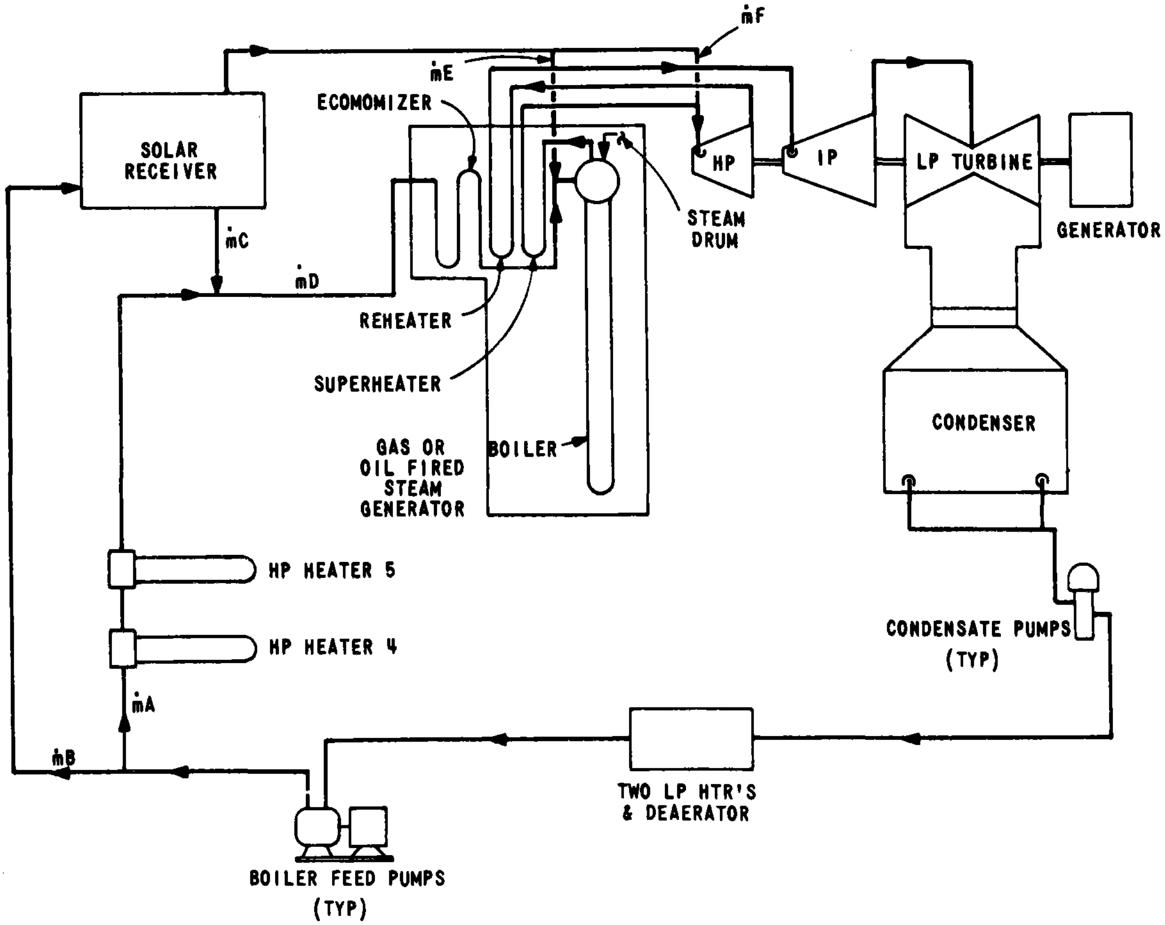
3.1.1.1 Selection Criteria. Selection criteria are important not only in determining which design alternative is preferred, but also in the definition of specific design alternatives by way of initially scoping the acceptable range of solutions. The selection criteria/requirements applied to the interface study are as follows.

- Provide at least 20 per cent repowering to ensure a meaningful solar demonstration to both the utility industry and DOE.
- Assess effects on plant heat rate.
- Determine fossil fuel displacement.
- Minimize complexity of operation and control.
- Evaluate cost effectiveness, i.e., the cost impacts of the repowering design.

3.1.1.2 Design Alternatives. The two general categories for repowering have already been identified as feedwater heating and steam generation. Although steam generation can be considered to have several options such as steam conditions, solar reheat, and repowering capacity, it is treated as a single option in this study, with those additional considerations addressed in separate studies as described in later sections of this report. Repowered feedwater heating options develop from the basic characteristics and limitations of the existing NES I equipment.

The different interface cases studied are illustrated on the simplified flow diagram of the plant (Figure 3-1). The inset matix of Figure 3-1 lists the mass flows at key cycle locations. In all cases, it is assumed that the existing cycle state conditions would be preserved. A performance summary for the five cases is given in Table 3-1. Case 1 represents the existing plant for a point of comparison, while Case 2 describes a solar steam generation design, with an arbitrary value of 20 per cent chosen for the repowering capacity (24 per cent steam flow is required for 20 per cent repowering because no solar reheat is being considered in this study). Feedwater heating Cases 3 through 5 consist of various combinations of high-pressure (HP) feedwater flow being diverted to the solar receiver for heating in lieu of using fossil-generated extraction steam. Clearly, the most feedwater heating possible exists when all flow bypasses HP Heaters 4 and 5 (Case 3). However, in an effort to achieve a greater fossil fuel displacement by employing more heat addition in the solar receiver, flow was also bypassed around the furnace economizer (Case 5). The 60 per cent flow through the economizer is the minimum allowable without danger of initiating boiling in that section of the steam generator, thus necessitating extensive and undesirable modifications to the existing plant. Case 4 is simply an intermediate point between limiting cases (3 and 5).

After the interface options were defined, the heat rate and fossil fuel impacts were determined; the results are presented on Table 3-1.



CASE	DESCRIPTION	MASS FLOWS AT LOCATION, PERCENT					
		A	B	C	D	E	F
1	EXISTING PLANT	100	0	0	100	0	0
2	STEAM GENERATION	100	0	24	76	0	24
3	FEEDWATER HEATING	0	100	100	100	0	0
4	FEEDWATER/ECONOMIZER HEATING	60	40	0	60	40	0
5	FEEDWATER/ECONOMIZER HEATING	0	100	60	60	40	0

FIGURE 3-1. REPOWERING INTERFACE CASES

TABLE 3-1. SOLAR INTERFACE CASES--PERFORMANCE SUMMARY

Case	1	2	3	4	5
Solar Receiver Output					
Main Steam Flow, per cent	0	24	0	0	0
H.P. Heater Flow, per cent	0	0	100	40	100
Economizer Flow, per cent	0	0	0	40	40
Solar Fuel Displacement, per cent	0	20.9	13.8	12.9	19.9
Turbine Heat Input					
Fossil, MW (MBtu/h)	364 (1,242.4)	288 (982.7)	326 (1,113.4)	319 (1,088.9)	303 (1,035.2)
Solar, MW (MBtu/h)	--	76 (259.7)	52 (178.1)	47 (161.2)	75 (256.7)
Total, MW (MBtu/h)	364 (1,242.4)	364 (1,242.4)	378 (1,291.9)	366 (1,250.1)	378 (1,291.9)
Gross Turbine Heat Rate, kWt/kWe (Btu/kWh)	2.35 (8,004)	2.35 (8,004)	2.44 (8,323)	2.36 (8,054)	2.44 (8,323)
Equivalent Fossil Heat Rate, kWt/kWe (Btu/kWh)	2.35 (8,004)	1.86 (6,331)	2.10 (7,176)	2.06 (7,015)	1.95 (6,669)
Heat Rate Improvement, per cent	Base	21**	10***	12***	17***

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*Turbine Output - 155,200 kW.

**Value not limited by cycle.

***Value is limited by cycle.

3.1.1.3 Conclusions. On the basis of the case results stated below, using the solar receiver to produce main steam is the preferred solar interface alternative. The fuel displacement impacts are greatest in Case 2, steam generation repowering; it should be noted that the displacement fraction for steam generation could be increased to 100 percent, while Cases 3 through 5 as shown are upper bound cases due to limitations in the amount of feedwater heating possible. Case 2 also exhibits the best equivalent fossil heat rate.

3.1.2 Preferred Operating Strategy

The choice of repowered unit operating strategy can significantly affect the value of the solar contribution. Areas of possible impacts include economic consequences and selection of system design alternatives, as well as unit operation and utilization. For the purposes of this study, NES I lifetime was established as 1985 to 1999, with unit operation including base load, intermediate, and peaking service. The objectives of the study were to identify the preferred operating strategy (if one existed) and to establish related design and operating criteria.

3.1.2.1 Selection Criteria. The criteria employed to identify the preferred operating strategy must be broadly based to allow for the wide range of possible strategies. The selection criteria used in the operating strategy study are as follows.

- Permit and encourage a meaningful and flexible demonstration of solar repowering.
- Assure compatible solar/fossil operation for both NES I and the balance of the PSO system throughout the plant lifetime.
- Maximize solar operation/utilization at NES I.

3.1.2.2 Alternative Strategies. While the number of possible operating strategies for a repowered plant is nearly unlimited, the major alternatives and their characteristics can be distilled to a relatively few cases. Extremes in operating strategy, characterized by base load and peaking operation, are illustrated on Figure 3-2a and c, with the principle difference between the cases being the amount of fossil-fueled generation taking place (although the solar output is maximized in both cases except for differences in load-dependent plant efficiencies). The minimum fossil load of 30 MW indicates the maximum stable turndown in the existing furnace. A more typical set of operating strategies for NES I is shown by Figure 3-2b and c, illustrating both the output variation with time-of-day and the changing plant service role with increased plant age and increased fuel prices.

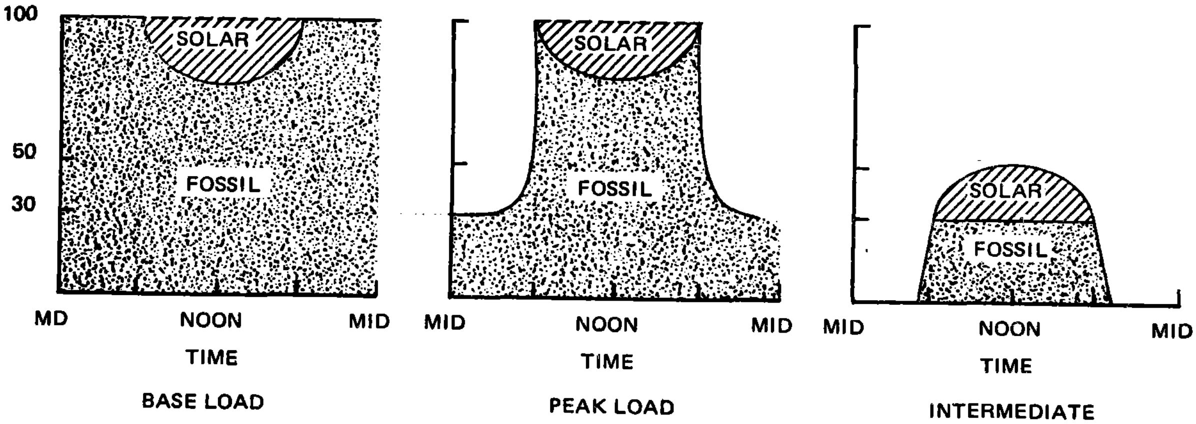

FIGURE 3-2. OPERATING STRATEGIES

In actual practice, the principles of "economic dispatch" would be used to load NES I in conjunction with the balance of the PSO system such that total system demand was satisfied at least cost. Those principles would result in the plant operating in a variety of modes that will reflect the overall condition of the PSO system and the level of power demand. This approach to determining the operating strategy is illustrated on Figure 3-3, which reflects the incremental generating cost for various generating stations. The basic principle is that, for a given demand (say 740 MW), the least system cost results from loading NES I with solar, SW 3, and NES 2 at 110, 190, and 440 MW, respectively. A power demand increase or decrease would be satisfied by changing the load on each operating unit such that the system incremental cost is minimized. The effects of solar repowering NES I can be observed in that its energy cost changed from 21.5 to 20.0 mills/kWh_e at 110 MW_e; hence, the unit will be used more extensively if it is repowered that if it is not, and its useful life will be, in effect, extended. The actual

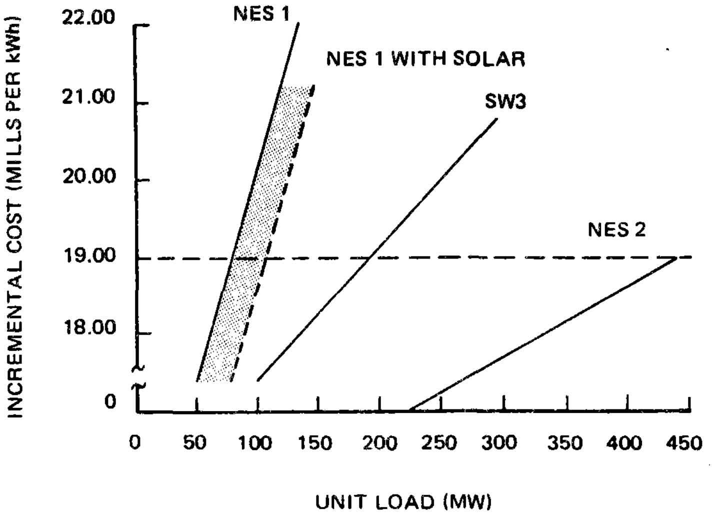

FIGURE 3-3. TYPICAL INCREMENTAL COST
AT $6.82/MWh ($2.00/MBtu)

dispatch curve will change with time as fuel costs and other factors change, and thus, the operating strategy (use pattern) of NES I will change over the years.

3.1.2.3 Conclusions. As a result of examining plant operating strategies, it was determined that no one strategy would apply to NES I, but rather a spectrum of strategies would be required during 1985 to 1999. Because the unit usage will vary with time, and because various strategies might be developed for a given usage level, it is not realistic to specify an operating strategy at present. Of equal importance were the determinations that designing to a specific strategy was inappropriate and that no strategy-related repowering restraints were identified.

3.1.3 Collector System

The collector system trade study is dissimilar from the other studies reported in Section 3 in that it is not a stand-alone study with a specific result, but rather it represents a methodology which is repeatedly exercised to provide inputs in support of other trade studies. This input is necessary because the collector system represents a large fraction of the repowering system cost, and because the collector/ receiver interface affects system performance appreciably. As such, it was necessary to develop collector system designs, with uniformly high levels of accuracy, for the various alternative receivers and reheat versus non-reheat solar designs.

3.1.3.1 Selection Criteria. The basic criterion applied to collector field design is to define the field geometry and layout which yields the greatest annual energy delivered to the receiver per unit of combined heliostat and tower cost; in other words, the best performance/cost ratio. A second criterion is that the field must deliver, at the March 21 noon design timepoint, sufficient power that the receiver absorbs 73.3 MW_t; this requirement implies that the field design must reflect the specific efficiencies and dimensions of the various receiver alternatives.

3.1.3.2 Design Alternatives. The possible alternatives in field design are many, ranging from field shape and size to heliostat packing density and receiver elevation. The approach used in defining the proper field, per the selection criteria, for each receiver considered was to build a collector system through the use of a heliostat field cell analytical model for the arrangement shown on Figure 3-4. This cell model is used in an analytic procedure which determines the proper heliostat ground cover ratio (density) in each individual field cell. As a result of this process, a single collector system preferred alternative was identified for each receiver.

3.1.3.3 Conclusions. No specific conclusions result from the collector system studies alone. As will be reported in later sections, different receivers did require individual heliostat fields tailored to their particular characteristics. However, the following determinations applicable to the analysis methodology and, hence, to the fields were made.

- Maximum field width is 980 m (3,215 feet)* due to site constraints.
- The field is level.
- Installed heliostat cost is $230/m^2.*

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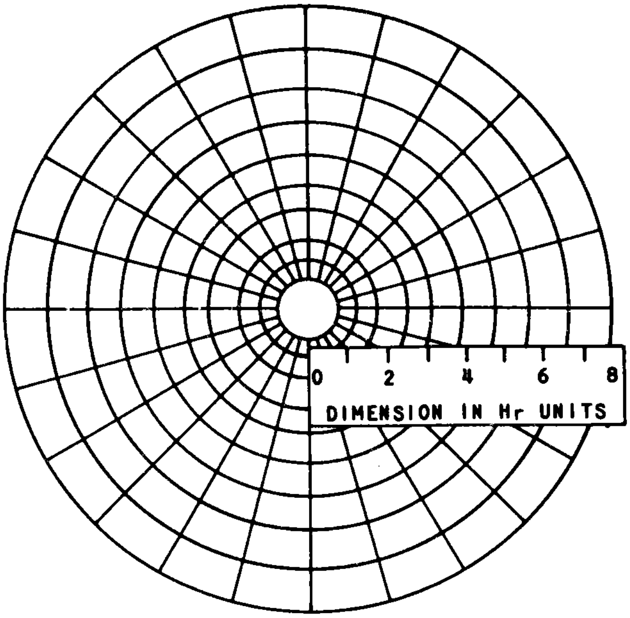
*These values were used in the trade studies and are altered in the conceptual design.



- POLAR GRID CALCULATIONAL SEGMENTS
- MAXIMUM FIELD RADIUS 7.5 Hr
- MINIMUM FIELD RADIUS 0.75 Hr
- COLLECTOR MAY BE OPTIMIZED FOR ANY SECTOR OF THE GRID

Hr = RECEIVER ELEVATION

FIGURE 3-4. FIELD CELL REPRESENTATION GRID

- Receiver tower costs are determined in accordance with the Sandia/ Stearns-Roger Tower Cost Model.
- Insolation is modelled via the ASHRAE* Clear Air Model, and the Design Point insolation is fixed at 0.95 kW/m^2.
- Atmospheric attuentation is modelled according to attenuation = exp (-slantrange/10,000 metres).

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*American Society of Heating, Refrigerating, and Air Conditioning Engineers.

3.1.4 Solar Versus Fossil Reheat

The steam cycle used at NES I includes reheating high-pressure turbine discharge steam prior to its introduction to the intermediate-pressure turbine. A basic system configuration question is whether all reheating should take place in the fossil steam generator or whether some reheating of steam must be provided using solar energy; if the latter option is selected, is it due to existing equipment characteristics (e.g., inability to have unbalanced reheat and main steam flows) or in order to provide a meaningful utility demonstration of the repowering technology. If solar reheating, as shown schematically in Figure 3-5, is found to be appropriate, it would impact the system by way of receiver tower design, collector system design, and additional piping to connect the turbine and solar reheater.

3.1.4.1 Selection Criteria. The selection criteria fall into three categories: programmatic, economic, and technical. The programmatic considerations, while including elements of the economic and technical criteria, can be expressed as electric utility industry acceptance that the repowering concept has been validly and successfully demonstrated, with the concept uncertainties adequately resolved. Economic and technical criteria are more concrete in nature and include the following.

- Capital costs.
- Operating costs, including thermal losses.
- Limits on fossil boiler operating flexibility.
- Solar reheater design and performance similarity to main solar receiver.

3.1.4.2 Design Alternatives. In addition to the basic question of whether to use some fraction of solar reheat at NES I or to rely entirely upon fossil-fuel reheat, there are also alternatives regarding solar reheat. These alternatives essentially consist of locating the reheat receiver on the same tower as the main receiver or of installing a separate tower/heliostat field dedicated exclusively to reheating;

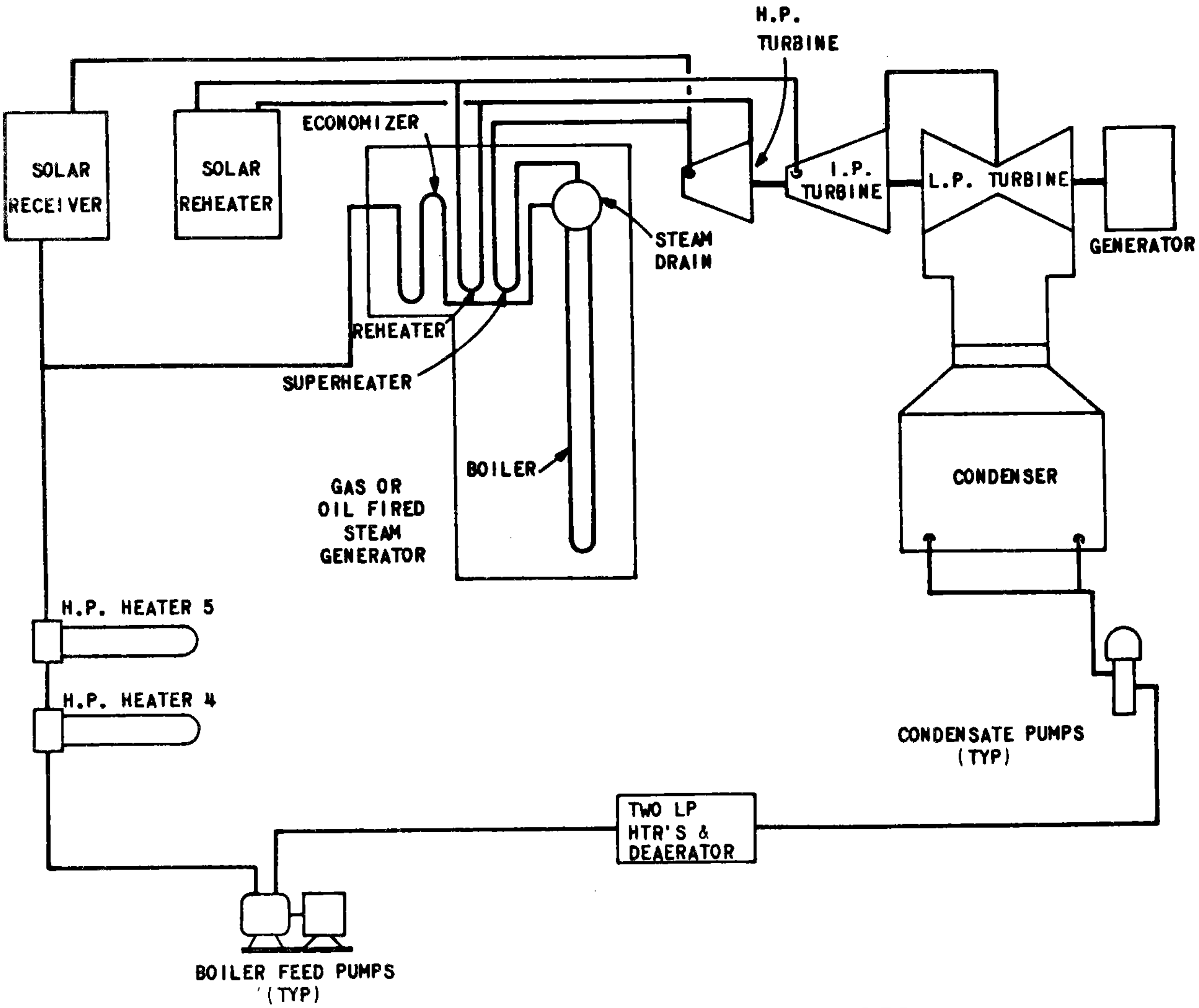


FIGURE 3-5. SOLAR REHEAT INTERFACES

these options are shown in principle on Figure 3-6. Notice that the separate field approach offers the advantage of significantly reduced reheater piping length.

Boiler flexibility is important because if no solar reheat was used, or if different fractions of solar main steam and solar reheat were used, the steam flows in different sections of the fossil boiler would be imbalanced. Such an imbalance can be compensated for by the following means.

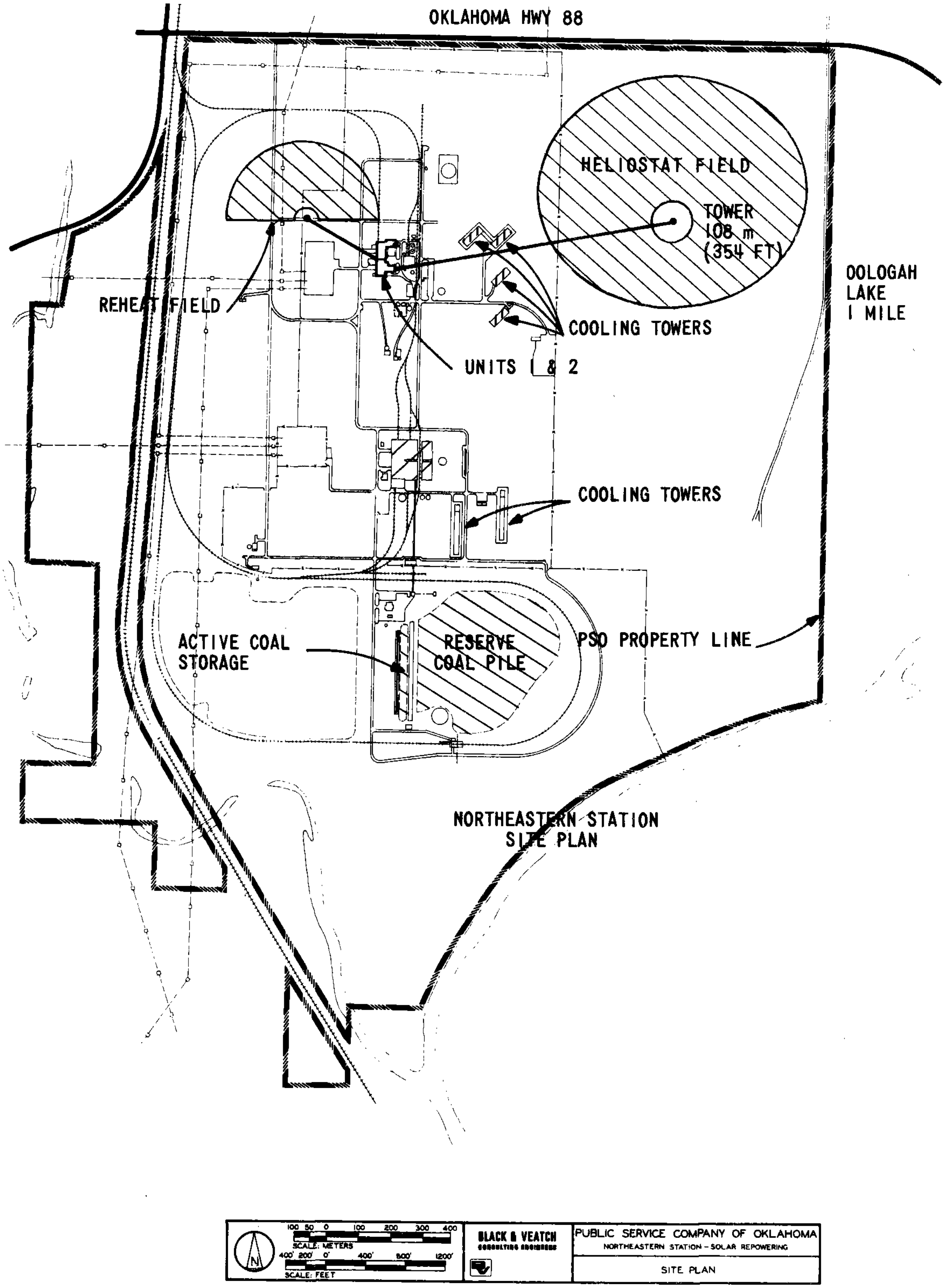
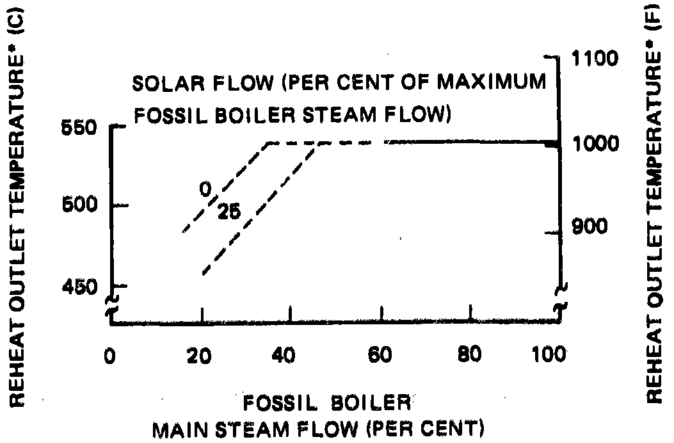


FIGURE 3-6. SOLAR REHEATER LOCATIONS

- Reheater attemperation spray.
- Excess combustion air changes.
- Burner control.
- Modification of furnace heat transfer surface.

Fossil boilers typically can sustain rated reheater temperatures over a range of approximately 65 per cent to 100 per cent load, but the particular characteristics of NES I provide additional flexibility; tests conducted on the unit established that the furnace reheater outlet temperature could be maintained at 538 C (1,000 F) with as little as 45 per cent fossil load and as much as 25 per cent solar main steam repowering, as shown on Figure 3-7. This would be accomplished via attemperator spray, with even greater flexibility being available if the burner control and excess air options were exercised.



*FOR 100% FOSSIL REHEATER STEAM FLOW

FIGURE 3-7. EXPECTED REHEAT STEAM TEMPERATURE

Evaluation of the solar reheat options consists of determination of costs and system performance. A key cost element in both solar reheat options is piping; the desire to keep steam pressure drops minimal and thus avoid increasing the plant heat rate requires that relatively large, expensive piping be used. Parametric studies to determine the consequences of various combinations of cold and hot reheat line sizes were conducted, resulting in a development of cost data.

3.1.4.3 Conclusion. Evaluation of the existing fossil boiler established that it was capable of operating with or without solar reheat, and therefore was not a factor in the reheat configuration decision. Developing the costs of the solar reheat options revealed that, even considering only a partial list of the cost components, the costs were high--in excess of \$2,000,000. For example, the piping cost alone for the solar reheater located on the same tower as the main receiver was about \$2,000,000. For the case of a separate reheat receiver and tower, the piping costs were less due to the reduced piping distance, but this was offset by the additional cost of the separate tower, heliostat, field, etc. Clearly, the economic consequences of solar reheat are significant.

From a technology perspective, the solar reheater does not present any major technological uncertainties beyond those of the main receiver. While reheater design would present the normal array of engineering problems, successful operation of the main receiver would establish the technological feasibility of the solar reheater.

On the basis of these analyses, it was determined that only fossil reheat would be used in repowering NES 1. This decision is based on the following.

- No economic incentive for solar reheat.
- Fossil boiler can provide 100 per cent reheat steam at 538 C (1,000 F) with 20 per cent repowering.
- Main receiver technology establishes reheater technology.

Solar reheat is not required in order to conduct a "meaningful repowering demonstration."

3.1.5 Steam Conditions

Rated steam conditions at the turbine throttle for the existing plant are 12.5 MPa/538 C/538 C (1,800 psi/1,000 F/1,000 F), with a 13.8 MPa/538 C/ 538 C (1,980 psi/1,000 F/1,000 F) overpressure capability. Because the long piping distance between the turbine and the solar receiver may result in significant steam pressure and temperature drops, the receiver outlet conditions may necessarily be appreciably

higher than the desired turbine throttle conditions. A trade study to evaluate the interactive effects of piping sizes, receiver design conditions, costs, and turbine cycle efficiencies was required.

3.1.5.1 Selection Criteria. The solar receiver steam conditions are influenced by a wide range of considerations. An overall requirement is clearly that the receiver steam conditions must be physically compatible with the existing turbine cycle; further, at the point of interface, the pressure of the receiver steam must match that of the fossil steam generator. Other key considerations are that the steam conditions upper bounds must be consistent with receiver technology and material limitations and, at the other end of the spectrum, the steam conditions must be challenging enough to represent a meaningful demonstration of solar repowering. Additional criteria include cost of electricity, capital cost, and applicability to other power stations.

3.1.5.2 Design Alternatives. The options available for design consideration fall into three general categories, with many subsets and combinations as specific alternatives. The general categories are as follows.

- Allow changes in the existing throttle conditions.
- Vary the receiver loop piping design to influence the "delivered" steam conditions for a fixed solar receiver condition.
- Alter the receiver steam conditions to achieve desired delivered steam conditions.

Each alternative can impact the plant design/performance/cost by way of overall plant heat rate, piping requirements, and receiver steam conditions requirements. The effects of throttle temperature and pressure on turbine cycle heat rate are shown on Figure 3-8. One design option would be to not operate NES I at the overpressure condition when solar steam was being generated, thus eliminating the requirement for a solar receiver to operate at these higher pressures. Another option would be to operate the turbine at a reduced throttle pressure, although this is not desirable because it would increase the plant heat rate.

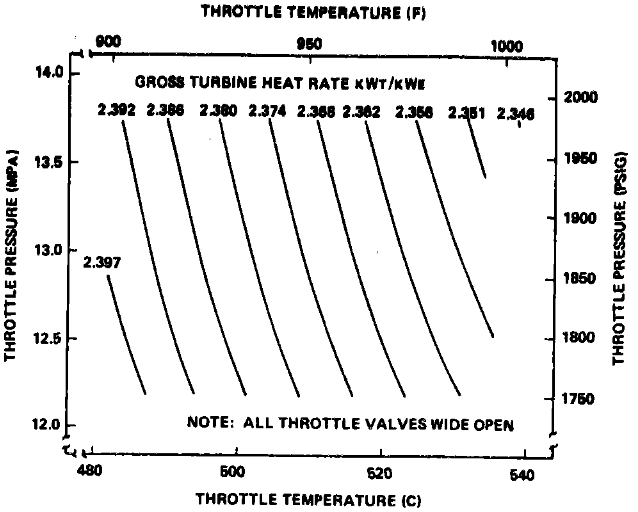


FIGURE 3-8. GROSS TURBINE HEAT RATE VERSUS TURBINE THROTTLE PRESSURE AND TEMPERATURE

For all cases, the receiver steam must be delivered at a pressure equal to that of the fossil steam generator steam at the turbine throttle.

Steam temperature at the turbine throttle can also be varied, although temperature reductions decrease turbine cycle efficiency. Unlike the case of steam pressure, it is not necessary for the fossil and solar steam to be of equal temperature; flow mixing will occur and, because of the small (approximately 20 per cent) fraction of repowering steam, the bulk steam temperature will remain near that of the fossil-generated steam as shown on Figure 3-9. Because it is generally acknowledged that state-of-the-art utility steam generation is limited to 538 C (1,000 F), the delivered, solar-generated steam will be somewhat cooler than 538 C (1,000 F).

The second design category influencing the preferred steam conditions was the receiver piping loop. Though many designs are possible, each one must be tailored to the steam pressure and temperature so that the requirements of applicable codes and standards are fulfilled. Further, the loop design itself (pipe size, insulation, etc) influences

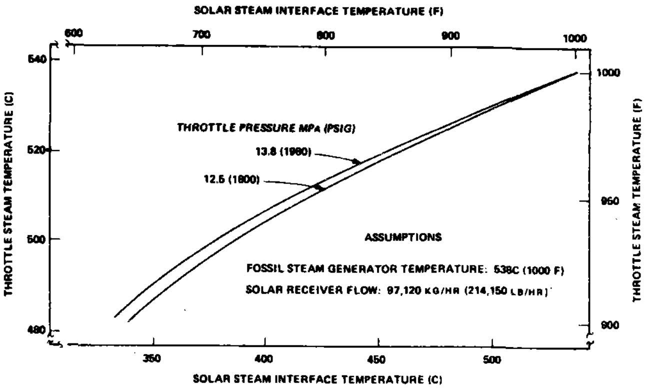


FIGURE 3-9. THROTTLE STEAM TEMPERATURE VERSUS SOLAR STEAM INTERFACE TEMPERATURE

pressure and temperature losses in transit as shown on Figure 3-10, and, therefore, the initial or delivered steam conditions. Evaluating a range of reasonable pipe sizes will reveal the significance of this consideration.

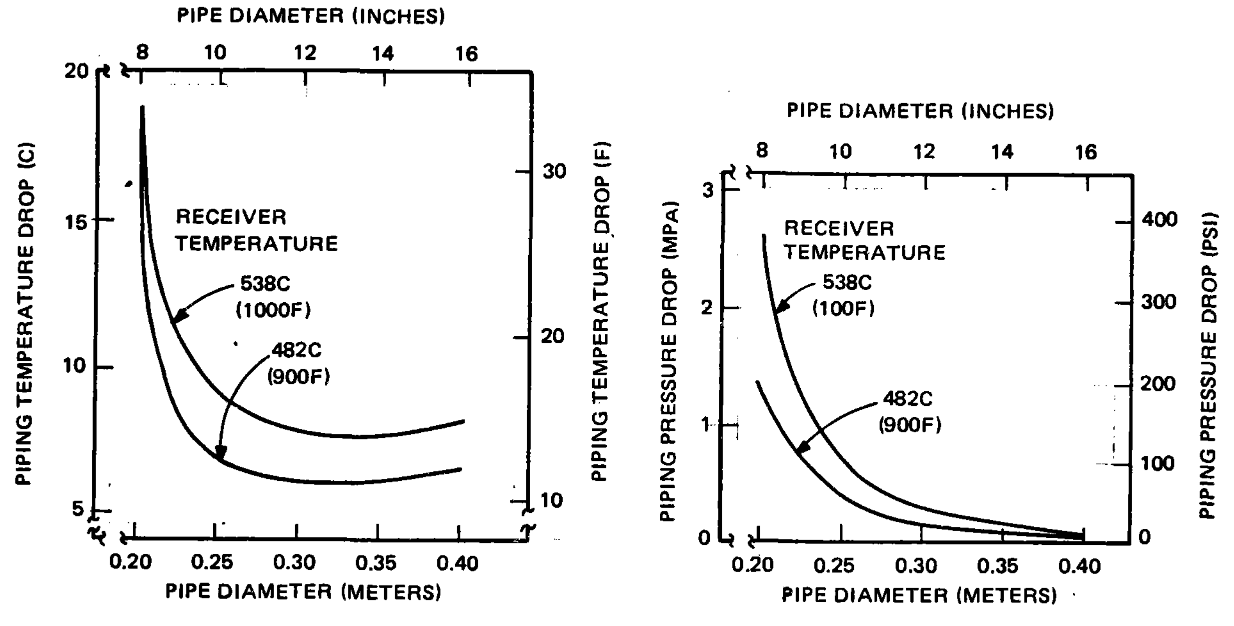


FIGURE 3-10. TRANSPORT PIPING LOSSES AT OVERPRESSURE CONDITION, 13.8 MPa (1980 psig)

The third design option category of receiver steam conditions assesses the plant impacts of varying the generated steam conditions. Lower pressure or temperature steam might be attractive if costs were reduced significantly, perhaps offsetting the lower cycle efficiency.

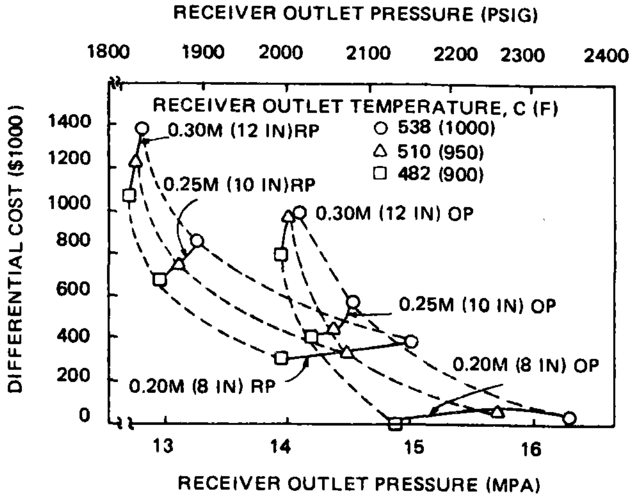
These various categories were evaluated by defining a series of possible designs, with key variables treated parametrically. The options considered are as follows.

Throttle Conditions	12.5 to 13.8 MPa (1,800 to 1,980 psi) ∿482 to 538 C (900 to 1,000 F)
Pipe Size	0.2 m, 0.25 m, 0.3 m (8 inches, 10 inches, 12 inches)
Receiver Steam Conditions	Range of values assessed as a result of the above.

3.1.5.3 Conclusions. The various design options described previously were evaluated for cost and performance (heat rate impacts). As a result of these analyses, it was possible to develop a differential cost for each alternative as a means of identifying the preferred steam conditions. This differential cost included piping and heliostats costs, as well as capitalized fuel costs.

The results of those analyses are shown on Figure 3-11. Several general trends are evident from the graph.

- Higher receiver outlet temperatures lead to greater costs because of the increased piping cost associated with long runs of high alloy materials. At higher pressures, this trend is tempered due to increased cycle efficiency (thus, fuel and heliostat costs), offsetting pipe costs.
- The increased first costs of larger diameter piping are not overcome by lower fuel costs associated with reduced pressure losses.
- Designs for overpressure operation are less costly because the increased plant efficiency and capacity more than offset the greater piping costs, as compared to a rated pressure operation.



RP – RATED TURBINE PRESSURE, 12.5 MPA (1800 PSIG)
OP – OVER PRESSURE, 13.8 MPA (1980 PSIG)

FIGURE 3-11. COST VERSUS RECEIVER OUTLET PRESSURE AND TEMPERATURE

On the basis of those data, the least costly alternative is the overpressure design, a 0.2-metre (8-inch) pipe, and a temperature of 482 to 538 C (900 to 1,000 F) (the accuracy of the analysis is such that no significance should be attributed to the slight cost differences shown).

There are, however, additional considerations not reflected on Figure 3-10. Receiver characteristics will change slightly with operating conditions, but not enough to significantly influence the preferred steam conditions. Pressure reductions have little effect on cost, weight, or efficiency, but temperature reductions slightly increase efficiency and slightly decrease receiver cost, weight, and size. An important receiver limitation for the repowering application is that the maximum working pressure at 538 C (1,000 F) is nominally 16.0 MPa (2,300 psig). In terms of the existing NES I plant capabilities, the present boiler feed pump lacks sufficient head to supply the solar receiver in an overpressure condition when the 0.2-metre (8-inch) lines are used; the use of an additional booster feed pump would be required in series the existing pump, thus reducing receiver loop operating reliability. These considerations mitigate against the use of the 0.2-metre (8-inch) line and the 538 C (1,000 F) steam temperature.

The steam conditions finally selected were 13.8 MPa/538 C/538 C (1,980 psi/1,000 F/1,000 F), on the basis that they are most representative of utility practice and would provide a convincing demonstration of the solar receiver technology, not only for repowering applications, but also for stand-alone systems. The 0.25-metre (10-inch) pipe was selected, with its slightly greater cost than the 0.2-metre (8-inch) pipe, the rated condition design option was justified by the enhanced demonstration value of overpressure operation and by its conformance to present PSO plans to operate NES I in an overpressure mode.

3.1.6 Flux Distribution

Flux distribution on the receiver surface is important in terms of both receiver performance and collector system performance. Requirements for receiver controllability and reliability favor a uniform flux level regardless of azimuthal direction. Alternately, collector fields are generally north-biased in order to provide good field efficiency, with the result that there is a large north-to-south flux imbalance. An evaluation of those effects at approximately the 80 MW_t incident power level for a receiver operating at water-steam temperatures (approximately 538 C (1,000 F)) was the purpose of this study.

3.1.6.1 Selection Criteria. A range of evaluation factors is applicable to this problem. Specific criteria are as follows.

Receiver considerations (cavity or external).

- Peak flux limits cannot be exceeded.
- Target (receiver) sized to balance spillage losses against reflection/radiation loss area.

Field considerations.

- Mirror area.
- Heliostat location.
- Redirected power.

3.1.6.2 Design Alternatives. The collector system can be configured in a 360-degree field layout, or in any number of partial section (e.g., 240 degrees, 120 degrees) field arrangements. Within each arrangement, there are an infinite number of possible heliostat patterns and locations, although only one will yield optimum performance in terms of maximum redirected power per unit of mirror area.

The receiver also offers design options; it can be of the external-type or cavity-type. The number of cavities is a variable and, in the case of the external receiver, its active surface can extend about the full 360-degree circumference or only a fraction thereof. In order to conduct the analysis, a range of representative field and receiver conditions was selected, and performances were evaluated to identify trends and guidelines for application to the subsequent conceptual design activities.

3.1.6.3 Conclusions. The results of the parametric analyses are presented on Figure 3-12, based upon an assumed 360-degree receiver. While no attempt was made to optimize these systems, it can be clearly observed that field performance improves rapidly with increasing field.angles to approximately 180 degrees. Beyond 180 degrees, performance, in terms of annual average incidence power per unit of mirror area, continues to improve more slowly while, on the basis of a single design point, field performance decays. While the actual performance also depends on receiver size, the trends are independent of receiver size.

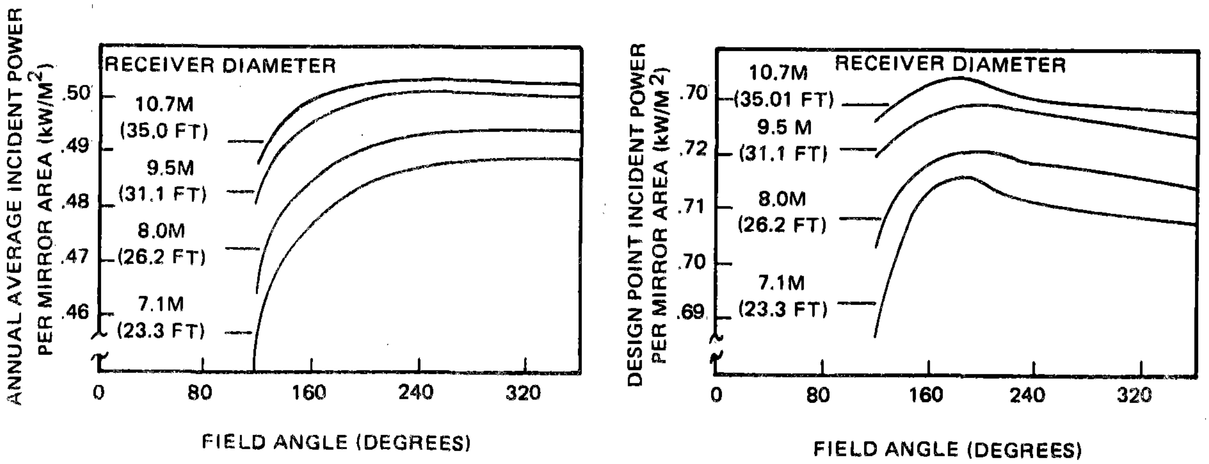


FIGURE 3-12. HELIOSTAT FIELD PERFORMANCE VERSUS FIELD ANGLE AND RECEIVER DIAMETER

A field angle of nominally 180 degrees to 240 degrees appears best, with the percentage performance change within that range being small. This data is for external receivers, though a cavity-type receiver would yield similar curves with a bias toward somewhat narrower fields due to foreshortening of the apparent aperture size at large field angles (additional external versus cavity receiver factors are discussed in Subsection 3.1.7).

Additional insights to flux distribution are provided by Figure 3-13. Plots of redirected power from a heliostat field and corresponding incident power upon a receiver are presented as functions of azimuthal sectors of the field and receiver. Several points are noteworthy.

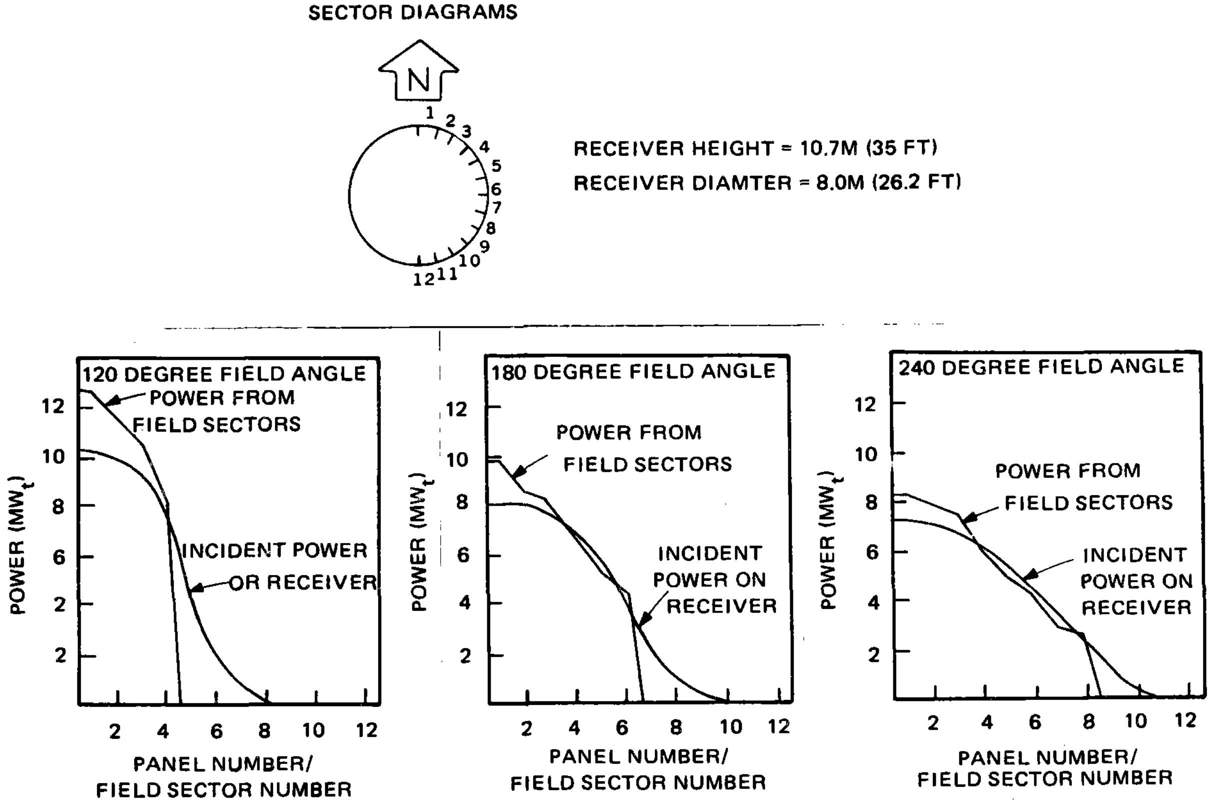


FIGURE 3-13. POWER VERSUS RECEIVER PANEL AND FIELD SECTOR

- The smaller sector fields have a higher peak incident receiver flux and, while the absolute value can be altered by receiver size and heliostat aim strategies, that basic characteristic will persist; small sector fields will exhibit higher peak flux levels and may exceed allowable receiver flux limits.
- The 180 degree field redirected power wraps around the receiver similarly to the 240 degree field (i.e., more that ±90 degrees from north) due to the large image size, suggesting that a receiver with an azimuth angle larger than the collector system may be desirable.

These scoping analyses indicate that a narrow field (e.g., 120 degrees) will result in excessive fluxes on the receiver surface, as well as reduced power/mirror area performance. For an external receiver, a 180 degree field appears to be preferred, although additional study is required to assess its compatibility with site restrictions at NES 1, allowable receiver flux levels ($<620\ \mathrm{kW/m^2}$), and total receiver absorbed power (approximately 73 $\mathrm{MW_t}$).

3.1.7 Cavity Versus External Receiver

As part of a thorough repowering design effort, alternate receiver configurations were investigated, including both cavity and external type receivers. The selection of receiver type is important in that it strongly influences the collector design and the cost, efficiency, and performance of the entire solar plant. Furthermore, since each solar plant application is unique, the choice of receiver type must be made after examining the plant's specific power requirements, land availability, and economics.

3.1.7.1 Selection Criteria. To select the preferred receiver type, parallel design studies were conducted to develop the performance and cost estimates for systems with both cavity and external type receivers. Both systems were developed to the point of receiver performance calculations, coupled with a collector optimization procedure that tailored the collector design to meet the receiver flux distribution requirements.

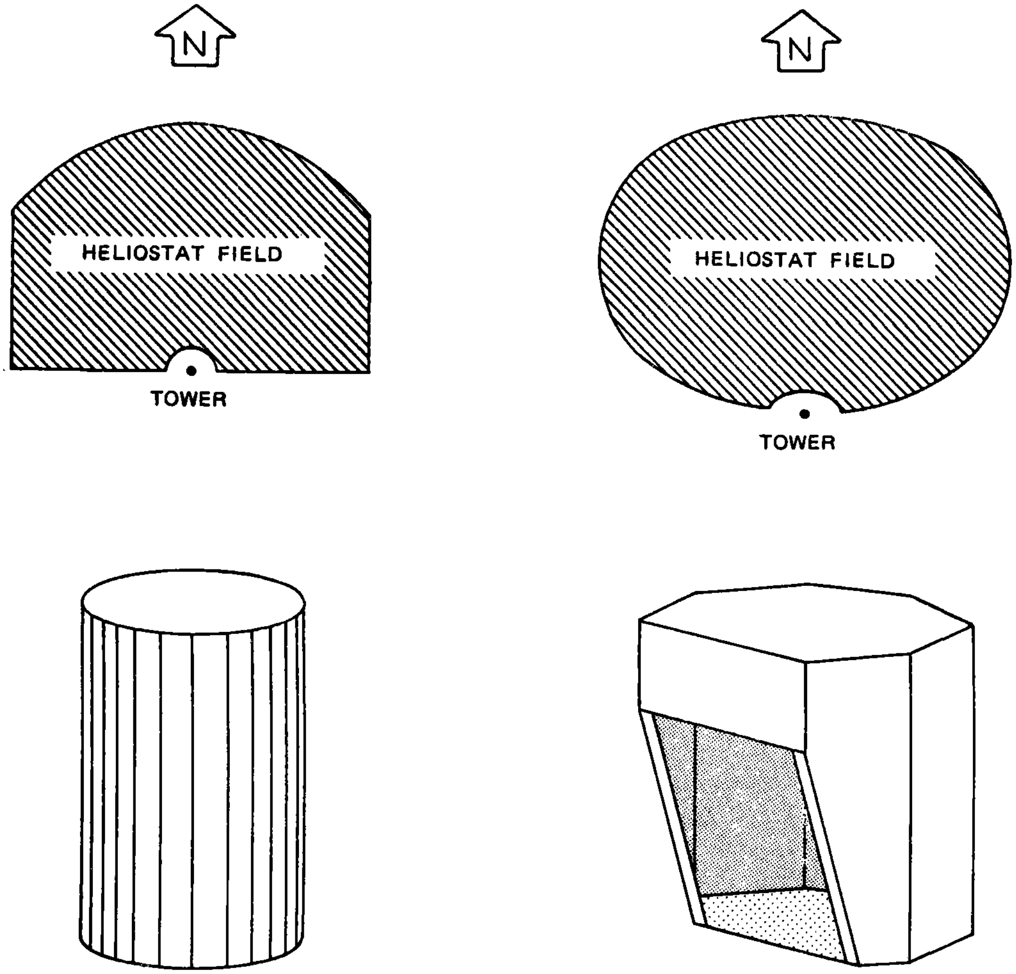
Each system was sized to deliver 73.3 MW_t to the water/steam at noon on March 21, the design point, using a reference insolation of 0.95 kW/m^2. Furthermore, each system was constrained to an area 880 metres wide to conform to the Northeastern Station plant site.

After the design studies, the two collector/receiver combinations were evaluated in terms of their cost and performance, and the results were compared to determine which design was most appropriate for this solar plant application.

3.1.7.2 Design Alternatives. As part of the design effort for an external receiver, a series of studies were conducted to determine the preferred receiver shape, size, and elevation. The first study identified the shape and size of the receiver as a cylinder 15.24 metres (50 feet) tall and 9.45 metres (31 feet) in diameter. The cylindrical shape allows flexibility in aiming heliostats to achieve the required heat flux distribution; the cylinder size minimizes the amount of redirected power that misses the receiver surface.

A second study, summarized on Figure 3-14, identified the shape of the collector field and the portions of the receiver cylinder covered with heat transfer panels. Optimization studies indicated that, to maximize the annual performance of the collector field, very few heliostats should be placed south of the tower where cosine losses are high. Furthermore, the studies indicated that all of the heliostats south of the tower could be moved to the northern part of the field without having a significant effect on the overall collector cost or annual performance (as in Subsection 3.1.6). Consequently, the collector field was restricted to a 180° sector north of the tower, redirecting power to primary, intermediate, and secondary superheater panels covering the north half of the receiver cylinder. Economizer panels were placed 30° beyond the superheater panels on the east and west sides of the receiver to pick up the incident heat flux spilling over from the superheater surfaces.

Finally, a trade-off study was conducted to determine the optimum external receiver elevation, trading off the better cosine effects and



EXTERNAL RECEIVER COLLECTOR CHARACTERISTICS	CAVITY RECEIVER COLLECTOR CHARACTERISTICS
2,255 HELIOSTATS	2,177 HELIOSTATS
4.1 x $10^5 m^2$ LAND AREA	4.7 x $10^5 m^2$ LAND AREA
880m E-W FIELD WIDTH	820m E-W FIELD WIDTH
640m N-S FIELD LENGTH	700m N-S FIELD LENGTH
124m RECEIVER ELEVATION (CENTER LINE TO GROUND)	134m APERTURE ELEVATION (CENTER LINE TO GROUND)

FIGURE 3-14. ALTERNATE COLLECTOR/RECEIVER CONFIGURATIONS

close heliostat packing associated with higher elevations with the higher tower and piping costs. The results indicated that the collector cost and annual performance cost were relatively insensitive to receiver elevation, but pointed to an optimum relative target elevation of 120 metres (receiver center line to heliostat center line).

The baseline collector/receiver design utilizing an external receiver configuration contains a total of 2,255 heliostats, occupying an area of 5.1 x 10^5 m^2 (126 acres). Performance calculations estimate the total spillage loss at the design point is 1.1 per cent, and the receiver thermal efficiency is 88.9 per cent.

In a parallel study, a baseline collector/receiver design, as also illustrated on Figure 3-14, was developed for a cavity type receiver. The use of multiple cavities was investigated early in the study, but it was found that a single cavity facing north would provide the best performance and least complexity for this solar plant application. The results showed that the use of a pair of cavities facing northeast and northwest offered the advantages of high field performance and low spillage losses, but suffered increased heat loss from the larger combined aperture area.

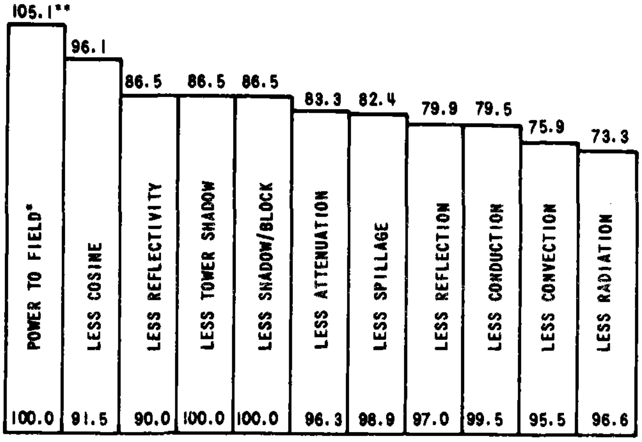
Trade studies using a square aperture shape showed that tilting the aperture 20° down from vertical lowered the total spillage loss, resulting in a 2 per cent savings in mirror area over the vertical orientation. Using that aperture shape and orientation, trade-offs in aperture size and elevation were made, leading to the final baseline design with a 9 metre by 9 metre aperture centered 130 meters (427 feet) above the heliostats.

The baseline cavity collector/receiver contains a total of 2,177 heliostats occupying an area of 4.7 x 10^5 m^2 (116 acres). The cavity itself has an octagonal shape 13.7 metres (45 feet) in height and diameter. The thermal efficiency of the cavity at the design point is 93.0 per cent, estimated through detailed performance calculations which considered the incident flux distribution from the field, multiple reflections within the cavity, and heat losses due to reflection, conduction, convection, and thermal radiation.

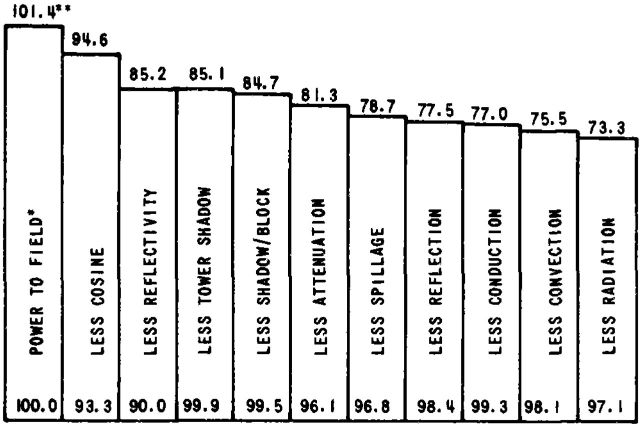
Figure 3-15 shows the collector/receiver efficiency stairsteps at the design point for both the external and cavity configurations. The diagrams show that when considering the combined effects of field performance and receiver spillage and thermal losses, the receiver efficiency of the cavity is higher than the external (93.0 per cent versus 88.9 per cent). In addition, Figure 3-15 shows that the cavity collector system has an advantage over the external in terms of the field cosine effect at the design point (0.933 versus 0.915). This higher cosine for the cavity system is a result of the field optimization procedure, which placed more heliostats north of the tower where their view of the aperture was better. For the external receiver, heliostats were spread to the east and west of the tower to reduce the peaks incident flux on the north side of the receiver, making the circumferential heat flux distribution more uniform. The resultant difference in field shapes can be seen on Figure 3-14.

3.1.7.3 Conclusions. As a result of the baseline cavity and external collector/receiver design studies, the cavity configuration will require approximately 3.6 per cent fewer heliostats than the external receiver, resulting in a heliostat cost savings of almost $1 million. However, B&W estimates the cost of the cavity receiver will be at least $1.5 million higher than the external receiver and, because of the larger size, the cavity will require a more massive and expensive support structure to accommodate the increased weight and high wind loads. Consequently, the external receiver configuration has the lower overall system cost.

The external receiver has several other advantages over the cavity. Its exposed heat transfer panels will be more accessible for maintenance, and it does not have the additional maintenance and replacement costs of refractory linings as required in the cavity. Furthermore, the external receiver can be equipped with an insulating door for weather protection (e.g., hail) and overnight heat retention, thereby, acquiring some of the attributes of a cavity design.



EXTERNAL RECEIVER



CAVITY RECEIVER

*BASED ON 0.95 kW/M^2 REFERENCE INSOLATION
**POWER IN MW_e WITH 73.3 MW_t ABSORBED AS AREA REQUIREMENT

FIGURE 3-15. DESIGN POINT EFFICIENCY STAIRSTEPS FOR EXTERNAL AND CAVITY RECEIVERS

In view of the cost savings, simpler design, and probable lower maintenance requirement, the external receiver was selected as the preferred configuration for the particular requirements of repowering NES I.

3.2 SYSTEM SIZE

A major decision in the selection of the preferred system was the size or amount of repowering. The cost of repowering increases with the amount repowered; however, 100 per cent repowering is not required for a meaningful demonstration. Criteria used to select the amount of repowering are as follows.

- Least capital cost demonstration meaningful to utilities.
- Power level sufficient to test components, control systems, etc.
- Power level to provide meaningful fuel reduction for unit operation.
- Acceptable plant arrangement.
- System extendable to other units and solar fractions.

Satisfying the above criteria did not require a trade study which optimized some measures of the system performance. For example, electricity generated has a cost per unit generated, but the repowering size criteria properly ignores seeking the least mills/kWh criterion, because any repowering system with a heliostat cost of $\$260/m^2$ will not be cost competitive with fossil fuel for a large utility system. The selection of the preferred system, therefore, focuses on that system which can be demonstrated at lowest inverted cost and still provide a meaningful demonstration.

Combined management and engineering judgements of PSO and B&V concluded that 20 per cent fossil fuel displacement (73.3 MW_t (250 MBtu/h)) at the design point (noon on March 21) was proper for the amount of repowering. It satisfies all criteria stated above.

3.3 TECHNOLOGY

The solar repowered system designed for NES I employs water/steam as the receiver fluid. The selection of water/steam in lieu of a molten salt or liquid metal as the receiver working fluid was motivated by three factors.

- Performance
- Technology Development
- Utility Acceptance

These influencing factors are discussed in the following paragraphs.

3.3.1 Performance

Proposed methods of storing solar energy typically are based on storing it as thermal energy via the sensible heat of a liquid storage medium, generally a liquid metal or a molten salt. Such systems generally propose to use the storage medium as the receiver fluid. This eliminates the costly charging heat exchangers required if a working fluid other than the storage medium, such as water/steam, is used. This also boosts system performance by eliminating the temperature differential required by the heat exchange process, and it also reduces system complexity by reducing the amount of equipment and controls needed. However, such systems incorporating storage still require discharging heat exchangers.

The solar repowered plant designed for NES I does not include thermal energy storage. The solar repowered system is designed for a hybrid mode of operation: steam generated in the solar receiver is delivered to the turbine simultaneously with steam generated in the existing gas-fired boiler. The gas-fired boiler offsets the variations in solar energy, providing a steady and reliable source of thermal energy, thus eliminating the need for energy storage. Without the impetus of thermal storage, water/steam becomes the most desirable receiver fluid and offers distinct performance advantages over fluids such as liquid metals and molten salts.

The most significant performance aspect of the use of water/steam as the receiver fluid is the resulting simplicity of the system. In the hybrid system, feedwater is diverted from the main stream feeding the fossil-fired boiler, piped to the solar receiver where it is heated to become superheated steam, and piped back to rejoin the main steam line feeding the high-pressure turbine. There are no pumps or heat exchangers with which to contend; there is no storage system to interface or control; and there are no exotic heat transfer fluids for which to provide high-temperature freeze protection or fire protection systems. The proposed baseline system, employing a water/steam receiver fluid and a hybrid mode of operation, offers the simplest, and thus the most reliable, means for the solar repowering of an existing power plant.

3.3.2 Technology Development

The different levels of development of the technologies for the utilization of various candidate receiver fluids is one of the stronger motivations for the utilization of water/steam. Water/steam solar receivers can be designed and constructed using existing, well-developed and proven methods and techniques. The Babcock & Wilcox Company, designers of the solar receiver of the repowered system, is sufficiently confident of the proposed design that they feel that a subsystem research experiment (SRE) to test the validity of the design is not warranted. This confidence in design is founded on the employment of design methodology and construction techniques proven through years of Babcock & Wilcox experience in the boiler industry. Comparable confidence in design or experience with hardware cannot be found for receiver fluids other than water/steam. Proponents of other receiver working fluids require costly and time-consuming tests to validate their solar receiver designs.

3.3.3 Utility Acceptance

Regardless of the advantages that a system design may offer, without general user acceptance, market penetration will be slow, at best. Utilities, by necessity, are conservative in action; change is accepted only following an adequate history of performance. The direct utilization of the sun as a source of energy for the generation of electricty constitutes a major change in utility philosophy. This, coupled with the use of exotic receiver fluids with which the utilities have not the required maintenance facilities, trained personnel, or experience, may constitute too much change to attract utility interest. A better approach is to first make the transition to utilization of solar energy via conventional technologies familiar to the utilities. Then, after experience is gained and solar energy is accepted as viable by the utilities, the second step can be taken towards utilization of exotic fluids and more complex systems, if such is warranted.

An appropriate analogy can be found in the power generation industry itself; that is, the development of nuclear power. The first commercial nuclear reactor began operation in 1956. The core coolant employed was water/steam because it reduced the technological risk. To date, every commercial reactor built has employed water as the core coolant. It is only very recently, after several decades of experience, that efforts to develop other reactor core coolants, such as molten salts or liquid metals, have been expanded to other than a small, experimental scale. The utilization of solar energy should be developed similarily; only after adequate experience has been gained harnessing a new source of energy with conventional technology should system complexity be increased and additional risks added via the use of less-developed technology.

3.3.4 Summary

For the baseline solar repowered plant, designed for a hybrid mode of operation, water/steam was selected as the receiver fluid because of the following.

- The resulting system simplicity and inherent reliability.
- The higher level of development of the associated technology.
- The higher level of acceptance by the electric power generation industry.

3.4 SYSTEM CONFIGURATION

The basic configuration of the repowering system was established through a series of engineering studies and decisions, as discussed in the previous portions of this section. Based on these trade studies, the baseline system supplies superheated steam to the turbine at a design point flow rate sufficient to displace 20 per cent of the unit's fossil fuel with a wide range of operating flexibility. The collector system selected maximizes the annual energy delivered to the receiver per unit cost, consistent with limits of peak flux and flux distribution on the receiver surface. The preferred water/steam receiver is an external configuration which supplies only high pressure steam (no solar reheat) at 13.8 MPa/538 C (1,980 psi/1,000 F). One other key decision which was made during the proposal effort and confirmed during the early stages of the project was not to include any thermal energy storage in the repowering system configuration; the rationale for that selection follows.

The proposed design for the solar repowering of an existing power plant is a water/steam solar receiver operating in parallel with an existing fossil fuel-fired steam generator. Water/steam solar receivers are compatible only with thermal energy storage in a parallel arrangement (as employed in the pilot plant at Barstow, California), due to the requirements for approach temperatures and pinchpoints in the storage charging and discharging heat exchangers; thus, the steam generated via a parallel storage system is necessarily at a lower temperature than the charging steam. If the system includes a parallel storage system, one of two conditions are required: the turbine may be of dual-admission configuration (e.g., the Barstow pilot plant) and, thus, be able to accept the two different-temperature steam conditions without suffering physical damage due to thermal stresses; or in a single-admission configuration, steam from the solar receiver may be delivered at a temperature sufficiently high that the resulting steam generated via storage is at the rated turbine inlet temperature, and steam from the receiver input to the turbine directly would first be cooled via spray attemperators to the rated turbine inlet temperature.

The Unit I turbine is a single-admission machine with a rated inlet temperature of 538 C (1,000 F), as is the case for most modern power plants. This temperature is very near the upper limit attainable from a water/steam solar receiver; thus, steam cannot be produced practically at a temperature sufficiently high so as to permit a parallel storage system to generate steam at a temperature of 538 C (1,000 F).

4.0 CONCEPTUAL DESIGN

In the previous section, the results of several trade studies performed on the project were presented. These studies identified key design characteristics of the preferred system which were then used as the baseline upon which the conceptual design was developed. The broad system-level features of that design are discussed in this section. A more detailed treatment of individual systems is contained in Section 5.0.

This section begins with a description of the overall system, followed by discussions of functional requirements, design and operating characteristics, site requirements, and system performance. Next, capital cost and operating and maintenance costs are summarized. The section is concluded with discussions of system safety, environmental impacts, and institutional and regulatory considerations.

4.1 SYSTEM DESCRIPTION

The solar repowering system is designed to supply superheated steam to the existing Unit 1. The repowering portion of the plant, which consists of four unique solar systems, is fully integrated with the existing unit.

The systems which comprise the repowering facility are the collector, receiver, receiver loop, and master control systems. Their overall function is to transform solar energy into thermal energy for use by the existing fossil-fueled plant, which is characterized by a single system, the fossil energy system. Functional relationships among these systems are illustrated in Figure 4-1. Key features and principle interfaces of these systems are described below; a more rigorous discussion of these systems is presented in Section 5.0.

Sunlight is intercepted, redirected, and concentrated by the collector system which consists of a field of computer-controlled, two-axis tracking heliostats. For the repowering design, DOE second generation heliostats are specified; key features of this heliostat include 49 square metres of reflective surface area, an effective reflectivity of

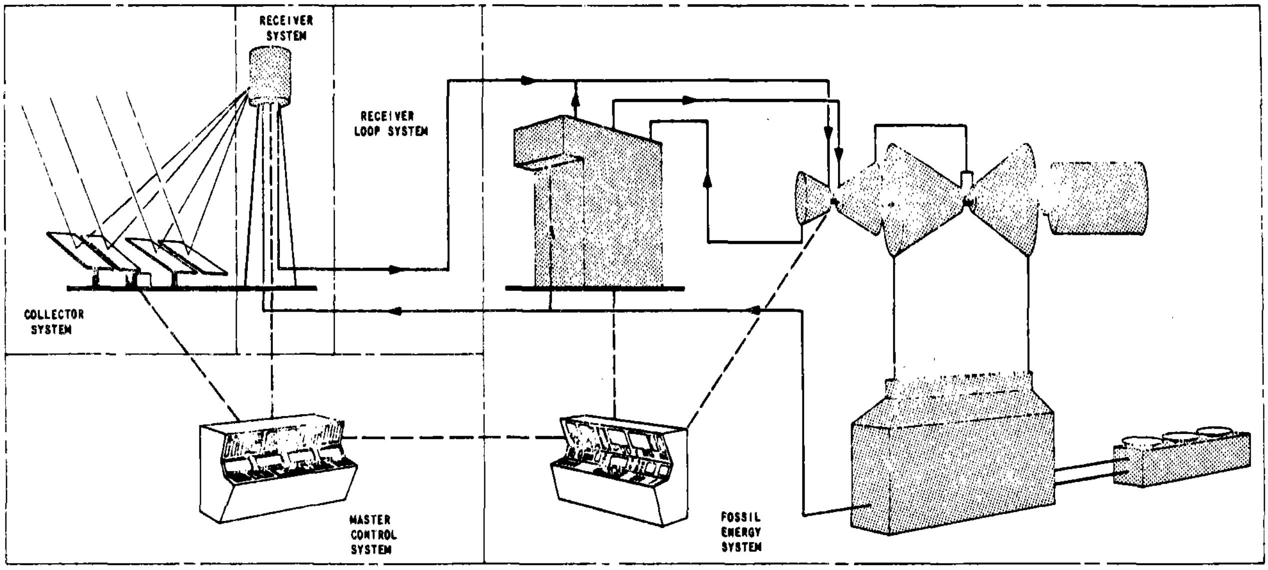


FIGURE 4-1. SOLAR REPOWERING SYSTEM SCHEMATIC

0.90, and separate motors for azimuthal and elevation steering. The collector field design consists of 2,255 heliostats located north of the receiver. Principal interfaces with other plant systems include the redirected solar flux onto the solar receiver, auxiliary power for heliostat drive motors from the existing plant, and control signals received from the master control system.

The water/steam receiver system absorbs solar energy, transforming it into thermal energy; this heat is then transferred to the working fluid, converting feedwater into superheated steam. For the repowering application, the receiver has symmetric external heat absorbing surfaces which extend 120 degrees either side of north. It employs a pumped circulation system and has three stages of superheating. The solar receiver is located atop a concrete tower which provides personnel access to the receiver and supports receiver piping and cables. Major interfaces with other systems are solar flux from the collector system, feedwater from and superheated steam to the receiver loop system, auxiliary power from the existing plant, and control signals exchanged with the master control system.

The function of the receiver loop system is to transport the working fluid between the receiver system and the fossil energy system. Key system features consist of insulated feedwater and steam piping, a tank at the base of the tower for draining the receiver, and a condensate return line which is also used for prewarming the receiver prior to start-up. Primary interfaces include feedwater and steam line connections to the receiver system, feedwater steam and condensate line connections with the fossil energy system, auxiliary power from the existing plant, and control signals to and from the master control system.

The master control system coordinates the operation of the collector, receiver, receiver loop, and fossil energy systems by receiving operating data from and sending command signals to each of these systems. In addition, the system serves as the data acquisition center for the repowered plant, collecting, analyzing, and displaying all critical plant parameters. The master control system provides the capability for start-up, normal operation, and shutdown (including emergency shutdown) in either a fully automatic or a manual mode. The key elements of the system are a control computer (including peripheral equipment and software), a multiplexed data link, and the control and display consoles. Although the principal master control system interfaces consist of command and operating data signals exchanged with the other plant systems, another interface involves the supply of auxiliary power from the existing plant facilities in order to operate system hardware.

The fossil energy system converts the thermal energy in superheated steam into electricity; thermal energy is obtained both from the sun and from the combustion of natural gas in the fossil energy system steam generator. The major components in the system include reheat turbine generator, gas-fired steam generator, and feedwater pump; this equipment transforms thermal energy into electricity, provides the primary source of main steam, as well as the only source of reheat steam, and delivers high-pressure feedwater to both the solar system and the fossil steam generator. Major interfaces include the exchange of feedwater, steam, and condensate with the receiver loop system, receiving and transmitting control and information signals with the master control system, receiving and providing auxiliary power to all other plant systems.

Thus, the five major systems which comprise the repowered plant are configured to perform their unique functions and are completely integrated into a functional system. The conceptual design of this integrated repowering system is the subject of the remainder of this section.

4.2 FUNCTIONAL REQUIREMENTS

The solar repowered plant designed for NES I at Oologah, Oklahoma, is to intercept and collect incident direct normal insolation. The collected solar energy is to be used to generate superheated steam from the feedwater flowing through the solar receiver. The superheated steam is subsequently merged with steam generated in a conventional fossil steam generator and delivered to a turbine for the generation of electricity.

The functional system requirements of the solar repowered plant designed for NES I are listed in Table 4-1. These requirements, as well as the plant instrumentation and control philosophy, are discussed in the following paragraphs.

4.2.1 Performance Requirements

The solar repowered plant is to operate in a hybrid mode: steam generated in the solar receiver is admitted to the turbine simultaneously with steam generated in the existing natural gas-fired steam generator. This arrangement provides great system flexibility and a reliable heat source while eliminating the need for thermal energy storage. The system has no thermal energy storage capacity.

At the design point of noon, March 21, at the reference site of Oologah, Oklahoma, the solar repowered plant is to collect a net power of 73.3 MW_t with a reference insolation of 950 W/m^2. This represents approximately 20 per cent of the total thermal input to the cycle at the plant rated output. The solar repowered plant is to have a solar fraction of 0.20.

At the design point, the collected thermal energy is employed to heat a 111,356 kg/h (245,278 lb/h) flow of feedwater to produce superheated steam. Feedwater is input to the solar portion of the repowered

TABLE 4-1. SYSTEM REQUIREMENTS

Performance Requirements	Value
Operating Mode	Hybrid
Design Point Power Level	
Thermal Energy (MW_t)	73.3
Equivalent (MW_e net)†	29.2
Design Insolation (W/m^2)	950
Design Point	Noon, March 21
Reference Site	Oologah, Oklahoma
Latitude	36° 26' N
Longitude	95° 42' W
Input Feedwater Conditions	
Temperature [C (F)]	247 (477)
Pressure [MPa (psi)]	19.1 (2,750)
Flow Rate [kg/h (lb/h)]	111,356 (245,278)
Delivered Steam Conditions	
Temperature [C (F)]	538 (1,000)
Pressure [MPa (psi)]	13.8 (1,980)
Solar Fraction (SF)	0.20
Storage Capacity (h)	None
Environmental Requirements	
Maximum Operating Wind* (including gusts) [m/s (mph)]	16 (36)
Maximum Survival Wind* (including gusts) [m/s (mph)]	36 (80)
Seismic Environment	UBC Zone I
Operational Horizontal Acceleration (g)	0.05
Survival Horizontal Acceleration (g)	0.10
Operating Temperature [C (F)]	
Minimum	-27 (-17)
Maximum	47 (117)
Reliability Lifetime Requirements	
Availability (Exclusive of Sunshine)	
Expected	0.95
Required	0.85
Lifetime (years)	
Design	30
Operational	15

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*At an elevation of 10 metres.

plant at a temperature of 247 C (477 F) and a pressure of 19.1 MPa (2,750 psi); superheated steam is returned to the power plant at a temperature of 538 C (1,000 F) and a pressure of 13.8 MPa (1,980 psi).

4.2.2 Environmental Requirements

The solar repowered plant is to operate in winds, including gusts, of speeds of up to 16 m/s (36 mph), as measured at a elevation of 10 metres. The plant is to survive winds of speeds of up to 36 m/sec (80 mph) without damage.

The solar repowered plant shall be able to operate during earthquakes with peak horizontal accelerations of up to 0.05 g; the system shall be able to survive earthquakes with peak horizontal accelerations up to 0.10 g without damage.

The solar repowered plant shall be able to operate in, and survive without damage, ambient air temperatures ranging from a low of -27 C (-17 F) to a high of 47 C (117 F).

4.2.3 Reliability and Lifetime Requirements

The components employed in the solar portion of the repowered plant are to be designed for a 30-year lifetime. This requirement is consistent with current power plant engineering practice, and it is compatible with the solar hardware currently being developed. The solar repowered plant, however, is to be operated for a period of only 15 years, at which time the existing power plant will come to the end of its useful lifetime. At that time, the solar portion of the repowered plant may have an associated salvage value.

For the solar repowered plant to be of sufficient reliability to be of practical use to the Public Service Company of Oklahoma, the solar portion of the repowered plant must have an availability of at least 85 per cent, exclusive of sunshine. As a result of component redundancy and design conservation, the solar repowered plant is expected to achieve an availability of at least 95 per cent, exclusive of sunshine.

4.2.4 Plant Instrumentation and Control Philosophy

The controls are divided into five major control systems. Separate, independent control systems are provided with the receiver, receiver loop, collector, and fossil energy systems; each of these control systems operates the equipment within its respective system. The fifth control system, the Master Control System, coordinates the activities of the other four control systems to provide fully automatic control of the entire solar repowered system.

4.2.4.1 Fossil Energy System Controls. This control system adjusts the fossil steam generator fuel flow, air flow, feedwater flow, superheat attemperator spray flow, reheat spray flow, and the turbine throttle valves, in order to automatically regulate the generated power, main steam pressure, boiler drum level, main steam temperature, and reheat steam temperature. This system also includes numerous controls for auxiliary equipment and a unit protection system to safely shut down the equipment during emergency conditions.

4.2.4.2 Receiver Controls. This control system adjusts the receiver feedwater flow, superheat spray flow, and superheater panel bias valves to automatically regulate the receiver drum level, receiver outlet steam temperature, and receiver panel temperature. The system also contains controls for the receiver vent and drain lines.

4.2.4.3 Collector Controls. This control system adjusts heliostat orientations to regulate the amount of solar insolation on the receiver and provide for safe operation of the heliostat field.

4.2.4.4 Receiver Loop Controls. This control system operates the receiver feedwater inlet and steam outlet shut-off valves and the steam line drain valves. This system also operates the pumps and valves in the condensate return line from the receiver to the fossil energy system.

4.2.4.5 Master Control System. This control system provides the coordination of the other four control systems during hybrid operation. This system provides the capability for an automated start-up and shutdown of the solar equipment. The Master Control System includes an emergency shutdown system to safely shut down the solar equipment during emergency conditions.

4.3 DESIGN AND OPERATING CHARACTERISTICS

The conceptual design of the solar systems at NES I provides approximately 20 per cent solar repowering with an associated fossil fuel savings of 20 per cent and a plant heat rate improvement of 19.8 per cent at the design point, as shown on Table 4-2. The design of the solar systems is based on achieving peak performance capability with a reference insolation level of 0.95 kW/m^2 at the design point; noon, March 21. The significant design parameters of the existing fossil energy system components and the new solar repowering systems are shown on Table 4-3.

4.3.1 Operating Characteristics

There are two modes of operation; fossil-only operation and combined fossil and solar operation. Fossil operation can be used at all times. Combined fossil and solar operation can be used whenever there is sufficient solar insolation available.

4.3.1.1 Fossil Operation. The fossil mode of operation uses the fossil steam generator as the only source of steam for the turbine. The steam generator can be fired on either natural gas or oil. The level of electrical generation is maintained at the value desired by the utility's load dispatch center. The load dispatch center is allowed to change the load dispatch value at a rate of 4.5 megawatts per minute. The automatic controls of the turbine generator maintain the unit's electrical output at the desired level.

Load control by the dispatch center is limited to periods when the turbine generator is operating at 12.5 MPa (1,800 psi) throttle pressure and net output between 50 MW and 143.8 MW. During start-up, shutdown, and overpressure conditions, 13.8 MPa (1,980 psi), control is maintained by the Unit I operator.

Operating conditions for the turbine generator at rated pressure and overpressure conditions are illustrated by the turbine cycle heat balances shown on Figures 4-2 and 4-3. The fossil steam generator operating characteristics are presented on Table 4-4.

TABLE 4-2. DESIGN POINT PERFORMANCE CHARACTERISTICS

	Fossil Only Operation	Fossil and Solar Operation
Unit Generation		
Gross Turbine Output, kWe	155,200	155,220
Auxiliary Power, kWe	10,041	10,251
Net Plant Output, kWe	145,179	144,969
Turbine Heat Input		
Fossil, MW_t (MBtu/h)	364.12 (1,242.38)	291.30 (993.90)
Solar, MW_t (MBtu/h)	0 (0)	72.82 (248.48)
Total, MW_t (MBtu/h)	364.12 (1,242.38)	364.12 (1,242.38)
Plant Heat Input		
Fossil, MW_t (MBtu/h)	435.24 (1,485.04)	348.23 (1,188.16)
Solar, MW_t (MBtu/h)	0 (0)	81.92 (279.51)
Total, MW_t (MBtu/h)	435.24 (1,485.04)	430.15 (1,467.67)
System Heat Rates		
Gross Turbine Heat Rate, MW_t/MW_e (Btu/kWh)	2.35 (8,004)	2.35 (8,004)
Equivalent Fossil Gross Turbine Heat Rate, MW_t/MW_e (Btu/kWh)	2.35 (8,004)	1.88 (6,403)
Equivalent Fossil Net Plant Heat Rate, MW_t/MW_e (Btu/kWh)	3.00 (10,229)	2.40 (8,196)

TABLE 4-3. DESIGN PARAMETERS

I. TURBINE GENERATOR	
Manufacturer	Westinghouse
Type	Two cylinder, tandem compound, double flow impulse-reaction, condensing, reheat, 0.58 metre (23 inch), last-stage blades, TC2F23LSB
Generator	200,000 kVA, 0.80 power factor, three-phase, 60 hertz, 0.52 MPa (60 psi) hydrogen pressure, 14,400 V
Exciter	Separately driven, 1,000 kW, 375 V dc, air-cooled motor generator
Cabability*	
Rated Steam Conditions	
Throttle Steam Pressure	12.5 MPa (1,800 psi)
Throttle Steam Temperature	538 C (1,000 F)
Reheat Steam Temperature	538 C (1,000 F)
Generator Output	143,800 kW_e
Turbine-Cycle Heat Rate	2.36 MW_t/MW_e (8,036 Btu/kWh)
Overpressure Steam Conditions	
Throttle Steam Pressure	13.8 MPa (1,980 psi)
Throttle Steam Temperature	538 C (1,000 F)
Reheat Steam Temperature	538 C (1,000 F)
Generator Output	155,220 kW_e
Turbine Cycle Heat Rate	2.35 MT_t/MW_e (8,004 Btu/kWh)
II. FOSSIL STEAM GENERATOR	
Manufacturer	Babcock & Wilcox
Type of Unit	Radiant reheat, pressure furnace
Continuous Rating	454,000 kg/h (1,000,000 lb/h)
Maximum Rating	522,000 kg/h (1,150,000 lb/h)
Design Pressure	16.1 MPa (2,325 psi)

TABLE 4-3 (Continued). DESIGN PARAMETERS

II. FOSSIL STEAM GENERATOR (Continued)	
Superheater Outlet Pressure	14.4 MPa (2,070 psi)
High-Pressure Steam Temperature	541 C (1,005 F)
Reheat Steam Temperature	541 C (1,005 F)
III. SOLAR RECEIVER	
Type	External receiver with closure doors, modular designed steam generator with pump circulation.
Receiver Diameter	9.5 m (31.2 ft)
Receiver Height	15.24 m (50 ft)
Active Surface (fully circumferential area of screen tubes and flat projected area of membrane tubes)	597.4 m^2 (6,430 ft^2)
Elevation of Receiver (ground to receiver midpoint)	124 m (407 ft)
Peak Flux	0.62 MW_t/m^2
Receiver Power Rating	82.45 MW_t (281.3 MBtu/h)
Superheater Outlet Conditions	
Rated Steam Flow	111,262 kg/h (245,287 lb/h)
Steam Pressure	15.0 MPa (2,155 psi)
Steam Temperature	544.2 C (1,011.6 F)
Receiver Design Pressure	17.0 MPa (2,450 psi)
Overall Receiver Efficiency	88.9 per cent
IV. COLLECTOR SYSTEM	
Type	Array of computer-controlled, two-axis tracking heliostats described in the DOE Collector Subsystem Requirements Specification, A10772, Issue C, October 10, 1979.
Heliostat Characteristics	
Total Size	49.05 m^2 (528 ft^2)
Number of Panels	12
Size of Each Panel	1.2 by 3.4 m (4 by 11 ft)

TABLE 4-3 (Continued). DESIGN PARAMETERS

IV. COLLECTOR SYSTEM (Continued)	
Spacing Between Sides	0.71 m (2.33 ft)
Elevation of Axis	4.08 m (13.4 ft)
Beam Quality (Reflected Beam)	± 2 milliradians (1 σ)
Pointing Accuracy (Reflected Beam)	± 1.5 milliradians (1 σ)
Number of Heliostats	2,255
Total Mirror Area	110,617 m^2 (1.19 by 10^6 ft^2)
Land Area Under Heliostats	510,000 m^2 (126 acres)
Maximum Field Width (east-west)	880 m (2,887 ft)
Maximum Field Length (north-south outer radius)	640 m (2,100 ft)

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*With all five feedwater heaters in service.

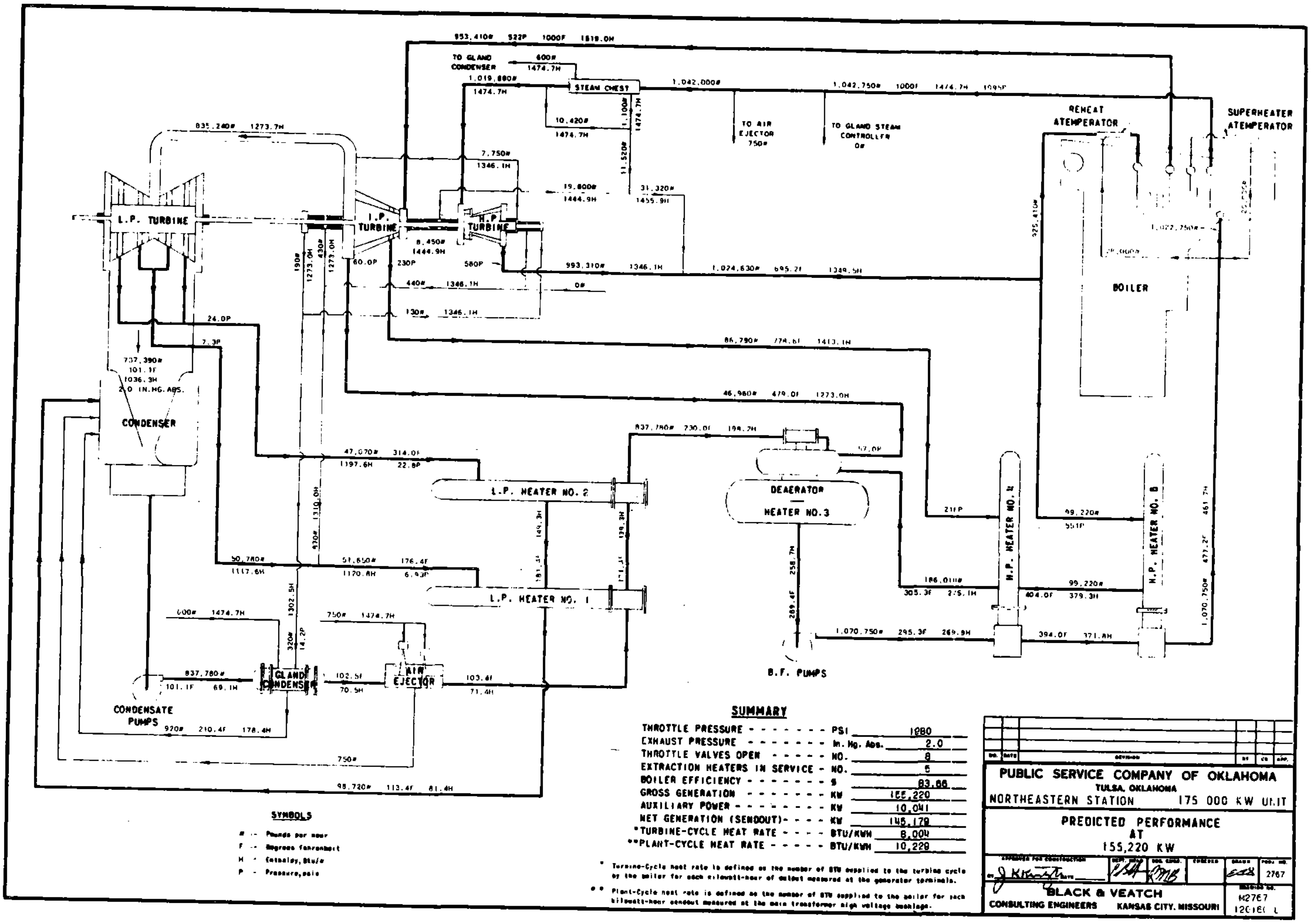

FIGURE 4-2. HEAT BALANCE-FULL LOAD, OVERPRESSURE

During fossil-only operation, the heliostats are placed in a stow position and the solar receiver steam line is isolated from the fossil energy system. If the receiver or steam piping temperature drop below atmospheric pressure, the receiver steam sections are filled with nitrogen for corrosion protection of the heat transfer surfaces. Freeze protection during normal short-term solar receiver shutdown periods is accomplished by activating the receiver circulation pump or circulating a small amount of warm feedwater from the fossil energy system through the receiver to maintain the receiver water temperature above 4.4 C (40 F).

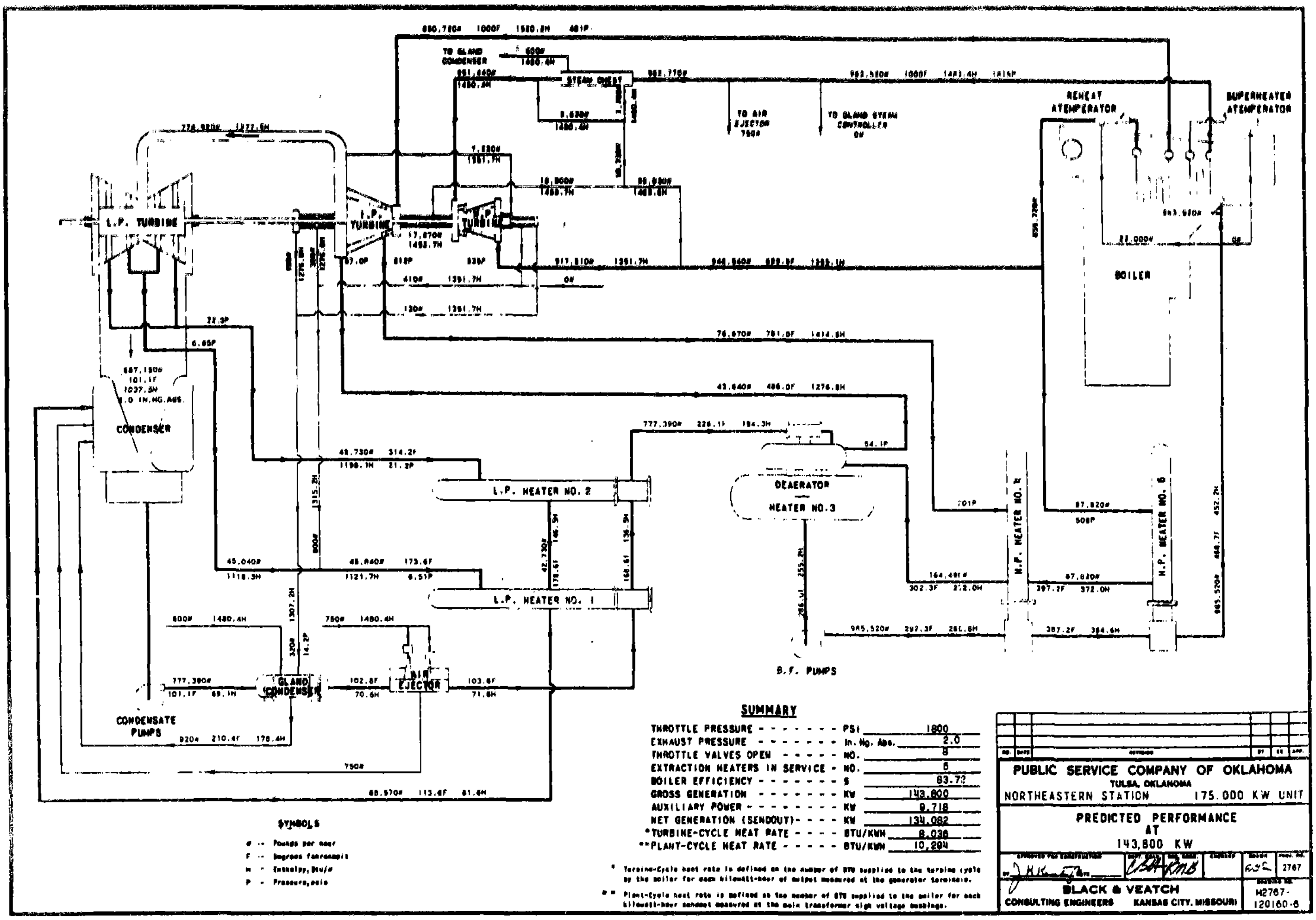

FIGURE 4-3. HEAT BALANCE-FULL LOAD, RATED PRESSURE

4.3.1.2 Combined Fossil-Solar Operation. During combined fossil and solar operation, the superheated throttle steam generated by the fossil steam generator is reduced by the amount generated by the solar receiver. The steam and feedwater conditions at the design point are presented on Figure 4-4 and Table 4-5. The design of the solar receiver and main steam transport pipe is such that the steam conditions at the interface with the fossil energy system are compatible with the existing turbine throttle steam conditions. The performance of the turbine generator is therefore unaffected by the solar repowering systems.

TABLE 4-4. FOSSIL STEAM GENERATOR OPERATING CHARACTERISTICS

	60 Per Cent Rated Capacity	Rated Capacity	Maximum Capability
Steam Output, kg/h (lb/h)	272,000 (600,000)	454,000 (1,000,000)	522,000 (1,150,000)
Reheat Steam Flow, kg/h (lb/h)	240,000 (530,000)	404,000 (891,000)	522,000 (1,150,000)
Excess Air Leaving Air Heater, per cent	25	7	7
Number of Burners in Use	15	15	15
Fuel, m^3/h (ft^3/h)	25,485 (900,000)	352,471 (1,416,000)	452,537 (1,818,000)
Flue Gas Leaving Air Heater, kg/h (lb/h)	396,000 (874,000)	537,000 (1,184,000)	692,000 (1,525,000)
Air Leaving Air Heater, kg/h (lb/h)	378,000 (834,000)	509,000 (1,123,000)	654,000 (1,443,000)
Steam Pressure at SH Outlet, MPa (psi)	12.9 (1,850)	12.9 (1,850)	14.4 (2,070)
Pressure Drop, Drum to SH Outlet, MPa (psi)	0.36 (37)	0.81 (102)	0.93 (120)
Pressure Drop through Economizer, MPa (psi)	0.23 (19)	0.47 (53)	0.59 (70)
Steam Pressure Entering Reheater, MPa (psi)	2.17 (300)	3.46 (486)	3.66 (515)
Steam Pressure Leaving Reheater, MPa (psi)	2.08 (287)	3.26 (458)	3.45 (485)
Steam Temp Leaving Superheater, C (F)	541 (1,005)	541 (1,005)	541 (1,005)
Steam Temp Entering Reheater, C (F)	316 (601)	349 (661)	368 (695)
Steam Temp Leaving Reheater, C (F)	541 (1,005)	541 (1,005)	541 (1,005)
Flue Gas Temp Leaving Economizer, C (F)	332 (630)	379 (715)	382 (720)
Flue Gas Temp Leaving Air Heater, C (F)	143 (290)	166 (330)	171 (340)
Air Temp Entering Air Heater, C (F)	38 (100)	38 (100)	38 (100)
Water Temp Entering Economizer, C (F)	215 (419)	241 (466)	154 (310)
Water Temp Entering Boiler, C (F)	258 (497)	274 (526)	239 (463)
Boiler and Superheater Draft Loss, kPa (inches of water)	0.40 (1.6)	0.75 (3.0)	1.22 (4.9)

TABLE 4-4 (Continued). FOSSIL STEAM GENERATOR OPERATING CHARACTERISTICS

	60 Per Cent Rated Capacity	Rated Capacity	Maximum Capability
Economizer Draft Loss, kPa (inches of wate	0.25 (1.0)	0.45 (1.8)	0.72 (2.9)
Air Heater Draft Loss, kPa (inches of water)	0.50 (2.0)	0.90 (3.6)	1.44 (5.8)
Dampers and Flues Draft Loss, kPa (inches of water)	0.02 (0.1)	0.07 (0.3)	0.12 (0.5)
Burner and Wind box Air Resistance, kPa (inches of water)	0.45 (1.8)	0.87 (3.5)	1.42 (5.7)
Duct Resistance, kPa (inches of water)	0.07 (0.3)	0.12 (0.5)	0.20 (0.8)
Air Heater Resistance, kPa (inches of water)	0.45 (1.8)	0.82 (3.3)	1.32 (5.3)
Net Resistance and Draft Loss, kPa (inches of water)	2.14 (8.6)	3.98 (16.0)	6.45 (25.9)
Dry Gas, per cent heat loss	3.90	4.01	4.18
Hydrogen and Water in Fuel, per cent heat loss	10.32	10.48	10.53
Moisture in Air, per cent heat loss	0.11	0.11	0.12
Unburned Combustible, per cent heat loss	0.00	0.00	0.00
Radiation, per cent heat loss	0.31	0.23	0.20
Unaccounted, per cent heat loss	1.50	1.50	1.50
Total heat loss, per cent	16.14	16.33	16.53
Efficiency of Unit, per cent	83.86	83.67	83.47

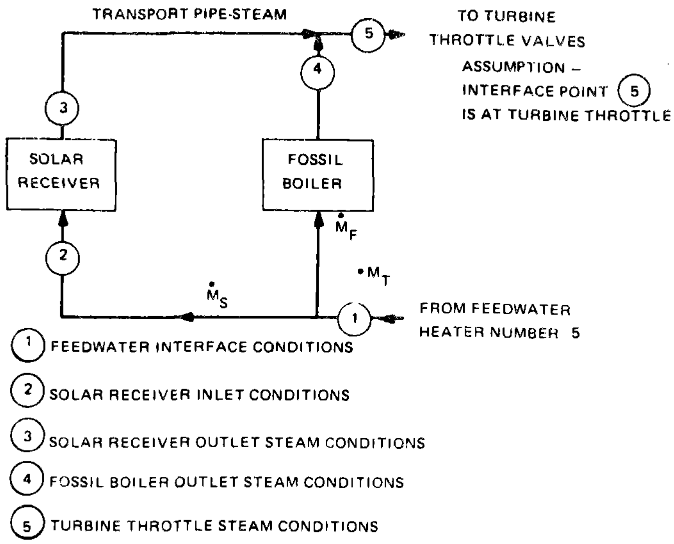

FIGURE 4-4. SOLAR/FOSSIL INTERFACE SCHEMATIC

To assure a stable flame pattern, adequate superheat and reheat steam temperature control, and the ability to respond to cloud transients, the fossil steam generator and the turbine generator will be operated above a minimum turndown, about 30 per cent load (50 MW_e). The solar receiver steam output will vary throughout the day, as shown on Figure 4-5. As solar generated steam becomes available, the minimum allowable turbine generator load will increase from 50 MW_e to about 88 MW_e at noon. The operating range of Unit I during combined fossil-solar operation is therefore 50 MW_e to 155 MW_e (with the lower generation level dependent on the amount of solar steam available).

The fossil steam generator provides all of the hot reheat steam and only part of the superheated steam to the turbine generator during combined fossil-solar operation. This results in a slight change in the expected reheat steam temperatures during combined fossil-solar operations, as shown on Figure 4-6. The worst case condition is at minimum turndown on the fossil steam generator (30 per cent flow) and maximum solar steam flow (25 per cent of maximum fossil steam flow). This condition would be infrequent and would still result in reheat steam temperatures greater than 482 C (900 F), which will not significantly affect the performance of the turbine generator.

TABLE 4-5. DESIGN POINT INTERFACE CONDITIONS*

Parameter	Feedwater Interface 1	Solar Receiver Inlet 2	Solar Receiver Outlet 3	Fossil Boiler Outlet 4	Turbine Throttle Valves 5
Fluid Flow	485,601 kg/h (1,070,750 lb/h)	111,241 kg/h (245,287 lb/h)	111,241 kg/h (245,287 lb/h)	361,661 kg/h (797,463 lb/h)	472,562 kg/h (1,042,000 lb/h)
Pressure	19.1 MPa (2,750 psi)	17.4 MPa (2,505 psi)	14.9 MPa (2,140 psi)	13.8 MPa (1,980 psi)	13.8 MPa (1,980 psi)
Temperature	247 C (477 F)	245.6 C (474 F)	544.2 C (1,011.6 F)	538 C (1,000 F)	538 C (1,000 F)

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*Interface points are illustrated on Figure 4-4.

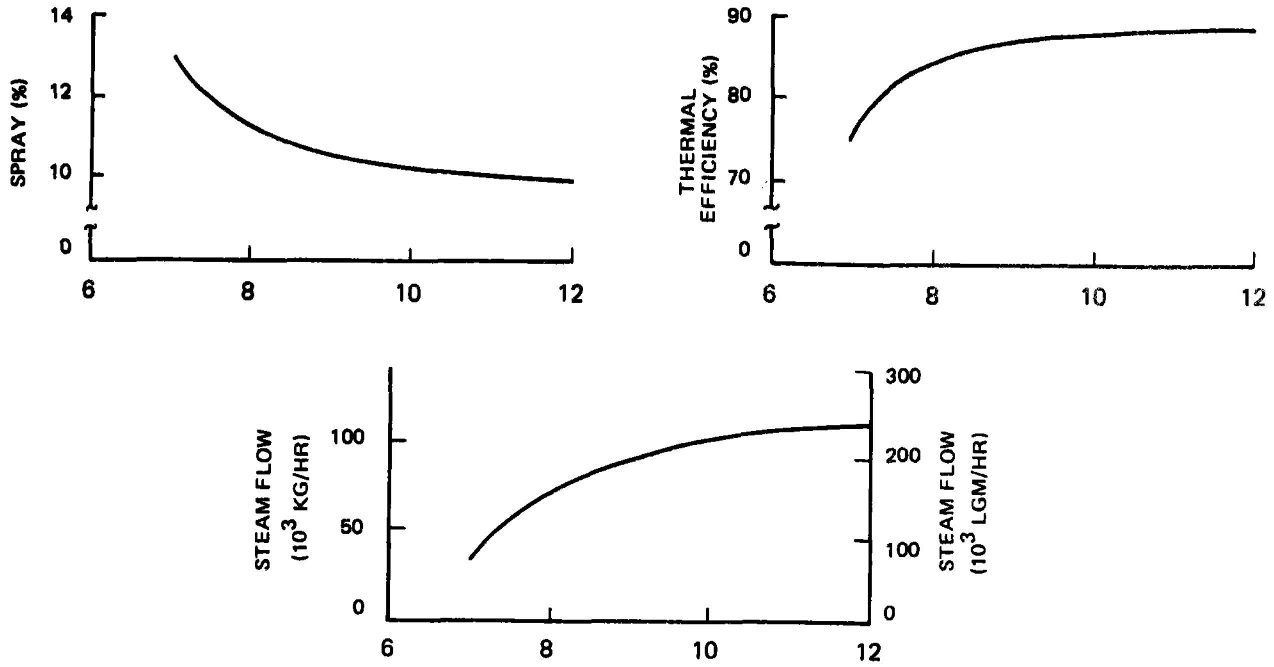
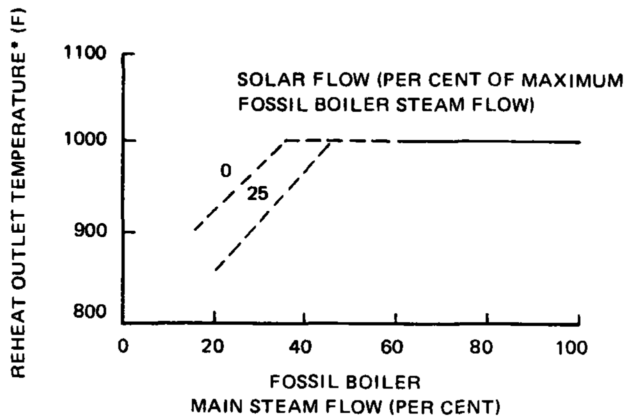


FIGURE 4-5. THERMAL PERFORMANCE OF SOLAR RECEIVER DURING EQUINOX DAY



*FOR 100% FOSSIL REHEATER STEAM FLOW

FIGURE 4-6. EXPECTED REHEAT STEAM TEMPERATURE

4.3.1.3 Solar System Start-Up. The time required for morning start-up of the solar systems is dependent on the amount of cooldown occurring during shutdown. During normal overnight shutdown, the receiver closure doors and piping insulation should maintain the bulk temperatures of the fluid and metals above 204 C (400 F). Steam from the fossil steam generator would be back fed through the main steam transport pipe to warm the solar receiver and place it in a condition ready to generate full load temperature and pressure steam shortly after sunrise. The warm-up rate would be controlled at about 4.4 C (8 F) per minute and would last about 1/2 hour.

If the receiver cools down to below the saturated steam temperature (about 100 C (212 F)), circulation of warm feedwater from the fossil energy system will be used to warm up the receiver water to 116 C (240 F). The water flow rate would be controlled to limit the rate of temperature rise in the receiver to 4.4 C (8 F) per minute. Final warm-up of the receiver would be accomplished with fossil steam as previously described.

4.3.2 Control Characteristics

The solar equipment will be capable of operation by a single operator who will simultaneously operate Unit 1 and Unit 2 at Northeastern Station. The mode of operation will be primarily automatic with manual override capability. All solar equipment will be operated from a centralized location in the existing control room for Unit 1. No operating personnel will be required in the receiver tower.

The controls are divided into five major control systems. Separate, independent control systems are provided with the receiver, receiver loop, collector, and fossil energy systems. Each of these control systems operates the equipment within its respective system. The fifth control system, the master control system, coordinates the activities of the other four control systems to provide fully automatic control of the entire solar repowered system. These control systems are described in Section 5.

4.4 SITE REQUIREMENTS

This section discusses site requirements in the context of site development, modifications to facilities, site structures and piping, and site electrical power.

4.4.1 Site Development

The heliostat field and receiver steam generator for the solar repowering project will be located in the northeast quadrant of the Northeastern Station, as shown in Figure 4-7. This area, presently a pasture, slopes gently to the southwest with generally less than 2 per cent grade. Site development will include minimal clearing and grading work followed by construction of security fencing and access roads with drainage provisions. Foundations for the receiver support tower and heliostats will be anchored to bedrock, which is covered by a thin soil mantle. Site date and site improvement are described in more detail in the following subsections.

4.4.1.1 Site Geology. The plant site is located entirely on the Oologah Formation, a geologic member of the Marmaton Group in the Desmoinesian series. This formation is represented by, in ascending order: the Pawnee Limestone; the Bandera Shale; and the Altamont Limestone. Pawnee Limestone is comprised of gray, massive crinoidal limestone, which is overlain by black, fissile shale. The Bandera Shale is a very thin, gray to brown, sandy shale which grades vertically into sandstone and black shale. The Altamont Limestone is composed of gray shale and limestone, overlain by black fissile shale and gray cherty limestone. Test borings for Units 1 through 4 at Northeastern Station indicated that the top surface of the Oologah Formation is slightly weathered.

A thin soil mantle, generally 0.3 to 1 metre (1 to 3 feet) thick, overlies the limestone bedrock. This soil is a silty clay which contains residual pieces of limestone. Specifically, the soil is classified as the Claremore Silt Loam, a soil formed under tall prairie grasses in material that weathered from limestone. It is easily worked, drains moderately well, but is susceptible to erosion. Due to its plastic nature, it is not good for borrow material.

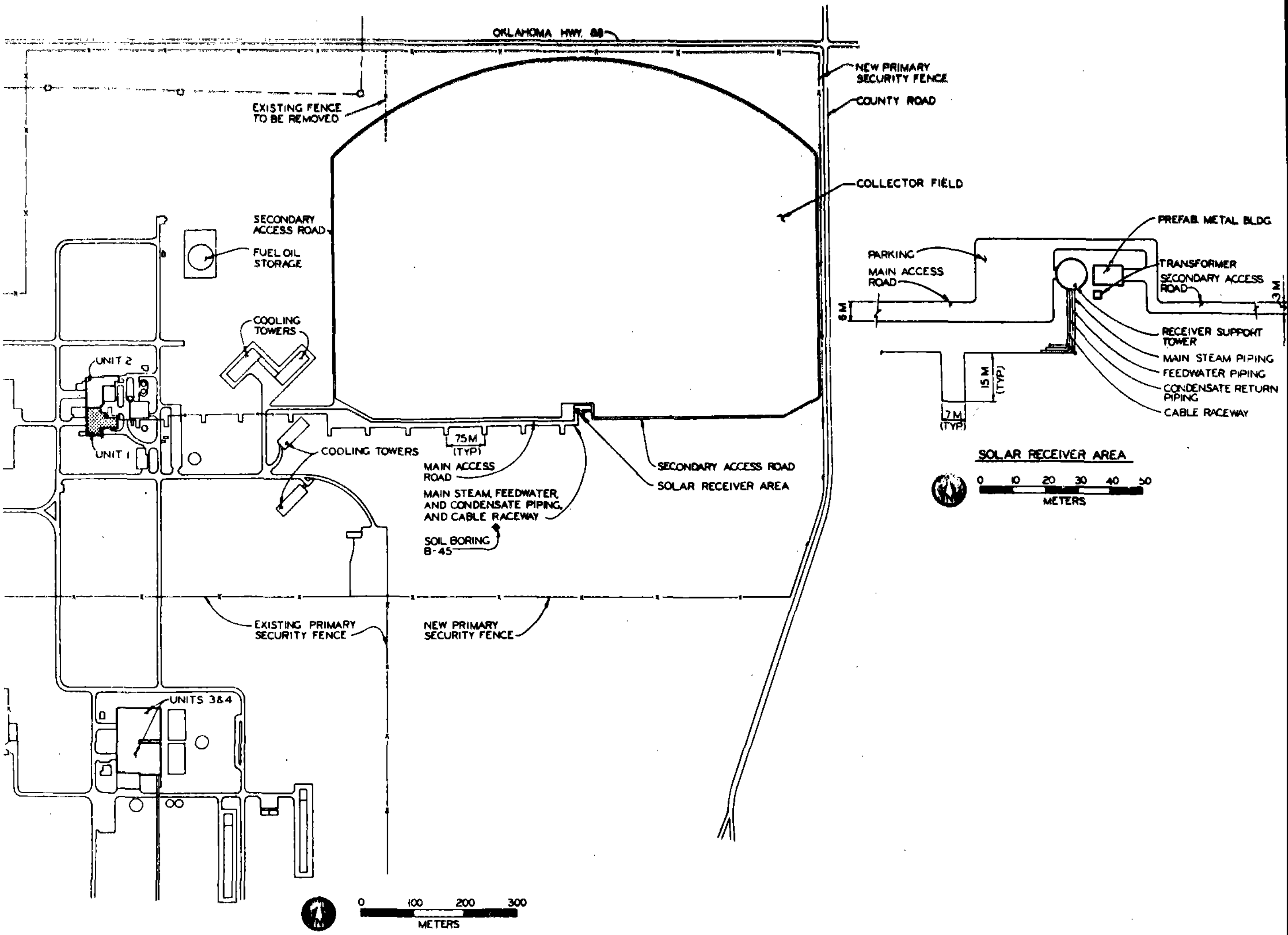


FIGURE 4-7. SITE ARRANGEMENT OF REPOWERED PLANT

The soil boring closest to the heliostat field indicates that a clay soil 0.8 metre (2.5 feet) of weathered limestone with some clay layers, which in turn, overlays the competent limestone. The heliostat field area slopes gently toward the southwest from about El 210 metres (690 feet) to EL 198 metres (650 feet). Natural drainage for the area is provided by two depressions, one of which includes a farm pond. The area is a pasture, with little brush and few trees.

4.4.1.2 Site Grading. Site grading work will be minimized to reduce costs and preserve natural drainage systems as much as possible. The dam for the farm pond will be removed and the natural drainage channels will be graded only as necessary to permit access of maintenance vehicles to the heliostats. Grading will be required in the vicinity of the tower and along access roads.

4.4.1.3 Site Improvement. Site improvement will consist of drainage provisions, access roads and parking, and security fencing. No site lighting will be required except at the receiver tower.

The natural present site drainage will be preserved, augmented only by drainage ditches adjacent to the access roads and by culverts where the roads cross natural drainage patterns.

A paved road will be provided to connect the existing road at the cooling towers to the receiver tower, as indicated on Figure 4-7. The parking area at the tower will also be paved to reduce dusting of the heliostat field. This main road and the parking area will be permanent-type construction with a crowned 6-metre (20-foot) wide traffic lane, 1.5-metre (5-foot) wide shoulders, and contoured drainage ditches. Surfacing will consist of a 0.08-metre (3-inch) asphaltic course on a 0.2-metre (8-inch) crushed rock prepared basecourse. The crushed rock basecourse will be underlain by a prepared subgrade of site materials selected for drainability. Drainage slope will be to the outer shoulder at about 0.021 metre/metre (1/4-inch per foot). Shoulders will not be paved, but will be oiled, and will be sloped to the ditches at about 0.042 metre/metre (1/2-inch per foot).

A secondary road will be provided from the receiver tower around the heliostat field. This 3-metre (10-foot) wide road will not be paved or provided with shoulders. It will be constructed of crushed rock and oiled to minimize dusting of the heliostat field.

The existing primary fencing section which now crosses the heliostat field area will be reused and supplemented with new fencing to surround the solar facility as shown in Figure 4-7. The existing perimeter fences of barbed wire along the site property boundaries will be removed where security fencing is provided. The security fencing will be galvanized steel chain link type with a three-strand barbed wire extension mounted at 45 degrees. The fabric height will be 1.8 metres (6 feet), and the overall height 2.1 metres (7 feet). It will not be necessary to provide gates.

The competent limestone has a very high load carrying capability. The allowable design bearing capacity has been conservatively established at 7.2 MPa (150 kips per square foot), so the size of the foundations bearing on the sound and unweathered limestone formation will be governed by the minimum practical dimensions, as determined by stresses due to shears and bending moments within the foundation rather than by the allowable bearing capacity of the limestone. Foundations for the heliostats and receiver tower are discussed in Sections 5.1 and 5.2, respectively.

4.4.2 Site Facilities

The existing facilities at Northeastern Station will be used to supply most of the auxiliary services required by the new solar repowering equipment. The following paragraphs summarize the required services and the plans to provide these services.

4.4.2.1 Service Water. No continuous requirements for service water have been identified. The design will include provisions for possible future connection to the existing plant service water system. Service water makeup to the chemical feed equipment will be by portable containers.

4.4.2.2 Service Air. A source of service air will be required during the construction phase and during periodic maintenance of equipment. A portable air supply system will be provided to meet these requirements.

4.4.2.3 Nitrogen. A separate nitrogen storage system will be provided for the solar repowering equipment. The nitrogen storage equipment will store nitrogen at high pressure for use in corrosion protection of the receiver, feedwater pipe, and transport pipe during plant shutdowns. The requirements of the nitrogen storage system are listed in the System Requirements Specification (Appendix A, Section 3.2).

4.4.2.4 Fire Protection. Hand-held and movable cart-mounted dry chemical fire extinguishers will be provided in the receiver tower area. No interconnection with the existing plant fire protection system is planned.

4.4.2.5 Communications. A communications system between the solar receiver tower and the main control room will be provided.

4.4.2.6 Water Treatment. The existing plant water treatment facilities will be used for analysis and treatment of the solar receiver water. No modifications to the existing facilities are planned.

4.4.2.7 Control Room. The solar equipment control panel and the master control system programmer's console will be located in the main control room for Units 1 and 2.

4.4.2.8 Control Equipment. The control equipment cabinets and computers will be located in an existing control equipment room adjacent to the main control room. No modifications to this room are planned.

4.4.2.9 Personnel Facilities. The existing plant office building and parking lot will accommodate the additional personnel needed for solar repowering. No modifications to these facilities are planned.

4.4.2.10 Storage and Maintenance. The existing plant warehouse and machine shop facilities will be used. No modifications to these facilities are planned.

4.4.3 Site Structures and Piping

Site structures and piping will be added to the existing plant facilities for the solar installation as described herein.

4.4.3.1 Site Structures. The solar receiver support tower structure will be added as described in Section 5.2. The heliostat support structures described in Section 5.1 also will be added. Miscellaneous structures to be added in the area of the solar receiver include a small building which will house the motor control center and diesel generator.

4.4.3.2 Piping. Piping will be added for the solar installation as described in Subsection 5.3.1. The piping interface with existing facilities will require branch welding the solar main steam, solar feedwater, and solar condensate return piping to existing piping. The solar condensate piping will also be attached to the existing condenser. Piping in the area of the existing Unit 1 will be supported from Unit 1 structural steel. Piping support structures will be added in the yard area, as indicated on Figure 4-7.

4.4.4 Site Electrical Power

The electrical power will be provided to all solar plant auxiliary loads. The auxiliary loads are defined as electrical loads required by the various auxiliary devices during shutdown, start-up, and the different operating modes of the solar repowering plant.

Two categories of additional electrical power will be required for solar repowering, normal plant ac, and uninterruptible ac. Normal plant ac will be used to supply power to collector and receiver system loads. Uninterruptible ac will be used to supply power to master control system computers and other critical control and instrumentation loads, where an interruption of power even for a few cycles cannot be tolerated under any circumstances.

4.4.4.1 Normal Plant AC Power. As shown in Figure 4-8, the source of the normal plant ac will be the existing medium voltage (4,160 volt -3ϕ) auxiliary power buses of Unit 1. In order to obtain a high degree of reliability, two redundant sources of power from different switchgear buses, one normal and the other standby, are used. The power will be carried over at 4,160 volts to enclosed distribution switchgear near the base of the receiver tower by a 5 kV solid di-electric cable. At the receiving end, 4,160 volt power will be distributed and transformed to lower voltages, as required for a most economic distribution.

Since the heliostats cover a wide area, primary power distribution in the heliostat field will be made by feeder circuits at 4,160 volts. Several low-profile, pad-mounted transformers will be sited in the collector field as close to the center of loads as possible. Secondary distribution of power to each heliostat will be made at either 120/208 volts, or as required by the specific heliostat.

In the event of a total blackout of the plant ac with a unit trip, emergency power will be required to slew heliostats away from the receiver as quickly as possible to prevent damage to the receiver. This emergency power is completely independent of the plant auxiliary power

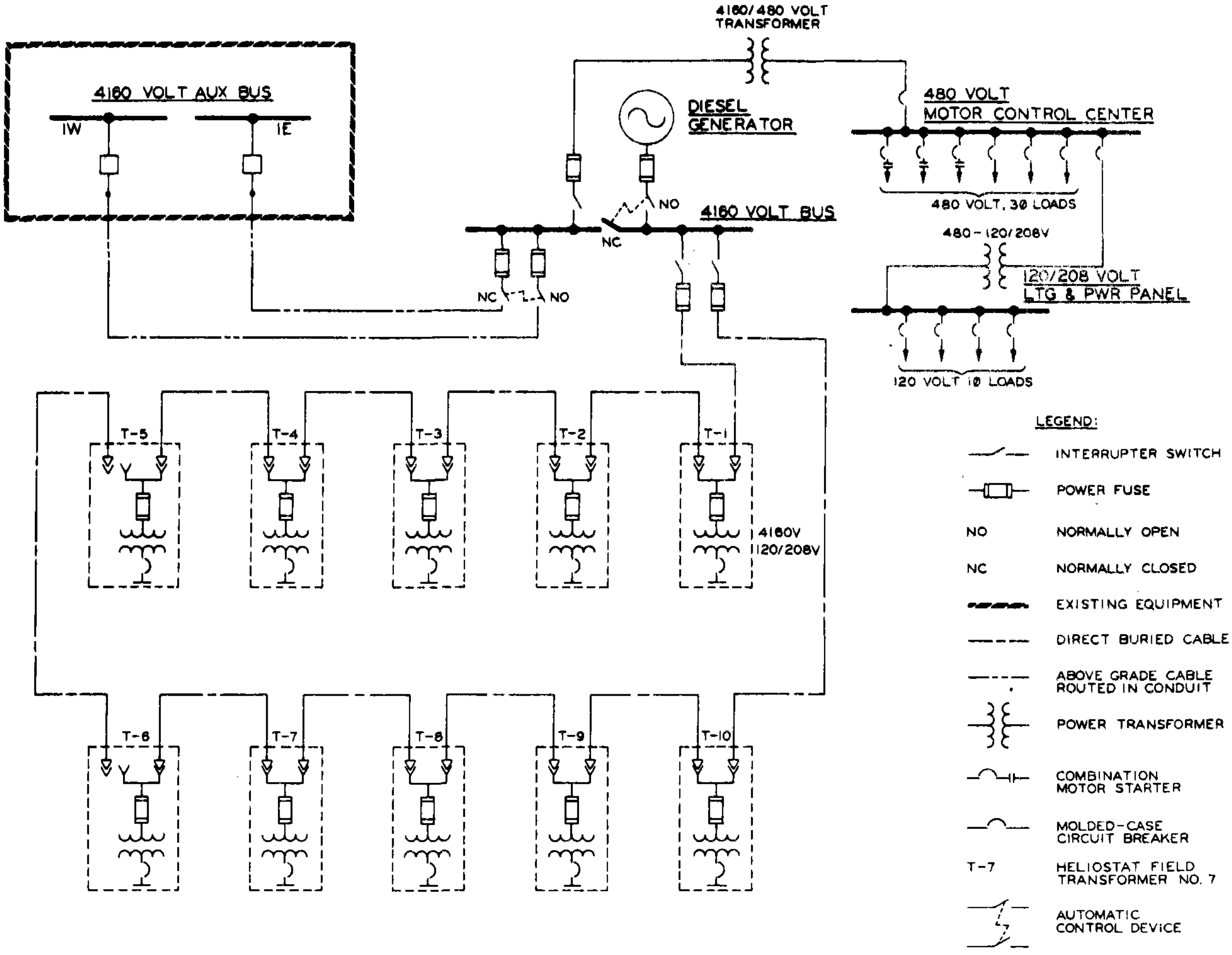


FIGURE 4-8. NORMAL PLANT AC POWER SUPPLY, ONE-LINE DIAGRAM

sources and will be supplied by a fast-start (10-second) diesel generator unit to be located near the solar tower.

Low voltage power at 480 volts will be distributed by two sections of a motor control center to be located at elevation 105.2 metres (345 feet) of the receiver tower. Normally all motors 100 horsepower and below and all motor-operated valves will be supplied with 480 volt power. A pad-mounted transformer will be located near the base of the tower which will feed power to this motor control center. The primary of this transformer will be connected by a feeder circuit to the 4,160 volt distribution switchgear.

All lighting, receptacle, and other small loads requiring 120 volt, single-phase will be supplied by a indoor dry type transformer and a lighting and power distribution panel.

4.4.4.2 Uninterruptible AC Power. The source of uninterruptible ac power supply will come from two full-capacity, redundant static inverters, as shown in Figure 4-9. Under normal operating conditions, each inverter will be supplying about half of the total uninterruptible ac power at 120 volts. In the event of an inverter component failure, a static switch transfers the inverter load to a regulated plant ac supply within 1/4 of a cycle. When the inverter supply is restored, the static switch automatically transfers the load back to normal status. A manual bypass switch is provided to transfer the load of one inverter to the other inverter. Thus, any one inverter can be taken out of service for maintenance purposes without power interruption to the load.

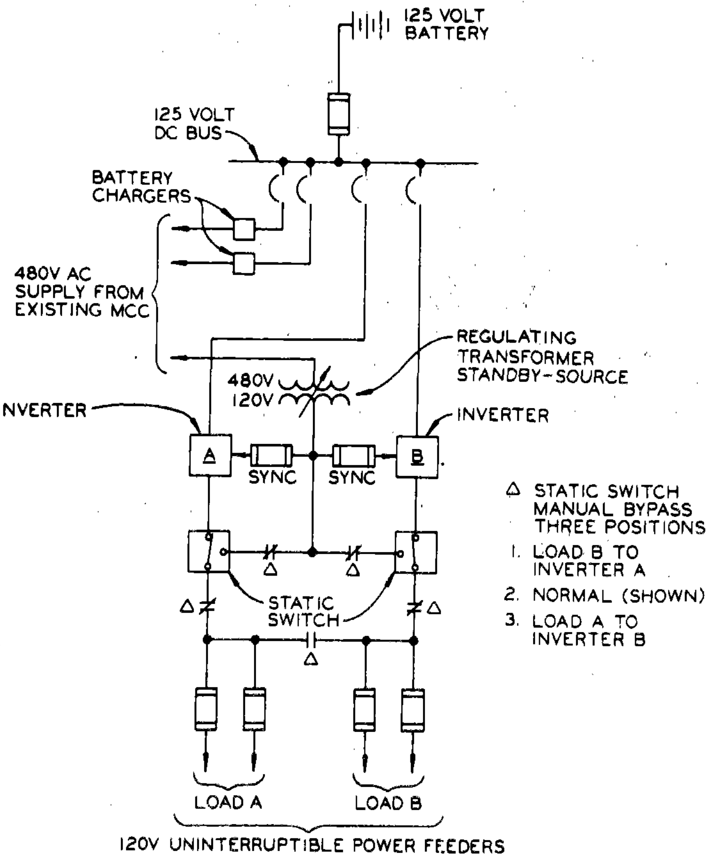


FIGURE 4-9. UNINTERRUPTIBLE POWER SUPPLY, ONE-LINE DIAGRAM

A dc input to the inverters will be provided by a 125 volt battery and two full-capacity, redundant battery chargers.

The uninterruptible ac power system equipment will be located at the main power plant.

4.5 SYSTEM PERFORMANCE

Design time point (noon, March 21) and annual system performance have been predicted using collector field efficiency data computed by the B&V optics codes, receiver efficiency data provided by B&W, and by characterizing the entire plant with the B&V computer code, STEPPE, Solar Thermal Electric Plant Performance Evaluator. The direct normal insolation was simulated using the ASHRAE Clear Air Model (discussed in Subsection 5.5.1 of the System Requirements Specification, Appendix A), with insolation modified with percentage sunshine data so as to include the effects of cloud cover. The annual average daily direct normal insolation resulting from this model was 5.35 kW/m^2, in close agreement with data interpolated from available insolation isopleth diagrams.[1, 2]

Figure 4-10 summarizes the design point and annual system performance, illustrating the relative sizes of various system losses. The design point solar-to-thermal efficiency (including field, receiver, and piping losses) is 69.3 per cent, resulting in 72.8 MW_t of steam power being delivered to the turbine. The annual average solar-thermal efficiency (including field, receiver, and piping losses, as well as receiver and piping heat-up requirements) is 56.9 per cent, resulting in 120 GWh_t of steam being delivered to the turbine by the solar system. This corresponds to an annual equivalent fuel displacement of 144 GWh_t.

The most significant losses for the solar-thermal conversion process, as seen in Figure 4-10, are the collector field reflectivity losses,

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[1] "On the Nature and Contribution of Solar Radiation," DOE Report HCP/T2552-01, Watt Engineering Ltd., March 1978, p. 202.

[2] "The Effects of Regional Insolation Differences Upon Advanced Solar Thermal Electric Power Plant Performance and Energy Costs," DOE Report DOE/JPL-1060-17, Jet Propulsion Laboratory, Pasadena, California, March 15, 1979, p. 19-31.

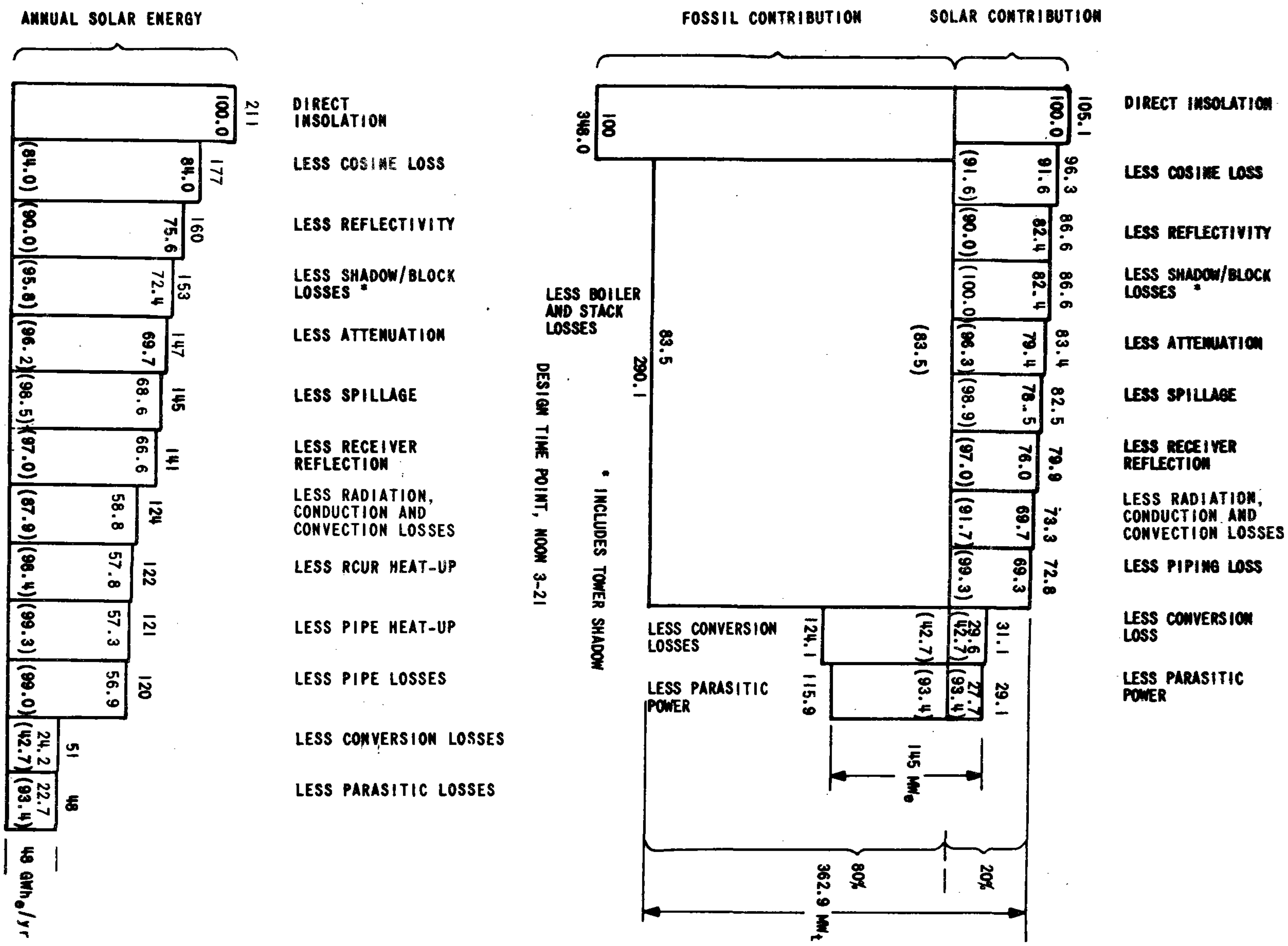

FIGURE 4-10. DESIGN TIME POINT AND ANNUAL SYSTEM EFFICIENCY STAIRSTEPS

cosine losses, and receiver thermal losses. A reflectivity of 90 per cent was prescribed by Sandia for this project and was therefore not further investigated. The collector field layout was designed using an optimization procedure aimed at maximizing annual energy redirected to the receiver; a small departure from the optimum heliostat location was required to obtain proper flux distributions on the east and west sides of the receiver. Within the constraints of proper receiver flux distributions, cosine losses have, therefore, been minimized. Receiver thermal losses, as well as reflective losses, have been reduced by the use of the screen tube design (discussed in Section 5.2), which creates a "psuedo cavity" effect, thereby increasing absorption and reducing convection losses.

The analysis in Figure 4-10 assumes that during solar operation, the plant is generating a net 145 MW_e. The design point solar contribution to this power generation is 29.1 MW_e, for a solar-to-electric efficiency of 27.7 per cent. The annual average solar contribution to power generator is 48 GWh_e, for an annual solar-to-electric efficiency of 22.7 per cent.

4.6 PROJECT CONSTRUCTION COST SUMMARY

This section contains the cost estimate for solar repowering of Northeastern Station Unit 1. The boundaries of the cost account categories are shown physically in Figure 4-11 and schematically in Figure 4-12. The estimate is summarized in Table 4-6 and Figure 4-13; the data supporting this estimate are given in Appendix A.

4.6.1 Basis of Cost Estimate

The project cost estimate is based on the following assumptions.

(1) The unit will be located near Oologah, Oklahoma.

(2) All costs in the estimate are expressed in January 1, 1980 dollars.

(3) Land, water supply system, transmission lines, and mobile equipment are not included.

(4) The receiver tower has a rock anchor short shell type foundation; heliostat foundations consist of drilled piers.

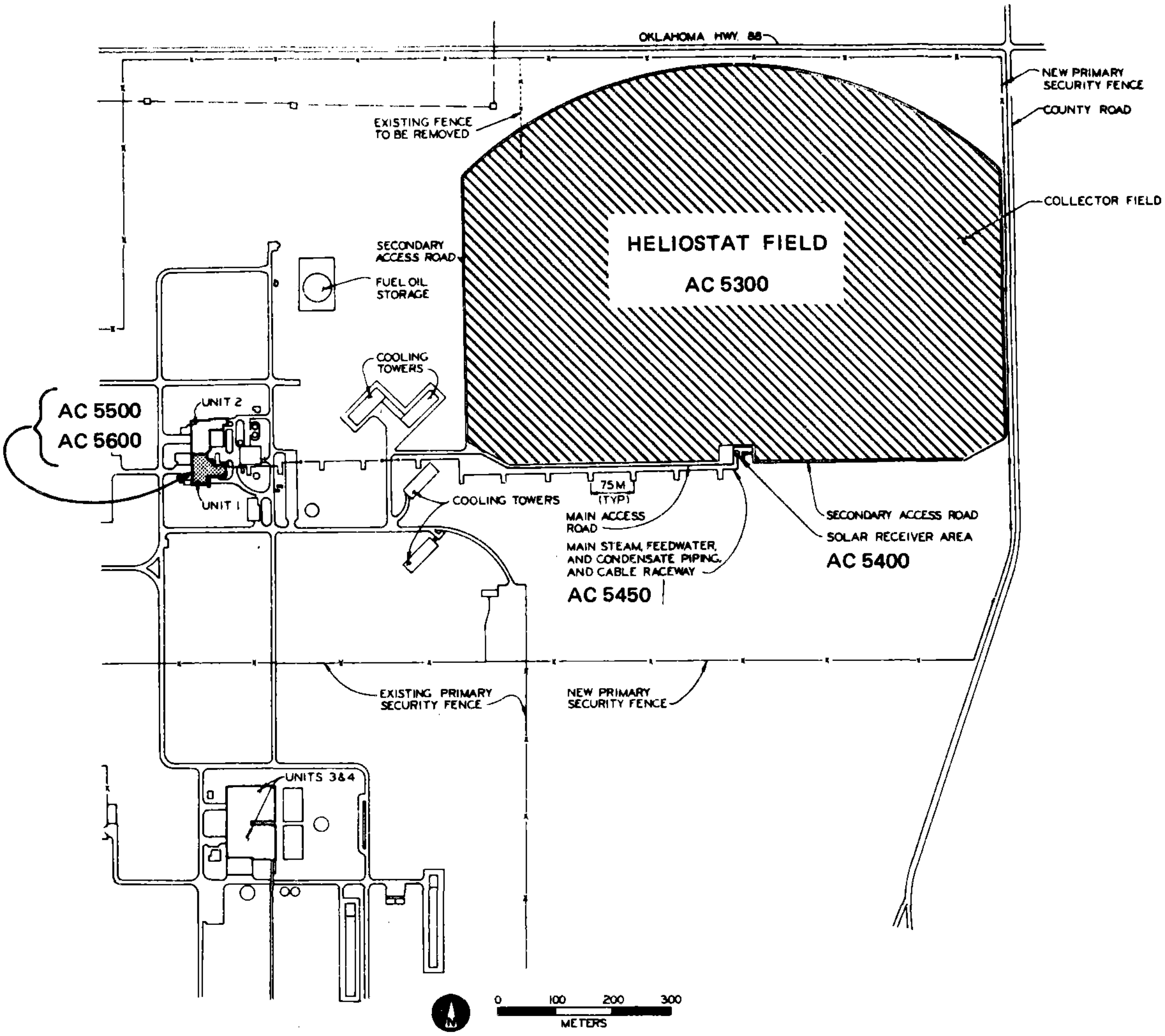

FIGURE 4-11. SITE ARRANGEMENT OF REPOWERED PLANT SHOWING COST ACCOUNT BOUNDARIES

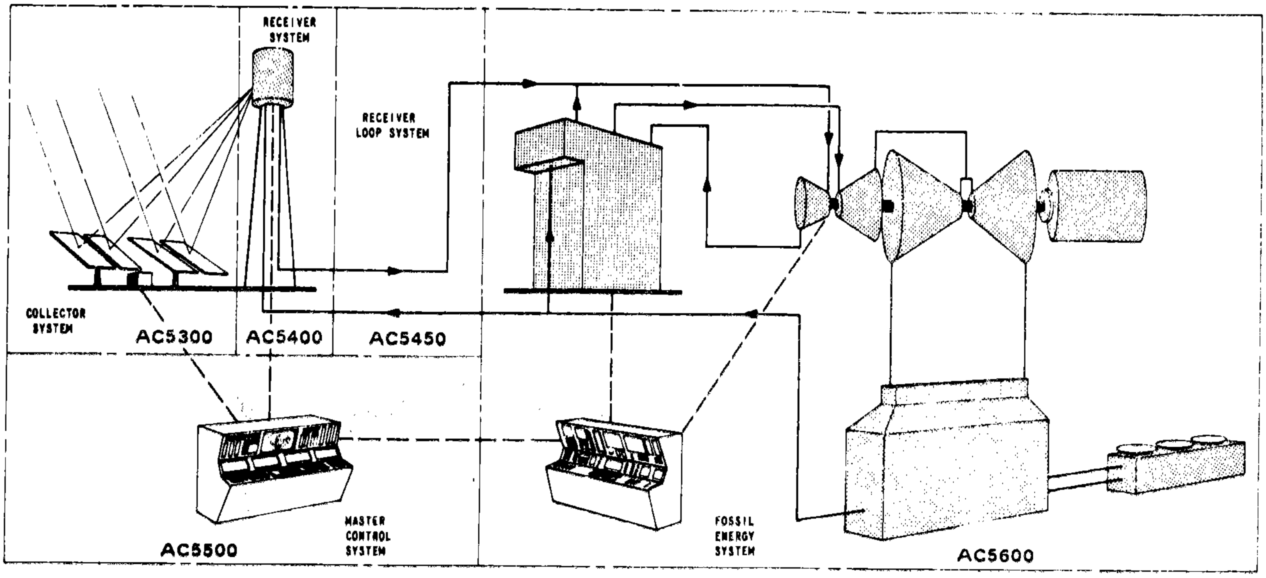

FIGURE 4-12. SOLAR REPOWERING SYSTEM SCHEMATIC SHOWING COST ACCOUNT BOUNDARIES

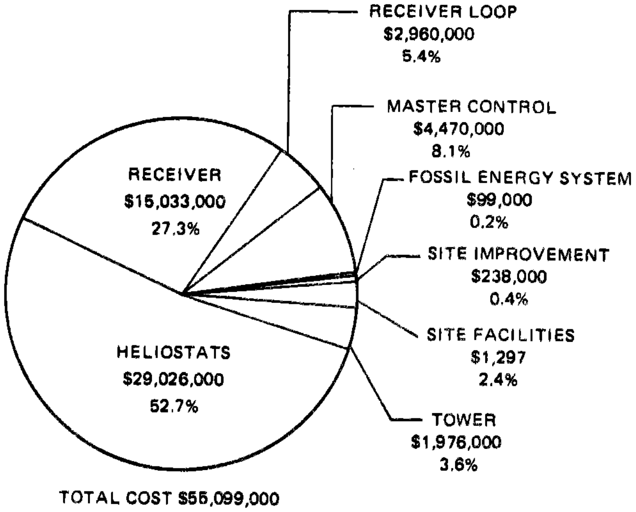

FIGURE 4-13. CONSTRUCTION COST ESTIMATE

(5) Labor costs are determined by man-hours multiplied by the appropriate craft rate; man-hour estimates are based on Black & Veatch experience involving similar tasks. Wage rates are based on the Tulsa, Oklahoma area.

TABLE 4-6. CONSTRUCTION COST SUMMARY (1980 $)

Account Number	Element Description	Construction Cost* Level 2	Level 1	Level 0
5000	Total Facility**	--	--	55,099
5100	Site Improvements	--	238	--
5200	Site Facilities	--	1,297	--
5300	Collector System	--	29,026	--
5310	Heliostats	28,770	--	--
5320	Other Costs	256	--	--
5400	Receiver System	--	17,009	--
5410	Tower	1,976	--	--
5420	Receiver	15,033	--	--
5450	Receiver Loop System	--	2,960	--
5451	Pipe Supports System	215	--	--
5452	Feedwater Piping System	613	--	--
5453	Main Steam Piping System	1,555	--	--
5454	Condensate Piping System	577	--	--
5500	Master Control System	--	4,470	--
5600	Fossil Energy System	--	99	--

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*Cost expressed in thousands of January, 1980 dollars.

**Total Facility Cost excludes owner's costs and operations and maintenance costs.

(6) A contingency of 10 per cent is included for all cost items calculated by Black & Veatch.

(7) The collector costs are based on unit costs supplied by Sandia. The receiver cost was estimated by Babcock & Wilcox. The tower cost is based on quantity takeoff and pricing of conceptual design data by Black & Veatch. The cost of the majority of the items included in the master control system were supplied by Bailey Controls Company. Other equipment and structure costs are based on power plant design projects recently completed by B & V.

4.6.2 Methodology

The methodology used to prepare the estimate is outlined by the following.

(1) Current design data are obtained for all items to be estimated.

(2) Quantity takeoffs of materials and/or a listing of equipment required for plant construction are prepared based upon a review of design drawings, design reports, and Black & Veatch experience.

(3) All cost items listed are priced based upon vendor quotations or recent Black & Veatch contract prices for similar tasks or items.

4.7 OPERATING AND MAINTENANCE COSTS AND CONSIDERATIONS

Knowledgeable estimates of operating and maintenance costs (those annual costs related to day-to-day operation of the plant, preventive maintenance, and repair of failures), are essential to the economic analyses of the repowered system. O&M costs contribute significantly to the cost of energy over the lifetime of the plant, and along with fuel costs, play a significant role in economic dispatch decisions once construction costs have been capitalized.

The O&M cost estimates for the solar portion of the repowered plant have been developed on a system-by-system basis. Each system was analyzed to identify key operational and maintenance requirements. Cost estimates for those requirements have been determined on the basis of

PSO and B&V experience, as well as by using available literature sources. In some cases, lack of operational experience has required an estimate based on engineering judgement.

The O&M cost estimate is shown in Figure 4-14. Table 4-7 gives a listing of the operations costs and of maintenance costs on a system-by-system basis. An expansion of this O&M cost table in Section 5.3 of Appendix A gives a further quantitative breakdown of the O&M items for each system, including estimated man-hours for various maintenance requirements. The following subsections will, therefore, discuss the identified O&M requirements in a primarily qualitative manner. Maintenance requirements will be discussed on a system-by-system basis.

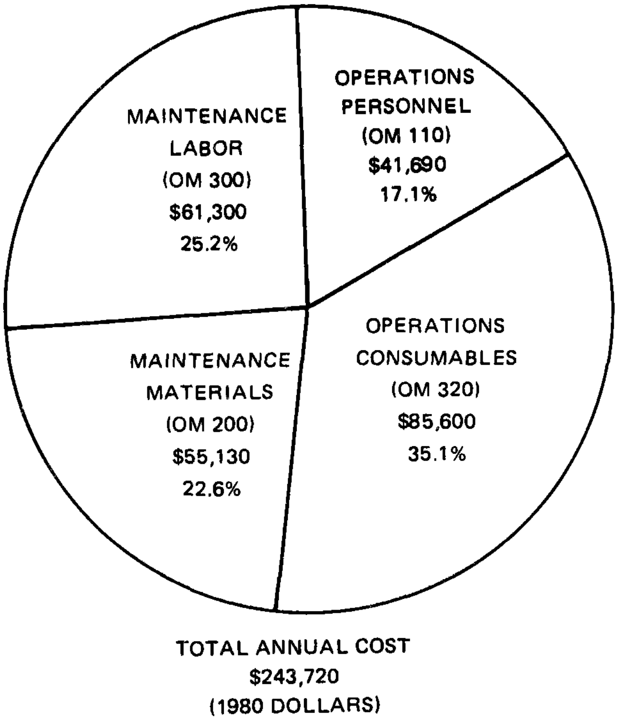

FIGURE 4-14. OPERATING AND MAINTENANCE COST ESTIMATE

4.7.1 Operations

Operating costs are divided into two categories, personnel requirements and consumables. Because operation of the solar system will be largely automated and, in addition, will be integrated into the total

TABLE 4-7. ANNUAL OPERATIONS AND MAINTENANCE COSTS (1980 DOLLARS)*

Operations

Personnel	$ 41,690
Consumables	$ 85,600
Total	$127,290

Maintenance

System	Maintenance Materials $	Scheduled Labor $	Unscheduled Labor $	System Total $
Site	--	1,350	--	1,350
Site Facilities	--	5,000	--	5,000
Collector	25,500	30,920	13,780	70,200
Receiver	13,050	4,360	2,240	19,650
Receiver Loop	4,250	740	890	5,880
Master Control	3,000	230	1,790	5,020
General	9,330	--	--	9,330
Total	55,130	42,600	18,700	116,430

Total O&M Cost:	$243,720

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*An expansion of O&M costs is given in Section 5.3 of the SRS.

plant operation, control room staffing for the solar system will consist of the equivalent of one man giving 50 per cent attention to solar system controls. Two roving plant operators will give full attention to the solar system.

Included in operating considerations are those materials consumed in day-to-day plant operation. Three major consumables have been identified.

- Nitrogen, used in blanketing the receiver drum and superheater to prevent oxidation following cooldown. This process is discussed in Section 5.2.
- Makeup water for boiler blowdown.
- Water treatment chemicals.

Of these three consumables, nitrogen comprises the vast majority of the cost.

4.7.2 Maintenance

Maintenance of the solar system will include scheduled maintenance (e.g., heliostat washing and preventive maintenance on pumps) and unscheduled (or corrective) maintenance. The following subsections will discuss these activities for each system.

4.7.2.1 Site. Site maintenance is expected to be minimal. The heliostat field area will be mowed about three times a year to facilitate access of maintenance vehicles to the heliostats and to prevent possible shading of heliostats or fouling of heliostat drive mechanisms.

4.7.2.2 Site Facilities. Most of the site facilities (e.g., control room and maintenance shops) for the repowered system are the same as for the existing system. As such, only minimal scheduled maintenance activities related solely to the solar system are anticipated.

4.7.2.3 Collector System. The largest portion of scheduled maintenance for the collector system will be heliostat washing. Three methods of washing have been identified: mobile high-pressure spray, mobile spray and brush, and a permanently fixed individual heliostat washing system. The high-pressure spray method has been chosen as the most appropriate for this sytem. It is assumed that heliostats will be washed 12 times per year. Other scheduled maintenance activities will include a semi-annual, walk-through inspection of heliostats for any signs of deterioration.

Lack of experience with large, continuously operating heliostat fields makes estimation of unscheduled maintenance for the collector system more uncertain than for other, more conventional systems. Components which can experience failure include electronic modules in the controllers, drive motors, and drive mechanisms. In most cases, repairs will be made by replacing faulty components with spares; the faulty components will be either repaired or new spares purchased in order to maintain a sufficient spare part inventory. More major maintenance tasks such as replacement of mirror facets are expected to be infrequent.

The estimated costs for collector field maintenance are in close agreement with estimated annual maintenance costs (after the first year in use) for the prototype heliostat with annual productions of 25,000 units per year.* This estimation is based on the rationale that maintenance annual costs will follow the expected learning curve and production rate cost curve rather than remaining at the cost level corresponding to low heliostat production.

4.7.2.4 Receiver System. Scheduled maintenance for the receiver system will be similar, in most respects, to that of conventional steam generators. The boiler drum will be opened annually to allow inspection for signs of deterioration. Likewise, the boiler, superheater, and economizer tubes will undergo annual visual inspection; this inspection will be scheduled to coincide with the annual repainting of the heat absorption surfaces so as to reduce the number of times scaffolding must be erected. The extent of repainting which will be necessary with the black Pyromark paint is not known; the cost estimate assumes total repainting each year.

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*"Solar Central Receiver Prototype Heliostat CORL Item B.d.", Final Technical Report, McDonnell Douglas Astronoutics Company, Report Number MDC G 7399 Volume I, August, 1978, 9-4.

Additional conventional aspects of scheduled receiver maintenance include packing of valves, routine pump maintenance, and recalibration of controls. Because these maintenance tasks can be accomplished from the interior of the receiver, they present no unusual requirements.

Unscheduled maintenance of the receiver will be minimized by the scheduled maintenance plan. Inevitably, failures in such components as valves and controllers will occur. Because these maintenance tasks are not unusual in a power plant, specialized skills and equipment will not be required. Failure of boiler, superheater, and economizer tubes is not expected in the lifetime of the system; the absence of corrosive combustion products interacting with tube surfaces is expected to reduce deterioration levels of these solar receiver components to below those of fossil boilers. However, the long lead time for superheater tubes (approaching a year), as well as the need for factory fabrication of the superheater panels, has resulted in the decision to purchase two spare panels. The costs for these panels ($200,000 each) is included in the capital cost estimates in accordance with PSO procedures. Similarly, a spare motor (cost: $190,000) for the circulating water pump has been included in the capital cost estimates because of a long replacement lead time.

4.7.2.5 Receiver Loop System. The receiver loop system is expected to have minimal maintenance requirements. The major capital cost item of the receiver loop will include semi-annual inspection of the piping and pipe supports, packing of valves, routine pump maintenance, and recalibration of controls. Unscheduled maintenance will include the repair or replacement of valves and pumps.

4.7.2.6 Master Control System. Scheduled maintenance for the master control system will be minimal, being limited primarily to occasional lubricating and cleaning of the printer. The moving head disc will require refurbishing every 5 years. This procedure, involving only a few man-hours of labor, will require replacement of the disc with a spare; the original will then be returned to the manufacturer for refurbishing. Unscheduled maintenance will make up the majority of master control system maintenance requirements. A fairly large inventory of spare computer electronic modules will be maintained to allow rapid repair of computer failures. Replaced modules will be shipped to the manufacturer for repairs, or replacement parts will be purchased. Printer and disc failures are expected to constitute a smaller fraction of the unscheduled maintenance requirements.

4.7.2.7 General. Maintenance material requirements for specialized equipment (e.g., maintenance vehicle), materials for general repairs (e.g., welding rods), and other maintenance consumables (vehicle fuel) have been included in the "General" category in Table 4-7.

4.8 SYSTEM SAFETY

Safety requirements for a power plant are established by a large number of applicable codes, standards, and regulations; they include the Occupational Safety and Health Administration (OSHA), the American National Standards Institute (ANSI), the National Electrical Manufacturers Association (NEMA), the ASME Boiler and Pressure Vessel Code, the Power Piping Code, the American Concrete Institute, the American Institute of Steel Construction, and other applicable federal and state regulations. Because of the water/steam nature of the repowering design for NES I, the system safety requirements are, except for collector field-related considerations, similar to a conventional fossil fuel power plant. The three basic categories of safety concerns, construction safety for personnel and equipment, operational safety for personnel and equipment (plant protection), and public safety, can be adequately controlled by conscientious design, safety features, careful construction techniques, and procedural controls.

4.8.1 Construction Safety

Normal good construction practices would be applied to the repowering plant; typical practices would include controlled personnel access to the construction site and to specific areas, regular inspection of construction equipment such as hoists and elevators, clearance areas at the tower base for falling objects, and the tethering of personnel working on the receiver tower. Special procedures and precautions would be developed to ensure proper heliostat control during installation, thus, avoiding the dangers of stray radiation burns for personnel working on the tower and of temporarily blinding personnel due to heliostat glint or glare. Special precautions will also be required during the interfacing of the Receiver Loop System with the Fossil Energy System; the dangers of the high energy steam in the existing steam line must be eliminated either by shutting down the existing NES I boiler for a period or by closing isolation valves. The temporary plant shutdown is the most probable method.

4.8.2 Operational Safety

Operational safety in a unit requires that both personnel safety and plant safety concerns be addressed. Personnel safety is monitored by a variety of design features and procedural methods. For example, heliostat maintenance could be preferentially scheduled for non-daylight hours, thus, eliminating the remote hazards of glint and burns. Alternately, daylight maintenance is not unreasonable when employing precautions, such as the wearing of dark eyeglasses to mitigate visual hazards and the disabling (opening the power circuit breaker) of heliostat-tracking mechanisms when servicing heliostats to prevent their movement. Personnel safety concerns may also result in upper portions of the receiver tower being declared off-limits during plant operation, although the location of the elevator within the tower shell affords adequate protection for many access requirements.

Additional personnel protection accrues as a result of good design practice and adherence to codes and standards. For example, stairwells are provided as a backup to elevators, with handrails and toe guards provided on platforms. and stairs as appropriate. Instrumentation and sensors are installed with isolation valves and instrument wells such that personnel can maintain these devices without exposure to steam or the need to shut down the plant.

Other design features include thermal insulation on piping (e.g., the Receiver Loop System) adequate not only to reduce thermal losses in a cost effective manner, but also to reduce temperatures below critical flesh burn levels. When condensate traps, drain lines, and/or vents are necessary design elements, care is taken to ensure that the discharge is contained and/or directed away from possible personnel locations.

Plant safety is also a critical aspect of system operational safety. The total system must be designed so that component or system failures inflict minimal resultant damage elsewhere. A key consideration for the repowering design is receiver/collector system failure. The receiver design concept and margins are such that nearly any possible collector system flux pattern (e.g., field power is lost, so the sun image drifts across the receiver with sun movement) can be accepted without damage, so long as the receiver circulating pump remains in operation. Alternately, should the receiver circulating pump fail, no receiver damage will occur if the heliostats are promptly defocused (<30 seconds). This capability is assured by providing a collector system backup power supply via an emergency power diesel generator. With these design features, fail-safe conditions are achieved, and the probability of coincident receiver/field failures becomes very small. Isolation valves on the Receiver Loop System provide the capability to interrupt feedwater or main steam flows if critical problems develop, thereby protecting the balance-of-plant.

4.8.3 Public Safety

The only solar-unique hazard to the public associated with a repowered NES I is collector system glare/glint and burn potentials. The possibility for burns is very remote due to the presence of a fence about the heliostat field perimeter, the long focal length of the heliostats, and the requirement for several heliostat beams to be coincident on a surface before dangerous radiation levels are developed. Slats in the perimeter fence will mitigate the glint/glare problems that might impact pedestrian or vehicular traffic.

Other safety hazards and control measures would be similar to those in existing power plants. The receiver tower presents an aviation obstacle, but it is similar to exhaust gas stacks and would include aircraft warning lights. Hot surfaces and high-pressure piping have some degree of inherent danger, but existing codes and standards successfully control these risks. Hazards regarding the use of chemicals for water treatment, construction, etc, and the potential contamination of ground water, soil, or air exist, but similar materials are in current use at NES I and elsewhere; many regulations regarding the use of such materials exist, including the Toxic Substances Control Act. An additional potential safety hazard for the repowered NES I would be the possible application of herbicides or dust control materials to the collector field, though this is not foreseen as a serious hazard.

On balance, the water/steam repowered NES I safety should be high. No severe or unusual safety issues such as the use of sodium or eutectic salts have been identified. Good design and operational practice, coupled with existing codes and standards, are expected to result in a plant compatible with the needs of construction, operational, and public safety.

4.9 PROJECT ENVIRONMENTAL IMPACT ESTIMATE

The environmental impact of the solar repowered plant is discussed in the following paragraphs in terms of construction and operation impacts; both positive and negative aspects are described.

4.9.1 Construction Impacts

Construction of new facilities required for solar repowering of the Northeastern Station Unit I may impact the local environment in several ways. These impacts range from socioeconomic changes to increases in noise and dust levels. However, given proper planning, the total effects of these impacts should be small.

Approximately 30 construction workers will be working at the site during the peak construction period. If these workers are hired locally or commute to the job site, the socioeconomic impacts will be small, although income levels and traffic patterns may be slightly affected. If construction workers move to the area, the socioeconomic effects may be slightly greater; an increased demand for goods and services in the area will result.

Dust and noise may increase, and rainfall runoff patterns may be adversely affected during plant construction. The primary source of the adverse effects will be construction of the receiver tower, access roads, and heliostat foundations. However, since the area under the heliostat field will not be graded or covered by asphalt, no large area impacts are anticipated. Additionally, since the plant site is removed from any population centers, noise level increases should not be greatly noticed.

The presence of construction equipment at the job site may be aesthetically displeasing. Also, the transportation of construction equipment to and from the site may temporarily affect traffic.

Birds, insects, and wildlife will be dispersed from the plant site during construction. Trees and shrubs will be removed from the site and the grass will be cut; however, since the site is presently largely grassland used for cattle grazing, these effects should be small.

4.9.2 Operation Impacts

Operation of the solar repowered plant will produce both beneficial and detrimental environmental impacts. Beneficial impacts arise from the decreased combustion of fossil fuels. Detrimental impacts arise from the use of a large land area for the heliostat field.

Because solar energy will be used to provide a portion of NES Unit I's thermal input power, less natural gas or oil will be required. Therefore, fewer combustion products will be emitted from the plant. Additionally, the secondary environmental impacts of natural gas production, processing, and delivery will be reduced.

Also, since Federal law (Power Plant and Industrial Fuel Use Act of 1978) restricts the use of natural gas for electric power generation in future years, PSO may be required to use an alternative fuel for power generation if solar energy was not used. Therefore, the environmental impacts associated with coal or nuclear power generation will be avoided.

In addition to beneficial environmental impacts, several detrimental environmental impacts will result from plant operation. Operation of the solar repowered plant may require a few additional workers at the plant site, the socioeconomic impacts of these few workers should be small, and negative impacts will be offset by the increased assessed value of the plant.

Dust levels, noise levels, and rainfall runoff patterns should not be significantly affected by plant operation. The land under the heliostat field will not be covered; the natural grass will be allowed to remain. Although the vegetation and soil within the heliostat field will receive less sunlight than ordinarily received, no significant change is anticipated. Operation of the heliostats and equipment within the receiver tower should not produce noticeable noise levels.

The receiver tower may be aesthetically displeasing to some. However, the uniqueness of the structure and its remoteness from population centers and heavily used highways should minimize any adverse reactions.

Use of the land for the plant will reduce rangeland acreage. Currently PSO leases the land for seasonal pasture. However, since only a few dozen cattle are grazed on the land, this effect should be small.

Effects on insects and wildlife should be small. After dispersal during construction, insects and small wildlife will be able to move back onto the plant site. Effects on birds are more difficult to anticipate, but flying into the focal zone or into the heliostat's reflective surface will probably destroy the birds. Migratory birds may fly into the receiver tower at night or during fog.

Construction of the plant will require the draining and filling of one stock pond and the destruction of its aquatic habitat. However, other stock ponds are plentiful in the area, and no destruction of rare or endangered species will occur.

Besides the hazard to birds, reflected sunlight from the heliostats may cause eye damage, or skin burns to plant personnel. This danger has been estimated to be most severe to personnel in the receiver tower near the focal zone and less severe for personnel on the ground within the heliostat field. For people on the ground outside of the plant site, danger is minimal. The chance of eye or skin damage to persons flying over the heliostat field is also minimal, assuming required clearances are observed.

4.10 INSTITUTIONAL AND REGULATORY CONSIDERATIONS

A number of federal and state laws and regulations govern the design/ operation of power plants. The following paragraphs summarize some of the major federal legislation which affects electric system planning and design decisions.

- The National Energy Conservation Policy Act provides for numerous grants and loans programs, which are aimed at stimulating public and private efforts to improve energy efficiency. These programs include weatherization grants for low-income families, grants for schools and hospitals, loans for installation of residential solar facilities, and loans for home improvements which improve energy use. Additionally, this law requires utilities to implement programs providing energy audits for their residential customers and advice on installation and financing of appropriate conservation measures. The act also requires the establishment of energy efficiency standards for certain buildings, industrial equipment, and large home appliances.
- The Power Plant and Industrial Fuel Use Act of 1978 expands the authority of DOE programs, which are aimed at replacing the use of natural gas and petroleum in power plants and industrial installations with alternate fuels, especially coal. The act basically prohibits the use of natural gas and petroleum in existing and new boilers after 1990 and restricts their use in years prior to this. Certain exemptions to these prohibitions are available upon demonstrating the infeasibility of using alternate fuels. Minor provisions of the act provide funding for reducing the negative impacts of increased coal production and for railroad rehabilitation.
- The Public Utility Regulatory Policies Act of 1978 establishes programs to encourage conservation and efficient energy use

through rate structures. This legislation sets forth 11 standards for rate design and other utility practices which must be considered by state regulatory authorities and nonregulated utilities. Other provisions include a hydroelectric development load program, authority for FERC to require system interconnections, and authority for favoring industrial congeneration facilities in the buying and selling of electric power.

- The Natural Gas Policy Act of 1978 implements a program for phasing out price controls on the first sale of natural gas over the next 7 years. Its purpose is to negate the price differential between previously regulated interstate sales and largely unregulated intrastate sales. Basically, the program allows for monthly increases in the ceiling prices of natural gas so that the cost of using natural gas compared to other fuels more equitably reflects the economics of energy use. The act also implements programs for distributing price increases across various use sectors, for protecting essential uses of natural gas such as in agriculture, and gives the President authority to allocate supplies during a natural gas emergency shortage.
- The Energy Tax Act of 1978 contains a number of incentives designed to achieve greater energy conservation and investment in alternate energy sources. Included in the legislation are tax credits for residential insulation and conservation measures, residential solar use, business investment in alternate energy facilities, development of geothermal resources, and the exemption of gasohol from excise duties. Negative incentives include a tax on gas guzzling automobiles and denial of investment tax credit and accelerated depreciation on new oil- or gas-fired boilers.

4.10.1 Permits and Licenses Required

The required clearances from federal and state administrative agencies are listed below.

- Oklahoma Department of Labor. Pressure Vessel Permit and Inspection.
- Oklahoma Department of Labor. Notice of Intent to Construct.

Furthermore, the EPA (under requirements of the National Environmental Policy Act) may require the preparation of an Environmental Assessment and, possibly, an Environmental Impact Statement before federal funds can be allocated to the project.

In addition to the above authorizations, there are several permits which might be required for the project. The following list consists of the relevant agency, the clearance, and what action would necessitate obtaining the clearance.

- United States Environmental Protection Agency. Wastewater Discharge (NPDES) Permit required if there is any change in the quantity or content of the existing discharge.
- Federal Aviation Administration. Approval of structure over 61 metres (200 feet) tall.
- Oklahoma State Department of Health. Open Burning Restrictions (Regulation 1) compliance required if open burning used during land clearing activities. The emergency diesel generator may require an air permit.
- Oklahoma Water Resources Board. Water Appropriation Permit required if there will be any increased use of ground water or surface water.

4.10.2 Air Quality Control Standards

Federal and state air quality control standards are described in abbreviated form below. These standards govern both ambient air and plant emissions. It should be noted, however, that since the solar repowering design will reduce the combustion of oil and gas, plant emissions levels will be beneficially affected.

4.10.2.1 Ambient Air Quality Standards.

- Federal Standards. The Environmental Protection Agency (EPA) has identified seven air pollutants which have an adverse effect upon public health or welfare and has issued air quality criteria for them. The seven air pollutants are as follow.

(a) Sulfur Oxides
(b) Particulate Matter
(c) Nitrogen Oxides
(d) Carbon Monoxide
(e) Photochemical Oxidants
(f) Hydrocarbons
(g) Lead

The combustion gas produced by a fossil fuel-fired steam generator may include sizable quantities of sulfur oxides, particulate matter, and nitrogen oxides. Since other pollutants will appear only in insignificant quantities, only those three pollutants will be discussed. The national primary and secondary ambient air quality standards applicable to the Northeastern Station are as follow.

	3-Hour Average* mg/m^3 (ppm)	24-Hour Average* mg/m^3 (ppm)	Annual Average** mg/m^3 (ppm)
Sulfur Dioxide			
Primary Standard	--	365 (0.14)	80 (0.03)
Secondary Standard	1,300 (0.50)	--	--
Particulate Matter			
Primary Standard	--	260	75
Secondary Standard	--	150	60
Nitrogen Dioxide			
Primary Standard	--	--	100 (0.05)
Secondary Standard	--	--	100 (0.05)

---

*The maximum 3-hour and 24-hour concentrations are not to be exceeded more than once during a year.

**The annual average for particulate matter shall be computed as a geometric mean, whereas the annual average for sulfur and nitrogen dioxide shall be computed as arithmetic means.

- Oklahoma Standards. The Division of Air Pollution Control of the Oklahoma State Board of Health adopted ambient air quality standards on December 4, 1976 which are identical to those promulgated by EPA for sulfur dioxide, particulate matter, and nitrogen dioxide.

4.10.2.2 Emission Limitations. There are no federal emission limits applicable to NES I. However, the Oklahoma Department of Health Regulations has established emission limitations for particulate matter, visible emissions, hydrocarbons, sulfur oxides, carbon monoxide, and nitrogen oxides, applicable to all existing sources. Since emissions from fossil fuel steam generators do not include significant quantities of hydrocarbons or carbon monoxide, these will not be summarized. An existing source which is altered, replaced, or rebuilt in such a manner that its air contaminant emisssions are increased is designated as a new source under Oklahoma Regulation 3. Since the Solar Repowering Project would not cause an emissions increase at NES I, the unit will continue to be subject to the emission limitations applicable to existing units. These emission limitations are summarized below.

- Particulate Emission Limitations. Particulate emission rates from fuel-burning equipment are governed by Oklahoma Regulation 6, which includes a graph showing a decreasing emission limit, expressed in pounds per million Btu, for boilers rated between 1 and 1,000 million Btu per hour heat input. The emission limit versus unit size is calculated using the following equation.

  $$\log_{10} Y = 0.25938 \log_{10} X + 0.03753$$

  where Y = particulate emission rate (lb/MBtu heat input)

  X = heat input rate (MBtu/h heat input)

  Oklahoma Regulation 7 limits the opacity of emissions to 20 per cent. However, the regulation allows deviations from the 20 per cent standard during the cleaning of a fire, building of a new fire, soot blowing, or other short-term occurrences. These deviations are limited to emissions of up to

60 per cent opacity for periods aggregating no more than 5 minutes in any 60 consecutive minutes or more than 20 minutes in any 24-hour period.

- Sulfur Dioxide Emission Limitations. Oklahoma does not impose a uniform sulfur dioxide emission rate limitation on existing fuel-burning sources. Instead, the maximum sulfur dioxide emission rate for each facility cannot exceed that required to prevent that source's ground level impact outside the property of the owner/ operator from exceeding the following time dependent ambient concentrations.

Time Period	Maximum Allowable Impact
	mg/m^3
5 minutes	1,350
1 hour	1,200
3 hours	650
24 hours	130

- Nitrogen Oxide Emission Limitations. Oklahoma has not established any nitrogen oxide emission rate limitations applicable to existing sources.

5.0 SYSTEM CHARACTERISTICS

The repowered plant, presented in an integral manner in Section 4.0, is described in this section on a system-by-system basis; that is, for the purposes of this section, the plant is divided into collector, receiver, receiver loop, master control, and fossil energy systems. The physical location of the five plant systems are shown in Figure 5-1. As the figure illustrates, the collector, receiver, and receiver loop systems are to the east and north of Unit 1; whereas, the master control and fossil energy systems are coincident with the existing Unit. Each of these systems is described in terms of its major components, functional requirements, design, operating characteristics, performance, and cost estimates. Additional information on each system is presented in the SRS.

5.1 COLLECTOR SYSTEM

The collector system for the repowered facility consists of 2,255 heliostats, along with the associated controllers and power distribution network. These heliostats are located north of the receiver tower in an area which covers 5.1 X $10^5 m^2$ (126 acres). This section of the report addresses the following topics related to the collector system design.

- Functional requirements.
- Receiver interface.
- Land constraints.
- Heliostat description.
- Field layout.
- Operation and control.
- Performance.
- Cost estmiates.

5.1.1 Functional Requirements

The design of the collector system is subject to a number of functional requirements, which relate to interfaces with other systems as well as to siting and climate considerations. Included in the functional requirements are the following.

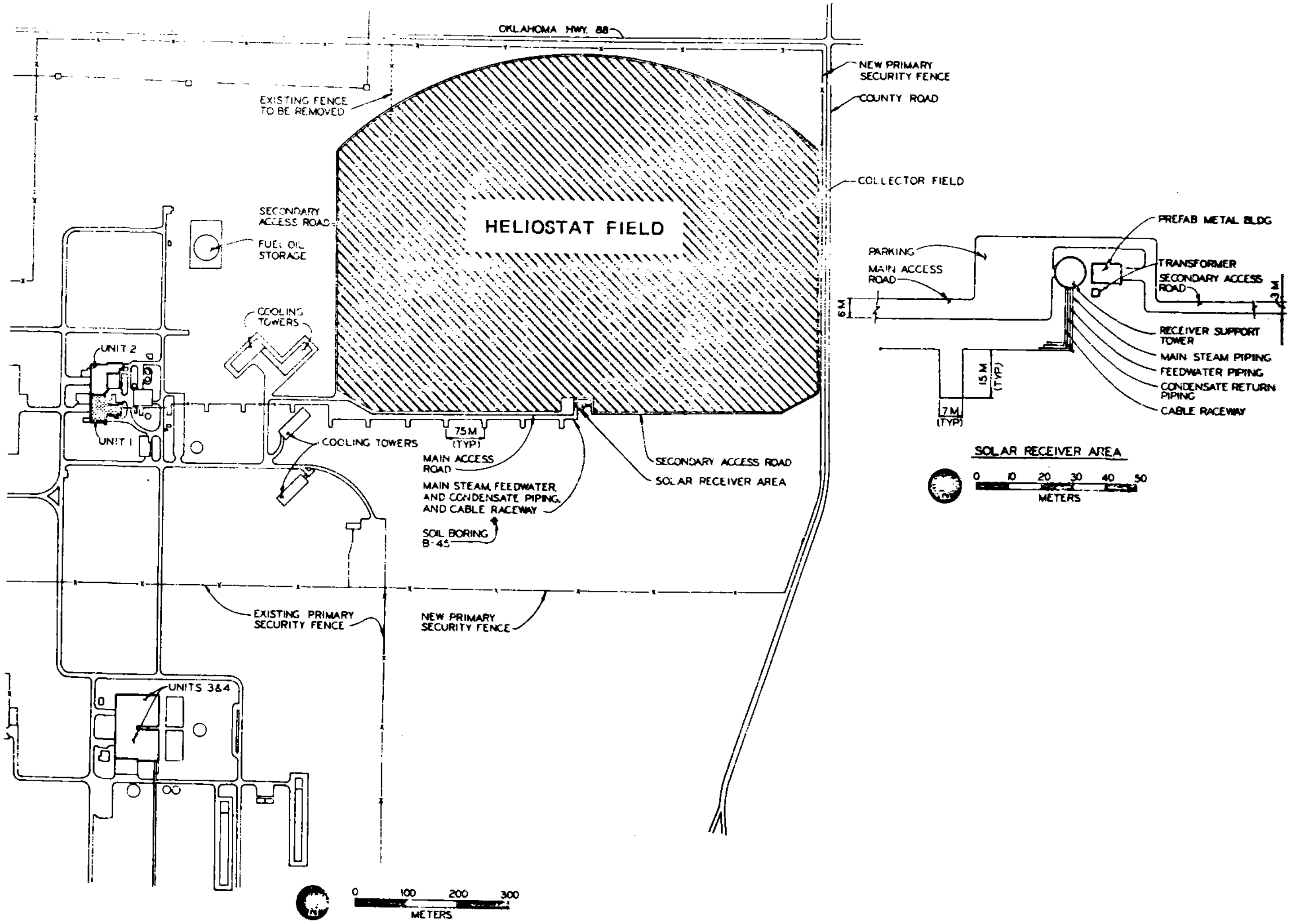


FIGURE 5-1. SITE ARRANGEMENT-NORTHEASTERN STATION SHOWING HELIOSTAT FIELD

- The design point power redirected to the receiver must result in 73.3 MW_t delivered to the working fluid.
- Annual energy redirected to the receiver per unit mirror area is maximized within constraints of available land shape and receiver flux distributions.
- Proper flux distributions on the receiver, resulting in material temperatures within design limits, must be maintained.
- Control of heliostats must allow diverse generations including normal tracking, start-up, shutdown, emergency shutdown, standby, and defocusing of select portions of the field.
- Heliostat foundations must provide rigid support for accurate beam direction, and have the capability to withstand extreme winds.

5.1.2 Receiver Interface

The results of the trade studies described in Section 3.1 led to the selection of an external receiver as the preferred system concept. The receiver itself is cylindrical in shape, 15.2 m (50 ft) tall, 9.4 m (31 ft) in diameter, and centered 124 m (407 ft) above the ground. The collector field occupies an area north of the receiver support tower, and redirects sunlight to heat transfer panels covering a 240-degree segment of the receiver cylinder. The collector/receiver is sized to deliver a total of 73.3 MW_t to the working fluid at March 21 noon, the design point.

5.1.3 Land Constraints

As illustrated in Figure 5-1, the width of the collector field is limited by the Units 1 and 2 cooling towers to the west, and by a roadbed to the east. In order to minimize the degradation of mirror reflectivity caused by precipitation from the cooling towers, the final design is constrained to an area 880 m (2,887 ft) wide, placing the western boundary at least 60 m from the cooling towers and leaving approximately 20 m (66 ft) at the eastern boundary for security fencing and a secondary access road. Studies indicate that the narrow field constraint affects the total mirror area requirement and annual performance by less than 0.5 per cent.

5.1.4 Heliostat Description

The baseline heliostat, which is the second generation heliostat developed in the DOE Heliostat Development Program, consists of 12 curved mirror panels attached to a single frame, with a total glass area of 49 m^2 (528 ft^2). The panels are adjusted on the frame (canted) to form an overall heliostat curvature which serves to reduce the beam size at the receiver. For the purposes of this study, it was assumed that the focal length of the panels and the focal length formed by on-axis canting were both equal to the heliostat slantrange, the distance from heliostat to target. On-axis canting refers to the perfect focusing of a heliostat when the sun, target, and heliostat lie on the same line.

Heliostat steering is accomplished by two ac motors driving the azimuth and elevation positions separately. The heliostat frame and drive motors are supported by a single pedestal attached to a concrete foundation. Below grade, the foundation is constructed as a drilled pier socketed into the competent limestone. Above grade, the pedestal is constructed as a circular column. A reinforcing cage extends the full height of the foundation. The dimensions and design forces are based on data produced for the second generation heliostat design in the DOE Heliostat Development Program.

5.1.5 Collector System Layout

The final collector field layout was developed through an optimization procedure that determined the number of heliostats required to meet the design point power requirement, and positioned those heliostats to maximize the annual energy collected per unit of mirror area. In other words, the field was optimized for annual rather than design point performance, but it was sized to deliver rated power at the design point.

The collector field layout resulting from the optimization procedure contains a total of 2,255 heliostats occupying an area of 5.1 x $10^5 m^2$ (126 acres), as illustrated in Figure 5-1. Heliostats are located in 48 circular arcs surrounding the receiver support tower, with the inner row 93.8 m (308 ft) and the outer row 640 m (2,100 ft) from the tower center line. Heliostats are located in a staggered pattern formed by circular arcs and diverging radial lines; the staggering arrangement allows close packing with a minimum of optical interference (blocking) among heliostats.

Because heliostats are located on diverging radial lines, the lateral spacings of heliostats within the rows ($rd\theta$) increase with distance from the tower. When the lateral separation becomes unacceptably large, the angular separation between radial lines is reduced by a factor of 0.75, causing the periodic readjustment in lateral separation shown in Figure 5-2. Counting outward from the tower, transitions in angular separation occur in rows 5, 10, 17, 24, 33, and 41; within those transition rows, heliostats are periodically deleted to avoid mechanical and optical interference.

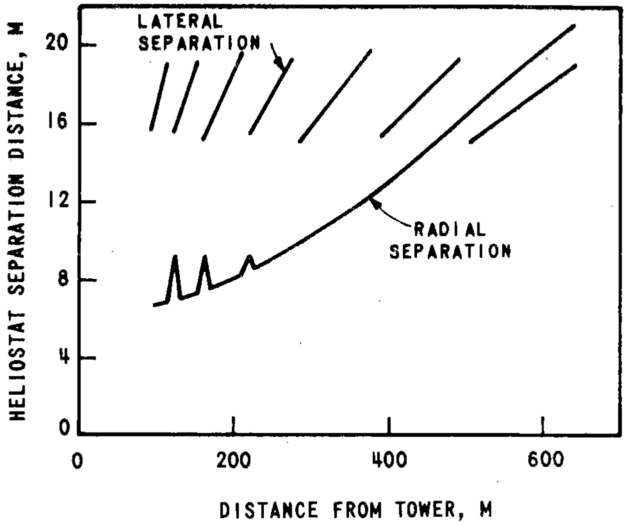


FIGURE 5-2. HELIOSTAT SEPARATION VERSUS DISTANCE FROM TOWER

Figure 5-2 shows the radial separation between rows also increases with distance from the tower, allowing heliostats to see over the neighboring heliostats in front without blocking. To prevent mechanical interference, the transition rows 5, 10, and 17 were given slightly larger spacings as illustrated by the spikes in the figure.

The field optimization procedure used in designing the collector field computed the ideal ground cover ratios (heliostat packing density) throughout the field. In general, for external receivers of this type, ground cover ratios are a strong function of distance from the tower, but are only moderately dependent on the azimuthal field position. Consequently, heliostats are placed in circular rows forming ground cover ratios that are independent of azimuthal location. Figure 5-3 illustrates the ground cover ratios as a function of field radius predicted by the optimization procedure and compares them to the actual values defined by the final field layout. The curves show that the final field layout approximates the ideal layout, with slight ground cover variations due to the staggered heliostat array pattern.

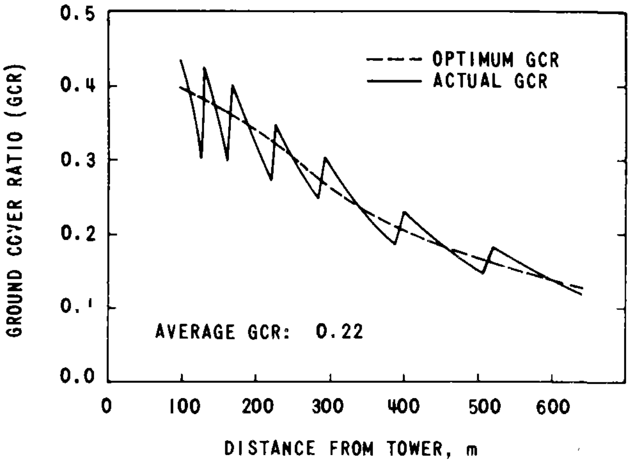


FIGURE 5-3. HELIOSTAT GROUND COVER RATIO VERSUS DISTANCE FROM TOWER

The actual X and Y locations of all 2,255 heliostats are included as part of Appendix A. Heliostats are numbered from one to 2,255 and are listed from the inner row to the outer, counting heliostats from the west end of the rows clockwise to the east. The X and Y coordinates are listed in metres with positive X east and positive Y north.

5.1.6 Collector System Operation and Control

Heliostat control is accomplished by a digital computer system which interprets operator commands, generates steering instructions for each heliostat individually, and performs monitoring and self-test routines.

Executive control is exercised by the Heliostat Array Controller (HAC), which interfaces with the Master Control System (MCS) and interprets commands entered by the operator via CRT. The HAC performs sun position calculations using the ephemeris tables and time inputs synchronized with Coordinated Universal Time through radio station WWV. The calculations use barometric pressure and temperature to make corrections to the sun position due to the atmospheric refraction.

The HAC interfaces with the heliostat field by sequentially addressing the 71 Heliostat Field Controllers (HFC), and transmitting the sun position data and command information. Through the HFC's, the HAC is capable of addressing individual heliostats and groups of heliostats on the entire field.

Each HFC controls up to 32 heliostats by accepting sun position and command data from the HAC and sequentially transmitting the information to the individual Heliostat Controllers (HC). The HFC also accepts status information from the HC's and transmits it to the HAC.

The HC is a microprocessor controller which receives data from the HFC and calculates the azimuth and elevation gimbal angles of the heliostat based on sun position and on the heliostat location and aim point coordinates stored in the microprocessor memory. The HC also services the ac motor control loop, advancing the motors until the calculated gimbal angles are reached. In addition, the HC has a self-check system which signals the HAC in the event of a failure. If command from the HAC is lost, the HC is capable of directing the heliostat to a stow position. In the case of a primary plant power outage, backup power is provided by a 2,750 kVA diesel generator.

In normal operating mode, the control system commands heliostats to track the sun and direct their beams to specific aim points on the receiver surface. An aiming strategy has been developed for the collector system which assigns a unique aim point location to each heliostat in the field. Each heliostat redirects its beam toward the receiver center line (i.e., no azimuthal shift); however, as shown in Figure 5-4, the vertical aim point of each heliostat on the receiver surface is one of four points and is a function of the heliostat's slantrange (the distance from the heliostat to target). The four point aim strategy is tailored to meet the incident flux requirements of the receiver. By spreading the beams vertically, incident power is evenly distributed without significantly increasing the total spillage loss. Subsection 5.1.1 of Appendix A presents an algorithm used to compute the aim point coordinates for any heliostat in the field based on that heliostat's location in the field and unique identification number.

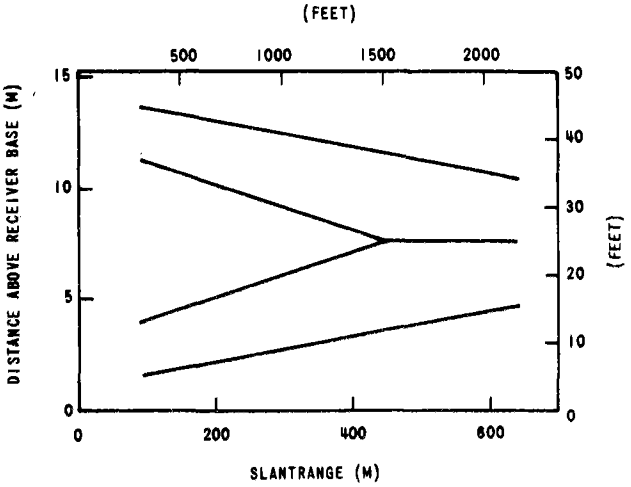


FIGURE 5-4. HELIOSTAT AIM-POINT STRATEGY

Two approaches are under consideration for the standby mode, with a final determination being deferred until detailed design. One approach, being fairly typical of prior central receiver designs, results in all the heliostats tracking the sun and redirecting their beams to a stationary point in space located east of the receiver, but at the receiver elevation. In the event of a power failure, the redirected image would drift further away (easterly) from the receiver, thus providing a failsafe design. An alternate approach, also thought to be feasible due to the improbability of failure of both the main and backup collector system power supplies, calls for heliostats to track the sun, redirecting their beams to one of two stationary points in space. Heliostats in the east half of the collector field will be assigned a standby position northwest of the receiver, allowing all heliostats on that side of the field to be brought from standby to the receiver without tracking across the tower or the normally unirradiated portion of the south side of the receiver. Similarly, heliostats in the west half of the field will be assigned a standby position northeast of the tower. The use of two standby points as described prevents heliostats from tracking across surfaces that are not actively cooled, and ensures that the beams will be directed away from the receiver during standby.

In addition to the normal operation and standby modes, heliostats may assume a directed position for cleaning, maintenance, or stowage on command from the Heliostat Array Controller or from local manual command at the Heliostat Controller.

Control software will provide time sequenced commands to the heliostats to execute predefined procedures such as start-up, shutdown, and emergency defocusing. In normal start-up, groups of heliostats are brought from stow position to standby by moving their beams from ground level up a vertical safety corridor to standby position. Then, upon command, the beams will be moved from standby to the receiver surface as needed. Evening shutdown will follow the reverse sequence, with beams redirected from the target to standby, then down the safety corridor to ground level.

Under emergency conditions requiring the immediate removal of power from the receiver surface, all heliostats are directed to stand by and wait for operator command to return to target or to stow position. Upon loss of command from the Heliostat Array Controller, the Heliostat Controllers initiate a stow sequence, using preprogrammed instructions to bring the beam down safely. Upon loss of power, the heliostats fail in place.

5.1.7 Collector System Performance

A detailed breakdown of the collector system performance at the design point (noon, March 21) is presented in the stairstep chart in

Figure 5-5. The collector is specifically designed to delivery 73.3 MW_t to the working fluid (82.1 MW_t incident) at the design point, assuming a receiver efficiency of 88.9 per cent and an insolation of 0.95 kW/m^2. Similarly, Figure 5-5 illustrates the annual average field performance stairstep; the reference isolation of 0.72 kW/m^2 is an annual average value based on the clear air insolation model described in Subsection 5.5.1 of Appendix A.

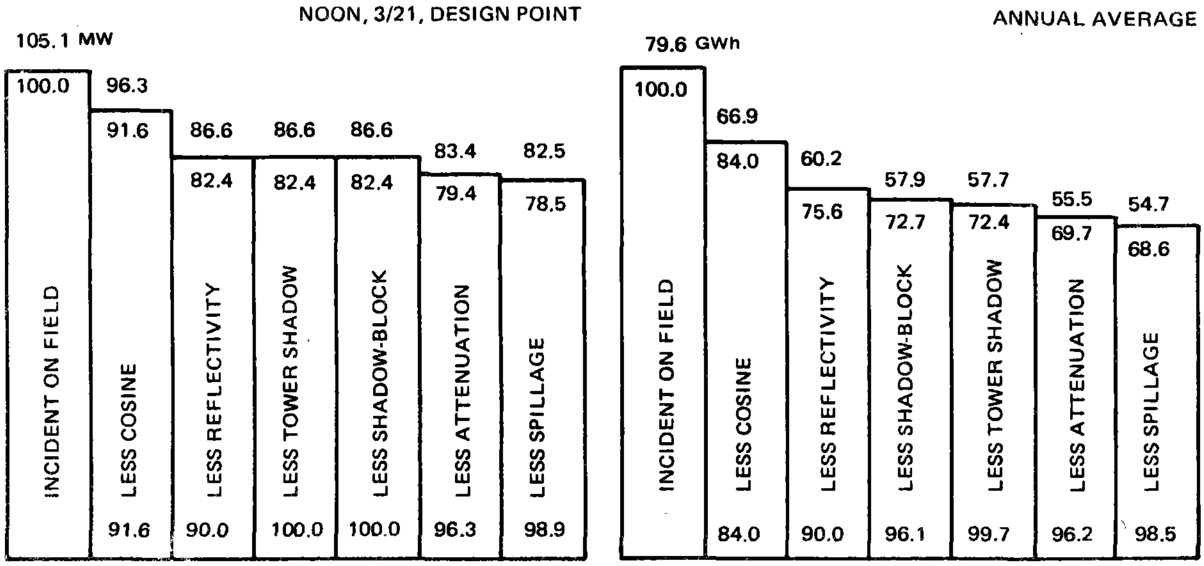


FIGURE 5-5. COLLECTOR SYSTEM EFFICIENCY STAIRSTEPS

Figure 5-6 demonstrates the relative effectiveness of heliostats in various portions of the collector field for the design point and on an annual average basis. The isopleths represent the power per unit of mirror area redirected to the receiver surface; they indicate that the most efficient heliostats are located directly north of the tower. Heliostats with the lowest efficiency are those in the southwest and southeast corners of the field. The current field design represents a departure from the optimum since heliostats in the southwest and southeast corners would deliver more annual energy to the receiver if they were placed along the northern edge of the field. However, the departure is necessary to reduce the peak incident flux on the north side of

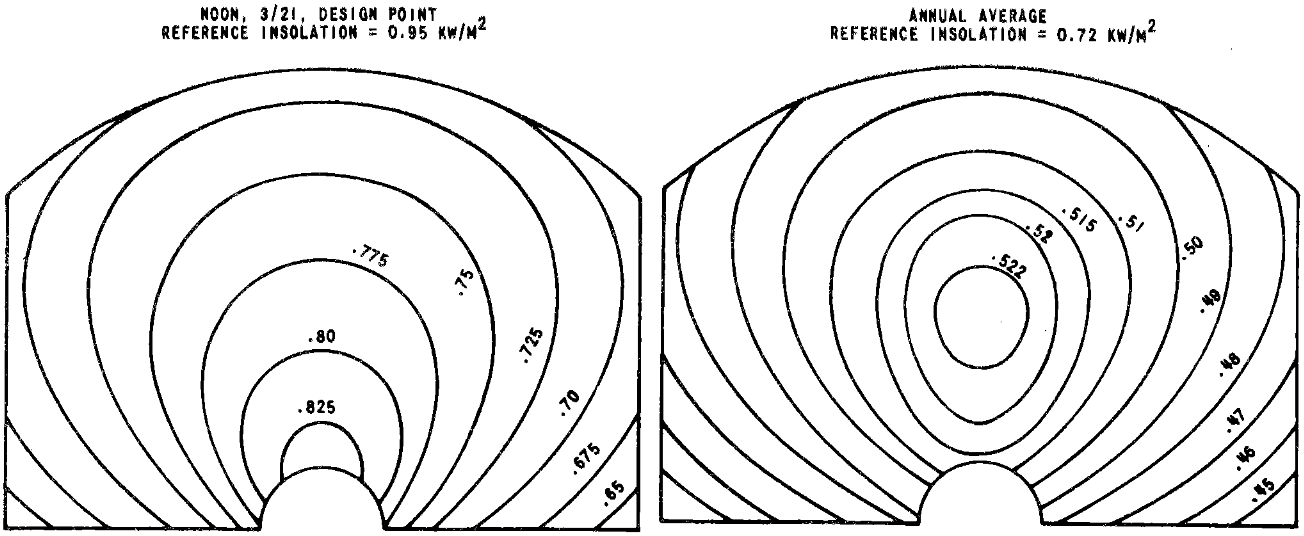


FIGURE 5-6. HELIOSTAT FIELD ISOPLETHS OF POWER INCIDENT ON RECEIVER PER UNIT OF MIRROR AREA

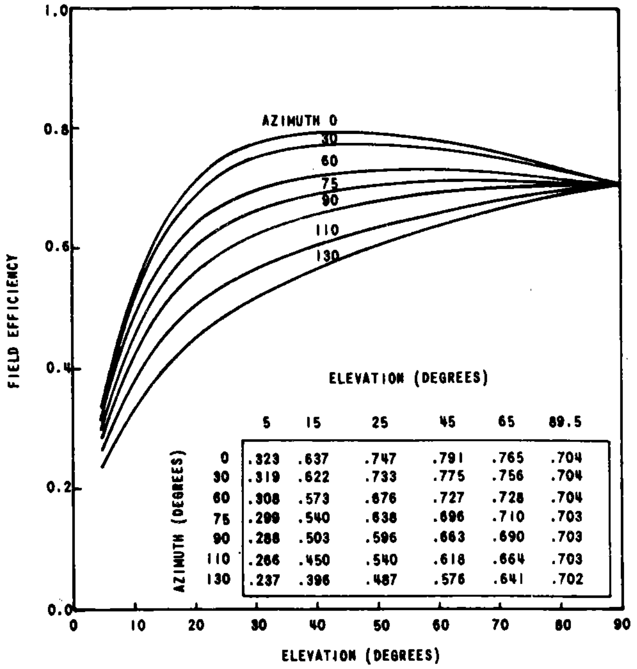
the receiver and redistribute more power to the west and east receiver panels, this field design results in less than I per cent loss in annual field performance.

Figure 5-7 presents the overall field efficiency values in graphical and tabular form for various sun azimuths and elevations. Field efficiency is defined such that its product with direct normal insolation and total field mirror area yields the total power incident on the receiver surface. The values shown here include the combined effects of cosine, tower shadow, heliostat shading and blocking, mirror reflectivity, atmospheric attenuation, and spillage.

The incident flux distributions on the receiver are presented in Section 5.2, and are discussed in terms of their impact upon receiver performance.

5.1.8 Collector System Cost Estimates

Cost estimates of the collector system have been made which include the cost of heliostats, foundations, wiring, field transformers, heliostat control electronics, and checkout. The sum of those costs is



AZIMUTH (DEGREES)	ELEVATION (DEGREES) 5	15	25	45	65	89.5
0	.323	.637	.747	.791	.765	.704
30	.319	.622	.733	.775	.756	.704
60	.308	.573	.676	.727	.728	.704
75	.299	.540	.638	.696	.710	.703
90	.288	.503	.596	.663	.690	.703
110	.266	.450	.540	.618	.664	.703
130	.237	.396	.487	.576	.641	.702

FIGURE 5-7. HELIOSTAT FIELD EFFICIENCY VERSUS SUN POSITION

estimated to be $260 per square metre of glass area, this results in a total collector system cost of $29.1 x 10^6.

5.2 RECEIVER SYSTEM

The primary function of the receiver system is to convert sunlight into usable thermal energy. This is accomplished by absorbing insolation (which is redirected onto the receiver surface by the collector system), thus, transforming solar energy into thermal energy and transferring that thermal energy into the working fluid. The thermal energy in the working fluid is then transported to the fossil energy system to be converted into electricity. Since the efficient conversion of solar energy to thermal energy is of prime importance to the repowering design, and since that conversion takes place in the solar receiver, the majority of this subsection is devoted to the description of the solar receiver. In addition to the receiver, however, the receiver tower, which supports the receiver above the heliostat field, is described in the latter part of this subsection.

5.2.1 Solar Receiver

The solar receiver has an external heat absorbing surface of nearly cylindrical shape with a diameter equal to 9.45 metres (31 feet) and a height equal to 15.24 metres (50 feet). The mid-height of the receiver active surface is located at an elevation of 124 metres (407 feet) above ground. The active surface covers 240 degrees of the receiver circumference with the azimuthal mid-point facing north. The receiver consists of 16 panels; 12 are superheaters and 4 are economizers. The superheater panels are composed of steam-cooled membrane wall tubes with water-cooled screen tubes in front of the membrane wall. The general arrangement of the receiver, as illustrated schematically in Figure 5-8, is symmetrical about a north-south axis. The panels are numbered in sequence from 1 to 15 (odd numbers) on the east side and from 2 to 16 (even numbers) on the west side of the receiver, starting from north.

The south 120 degrees of the receiver cylinder does not include active heat transfer surface and is closed with a nonabsorbing steel casing. Two closure doors, each of 120-degree angular width, are stored on the south side of the receiver during normal solar operation.

5.2.1.1 Screen Tubes. The analyses of the unique characteristics of the heat flux incident on the receiver led to the development of a receiver design concept which can withstand the severe duty imposed by the expected variations of solar insolation.

The method used for reducing the heat flux of a panel to an acceptable or desirable level without increase of the receiver size or weight consists of the use of spaced tubes which form a screen in front of the panels. The screen tubes are cooled by subcooled or boiling water which absorbs part of the incident heat. One row of screen tubes can reduce the heat flux by 30 per cent to 70 per cent depending on tube size and spacing. The fraction of incident radiation absorbed by screen tubes is shown on Figure 5-9.

By establishing the proper variable spacing of screen tubes, it is possible to obtain a relatively uniform, low level, peak heat flux pattern around the circumference of the receiver as shown on Figure 5-10.

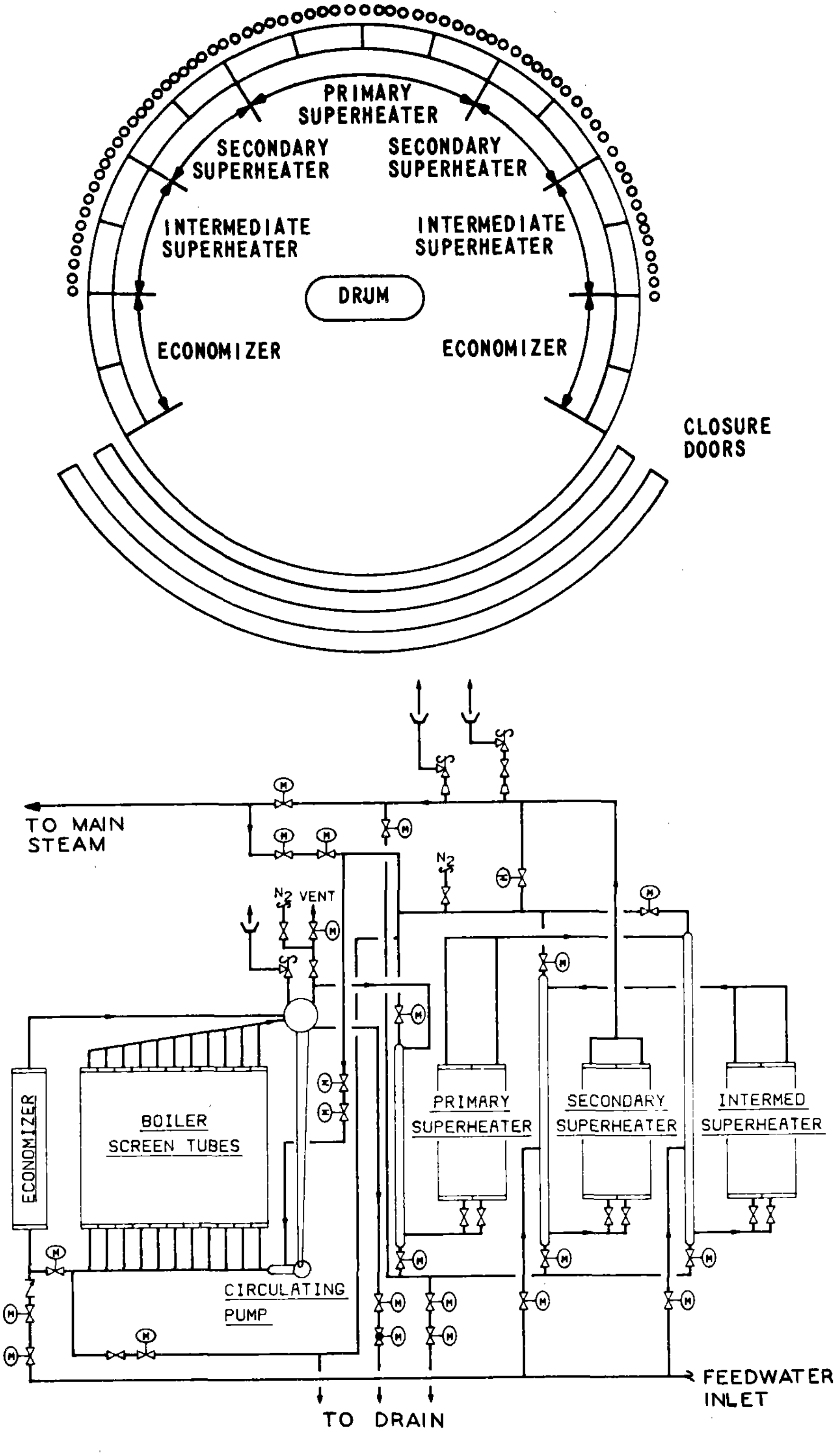


FIGURE 5-8. EXTERNAL RECEIVER SCHEMATIC

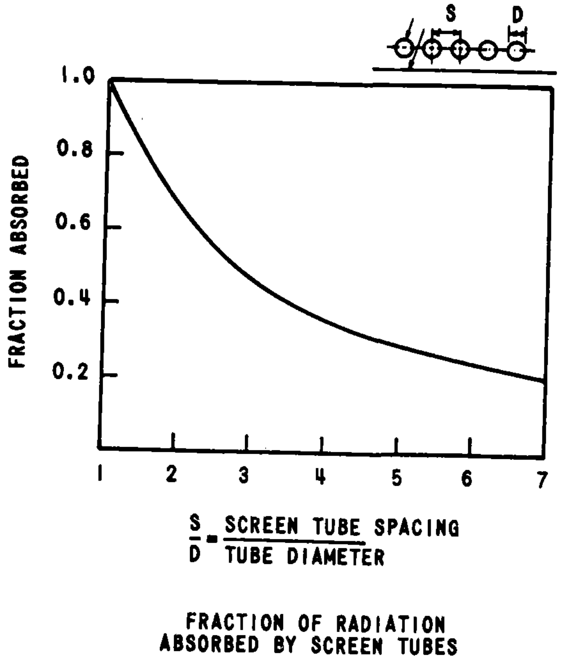


FIGURE 5-9. FRACTION OF RADIATION ABSORBED BY SCREEN TUBES VERSUS SCREEN TUBE SPACING

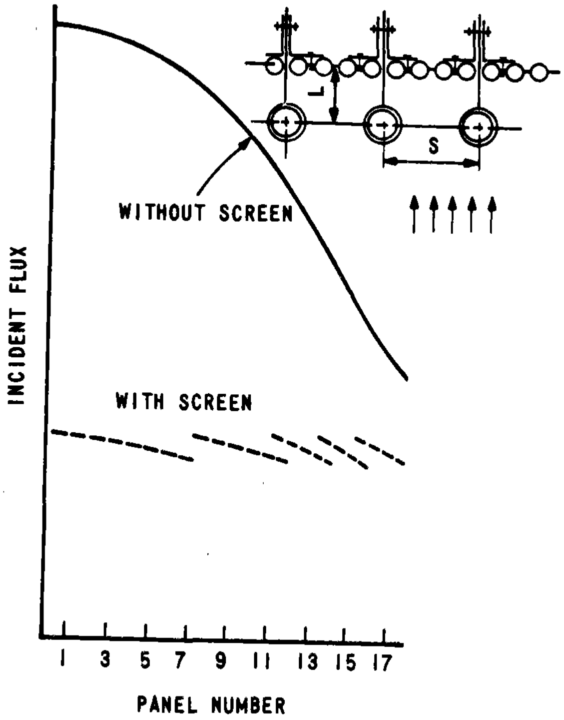


FIGURE 5-10. ILLUSTRATION OF ROLE SCREEN TUBES PLAY IN LEVELIZING FLUX ON SUPERHEATERS

The use of screen tubes as boiler section in front of the superheater panels provides a significant advantage for the reliable receiver operation. With this arrangement of heating surface, any diurnal, seasonal, and cloud shadowing variations of incident heat flux affect the boiler and the superheater in the same degree. Thus, this construction reduces the limitations due to boiler/superheater flow unbalances that might be imposed on operation of the receiver, especially during periods of unbalanced cloud coverage.

Because the screen tubes are cooled by subcooled or boiling water, the metal temperatures are much lower than those of the superheater panels. Thus, the overall mean external metal temperature of the receiver is much lower than for a design without screen tubes. The effect is a reduction of the heat losses from the receiver due to emissivity and convection to the surrounding air. Reradiation losses from the superheater should also be reduced due to the fact that a significant portion of the energy reradiated from the superheater is absorbed on the rear of the screen tubes. The result is an increased thermal efficiency of the receiver.

In recirculation boiler design, the screen tubes may be cooled by subcooled or boiling water. Ribbed tubes with internal spirals are used in the screen to avoid DNB (departure from nucleate boiling). In this design, there is no film boiling and associated critical heat flux (i.e., DNB) temperature oscillation. Pump-assisted circulation is employed to maintain the required mass velocity and circulation ratio (steam quality) at all predictable operating conditions, including extremes of insolation distribution. Ribbed screen tubes operating with nucleate boiling can withstand very high heat fluxes without excessive thermal stresses. Accordingly, the high water, side heat transfer rate of the tubes allows the use of low alloy material (SA-213 T2) for the screen tubes.

A sectional view of the basic panel design is shown on Figure 5-11. The screen tubes originate at an inlet header on the bottom and terminate at outlet headers at the top. Water/steam flows upward through the tubes. The inlet header is supplied from the circulating pump discharge manifold. The outlet header collects the steam and water mixture of low steam mass fraction (quality) and discharges it to the steam separating vessel.

The screen tubes are attached to the superheater panels at a distance depending on tube size. Attachments maintain the appropriate spacing and avoid vibration. The attachment device provides a sliding fit support to compensate for differential thermal growth of the screen tubes and membrane panel. The design of this vibration support, shown on Figure 5-12, is an investment casting made of the same material as the membrane panel and is bolted to the rear of the membrane, thus, it is not exposed to the incident heat flux. A slot in the membrane permits

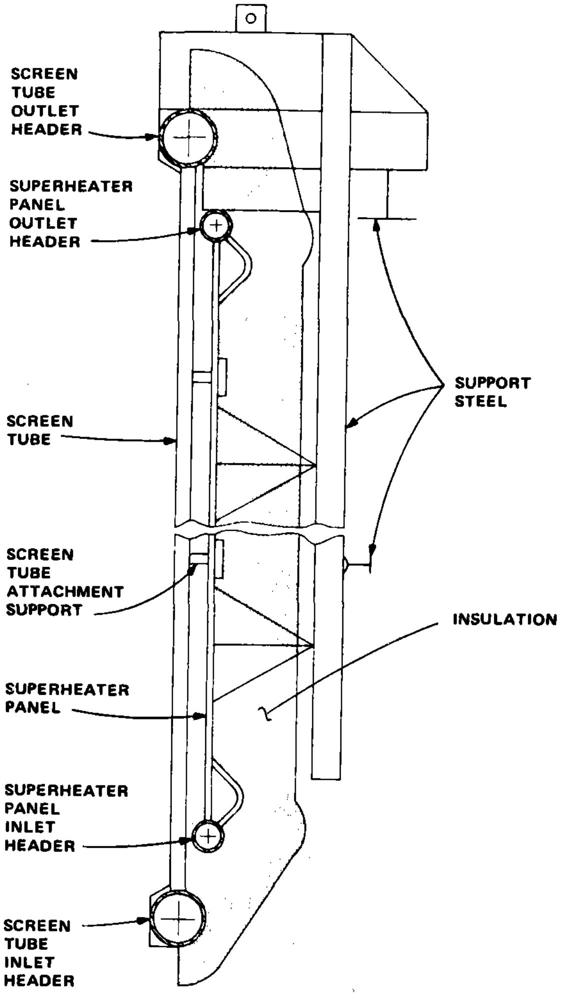


FIGURE 5-11. RECEIVER PANEL DESIGN

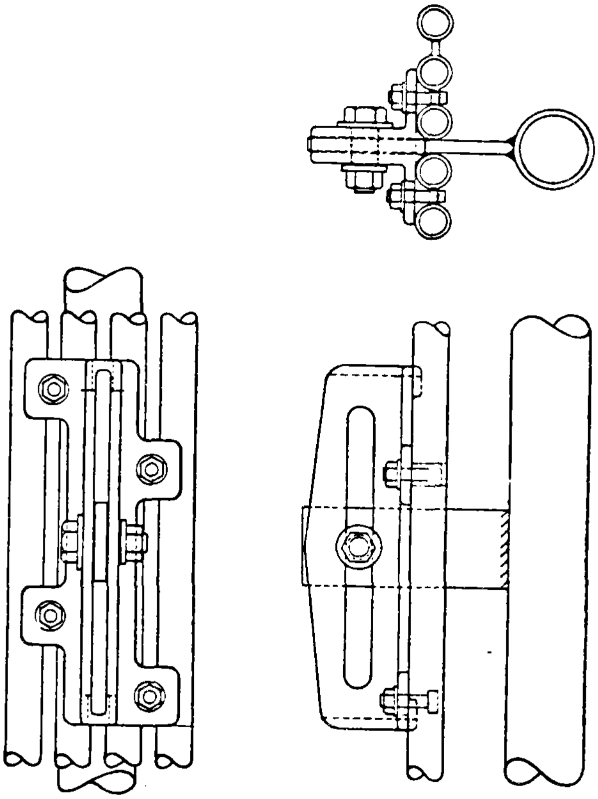


FIGURE 5-12. SCREEN TUBE VIBRATION SUPPORT

the penetration of the screen support bar which is welded to the screen tube. The support bar is guided through a round pin in a pair of vertical slots provided in the casting. This construction provides freedom of relative movement only in vertical direction.

One of the first considerations to be addressed in the design of the solar receiver is the determination of the sizes and physical relationship of the superheater and screen tubes. The variable parameters that must be set in order to achieve the desired uniform flux distribution on the superheater panels and the effects of screen tube spacing and stand-off distance on uniformity of heat flux to the membrane tubes are shown on Figure 5-13.

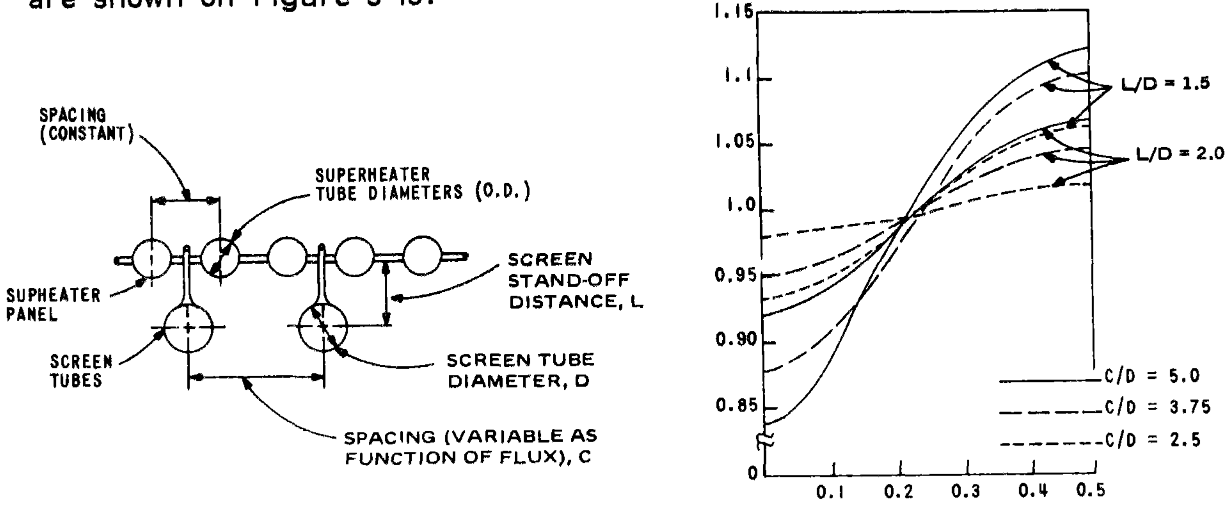


FIGURE 5-13. EFFECT OF SCREEN TUBE SPACING AND STAND-OFF DISTANCE ON UNIFORMITY OF HEAT FLUX ON MEMBRANE TUBE WALL

5.2.1.2 <u>Membrane Panels</u>. The superheater panels consist of small diameter Incoloy 800H tubes welded together with 9.5 mm (3/8 inch) wide bars about 5 mm (0.19 inch) thick of the same material to form a membrane construction. The inlet and outlet headers are also of the same material (Incoloy 800H) to provide uniform thermal expansion. The steam flow in the superheater panels is always upward in order to ensure positive steam flow in all tubes during fast cloud transients, when the heat flux can change from near zero to full value in 10 seconds. The panel is provided with structural steel buckstays to maintain its flat shape and to hold it to the tower structure. The panel is free to expand downward from the support grid and sideward about its center line.

Each panel has the same width and length. The screen tubes are arranged in front of the membrane panel to shield the panel from excessive heat flux levels. The screen tubes are always located in line with the membrane so that the vibration support bar can penetrate directly through the slot in the membrane panel. The spacing of the screen tube is, therefore, always a multiple of the membrane wall tube spacing. Depending on panel location around the tower periphery, the size of the screen tubes and their spacings vary. On the north side, the spacing is closer than on the east or west sides.

The screen tubes are assembled together with the membrane wall in the shop to form a single shipping unit. All headers and buckstays are shop-assembled. Insulation, applied at the plant site before the panel assembly is lifted into its position on the tower, is applied in two layers to a thickness of 0.2 metre (8 inches) with staggered joints. High temperature blocks are placed next to the membrane with medium temperature blocks of mineral fiber over it. The insulation is held in place by heat resistant studs welded to the back of the membrane bars. Aluminum lagging is applied over the insulation.

A tee-shaped member clipped to the membrane panel permits unrestrained lateral growth in both directions from the center, where the tee is fastened to the membrane. Brackets welded to the tee member slide along two I-beams, which represent the buckstay, to permit unrestricted longitudinal expansion and contraction. The I-beams are outside of the insulation and always remain cold, while the tee-shaped member is below the insulation and is hot during boiler operation. The panel upper headers are attached to a horizontal member, which is welded to the upper ends of the buckstays. Two lifting lugs on the horizontal member are used to place the panel on the receiver support grid. The buckstays are attached at several elevations to the horizontal trusses of the main support structure. The surface of the tubes that are exposed to solar radiation is coated with Pyromark black paint, which has a high absorptivity coefficient.

It should be noted that the materials of economizer panels and headers are different from those of superheater panels and headers. The general design data for solar receiver panels and screen tubes are listed in Table 5-1 and Table 5-2.

TABLE 5-1. GENERAL DESIGN DATA FOR SOLAR RECEIVER PANELS (External Type, Diameter 9.5 m (31.2 ft), Active Height 15.24 m (50 ft)

Membrane (Superheater)	
Tube and Membrane Material	800H
Tube Wall Thickness	2.54 mm (0.100 in)
Active Tube Length	15.24 m (50 ft)
Total Tube Length	15.85 m (52 ft)
Membrane Thickness	4.76 mm (0.187 in)
Inlet Header OD	0.114 m (4.5 in)
Outlet Header OD	0.114 m (4.5 in)
Header Material	800H
Design Pressure	16.9 MPa (2,450 psia)
Screen Tubes (Multi-Lead Internal Ribs)	
Tube Material	SA-213-T2
Tube Wall Thickness	3.76 mm (0.148 in)
Active Tube Length	15.24 m (50 ft)
Total Tube Length	16.15 m (53 ft)
Inlet Header OD	0.168 m (6.625 in)
Outlet Header OD	0.168 m (6.625 in)
Header Material	SA-210C
Membrane (Economizer)	
Tubes and Membrane Material	SA-210-A1
Tube Wall Thickness	3.43 mm (0.135 in)
Active Tube Length	15.24 m (50 ft)
Total Tube Length	15.85 m (52 ft)
Membrane Thickness	6.35 mm (0.250 in)
Inlet Header OD	0.168 m (6.625 in)
Outlet Header OD	0.168 m (6.625 in)
Header Material	SA-106-C
Design Pressure	17.25 MPa (2,500 psia)

TABLE 5-2. RECEIVER PANEL DATA

	Screen Tube (Boiler)					Membrane Tube						
Panel	Number	Space cm (in)	OD cm (in)	ID cm (in)	Flow kg/h (lb/h)	Type	Number	Space cm (in)	OD cm (in)	ID cm (in)	Flow kg/h (lb/h)	Efficiency per cent
1	15	8.573 (3.375)	3.493 (1.375)	2.629 (1.035)	37,134 (81,868)	SH 1	43	2.858 (1.125)	1.905 (0.750)	1.346 (0.530)	25,369 (55,928)	91.06
3	15	8.573 (3.375)	3.493 (1.375)	2.629 (1.035)	37,134 (81,868)	SH 1	43	2.858 (1.125)	1.905 (0.750)	1.346 (0.530)	25,369 (55,928)	91.08
5	15	8.573 (3.375)	4.128 (1.625)	3,264 (1.285)	37,134 (81,868)	SH 3	43	2.858 (1.125)	1.905 (0.750)	1.346 (0.530)	28,164 (62,092)	88.97
7	15	8.573 (3.375)	4.128 (1.625)	3.264 (1.285)	37,134 (81,868)	SH 3	43	2,858 (1.125)	1.905 (0.750)	1.346 (0.530)	28,164 (62,092)	88.87
9	11	11.43 (4.500)	3.810 (1.500)	2.946 (1.160)	27,232 (60,037)	SH 2	43	2.858 (1.125)	1.905 (0.750)	1.346 (0.530)	28,164 (62,092)	88.87
11	11	11.43 (4.500)	3.493 (1.375)	2.629 (1.035)	27,232 (60,037)	SH 2	43	2.858 (1.125)	1.905 (0.750)	1.346 (0.530)	28,164 (62,092)	86.45
13	0	--	--	--	--	ECON	32	3.81 (1.500)	2.54 (1.000)	1.786 (0.703)	25,369 (55,928)	85.42
15	0	--	--	--	--	ECON	32	3.81 (1.500)	2.54 (1.000)	1.786 (0.703)	25,369 (55,928)	57.03

NOTES: (1) SH 1--primary superheater; SH 2--intermediate superheater; SH 3--secondary superheater; ECON--economizer.

(2) Panels with even number located on the west side of receiver are identical to those with next lower odd number on the east side.

(3) The width of each panel is 1.24 m (4.06 ft).

5.2.1.3 Flow Sequence Through the Steam Generator. The flow sequence through the steam generator is illustrated on Figures 5-8 and 5-14. Feedwater is introduced into the four economizer panels. The flow of the feedwater is controlled by a conventional three-element feedwater regulator, which uses a signal from drum level and from steam flow to regulate the feedwater flow to the steam generator. The water is preheated in the economizer panels and is injected into the drum, where it is mixed the saturated water discharged from the cyclone separators. Slightly subcooled water (331 C or 628 F) flows from the drum, through an external downcomer, and is pumped through supply pipes into the lower headers of the screen tubes comprising the boiler section. The water is distributed to the screen tubes where steam generation takes place. The resultant steam/water mixture (of average steam fraction less than 0.30) passes through riser pipes into the steam drum, where the water and steam are separated by cyclone separators and steam scrubbers. The separated saturated water is mixed with feedwater from the preheater (economizer) and flows through the downcomer to the glandless, wet motor, circulating pump to the recirculated. A single pump with no shut-off valves is used.

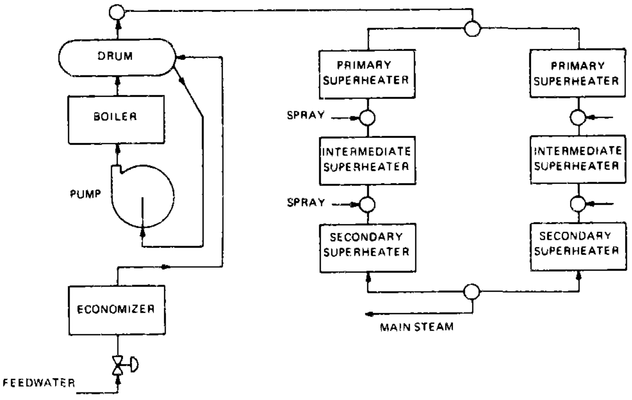


FIGURE 5-14. SOLAR RECEIVER SCHEMATIC FLOW DIAGRAM

The superheater is divided into two symmetrical flow paths, east and west, each consisting of three series passes. There are two panels per pass in each flow path, with spray attemperation between the passes;

thus, four attemperators are provided. The two flow paths and the spray attemperation are needed to compensate for the large diurnal, seasonal, and cloud-induced variations of incident power on the west and east sides of the receiver. A butterfly control valve is located at the inlet to each superheater panel to provide for flow distribution to panels during severe cloud transients and during early morning and late afternoon operation. The biasing of the butterfly valves is needed only at extreme transients when superheater temperatures become excessive.

Moisture-free steam from the drum flows through saturated connections and a single steam downcomer to the primary superheater, where it is heated to about 420 C (788 F). The steam leaving the primary superheater is lead through two steam downcomers, one in each flow path, to the intermediate superheater. A spray attemperator, which consists of an atomizing nozzle and a venturi sleeve, is located in each steam downcomer pipe. Additional feedwater is injected into the steam as required to control the final steam temperature.

The steam leaving the intermediate superheater, at an average temperature of about 449 C (840 F), passes through a second stage attemperator located in each steam downcomer. At design conditions, no spray is needed at this stage. From the attemperator, the steam enters the secondary superheater, where it is heated to the final steam temperature of 544 C (1,011 F) at the required pressure.

5.2.1.4 Receiver Thermal Performance. The heat flux map for the solar receiver at the design point of equinox noon, as shown in Table 5-3, was obtained using proprietary Black & Veatch computer software. The heliostat aim strategy selected for the receiver is to provide a uniform vertical heat flux distribution. The vertical heat flux for panel 1 (north) is presented in Figure 5-15; as indicated in the figure, the peak heat flux on the receiver is 626 kW/m^2. The power distribution to the receiver superheater panels is shown in Figure 5-16; this figure illustrates the safety margin in the design by identifying the allowable power level and the amount actually absorbed by each panel.

TABLE 5-3. RECEIVER FLUX MAP

```
THE TIME POINT UNDER TEST IS:  DAY = 80, HOUR = 12
TOTAL POWER WAS 83.381 MEGAWATTS
82.638 MW HIT THE CYLINDER
.744 MW MISSED THE CYLINDER
INSOLATION = 0.95 KW/SQM

MAP OF THE INCIDENT FLUX (KW/SQ METER) AS VIEWED FROM THE FIELD IS

METERS     |
ABOVE BASE |                                                      ° CW FROM NORTH
OF CYLINDER| 353 338 323 308 293 278 263 248 233 218 203 188 173 158 143 128 113  98  83  68  53  38  23   8
___________|__|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|___|__
     14.48 | 128 135 123 121  97  70  32   4   1   0   1   0   0   1   0   1   4  32  70  97 121 123 135 128
     12.95 | 412 353 357 333 294 207  77  14   1   0   0   0   0   0   0   1  14  77 207 294 333 357 353 412
     11.43 | 473 412 390 388 330 204  86  19   3   0   0   0   0   0   0   3  19  86 204 330 388 390 412 473
      9.91 | 594 578 542 449 373 254 102  14   6   0   0   0   0   0   0   6  14 102 254 373 449 542 578 594
      8.38 | 592 584 520 499 356 254 110  26   6   1   0   0   0   0   1   6  26 110 254 356 499 520 584 592
      6.86 | 626 593 522 470 383 233 104  27   3   1   0   0   0   0   1   3  27 104 233 383 470 522 593 626
      5.33 | 595 539 503 473 359 250 109  18   6   1   0   0   0   0   1   6  18 109 250 359 473 503 539 595
      3.81 | 459 470 450 392 337 219  93  18   4   1   0   0   0   0   1   4  18  93 219 337 392 450 470 459
      2.29 | 400 375 391 330 275 219  65  11   1   0   0   0   0   0   0   1  11  65 219 275 330 391 375 400
      0.76 | 113 117 130 116  99  71  20   4   0   0   0   0   0   0   0   0   4  20  71  99 116 130 117 113
```

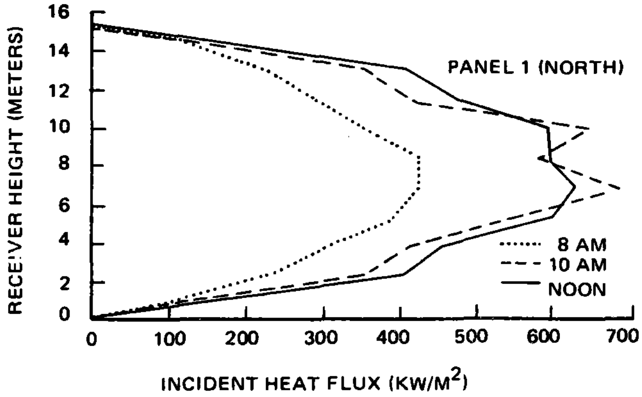


FIGURE 5-15. VERTICAL INCIDENT HEAT FLUX DISTRIBUTION AT VARIOUS TIMES OF DAY

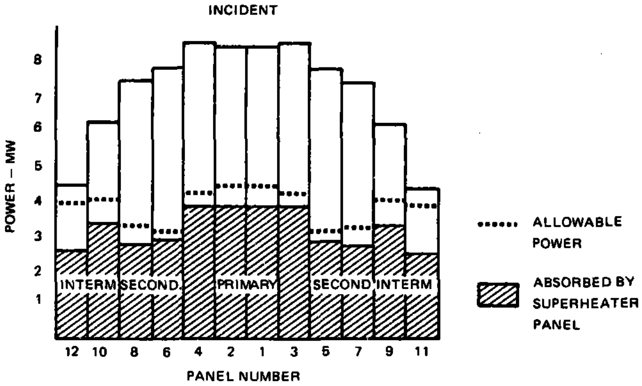


FIGURE 5-16. POWER DISTRIBUTION TO SUPERHEATER PANELS

Based on the flux maps for various times and the predetermined configuration and dimension of screen and membrane tubes of the receiver, calculations have been conducted to predict steady-state, thermal-hydraulic performance of the receiver. The summary results at the design point of equinox noon are tabulated in Table 5-4. The thermal performance of the solar receiver during equinox is presented in Figure 5-17. This figure contains information about thermal efficiency, steam flow, and the spray during the morning hours of the day. The afternoon performance is a mirror image of the morning graphs.

The fluid and tube wall temperature profiles along the heated length of the economizer, the boiler, and the superheater tubes are

TABLE 5-4. PERFORMANCE OF SOLAR RECEIVER AT DESIGN POINT

Superheater Outlet			
Pressure	MPa (psia)	14.53	(2,155)
Temperature	C (F)	543.9	(1,011)
Pressure Drop Through Superheater	MPa (psi)	1.19	(173)
Drum Pressure	MPa (psia)	15.72	(2,358)
Flow Rate	kg/h (lb/h)		
Primary Superheater (or Preheater)		99,382	(219,102)
Spray Attemperator 1		1,095 4	(24,149)
Intermediate Superheater		110,336	(243,251)
Spray Attemperator 2		0	(0)
Secondary Superheater		110,336	(243,251)
Per Cent Spray		9.93	
Circulation Flow		441,343	(973,000)
Circulation Ratio		4	
Circulation Pump Power	kW	60	
Feedwater Temperature	C (F)	238	(474)
Incident Power	MW_t (MBtu/h)	82.45	(281.32)
Radiation Loss	MW_t (MBtu/h)	2.58	(8.53)
Convection Loss	MW_t (MBtu/h)	3.6	(12.29)
Conduction Loss	MW_t (MBtu/h)	0.42	(1.43)
Reflection Loss	MW_t (MBtu/h)	2.55	(8.70)
Absorbed Power	MW_t (MBtu/h)	73.30	(256)
Efficiency	Per Cent	88.9	
Power Absorbed by Components			
Preheater	MW (MBtu/h)	2.89	(9.85)
Evaporator	MW (MBtu/h)	39.42	(134.49)
Primary Superheater	MW (MBtu/h)	12.68	(43.25)
Intermediate Superheater	MW (MBtu/h)	9.33	(31.84)
Secondary Superheater	MW (MBtu/h)	8.99	(30.66)

TABLE 5-4 (Continued). PERFORMANCE OF SOLAR RECEIVER AT DESIGN POINT

Peak Flux at Equinox Noon	kW/m^2 (kBtu/h-ft^2)	626	(198.4)
Average Flux at Equinox Noon	kW/m^2 (kBtu/h-ft^2)	273	(86.6)
Peak Superheater Tube OD Temperature	C (F)	579.2	(1,074.6)
Peak Screen Tube OD Temperature	C (F)	388.0	(730)
Maximum Steam Temperature Leaving Tube	C (F)	589.6	(1,093.3)
Maximum Upset Tube OD Temperature	C (F)	627.8	(1,162.0)

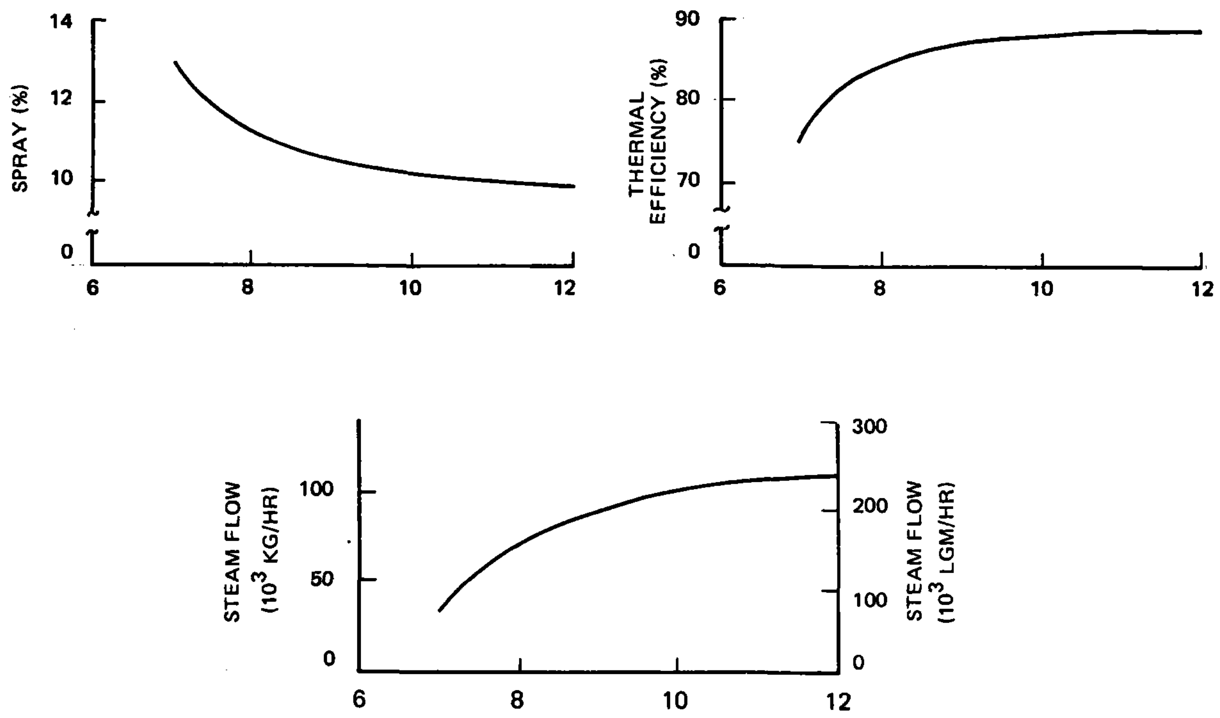


FIGURE 5-17. THERMAL PERFORMANCE OF SOLAR RECEIVER DURING EQUINOX DAY

depicted on Figure 5-18. Also shown are the highest possible unbalanced steam temperatures and upset metal temperatures caused by extreme flow imbalance due to a combination of the following reasons.

- Header maldistribution.
- Tube and manufacturing tolerances.
- Screen tube deflection.
- Panel flux gradient.
- Heat flux peaks (resulting from heliostat misalignments, etc.).

The total heat flux upset factor (F_Q) varies in both vertical and horizontal directions along the receiver. However, the flow unbalanced factor (F_U) only changes from panel to panel and remains constant along the tube. It is estimated that the maximum heat flux upset factor is about 1.549 (+55 per cent); the minimum flow unbalanced factor is about 0.805 (-20 per cent) at the design point, assuming that flow control

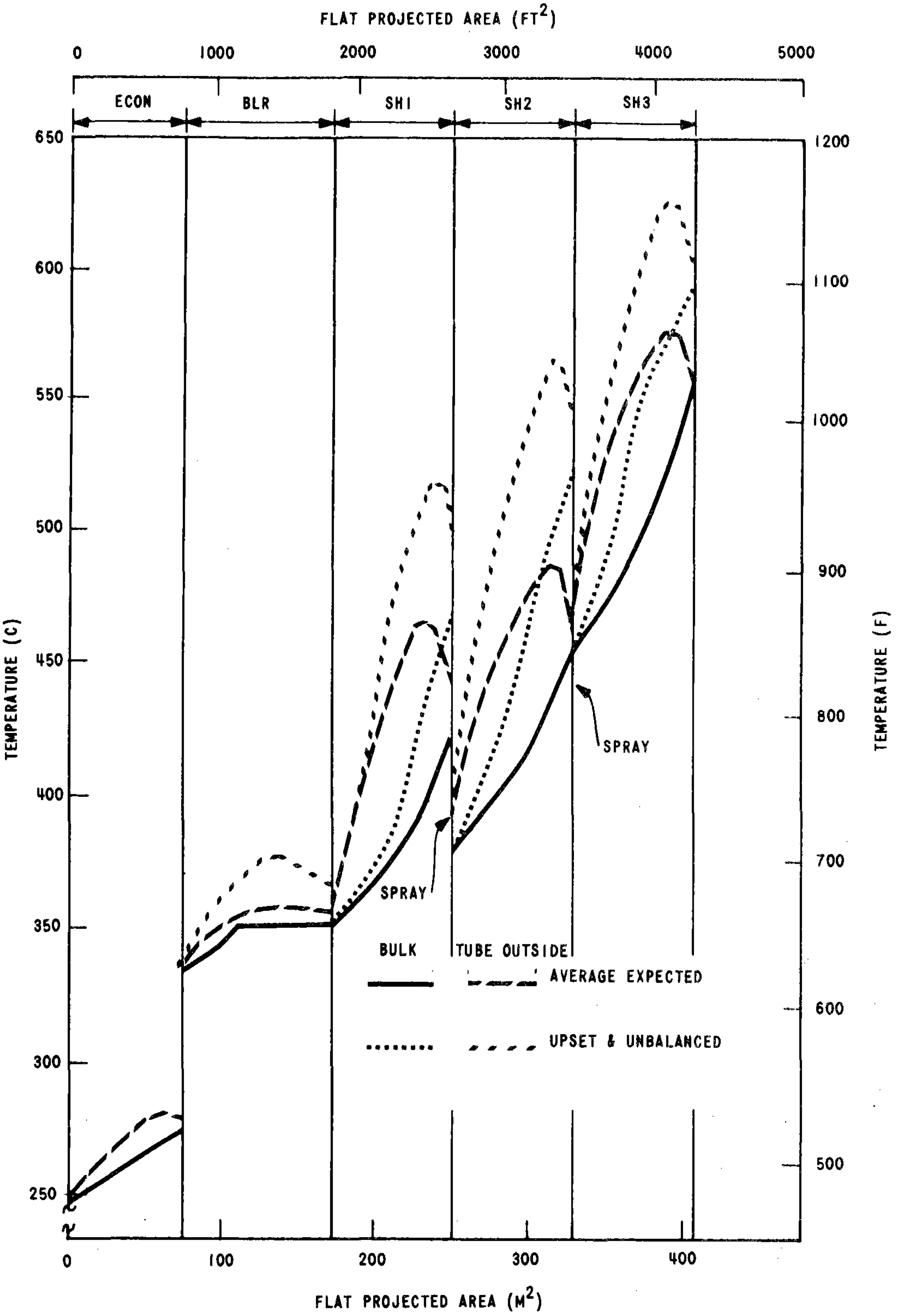


FIGURE 5-18. FLUID AND METAL TEMPERATURE PROFILE OF RECEIVER

valves are not biased. The highest upset metal temperatures are in the secondary superheater (Figure 5-18). It is seen that the fluid temperature in the economizer and superheater tubes continuously increases. However, the tube metal temperature increases and then decreases along the receiver height. This is due to the fact that the incident flux becomes small near the top of the receiver. With actuation of the biasing valves, the upset temperatures can be significantly reduced; these biasing valves are needed only for transients, caused by cloud passage.

The ambient air temperature and the speed of the wind have a significant effect on the receiver thermal losses. The wind speed at receiver elevation varies from 0 to 32 m/sec (0 to 105 fps), and the range for ambient air temperature is from -27 C (-16.6 F) to 47 C (116.6 F). The losses are calculated by the methods presented in Reference 1.*

The total loss and the thermal efficiency versus wind speed with ambient air temperature as a parameter are plotted in Figure 5-19. The solid lines represent the loss, and the dash lines correspond to the thermal efficiency. It is seen that the loss increases either when the wind speed increases or the air temperature decreases. The reversed trends are discovered for the thermal efficiency. It is also found that both solid and dash lines become more steep as the wind speed increases. In other words, the effect of the air temperature becomes more important when the wind speed is great.

The results of all cases under investigation indicate the wind speed has the predominant effect on the convective loss. On the other hand, the effect due to the ambient temperature and the wind speed on the radiation loss is very small. The radiative loss mainly depends on the metal surface temperature (the fourth power of the absolute temperature). Therefore, the radiative loss increases when the incident power increases.

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*Reference 1--Sandia Report Number SAND 79-8177, Solar Advanced Steam/ Water Receiver, Appendix C.

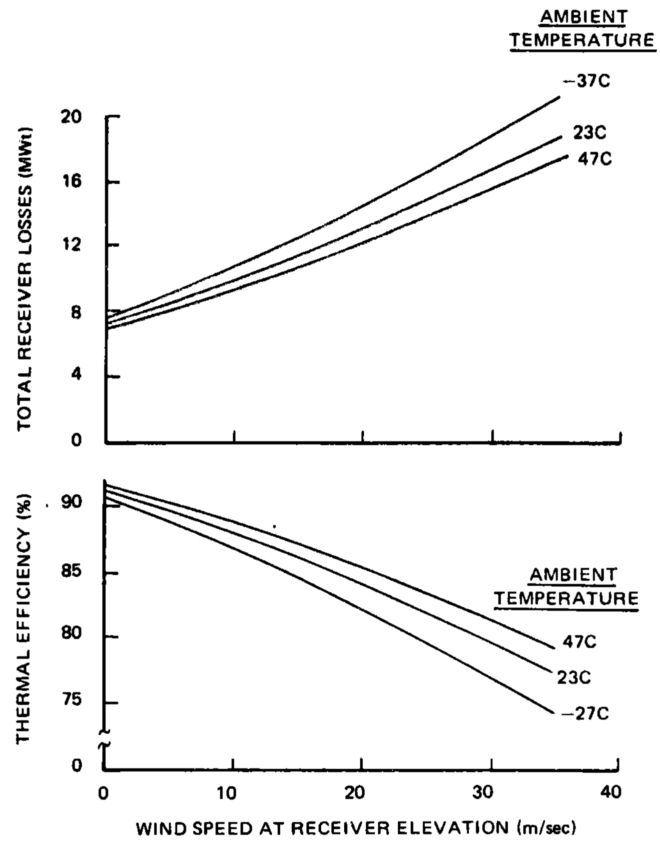


FIGURE 5-19. RECEIVER PERFORMANCE VERSUS WIND SPEED AND AMBIENT TEMPERATURE

5.2.1.5 Receiver Controls. The controls for the receiver system modulate feedwater flow, economizer recirculation, secondary superheater outlet temperature, and the flow of each superheater panel.

5.2.1.5.1 Feedwater Flow Control. The feedwater flow is controlled to maintain the proper water level in the drum. During normal operation, the drum level is controlled to a common operator set point by a three-element feedwater control. Measured steam flow less the attemperator flows is used to establish the feedwater flow demand. Measured drum level is compared to the set point, and the resulting error is applied to a proportional plus integral controller, which is used to correct the feedwater flow demand. The corrected demand is compared with measured flow and applied to a proportional plus integral controller to position the feedwater flow control valve.

During start-up and shutdown, when there is little or no steam flow from the receiver, a single-element feedwater flow control based on only drum level is used. Also, a high-level dump valve on the drum is used to assist in controlling drum level swell during start-up. If drum level exceeds a high-level set point, a proportional controller is used to position the dump valve to limit the drum level rise.

5.2.1.5.2 Economizer Recirculation Valve Control. The economizer recirculation valve is automatically closed when feedwater is flowing to the receiver or when no recirculating pump is in service. The valve is automatically opened when no feedwater is flowing in the associated path and a recirculating pump is in service in that flow path. Feedwater flowing requires that a feed pump be running.

5.2.1.5.3 Steam Temperature Control. The secondary superheater outlet temperature of each of the flow paths is independently controlled to a common set point by use of water attemperation at the outlets of the primary and intermediate superheater panels.

The secondary superheater outlet temperature for each flow path is compared with the common set point. The resulting error signals, in conjunction with a feedforward function from the steam flow in each flow path, generate the total attemperator flow demand for each flow path. A maximum attemperator flow demand is developed, based on the steam flow through the flow path and the primary superheater outlet temperature, to prevent the first stage of attemperation from spraying when the outlet of the attemperator contains moisture. The maximum attemperator flow limit is based on not allowing the attemperator outlet temperature to go below a predetermined limit. Initially, the total attemperator flow is through the first-stage attemperator. Once the first-stage attemperator flow demand is at the maximum allowed, any additional attemperator flow demand is applied to the second-stage attemperator. A degree of overlap in the operation of the two attemperators is provided to prevent loss of temperature control when bringing in or removing the second stage of attemperation. During a transient, both attemperators may move in parallel to minimize the temperature swing associated with the transient.

The spray demand for each attemperator is compared to its measured flow, to develop the demand for each attemperator flow control valve. A block valve associated with each attemperator control valve is interlocked to close whenever its control valve is demanded closed.

5.2.1.5.4 Panel Bias Valve Control. Each of the 12 superheater panels has a bias valve at its inlet controlled by a deadbanded proportional controller. These valves, under normal temperature conditions, are throttled to approximately 70 per cent open. If, during a transient, the outlet temperature exceeds the deadband, the valve is repositioned to divert flow away from a cold panel or increase flow in a hot panel. If the demand for panel bias valve opening exceeds a predetermined amount, a proportional demand signal is provided to the mirror field control for directing some heliostat groups away from the hot flow path.

5.2.1.6 Arrangement of Receiver. The general arrangement of the receiver in sectional side view is depicted on Figure 5-20. The drum is suspended from the top girders by U-shaped support rods. This is a standard B&W construction used on fossil power boilers. The columns and the levels of horizontal trusses are also shown. The steam generator panels of the type described before with their horizontal and vertical buckstays are indicated on the extreme left side of the drawing. The panels are supported directly from the main structural support. The revolving crane and the hoist are shown in the top housing. The closure doors are shown in their stowed position (receiver operating). A plan view of the main receiver at drum elevation is shown on Figure 5-21.

5.2.1.6.1 Closure Doors. The advantages of the external receiver are enhanced by the use of closure doors. These insulating doors reduce the cooldown rate of the pressure parts when there is no solar input, as shown in Figure 5-22.

Several designs of doors were briefly investigated. The most viable design consists of two curved, insulated, tambour type, sliding doors moving on trolleys over the absorber surface of the receiver. In closed position, one shell covers the east half of the receiver tubes, and the other shell covers the west half. The two shells move on rails

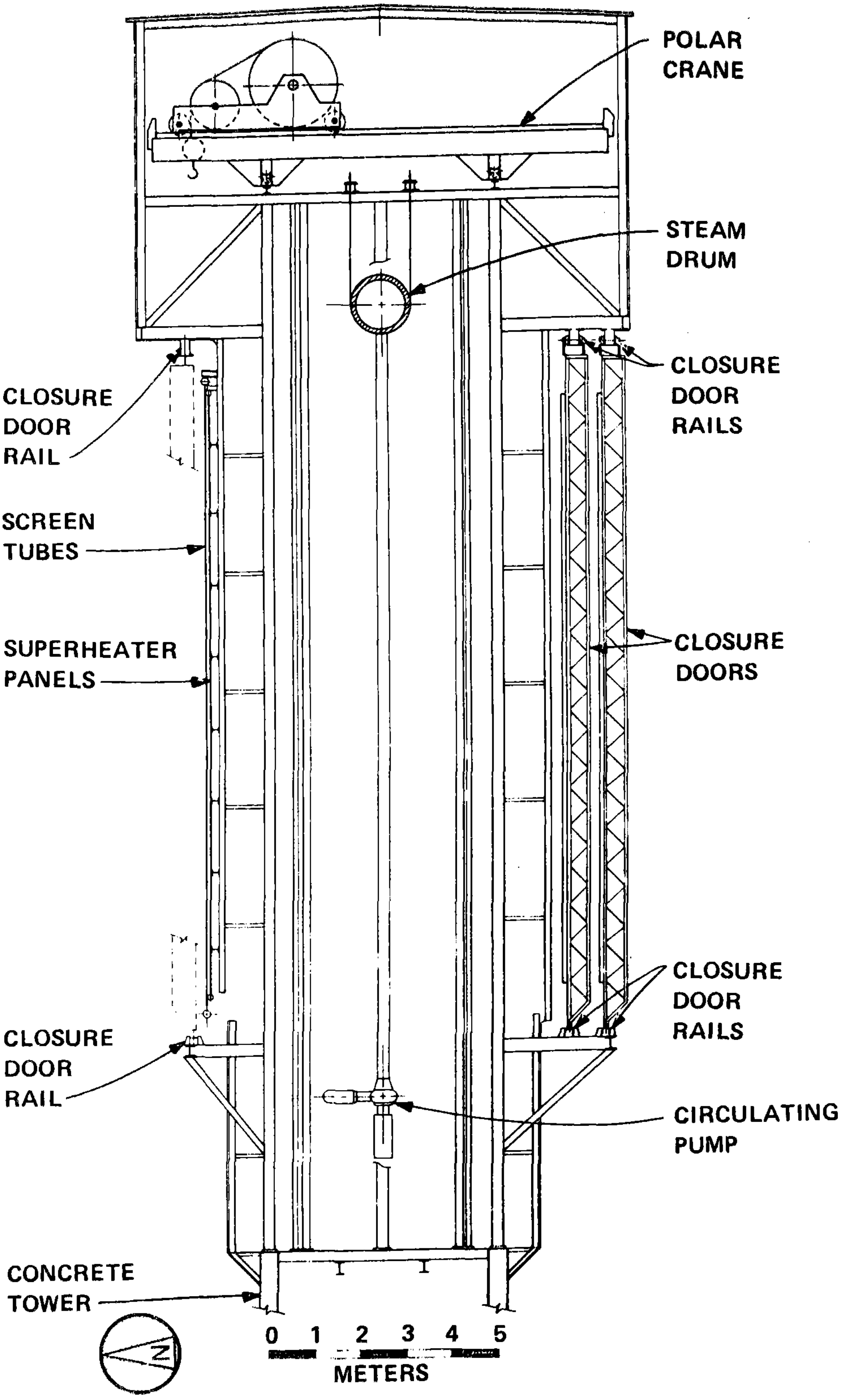


FIGURE 5-20. RECEIVER ELEVATION

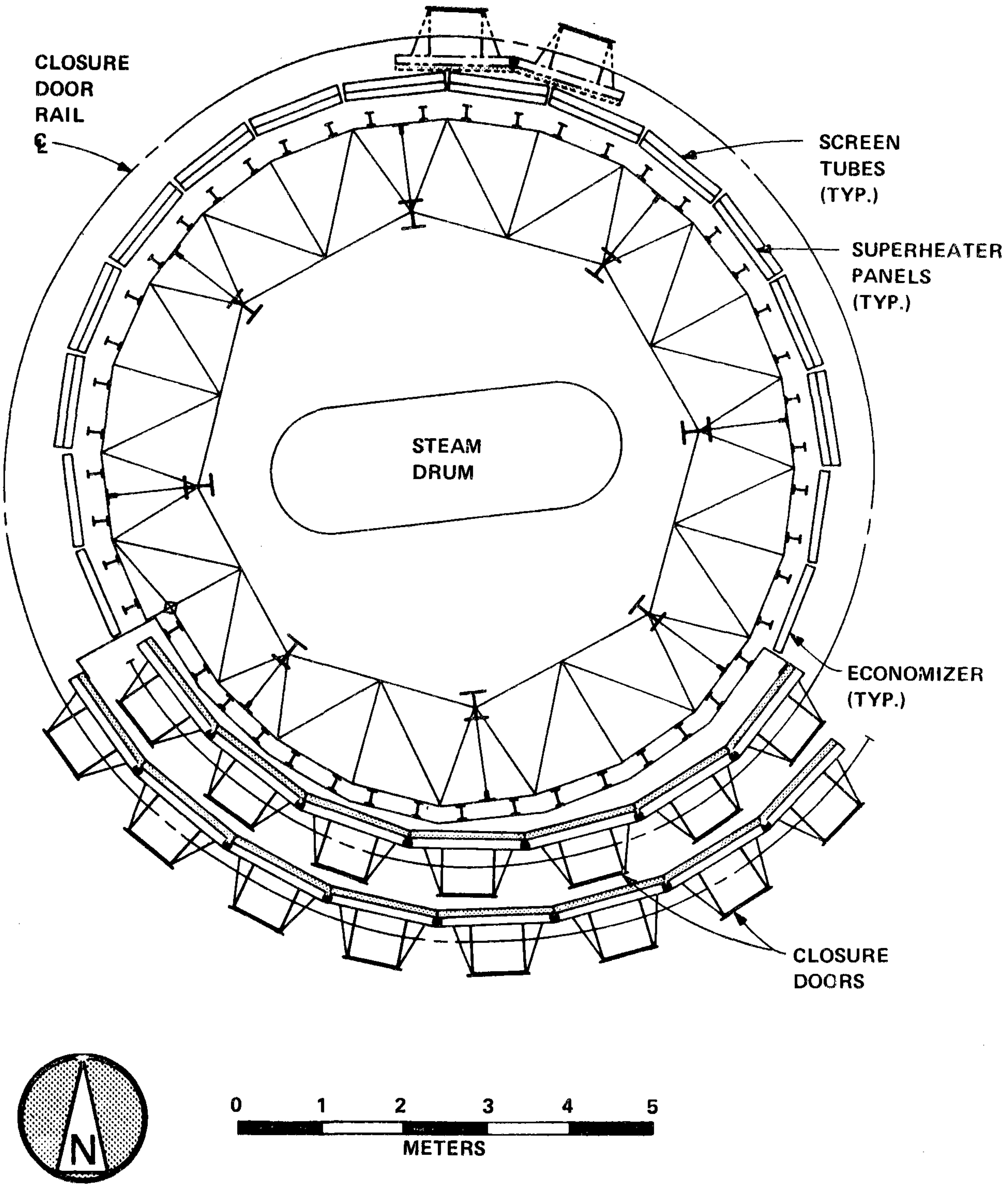


FIGURE 5-21. RECEIVER PLAN AT DRUM LEVEL

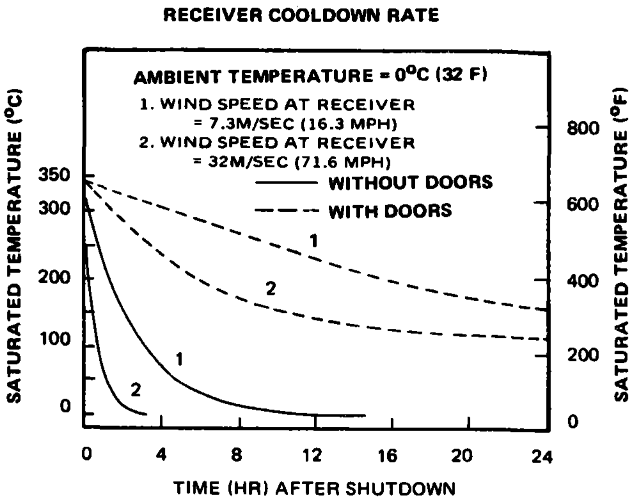


FIGURE 5-22. RECEIVER COOLDOWN CHARACTERISTICS

attached to the receiver support structure. The door consists of 1.4 m (4 ft, 7 in) wide panels about 17.7 m (58 ft) long, each made of standard steel joists, cross-braced for stiffness. The panels are hinged together. Seven panels form the east door, and eight panels make up the west door. A trolley drive, operated by a 5.6 kW (7.5 hp) electric motor, will move the door into open or closed position. The door hangs on the upper rails and is guided in the bottom rails.

For structural reasons, the doors are designed to be very stiff, in order not to deflect, warp, or wobble excessively under gusty winds, which could cause them to hit and damage the receiver tubes. The weight of the two doors with 0.13-metre (5-inch) insulation is about 63,000 kg (140 kips). The additional weight of support steel is over 27,000 kg (60 kips). Thus, the door adds more than 90,000 kg (200 kips) to the overall weight of the receiver.

No detailed evaluation was performed on the benefits that can be obtained from the use of the doors. A rough estimate indicated that the value of the daily saving on energy would not pay for the additional cost of the doors; however, by including the cost of nitrogen required for blanketing the receiver without doors during overnight shutdown, and considering the improved operation (easier for operator to start up solar receiver), the closure doors appear to be beneficial.

5.2.1.6.2 Support Structure. The main support steel for the external solar receiver consists of the structural components required to carry the receiver weight, the hoist, ice load, wind load, and seismic effects. The receiver components and the support structure are designed to withstand UBC Zone I earthquake conditions or 47 m/s (105 mph) gusts at ground level (exponentially increased for height). The design was performed only on a level required to obtain a cost estimate.

The receiver is suspended from a steel grid made up of large girders attached to eight vertical columns. The columns are equally spaced on a 6.1-metre (20-foot) diameter circle and are anchored to a concrete base plate at the top of a jump formed concrete tower. Circular (octagonal) trusses brace the columns at several elevations. Every other bay between the columns is diagonally braced for stability and to transfer the loads to the tower. A schematic arrangement of the column and bracing is shown on Figure 5-23, which also shows a typical horizontal truss.

At the top of the structural steel, there is a revolving crane with a hoist capable of lifting 9,000 kg (10 tons) from ground level to the top of the columns. The hoist is of the type used in coal mines. The crane and hoist are housed in the top enclosure, which is covered with a slightly conical roof.

Platforms, stairs, and railing are provided around the drum, pump, headers, valves, and crane to facilitate inspection, operation, and maintenance.

5.2.1.7 Start-up and Shutdown Procedures. Several start-up and shutdown scenarios must be accommodated due to the unpredictable nature of insolation. For each scenario identified, a step-wise procedure is described.

5.2.1.7.1 Morning Start-Up (Receiver Cold). The primary consideration for start-up in the morning following a prolonged shutdown (greater than overnight) is to prewarm the receiver with feedwater from the turbine

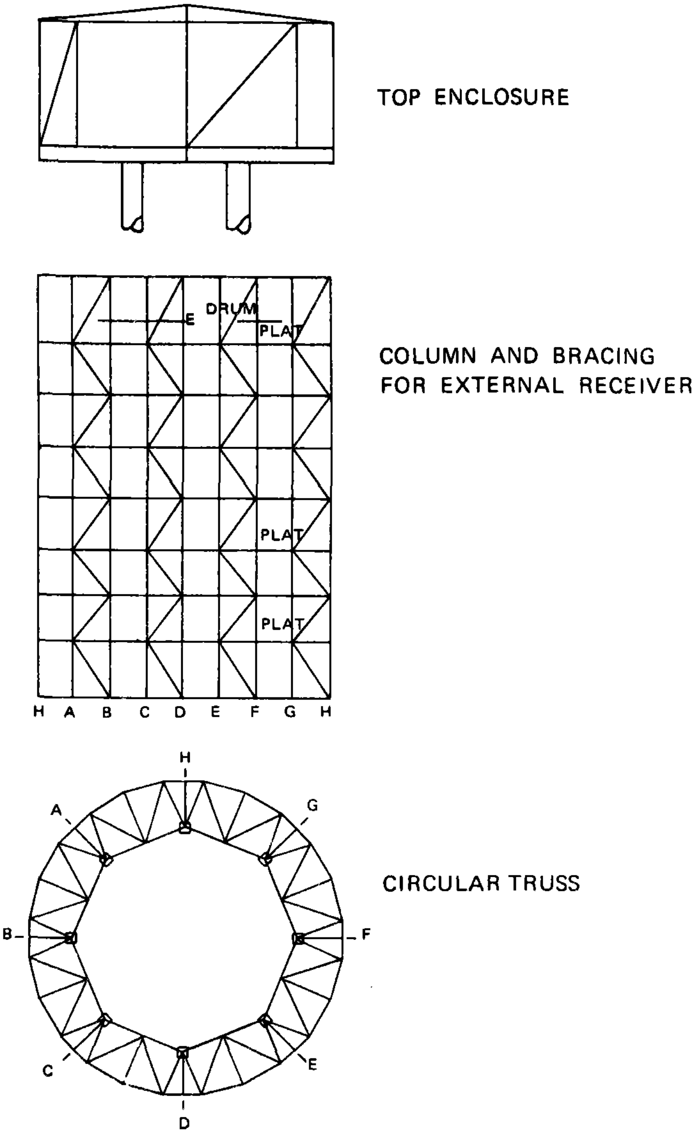


FIGURE 5-23. RECEIVER SUPPORT STRUCTURE

cycle or with main steam from the fossil boiler, to allow complete solar insolation at sunrise. The initial conditions of the receiver are near ambient temperature with a nitrogen blanket at slightly above atmospheric pressure. The warm-up procedure brings the receiver to main steam line pressure and saturation temperature by sunrise.

Although feedwater can be used to prewarm the receiver, the expected trends during cold start-up of steam consumption, energy required, receiver pressurization, and temperature are shown on Figure 5-24. In this case, fossil energy system main steam at 12.5 MPa (1,800 psi) and 538 C (1,000 F) is utilized to provide about 13 MWh (44 x 10^6 Btu) of energy to the solar receiver via the main steam line. About 17,500 kg (38,700 lb) of steam are needed to heat up the receiver metal and fluid and to overcome losses to the surroundings.

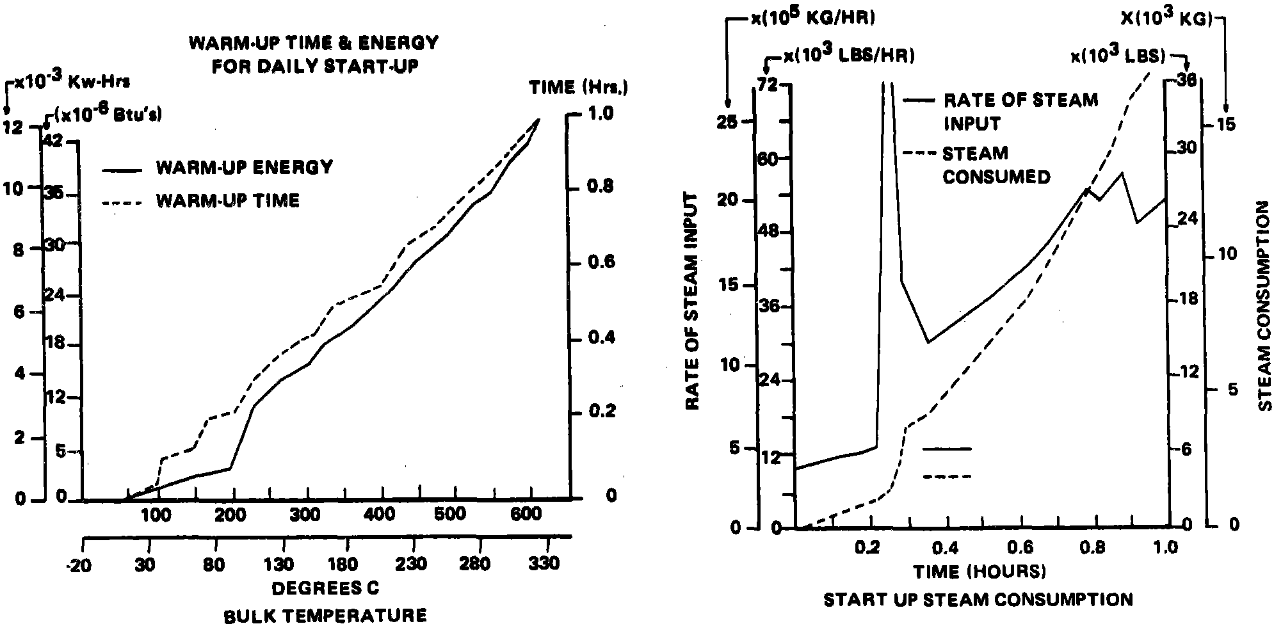
First, the boiler circulation system is heated from ambient to 100 C (212 F) saturation temperature. At 100 C, the superheater is heated by admitting steam through vent valves and removing condensate through drain traps. Then, the circulation system and the superheater are warmed up to 538 C (620 F) together. This accomplishes a cost savings in energy by reducing radiation and convection losses to the surroundings.

Additional start-up equipment required for a solar receiver are a steam sparger inductor to warm-up the boiler water and circulation system, a drum level dump valve, superheater condensate traps, and a warm-up valve to control rate of pressurization.

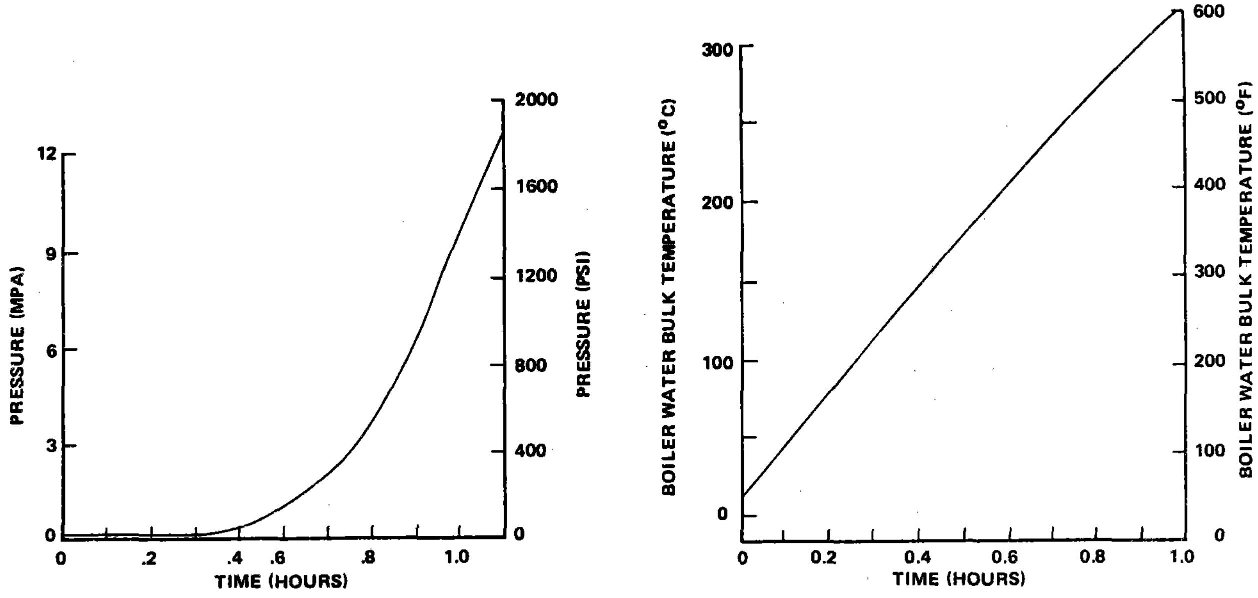
The sequence for cold start-up is shown in Table 5-5.

5.2.1.7.2 Morning Start-up (Receiver Warm). The flow sequence and valves used in the start-up procedure are shown on Figure 5-25. A complete listing and description of the receiver valves are given in Table 5-6. The receiver themal energy is banked overnight by using the closure doors to reduce losses. As shown on Figure 5-22, the initial conditions for morning start-up may vary from 0.172 MPa (25 psia) and 115.6 C (240 F) to 1.72 MPa (250 psia) and 205 C (400 F), depending on ambient conditions.

The fossil steam generator supplies 8.8 MWh (30 x 10^6 Btu) of energy, using about 13,600 kg (30,000 lb) of main steam to warm up the solar receiver to saturation temperature, and pressurize it corresponding to steam line pressure existing at sunrise. The closure door is opened just prior to sunrise, with the receiver at conditions such that it can accept solar insolation.



START UP STEAM CONSUMPTION



START UP PRESSURIZATION

RECEIVER START UP TEMPERATURE

FIGURE 5-24. RECEIVER WARM-UP DATA AT START-UP

TABLE 5-5. START-UP SEQUENCE--RECEIVER COLD

(1) Vent and fill to slightly above normal water level with feedwater (mix as required to match within 65 C (150 F) of bottom lower drum metal temperatures).

(2) Open economizer circulation valve E, superheater drains, and trap system H. Superheater steam vent valve F remains closed until drum is warmed to saturation 100 C (212 F).

(3) Start boiler circulating pumps.

(4) Close nitrogen blanketing valves, open turbine end main steam stop valve, open warm-up valve B, and control prewarm-up of economizer and screen at prescribed rate. Note: This valve controls pressure and, thus, saturation temperature rate of change 5.6-3.3 C/min (10-6 F/min).

(5) Steam sparger inductor valve D is used to warm up the drum, screen tubes, economizer panels, and all associated connection piping. Open valve F when the drum water reaches saturation temperature 100 C (212 F). Steam is admitted through valve F into the SH, and condensation is returned through traps at H. If SH vent to atmosphere is open, close at 0.172 MPa (25 psia).

(6) As volume of water in drum swells on warm-up, excess is dumped through G to maintain level slightly higher than normal set point (single-element controller). Note: Time to warm-up to 12.5 MPa (1,800 psi), 327 C (620 F) is about 1 hour after start of step 4, depending on ambient conditions, etc.

(7) At sunrise, open closure doors and focus heliostats on receiver. Receiver is at (12.5 MPa (1,800 psi), 327 C (620 F).

(8) Steam evaporation begins at first insolation at a rate corresponding to net power input to screen tubes and economizer. Open main steam stop valve A. Close steam sparger inductor valve D. Close superheater vent valves F. Superheat spray attemperators must be available for use.

TABLE 5-5 (Continued). START-UP SEQUENCE--RECEIVER COLD

(9) Drum level dump valve G should be closed (automatically) as steam flow occurs. The feedwater flow is started when drum level drops below normal. Economizer circulation valve E is closed as this occurs. Drum level control is automatic.

(10) The warm-up valve B and superheater drains H are closed.

TABLE 5-6. LIST OF RECEIVER VALVES

Number	Service	Type	Operator*	Size m (in)	Quantity
1	Feedwater Regulator	Globe	Control	0.15 (6)	1
2	Feedwater Stop	Gate	Motor	0.15 (6)	1
3	Feedwater Check	Nonreturn		0.15 (6)	1
4	Economizer Drain	Globe	Motor	0.025 (1)	1
5	Economizer Pressure Test	Globe		0.025 (1)	2
6	Economizer Vent	Globe		0.025 (1)	2
7	Drum Atmospheric Vent	Globe	Motor	0.025 (1)	2
8	Drum Safety Valve	Safety	Spring	0.076 (3)	1
9	Drum Pressure Test	Globe		0.025 (1)	2
10	Drum Pressure	Globe		0.025 (1)	2
11	Drum Nitrogen	Globe	Motor	0.025 (1)	1
12	Steam Sampling	Globe		0.025 (1)	2
13	Continuous Blowdown	Globe	Motor	0.025 (1)	2
14	Chemical Feed	Globe		0.025 (1)	2
15	Water Sampling	Globe		0.025 (1)	2
16	Remote Level Transmitter	Globe		0.013 (1/2)	4
17	Water Gage Glass	Globe		0.013 (1/2)	2
18	Water Gage Drain	Globe		0.013 (1/2)	2
19	Drum Level Dump Shut-Off	Gate	Motor	0.051 (2)	1
20	Drum Level Dump	Globe	Control	0.051 (2)	1
21	Pump Auxiliary	Globe		0.025 (1)	20
22	Sparger Check	Nonreturn	Motor	0.038 (1-1/2)	1
23	Sparger	Globe	Control	0.038 (1-1/2)	1
24	Receiver Blowdown	Globe	Motor	0.025 (1)	3
25	Economizer Circulation	Nonreturn	Motor	0.038 (1-1/2)	1
26	Attemperator Block	Gate	Motor	0.038 (1-1/2)	8
27	Attemperator Spray	Globe	Control	0.038 (1-1/2)	4
28	Attemperator Check	Nonreturn		0.038 (1-1/2)	4
29	PSH Panel	Butterfly	Control	0.076 (3)	4
30	ISH Panel	Butterfly	Control	0.076 (3)	4
31	SSH Panel	Butterfly	Control	0.076 (3)	4
32	SH Vents	Globe	Motor	0.025 (1)	6
33	SH Vent Shut-Off	Globe	Motor	0.051 (2)	1
34	SH Nitrogen	Globe	Motor	0.025 (1)	2
35	SH Drain	Globe	Motor	0.025 (1)	6
36	SH Drain Shut-Off	Globe	Motor	0.038 (1-1/2)	1
37	SH Trap	Trap		0.025 (1)	6
38	MS Pressure Test	Globe		0.025 (1)	2
39	MS Safety Valve	Safety	Spring	0.064 (2-1/2)	1
40	MS Electromagnetic Shut-Off	Gate	Motor	0.076 (3)	1
41	MS Electromatic	Relief	Electric	0.064 (2-1/2)	1
42	MS Stop Valve	Gate	Motor	0.25 (10)	1
43	Warm-Up, Shut-Off Valve	Gate	Motor	0.076 (3)	1
44	Warm-Up Valve	Globe	Control	0.076 (3)	1

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*Manual if not otherwise denoted.

PSH--Primary Superheater, ISH--Intermediate Superheater, SSH--Secondary Superheater, SH--Superheater, MS--Main Steam

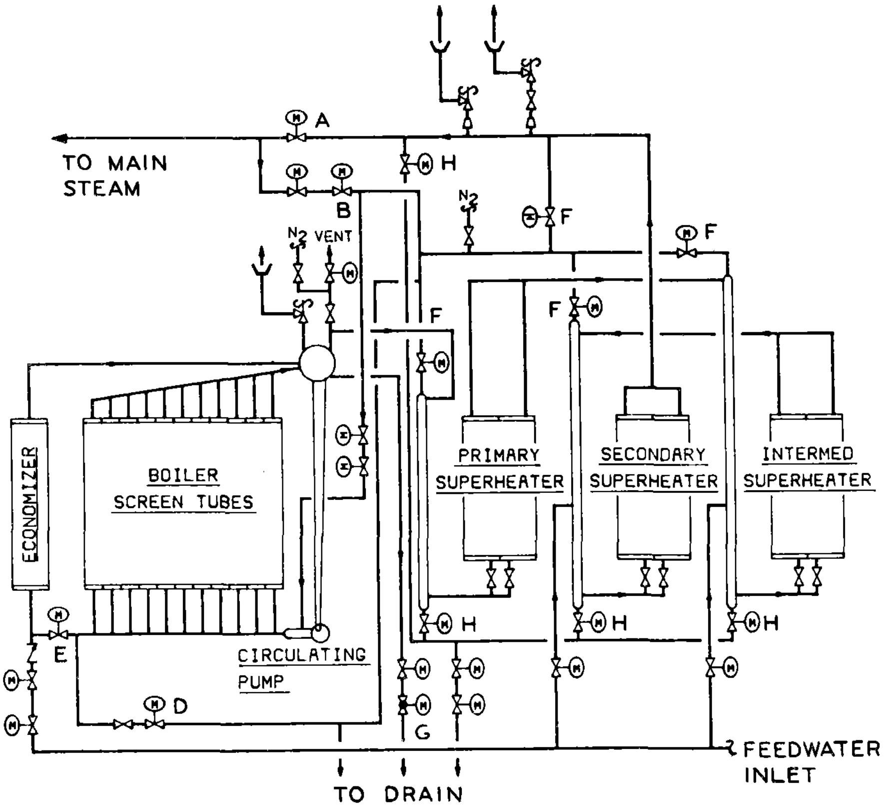

FIGURE 5-25. SCHEMATIC LOCATION OF KEY RECEIVER VALVES

The sequence for warm start-up (with the closure doors) is listed in Table 5-7.

5.2.1.7.3 Mid-Day Start-Up. For start-up after sunrise, selective heliostat focusing is required to duplicate the morning solar power input to the receiver. Other procedures are the same as either the cold or warm morning start-up procedures.

5.2.1.7.4 Variable Pressure Start-Up. When variable throttle pressure control is utilized, the receiver warm-up to match the main steam line pressure at the turbine can proceed in a shorter period of time with lower requirements for fossil-supplied energy. In addition, solar energy is used earlier to overcome the heat capacity effects, to increase steam conditions along with the throttle pressure ramp.

TABLE 5-7. START-UP SEQUENCE--RECEIVER WARM

1. Establish circulation with boiler circulating pump. Make sure economizer circulation valve E, superheater drains, and trap system H are open.
2. Open superheater vent valve F. Open warm-up valve B and sparger inductor valve D. Pressurization and saturation temperature are controlled at a prescribed rate of change.
3. As volume of water in drum swells on warm-up, excess is dumped through G to maintain level slightly higher than normal set point (single-element controller).
4. The closure doors are opened just prior to sunrise, when the receiver attains steam line pressure and is ready to accept solar energy.
5. At sunrise, open the main steam stop valve A, close steam sparger inductor valve D. Close superheater vent valve F. Superheat spray attemperators must be available for use.
6. Drum level dump valve G should be closed (automatically) as steam flow occurs. The feedwater flow is started when drum level drops below normal. Economizer circulation valve E is closed as this occurs. Drum level control is switched to the three-element control for normal operation.
7. The warm-up valve B and superheater drain H are closed.

5.2.1.7.5 Shutdown Procedures. The receiver is shut down by reducing the solar insolation due to either sunset or selected defocusing of heliostats. As steaming capacity is reduced, the load supplied by the solar receiver is carried by the fossil boiler. A steady load demand on the turbine will aid in an orderly transfer of load between the receiver and fossil boiler.

At the point of minimum solar energy input, the main steam stop valve A can be shut and the closure doors shut. As the receiver cools and the drum water level shrinks, feedwater is required to maintain desired level.

The receiver will usually be either banked to conserve energy or cooled and drained to prevent freezing. When the receiver pressure drops below 0.11 MPa (16 psia) or when the unit is to be put into storage, wet or dry, a nitrogen blanket is admitted to the superheater and drum vents to protect those surfaces from corrosion. Normal idle boiler lay-up techniques should be followed.

5.2.1.7.6 Draining Criteria. The surface temperature of the receiver can dramatically decrease during the night, especially in the cold and windy winter time. It is possible that, without circulating turbine cycle feedwater through the receiver, the surface temperature and the water in the receiver will reach, and even drop below, the freezing temperature of water. Advanced planning with knowledge of the criteria for draining is required to avoid freezing. The steady-state limiting curve for draining the receiver in terms of wind speed and ambient air is shown in Figure 5-26; the advantage of the closure doors is also shown in the figure. The region under the curve is defined as the draining region.

5.2.1.8 Receiver Cost and Weight Estimate. An estimate of the weight and cost of the various components of the external receiver with closure doors is listed in Table 5-8. The estimate was performed using the Babcock & Wilcox Company's experience in the design and manufacture of steam generating equipment.

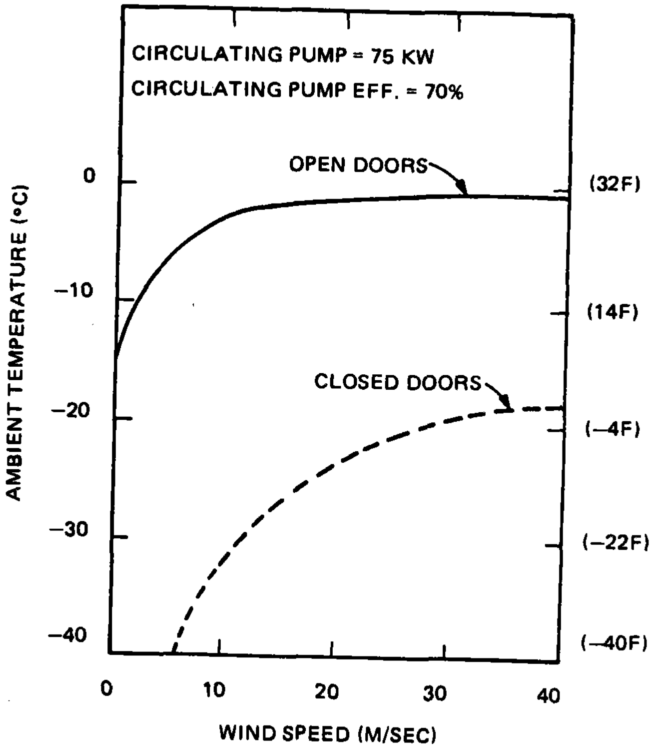

FIGURE 5-26. RECEIVER DRAINING REQUIREMENTS VERSUS AMBIENT CONDITIONS

Estimates of material for the steam generator, structural steel, and other associated equipment are based on current material costs from vendor quotes or catalog prices. Labor for shop fabrication is based on consolidated data for shop fabrication of similar type equipment. Labor costs reflect current wage rates at Babcock & Wilcox Company manufacturing facilities.

Cost estimates for pumps, valves, controls, and other accessory items are based on vendor quotations, catalog prices, and historical data for cost of similar equipment.

Transportation costs are based on current freight rates for delivery of equipment to the Oklahoma area. Costing of field construction of the receiver support structure and installation of the absorber pressure parts with associated equipment was done using the Babcock & Wilcox Company's expertise in construction and installation of steam generating and other various types of equipment. Estimates were based primarily on

TABLE 5-8. COST AND WEIGHT ESTIMATE FOR EXTERNAL RECEIVER WITH CLOSURE DOORS

	Weight		Price
	(1,000 kg)	(1,000 lb)	($1,000)
Boiler and Mountings	73	160	1,050
Circulating Pump and Motor	5	11	240
Economizer	11	25	70
Superheater and Piping	74	164	2,700
Controls	18	40	480
Insulation and Lagging*	136	300	630
Structural Steel, Platforms, and Crane	277	610	510
Casing and Siding	73	160	150
Closure Door (with insulation)	63	140	400
Working Fluid	15	33	
Engineering			1,000
Freight			50
Erection**			2,350
	775	1,643	9,630

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*Field applied.

**Erection based on labor rate of $18/h.

basic and historical data for construction and installation of steam generating and other similar equipment. The field labor cost of $18/h reflects current prevailing construction rates for the Tulsa, Oklahoma area.

5.2.2 Receiver Support Tower

The solar receiver will be supported atop a reinforced concrete tower as shown in Figure 5-27. This tower will be designed as a circular shell, similar to a chimney, to resist gravitational, winds, and seismic loads. In addition to supporting the solar receiver, the tower will house electrical equipment, piping, and accessories.

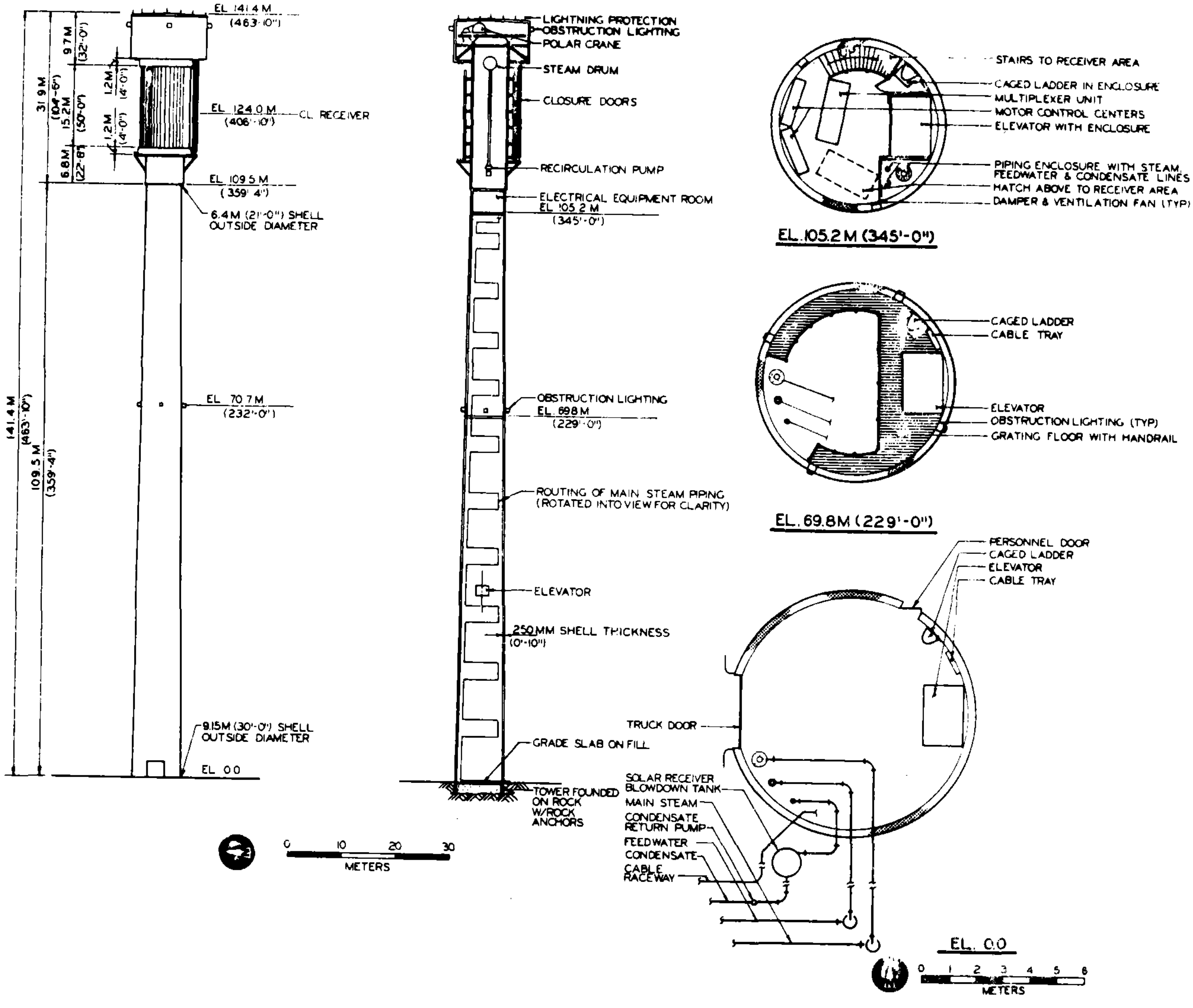


FIGURE 5-27. RECEIVER TOWER

5.2.2.1 Structural Design of Tower. The support tower will be 109.5 metres (359 feet, 4 inches) high above grade, tapering from 9.145 metres (30 feet, 0 inches) in diameter at the base to 6.40 metres (21 feet, 0 inches) in diameter at the top. The shell will have a uniform thickness of 250 mm (10 inches). The tower will be founded on the competent limestone, approximately 2.0 metres (6 feet, 0 inches) below grade. Rock anchors will resist overturning moments. A grade slab will bear on structural backfill inside the tower. Eight structural steel columns will carry the solar receiver loads to baseplates embedded in the top surface of the support tower; the shell near the top will be locally thickened to approximately 450 mm (18 inches). Reinforced concrete platforms at Elevation 109.5 metres (359 feet, 4 inches) and Elevation 105.2 metres (345 feet, 0 inches) will be supported on structural steel framing, which is fixed to the walls of the tower. A partial floor at Elevation 69.8 metres (229 feet, 0 inches) is comprised of grating on structural steel framing.

5.2.2.2 Tower Accessories and Equipment. Tower accessories include an elevator, caged ladder, interior platforms, polar crane, lightning protection, interior lighting, aircraft obstruction lighting, communications equipment, and a ventilation system. Adjacent to the tower is a prefabricated metal building housing electrical equipment which could not be economically housed within the tower: switchgear, diesel generator, and batteries and charger. Also, outside the tower are the main transformer and a blowdown tank and pump for the condensate return piping.

Piping is conventionally supported from the tower walls. The main steam line will require numerous expansion loops, as indicated in Figure 5-27. The feedwater piping will require only one-third as many loops as the main steam.

Power and control cables will be supported on a cable tray attached to the tower wall. The electrical equipment room accommodates motor control centers and multiplexers in a partially controlled environment. The room is sealed off from updrafts due to the chimney effect, and provided with ventilation fans and dampers.

Access to the electrical equipment room near the top of the receiver support tower is provided by an elevator within the tower interior. Because of space limitations, the elevator is a small, light-duty elevator for personnel and light equipment transport. The elevator platform is approximately 1.0 metres by 1.9 metres (3 feet, 4 inches by 6 feet, 4 inches), with capacity for 1,000 kg (2,200 lb). A caged ladder, within the tower interior, also provides personnel access from grade to the electrical equipment room, providing a backup to the elevator. From this electrical equipment room to the solar receiver atop the tower, access is provided by a stairway.

Small equipment and components are lifted from the electrical room to the receiver elevation above the tower interior by a chain hoist, supported from the receiver support structural steel. This hoist will be employed to lift repair equipment and replacement parts or components, weighing no more than 1,000 kg (2,200 lb) (elevator capacity), needed at the receiver elevation; replacement boiler tubes and superheater panels will not be handled by this hoist, but by the polar crane. During construction, a temporary derrick will be used to lift major structural and equipment components of the receiver to the top of the tower. Such major loads may be raised prior to construction of interior platforms.

A polar crane mounted atop the solar receiver will be used to lift replacement boiler tubes and superheater panels to the receiver. The polar crane telescopes radially so that it can be withdrawn to be within the outer diameter of the receiver, avoiding exposure to spillage or misdirected solar energy. The polar crane rotates on rails about the vertical axis of the receiver for a full 360 degrees, providing full access to all superheater panels and boiler tubes of the receiver. Equipped with a scaffold, the polar crane will permit close inspection of the solar receiver's surface and, when required, resurfacing of the receiver's high-absorptivity coating.

Four flashing, high-intensity white obstruction lights are provided near the top and mid-height of the tower. Conventional lighting is provided at all platforms, adjacent to the caged ladder, within the elevator, and within the prefabricated metal building.

Lightning protection is comprised of air terminals spaced approximately 2.4 metres (8 feet, 0 inches) apart around the perimeter of the roof over the receiver, two interconnected down conductors, and a ground loop around the tower below grade.

5.3 RECEIVER LOOP SYSTEM

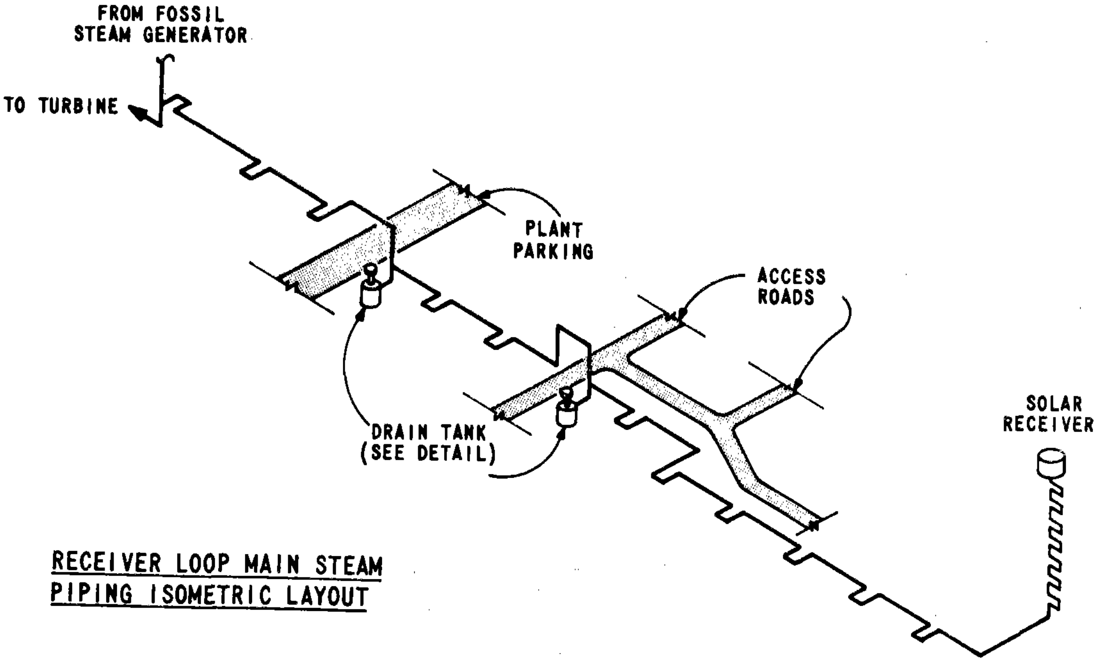
The receiver loop system provides the piping interface between the existing fossil energy system and the receiver system installed with the solar facility. The following sections describe the system and major components as well as provide the key design and operating characteristics.

5.3.1 General Description and Function

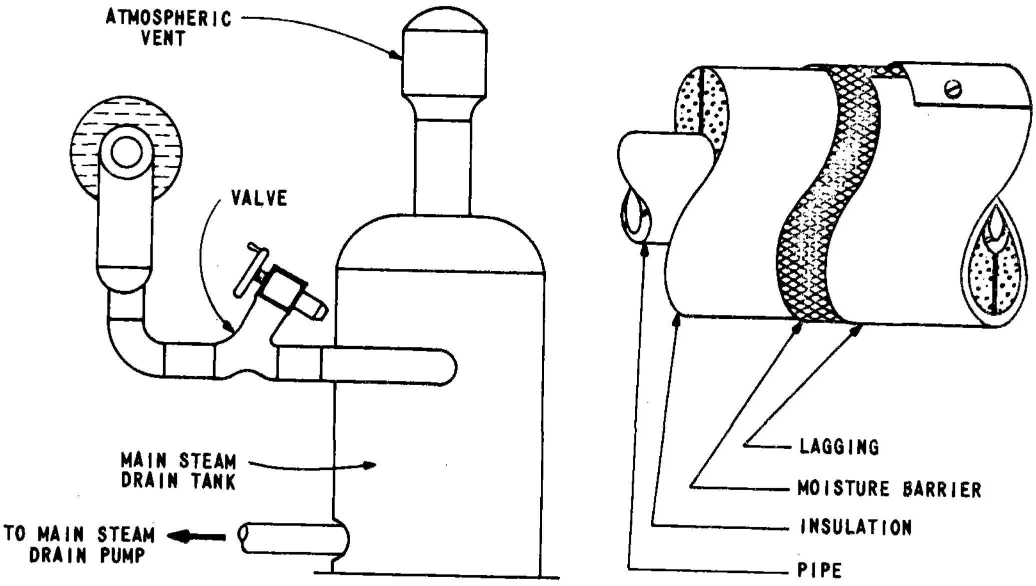
The receiver loop system, shown schematically in Figure 5-28, transports high-pressure, high-temperature solar steam from the receiver system to the existing fossil energy system for delivery to the high-pressure turbine steam chest. The receiver loop system interfaces with the receiver system at the solar receiver superheater outlet, after the superheater outlet stop valve. The receiver loop system interfaces with the fossil energy system at the connection to the existing main steam piping near the fossil steam generator.

The receiver loop system transports feedwater to the receiver system from the existing fossil energy system for solar boiler feedwater makeup, and for attemperating sprays to control solar receiver steam temperatures. The receiver loop system interfaces with the fossil energy system at the feedwater piping after the fifth feedwater heater, ahead of the fossil feedwater regulating valves. The receiver loop system interfaces with the receiver system at the receiver economizer inlet regulating valves, and attemperating spray control valves.

The receiver loop system provides for the return of drains from the receiver system to the existing fossil energy system. The receiver loop system interfaces with the receiver system at all drain piping connections. The drains recirculate feedwater during warm-up, collect condensate at saturation temperature during start-up, and drain the receiver during periods of extended shutdown. The receiver loop system interfaces



RECEIVER LOOP MAIN STEAM PIPING ISOMETRIC LAYOUT



PIPING DRAIN DETAIL

PIPING INSULATION DETAIL

FIGURE 5-28. RECEIVER LOOP MAIN STEAM PIPING ISOMETRIC with the fossil energy system at the deaerator, condenser, and existing steam generator blowdown tank. The interfaces with the deaerator and condenser allow return of condensate to the fossil cycle, and the interface with the existing blowdown tank allows for the disposal of condensate drained from the receiver.

The installation incorporates features to assure the draining of all collected condensate from main steam piping, prior to opening of the solar main steam stop valve, to prohibit the potentially damaging introduction of water into the turbine unit. Provisions are in accordance with the turbine generator manufacturer's instructions, with consideration given to the significant lengths of piping involved in comparison to representative fossil installations. Water induction results from the accumulation in steam piping of water that is inadvertently delivered to the turbine. The water accumulation may be due to condensate in steam piping, or water carry-over from attemperating sprays in the superheater caused by abnormal valve operation. Features incorporated to prevent the induction of water to the turbine include steam piping insolation valves, steam pipe drain lines to remove condensate, and redundant spray water isolation valves.

Drains from the receiver and drains from main steam piping near the receiver are taken to the solar receiver blowdown tank located near the receiver base. Drains from the main steam piping near Unit I are taken to the existing fossil energy system blowdown tank. Drains from the interconnecting main steam piping in the yard area are taken to main steam drain tanks located adjacent to the piping at drain points. Condensate collected in the solar receiver blowdown tank and in the main steam drain tanks is pumped by the condensate return pumps or main steam drain pump to the existing fossil blowdown tank for disposal, or alternatively, the condensate is returned to the existing fossil energy system condenser or deaerator. The receiver loop system includes chemical feed additive equipment for chemical treatment of the solar receiver water. The receiver loop system also includes filtering equipment for removal of chemical solids from the condensate returned to the fossil energy system condenser and deaerator.

5.3.2 Major Equipment Description

The major equipment included with the receiver loop system will be as described herein.

A condensate return pump will be required to return condensate from the solar receiver blowdown tank to the existing fossil system. The pump will be a full-capacity centrifugal pump rated to deliver 0.011 m^3/sec (175 gpm) at 61 metres (200 feet) head. The pump will be designed for pumping saturated liquid at 100 C (212 F), with the casing design conditions of 0.45 MPa (50 psi) at 121 C (250 F). The pump will be electric motor-driven with a motor horsepower of approximately 7.5 kW (10 hp).

Two main steam drain pumps will be required to return condensate from the main steam drain tanks to the existing fossil unit. The pumps will be designed for pumping saturated liquid at 100 C (212 F), with the casing design conditions of 0.45 MPa (50 psi) and 121 C (250 F). The pumps will each be electric motor-driven with approximate motor horsepower ratings of 3.7 kW (5 hp).

A solar receiver blowdown tank will be required to serve the solar receiver drains and the main steam pipe drain near the receiver. The tank will be of carbon steel construction, with in internal stainless steel wear plate at the inlet connection. The tank will vent to atmosphere, and will drain to the condensate return pump. The tank will be approximately 1.2 metres (48 inches) in diameter and 2.1 metres (84 inches) tall.

Two main steam drain tanks will be required to serve the two main steam pipe yard area drains. The tanks will be of carbon steel construction, with an internal stainless steel wear plate at the inlet connection. The tanks will vent to atmosphere, and will drain to the main steam drain pumps. The tanks will be approximately 0.9 metres (36 inches) in diameter and 2.1 metres (84 inches) tall.

Condensate filtering equipment will be required to remove chemical solids from water returned from the solar receiver to the existing deaerator or condenser. The equipment will include redundant, full-capacity, regenerative type filters. The filter pressure vessels will be designed for operation at 0.79 MPa (100 psi) and 121 C (250 F). The filtering equipment will include bypass, isolation, and drain valves and piping as required to facilitate operation.

Chemical feed equipment will be required for the addition of chemicals to the receiver feedwater makeup to control receiver water chemistry. The equipment will include a chemical solution tank suitable for batch mixing, a chemical solution tank mixer, and a chemical feed pump. The chemical feed pump will be a diaphragm type pump rated to deliver approximately 10^{-6} m^3/sec (1 gph) at 21.0 MPa (3,025 psi) from the solution tank to the feedwater piping.

5.3.3 Piping and Valve Design Characteristics

The receiver loop system piping and valves will be designed in accordance with the ANSI Power Piping Code, B31.1.

The loop system main steam piping design conditions are based on the maximum expected sustained presure at the piping inlet, plus a suitable margin, as follows.

Design pressure	14.86 MPa (2,140 psi)
Design temperature	549 C (1,020 F)

The main steam piping wall thickness and pipe diameter are selected to achieve a reasonable fluid velocity, and to limit the piping pressure drop to a value that is compatible with the pressure requirements at the interfaces with the receiver and fossil energy systems. The main steam pipe selected is as follows.

Material	ASTM A335 Grade P22 seamless 2-1/4 chrome, 1 per cent moly allow steel
Size	0.25-metre (10-inch) piping with 0.21-metre (8.250-inch) ID and 0.037-metre (1.472-inch) minimum wall
Insulation	0.15-metre (6-inch) thickness with bright metal jacketing
Length	1,612 metres (5,289 feet)

The loop system feedwater piping design conditions are based on the maximum system pressure at feedwater pump shut-off operation as follows.

Design pressure	21.38 MPa (3,085 psi)
Design temperature	260 C (500 F)

The feedwater piping size is selected from standard piping sizes with nominal wall thickness. The allowable feedwater piping pressure drop is compatible with the requirements at the interfaces with the receiver and fossil energy systems. The feedwater piping selected is as follows.

Material	ASTM A106 Grade B carbon steel
Size	0.15-metre (6-inch) piping with double extra strong wall thickness
Insulation	0.06-metre (2-1/2-inch) thickness with bright metal jacketing
Length	1,337 metres (4,387 feet)

The loop system condensate drain piping design is based on the maximum expected return water conditions as follows.

Design pressure	0.79 MPa (100 psi)
Design temperature	121 C (250 F)

The condensate piping size is selected from standard piping sizes with nominal wall thickness. The condensate piping selected is as follows.

Material	ASTM A106 Grade B carbon steel
Size	0.10-metre (4-inch) piping with standard weight wall thickness
Insulation	0.06-metre (2-1/2-inch) thickness with bright metal jacketing
Length	1,337 meters (4,387 feet)

The main steam, feedwater, and condensate piping include sufficient length to provide expansion loops required to accommodate the thermal growth resulting from warming of the pipes from ambient temperature to operating temperature conditions.

The valves included with the receiver loop system will be as indicated herein. Valves for main steam service will be ANSI B16.34 Class

2500 valves with the body constructed of materials equivalent to ASTM A217 Grade WC9 (2-1/4 chrome, 1 per cent moly allow steel). Valves for feedwater service will be ANSI B16.34 Class 2500 valves, with the body constructed of materials equivalent to ASTM A216 Grade WCB (carbon steel). Valves for condensate service will be ANSI B16.34 Class 150 for 0.06-metre (2-1/2-inch) and larger valves, and Class 600 for 0.05-metre (2-inch) and smaller valves. Valve body materials will be equivalent to ASTM A216 Grade WCB (carbon steel). All valves size 0.06-metre (2-1/2-inch) and larger will have butt-welding ends, and all valves size 0.05-metre (2-inch) and smaller will have socket-welding ends.

5.3.4 Operating Characteristics

The receiver loop system operation is based on the solar receiver operating mode. Under normal operation, feedwater is supplied to the solar receiver to maintain the proper drum level, and solar generated main steam is supplied from the solar receiver superheater outlet to the fossil energy system main steam piping. At normal operating pressure and temperature conditions, the accumulation of condensate at drain points in the receiver loop system piping is not expected. The main steam piping drains will be closed under normal operation, except for emergency conditions. The receiver blowdown tank will collect water under normal operation only if water is drained from the solar receiver drum for control of receiver chemistry. The condensate return pumps will operate during these periods of draining based on tank water level.

The steam conditions during normal operation at the solar receiver superheater outlet and at the interface with the existing main steam piping will be as required to match the existing turbine throttle steam conditions as follows. The heat loss and pressure drop through the receiver loop feedwater and steam lines are shown in Figure 5-29.

	Receiver System Interface	Fossil Energy System Interface
Flow Rate	111,241 kg/h (245,287 lb/h)	111,241 kg/h (245,287 lb/h)
Overpressure	14.86 MPa (2,155 psia)	13.7 MPa (1,996 psia)

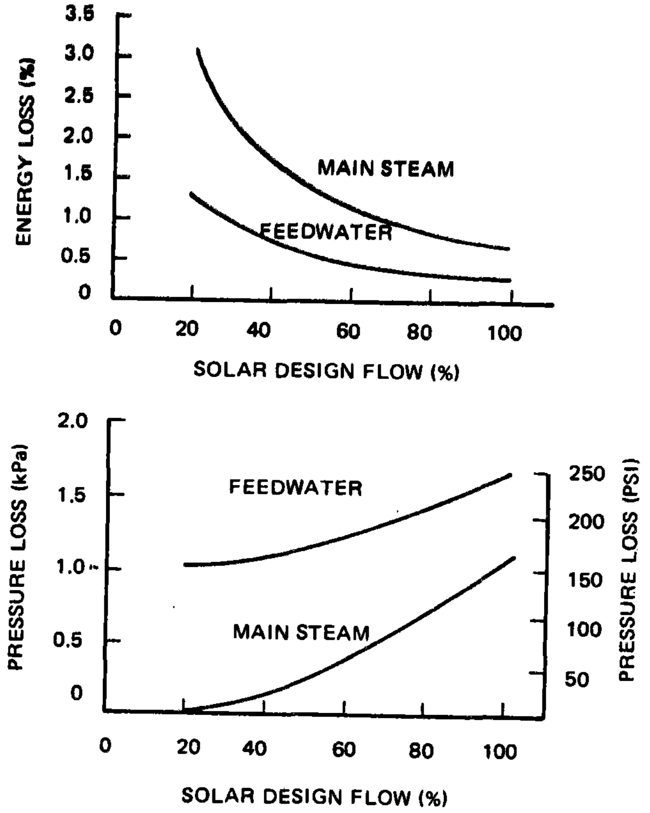


FIGURE 5-29. RECEIVER LOOP SYSTEM OPERATING CHARACTERISTICS

	Receiver System Interface	Fossil Energy System Interface
Rated Pressure	13.62 MPa (1,975 psia)	12.51 MPa (1,815 psia)
Temperature	544 C (1,011 F)	538 C (1,000 F)

The receiver loop system provides feedwater to the receiver, and returns condensate from the receiver, for receiver warming before start-up and for freeze protection during shutdown operation in winter months. After completion of pre-warming by feedwater recirculation, the loop system main steam piping provides steam from the fossil energy system for final warming of the receiver above 116 C (240 F) to within 111 C (200 F) of the full load saturation temperature (about 219 C, 426 F), in preparation for start-up. The maximum warming steam flow rate is 18, 144 kg/h (40,000 lb/h).

The maximum and minimum feedwater conditions corresponding to the required operating modes are as follows.

Normal Operation--Design Point Conditions

	Fossil Energy System Interface	Receiver System Interface
Feedwater Flow	111,241 kg/h (245,287 lb/h)	111,241 kg/h (245,287 lb/h)
Pressure	19.07 MPa (2,750 psi)	17.38 MPa (2,505 psi)
Temperature	247 C (477.2 F)	246 C (475.2 F)

Start-up and Shutdown Operation

	Fossil Energy System Interface	Receiver System Interface
Maximum Flow Condition		
Feedwater Recirculation	34,000 kg/h (75,000 lb/h)	34,000 kg/h (75,000 lb/h)
Pressure	20.93 MPa (3,020 psi)	19.79 MPa (2,855 psi)
	Fossil Energy System Interface	Receiver System Interface
Temperature	186 C (366.5 F)	185 C (365.5 F)
Minimum Flow Condition		
Feedwater Recirculation	2,300 kg/h (5,000 lb/h)	2,300 kg/h (5,000 lb/h)
Pressure	20.93 MPa (3,020 psi)	19.97 MPa (2,880 psi)
Temperature	186 C (366.5 F)	185 C (365.5 F)

During shutdown and start-up operation, condensate collected in the receiver superheater, and the main steam piping is drained to the receiver blowdown tank and main steam drain tanks. The collected condensate is pumped to the deaerator, condenser, or existing fossil steam generator blowdown tank. The draining and pumping of condensate is automatically initiated and terminated by level sensing devices at the piping drain points and in the associated tanks. Condensate returned to the deaerator or condenser is processed through filtering equipment to remove chemicals potentially carried from the receiver drum.

5.4 MASTER CONTROL SYSTEM

The Master Control System (MCS) coordinates the operations of the collector, receiver, receiver loop, and fossil energy systems to ensure safe and proper operation of the entire integrated repowered plant. The Master Control System operates at the highest level in the control hierarchy shown on Figure 5-30. The Master Control System issues commands to the control systems at the lower level of this hierarchy and receives feedback status information from these control systems. The Master Control System provides the capability for automatic start-up, normal operation, and shutdown of the collector, receiver, and receiver loop systems. The Master Control System will also issue emergency shutdown commands whenever critical process parameters exceed allowable operating limits.

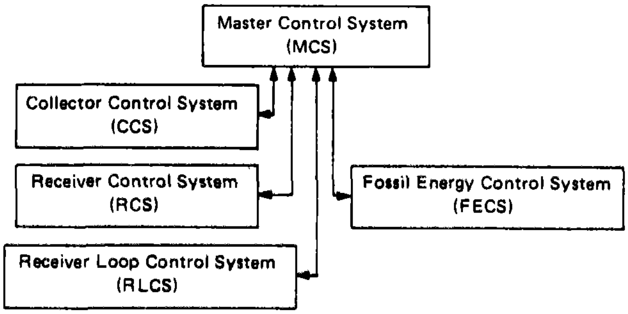


FIGURE 5-30. CONTROL SYSTEM HIERARCHY

This system will also serve as a centralized data acquisition system which monitors, analyzes, and displays all critical solar system and subsystem parameters.

Process simulation capabilities which will be used to train the power plant operating personnel will also be provided in the MCS.

5.4.1 Major Components

The Master Control System consists of a control computer, computer peripheral equipment, control and display consoles, interface equipment to the other process systems, and all software required for a fully operational system.

The hardware configuration of the MCS is shown in Figure 5-31. The basic element of the MCS will be a single mini-computer that will perform all data acquisition, control logic, and peripheral control functions. This computer will be supported by a complete set of peripherals for program editing and loading, for display of operation parameters to the operator, and for storage of data for offsite analysis. The computer will be located in a room adjacent to the control room. Remote mutliplexing equipment will be located in the receiver tower. The MCS will include a control panel, located in the Unit I control room, which will contain all displays and manual controls for operating the solar equipment.

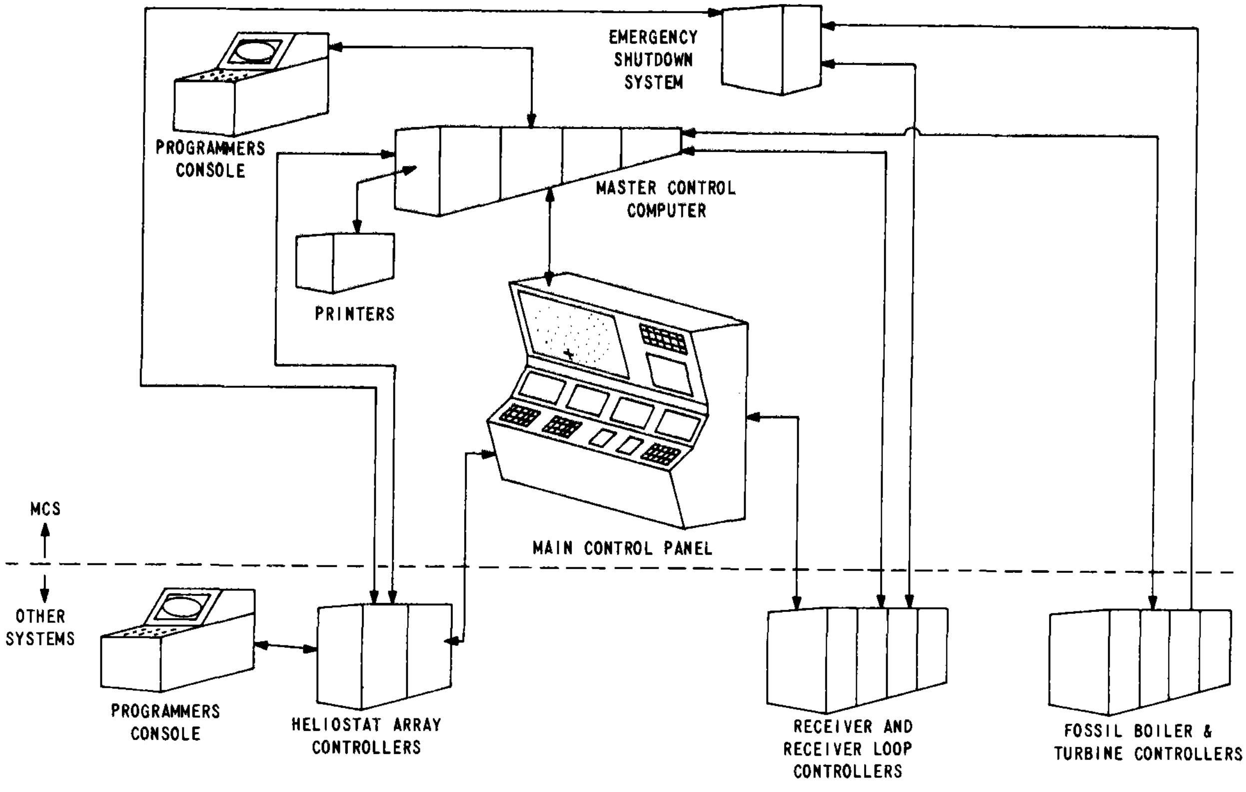


FIGURE 5-31. MASTER CONTROL SYSTEM

The MCS will be comprised of the following major hardware components.

5.4.1.1 Control Panel. The control panel is a standup bench front panel which contains all MCS, CCS, and RCS operator displays and controls. The panel includes a 1.2 metre by 1.2 metre (4 foot by 4 foot) graphic display panel which indicates, at a glance, the operational status of each heliostat. This panel is estimated to be 3 metres (10 feet wide), 2 metres (7 feet) high, and 1.2 metres (4 feet) deep.

5.4.1.2 Control Computer. The control computer is a minicomputer with 512 K words of high speed random access working memory. The central processing unit has a 32 bit parallel bus and arithmetic unit memory management system which includes the following.

- 1,024 memory mapping registers.
- Auto memory allocation hardware.
- Memory protect on 512 k word basis.
- Multi-port memory interface.
- 640 nanosecond effective cycle time.
- 15 general purpose registers.
- Bit, byte, word, double work, and file manipulation.
- Fixed and floating point arithmetic hardware.
- 174 microprogrammed instructions.
- Context switching file with 240 registers.
- 11 interrupt levels, exapndable to 16.
- Control console.
- Memory parity.
- Power Fail/Auto start.

5.4.1.3 Auxiliary Memory. A five megaword moving head disk and a four megaword drum are used as auxiliary memory for the control computer.

5.4.1.4 Programming Terminal. A console with cathode ray tube and keyboard is provided for interrogating and modifying the computer software.

5.4.1.5 Magnetic Tape Unit. An IBM compatible nine-track tape unit is provided for program entry and long-term data storage for offsite analysis.

5.4.1.6 Cathode Ray Tubes and Keyboards. Eight color intelligent CRT terminals with 64 alphaneumeric characters and 64 microprogrammed graphic characters are provided for operational data displays. The CRT's use a EIA RS-232-C compatible interface at serial rates up to 9600 BAUD. Each CRT is accompanied by an alphaneumeric keyboard and function push buttons for interactive display selection and modification.

5.4.1.7 Printers. Printers with 120 characters per second printing speed and 132-column print are provided for hard copy documentation. Each printer is complete with pedestal and enclosures.

5.4.1.8 Emergency Shutdown System. The emergency shutdown system is a hardwired relay cabinet with power supply.

5.4.1.9 Computer Input/Output System. The input/output system uses remote mutliplexing stations in the receiver tower and a digital data highway for communication between the control computer and the receiver and receiver loop systems. Asynchronous serial binary (EIA RS-232C) ports are provided with the control computer for communications to the collector system.

5.4.2 Functional Control Requirements

The MCS coordinates the independent controls of the other systems (RCS, CCS, RLCS, and FECS). The major control functions of the MCS are as follows.

- Automated start-up of the solar equipment.
- Coordination of the collector and receiver during solar operation.
- Coordination of the receiver and fossil boiler during solar operation.
- Automated shutdown of the solar equipment.
- Emergency shutdown of solar equipment during abnormal situations to prevent equipment damage.

5.4.2.1 Automated Start-up. Because of the relatively large number of control actions necessary during the start-up of the solar equipment, and because the equipment is to be operated by a single operator who will also have additional non-solar responsibilities, it is necessary to automate the solar equipment start-up and minimize the required operator participation.

The automated start-up program controls all solar equipment. This program is quite comprehensive in order to safely start the equipment during a large variation in available solar insolation conditions. The complexity is equivalent to automatic turbine start-up programs which are routinely used in many new power plants. The start-up program for a normal diurnal start-up consists of several phases as follows.

- Prestart Phase. All solar equipment and systems controls are checked to determine that they are in the proper configuration for start-up (all steam lines drained of condensate, all controls on automatic, all heliostats respond to standby commands, etc).
- Receiver Warm-up Phase. The receiver water temperature is slowly increased at a rate not to exceed 4.4 C (8 F) per minute and heated to approximately 232 C (450 F) in this phase. The water warm-up is begun by circulating heated feedwater or steam from the fossil energy system through the receiver and back to the fossil energy system through the receiver drum drain system. The feedwater warm-up sequence is then augmented by the injection of steam from the fossil energy system into the receiver water.
- Solar Steam Generation Phase. The mirrors are rapidly focused on the receiver in a predetermined sequence. As the receiver warms, the steam pressure and temperature rise. The steam temperature is controlled to stay below 538 C (1,000 F). When the pressure equals the existing turbine steam inlet pressure, the solar steam stop valve is gradually opened and solar generated steam injected into the turbine.

A mid-day start-up sequence is slightly more complicated since a significantly greater amount of solar energy is available. During the Solar Steam Generation Phase, mirrors are sequenced on target more slowly to prevent overheating of the receiver.

This start-up sequence is automated to the extent that the required operator participation is limited to push-button initiation of each of these phases. The MCS keeps the operator apprised of the status of the start-up through CRT messages on the control panel. The operator is able to interrupt the automated sequence at any point and complete the start-up manually.

5.4.2.2 Coordination of Collector and Receiver Systems. The main objective in this coordination is the prevention of over temperature conditions in the receiver panels.

The coordination requirements of the MCS are minimal during solar operation. This is due to the receiver design and the incorporation of receiver steam temperature controls in the receiver system which will maintain the proper temperatures during essentially all normal operation conditions. The MCS attempts to focus all available heliostats on the receiver to maximize the solar insolation. Should an abnormal condition arise in which the receiver controls are unable to maintain temperatures below critical limits in the receiver panels, the MCS automatically defocuses heliostats according to a predetermined sequence to reduce the solar insolation to a point that the receiver controls are again able to control temperatures. When the abnormal condition has passed, the MCS automatically refocuses all heliostats.

5.4.2.3 Coordination of Receiver and Fossil Energy Systems. The main objective in this coordination is the regulation of the steam pressure to the turbine. The coordination requirements of the MCS are minimal. This is due to the existing steam pressure controls of the fossil boiler and the capability of the fossil boiler to regulate its firing rate to maintain the desired pressure during all normal expected transient conditions of the solar receiver. The fossil boiler is capable of increasing and decreasing its steam flow generation at a rate of 20,400 kg (45,000 pounds) per minute. The MCS does transmit a measurement of the solar receiver steam flow to the existing fossil boiler control system. This system will use this signal in a feedforward control strategy to assist in the pressure control. Should an unexpectedly severe solar transient cause a very rapid change in receiver steam flow which exceeds the capability of the fossil boiler to compensate, one of two things will occur. If the pressure drops rapidly, a small reduction in load output of the turbine occurs until the boiler can respond. If the pressure rises rapidly, a pressure relief valve in the fossil energy system will be actuated. Neither one of these eventualities is a serious operational problem.

5.4.2.4 Automated Shutdown. An automated shutdown is required for the same reasons that an automated start-up is required. The shutdown program safely shuts down the solar equipment and places all equipment into an overnight storage condition. The shutdown program for a normal shutdown consists of the following phases.

- Shutdown Phase. All heliostats are placed in the standby position. When the steam flow from the solar receiver drops to zero, the solar steam stop valve is closed.
- Storage Phase. All heliostats are commanded to their stow positions. All receiver panel bias valves are closed to minimize heat loss from the receiver during shutdown.

As in the automated start-up program, the operator participation is limited to the push-button initiation of each phase. Manual intervention at any point in the shutdown sequence is possible.

5.4.2.5 Emergency Shutdown. The MCS monitors critical solar equipment parameters and operating conditions of all critical plant equipment. Upon detection of any abnormal condition which would compromise the safety of personnel or integrity of equipment, the MCS triggers an emergency shutdown of all solar equipment. The shutdown consists of the following actions done in parallel.

- Command all mirrors to stow position.
- Close the solar steam stop valve.
- Open all receiver superheater and steamline drain valves.
- Close all lines that may be capable of water injection to the turbine.
- Start-up of the standby emergency diesel generator.

The main objectives of this emergency shutdown are to immediately remove all input energy from the system and prevent any possibility of water induction into the turbine.

This emergency shutdown system functions independently of all other elements in the MCS to ensure a safe shutdown.

The conditions that automatically trigger an emergency shutdown are as follows.

- High receiver drum water level.
- Low receiver drum water level.
- Turbine trip.
- Fossil boiler trip.
- Loss of main source of electrical power to heliostat control motors.
- Loss of main source of electrical power to control system.

The plant operator may also trigger an emergency shutdown from the main control room.

5.4.2.6 <u>Control Logic</u>. The functional control requirements of MCS, described in the preceding articles, require control logic which is predominantly discrete (boolean) in nature. This control logic, with the exception of the emergency shutdown logic, is programmed in software in the control computer. An example of the type of logic that is used is shown in Figure 5-32. The example in this figure is an excerpt from the automatic start-up program in the MCS. All control logic is documented in this format. The computer is directly programmed from these diagrams by using a specialized high-level computer control language.

5.4.3 Functional Data Acquisition Requirements

The MCS includes the facility to acquire plant data, analyze this data, display performance data to the operator, and store data for future detailed analysis.

- Data Acquisition. The MCS scans plant input data at individual point adjustable scan rates of from once a second to once every 30 seconds. The MCS stores the most current values of each input for further analysis and/or display. The estimated input counts are as follows.

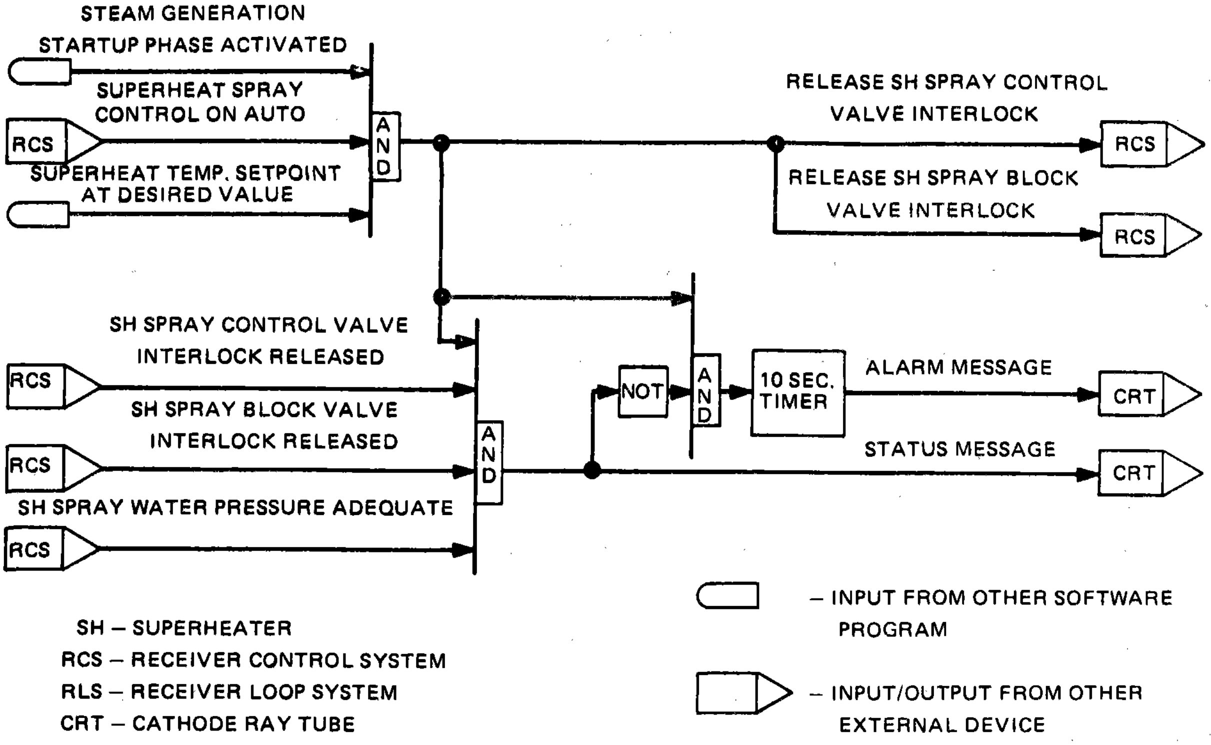


FIGURE 5-32. AUTOMATIC START-UP LOGIC DIAGRAM

Measurement	Quantity
Temperatures	150
Pressures	20
Flow rates	10
Valve positions	50
Water levels	5
Control valve positions	15
Miscellaneous discrete status inputs (level switches, breaker positions)	50
Heliostat status	2,255

- Data Analysis. The MCS performs real-time data processing on all inputs. This processing consists of conversion to engineering units, detection of bad or unreasonable data, data averaging, and other required processing. The MCS also performs periodic performance calculations to determine the performance of the unit and the unit solar components.

- Data Display. The MCS displays operational data to the plant operator. The displays are updated at least once every 2 seconds.
- Data Storage. The MCS includes long-term data storage capabilities. Both raw input data and computation results are stored on magnetic media for offsite analysis.

5.4.4 Operator Training Requirements

The primary operation of the MCS is automatic. However, manual over-ride controls are provided. The MCS provides training capabilities for the plant operators in the use of the control system.

The MCS contains a simulation of the solar-related process equipment. During periods when the solar equipment is not utilized (i.e., evenings or cloudy days) the operator is able to enter a simulation mode of operation. In this mode, all control outputs to the real process are deenergized. These outputs are channeled instead to the process simulation. The simulation develops process feedback responses similar to the actual process.

The operator is able to operate all controls and see realistic control panels displays of all feedback information from the simulation. The simulation provides realistic process simulation for normal operation including equipment start-up. A limited number of abnormal and emergency conditions are simulated for operator training.

The real-time model (RTM) for the training simulator includes the solar receiver, collector, and the receiver loop systems. The existing oil-fired drum boiler, turbine, and remainder of the fossil energy system are modeled only in sufficient detail to permit operator training in the solar repowering aspect of the plant operation. The RTM has solar insolation input for each of the heliostat groups and for each of the mirrors in two of the groups.

The RTM is capable of simulating the normal and abnormal operation of the plant. The normal operation includes start-up and shutdown of the solar part, and the steady state and dynamic operation of the plant under typical load demand, solar patterns, and cloud conditions. The abnormal operation includes events such as turbine trip, heliostat group or mirror failure, recirculating pump failure, and sensor failure (steam temperature, feedwater flow, drum level, etc.).

The RTM resides in the master control system computer. The model interfaces with the rest of the training simulator through an input table and an output table in the core memory (see Figure 5-33). The input table contains instantaneous values of valve position commands, heliostat position commands, status of components, etc. The values are written by the monitoring and control system and are read by the RTM. The output table contains instantaneous values of MW_e, pressure, temperature, etc. The values are written by the RTM and are read by the instrumentation and control system.

The initial parameters of the model are determined from the design data. Final values are determined from actual plant test data.

The RTM is developed in a cost-effective manner by using a modular modeling system which has modules of many power plant components and several powerful analysis tools.

5.4.5 Design Considerations

The design considerations presented below include the criteria which guided the design process, interfaces with other plant systems, and the use of redundancy to ensure high availability and plant safety.

5.4.5.1 Design Criteria. The MCS equipment meets the following design criteria.

- Reliability. The MCS has an availability of over 99.5 per cent. The availability is achieved through the use of simple designs, proven highly reliable components, and redundant elements whenever it is cost effective.
- Flexibility. The MCS has the capabilities to modify control strategies easily at the plant site without extensive hardware or wiring changes.

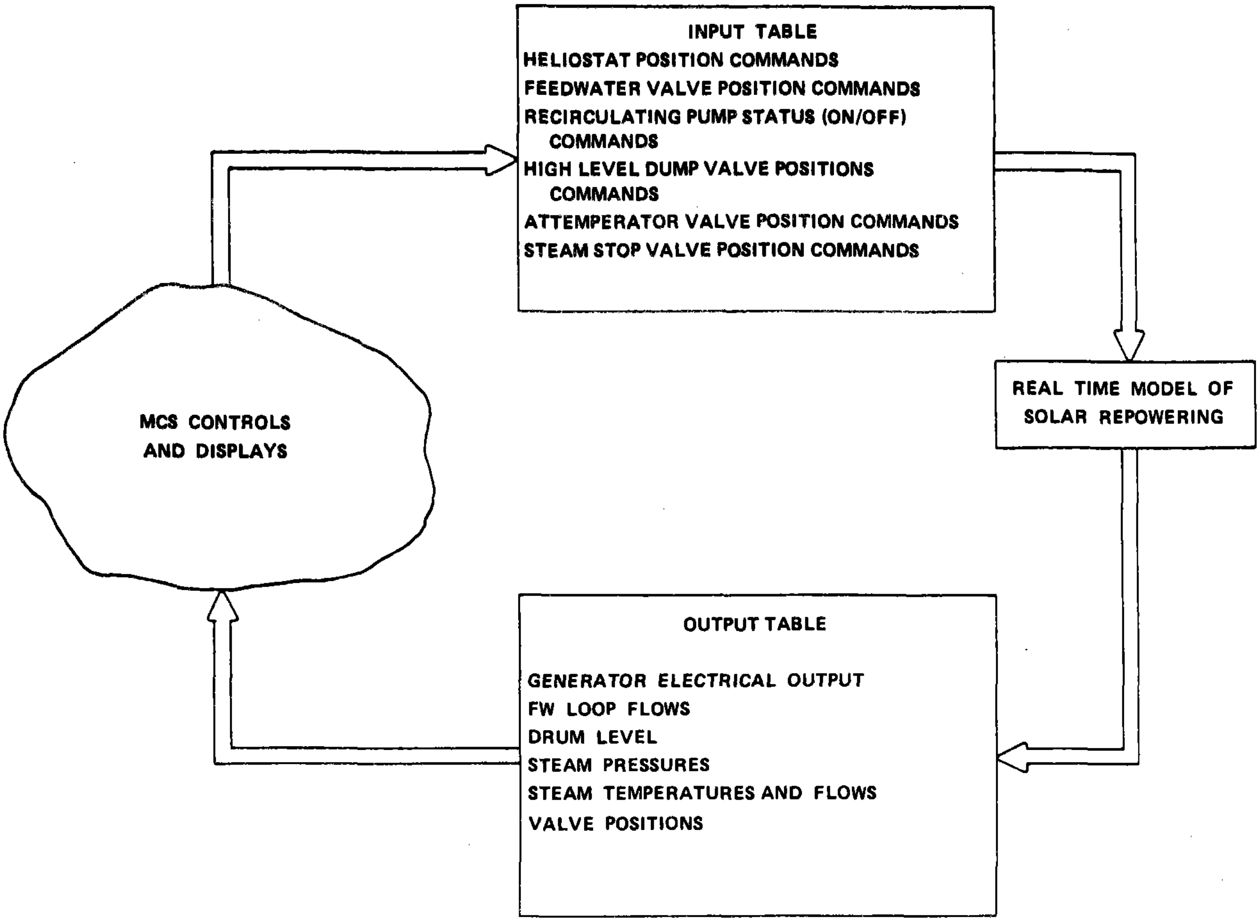


FIGURE 5-33. INTERFACES BETWEEN REAL TIME MODEL AND REST OF MCS

- Cost Effectiveness. The MCS uses commercially available equipment throughout. All equipment supplies are generically similar throughout the MCS. The equipment configuration minimizes cabling costs by using remote multiplexing.
- Ease of Maintenance. All equipment is easily maintainable by normal power plant personnel. The equipment configuration consists of generically similar equipment, wherever practical, for ease of maintenance.
- Ease of Operation. All control panel displays are easily read from a distance of 3 metres (10 feet). All manual controls

are arranged to allow all operations by a single plant operator.

- Operating Environment. Any equipment located in the receiver tower is capable of continuous operation over an ambient temperature range of -28 C to 54 C (-20 F to 130 F) and a relative humidity of 5 per cent to 95 per cent non-condensing. All equipment in the centralized control room is capable of continuous operation over an ambient temperature range of 4 C to 32 C (40 F to 90 F). Electrical power for the MCS is a nominal 120 volt, single-phase, 60 hertz alternating current.
- Expandibility. The computer system has the capability of adding at least 25 per cent additional working memory for future expansion. The central processing unit allows for a 25 per cent spare duty cycle under worst case loading conditions and 40 per cent spare duty cycle under normal loading conditions.

5.4.5.2 Interface Requirements. The MCS communicates with all other systems. These communications take the form of control commands from the MCS to the other subsystems and status information from the other subsystems to the MCS.

The interface between the MCS and the Collector System consists of a digital data transmission link between the master control computer and the heliostat array controller. Typical communication signals between the two systems are shown on Figure 5-34.

The interface between the MCS and the Receiver System and between the MCS and the Receiver Loop System consists of a digital data transmission link between the master control computer and the Receiver Control System. Typical communications signals between the systems are shown on Figures 5-35 and 5-36.

The interface between the MCS and the fossil energy system consists of signal cables between the control computer and the turbine and fossil boiler control systems. Since the existing fossil boiler control system is pneumatic, electric to pneumatic and pneumatic to electric signal

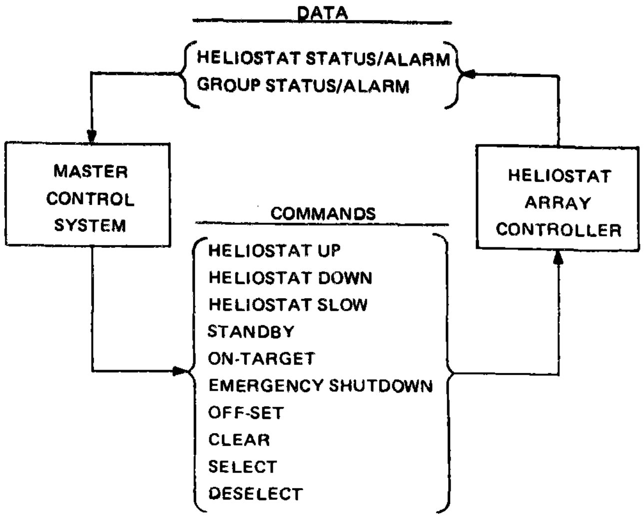


FIGURE 5-34. MCS/COLLECTOR CONTROL COMMUNICATIONS

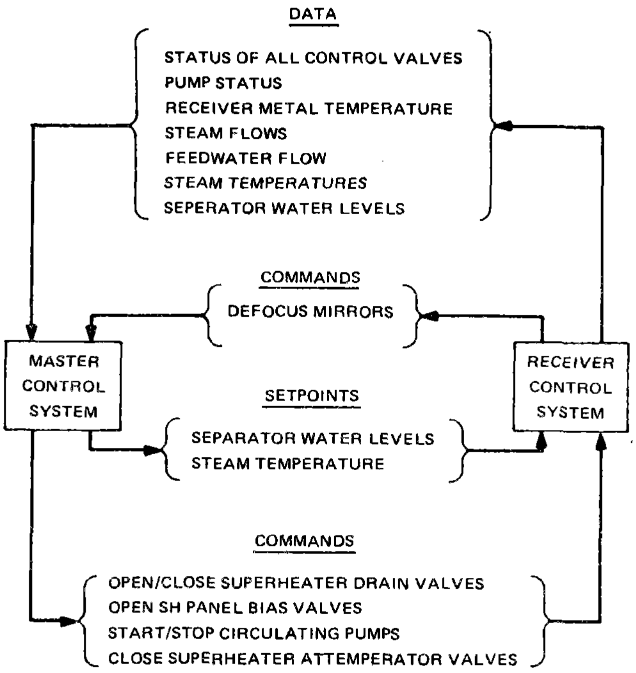


FIGURE 5-35. MCS/RECEIVER CONTROL COMMUNICATIONS

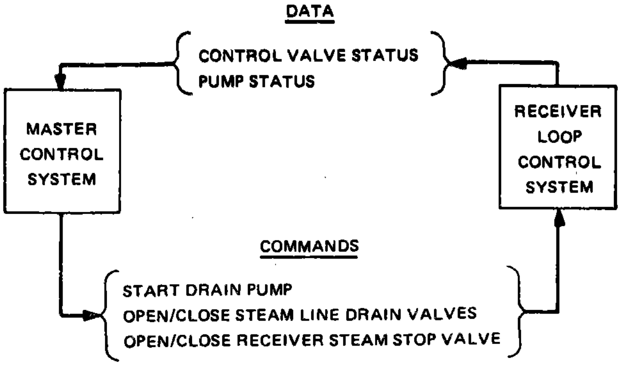


FIGURE 5-36. MCS/RECEIVER LOOP CONTROL COMMUNICATIONS

converters are used. Typical communications between these systems are shown on Figure 5-37.

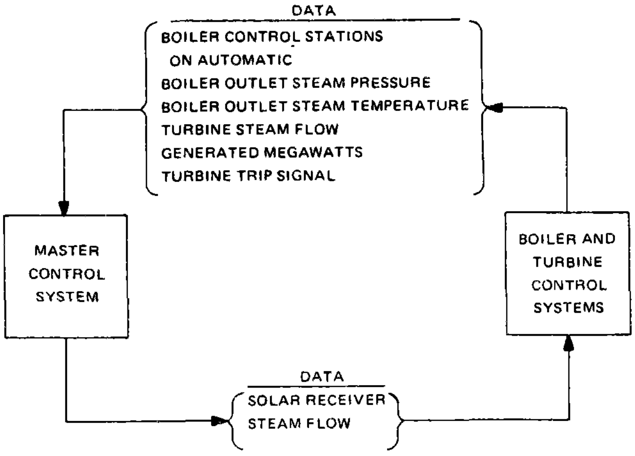


FIGURE 3-37. MCS/FOSSIL ENERGY CONTROL COMMUNICATIONS

The hardware interfaces between the MCS and the other systems are depicted on Figure 5-38.

The interface between the MCS and the collector control system consists of a RS-232 link between the master control computer and the heliostat array control computer. The heliostat array control computer will directly interface with a pair of CRT's on the control panel to permit manual collection control in the event of a MCS control computer failure.

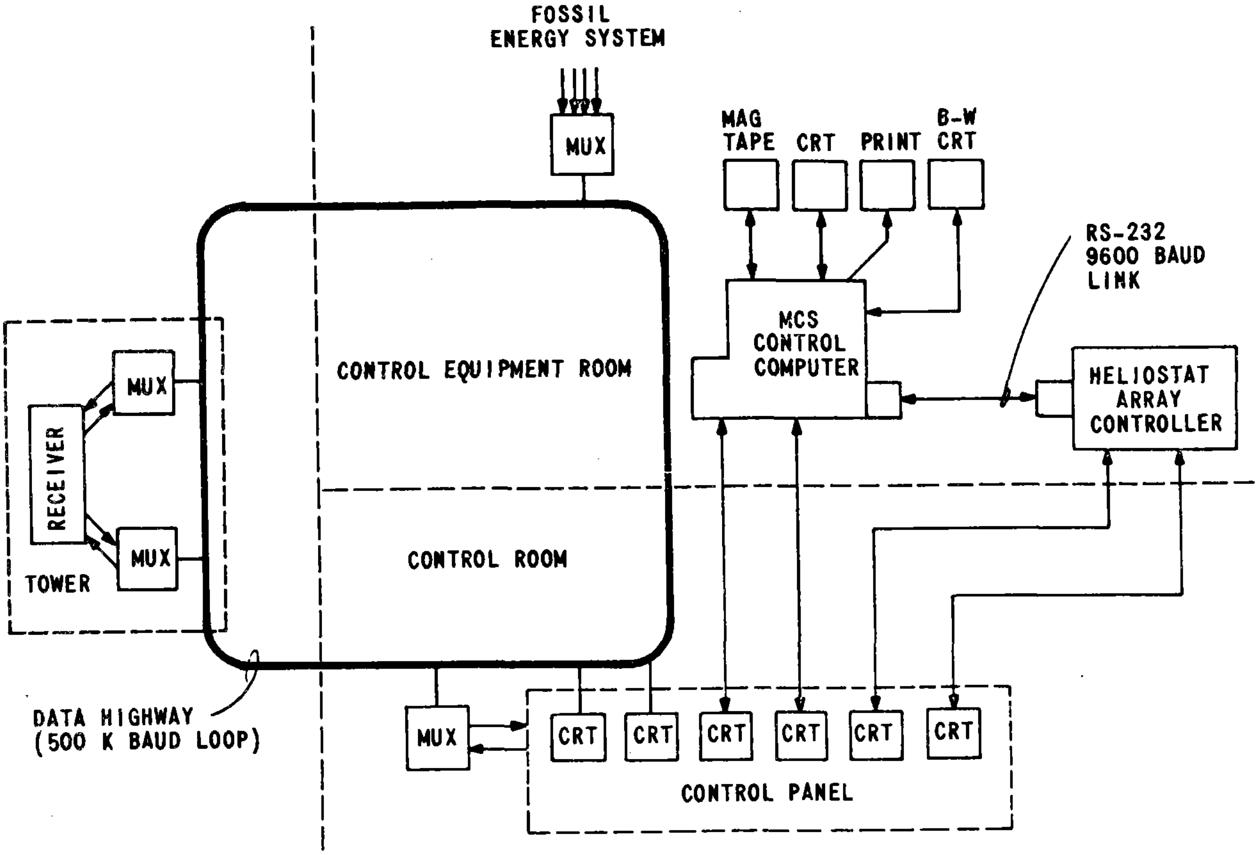


FIGURE 5-38. MCS HARDWARE INTERFACES

The interfaces between the MCS and the receiver, receiver loop, and electric power generating systems utilize a high-speed (500 K band) data highway. This data highway is a redundant twinax cable loop which runs between the receiver tower and the control room complex. The MCS control computer is connected to this highway with an RS232C data port. The receiver and receiver loop systems are connected to the highway through remote multiplexing stations located at the tower. The electric power generating system is connected to the highway with cables run to a multiplexing station at the control equipment room. An additional multiplexer station and a pair of intelligent CRT's are also connected to the highway at the control panel. This provides manual control capability for the receiver and receiver loop systems in the event of a MCS control computer failure.

5.4.5.3 Computer Configurations. The requirements of the MCS are best met by using digital computer equipment for the operational control and data acquisition functions. A single central processor is used for these functions for reasons of cost effectiveness and simplification of interfaces.

Figure 5-39 shows the configuration of the MCS central processing unit and its peripheral equipment. The central processing unit (CPU) is a powerful mini-computer of the MODCOMP family with 512 K words of random access working memory. The CPU communicates with its peripheral equipment, over a high-speed I/O bus. The peripheral equipment is connected to the I/O bus through hardware peripheral driven circuits. The peripherals are: a 5 million word moving head disc and a 4 million word magnetic drum used for auxiliary storage of compouter programs; a programmer's terminals to be used by the computer programmer for computer troubleshooting; a free-standing console to be used by the control engineer for modifications to applications programs (such as CRT graphic displays and process control logic); three printers for hard copy of alarms, performance results, and other equipment operational messages; two color graphic CRT's to display alarms and process parameters to the plant operator; two keyboards to be used by the plant operator to select displays for the CRT's; and a magnetic tape unit for long-term storage of plant data.

5.4.5.4 Equipment Redundancy. Equipment redundancy is used where cost effective to achieve high control system availability and to insure that a safe shutdown will occur during emergency conditions.

5.4.5.4.1 Equipment Availability. The computer control equipment used in the MCS has a very high availability. As reported in the IEEE Power Plant Computer Reliability Survey of 1978, equipment of this type has availability of over 99.5 per cent. Because of this high availability, the expense of providing redundant equipment, and the fact that the other systems can be operated manually during a MCS failure, no redundancy is planned for the MCS control computer. The multiplexed data communication links to the RCS and CCS, however, are redundant because of the vulnerability of these links and the low cost of this redundancy.

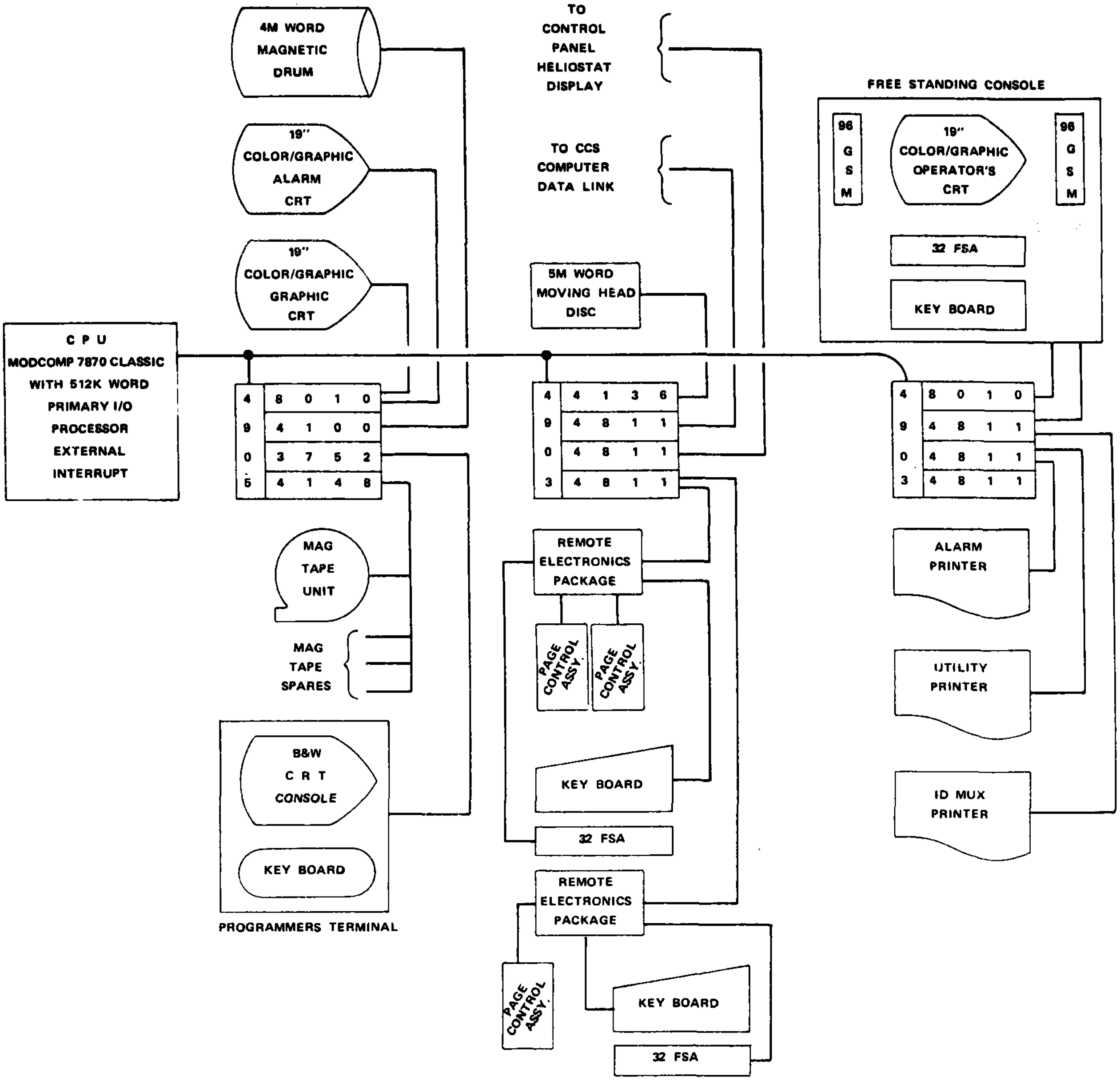


FIGURE 5-39. MCS COMPUTER CONFIGURATION

5.4.5.4.2 Emergency Shutdown System. Because of the need to insure a safe equipment shutdown during emergency conditions, a separate independent Emergency Shutdown System is incorporated into the MCS. This system is generically different from the control computer in order to reduce the probability of common mode failures. The Emergency Shutdown System incorporates redundancy in the form of multiple sensing elements and voting circuits.

5.5 FOSSIL ENERGY SYSTEM

The fossil energy system contains the existing power plant equipment and the fossil fuel which is used during hybrid operation and maintains normal plant operation during periods of reduced or no insolation.

5.5.1 System Description

The fossil energy system consists of the existing fuel supply, fuel storage and transfer facilities, steam generator, turbine generator, condenser, condensate pumps, feedwater heaters, and boiler feed pumps. Descriptions of the components, as recorded in the NES I Engineering Summary, are listed as follows.

- Fuel Supply, Storage, and Transfer Facilities. Natural gas is supplied under pressure by the Transok Pipeline Company. The fuel is dehydrated and purified before passing through high- and low-pressure regulating stations. The fuel is then supplied to Unit I through a 14-inch header. Fuel oil is stored in a single 100,000 barrel, earth berm protected tank located northeast of the central complex area. Fuel delivery is by truck transport. Two fuel oil unloading pumps, each with a capacity of 450 gallons per minute, are provided for transfer operation.
- Steam Generator.

Manufacturer	Babcock & Wilcox
Type of Unit	Radiant reheat, pressure furnace
Continuous Rating, pounds of steam/hour	1,000,000

Maximum Rating, pounds of steam/hour	1,150,000
Design Pressure, psi	2,325
Superheater Outlet Pressure, psi	2,070
High-Pressure Steam Temp, F	1,005
Reheat Steam Temp, F	1,005

- Turbine Generator.

Manufacturer	Westinghouse
Type	Two cylinder, tandem compound, double flow impulse-reaction, condensing reheat--23-inch last-stage blades, TC2F23LSB
Generator	200,000 kVA, 0.80 power factor, three-phase, 60 hertz, 60 psi hydrogen pressure, 14,400 V
Exciter	Separately driven, 1,000 kW, 375 V dc, air-cooled motor generator

- Condenser.

Manufacturer	Westinghouse
Type	Horizontal, two pass deaerating surface condenser
Surface Area	120,000 square feet
Tube Material	Inhibited admiralty
Cooling Water	119,000 gpm
Air Ejector	
Number of Units	1
Type	Steam jet, twin element, two- stage
Priming Ejector Type	Steam jet, single-stage

- Condensate Pumps.

Manufacturer	Westinghouse electric
Type	Vertical pit type
Number of Pumps	Three

Pumping temperature, F	130
Total Dynamic Head, feet of water	450
Capacity, gpm	1,300
Speed, rpm	1,170
Motor	250 hp, 4,160 V drip-proof, vertical

- Feedwater Heaters.

(a) Low-Pressure Heater Number 1.

Manufacturer	Lummus
Number	One
Type	U-Tube
Heating Surface, effective	4,900
Tube Material	Inhibited admiralty
Design Steam Pressure, psi	150

	Steam	Feedwater
Capacity, pounds/hour	54,598	857,176
Inlet Temperature, F	178.1	102.5
Outlet Temperature, F	112.5	173.1

(b) Low-Pressure Heater Number 2.

Manufacturer	Lummus
Number	One
Type	U-tube
Heating Surface, effective	3,070
Tube Material	Inhibited admiralty
Design Steam Pressure, psi	150

	Steam	Feedwater
Capacity, pounds/hour	47,512	857,176
Inlet Temperature, F	321	173.1
Outlet Temperature, F	183.1	228.5

(c) High-Pressure Heater Number 4.

Manufacturer	Lummus
Number	One

Type	Multilok U-tube
Heating Surface, effective	5,940
Tube Material	70-30 cupro nickel
Design Steam Pressure, psi	300

	Steam	Feedwater
Capacity, pound/hour	87,059	1,047,280
Inlet Temperature, F	792	293.5
Outlet Temperature, F	303.5	395.6

(d) High-Pressure Heater Number 5.

Manufacturer	Lummus
Number	One
Type	Multilok U-tube
Heating Surface, effective	4,970
Tube Material	70-30 cupro nickel
Design Steam Pressure, psi	750

	Steam	Feedwater
Capacity, pound/hour	97,615	1,047,230
Inlet Temperature, F	694	395.6
Outlet Temperature, F	405.6	478.8

Deaerator.

Manufacturer	Cochrane
Number of Units	One
Type	Jet tray, direct contact
Maximum Output, pounds/hour	1,300,000
Water Storage Capacity, gallons	18,000
Operating Guarantee	0 to 0.005 oxygen,cc/litre
Vent Condenser	External tube and shell

Boiler Feed Pumps.

Manufacturer	Pacific pumps
Type	Centrifugal 10-stage
Number of Pumps	3
Capacity, each	650,000 pounds/hour

Total Dynamic Head	2,535 psi
Speed	3,600 rpm
Motor	3,000 hp, 4,160 V

A simplified flow diagram of the fossil energy system is shown on Figure 5-40. The fossil energy system will have two flow patterns: water-steam and fuel-air-flue gas.

Water leaving the condenser is pumped by the condensate pumps through two low-pressure feedwater heaters and into the deaerator. The boiler feed pumps then pump the feedwater from the deaerator through the two high-pressure feedwater heaters and into the steam generator. As this feedwater leaves the feedwater heaters, a portion of the feedwater is bypassed to the receiver loop system. In the steam generator, the feedwater is transformed to superheated steam. This main steam leaves the steam generator, is then mixed with the high-pressure, high-temperature steam from the solar receiver, and enters the high-pressure turbine. Steam from the high-pressure turbine exhaust (cold reheat) is returned to the steam generator, where it passes through the reheater section and is returned (hot reheat) to the intermediate-pressure turbine. Steam from the intermediate-pressure turbine then enters the low-pressure turbine and is exhausted to the condenser. Condensate drains and recirculated feedwater from the receiver and the receiver loop system are piped back to the fossil energy system and routed to either the deaerator, condenser, or the existing steam generator blowdown tank as required.

Natural gas is supplied to Unit I from the Transok Pipeline Company. Two centrifugal forced draft fans supply combustion air to the furnace. The combustion gas flows from the furnace through the economizer and air heater before being discharged to the stack.

5.5.2 Functional Requirements

The requirements of the fossil energy system are as follows.

5.5.2.I Operating Requirements. The solar receiver has three modes of operation which include normal operation, routine shutdown and start-up operation, and cold start operation. The fossil energy system responds to these modes of operation according to the following.

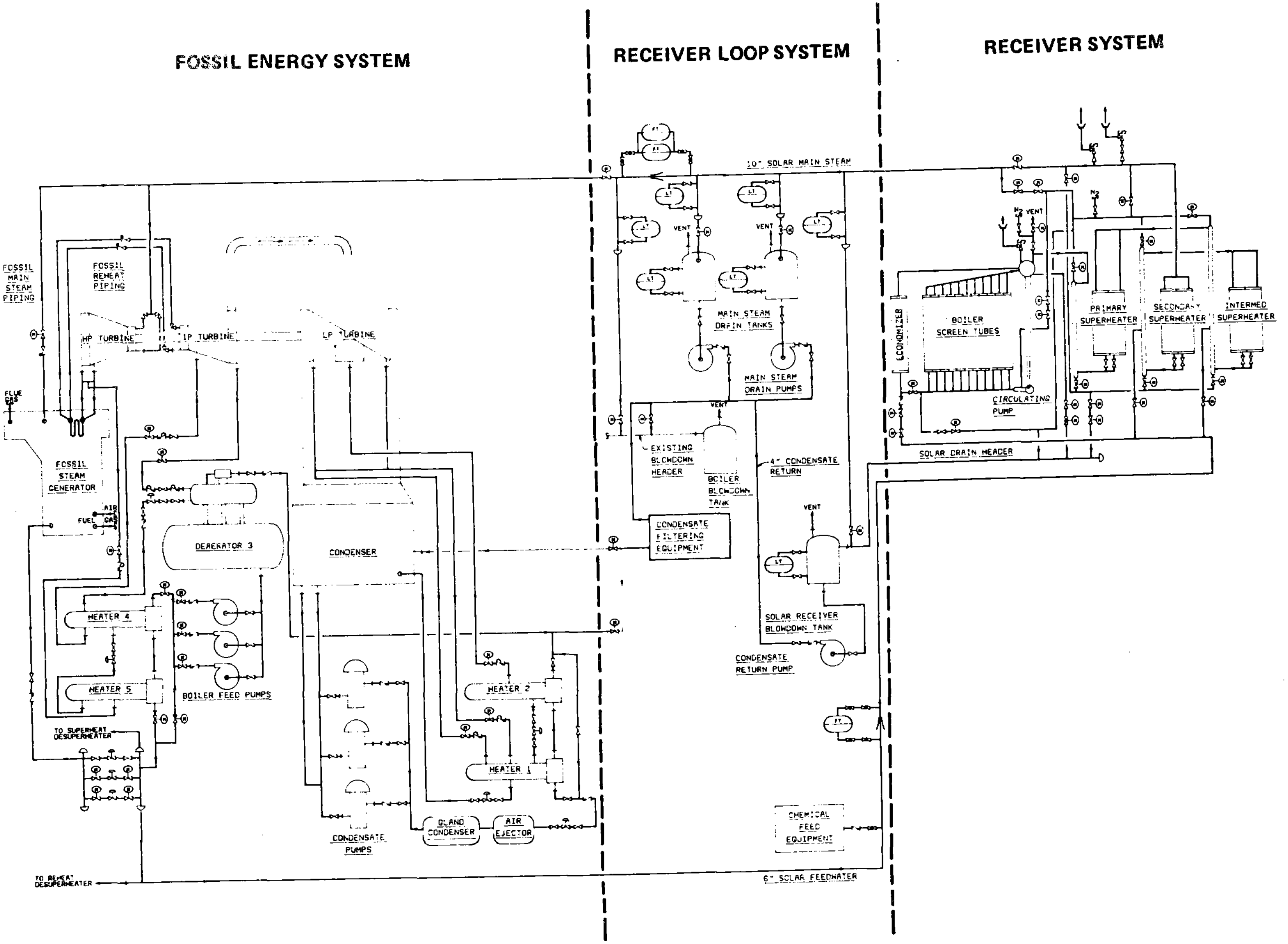


FIGURE 5-40. SOLAR REPOWERING FLOW SCHEMATIC

- Normal Operation. Under normal operating conditions, the fossil steam generator will respond to load changes and fluctuations in solar output. During overnight periods, the fossil steam generator will operate at minimum boiler turndown, 30 per cent of maximum load, or about 50 MW. During sunlit hours, the fossil steam generator operating range with solar power available is from minimum boiler turndown, up to a maximum turbine generator load of 155 MW.
- Routine Shutdown and Start-up Operation. During routine shutdown and start-up of the solar systems operation in the winter months, the fossil steam generator will be maintained at minimum load (30 per cent). For freeze protection during shutdown operation, feedwater will be circulated to the receiver and then returned to the deaerator, so that the receiver temperature will be maintained above 4.4 C (40 F). Prior to sunrise, feedwater flow will be increased to warm up the receiver water to about 116 C (240 F). The water flow will be controlled to limit the rate of temperature rise in the receiver to 4.4 C (8 F) per minute. Just before sunrise, superheated steam from the fossil steam generator superheater outlet will be fed back through the receiver loop piping for heating the solar receiver drum to near the full load saturation temperature. Spargers will be used to introduce the steam from the fossil steam generator (via the mainsteam line) to the solar receiver boiler water circulating pump suction line.

  Steam consumption for preheating will be about 18,000 kg/h (40,000 lb/h). Condensate is collected and returned through the receiver loop system and drained to the fossil energy system.
- Cold Start Operation. Prior to start-up of the receiver system, the fossil energy system boiler feed pumps will fill the receiver with approximately 4,536 kg (10,000 pounds) of

warm feedwater. The receiver will be filled at a controlled rate to avoid thermal shock. Makeup to the fossil energy system will be through the condenser from the existing 378.5 m^3 (100,000-gallon) capacity, deionized water storage tank. After the receiver is filled, start-up will be similar to diurnal start-ups described previously, with the exception that start-up times will be extended to allow for warm-up of the main steam transport pipe.

5.5.2.2 Design Requirements. No modifications to the existing fossil energy system are required except for the interfaces. Requirements at the interfaces are described below.

5.5.2.3.1 Interface Requirements. The requirements at the interfaces with the fossil energy system will be as follows.

- Feedwater Interfaces. The fossil energy system interfaces with the receiver loop system at the feedwater line after the fifth feedwater heater.

  The conditions at the interface will vary with unit load and receiver steaming capacity. The maximum and minimum conditions corresponding to the required operating modes are as follows.

Normal Operation, Design Point Conditions

Feedwater flow to receiver	111,260 kg/h (245,287lb/h)
Pressure	19.07 MPa (2,750 psi)
Temperature	247 C (477 F)

Start-up and Shutdown Operation

Minimum feedwater recirculation	2,300 kg/h (5,000 lb/h)
Maximum feedwater recirculation	34,000 kg/h (75,000 lb/h)
Pressure	20.93 MPa (3,020 psi)
Temperature	186 C (366.5 F)

- Main Steam Interfaces. The fossil energy system also interfaces with the receiver loop system at the connection of the transport pipeline and the fossil main steam piping near the fossil steam generator. Steam conditions at the interface will match the existing Unit 1 steam conditions as follows.

Normal Operation, Design Point Conditions

Flow rate	111,260 kg/h (245,287 lb/h)
Overpressure	13.76 MPa (1,995 psia)
Rated pressure	12.51 MPa (1,815 psia)
Temperature	538 C (1,000 F)

Under start-up conditions, the fossil energy system will supply steam to the receiver loop system for receiver warm-up at a flow rate of 18,000 kg/h (40,000 lb/h).

- Drain Lines. Drain lines from the receiver will interface with the fossil energy system at the deaerator, condenser, and existing steam generator blowdown tank. The interface points will be sized to accommodate the maximum expected recirculation flow stated above.

5.5.3 Performance

The turbine cycle of the fossil energy system will not be affected by the solar repowering project since solar steam will be at the same pressure and temperature as the superheated steam from the fossil steam generator. Operating conditions for the turbine generator at rated pressure and overpressure conditions are illustrated by the turbine cycle heat balances shown previously in Section 4.3.

The fossil steam generator provides all of the hot reheat steam and only part of the superheated steam to the turbine generator during combined fossil-solar operation. This results in a slight change in the expected reheat steam temperatures during combined fossil-solar operating. Predicted performance of the fossil steam generator has been discussed previously in Section 4.3.

5.5.4 Cost Estimates

No cost versus performance tradeoff studies were required for the fossil energy system per se. The capital cost associated with interfacing the solar repowering equipment with the existing facility is $131,000; backup data for this cost estimate are provided in Section 5.3 of Appendix A.

6.0 ECONOMIC ANALYSIS

A primary consideration in the economic evaluation of the solar repowering of NES I is the determination of the value it could provide to PSO. The value was determined in the context of the PSO operating system and derived from the savings in production cost by fuel displacement and the deferral of capital investment because of the extension of the usable life for NES I. System simulations were used to develop valid estimates of these values.

The system characteristics, performance, and costs, described in the previous section, are the basis for the economic analysis described herein. This section begins with a discussion of the methods and assumptions used in the economic analysis, which is followed by a discussion of the simulation models used to evaluate the performance and value of the solar repowered unit. An important facet of the economic analysis was that the determination of the value of repowering was done by PSO using their own computer programs and financial evaluation methods. This procedure ensured that the results of the evaluation would be realistic and consistent with actual practices used by the utility in its decision-making process. The section ends with a discussion of the benefits to PSO of solar repowering NES I.

6.1 METHODOLOGY

The methodology used to determine the value to PSO of the repowered hybrid facility was based on estimating the impact that facility would have on the economic performance of the PSO system. The economic analysis for both annual fuel savings and capacity credit associated with deferral of the retirement of Unit I were achieved by analyzing two system generation addition schedules. The baseline schedule reflected the non-repowered case and included the retirement of NES I in December of 1994. The second schedule reflected the implementation of repowering and included an extension of the NES I lifetime to the year 2000.

There were two parts to the analysis. The first was the evaluation of the solar plant energy contribution which was determined by simulation. The second was the evaluation of how that energy contribution affects the operation and economics of the PSO system. This economic analysis process is illustrated in Figure 6-1; the various steps in the process are briefly discussed in the succeeding paragraphs of this section.

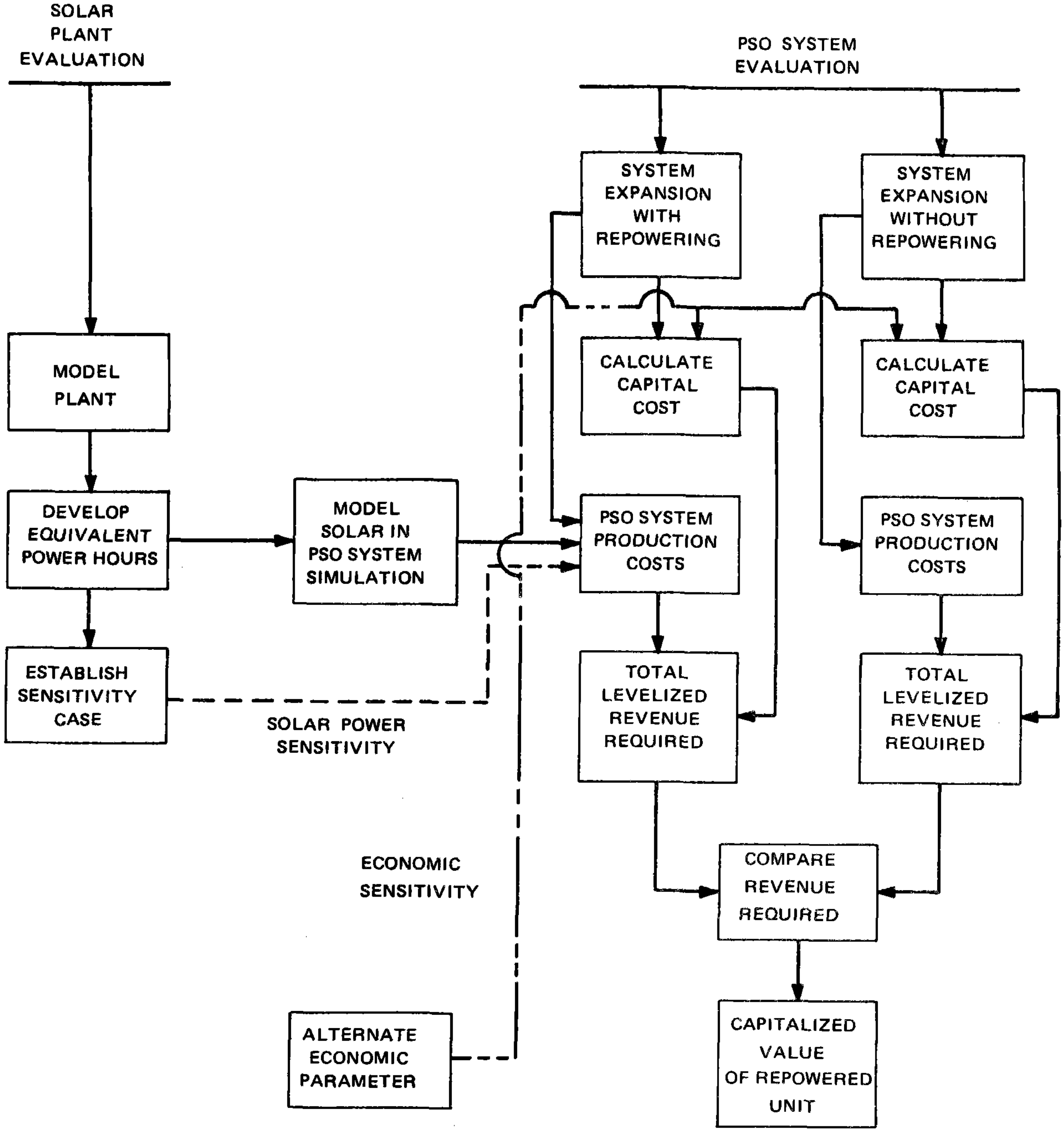


FIGURE 6-1. ECONOMIC ANALYSIS PROCESS

6.1.1 Solar Plant Evaluation Methodology

The performance of the repowered facility was determined using the Black & Veatch computer code, Solar Thermal Electric Plant Performance Evaluator (STEPPE). STEPPE simulates the solar repowered plant by exercising the performance of each system (collector, receiver, receiver loop, and fossil energy) described in the conceptual design of Section 5 with insolation data and system loads as inputs. The program includes the capability to model such features as hybrid systems, reheat cycles, thermal deficits due to diurnal and cloud-caused shutdowns, and grid demand. STEPPE was used to provide daily performance characteristics which were subsequently used to evaluate the solar plant's annual performance. Details of the performance simulation are given in Subsection 6.3.1.

6.1.2 PSO System Evaluation Methodology

Determination of the value of the repowered unit to PSO was accomplished by PSO by differencing the cost of operating the entire PSO system with and without the solar repowered unit. These costs were obtained by simulation of the PSO system using PROCOS, a simulation program widely used by the electric utility industry.

Elements of the methodology are described below.

- System Expansion Plans. Two reference expansion schedules were used. The first was the current PSO schedule which assumes NES 1, with its 150 MW of capacity, would be retired in December 1994. The second was the same schedule, but assumes that the solar repowering would extend the economic life of the 150 MW unit until the year 2000. By establishing and evaluating the two plans, any capacity credit associated with the repowering project was explicitly included in the total evaluation. This is a necessary feature of any realistic, utility-oriented evaluation.
- Capital Cost Calculation. Appropriate capital costs were calculated for the unit additions under both expansion plans.

- PSO System Production Costs Determination. Annual power production costs were calculated for the PSO system by the use of a PSO in-house system simulation code. The code is discussed further in Section 6.3.2.
- Total Levelized Revenue. Annual revenue requirements consist of the sum of the annual production costs and the annual required return on capital investment. Annual return on investment includes proper accounting for tax effects (the tax deductible nature of interest as well as the allowed investment tax credit) and depreciation. For each year of each plan, the total annual revenue requirements and the levelized revenue requirements of the series of annual requirements through that year are calculated and compared. Only the comparison of the levelized revenue requirements is a true indicator of the economic value of a plan.

  An important feature of the method is that the actual annual revenue requirements are used; this allows the valid comparison of plans that include units of different operating periods.
- Value Determination. Normal PSO practice is to calculate the actual and levelized revenue requirements for each year of a 40-year period beginning with the year of unit addition. These data are then used to calculate a present-worth value of the alternative. For the present evaluation, the period was 1985 through 2024. Use of a long evaluation period allows a proper assessment of the long-range impacts of each alternative.
- Sensitivity Studies. The economic evaluation sensitivity to the solar repowering level and the selection of economic factors was studied. The power level was increased to 50 MW_e and both PSO economic evaluation assumptions and a set of assumptions provided by DOE were used.

6.2 ASSUMPTIONS

The development of the economic analysis required a number of assumptions. Assumptions necessary for the solar plant performance model and those necessary for the system economic evaluation are given in the next subsections.

6.2.1 Solar Model Assumptions

Several assumptions and approximations were made in modeling the repowered system with the B&V computer code, STEPPE. The major assumptions and approximations, along with assessment of their associated impacts, are listed below.

- Insolation data input was based on the ASHRAE Clear Air Model, modified by monthly percentage sunshine data so as to include the effects of cloud cover. The resultant average daily direct normal insolation (5.35 kWh/m^2 day) is in close agreement with available insolation data.
- "Annual" performance was extrapolated from predictions for 12 representative days (one each month). Experience with STEPPE has shown that this approach gives results which are identical (typically to three significant figures) to those for 365-day modeling with STEPPE when the clear air insolation model is being used.
- As a result of using the clear air model, no mid-day receiver start-ups were modeled. This assumption causes a slight overestimation of annual energy production.
- No solar system shutdowns due to extreme weather conditions (e.g., high winds or extremely low temperatures) were modeled, on the assumption that they were sufficiently infrequent to be unimportant.
- Receiver start-ups were modeled as constant pressure start-ups. The possible use of a variable-pressure receiver start-up procedure causes slight underestimation of the annual energy from the solar system.

6.2.2 Economic Evaluation Assumptions

The assumptions for economic evaluation include financial and economic parameters, fuel costs, O&M costs, and capital costs. For the present evaluation, two sets of assumptions were developed; one set consistent with PSO's internal policies, and one set prescribed by DOE/Sandia. Table 6-1 shows these assumed bases.

6.3 SIMULATION MODELS

Two simulation models were used, one modeled the characteristics of the hybrid repowered unit and the other the dispatch and the operating costs of the PSO system.

6.3.1 Solar Plant and System Simulation Model

Performance modeling of the solar repowered plant was conducted using the Black & Veatch computer code STEPPE. STEPPE predicts plant performance by integrating power traces computed at discrete time points to provide a daily or annual energy trace through the plant.

The logic flow for STEPPE is shown in Figure 6-2. At each time point (each 15 minutes in the study reported here), the power flow is traced through the plant (e.g., power to the receiver, power from the receiver, and power to the turbine). At the end of each day, and following the last day of the run, the power trace is integrated to give the aggregate energy traces over the modeled period. Modeling capabilities include the following.

- Weather data from an appropriate tape or an artificial model. In this project, an artificial model was used for dry bulb temperature, based on 30-year normal daily minimum, average, and maximum temperatures for Tulsa.(1)
- Insolation data from a weather tape, or the ASHRAE Clear Air Model. In the repowering project, the ASHRAE model was used, and results were modified to include the effects of cloudy days using per cent sunshine data for Tulsa.(1)

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(1) Normals based on the 1941-1970 period, "Local Climatological Data, 1978, Tulsa, Oklahoma," National Climatic Center, Ashville, NC.

TABLE 6-1. ECONOMIC EVALUATION PARAMETERS

Financial Factors	Per Cent
Discount Rate	13.0*
Investment Tax Credit	10.0
AFUDC	10.5**
Property Tax Rate	2.0
General Inflation Rate	7.0
Combined State and Federal Income Tax Rate	50.0

Fuel Cost Projections	PSO		DOE	
Fuel	1980 Cost $/MBtu	Escalation Rate per cent	1980 Cost $/MBtu	Escalation Rate per cent
Oil	--	--	4.00	12
Natural Gas	2.80	8	2.50	11
Coal	1.41	8	1.25	10
Lignite	0.99	8	--	--
Nuclear Fuel	***	***	0.85	9

Unit Capital Cost Projections				
Unit Type	1980 Cost $/kW	Escalation Rate per cent	1980 Cost $/kW	Escalation Rate per cent
Nuclear	861	7	1,000	8
Coal	589	7	860	8
Lignite	621	7	N/A	N/A
Combined Cycle (oil)	N/A	N/A	360	8
Combustion Turbine (oil)	N/A	N/A	190	8

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*Capital structure of 57 per cent debt with a return of 11.5 per cent; return on equity 15.0 per cent.

**Compounded semiannually.

***Varies over first years (actual costs).
1987--$1.41
1988--$1.29
1989--$1.17 and escalated at 8 per cent/per annum.

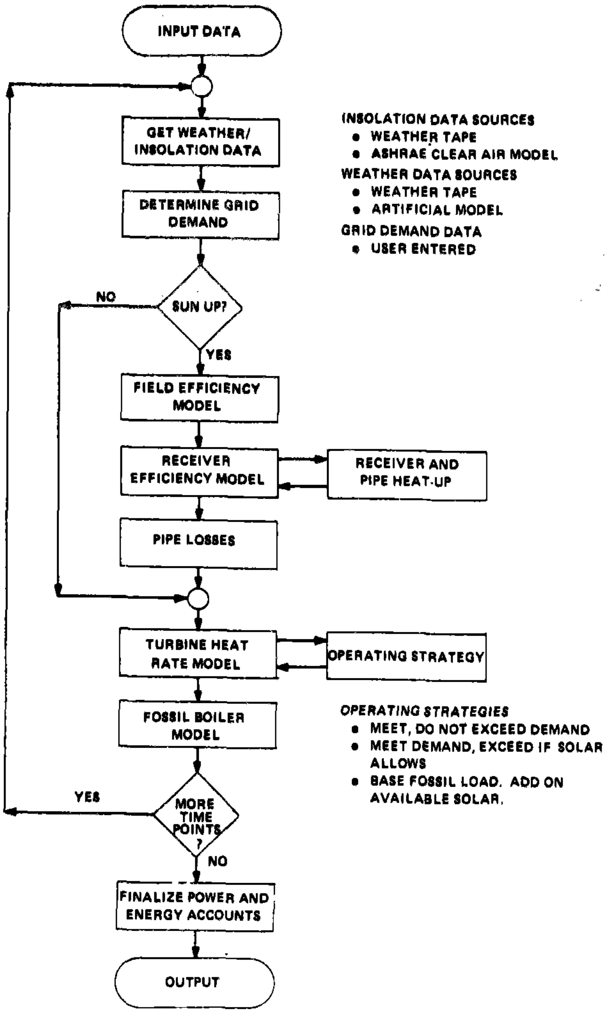

FIGURE 6-2. STEPPE PROGRAM LOGIC FOR FOSSIL HYBRID SYSTEM

- Heliostat field efficiency as a function of sun azimuth and elevation. Data used were computed by the Black & Veatch central receiver system optical codes.
- Receiver efficiency/loss data as a function of input power and dry bulb temperature. Data were provided by B&W based on their solar receiver design.
- Receiver start-up energy, including fossil steam preheating, with heat capacities, losses, and temperature ramp rates.

- Solar main steam piping losses and heat-up requirements. Data based on the receiver loop system conceptual design were used.
- Fossil energy system characteristics (e.g., turbine heat rate versus power generated, fossil steam generator efficiency).
- Existing plant auxiliary power requirements modified to include solar auxiliary power.

STEPPE also has the capability to model thermal storage and a solar reheater, neither of which were utilized in this project.

The ASHRAE insolation model and artificial weather model were utilized in the absence of a weather tape (SOLMET or Typical Meteorological Year) giving direct normal insolation for the Tulsa area. For annual data, STEPPE was run for 12 representative days (rather than 365 days) based on previous experience which indicates a highly comparable accuracy (less than 1 per cent difference) when the ASHRAE insolation model and artificial weather model are used.

Five types of plant operating strategies can be modeled using STEPPE. These are described briefly below.

- Load dispatch demand, with a hybrid fossil system. Meet, but do not exceed the user-entered net electrical demand while utilizing as much solar energy as is possible. Defocus any solar energy greater than the user level specified.
- Sunfollowing with a hybrid fossil system. Meet the user-entered minimum net electrical demand with a combination of solar and fossil energy; if excess solar energy is available, exceed the user-entered electrical demand.
- Sunfollowing, with a base fossil load. Use all solar energy available. The total output is the sum of the fossil and the solar contributions.
- Sunfollowing, with thermal storage. Generate as much electricity as possible, using solar and/or storage, at each time point.
- Load dispatch demand, with thermal storage. Meet, but do not exceed the user-entered net electrical demand if solar and/or storage can provide the necessary power.

The user-entered demands in the above strategies are specified on an hourly basis, giving the capability to model a wide range of load profiles.

Plant Operation Strategies modeled for the repowering project utilized STEPPE Strategies 1 and 3 listed above.

6.3.2 PSO System Simulation

Power production costs were estimated through the use of a computerized mathematical model, a specially developed version of PROCOS that simulates PSO system operation. The production costs include fuel costs, operating and maintenance (O&M) costs, and power purchase costs. The PROCOS computer program is the basic tool used by PSO for planning studies and fuel forecasting.

The production cost computer program utilizes as its basis the principle of economic dispatch. A detailed description of this principle is beyond the scope of this document; the subject is discussed in a number of references.* The essence of optimum allocation of load among a number of generating units is achieved by dispatching each unit so that all units operate at the point of equal incremental costs. This principle is routinely applied in actual power system operating practice as well as in planning investigations.

The economic dispatch incremental cost principle, as expressed in mathematical terms, is translated into a computer code algorithm. Constraints are applied to this optimization algorithm in order to reflect the fact that, in normal utility system operation, the opportunities for mathematically true least cost dispatch are modified because of planned and unscheduled unit outages, reliability considerations, unit start-up limitations, system stability requirements, and similar factors. The PROCOS program can, thus, be characterized as a constrained (optimum) economic dispatch.

The program requires three principal inputs in order to perform the optimization.

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*See, for example, Leon K. Kirchmayer, Economic Operation of Power Systems, John Wiley & Sons, Inc., 1958.

- Load Models. Two load models are specified for each week for a year. The load models were developed from historical system load data and reflect weekly on-peak and off-peak periods.
- Generating Unit Operating and Cost Parameters. For each unit which is available during the planning period, unit heat rate data, minimum and maximum loadings, fuel and O&M base year costs, and annual escalation rates are required.
- Specific Load and Energy Data. For each week, the projected peak load and load factor are computed. The total peak load generation required includes loads to satisfy system losses and any external sales requirements. In PROCOS for the PSO system, the load shape plus off-system sales less off-system purchases is the generation curve. Units are dispatched against this generation curve for each week in a probabilistic manner.

The determination of PSO system production costs with solar repowering incorporates the same methods and computer code used for more typical investigations. However, the unique technical and economic characteristics of the solar repowered unit require special modeling, so that the heat rate and output power of the repowered unit are properly adjusted to reflect the solar input.

In normal production cost simulations involving fossil and nuclear units, the load model is used to represent the variations in system load, and the units are dispatched at varying levels of output to meet the loads. However, when a solar unit is to be simulated, the load model must reflect both the time variation in system load and also the time variation in the output of the solar unit.

To represent this time-varying capacity in the computer code, equivalent hours at full solar power were calculated for each month of the year. This discrete representation of the solar unit was combined with the daily load variations by limiting the available hours of solar operation against the weekly system peak load period load shape. This simplifying assumption was possible due to the flat nature of the PSO daily load pattern during the periods of peak solar insolation.

Following the constraint on unit loading so that the amount of solar capacity available in each load period was accurately represented, the only remaining task in modeling the solar repowered facility was to modify the heat rate curve of NES I and the fuel cost to reflect the solar input into the thermal unit.

The fuel adjustment was accomplished by modeling the 150 MW NES I as a hybrid unit. For periods of full equivalent solar hours, the fuel cost of the hybrid unit was adjusted to 4/7 (57.14 per cent) of the fuel cost corresponding to the normal fossil-fired heat rate. For the time periods in each week when the solar unit was not available, the normal fossil-fired heat rate and cost were used.

6.4 RESULTS AND CONCLUSIONS

The predicted operating performance of the solar repowered NES I, the results of the economic analysis, and the conclusions reached about the economic value of the repowered unit to PSO are contained in Sections 6.4.1, 6.4.2, and 6.4.3, respectively.

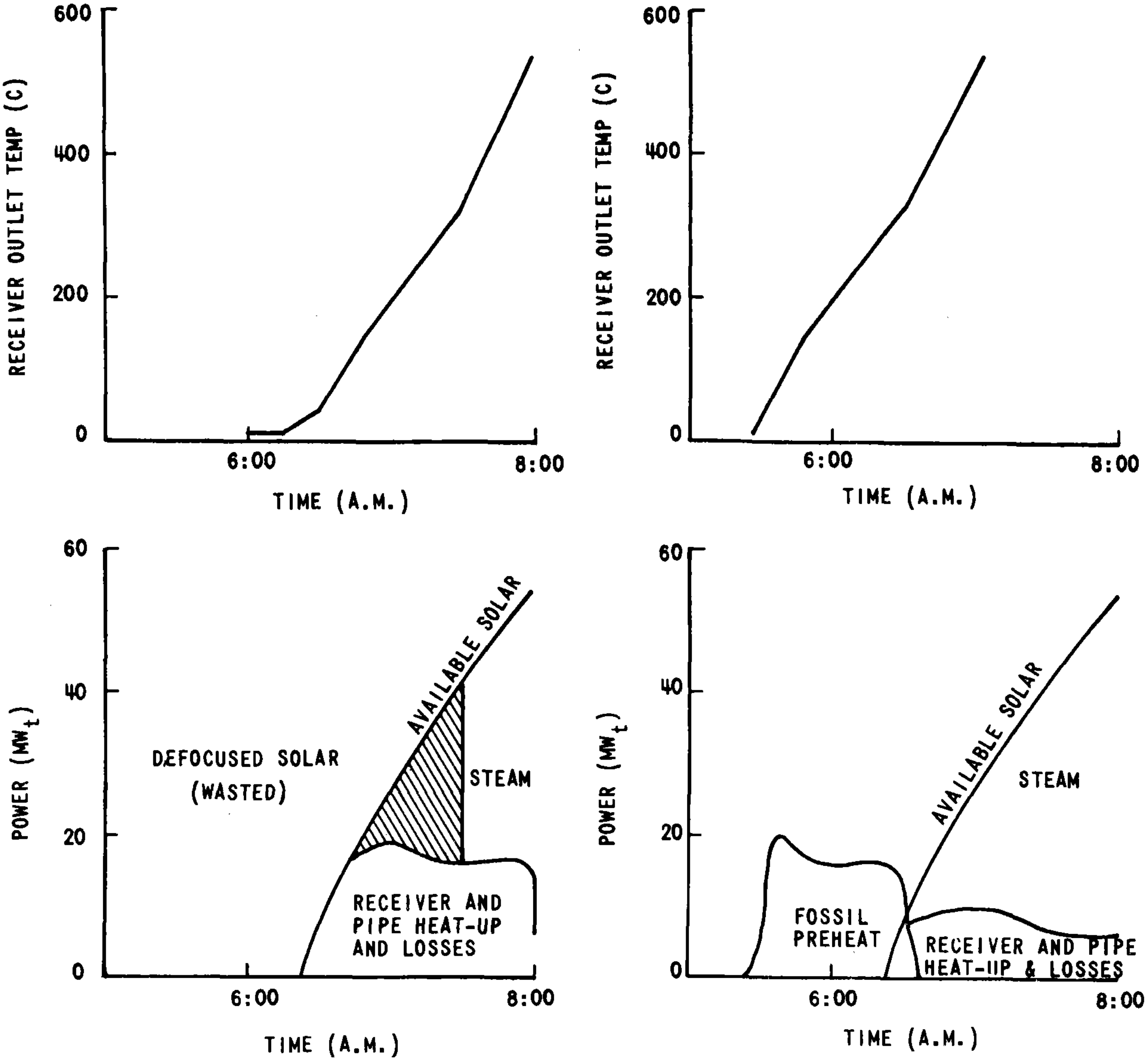
6.4.1 Solar Repowered Plant Operating Characteristics

Annual performance of Northeastern Station Unit I, including the solar repowering system, was evaluated using STEPPE. Performance analyses were made using a range of representative plant operating strategies in order to evaluate the impact of solar repowering on the overall plant heat rate. Additional performance analyses considered various receiver start-up options to determine the significance of preheating the receiver with fossil fuel and of utilizing closure doors to reduce receiver cooldown.

To provide input for the economic dispatch analysis, STEPPE was used to predict the daily available net energy output of the solar portion of the repowered NES I. This "available" energy represents the greatest amount of energy (steam) that the solar system can produce on a given day; the solar energy actually utilized by the plant depends upon the utility economic dispatch strategy. The term "net" indicates that an appropriate energy penalty has been imposed for any fossil energy utilized in preheating the solar receiver.

The daily available net energy from the solar system is dependent upon the method of starting the receiver following cooldown. To determine the maximum available net energy delivered by the solar system, as well as to quantify the impacts of various receiver start-up methods, several receiver start-up options were analyzed. These analyses demonstrated that available net energy can be increased somewhat by the use of fossil energy preheating of the receiver (to prepare the receiver to utilize all available solar energy early in the morning) and further increased by the use of receiver closure doors (to reduce nighttime cooldown losses) as discussed in Section 5.2. The impact of fossil preheating is illustrated on Figure 6-3. Two cases are shown: no fossil preheating and proper fossil preheating. With no fossil preheating, heliostats must be defocused in early stages of receiver start-up to prevent receiver tubes from exceeding the allowable metal temperature ramp rates. Furthermore, in later stages of receiver start-up, large amounts of steam are produced at relatively low outlet temperatures, which reduces the turbine heat rate and may require the defocusing of heliostats to prevent possible introduction of saturated steam into the turbine. With the appropriate use of fossil preheating, the receiver is warmed to a temperature which permits full use of the early morning solar power levels. Premature fossil preheating results in a "waiting period" during which the available solar power cannot maintain the receiver temperature; fossil energy necessary to maintain the receiver temperature during the waiting period is wasted.

Table 6-2 gives a listing of the annual available net energies as computed by STEPPE for four receiver start-up options, plus a fifth "ideal" case where receiver cooldown does not occur (as in the case of perfect receiver closure doors). These annual available net energies are also expressed in Table 6-2 as a number of "equivalent hours per day," where equivalent hours are the average daily net energy divided by the design point power. The greatest, realizable annual available net energy from the solar system would occur with closure doors and diurnal fossil preheating of the receiver; fossil preheating would be utilized



(a)
NO FOSSIL PREHEAT

(b)
PROPER FOSSIL PREHEAT

FIGURE 6-3. RECEIVER STARTUP ALTERNATIVES: MARCH 21, NO CLOSURE DOORS

when multiple days without sunshine result in excessive cooling of the receiver.

In order to illustrate the impact of the solar system on overall plant performance, four hypothetical operating strategies have been

TABLE 6-2. ANNUAL ENERGY OUTPUT FROM SOLAR SYSTEM

Start-Up Method	Net Energy (GWh_t)*	Equivalent Hours**
No fossil preheat, no closure doors	117	4.40
Fossil preheat, no closure doors	119	4.45
No fossil preheat, with closure doors	120	4.51
Fossil preheat,*** with closure doors	120	4.51
No cooldown (start-up not required)	121	4.55

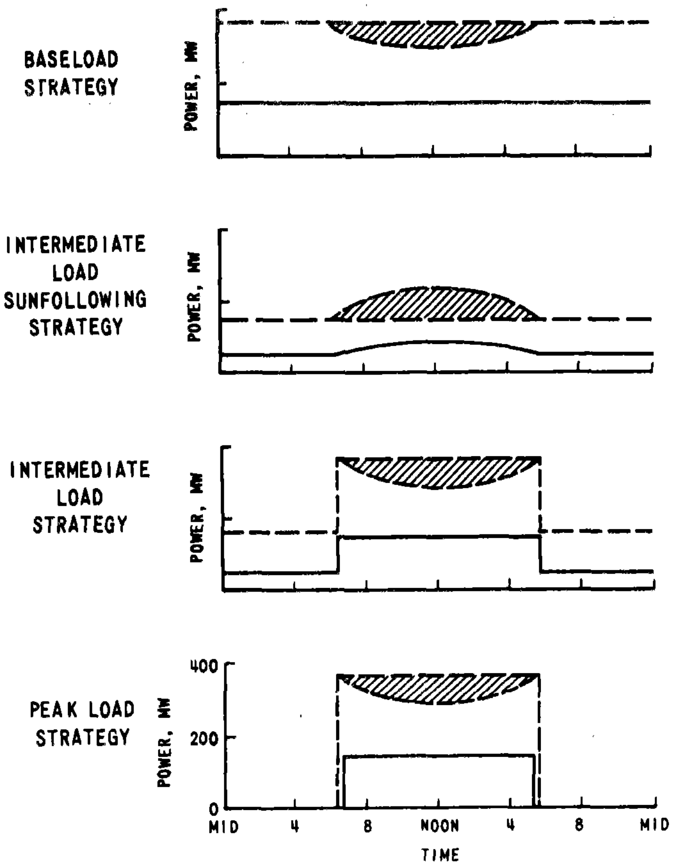
---

*Annual net available energy from the solar system. Fossil energy for preheat has been subtracted out.

**Daily net available energy divided by design point power.

***Fossil preheating of the receiver with closure doors showed no performance improvement for overnight cooldown. Fossil preheating would improve performance for cold receiver start-ups (after extended shutdowns) with closure doors.

analyzed. These four operating strategies, along with annual energy summaries, are illustrated in Figure 6-4. In each of the strategies, it was assumed that all of the available net solar energy would be dispatched.



ANNUAL ENERGY SUMMARIES (GWh)

THERMAL TO TURBINE	3,180
FROM SOLAR	120
FROM FOSSIL	3,060
NET ELECTRICAL GENERATED	1,270
PER CENT SOLAR CONTRIBUTION	3.8*
THERMAL TO TURBINE	1,438
FROM SOLAR	120
FROM FOSSIL	1,318
NET ELECTRICAL GENERATED	523
PER CENT SOLAR CONTRIBUTION	8.3*
THERMAL TO TURBINE	2,079
FROM SOLAR	120
FROM FOSSIL	1,959
NET ELECTRICAL GENERATED	795
PER CENT SOLAR CONTRIBUTION	5.8*
THERMAL TO TURBINE	1,567
FROM SOLAR	120
FROM FOSSIL	1,447
NET ELECTRICAL GENERATED	625
PER CENT SOLAR CONTRIBUTION	7.7*

* CONTRIBUTION BASED ON A TYPICAL MIXTURE OF CLEAR AND CLOUDY DAYS.

– – – – – – THERMAL POWER TO TURBINE
———— NET ELECTRICAL POWER GENERATED

FIGURE 6-4. ENERGY SUMMARIES WITH ALTERNATIVE HYPOTHETICAL OPERATING STRATEGIES

The Baseload Strategy corresponds to operation of NES I at 145 MW_e 24 hours per day. The Intermediate Load Sunfollowing Strategy has the solar contribution to generation superimposed upon a base fossil contribution of 50 MW_e. The Intermediate Load and Peak Load Strategies result in 145 MW_e generation in daylight hours, with 50 MW_e generated at night for the Intermediate Load Strategy and with no nighttime generation for the Peak Load Strategy. The per cent energy displacement and other impacts of solar repowering are dependent upon the plant operating strategy, as shown in the annual energy summary.

The impact of the solar system on plant heat rate is graphically illustrated by the family of curves of effective plant heat rates versus net generated power shown in Figure 6-5. As used here, the term plant heat rate means the energy input to the plant in the form of fossil fuel divided by the net electrical plant output. The topmost curve shows the heat rate for the existing fossil plant. The next lower curve illustrates the annual average effective (fossil fuel consumption) heat rate for the plant when generating a constant load 24 hours a day throughout the year. The third curve identifies the annul average heat rate during daylight hours when generating a constant load during the daytime, including cloudy days, throughout the year. The fourth curve gives average plant heat rate for generation during daylight hours on clear days. The lowest curve predicts the effective instantaneous heat rate when the solar system provides its rated design point power (73.3 MW_t).

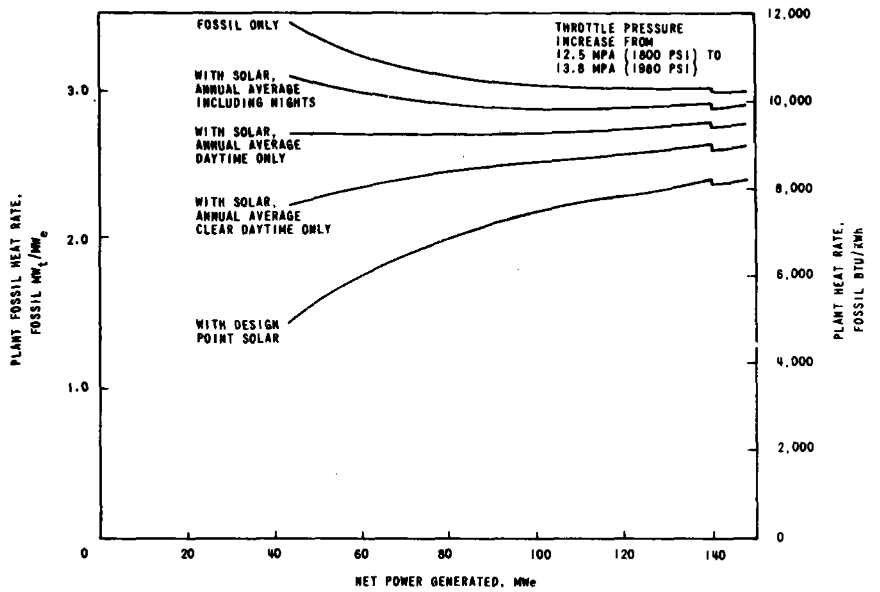


FIGURE 6-5. EFFECTIVE PLANT HEAT RATES WITH SOLAR REPOWERING

6.4.2 Economic Factors

The results of the economic analysis are presented in terms of production costs, capital requirements, revenue requirements, and value of solar repowering to PSO. The section ends with the conclusions reached as a result of performing the economic analysis.

6.4.2.1 Annual Production Costs. A total of eight plans were established and evaluated to calculate the annual change in production costs. The plans are described below.

Plan 1. Base case plan. No solar repowering; normal PSO expansion plan. PSO capital and fuel cost projections.

Plan 2. Solar repowering. 150 MW of capacity addition is deferred from 1995 to 2000. PSO capital and fuel cost projections.

Plan 2A. Identical to Plan 2 except that the normal PSO expansion plan was used.

Plan 3. Identical to Plan 1 except that DOE projected capital and fuel costs were used.

Plan 4. Identical to Plan 2 except that DOE projected capital and fuel costs were used.

Plan 4A. Identical to Plan 2A except that DOE projected capital and fuel costs were used.

Plan 5. Identical to Plan 2 except that the solar component was assumed to have a 50 MW contribution.

Plan 6. Identical to Plan 4 except that the solar component was assumed to have a 50 MW contribution.

The plan logic was established to permit the explicit examination of the issues. Thus, comparison of Plans 1 and 2 shows the fuel cost savings due to the solar unit, including the impact of the deferral of 150 MW of coal capacity. Comparison of Plans 1 and 2A shows the fuel savings due to the solar unit only. Comparisons of Plan 3 with Plan 4 and Plan 3 with Plan 4A yield similar information for DOE cost projections. Comparisons of Plan 1 with Plan 5 and Plan 3 with Plan 6 show the impacts of solar plant size for PSO and DOE cost projections, respectively. A total of six costs differentials were established.

Case I--Plan I versus Plan 2.

Case II--Plan I versus Plan 2A.

Case III--Plan 3 versus Plan 4.

Case IV--Plan 3 versus Plan 4A.

Case V--Plan I versus Plan 5.

Case VI--Plan 3 versus Plan 6.

The basic cost data for these case comparisons are given in Table 6-3 which shows the annual system operation cost for each plan. Table 6-4 shows the decrease or increase in the annual production costs due to the solar repowering for each case. Table 6-4 shows that for plans which include the deferral of capacity (Plans 2, 4, 5, and 6), the repowering tends to result in an increase in system operating costs due to the deferral of low cost coal capacity, even though less actual fossil fuel energy (Btu) is used.

6.4.2.2 Capital Requirements. Table 6-5 shows the comparative capital investment schedules for each plan. Only the years affected by solar investment and capacity deferrals are explicitly shown in Table 6-5. For other years, the capacity addition for each plan was the same; therefore, costs were not relevant.

6.4.2.3 Revenue Requirements. Actual and levelized annual revenue requirements were determined for each plan. Actual revenue requirements for the planning cycle years are given in Table 6-6. Solar unit lifetime was set at 15 years, while that of the fossil unit was set at 24 years. Both unit types were assumed to have zero salvage value and equal property tax and insurance requirements. An investment tax credit of 10 per cent was used for both units.

6.4.2.4 Value of Solar Repowering to PSO. The annual revenue requirements provide the proper form of the economic data to permit the final calculations of the value or worth of the solar repowered unit to PSO. Table 6-7 summarizes the value calculations. In all cases considered, the solar hybrid repowering plant, with its estimated costs and performance, has a total present-worth value to PSO below the present-worth of constructing the solar repowering addition. This is true even considering that the present-worth to PSO of the construction cost of the solar

TABLE 6-3. ANNUAL SYSTEM OPERATING COSTS* ($ MILLIONS)

Year	Plan 1	Plan 2	Plan 2A	Plan 3	Plan 4	Plan 4A	Plan 5	Plan 6
1985	488.5	487.3	487.3	497.6	496.3	496.3	486.3	495.2
1986	552.7	551.0	551.0	579.7	577.8	577.8	549.6	576.4
1987	550.2	548.9	548.9	591.8	590.4	590.4	547.4	588.7
1988	590.6	589.0	589.0	661.3	659.4	659.4	588.2	658.1
1989	600.9	599.8	599.8	701.4	699.9	699.9	597.5	696.7
1990	571.7	570.2	570.2	698.1	696.1	696.1	509.0	694.3
1991	633.8	631.7	631.7	797.5	794.7	794.7	630.7	793.1
1992	658.7	658.0	658.0	848.1	846.9	846.9	650.6	844.5
1993	758.5	756.1	756.1	990.1	986.6	986.6	755.4	985.1
1994	766.1	764.8	764.8	1,026.7	1,024.4	1,024.2	763.3	1,018.9
1995	795.7	816.9	795.4	1,094.9	1,127.5	1,094.4	814.1	1,122.6
1996	954.0	970.7	953.5	1,332.4	1,360.6	1,329.3	973.9	1,357.3
1997	854.1	856.3	856.3	1,261.0	1,270.6	1,261.5	855.3	1,263.4
1998	1,003.5	1,019.4	1,007.5	1,488.5	1,517.2	1,488.9	1,021.0	1,509.0
1999	1,049.2	1,065.5	1,050.9	1,605.9	1,634.4	1,600.0	1,065.1	1,631.4

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*Includes fuel and O&M costs.

TABLE 6-4. ANNUAL SAVINGS (INCREASE) IN SYSTEM OPERATING COSTS* DUE TO SOLAR REPOWERING ($1,000)

	Case I	Case II	Case III	Case IV	Case V	Case VI
Fuel Projection	PSO	PSO	DOE	DOE	PSO	DOE
Capacity Deferral for Repowering	Yes	No	Yes	No	Yes	Yes
Solar Capacity, MW	30	30	30	30	50	50
Year						
1985	1,200	1,200	1,300	1,300	2,200	2,400
1986	1,700	1,700	1,900	1,900	3,100	3,400
1987	1,300	1,300	1,400	1,400	2,800	3,100
1988	1,600	1,600	1,900	1,900	2,400	3,200
1989	1,100	1,100	1,500	1,500	3,400	4,700
1990	1,500	1,500	2,000	2,000	2,700	4,800
1991	2,100	2,100	1,800	1,800	3,100	4,400
1992	700	700	1,200	1,200	2,100	3,600
1993	2,400	2,400	3,500	3,500	3,100	5,000
1994	1,300	1,300	2,300	2,300	2,800	7,800
1995	(21,200)	300	(32,600)	500	(18,400)	(27,700)
1996	(16,700)	500	(28,200)	3,100	(19,900)	(24,900)
1997	(2,200)	(2,200)	(9,600)	(500)	(1,200)	(2,400)
1998	(15,900)	(4,000)	(28,700)	(400)	(17,500)	(20,500)
1999	(16,300)	(1,700)	(30,500)	5,900	(15,900)	(25,500)

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*Includes fuel and O&M costs.

TABLE 6-5. COMPARATIVE CAPITAL INVESTMENT SCHEDULES ($ MILLIONS)

	Plan 1	Plan 2	Plan 2A	Plan 3	Plan 4	Plan 4A	Plan 5	Plan 6
Cost Projection	PSO	PSO	PSO	DOE	DOE	DOE	PSO	DOE
Capacity Deferral	No	Yes	No	No	Yes	No	Yes	Yes
Year								
1985		65.0	65.0		65.0	65.0	65.0	65.0
1995	301.0	73.1	301.0	562.0	137.4	562.0	73.1	137.4
2000	450.8	758.1	450.8	881.8	1,483.0	821.8	758.1	1,483.0
Total	751.8	896.2	816.8	1,443.8	1,685.4	1,508.8	896.2	1,685.4

TABLE 6-6. ANNUAL SYSTEM REVENUE REQUIREMENTS ($ Millions)

Year	Plan 1		Plan 2		Plan 2A		Plan 3		Plan 4		Plan 4A		Plan 5		Plan 6	
1985	488.5	1	495.4	2	495.6	2	497.6	1	504.4	2	504.7	2	494.4	2	503.3	2
1986	552.7	1	566.6	2	566.6	2	579.7	1	593.5	2	593.6	2	565.2	2	592.1	2
1987	550.2	1	563.5	2	563.5	2	591.8	1	604.9	2	605.0	2	562.0	2	603.2	2
1988	590.6	1	602.5	2	602.5	2	661.3	1	672.9	2	673.0	2	601.7	2	671.6	2
1989	600.9	1	612.3	2	612.3	2	701.4	1	712.4	2	712.5	2	610.0	2	709.2	2
1990	571.7	1	581.8	2	581.8	2	698.1	1	707.7	2	707.9	2	580.6	2	705.9	2
1991	633.8	1	642.4	2	642.4	2	797.5	1	805.3	2	805.5	2	641.4	2	803.8	2
1992	658.7	1	667.8	2	667.8	2	848.1	1	856.7	2	856.9	2	666.4	2	854.3	2
1993	758.5	1	765.2	2	765.1	2	990.1	1	995.6	2	995.8	2	764.4	2	994.1	2
1994	766.1	1	773.1	2	772.6	2	1026.7	1	1032.7	2	1032.5	2	771.6	2	1027.2	2
1995	838.7	2	834.9	1	846.0	2	1175.1	2	1154.7	1	1192.3	2	832.2	1	1149.9	1
1996	1038.4	2	998.2	1	1044.9	2	1490.0	2	1406.1	1	1493.9	2	1001.4	1	1402.8	1
1997	935.2	2	882.4	1	943.9	2	1412.5	2	1314.0	1	1419.4	2	881.5	1	1306.9	1
1998	1081.4	2	1044.2	1	1091.3	2	1634.0	2	1558.7	1	1640.3	2	1045.8	1	1550.5	1
1999	1124.1	2	1089.2	1	1131.2	2	1745.8	2	1676.0	1	1745.3	1	1088.7	1	1671.0	1
2000	136.2	2	129.4	1	140.0	2	260.1	2	248.2	1	263.8	2	129.4	1	248.2	1
2001	195.4	1	229.4	2	195.4	1	376.2	1	447.4	2	376.2	1	229.4	2	447.4	2
2002	187.8	1	220.5	2	187.8	1	361.4	1	430.0	2	361.4	1	220.5	2	430.0	2
2003	190.3	1	211.8	2	180.3	1	347.1	1	413.2	2	347.1	1	211.8	2	413.2	2
2004	173.1	1	203.4	2	173.1	1	333.3	1	396.8	2	333.3	1	203.4	2	396.8	2
2005	166.2	1	195.3	2	166.2	1	319.9	1	381.0	2	319.9	1	195.3	2	381.0	2
2006	159.5	1	187.5	2	159.5	1	307.0	1	365.8	2	307.0	1	187.5	2	365.8	2
2007	153.0	1	179.9	2	153.0	1	294.6	1	351.0	2	294.6	1	179.9	2	351.0	2
2008	146.8	1	172.6	2	146.8	1	282.6	1	336.8	2	282.6	1	172.6	2	336.8	2
2009	140.8	1	165.6	2	140.8	1	271.1	1	323.1	2	271.1	1	165.6	2	323.1	2
2010	135.1	1	158.9	2	135.1	1	260.1	1	309.9	2	260.1	1	158.9	2	309.9	2
2011	129.6	1	152.4	2	129.6	1	249.5	1	297.2	2	249.5	1	152.4	2	297.2	2
2012	124.4	1	146.2	2	124.4	1	239.4	1	285.1	2	239.4	1	146.2	2	285.1	2
2013	119.4	1	140.2	2	119.4	1	229.8	1	273.5	2	229.8	1	140.2	2	273.5	2
2014	114.6	1	134.6	2	114.6	1	220.7	1	262.5	2	220.7	1	134.6	2	262.5	2
2015	110.1	1	129.1	2	110.1	1	212.0	1	251.9	2	212.0	1	129.1	2	251.9	2
2016	105.9	1	124.0	2	105.9	1	203.8	1	241.9	2	203.8	1	124.0	2	241.9	2
2017	101.9	1	119.1	2	101.9	1	196.0	1	232.4	2	196.0	1	119.1	2	232.4	2
2018	98.1	1	114.5	2	98.1	1	188.7	1	223.4	2	188.7	1	114.5	2	223.4	2
2019	80.6	1	106.8	2	80.6	1	155.9	1	208.6	2	155.9	1	106.8	2	208.6	2
2020	58.4	1	98.2	2	58.4	1	114.2	1	192.0	2	114.2	1	98.2	2	192.0	2
2021	56.3	1	94.6	2	56.3	1	110.0	1	185.1	2	110.0	1	94.6	2	185.1	2
2022	54.3	1	91.3	2	54.3	1	106.2	1	178.6	2	106.2	1	91.3	2	178.6	2
2023	52.5	1	88.2	2	52.5	1	102.6	1	172.6	2	102.6	1	88.2	2	172.6	2
2024	29.9	1	50.3	2	29.9	1	58.5	1	98.3	2	58.5	1	50.3	2	98.3	2

TABLE 6-7. VALUE TO PSO OF SOLAR REPOWERING (1980 Present-Worth $1,000,000)

Case	I	II	III	IV	V	VI
Solar Component Capacity, MW	30	30	30	30	50	50
Cost Projection Parameters	PSO	PSO	DOE	DOE	PSO	DOE
Capacity Deferred	Yes	No	Yes	No	Yes	Yes
Value Due to Operating Savings, 1980 $	(4.7)	4.0	(10.8)	6.9	(0.3)	(0.2)
Value Due to Capacity Deferral, 1980 $	17.1	0.0	27.7	0.0	17.1	27.7
Present-Worth Total Value, 1980 $	12.4	4.0	16.9	6.9	16.8	27.5
Present-Worth $/kW Solar	403	133	563	230	336	550
Equivalent Construction Value to PSO, 1985**	18.3	5.8	25.3	10.0	24.6	39.9
Value to PSO, per cent of cost estimate*	28.2	8.9	38.9	15.4	--	--

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*As-built investment including AFUDC in 1985 is $65.00 M.

**See Subsection 6.4.2.4 for the derivation of these results.

addition is less than the $55.1 million construction cost estimate; the reduction is due to the fact that the escalation (inflation) rate is less than the PSO discount rate.

These calculations were further tested by establishing two additional cases, Case VII and Case VIII. Case VII compared Plans 1 and 2, but with a 1985 capital investment of $18.3 million for the repowered unit. Case VIII compared Plans 3 and 4, but with a solar investment of $25.3 million. In both cases, the plan with solar showed lower levelized revenue requirements starting in 1996 and continuing through the evaluation period except that for the final year the levelized annual costs were equal. In essence, the value of the solar repowered plant in 1985 to PSO for Plan 2 is $18.3 million or 28.2 per cent of its estimated construction value in 1985. Certain of the assumptions (namely, the low solar forced outage due to severe weather, and the modeling assumption that peak insolation coincided with system peak load) would tend to reduce the value.

Another economic evaluation factor worth citing, as shown in Table 6-7, is that the major value of the repowering is the extension of the economic life of NES 1. It was assumed that natural gas will be available by exemption under the Fuel Use Act during non-solar operation times and for operation at minimum turndown.

If the Fuel Use Act exemption cannot be obtained so as to justify the extension of the retirement date of NES 1, then PSO will be forced to follow its planned capacity addition schedule. Such a schedule would reduce the value of the solar repowering to $4.0 million (1980 dollars), the value to PSO of the projected fuel costs savings.

6.4.3 Conclusions

The detailed analysis presented earlier in this section confirmed and quantified the expected conclusions. The three main conclusions and commentary are presented below.

- The value of solar repowering to PSO is less than the construction cost estimate.

There is an economic shortfall of 72 per cent; this shortfall does not include an allowance for the additional investment risk associated with a new and promising technology. This shortfall is traceable to three main factors. First, the heliostat cost used in the analysis ($\$260/m^2$) is greater that the $\$70/m^2$ predicted required level for mature heliostat production. Second, the cost estimate includes engineering, development, and operational data gathering associated with a first-of-a-kind installation. Third, the 15-year lifetime assumed for the repowered unit is only 1/2 of the normal 30-year lifetime planned for an electrical generating unit.

- 30 MW_e of solar repowering is the most cost effective size for NES I.

At 30 MW_e of solar repowering, the capital cost required is minimum consistent with a meaningful demonstration; the cost per kW of installed capacity is also minimum for this site. All technological and operating aspects of a hybrid solar central receiver electric generating plant would be exercised and evaluated.

- The amount of fossil fuel displaced is not sensitive to the operating strategy, assuming solar energy is fully utilized.

Altering operating procedures affects the value of the solar repowered unit to PSO because of the fuel mix, but the actual amount of fuel displaced is associated with the performance of the solar system.

7.0 DEVELOPMENT PLAN

The conceptual design, performance, and economic analyses presented in the prior sections provide the technical and economic groundwork for this development plan. The plan addresses technical, economic, and organizational issues from engineering design to construction, testing, and PSO ownership. The schedule, milestones, and critical dates for approval/ authorization are compatible with those presented in the Solar Repowering/ Industrial Retrofit Program Element Plan.

The organizational roles for the engineering and construction phase provide for PSO to be the prime contractor who would assign to Black & Veatch the responsibility for overall project management services and integration of engineering design, construction management, start-up and check out, and system performance evaluation phases. The engineering task begins with the preparation of a management plan containing a detailed work breakdown structure (WBS) for the preliminary design, the detailed design, procurement services, review procedures and approvals, and detail design. A preliminary WBS would be included in the management plan for the check out and start-up phases and the first-year system performance and evaluation phase.

Based on the WBS, a precedence diagram, milestone chart and milestone log would be prepared. These documents would indicate those elements of the WBS which were on the critical path as well as requirements for long lead time procurements. The work elements in the design and construction phases will be overlapped (fast tracked) to meet the October 1984 date for operational status. From these documents and the engineering cost estimates, the cash flow requirements would be determined. A preliminary estimate of cash flow requirements by fiscal year is given in Section 7.6.

No Subsystem Research Experiment (SRE) is necessary for the proposed system. The only equipment which has any novelty is the solar receiver; however, B&W is confident of the screen tube and superheater panel design and recommends that the receiver be designed and installed without an SRE. This recommendation is based upon B&W's design and analysis expertise in steam generators and utility industry acceptance of B&W's product and warranties. It reflects the real world situation that the relative absorptions between steam generation and steam superheating as well as among the superheater panels are not always predicted precisely. To accommodate these uncertainties, the receiver design includes several features that are adjustable. These include large quantities of superheater spray attemperation, conservative design of superheater panels, and the ability to modify relative absorption of any panel by modifying the size of the screen tubes. Such alterations also occur on some fossil units, and an outage may be required to modify the boiler for unexpected imbalances in absorption. The occasional need for such adjustments to meet guarantees is understood by operating companies and their engineers.

Further discussion of the design phase, construction phase, system check out and start-up phase, system performance evaluation phase, and the joint user/DOE operations phase follow. A schedule, milestone chart, and cash flow are presented, as well as a discussion of the roles of site owner, government, and industry.

7.1 DESIGN PHASE

The design phase includes preparation of the management plan, WBS, documents required for legal and regulatory approvals, preliminary design, detailed design, and procurement documents. In concert with the Solar Repowering/Industrial Retrofit Program Element Plan, the first 9 months' effort of the design phase is termed preliminary design; the next 12 months' effort is termed detailed design.

Preliminary design will use information contained in this conceptual design study as a point of departure for the preparation of the management plan, WBS, and legal and regulatory documents. During this period, engineering design and procurement specifications required for long lead time elements will be prepared to meet the critical path requirements developed early in the program (see Section 7.6 for preliminary schedule). The solar receiver would be provided by B&W, its material for fabrication is the first procurement of the project. The solar receiver is on the critical path with a requirement for fabrication release of March, 1982. Legal and regulatory documents, including preparation of permits for construction, will culminate the preliminary design.

The approval to begin detailed design of the facility authorizes the filing of the legal and regulation documents to obtain approval for construction. Detailed design will include preparation of all construction and procurement specifications for bids. The detailed design phase will end in April 1983, 8 months after initiation of the first construction award is made in September 1982.

Engineering functions to be performed in the preliminary and detailed design efforts include the following.

- Optimization studies.
- Design guidance documents.
  (a) System design specifications.
  (b) Piping and instrumentation diagrams.
  (c) One-line electrical diagrams.
- Design finalization.
  (a) Material selection for each component.
  (b) Component location and installation specifications.
  (c) Interface connections.
  (d) System descriptions.
- Engineering drawings.
  (a) Site drawings.
  (b) Plant equipment layout drawings.
  (c) Construction contract drawings.
  (d) Equipment contract drawings.
- Review of manufacturer's drawings.
  (a) Conformance to specifications.
  (b) Interface requirements.

7.2 CONSTRUCTION PHASE

Until authorization to begin the construction phase, the only long lead time equipment purchased was material for the receiver. Authorization for construction is required by June 1982 to release the site facilities specification for bid. Actual construction will start in August 1982 with the award of a contract for site facilities.

The construction and procurement packages to be issued are listed in Table 7-1. Except for the solar receiver, all procurement will be based on competitive bids. This approach provides the least cost facility.

A detailed presentation of the time sequence for the construction phase is given in Section 7.6.

Construction management services will be provided by B&V. These services include monitoring all construction, maintaining records of compliance with specifications, providing inputs to and updating the CPM control schedule, construction cost management, and reporting.

Equipment and materials would be supplied by manufacturers and suppliers under contracts and purchase orders prepared and issued by B&V as an agent of PSO. Construction would be performed by qualified contractors under fixed price contracts with DOE/PSO approval.

7.3 SYSTEM CHECKOUT AND START-UP PHASE

The overall objective of this project phase is to verify the operational readiness of the plant and to place it in initial operation. As such, the status of the plant must be confirmed component by component, progressing to the point where entire systems have been prepared for operation. A key aspect of this process is determining that individual components not only operate properly by themselves, but also that the various component interactions function properly, as in the case of a sensor, a controller, a valve, and a pump. This orderly, step-by-step process is a normal part of the start-up procedure for any power plant.

The functional system design approach evolved and perfected by the Black & Veatch Power Division is used on all Black & Veatch power plant projects to facilitate efficient and timely checkout and start-up. Successful system checkout and acceptance testing in concert with a firm schedule is the key to on-time and successful Plant Integrated Acceptance Testing. Construction work must be coordinated to allow completion of functional systems in appropriate sequence for checkout and start-up.

TABLE 7-1. CONSTRUCTION AND PROCUREMENT PACKAGES

Name	Issue Date	Construction Period	Description
Site Development and Facilities	May 1982	September 1982 to November 1982	Excavating heliostat and tower area; erect security fence; construct maintenance roads.
Tower	October 1981	November 1982 to April 1983	Erect receiver tower shell.
Heliostats	October 1981	August 1983 to September 1984	Furnish and install heliostats and heliostat computer and controls.
Receiver Loop	April 1983	August 1983 to September 1984	Furnish and install piping from Unit 1 to and up tower to receiver. Install mechanical equipment.
Master Control System (MCS)	September 1982	January 1983 to September 1983	Furnish and erect MCS in existing control room; pull power cable from Unit 1 to tower; install electrical equipment.
Solar Receiver	August 1981	August 1983 to September 1984	Furnish and erect.
Heliostat Foundations	October 1982	July 1983 to August 1984	Erect heliostat foundations and heliostat transformers pads.
Mechanical Equipment	June 1982	August 1983 to June 1984	Furnish miscellaneous drain tanks and pumps.
Electrical Equipment	November 1982	August 1983 to August 1984	Furnish motor control center in tower and existing control room.
Elevator	June 1982	June 1983 to August 1983	Furnish and erect.
Receiver Loop Support System	December 1982	November 1982 to August 1983	Install pipe rack and foundation cable tray from Unit 1 to tower, and items not included in any other work package at this time. Fast-track can be used where needed.

The proper sequence of functional systems completion as well as the checkout and testing of certain functional systems may begin months before the scheduled date for completion of System Checkout and Acceptance Testing.

In order to assure that all the required tests are conducted and that adequate records are maintained, extensive documentation is required. Documentation typically prepared for checkout and testing each system includes the following.

- System Description.
- Piping and Instrument Diagrams.
- Pipeline Listing.
- Manufacturers' Equipment Drawings.
- Manufacturers' Instruction Manuals.
- Logic Diagrams.
- Electrical Schematic Diagrams.
- Circuit Lists.
- Accessory Equipment Lists.
- System Completion Checklist.
- Preoperational Checkout Procedures.
- System Data Forms.
- System Operating Description and Maintenance Instructions.

7.3.1 System Checkout and Acceptance Testing

System checkout and acceptance testing are the final steps on a system level which verify that the work has been accomplished to the full intent of the design and to the satisfaction of PSO, B&V, and DOE. A prespecified procedure of complete systems checkout prior to integrated operation is an orderly and proper approach to start-up of any power plant, and is particularly applicable to repowering NES I.

Before starting systems checkout and acceptance testing, many important functions are performed to verify that equipment, materials, and construction are in accordance with the contract documents. Careful review of manufacturers' drawings, data, and records provides an early examination of details for conformance with contract documents at the component level. The project instructions prepared for the processing and review of manufacturers' drawings and data provide the procedures and the B&V Quality Assurance Program pertaining to processing and review of manufacturers' drawings and data which gives project management the assurance that the written procedures for this important function are being rigorously followed.

Careful processing and review of manufacturers' drawings and data identify, at an early stage in the manufacturing process, errors or deviations which, if undetected at that time, would later be cause for rejection or refabrication of equipment or materials with consequent adverse impact on the project schedule. Where feasible and consistent with accepted good industry practice, operating equipment should be factory assembled and tested. When deemed necessary, such equipment is examined at the factory, and performance tests are witnessed by B&V. Requirements for fabrication and assembly tests and examinations are provided in procurement specifications either directly or by reference to recognized national codes or standards.

System Checkout and Acceptance Testing is accomplished in three steps.

- System Completion Checks.
- Preoperational Checkout Tests.
- System Operating Tests.

7.3.1.1 System Completion Checks. These visual checks are to ensure that system components have been properly installed, connected, and lubricated, and that each system is ready for preoperational checkout. To facilitate these checks, System Completion Checklists would be prepared by B&V for each system; they would include the following sections.

- System Function and Description. A basic description of the system and its major components.
- System Operation. A brief description of the operation to assist checkout personnel in determining that components are correctly installed.
- Tabulation of Applicable Reference Documents. A list to provide ready access to appropriate reference information on system components.

- System Completion Checklist Forms. A set of forms for each system and significant system components which is used to provide a record that all required items have been checked prior to preoperational checkout and testing. Figure 7-1 is a sample page from a System Completion Checklist used on an actual power plant project.

Power Supplies	Installed	Connected	Protective Devices Checked
6,900 Switch-gear 301			
MCC Essential Service Bus 1			
MCC Essential Service Bus 2			
MCC 301 C			

Accessory Equipment and Instrumentation

Pressure Switches	Installed	Connected	Electrically Connected	Calibrated
PS-3437				
PS-3439				
PS-3479				
PS-3575				

FIGURE 7-1. SYSTEM COMPLETION CHECKLIST

7.3.1.2 Preoperational Tests. These functional tests are implemented by a set of Preoperational Checkout Instructions which is prepared for each functional system. The purpose of these tests is to assure, as extensively as possible prior to system operating tests, that each system is functionally correct. An operational checkout section of each set of Preoperational Checkout Instructions will be used to check those parts of a system which cannot be checked until the system is placed into actual operation.

Preoperational Checkout Instructions for each system include the following sections.

- Description of scope of checkout.
- List of applicable reference documents.
- List of required support systems.
- Description of preparations required for checkout.
- Preoperational checkout procedures.
- Description of post-checkout procedures to return system to original status from the special preparations.

7.3.1.3 System Operating Tests. After completing the System Checklist Tests and the Preoperational Tests, PSO would implement System Operating Tests. These tests, which are conducted as the systems become operational, have the following objectives.

- Start up and functionally test all systems which can be operated without integrated plant operation.
- Gain experience in the operating characteristics of the functional systems.
- Permit the transition from individual system tests to integrated acceptance tests to be as smooth as possible.

PSO would conduct these tests based on detailed test procedures and would carefully monitor the tests to make certain that these procedures are followed. This testing will be similar to the sequential functional testing of components and systems.

7.3.2 Plant Integrated Acceptance Testing

As indicated previously, the key to successful on-time integrated operation is timely and successful completion of the systems checkout and testing. It is imperative that all systems be thoroughly checked out and tested before integrated operation, even on a trial basis, is initiated. For instance, attempting initial integrated operation without all safety interlock systems operating satisfactorily involves unacceptable risks. A detailed test plan which defines plant initial integrated operation and acceptance would be prepared.

7.3.3 Key Checkout/Start-Up Elements

Although the development of a comprehensive list of key elements for check-out is beyond the current work scope, it is possible to highlight some areas of consideration. These include the following.

- Collector System operation when the sun is obscured or at night to provide operator experience without a requirement for receiver operation.
- Hydrostatic pressure testing of pressurized system.
- Simulated system operation for operator training and Master Control System checkout (data display and control algorithms).
- Rehearse emergency reactions and verify proper equipment response.

7.4 SYSTEM PERFORMANCE VALIDATION PHASE

The overall objective of this project phase is to gather initial base line operating data and to empirically establish basic performance characteristics. This process focuses on integrated system operation over a range of conditions and comparisons of that operation with design expectations. It represents a significant step beyond the Checkout and Start-up Phase, which is scoped to initiate the intended functions of components/systems (a pass/fail mode) rather than to evaluate their performance. This project phase can be visualized as a limited-term test program. The issues of long-term operation and system utility to PSO are addressed in the subsequent Operations Phase.

7.4.1 Test Plan

This performance validation project phase would be governed by a comprehensive test plan developed around the repowering program objectives. Specific test objectives would be defined and may include the following.

- Determine repowering system performance characteristics (e.g., efficiency, response times).
- Verify design predictions of operating conditions.
- Verify material and component performance.
- Provide supplementary information applicable to system design refinement.

In the course of addressing those objectives, a series of specific technical issues would be considered, including the following.

- Receiver efficiency and loss mechanisms.
- Heliostat field efficiency and optical characteristics.
- Flux distributions and aim strategies.
- System power capacity.
- Steam conditions at receiver outlet and at the fossil system interface point.
- System upsets during cloud transients (actual and/or simulated).
- System stability and load sensitivity.
- Start-up, shutdown, and control techniques/precisions.
- Receiver cooldown characteristics.
- Response times.

To ensure that these issues are properly addressed and that performance data will be available in a form that allows the various interactive phenomena to be individually discerned and evaluated, specific test conditions and methods would be prescribed in the Test Plan. The data system and instrumentation capabilities for the plant would also have to be developed interactively with the Test Plan to ensure that adequate data are acquired. The plant operating procedures would provide the stepwise procedural guidance to implement the Test Plan, with special test procedures being developed for test conditions or requirements not covered by normal plant procedures.

The Test Plan would also include expected results for the test conditions, thus, providing a point of initial data comparison. Subsequent data evaluation would establish actual system performance, determine system capabilities and limits, and provide a basis for system performance validations. Should performance problems or shortcomings develop, the test data will contribute to enhanced system insights and understandings, to design modifications, and/or to refinement of analysis/design methods for future system designs. As necessary, operating procedures and guidelines for subsequent PSO day-to-day use will be altered to reflect actual system characteristics.

This project phase will result in the demonstrated operation of the integrated repowering system in conjunction with the existing NES I. Not only will test data be acquired for analytical evaluation, but plant operators will acquire hands-on experience and a degree of confidence/comfort with the system, thus, encouraging their acceptance of and support in the continued use of the solar hybrid system. The equally important long-term issues such as reliability, performance stability, performance predictability, and maintenance requirements will be addressed in the Operations Phase, with the experience of Performance Validation as an underlying point of reference.

7.5 JOINT USER/DOE OPERATIONS PHASE

For an initial period to be determined, ownership of the solar repowering facility may reside in both PSO and DOE. PSO will operate the facility for this test and evaluation period, during which data will be compiled on fuel displaced, system performance, operating and maintenance costs, equipment failures, and downtime due to scheduled and unscheduled maintenance.

At the end of the test and evaluation phase, the facility's performance and future value to PSO will be evaluated. It is anticipated that the result of this evaluation will provide for transfer of full ownership of the facility to PSO.

7.6 SCHEDULE AND MILESTONE CHART

The primary management control system for the project is the schedule and resource control system (SRCS) and its associated milestone chart. The basis for the SRCS is a comprehensive CPM schedule developed to a detailed WBS, with durations, man-day allotments, and interfaces assigned to each element in the detailed WBS. All team members would participate both in the development of the master project schedule and in the periodic updating process. Monthly project status and variance reports would be generated by Black & Veatch from inputs supplied by all parties. Corrective actions to be taken will be defined in monthly project review meetings. The schedule and resource control system is capable of providing the following reports.

- Project Status.
- Cost Management.
- Manpower Management.
- Cost Performance.

A Major Milestone Schedule and Arrow Diagram Method display are given in Figures 7-2 and 7-3, respectively. These are based on the 180 activity CPM schedule shown in Figure 7-4 and the readable close-up shown in Figure 7-5. The cash flow, given in Table 7-2 in 1980 dollars, is based on the time sequence of expenditures in concert with the CPM schedule.

7.7 ROLES OF SITE OWNER, GOVERNMENT, AND INDUSTRY

PSO is the site owner and will be the prime contractor/operator of the solar repowering facility. The facility capital cost is above its commercial and R & D value to benefit PSO's customers; therefore, there is a need for the government to provide a cost incentive to PSO commensurate with this cost differential, and to underwrite the risk to implement a new technology. The proposed roles of PSO and DOE are analogous to a venture capital situation where DOE has the role of the venture investor and PSO maintains its role as a secured investor with an assured return. Both DOE and PSO have a stake in the R&D aspects. The project will proceed to completion unless an agreement to terminate is jointly made at pre-established project decision milestones. Examples of reason for termination are technical obstructions, cessation of need for the program's performance validation data, funds authorization, etc. Based upon the tacit assumption that the solar repowered system will perform as evaluated in the design phase, a payment of the fair market value of DOE's interest would be made by PSO and full ownership would transfer to PSO after a performance validation period.

For the design and construction phases, Black & Veatch, as a subcontractor to PSO, will provide engineering services commensurate with current PSO/B&V relationships for power plant construction. In this role, Black & Veatch would provide Project Management Services to PSO. The role of other industry members (equipment suppliers, construction

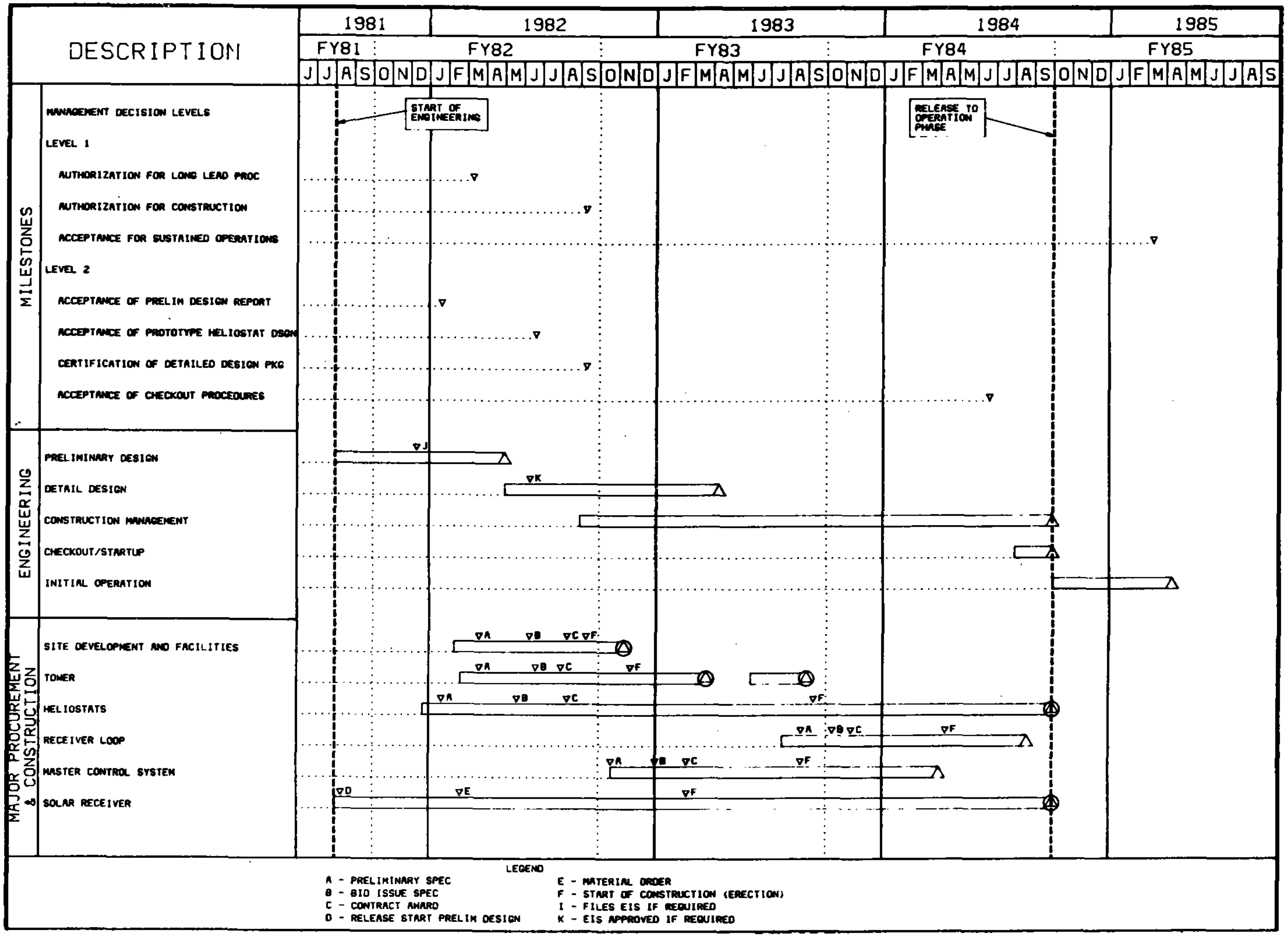


FIGURE 7-2. MAJOR MILESTONES SCHEDULE

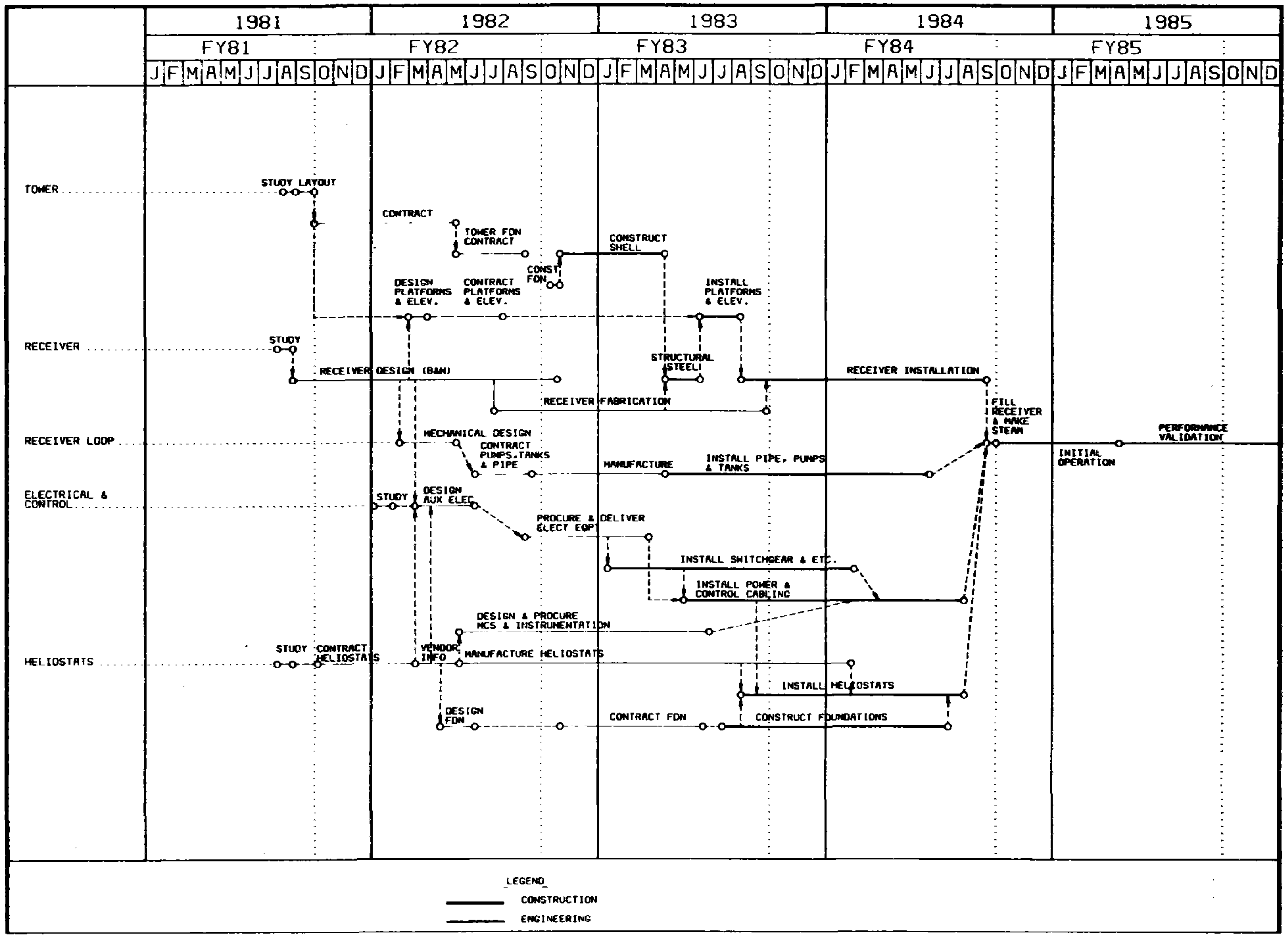


FIGURE 7-3. ARROW DIAGRAMMING METHOD DISPLAY OF MAJOR MILESTONES

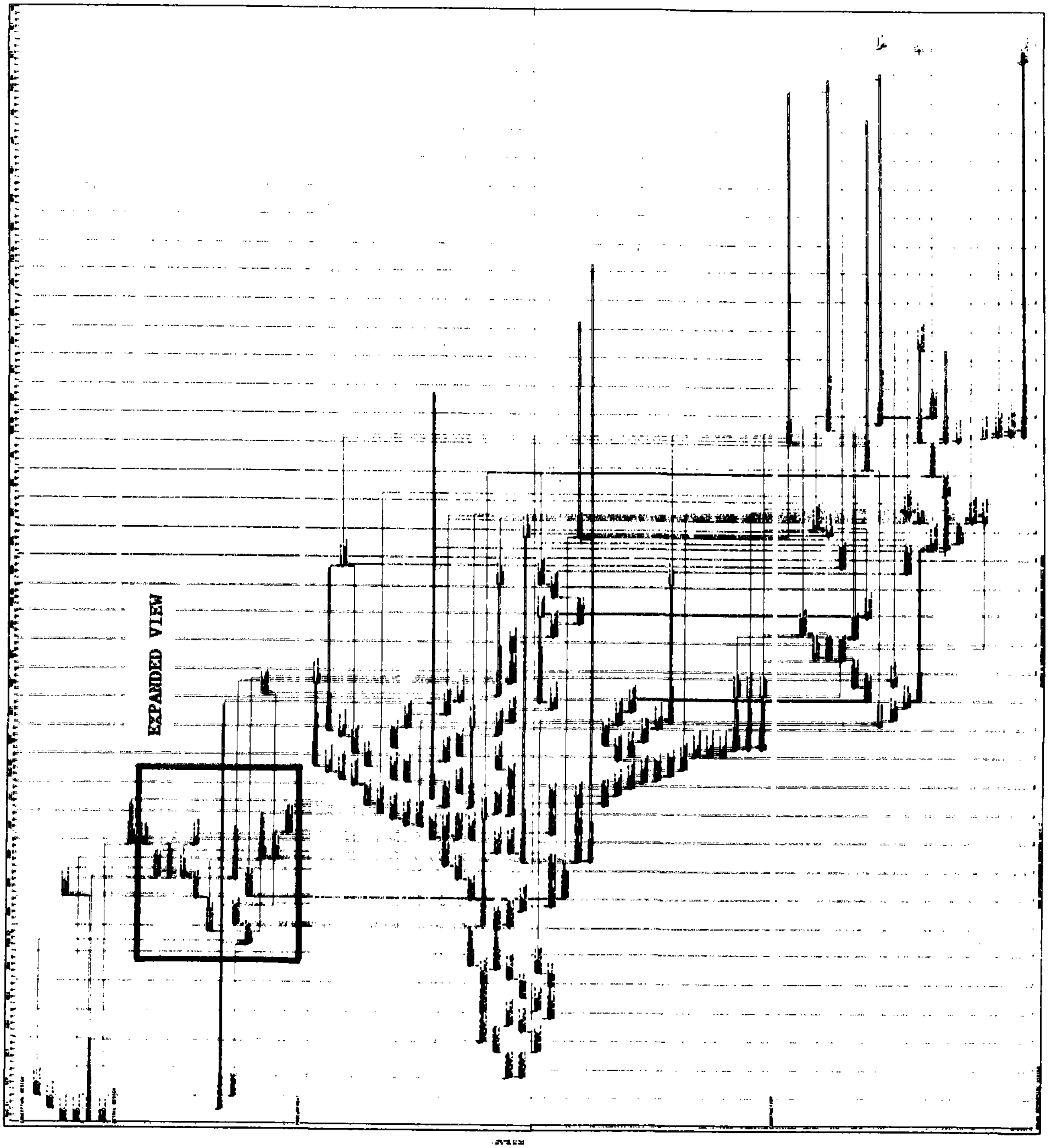


FIGURE 7-4. CPM SCHEDULE

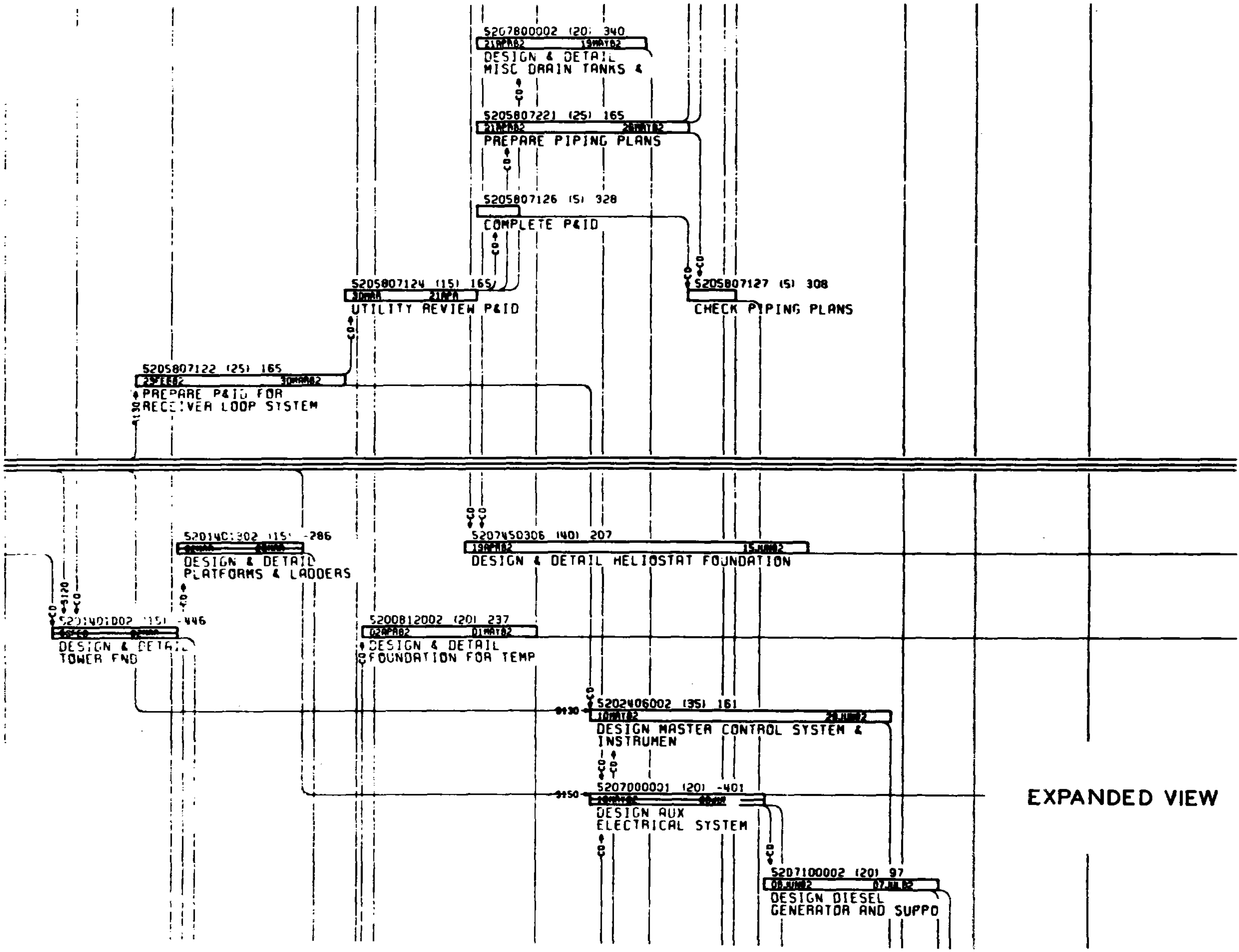


FIGURE 7-5. EXPANDED VIEW OF CPM SCHEDULE

TABLE 7-2. CASH FLOW REQUIREMENTS

	Expenditures in Thousands of 1980 Dollars				
Year	1981	1982	1983	1984	1985
Calendar Year	471	11,212	16,065	23,819	3,532
Fiscal Year	114	6,245	19,036	24,262	5,442

contractors, etc.) will also follow the normal patterns used by PSO under an established quality assurance program for large capital investments.

For operation during the system performance and validation phase, PSO will provide operating personnel and materials. Black & Veatch and appropriate equipment suppliers will provide operator training and technical support. This support will include operator indoctrination in personnel and equipment safety procedures as part of a safety assurance program.

A suggested cost sharing plan is for government research agencies to fund engineering and equipment with the utility funding erection, project management, and operation. The utility would purchase the government's interest after successful demonstration test at the fair market value giving consideration to construction funds previously expended. In the event of unsuccessful operation, the government would be responsible for removal of the solar equipment and restoration of the utility's site.

8.0 TEST PROGRAM

Following is the description of the test program established at the proposed site to determine the magnitude of impact that environmental factors have on plant design and performance. The program, the methodology employed, and the equipment utilized are described, and the results of the test program are presented.

8.1 BACKGROUND

The performance of the solar repowered plant is dependent on the performance of the collector system; that performance is determined primarily by the amount of insolation available and by the cleanliness of the heliostat mirrors. There are a number of features of the repowering site that may impact system performance, especially via heliostat mirror cleanliness.

As shown in Figure 8-1, the repowered plant (Unit 1) is located adjacent to Unit 2, a 470 MW_e oil- and natural gas-fired power plant. The four cooling towers serving these two units are located to the east, between Unit 1 and the proposed collector field. The proximity of these cooling towers to the collector field is of concern for two reasons. Water droplets, which are entrained in the plume from the cooling towers, precipitate out of the plume when air velocities are no longer great enough to keep the droplets in suspension. The precipitating droplets, known as cooling tower drift, may settle onto heliostat mirrors. In addition, cooling tower drift contains significant levels of total dissolved solids (TDS); the solids which land on the mirror surfaces would remain after the water has evaporated, thus reducing mirror reflectivity. The second reason for concern is that, during cold weather, the plume from the cooling towers condenses, forming a large, white, opaque, man-made cloud. Winds may carry the opaque plume such that it shadows a portion of the collector field, thus, affecting system performance. In a similar manner, the cooling towers for Units 3 and 4 pose concerns for the collector field performance; however, this concern is tempered by the greater distance from these cooling towers to the collector field.

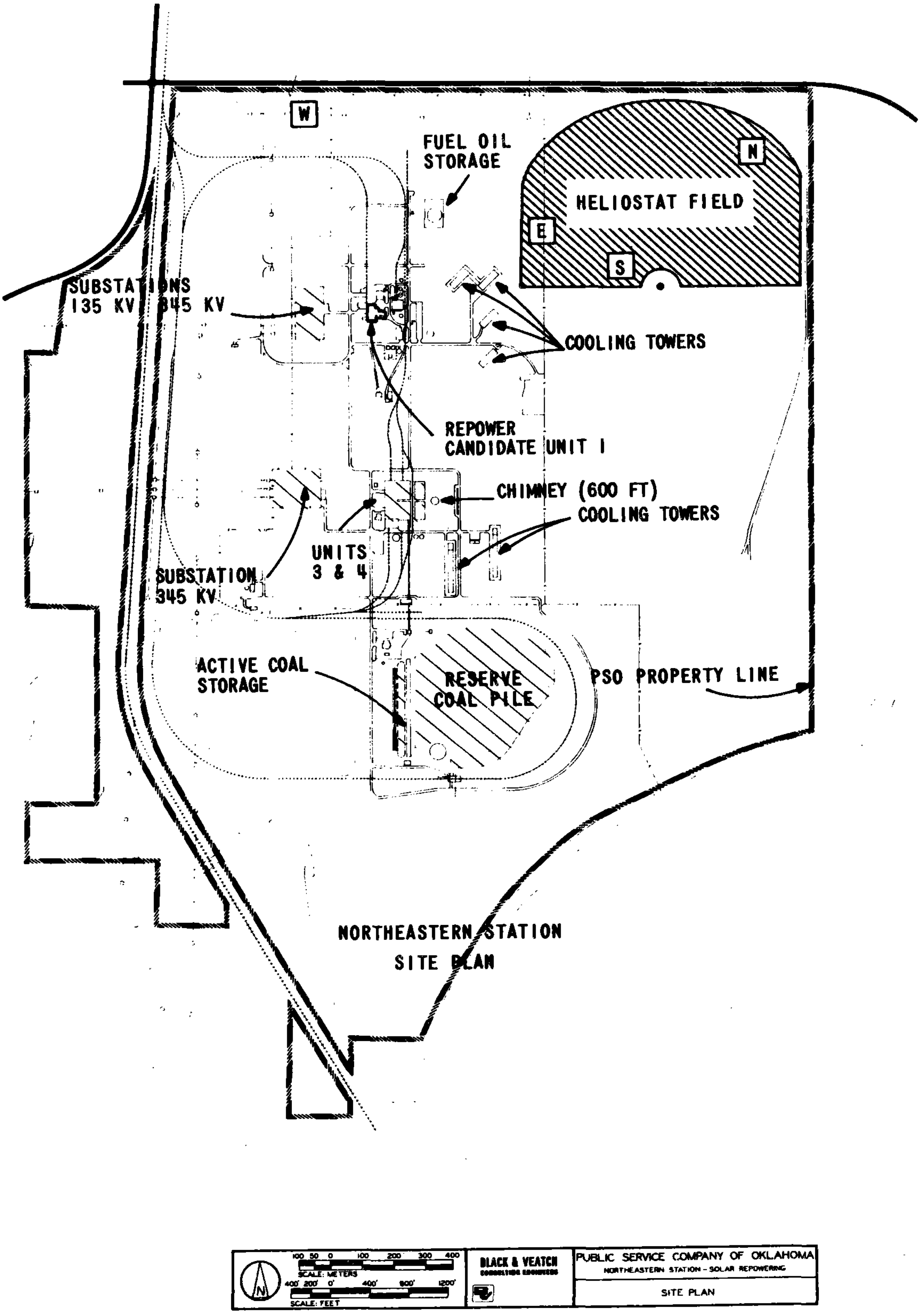


FIGURE 8-1. SITE ARRANGEMENT OF NORTHEASTERN STATION SHOWING PLACEMENT OF THE FOUR HELIOSTAT SIMULATORS

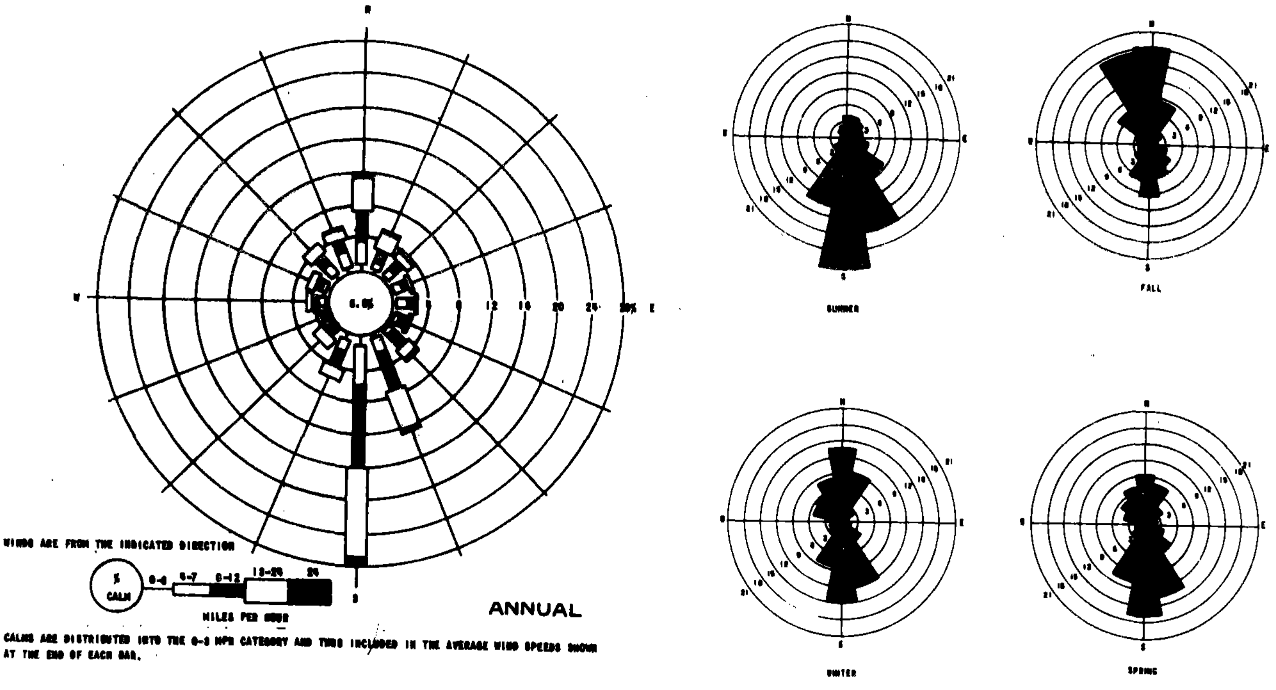
Northeastern Station Units 3 and 4, located about 0.8 kilometres (1/2 mile) due south of Units 1 and 2, are 450 MW_e coal-fired plants; the coal pile serving Units 3 and 4 is located about 1.2 kilometres (3/4 mile) south of the proposed collector field. Coal pile activity is essentially continuous; that is, coal is constantly being added to or taken from the coal pile. This activity produces a significant amount of airborne coal dust. This dust could be carried by the wind over the collector field, where some of the dust may settle onto the heliostats, degrading mirror reflectivity.

Of minor concern to the heliostat field performance is dust from the roads bordering the Northeastern Station site. The section of the site to be occupied by the proposed collector field is bordered to the north by a major highway and to the east by a gravel road. These roads constitute sources of airborne dust which could settle onto the heliostats, reducing mirror reflectivity.

The land in the vicinity of the Northeastern Station is characterized as grassy prairie or pastureland. The local vegetation is a source of airborne particles in the form of pollens which may also settle onto the heliostats, reducing mirror reflectivities. Furthermore, the Oologah reservoir, which lies about 1.6 kilometres (1 mile) to the east of the proposed collector field, may have effects on the performance of the solar repowered plant that are not immediately apparent.

The wind patterns at the proposed solar repowered plant site are depicted by the annual and seasonal wind roses shown in Figure 8-2. Because the wind blows primarily either from the south or from the north, coal dust deposition on heliostat mirrors is of concern, whereas drift from the cooling towers is carried over portions of the collector field for a small percentage of the year.

A test program was designed and implemented to determine the magnitude of impact on proposed collector system performance that the above-discussed factors may exert. The test program consisted of two separate subprograms; the insolation monitoring program and the dust accumulation test program. These are described in the following paragraphs.



WINDS ARE FROM THE INDICATED DIRECTION

CALMS ARE DISTRIBUTED INTO THE 0-3 MPH CATEGORY AND THUS INCLUDED IN THE AVERAGE WIND SPEEDS SHOWN AT THE END OF EACH BAR.

FIGURE 8-2. ANNUAL AND SEASONAL WIND ROSES FOR OOLOGAH, OKLAHOMA

8.2 INSOLATION MONITORING PROGRAM

As part of the test program, a station was established to monitor direct normal insolation at the proposed site. Prior to this program, there were no stations in Oklahoma monitoring insolation, either direct normal or total horizontal. Most data reported in the literature for sites in Oklahoma have been extrapolated from insolation data at other remote sites via empirical methods based on meteorological measurements such as percentage of possible sunshine. The insolation monitoring station established at the proposed site provided actual data which will aid in characterizing the site and determining its suitability; these data may also be subsequently utilized in evaluation of system transient behavior due to clouds.

8.2.1 <u>Equipment</u>

The equipment for the insolation monitoring station was purchased from the Eppley Laboratory, Inc., and consisted of a normal incidence pyrheliometer (Eppley Model NIP), a solar tracker (Eppley Model ST-1), and an electronic integrator with printer (Eppley Model 411-6140). The pyrheliometer and solar tracker are shown in Figure 8-3, installed at the monitoring station.

FIGURE 8-3. NORMAL INCIDENCE PYRHELIOMETER AND SOLAR TRACKER INSTALLED ATOP THE NORTH AMBIENT AIR MONITORING STATION

This equipment monitored the direct normal insolation (power per unit area) and integrated it with respect to time; thus, the insolation data were recorded as cumulative energy (per unit area). Insolation data were recorded in units of Watt-hours per square metre by a paper-tape printer, listing the cumulative energy at specified time intervals along with the local time. For the majority of the test program, the printer was set to record the insolation data every 10 minutes; for a few days, the printer was set to record data every minute to permit more detailed insolation profiles to be measured.

8.2.2 Location

The insolation monitoring station was located at the North Ambient Air Monitoring Station established by the Public Service Company of

Oklahoma near the proposed site. Referring to Figure 8-1, the North Ambient Air Monitoring Station is located 3.2 kilometres (2 miles) due north of Units 3 and 4. This site was selected because of its proximity to the proposed collector field, because it provided an existing shelter designed to house such equipment, and because it is serviced by Public Service Company of Oklahoma personnel at a frequency compatible with the minor adjustment requirements of the insolation monitoring equipment.

The normal incidence pyreheliometer with solar tracker was mounted on the roof at the North Ambient Air Monitoring Station such that it has an unobstructed view of the southern sky (see Figure 8-3). The signal from the pyreheliometer was routed to the integrator-printer within the station, where the data were recorded on paper tape.

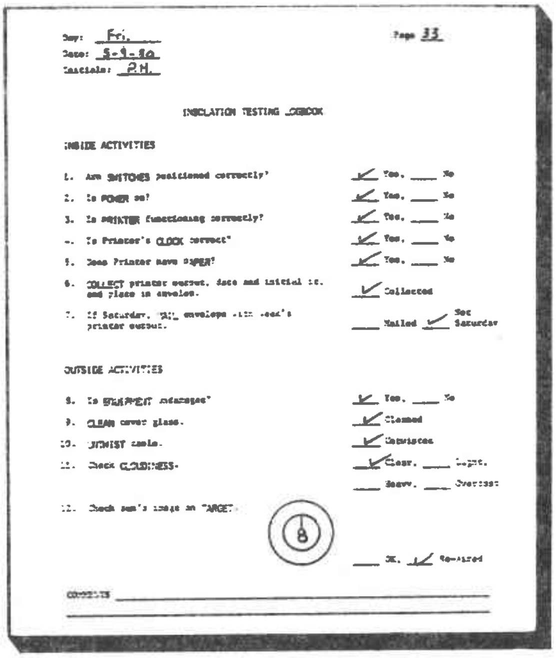
8.2.3 Methodology

Four times per week, Public Service Company of Oklahoma instrument technicians visited the monitoring station to perform routine checks and make minor adjustments to equipment. Maintenance of the insolation monitoring equipment consisted of visual checks to ensure that the equipment was functioning properly and minor adjustment to the solar tracker to keep the pyreheliometer properly oriented. For control purposes, the maintenance on the insolation monitoring equipment was governed by procedural checklists constituting a logbook. A checklist was filled out for each visit to the site, verifying that the procedures had been performed; a sample checklist is shown in Figure 8-4.

Once each week, the data tape and copies of the logbook were collected and mailed to Black & Veatch for analysis; a sample of the data tape is shown in Figure 8-5. The daily totals of cumulative incident direct normal insolation were determined and then employed to calculate a monthly average. The data on the tapes were subsequently entered into a computer, which, via a graphics routine, produced plots of insolation for each day; sample plots are contained in Appendix B.

8.2.4 Results

Operation of the insolation monitoring station commenced February 20, 1980, and has proceeded continuously since, with but a few brief interruptions due to loss of power. The data recorded on the



Day: Fri.
Date: 5-9-80
Initials: P.H.
Page 33

INSOLATION TESTING LOGBOOK

INSIDE ACTIVITIES

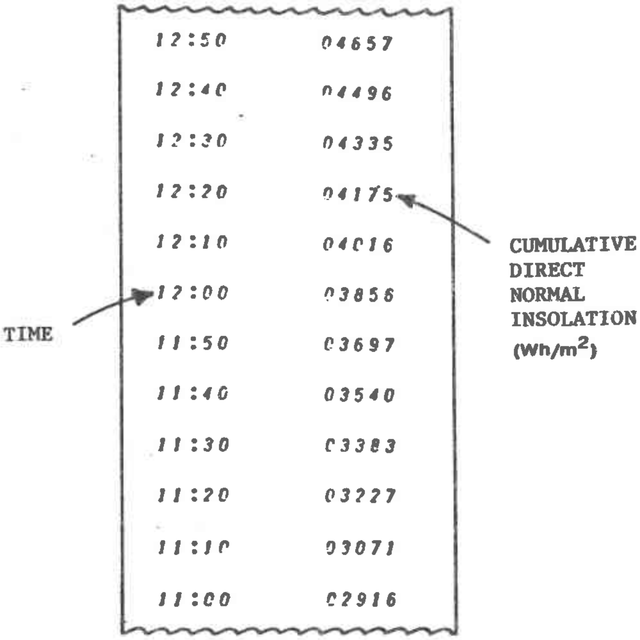
1. Are SWITCHES positioned correctly? ✓ Yes, ___ No
2. Is POWER on? ✓ Yes, ___ No
3. Is PRINTER functioning correctly? ✓ Yes, ___ No
4. Is Printer's CLOCK correct? ✓ Yes, ___ No
5. Does Printer have PAPER? ✓ Yes, ___ No
6. COLLECT printer output, date and initial it, and place in envelope. ✓ Collected
7. If Saturday, MAIL envelope with week's printer output. ___ Mailed ✓ Not Saturday

OUTSIDE ACTIVITIES

8. Is EQUIPMENT undamaged? ✓ Yes, ___ No
9. CLEAN cover glass. ✓ Cleaned
10. UNTWIST cable. ✓ Untwisted
11. Check CLOUDINESS. ✓ Clear, ___ Light, ___ Heavy, ___ Overcast
12. Check sun's image on TARGET. ___ OK, ✓ Re-aimed

COMMENTS ___

FIGURE 8-4. EXAMPLE OF PROCEDURAL CHECKLIST FROM INSOLATION TESTING LOGBOOK



```
12:50     04657
12:40     04496
12:30     04335
12:20     04175
12:10     04016
12:00     03856
11:50     03697
11:40     03540
11:30     03383
11:20     03227
11:10     03071
11:00     02916
```

FIGURE 8-5. EXAMPLE OF PAPER DATA TAPE OUTPUT

paper tape during the duration of the test program is maintained at Black & Veatch and has been entered into a computer for analysis. Following are the results of the analyses of the collected insolation data.

A summary of the results of the insolation monitoring is shown in Table 8-1, giving the daily average of cumulative direct normal energy for each month, along with the standard deviation and the high and low values. The values shown for the month of February are based only on measurements of insolation for the latter 8 days of the month, as the first full day of monitoring was February 22; as such, these values may not correctly represent the entire month of February. Due to intermittent power failures, at least two days' worth of data were lost from each of the remaining months. Nine days' worth of data were lost during

TABLE 8-I. DIRECT NORMAL INSOLATION AT OOLOGAH, OKLAHOMA FOR 1980

Direct Normal Insolation*	February**	March	April	May***
Mean	4.88	4.08	5.34	4.39
Standard Deviation	3.98	3.36	3.46	2.86
Maximum	9.44	9.49	9.93	9.63
Minimum	0.07	0.00	0.00	0.00

---

*Direct normal insolation is expressed in units of kWh/m^2 per day.

**First full day of monitoring was February 22.

***Nine days' worth of data were lost due to power interruptions.

the month of May; thus the values reported may not accurately represent the month of May.

The measured values shown in Table 8-I may not be characteristic or typical of the proposed solar repowered plant site because of temporal variations in insolation. An indication of whether the values shown in Table 8-I are high or low with respect to the characteristic values for the location can be obtained via examination of percentage of possible sunshine data.

The weather station in Tulsa, Oklahoma, some 20 miles from the proposed solar repowered plant site, measures percentage of possible sunshine; this station does not monitor any other measure of insolation. Table 8-2 gives the historical monthly averages of percentage of possible sunshine for Tulsa. Also shown are the percentages of possible sunshine for 1980.

As shown, the percentages of possible sunshine for February and March are below their corresponding historical average values while the percentages of possible sunshine for the months of April and May are slightly above their corresponding historical average values. Thus, the month of May; thus the values reported may not accurately represent the month of May.

The measured values shown in Table 8-1 may not be characteristic or typical of the proposed solar repowered plant site because of temporal variations in insolation. An indication of whether the values shown in Table 8-1 are high or low with respect to the characteristic values for the location can be obtained via examination of percentage of possible sunshine data.

The weather station in Tulsa, Oklahoma, some 20 miles from the proposed solar repowered plant site, measures percentage of possible sunshine; this station does not monitor any other measure of insolation. Table 8-2 gives the historical monthly averages of percentage of possible sunshine for Tulsa. Also shown are the percentages of possible sunshine for 1980.

As shown, the percentages of possible sunshine for February and March are below their corresponding historical average values while the percentages of possible sunshine for the months of April and May are slightly above their corresponding historical average values. Thus, referring to Table 8-1, the direct normal insolation received at Oologah during the months of February and March are somewhat lower than can be expected over the long term, and the insolation values for April and May are somewhat higher.

Of particular interest is the month of April. The value of percentage of possible sunshine for the month of April is seen to be just slightly less than the historical annual average value. This, coupled with the fact that the month of April occurs shortly after the vernal equinox, suggests that the daily average direct normal insolation recorded for the month of April should be approximately equal to the daily average value for the year. From the map of direct normal insolation isopleths (annual average-day values) contained in the document, <u>On The Nature And Distribution of Solar Radiation</u> (HCG/T2552-01), the average-day value of direct normal insolation incident at Oologah, Oklahoma, is interpolated to be 5.4 kWh/m^2 per day. This value is in isopleths (annual average-day values) contained in the document, On The Nature And Distribution of Solar Radiation (HCG/T2552-01), the average-day value of direct normal insolation incident at Oologah, Oklahoma, is interpolated to be 5.4 kWh/m^2 per day. This value is in excellent agreement with the measured site data for April. Thus, the measured data tend to confirm the value predicted by the map; from the limited data available, the insolation at the proposed solar repowered plant site cannot be said to be significantly different from that predicted for the site in the literature.

In addition to determining average insolation characteristics of the proposed site, the measured data were employed to generate insolation profiles, which further characterize the proposed site's insolation availability. Two insolation profiles that were generated from measured data are shown in Figure 8-6: one is for a partly clear day, the other for a day with intermittent clouds. Such profiles may be employed in subsequent evaluations of the solar repowered plant's response to cloud-induced transients in insolation. Appendix B provides a compendium of daily insolation profiles.

8.3 DUST ACCUMULATION TEST PROGRAM

As part of the test program, a program was established to quantify the effects of dust accumulation on heliostat mirrors at the proposed site. As discussed previously, there are a number of sources of mirror surface contamination at the proposed site: the coal pile and cooling towers to the south, cooling towers to the west, a highway to the north, a gravel road and a reservoir to the east, and a variety of pollen-bearing vegetation surrounding the site. The data resulting from this test program quantify the magnitude of the effects of such sources of contamination, providing estimates of the average degradation of reflectivity due to mirror surface dust accumulation. These data also help establish operating and maintenance costs by providing an indication of the required frequency of heliostat washing.

8.3.1 Equipment

The equipment required by the dust accumulation test program consisted of four heliostat simulators, devices specially designed and

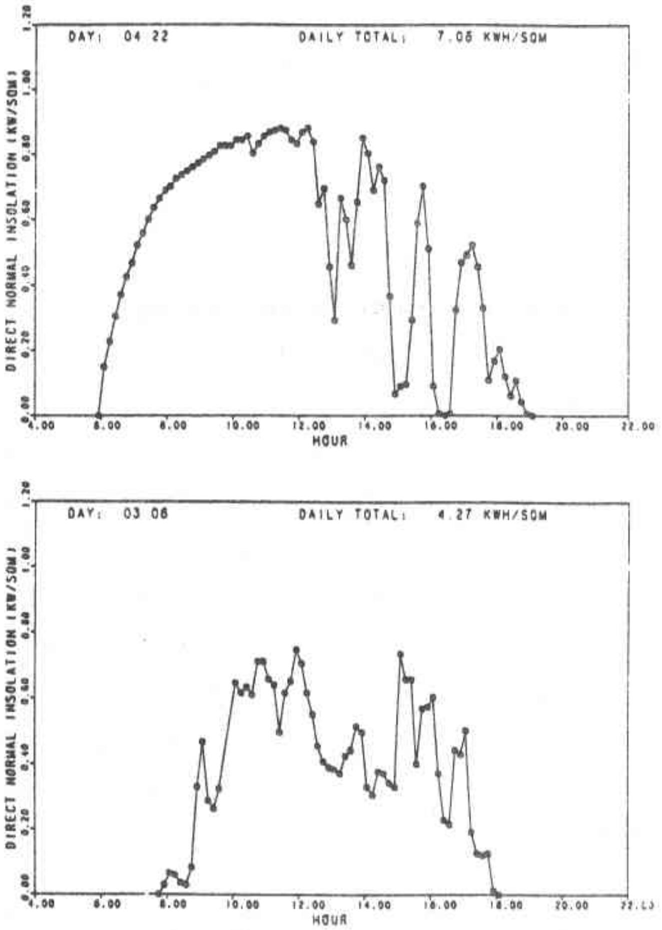


FIGURE 8-6. EXAMPLES OF INSOLATION PROFILES DRAWN FROM DATA COLLECTED AT OOLOGAH, OKLAHOMA

constructed for this program. A heliostat simulator, pictured in Figure 8-7, consists of a 0.6-metre x 0.6-metre (2-foot x 2-foot) metal array table and associated apparatus necessary to rotate the table in a manner so as to mimic the motion of a heliostat. The metal array table supports an array of 0.05-metre x 0.05-metre (2-inch x 2-inch) coupons of mirrors, representing one facet of a heliostat mirror.

During the design of the dust accumulation test program, discussions with other organizations that were performing or have performed similar tests identified two prevalent faults of other test programs. Previously, all similar programs have employed fixed-position arrays of

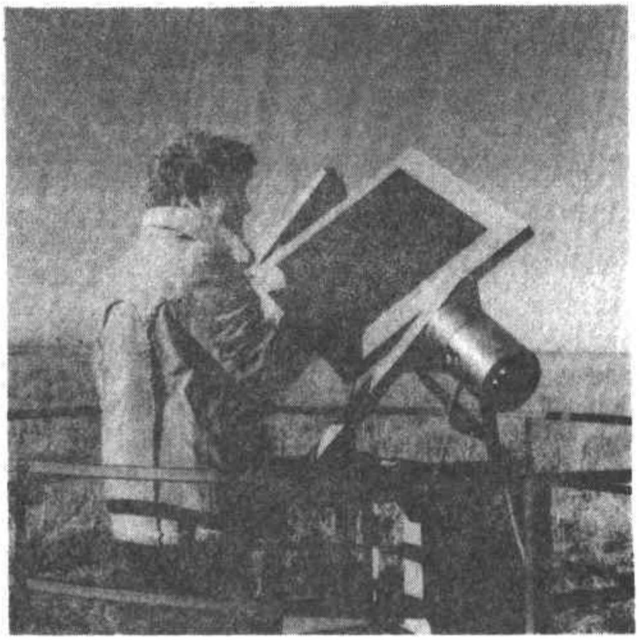


FIGURE 8-7. HELIOSTAT SIMULATOR IN PLACE AT THE PROPOSED SITE

test specimens. This is of general concern, as the dust accumulation on a fixed-position sample may not characterize the dust accumulation expected on a moving heliostat mirror, especially in consideration of the fixed array's inability to be placed in the down-facing stow position. Another concern was the small size of the test samples, necessitated by the limitations of the reflectometers employed for sample analysis. Typically, samples previously employed were no larger than 0.15 metre x 0.15 metre (6 inches x 6 inches). Because of their small size, such samples did not aerodynamically simulate a heliostat mirror facet and the dust deposition on these samples may not characterize dust accumulation expected on actual heliostat mirror facets.

The design of the heliostat simulators used in the PSO test program eliminates the two faults discussed above. As previously noted, the metal array table supporting the test mirror coupons is rotated by an electric actuator which is controlled by a solid-state programmable timer and powered by two automotive-type batteries. The timer is programmed to command the rotary actuator, and hence the array table, to one of four possible angular positions. At 6:00 a.m., approximately sunrise, the array table is rotated to its first position: face-up, tilted to the south and east. At 10:00 a.m., the array table is rotated to its second position: face-up, tilted to the south. At 2:00 p.m., the table proceeds to the third position: face-up, tilted to the south and west, as shown in Figure 8-7. At 6:00 p.m., approximately sunset, the array table is rotated to the fourth position, the stow position: face-down. The cycle is repeated each day, thus, approximating the motions of an actual heliostat. In this manner, dust accumulation should be representative of that expected to accumulate on an actual heliostat.

The reflectometer employed for test analysis required samples (coupons) 0.05 metre x 0.05 metre (2 inches x 2 inches) in size. Despite this small sample size, the array of test mirror coupons was configured so as to aerodynamically approximate a heliostat mirror facet. The coupons were magnetically attached to the metal array table; self-adhearing magnetic tape laminated to the backs of the coupons held the coupons on the table. This allowed the coupons to be butted against each other, forming what aerodynamically appeared to be a single, large facet. In this manner, dust accumulation should be representative of that expected to accumulate on an actual heliostat.

8.3.2 Location

The four heliostat simulators were deployed at the proposed site as shown in Figure 8-1. The east simulator was placed to represent the heliostats in the collector field that are the closest to the cooling towers serving Units 1 and 2. The south simulator was placed in the proposed collector field so as to represent those heliostats closest to the coal pile and cooling towers serving Units 3 and 4. The north simulator was positioned so as to represent the heliostats farthest away from the cooling towers and coal pile. In this manner, a cross section of the conditions existing within the proposed collector field is obtained and, thus, the dependence of dust accumulation on field position may be evaluated.

The west simulator was placed outside of the proposed collector field for two reasons. In the location shown, the west simulator is the farthest away from the coal pile and cooling towers that it can be and still be on property owned by the Public Service Company of Oklahoma. Thus, in this position, the west simulator provides a check point by which the dependence on location of the effects observed in the collector field can be better evaluated. Also, if the effects observed in the proposed collector field were judged to be unacceptable, data would be available for an alternate collector field location.

8.3.3 Methodology

Every Monday and Friday, a technician of the Public Service Company of Oklahoma visits each of the four heliostat simulators. At each simulator, one test mirror coupon is removed and its identification is recorded, documenting the date of removal. Upon removal, the coupons are placed in a holder (photographic slide tray), and the holder is then encased in a plastic bag to exclude extraneous dust. The removed coupon is replaced with a "dummy" coupon, thus, preserving the aerodynamics of the test array.

When a sufficient number of test coupons have been collected, the coupon holder is covered with a protective, shock-absorbing wrap and sealed in a mailing tube, along with a copy of the collection log. The coupons are then mailed to the Battelle Pacific Northwest Laboratories (PNL) for testing.

At PNL, the total hemispherical reflectance of each test coupon is measured. This measurement indicates the degradation of reflectivity due to absorption (in lieu of scattering) by the dust particles adhered to the surface of the mirrors. Some of these samples are then selected for specularity and diffuse reflectance measurements to determine scattering.

The total hemispherical reflectivity data are then plotted versus time for each of the four heliostat simulators. These plots are to be compared to graphs of daily wind direction and rainfall to identify any trends or correlations. Further conclusions are to be drawn from the correlation of the specularity and diffuse reflectance test results with the historical plots of total hemispherical reflectance. These data provide an indication of the average reflectivity that can be expected for the heliostats within the proposed collector field, quantifying the magnitude of the combined effects of the various sources of dust and surface contamination at the site.

8.3.4 Results

The mirror test coupons were placed on the four heliostat simulators on February 22, 1980. Collection of coupons commenced on February 25, 1980 and has proceeded regularly since then, with coupons being collected each Monday and Friday. The collected coupons were subsequently delivered to PNL for testing. The data records from these tests are maintained at Black & Veatch. Following are the graphical representations summarizing the data and the corresponding interpretations.

The results of the total hemispherical reflectance measurements are depicted graphically for each of the four heliostat simulators in Figure 8-8. The upper graphs in the figure depict the per cent degradation of net mirror reflectivity due to the absorption of the incident light by the accumulation of dust on the mirror surfaces. These values were computed by calculating the differences between the clean-mirror reflectivity and the reflectivities as measured by PNL, and then by normalizing the differences to the clean-mirror reflectivity. This procedure isolates the effects of the dust accumulations from clean mirror reflectivity. Referring to Figure 8-8, it is seen that by March 10, the mirrors of the east heliostat simulator have become sufficiently soiled such that almost 3 per cent of the incident light is absorbed by dirt accumulation.

The clean-mirror reflectivity of the coupons was taken to be the average reflectivity of selected coupons. Six coupons were selected, cleaned, and measured; the average of their measured reflectivities was calculated to be 0.837. Observed deviations between a measured reflectivity and the average reflectivity were as great as 0.003 reflectance

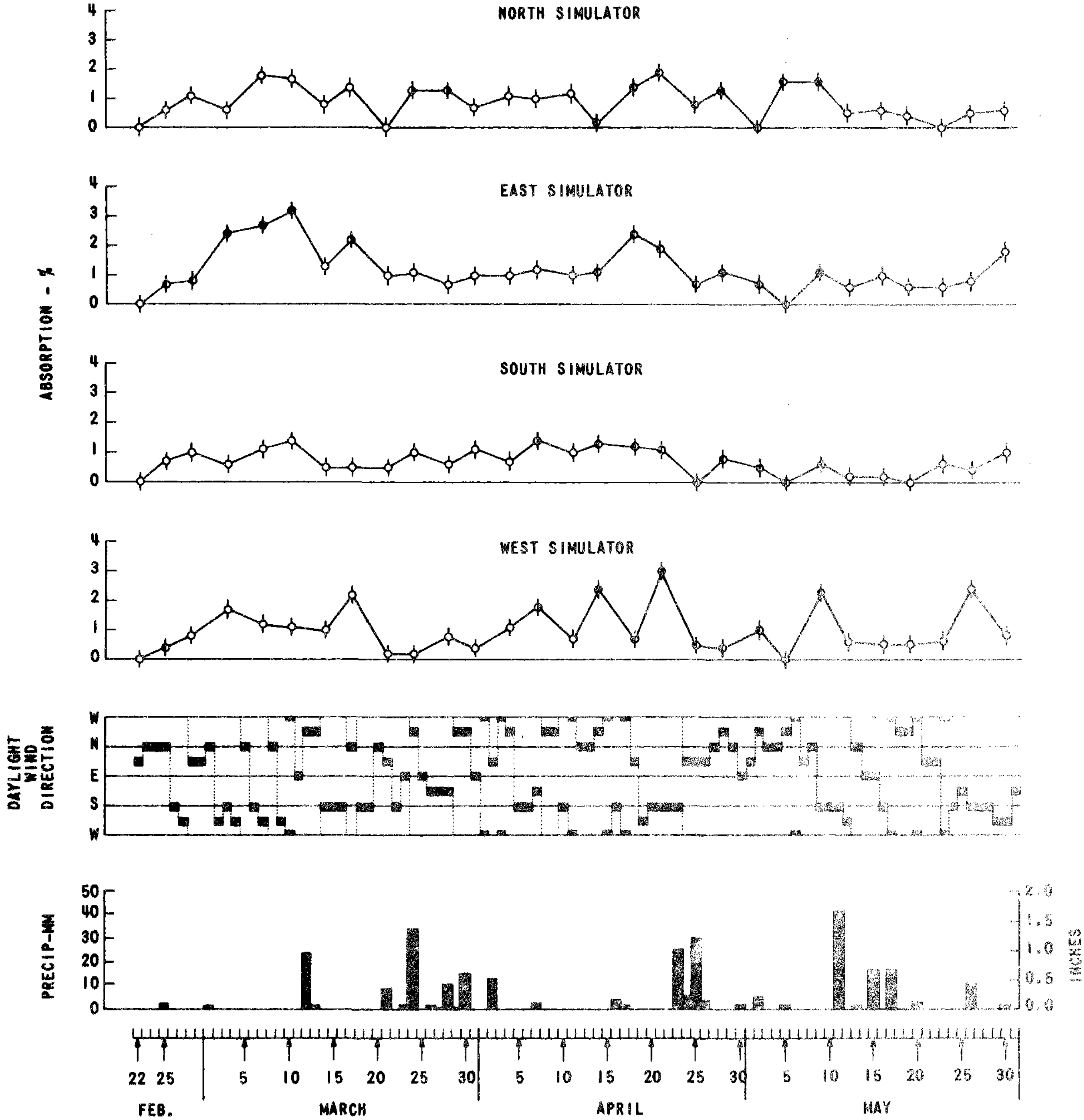


FIGURE 8-8. HELIOSTAT SIMULATOR TEST DATA; ◑ SELECTED FOR SPECULARITY MEASUREMENTS, ◐ SELECTED FOR DIFFUSE REFLECTANCE MEASUREMENTS

units. This variance is represented by the error band defined by the vertical bars in the four plots of per cent absorption.

The two lower graphs shown in Figure 8-8 are histograms of the predominant wind and precipitation occurring at the site during the test period. The predominant wind direction is shown for each hour from 6 a.m. to 6 p.m. and quantized to one of the eight points of the compass. The dotted vertical lines connecting the directional data indicate the paths of changes in wind direction. The precipitation data are shown in units of liquid equivalent: if the precipitation occurred in the form of snow or sleet, it was melted before the measurement was made. It is interesting to note that the months with higher-than-average percentages of possible sunshine, April and May (see Table 8-2), had lower-than-average amounts of precipitation, and vice versa.

Three very important observations are made via examination of Figure 8-8. First, the largest decrease in reflectivity observed due to absorption is nominally 3 per cent, and the average decrease in reflectivity due to absorption is approximately 1 per cent. This is important in that it indicates that accumulation of coal dust on the mirrors is not of great significance. Because carbon is an electrical conductor, coal dust degrades reflectivity primarily via absorption in lieu of scattering.

A second observation is made via the comparison of the precipitation histogram and the absorption loss graphs: total hemispherical reflectivity is nearly restored to the clean-mirror value following precipitation. This is important for three reasons. First, it means that the heliostats may be easily cleaned by washing. Second, the heliostats should not require washing very often because of the frequency of rains at the proposed site. And third, the reflectivity of the heliostats should be maintained naturally at a relatively high average value by the rains.

However, the most important observation to be made from examination of these figures is in regard to the predominant source of mirror contamination. The proximity of the coal pile, in light of its position with respect to the proposed collector field and the prevailing wind direction, resulted in concern about the suitability of the proposed site. However, the comparison of the east and south heliostat simulator data shows clearly that the coal pile is not the predominant source of surface contamination. The east heliostat simulator, which is closest to the cooling towers of Units 1 and 2, shows a greater decrease in reflectivity during the period preceeding the rain of March 12 than does the south heliostat simulator, which is closest to the coal pile. Wind data show that coal dust was indeed carried towards the two simulators, yet a significant difference exists between the reflectivities of the east and south heliostat simulators. Therefore, it is concluded that the cooling towers are the predominant source of contamination. This is borne out by the comparison of all four absorption plots; the heliostat simulator nearest the cooling towers experienced the largest decrease in reflectivity.

This last observation is important in that the presence of the coal pile is not as significant as was first thought by some. It is, in fact, the cooling towers that have the greatest influence on mirror reflectivity. In light of the prevailing wind directions at the proposed site, the placement of the proposed collector field with respect to the cooling towers is quite good.

The plots in Figure 8-8 show the degradation of heliostat reflectivity due to absorption by the accumulated surface dust; however, this is not the total degradation of reflectivity. The total degradation consists of the sum of degradation due to absorption and the degradation due to scattering. Test measurements of degradation due to scattering are time consuming and only a fraction of the mirror test coupons were used for these tests, as shown in Figure 8-8. Scattering was measured by determining specularity and diffuse reflectance. The measurement of specularity indicates the degree of scattering in a small cone surrounding the specular ray; the measurement of diffuse reflectance indicates the degree of diffuse (hemispherical) scattering. Comparison of these indicators provides insights to the makeup of the dust accumulations.

The specularity of the eight coupons measured were uniformly high. An insignificant amount of light is scattered into the near-specular region so that little loss is associated with this mechanism. The measurement of the diffuse reflectivities of five of the coupons showed trends that correlated strongly with the trends exhibited by the absorption measurements: the losses due to diffuse reflection increase with time but are reduced to nearly zero by precipitation, and the losses due to diffuse reflection are significantly higher for the heliostat simulator closest to the cooling towers. Thus, it is concluded that rain will keep diffuse reflectance losses to a minimum, and the cooling towers are the predominant source of surface contamination.

The mirror coupon with the highest losses due to diffuse reflectivity also had the highest losses due to absorption: the coupon collected from the east heliostat simulator on March 10 (see Figure 8-8). The diffuse reflectance loss of this coupon was slightly less than 7 per cent, giving a total decrease in reflectivity (absorbed + diffusely reflected) of approximately 10 per cent. The average loss due to diffuse reflectivity was nominally 4 per cent, yielding an average total loss of reflectivity for the test period of only slightly over 5 per cent.

The results of the scattering measurements, that near-specular scattering is negligible and diffuse scattering is the more significant, is opposite of the results of such tests on mirrors exposed to the Albuquerque, New Mexico environment. This reversal indicates that the type of dust accumulating on the mirror surfaces in Oologah, Oklahoma is radically different than the dust accumulating on mirrors in Albuquerque. PNL speculates that the dust particles on the Oologah samples are very small and angular in comparison to the particles on the Albuquerque samples, resulting in the difference in optical characteristics.

Although the dust accumulating on the mirrors at Oologah is apparently different than that accumulating on heliostats in Albuquerque, the net results are essentially equivalent to those reported by Sandia Laboratories.

8.4 CONCLUSIONS

After conducting the tests at Oologah, analyzing the data collected, and studying the results, several conclusions for both parts of the program were reached.

8.4.1 Insolation Monitoring Program Conclusions

The following conclusion is reached as a result of the insolation monitoring program.

- The limited data collected during the test program tend to substantiate the value of 5.4 kWh/m^2 as the annual average daily direct normal insolation incident at Oologah, Oklahoma, as interpolated from published isopleth maps.

8.4.2 Dust Accumulation Test Program Conclusions

The following conclusions are reached as a result of the dust accumulation test program.

- The average degradation of mirror reflectivity due to dust accumulation observed during the test period was nominally 5 per cent; the peak value observed was nominally 10 per cent.
- The cooling towers, rather than the coal pile, are the predominant source of mirror surface contamination.
- The dust accumulations on the mirror surfaces are easily washed away, almost fully restoring the optical performance of the mirrors.

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