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Topical Report

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Solar Repowering/ Industrial Retrofit Systems

Category B: Industrial Retrofit for Process Heat Application

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I. INTRODUCTION

This report summarizes activities performed from program beginning on 28 September 1979 through February 29, 1980. The objective of the program is to develop a conceptual design for a solar thermal enhanced oil recovery (STEOR) system to be used for the production of heavy crude oil. Martin Marietta Corporation provides overall program management and also contributes heavily to the development of specifications, system selection, conceptual design (collector system sizing, layout and design), performance analysis and economic evaluations. Exxon as the potential system user provides the specific site, and has major input to system specifications, system selection, conceptual design, process analysis and economic evaluations. Foster Wheeler has responsibility for the analysis, design and cost estimating of the receiver. Black and Veatch is performing the analysis, design and costing of the field piping system, as well as evaluating tower and heliostat foundation requirements.

The major efforts during this first half of the program have centered around Task 1 - System Requirements Specification, Task 2 - Selection of Site-Specific System Configuration, Task 3 - Plant Conceptual Design, Task 4 - Plant Performance Estimates and Task 5 - Plant Cost Estimates and Economic Analysis.

The initial System Requirements Specification prepared by Sandia Laboratories has been modified in format to conform more closely to the STEOR application, and some system-related information has been inserted. The kinds of information included at this time are primarily confined to site description, collector design and receiver design.

The largest activity has been conducting parametric studies which are necessary to the selection and design of the preferred site-specific system. Evaluations of system size, collector/receiver module configuration, steam generator design, tower design, field piping design, control methods and operating strategy have been performed. These areas will continue to be reassessed as the conceptual design matures and economic factors become more definite.

II. SYSTEM SELECTION AND CONCEPTUAL DESIGN DESCRIPTION

A. THERMAL ENHANCED OIL RECOVERY PROCESS

1. Site Description

The site of Exxon's solar thermal enhanced oil recovery project is in the Edison oil field which is located in parts of sections 13, 14, 15, 18, 19, 22, 23 and 24 of Kern County, California. This is on the east side of the San Joaquin Valley, seven miles southeast of Bakersfield. Principal access is by California Highways 58 and 99 (Figure 1).

Figure 2 shows the Exxon leases at Edison and the location of the STEOR site. The site is due east of Tejon Highway in Exxon Lease 808794 where both the surface and mineral rights are owned by Exxon. It is approximately one half mile from the Exxon field office on Hermosa Road. The site area is approximately 303,512 m^2 (75 acres).

The terrain is flat, alluvial plain ranging in elevation from about 213 m (700 feet) in the northeast to 152 m (500 feet) in the southwest. The area is free of standing water and is not subject to flooding. The field is in earthquake Zone 4 in the Uniform Building Code and structure must be designed to appropriate specifications. The last major quake was in 1952 and measured 7.5 to 7.7 on the Richter scale. The Uniform Building Code puts the soil of the Edison field in Class 4 (SC), sand and clay.

The climate at Bakersfield is warm and semi arid. Average temperature is 18.3 C (65 F) varying from 8.9 C (48 F) in winter to 28.9 C (84 F) in summer. Annual precipitation averages 0.15 m (5.8 in.). Snow is rare and no accumulations of greater than 0.038 m (1.5 in.) have been recorded. Southeasterly winds, originating in the Tehachapi Mountains can, at times, reach velocities of 26.8 mps (60 mph). The most recent severe wind storm occurred in December 1977, with gusts to 33.5 mps (75 mph).

There are few zoning or other use restrictions on this and surrounding land. It is five miles to the outskirts of Bakersfield and no extensive residential or commercial activities are anticipated during the period while oil is being produced. Residential and commercial activities in the Bakersfield area are expanding to the southwest of the city, away from the intensive oil producing areas. Access to the site is by publicly owned roads adjacent to the test site. The closest non-Exxon lease to the south of the test site is owned by Mobil and is in active oil production. Kern County Airport

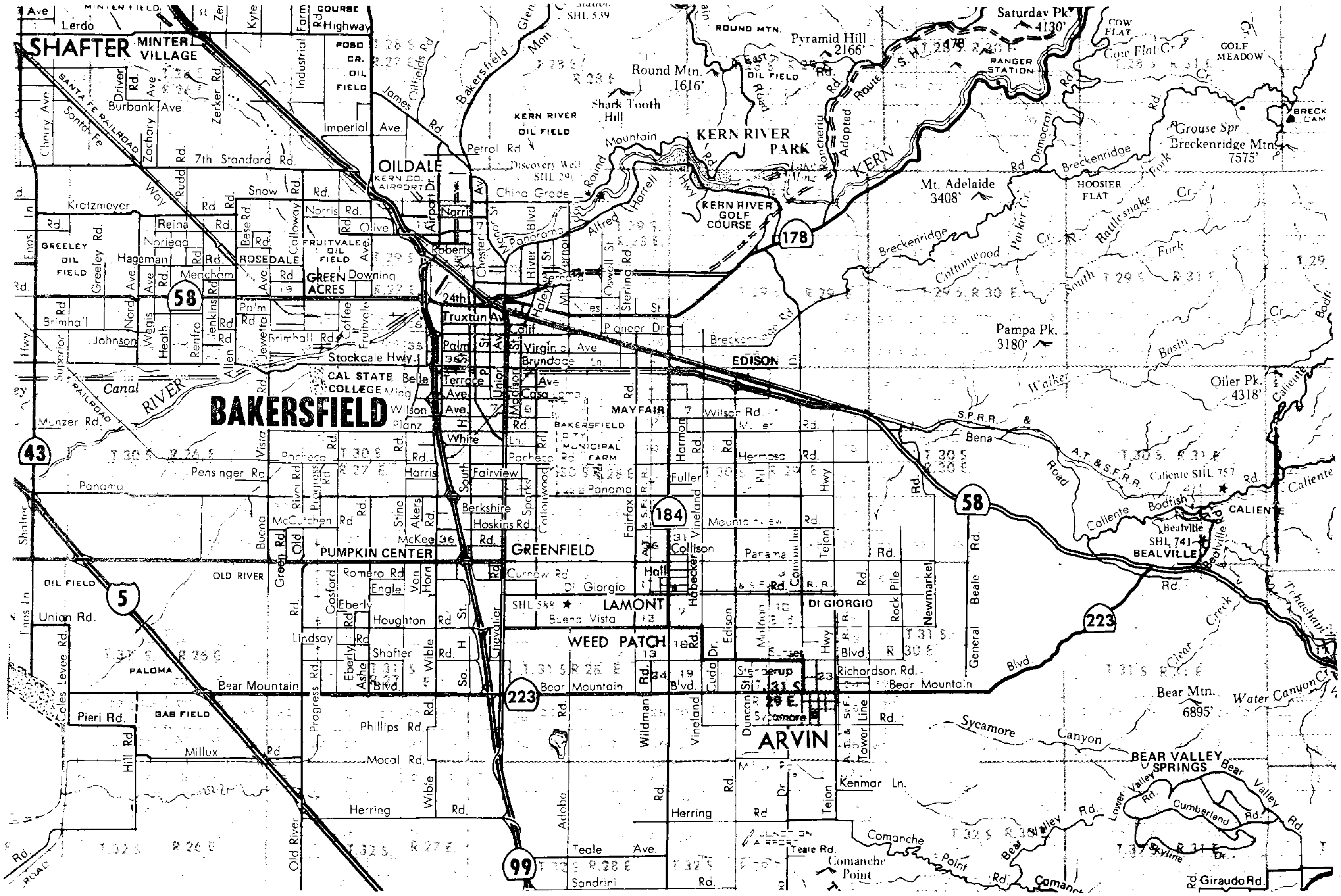

Figure 1 Bakersfield Area Map

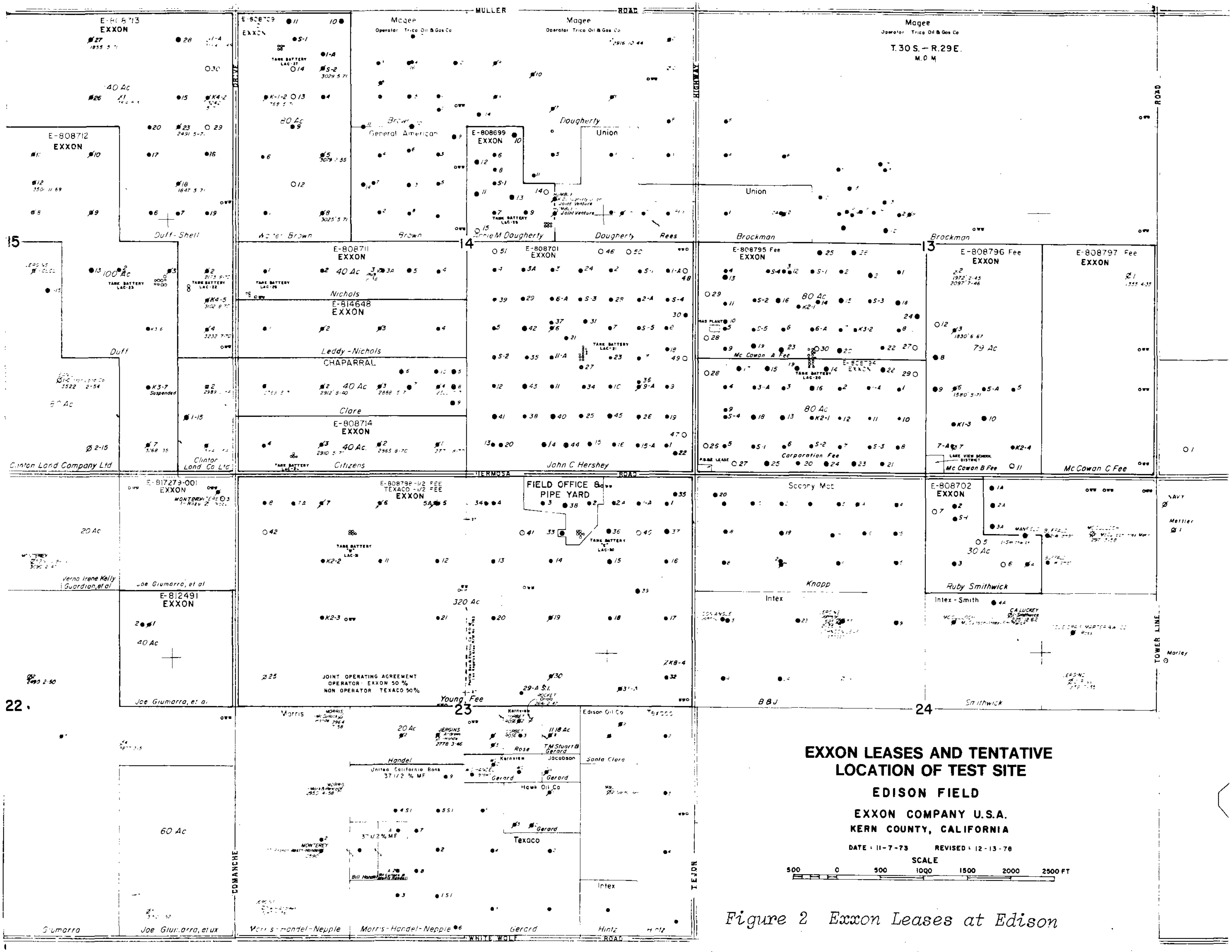

Figure 2 Exxon Leases at Edison

is located approximately 32.2 km (20 miles) to the northwest of the test site. The test site is outside the airport control zone.

Land surface in the test site area is currently used for raising potatoes. One crop per year is normally harvested. Since the test site is Exxon owned there is no problem cancelling the agricultural lease with 60 days notice.

Shipments to the Edison field area can be made by truck, plane or railroad. Weight limitation on California Routes 58 and 99 and on local roads is 90,720 Kg (100 tons). Items measuring 3.66 by 30.5 m (12 by 100 ft) or larger can be shipped by truck but must be escorted. Heavy and bulky equipment is usually shipped by rail (Southern Pacific Railroad) to the freight depot at Edison which is 8 km (5 miles) northwest of the field. There are no overpasses on the roads between the depot and the field.

Water supply for steam generation is provided from Exxon owned and operated wells. The wells draw water from a depth of 305 m (1000 ft). Water is distributed to the site by portable lines and is treated in portable units containing ion exchange beds (Thermotics Model WS42302A). Table 1 contains water quality information before and after treatment. Produced water is separated from oil in the separator tanks distributed throughout the field. This water along with the waste water from the water treating units is reinjected into the Schist zone through well numbers 5A, 6, 7 and 34 on the Young Fee.

Table 1 Water Quality Data - Impurities in PPM

Impurities	As Produced From Well	After Treatment
Calcium	54.4	<0.5
Magnesium	12.6	<0.5
Sodium	50.6	210
Bicarbonates	298.9	
Chlorides	36.1	
Sulphates	2.2	
Nitrates	0.44	
Total Hardness as $CaCO_3$	187.66	<0.5
ph	7.4	9.0

The utility servicing the field is Pacific Gas & Electric. An existing substation shown in Figure 2 at the southwest corner of section 13 is rated for 1900 kW. Currently the maximum load is 500 kW. Incremental requirements for STEOR will be easily accomodated. Electric power is brought to the site by overhead cable on utility poles along Hermosa Road

Reservoir Characteristics - The Edison field is composed of six producing areas. Exxon-operated properties are in the main area, which is the largest and most productive area. The dominant structure in the main area is the uplifted, southwesterly tilted, fault block in the basement complex. Overlying sediments overlap and buttress against the high relief structure. Oil accumulation and migration limits result from sand lenticularity and faulting in the nonmarine Kern River Zone and interconnected fractures in the metamorphic Schist zone, with capping by overlying sediments. Reservoir data is summarized in Table 2.

Table 2 Summary of Reservoir Data

	Kern River Sand Edison Field
Depth to formation top, m (ft)	335 (1100)
Oil gravity, °API	16-19
Current reservoir pressure, MPa (psig)	1.034 (150)
Average net sand thickness, m (ft)	24.4 (80)
Reservoir temperature, C (F)	35 (95)
Oil viscosity at reservoir temperature, cp	310
Average permeability to air, md	1500
Average porosity, %	27
Average oil content, liter/m^3 (BBL/AF)	148 (1150)
Average oil saturation, %PV	55
Formation dip, degrees	8-10
Pattern size, m^2 (acres)	10116-20232 (2.5-5)

2. Existing Process and Operation

The Edison field is currently in steam stimulation. The steam soaking approach is in use, a batch operation in which the following steps are taken:

1) Saturated steam at 260 to 288 C (500 to 550 F) and 75 to 80% quality is injected into a well for 5 to 7 days. The steam flow rate is about 180 ℓ/m (50 gpm) of water equivalent.

2) The well is closed and steam "soaked" for about 4 days. The injected steam permeates and heats the oil/rock/sand formation, and reduces the viscosity of the oil.

3) The well is opened and oil pumped out for about the next 50 to 70 weeks, after which the steam soak process is repeated.

The Fossil Fired Boilers with the following specifications (Table 3) are on site.

Table 3 Existing Fossil Fuel Fired Steam Production

	Projected Operations with 7.33 MW (25 MBtu/h) Boiler & Flue Gas Scrubber
Boiler Operating Mode	Portable
Boiler Rated Capacity, MW	7.33
% of Rated Capacity in Operation	100
% of Rated Capacity Required for Flue Gas Scrubber	10
Service Factor, %	80
Heat Delivered to Wells, MWh/y	4.63×10^4
75% Quality Steam Delivered, m^3/y (Mbbl/y)	716 (0.451)
Boiler Thermal Efficiency, %	87
Heat Supplied by Fuel Oil, MWh/y	5.92×10^4
Quantity Fuel Oil, m^3/y (bbl/y)	5420 (3.41×10^4)
Diesel Fuel Required for Electric Power Generation, m^3/y (bbl/y)	369 (2319)
Heat Supplied by Diesel Fuel, MWh/y	3662
Electric Power Required, kW_eh/y	2.17×10^6
Heat Equivalent of Electric Power, MWh/y	7.3×10^3
Total Heat Required, MWh/y	7.03×10^4
bbl -(Oil Barrel)= 0.159 m^3 (42 U.S. Gallons)	

The steamers burn heavy crude oil, and 9 to 10% of the steam generated is used in the flue-gas desulpherization scrubber. As a result of moving and maintenance, the boiler service factor is about 70%.

In a typical operation, 1,590 m^3 (10,000 BBL) of water will be converted to steam and injected into the well (plus an additional 9 to 10% for the scrubber). To accomplish this, about 115 m^3 (724 bbl) of crude oil will be burned (about 106 m^3 of oil would be required if no scrubber were used) as shown in Figure 3.

3. Projected Operation in Solar Mode

It is anticipated that solar generated steam would be used in parallel with crude-fired boilers for steam drive operations scheduled to begin in 1985-86. The crude-fired boilers will operate continuously, while the solar central receiver will produce steam whenever there is sufficient insolation. In steam drive approximately 67.6-75.5 m^3 (425-475 barrels) of water per day as saturated steam is injected into each of a pattern of injection wells. Production wells are interspersed among the injection wells in 1012 m^2 (2-1/2 acre) patterns. This will require considerable infilling of new wells at Edison as illustrated in Figure 4. The steam lowers crude oil viscosity and increases formation pressure causing oil to flow out of the production wells (Figure 5). At Edison it is estimated that each pattern would produce all oil recoverable by this technique in about three years. Then the steam lines would be installed on an adjacent pattern and the process repeated until the field is depleted. The performance of the process is quite sensitive to local variations in geology.

Current plans for Edison call for steaming the most productive section of the field (Figure 4) pattern at a rate of 954 m^3 (6000 BWPD) of steam into 12 to 14 injection wells at a time over a period of 26 years. Using current oil fired boiler technology approximately 11.9 m^3 (75 BBL) of crude oil are required to produce 159 m^3 (1000 barrels) of steam for injection. In addition, .85 m^3 (5.2 BBL) of Diesel Fuel and 4800 kWH of electricity are consumed for every 159 m^3 (1000 BBL) of steam injected. This does not include energy for water purification or raw material transport which would be similar for both fossil and solar systems. This steaming rate would require use of four fossil fired 7.33 MW (25 MBtu/hr) boilers.

B. SOLAR RETROFIT SYSTEM CONCEPT

1. Conceptual Approach

Several important criteria were considered in the conceptual development of the STEOR system. The prime concern was to ensure conformance of the solar hardware with physical and operational

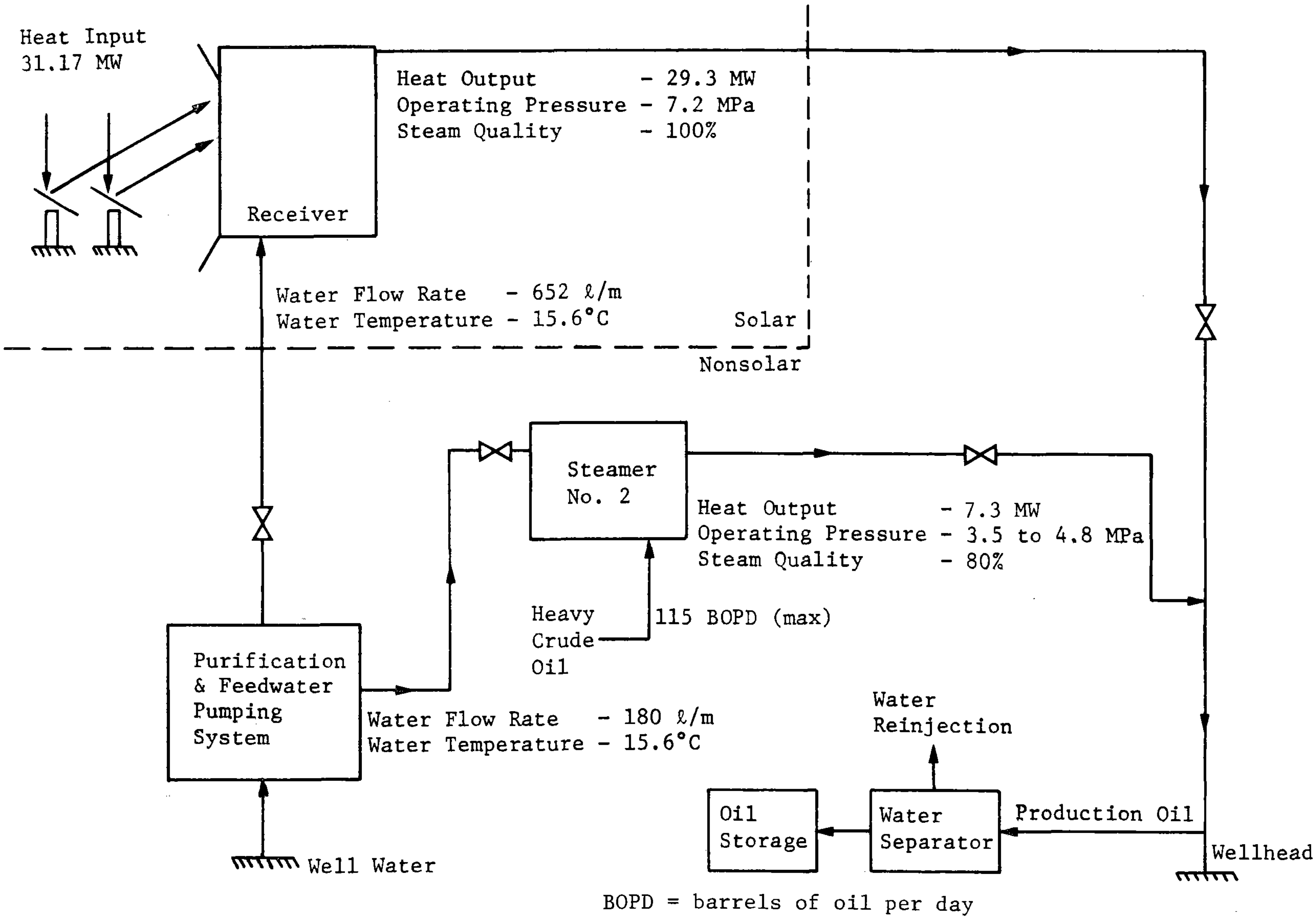

Figure 3 Energy Flow Diagram

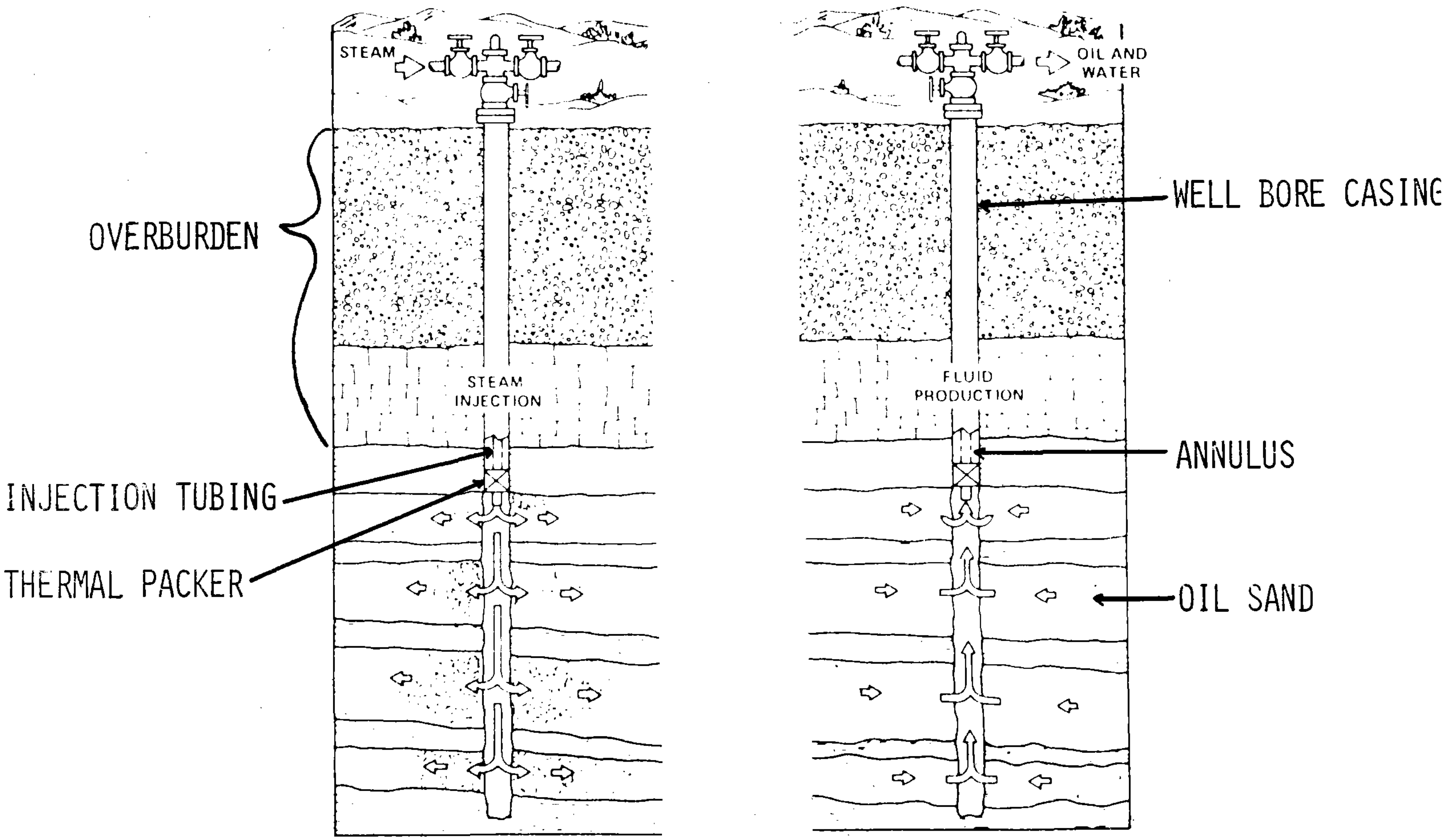

Figure 4 Steam Stimulation

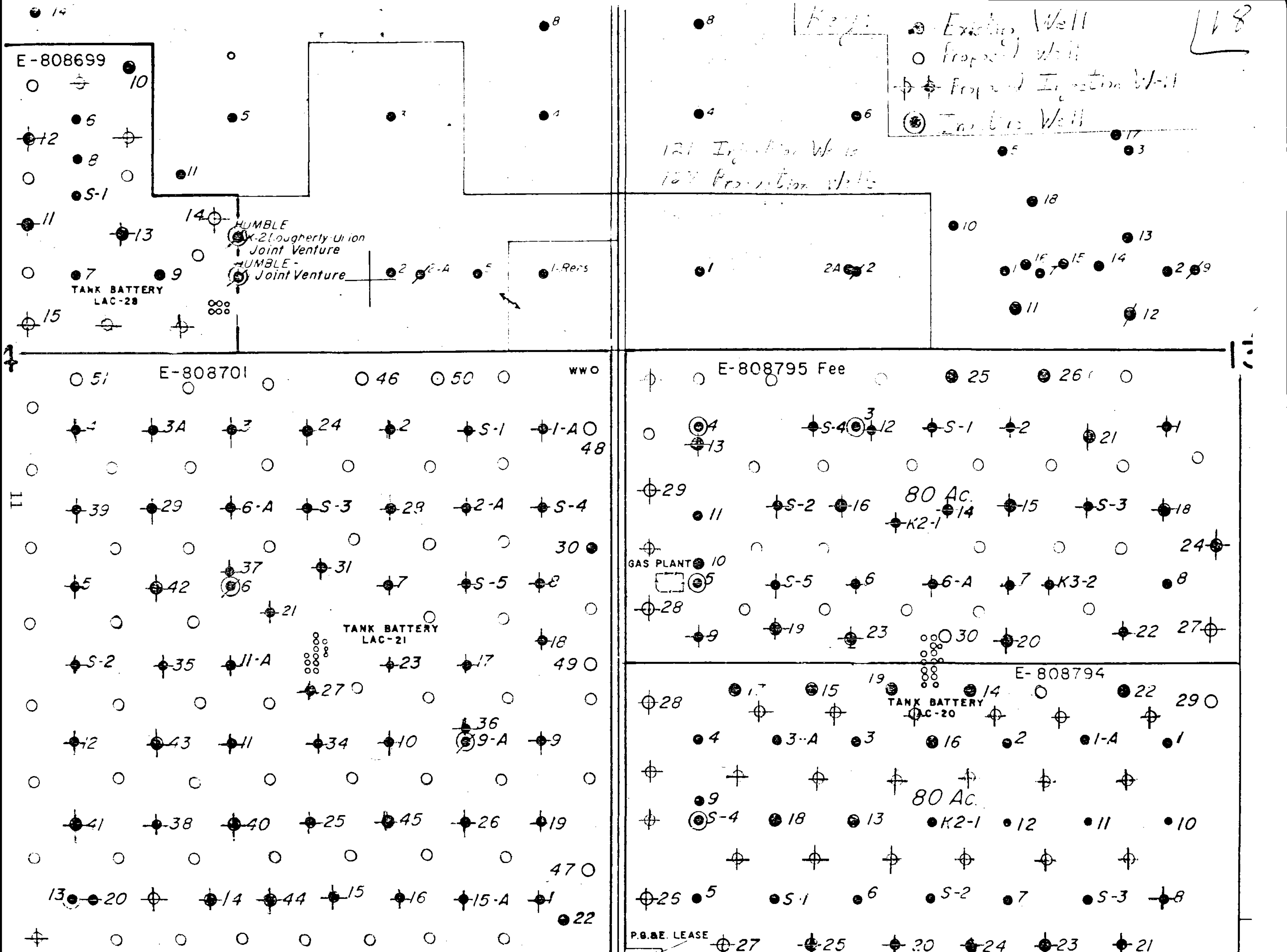

Figure 5 Field Map

features of the crude oil production process in general, and the Edison field site in particular. Other major factors include potential for minimizing the cost of energy conversion and maximum utilization of mature solar thermal technology.

The first step in developing the solar thermal system concept was to evaluate the site and select a location for the collector/receiver module. Exxon's Edison field operation consists of several separate leases, most of which are not owned by Exxon. Our original information at the start of this program was that only one lease (No. 808794) was totally owned by Exxon, so it was selected as the collector/receiver module location. The configuration of lease No. 808794, the presence of oil pumps and tanks, and the requirement to provide operational access and boundary easements all combined to constrain the collector field layout and size. More recent information indicates Exxon also owns lease No. 808795 which is identical in size and geometry, and lies adjacent to least No. 808794 on the north side. This development doubles the gross land area available--from 323,746 m^2 (80 acres) to 647,492 m^2 (160 acres)--thereby opening up new options regarding system sizing and collector/receiver configurations. These options will be evaluated during the last half of the program.

The central receiver type of solar thermal power system was selected for this application for several reasons. The steam conditions required for the TEOR process are well within central receiver capability. Since the process steam is not superheated, the receiver design is simplified and low cost carbon steel can be used throughout the steam generator circuitry. Also, the absence of superheater panels eliminates the need for steam temperature controls, since output steam conditions can be established with only a simple pressure regulation device. The normal spacing of heliostats necessary for physical clearance and minimizing shadowing and blocking provides more efficient operational access to the oil field than would a continuous distributed system. Finally, the capability for high solar concentration and low thermal losses offers the highest potential for minimizing energy conversion costs.

2. System Description

Figure 6 illustrates the current baseline system concept. A collector field composed of individually driven heliostats reflects and concentrates the solar radiant power into a cavity receiver which is mounted on a steel tower. Interior surfaces of the receiver consist of water preheat and boiler panels which, together with a steam drum interconnecting piping and controls,

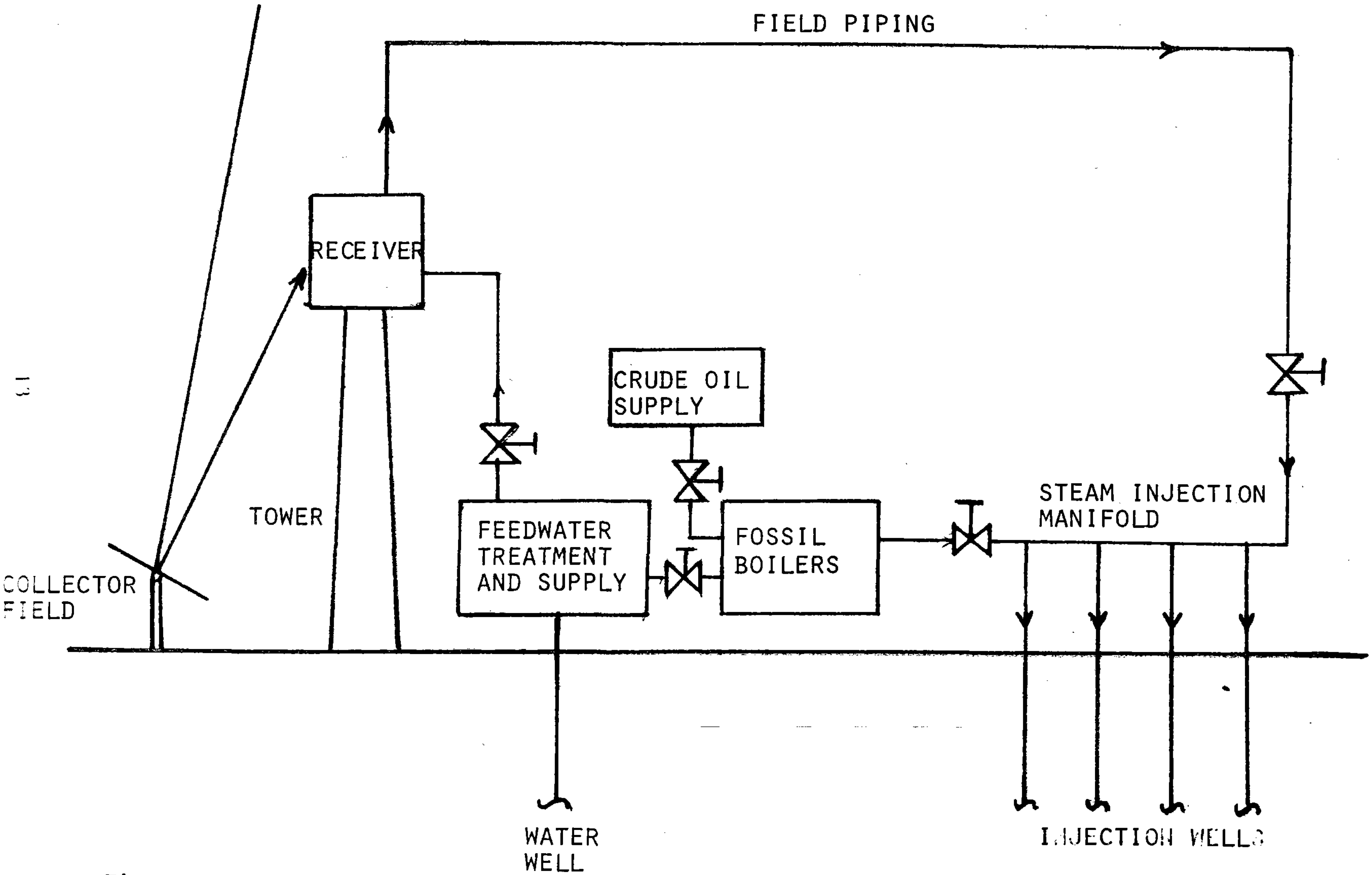

Figure 6 Process Schematic

form a natural circulation steam generator. Water enters the receiver at 15.6 C (60 F) and steam exits at 297 C (567 F) and 82 percent quality.

The solar thermal system will be operated in conjunction with existing crude oil fired boilers. The planned operating mode is to utilize the crude oil fired boilers continuously, and add receiver steam whenever sufficient insolation is available. Control and operation of the solar and fossil system will be initially independent of one another, with the only physical interface being a simple mixing header. An alternative mode being considered would totally decouple the operation by using separate supply headers to service different groups of injection wells from the solar and fossil systems.

The baseline solar power system is sized to produce 29.3 MW (100,000,000 Btu/hr) in the form of steam at noon on day 58 at an insolation of 0.95 kW/m^2. The cumulative annual energy production of 55.87 MW-HR (190.674 Btu) will provide about 25 percent of the total planned steaming capacity at Edison. The option of building an identical collector/receiver module on lease 808795 would increase the solar contribution to about 50 percent of the required process energy.

The collector field design uses specifications supplied by the Sandia Laboratories for second generation heliostats. The heliostats are arranged in a radial pattern encompassing a 2.62 radian (150°) circular sector. The receiver is arranged into two cavities and is supported by a steel tower. Each subsystem is discussed in more detail in following sections.

C. MAJOR SUBSYSTEMS

1. Collector Field/Receiver Configuration

The collector field is a 150° north field containing 818 heliostats. The collector field is divided into two 75° sectors for the twin-cavity receiver arrangement as shown in Figure 7. DELSOL calculated that 812 heliostats were required to produce the desired receiver power output of 29.3 MWt at noon day 58. However, DELSOL could not account for heliostats being displaced by oil wells which require a 9 m (30 ft) clearance. The heliostats that were displaced by wells were relocated at the outer edges of the collector field where there is a drop off in heliostat efficiency. To overcome the resulting lower efficiencies,

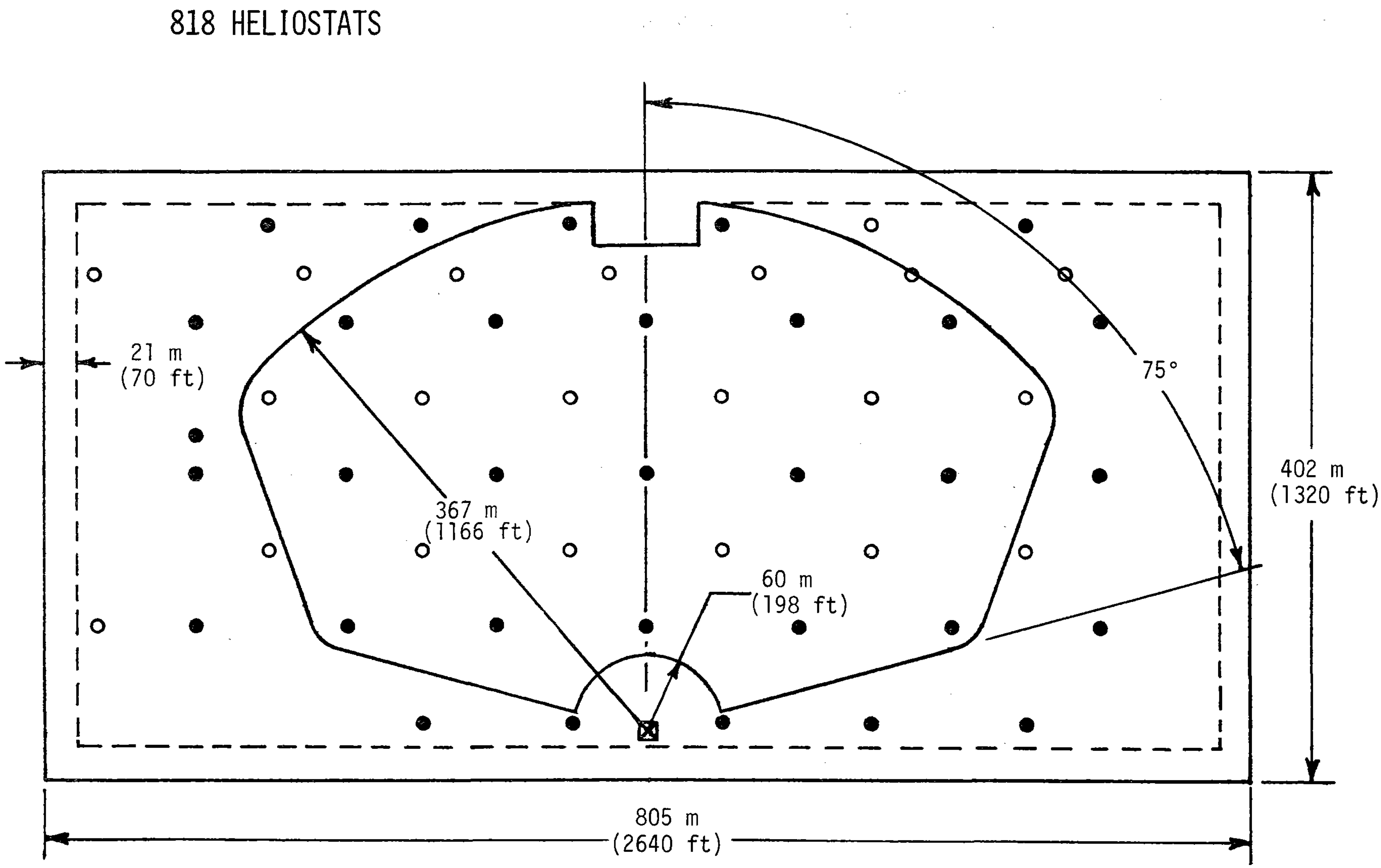

Figure 7 Collector Field Boundary

6 additional heliostats were added to the collector field to maintain the receiver output. The University of Houston collector field program RCELL was used to determine the coordinates of heliostats for a 90 meter tower.

In addition to well clearance, roads are required to provide normal oil well servicing. These roads are 9 m (30 ft) wide. Rather than use the existing east-west roads, which would displace many heliostats, roads would be established between heliostat rows. There is only one area that does not meet the 9 m (30 ft) road requirement and that is the space between rows 1 and 2 as shown in Figure 8. This does not present any problem in that there are no wells between these two rows.

The receivers that were considered for the 150° field were single-cavity and twin-cavity configuration.

The single-cavity configuration, as shown in Figure 9, has aperture that faces north that is 18 m (50 ft) in width and 6.3 m (20.7 ft) in height. The single-cavity required that the aperture width be stretched in order to capture the energy projected from the heliostats is in the southern corners of the collector field. This increase in the aperture width resulted in a cavity width of 22 m (72 ft).

The twin-cavity configuration has two 5.5 m x 5.5 m (18 ft x 18 ft) apertures that are rotated 37.5° from the north axis, as shown in Figure 10. The two adjacent cavities have a combined width of 13 m (42.6 ft).

The twin cavity was selected over the single cavity configuration because of its more compact receiver in addition to being more efficient. Table 4 shows the efficiency comparisons of the two receiver configurations.

Table 4 Cavity Comparisons

	Design Point Losses			
	Reflection	Radiation	Convection	Total
Single-Cavity	2.10%	5.64%	2.68%	10.42%
Twin-Cavity	1.56%	1.51%	2.41%	5.48%

The excessively large aperture for the single cavity makes it impractical to use the single-cavity configuration.

Not to Scale

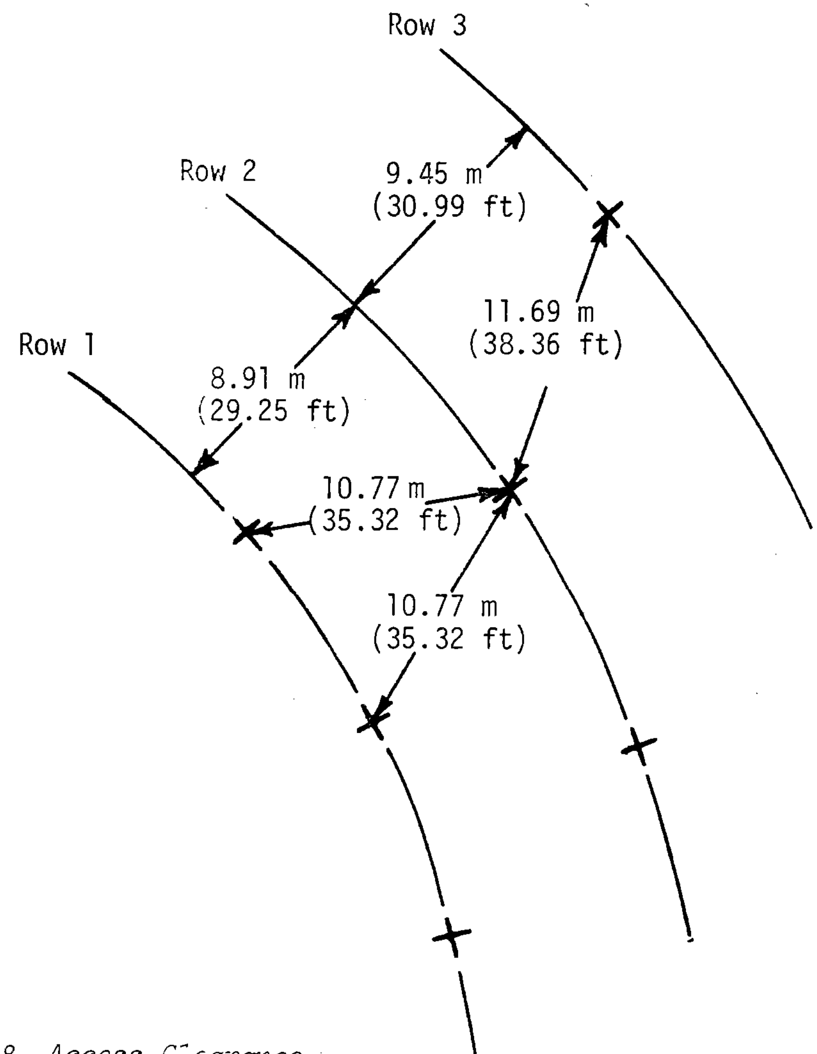

Figure 8 Access Clearance

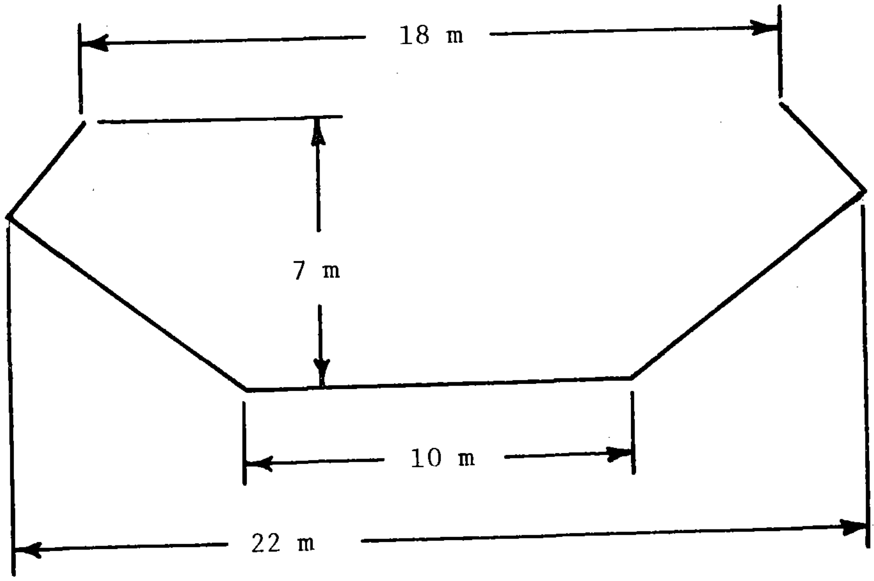

Figure 9 Single-Cavity Configuration

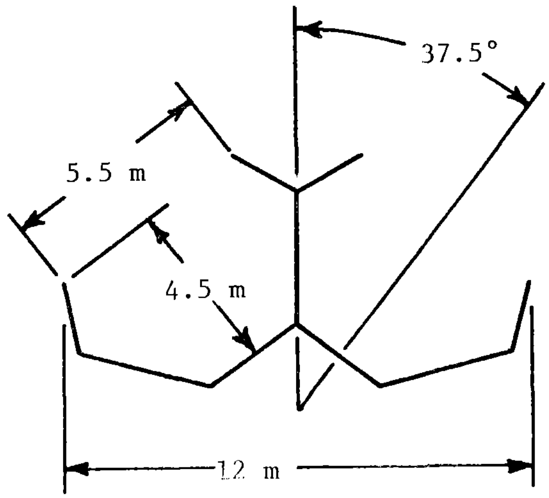

Figure 10 Twin-Cavity Configuration

2. Receiver

a. Conceptual Design Description

General - The basic receiver concept is a cavity-type, natural circulation steam generator, with separate preheat circuitry. The receiver is designed to produce steam at 297 C (567 F), 8,274 kPa (1200 psia), with a thermal output of 29.3 MW (100×10^6 Btu/h). Approximately 21 percent of the total thermal duty is required to preheat the feedwater from 16 C (60 F) to 149 C (300 F). Because of the dissolved solids in the feedwater, a substantial amount of continuous blowdown from the drum is necessary to maintain the total dissolved solids in the boiler water below the maximum tolerable concentration. At the operating pressure, the blowdown required for the feedwater quality specified in Martin Marietta/ Exxon Solar Thermal Enhanced Oil Recovery System Specification is equal to 17.5 percent of the feedwater flow. The hot blowdown water is recombined with the saturated steam from the drum at the outlet of the receiver to salvage the heat in the blowdown water. This results in an approximate 82 percent quality steam at the receiver outlet. A summary of the operating and design conditions for the receiver is shown in Table 5.

Table 5 Receiver Operating and Design Conditions

Design Point:	Noon, Winter Solstice	
	Insolation	= 0.95 kW/m^2 (301 Btu/h·ft^2)
Thermal Input :	31.5 MW (107.5×10^6 Btu/h)	
Thermal Output:	29.3 MW (100×10^6 Btu/h)	
Receiver Output -	Pressure :	8,274 kPa (1200 psia)
	Temperature:	297 C (567 F)
	Quality :	82% by weight
Feedwater Input -	Pressure :	10,342 kPa (1500 psia)
	Temperature:	15.6 C (60 F)
Flow Rates -	Feedwater :	43,590 kg/h (96,100 lb/h)
	Saturated Steam:	36,015 kg/h (79,400 lb/h)
	Drum Blowdown :	7,575 kg/h (16,700 lb/h)
Preheater Duty:	6.05 MW (20.7×10^6 Btu/h)	
Peak Absorbed Heat Flux:	694 kW/m^2 (220,000 Btu/h·ft^2)	
Environments -	Ambient Temperature:	-6.7 C/46 C (20 F/115 F)
	Winds :	40 m/s (90 mph)
	Seismic Zone :	UBC Zone 4
	Ground Acceleration:	0.3 g (min.); 0.5 g (average)

A schematic flow diagram illustrating the essential instrumentation, valving, and controls of the receiver is shown in Figure 11. Control of feedwater is accomplished by a feedwater regulator that matches feedwater flow to the total flow leaving the receiver, with a trimming override in response to drum level. The total flow leaving the receiver is determined by measurements of the blowdown flow and the saturated steam flow. The blowdown flow is regulated by a preset blowdown ratio with reference to the measured feedwater flow. Feedwater from the water-treatment system is first heated in the preheater before it enters the drum. Incident solar energy heats water in the boiler section and vaporizes a portion of it, creating a density gradient between the water in the downcomers and steam/water mixture in the heated boiler panels. This promotes a natural circulation of the steam/water mixture upward to the drum and water downward from the drum to replenish the boiler panels. In the drum, the water is separated from steam by density differences and, after mixing with incoming feedwater, enters the downcomers for another trip around the boiler circuits. Saturated steam from the drum is routed to a mixing header at the bottom of the receiver, where it is combined with the blowdown flow. The mixture is then piped down the tower to field distribution piping.

Conceptual arrangements of two receiver configurations, namely, two-cavity and single-cavity, were generated and are described in the following sections.

Two-Cavity Receiver - This concept, featuring an integrated two-cavity receiver, was devised for a 150-degree north collector field. The receiver is symmetric with respect to a north-south line passing through the common wall which partitions the two cavities, as shown in the plan view of Figure 12. The aperture of each cavity is 5.5 m x 5.5 m (18.04 ft x 18.04 ft) with its centerline extending at an angle of 37.5° from the common wall. The allocations of preheater and boiler surfaces on cavity walls are also shown in this plan view. The first pass of the preheater is located at the central portion of the common wall. The inboard portion of the common wall, two rear walls and two sidewalls, are lined with boiler panels. Since considerable incident solar energy falls upon the cavity roof, a large portion of the roof is covered by two serpentine panels of the preheater, as shown in the top plan view of Figure 12. Two simplified sectional elevation views of the receiver are also depicted in this figure, with Section A-A cutting through the centerline of the north-east cavity and Elevation B-B looking straight into the aperture of this cavity. All preheater and boiler panels are made of carbon steel tubes that are joined along their length by continuous-weld

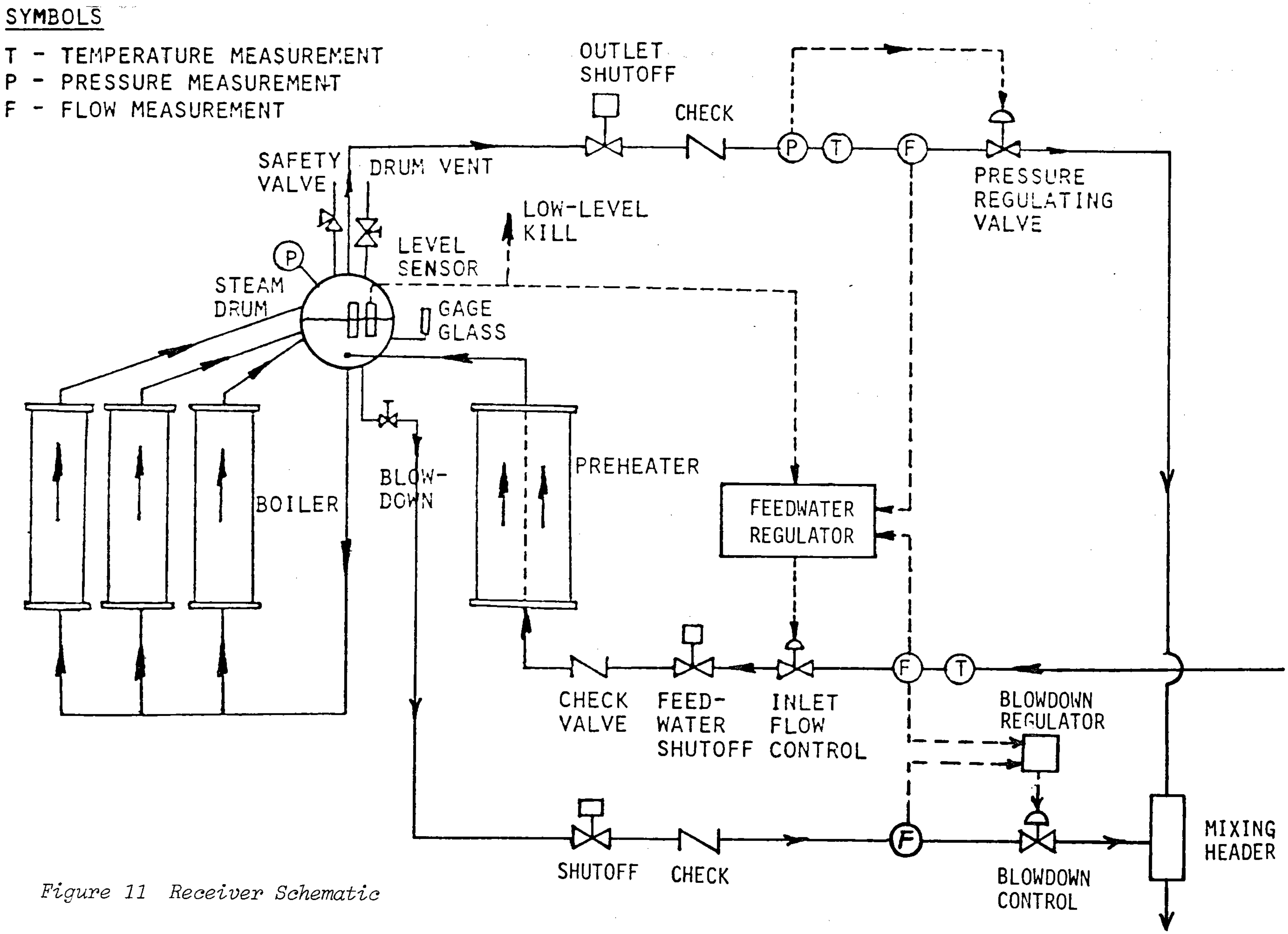

Figure 11 Receiver Schematic

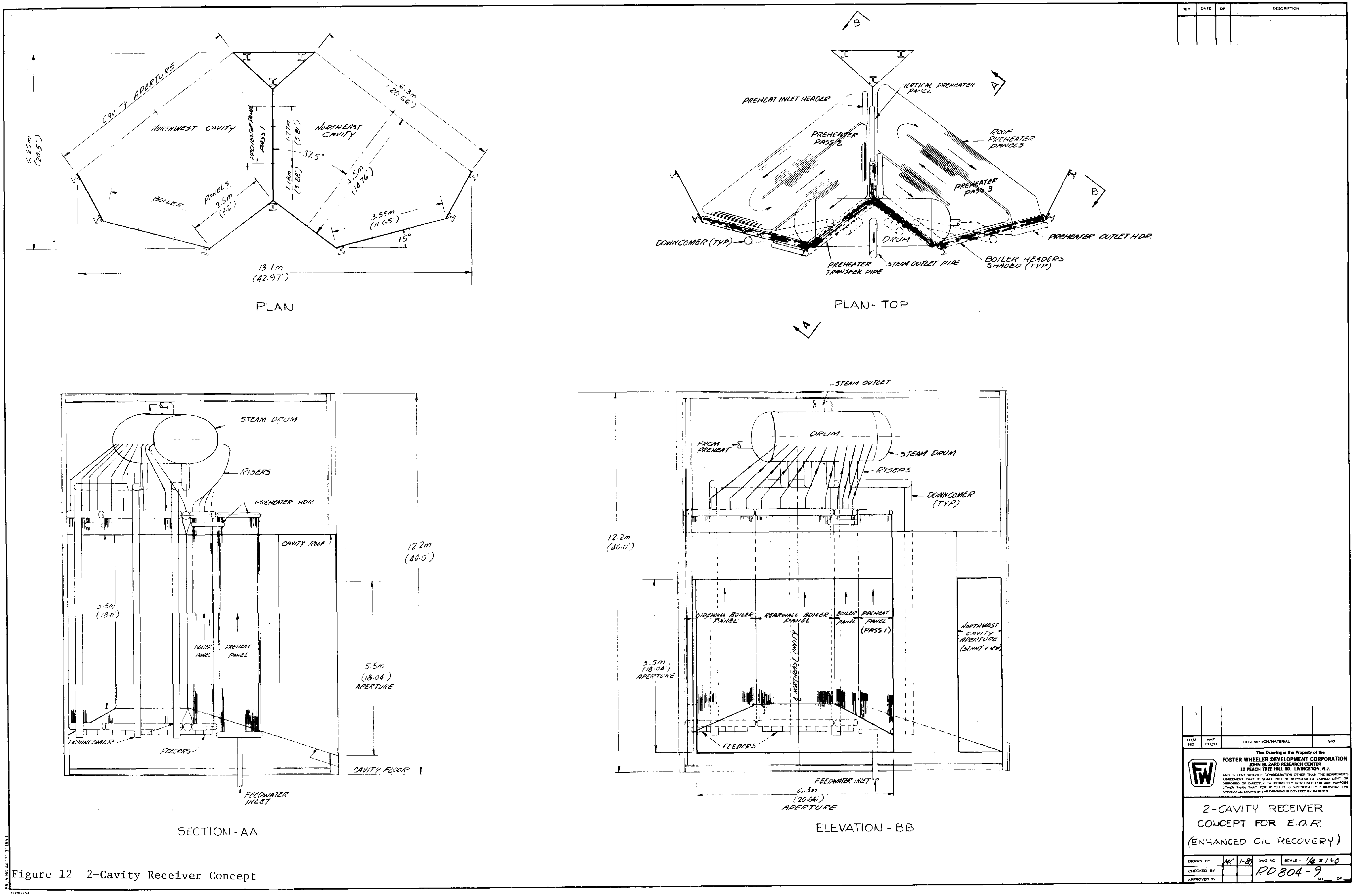

Figure 12 2-Cavity Receiver Concept

integral fins to form flat Monowalls™. This type of panel is structurally rigid, can be handled in shipment and during erection with relative ease, and is impenetrable to incident solar flux.

As shown in the figure, feedwater enters at the lower header of the vertical preheater panel (Pass 1), and flows upward inside the tubes while being heated by the incident heat flux along the length of the pass. Water is collected at the upper header and piped to the inlet header of the roof preheater panels. After it traverses back and forth through the serpentine panel (Pass 2) on the roof of the northwest cavity, heated water is collected and routed by a transfer pipe to the roof panel (Pass 3) in the other cavity. There, water is further heated until it exits from the outlet header and discharges into the drum. From the drum, boiler water flows through four downcomer pipes and branching feeders to the lower headers of the boiler, where the flow is divided among the various upflow boiler panels. As the water flows upward through the tubes, a portion of it is converted into steam by the absorbed heat. The resultant mixture of water and steam leaving the tubes is collected in the upper boiler headers and carried back to the steam drum through risers.

The shell of the receiver consists of preheater and boiler panels, cavity floor and roof plates, enclosure and stiffeners. Interior surfaces of the cavity that are not covered with preheater or boiler panels are lined with either flat steel plates or corrugated Incoloy plates coated with reflective material. Outside surfaces of the receiver, as well as drum and exterior piping, are insulated to reduce thermal losses to the ambient environment. The aperture of each cavity is provided with an insulated door that can be closed to minimize heat loss and resultant cooling of the receiver during overnight shutdown.

The entire receiver is suspended from a structural-steel framework attached to the support columns. All pressure parts of the receiver are free to expand laterally and down. The structural framework also supports the enclosure. The preheater and boiler panels that receive solar energy from only one side can be held in position and braced at the back against thermal stress and wind and seismic loads by conventional structural-steel buckstays. The panels that form the partition wall between the two cavities are heated by radiant flux from both sides during operation. This reduces circumferential temperature gradients of the tubes and results in much less thermal stresses in the tubes. Since the length of these panels is only about 6.7 m (22 ft), preliminary calculation indicates that no intermediate horizontal support in the heating zone is required.

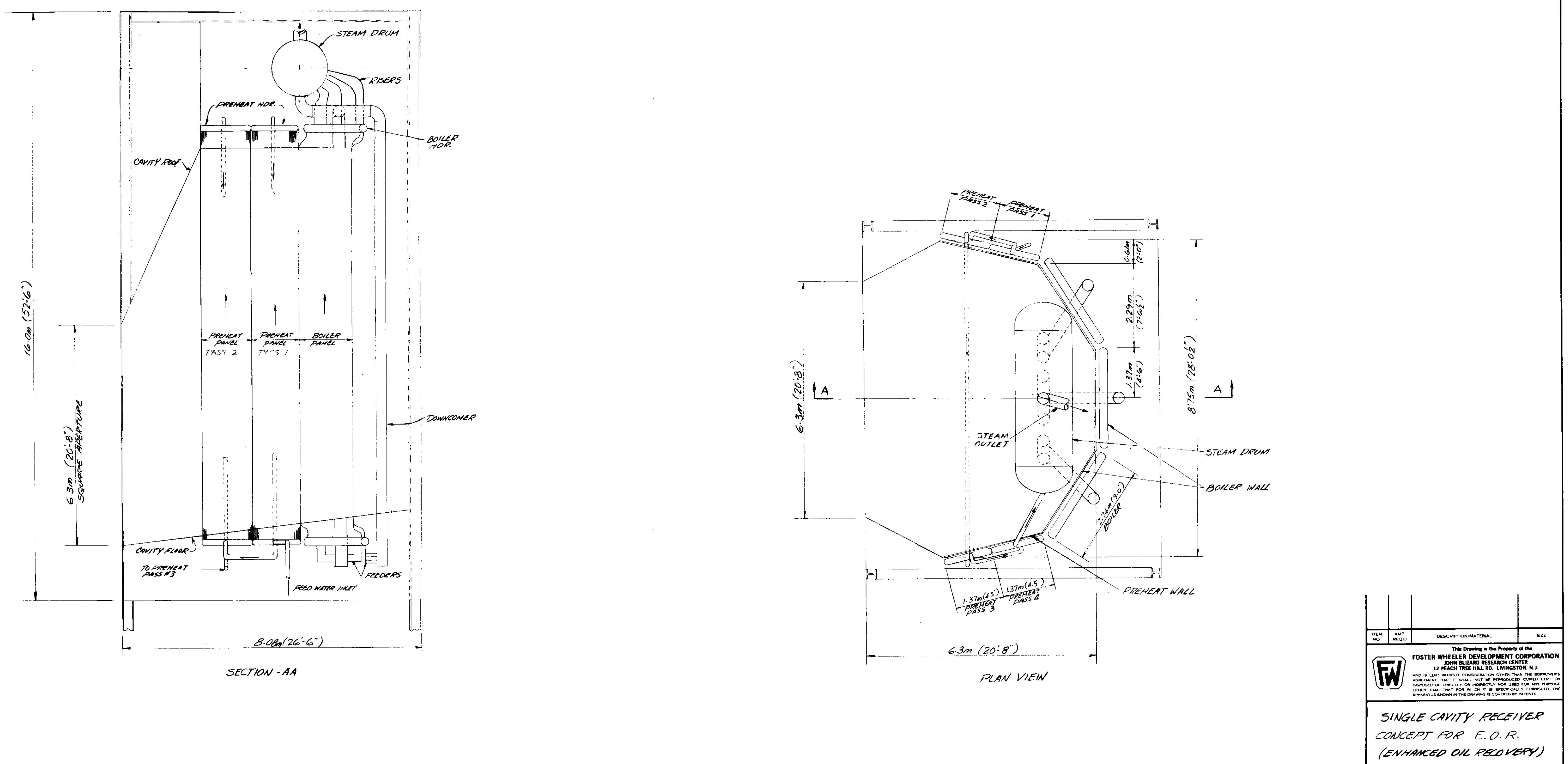

Figure 13 Single Cavity Receiver Concept

Single-Cavity Receiver - This concept was generated for a 90-degree, all-north collector field. A plan view and a sectional side elevation of the receiver are shown in Figure 13. With a square cavity aperture facing north, the receiver configuration is axisymmetrical with a north-south centerline. Five of the seven vertical walls are the active solar absorption surfaces and consist of either preheater or boiler panels. The same type Monowall™ construction described previously is used for these panels.

As shown in the figure, boiler panels are located at the rear wall and the two sidewalls next to it. Preheater panels, covering the remaining two active sidewalls, consist of four-up-flow passes in series (two on each sidewall). Feedwater enters at the lower header of the first preheater pass and is heated by the incident heat flux while flowing upward inside the tubes. At the upper header, the water is collected and piped down to the lower inlet header of the second pass. After it is further heated in this pass, water is transported by an interconnecting pipe from the upper collecting header down to the bottom of the unit and across under the cavity floor to the inlet header of the third pass on the opposite sidewall. From there, the water flows through the final two passes in much the same manner as it does through the first two passes. The preheated water exits finally from the upper header of the last preheater pass and is piped to the drum.

Six down-take pipes are used to carry boiler water from the bottom side of the drum to three downcomers. At their lower ends, these downcomers are connected by a number of risers to the inlet headers of three boiler panels. The water/steam mixture produced in these boiler panels is collected in the upper headers and carried back to the drum via risers.

The low incident flux intensity falling on the cavity roof, in this configuration, does not require any active cooling of the roof. Corrugated Incoloy or flat steel plates with reflective coating is used to cover the roof as well as the two remaining non-active sidewalls and cavity floor. The receiver is top-supported, fully insulated, and equipped with an aperture door, in much the same way as in the two-cavity concept.

b. *Trade Studies* - The receiver trade studies performed are briefly summarized as follows:

Surface Arrangement - Based on the preheat requirement and heat flux distributions on the receiver interior surfaces, different surface allocations of preheater and boiler were considered for both two-cavity and single-cavity configurations. Preheat of the feedwater from 16 C (60 F) to 149 C (300 F) was chosen in order to reduce the temperature gradient across the thermal sleeve that protects the joint of feedwater pipe and steam drum. The selected arrangements for the two configurations were described in the preceding section.

Steam Drum - Since the steam injection application does not require dry saturated steam, mechanical separators can be eliminated from the drum internals to effect a cost saving. Based on the operating pressure and steam loading, drums with different inside diameters and lengths were compared. A 1.37 m (54 in.) I.D. drum was selected for each of the two concepts.

Boiler Circulation - A simplified analytical computer model was set up to check the adequacy of boiler circulation. It consisted of circuits representing downcomers, feeders, vertical boiler panels and risers. Different sizes of boiler tubes were analyzed for the different heat absorption conditions. Tubes of 50.8 mm (2.0 in.) O.D. were found adequate for all boiler panels. The results of this study were used to generate the boiler circuitry for the conceptual design.

Preheater Circuit - Tube size, width and orientation of flow pass, heat flux variation, and pressure drop were the key parameters considered in the design of the preheater flow circuit. Tubes of 25.4 mm (1.0 in.) O.D. were chosen for all preheater panels. The pressure drop through the preheater was approximately 207 kPa (30 psi).

Pressure Parts Sizing - Based on ASME Code, Section I, the required wall thicknesses of boiler and preheater tubes, headers, downcomers, feeders, risers, connecting piping and drum were determined.

Seismic Design Requirement - The lateral accelerations at the top of the receiver tower were calculated using the correlations recommended by Sandia-Livermore. An average peak ground acceleration of 0.5 g for UBC Seismic Zone 4 was used. The corresponding lateral tower-top acceleration equals 0.82 g for a 90-m (295-ft) concrete tower, and 0.62 g for a steel tower of the same height.

c. Weight and Cost Estimates - Preliminary weight and cost estimates of the two receiver configurations were made for the overall system economic evaluation. Without the concepts being fully developed, these estimates were based on the results of trade studies and the preliminary arrangement sketches. The results are summarized in Table 6. The cost shown includes material, fabrication, erection and home office expenditures.

Table 6 Weight and Cost Comparison of the Candidate Receiver Concepts

Receiver Configuration	Two-Cavity	Single-Cavity
Total Weight, 10^3 kg (10^3 lb)	141 (310)	139 (307)
Capital Cost, M$	2.03	1.93

C. FIELD PIPING STUDY

The purpose of this study is to develop the most economical piping scheme for transporting the steam produced in the receiver to the injection wells.

1. System Arrangement

Assuming 12 wells are to be injected simultaneously, a well pattern was selected which, to the extent possible, would be similar throughout the field. The well injection pattern and the field piping arrangement are shown in Figures 14 and 15, respectively. For this field arrangement, piping generally runs parallel to the field boundaries. Addition at new injection wells can be accomplished by taking wells out of service at one end of the well pattern and adding wells to the other end. Further, this arrangement lends itself to a complete relocation of the well pattern mainly by adding or removing lengths of main header piping.

2. Pipe Sizes

Pipe sizes were selected based on the following two criteria.

- o The steam pressure at any well head should not be less than 5.516 MPa (800 psia). Thus, with 6.895 MPa (1000 psia) steam pressure available at the nearest well, a maximum pressure loss of 1.379 MPa (200 psi) was established for the additional piping system necessary to reach the farthest well.

- o A maximum steam velocity of approximately 120 m/min/mm (ID) [1000 ft/min/in. (ID)] was selected as a reasonable value to minimize pipe erosion.

The piping system consists of two principal sections.

- o Main Header - header pipe from the receiver to a point just ahead of the injection well pattern.

- o Branch - pipe from the main header to the injection wells.

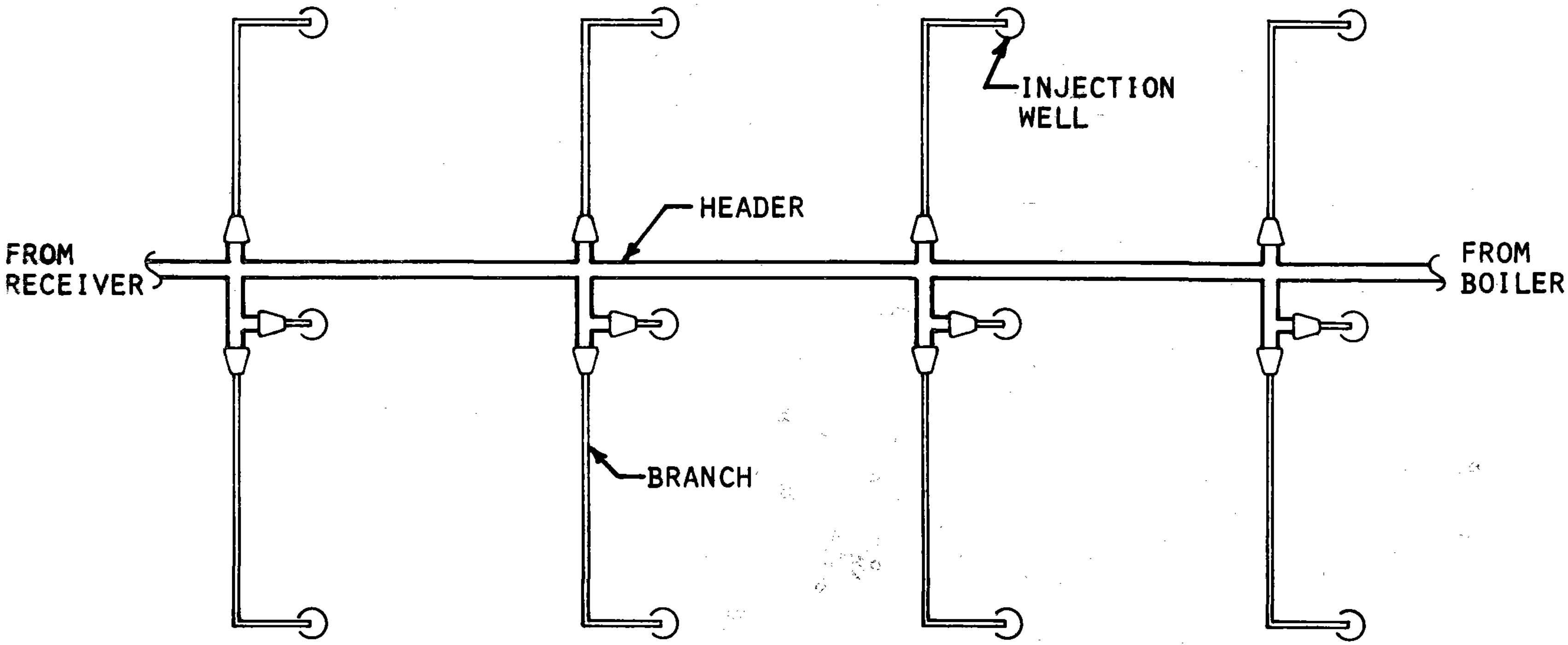

Figure 14 Well Injection Arrangement

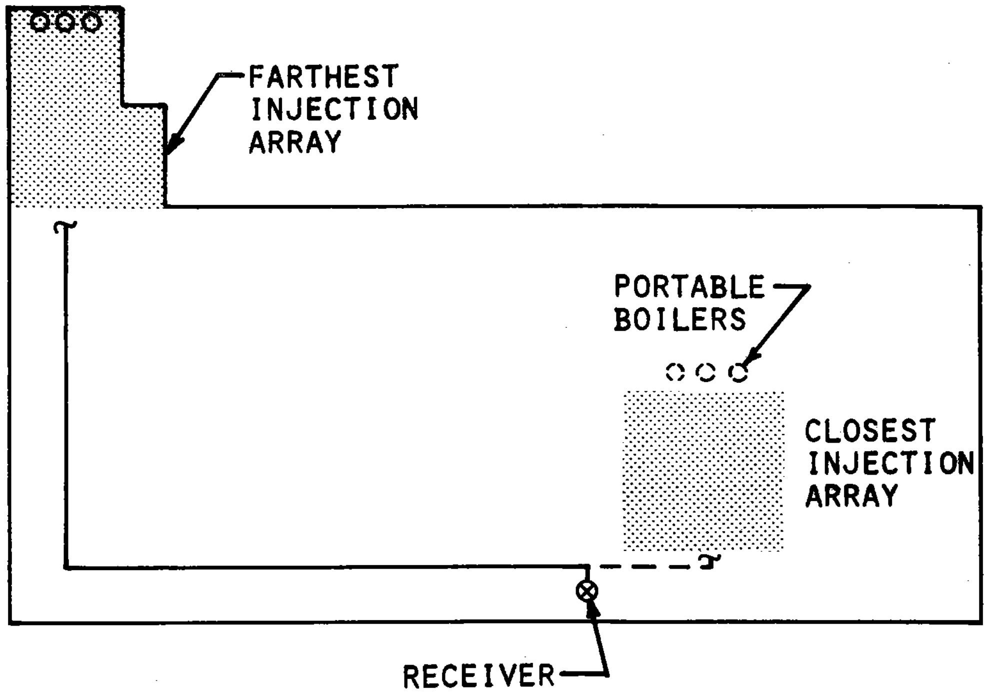

Figure 15 Field Arrangement

The design steam flow is 43,500 kg/hr (96,000 lb/hr); this flow consists of 36,000 kg/hr (79,400 lb/hr) steam produced by the receiver and 7600 kg/hr (16,700 lb/hr) of receiver blowdown (which is injected in the main header just downstream of the receiver). This steam quality is approximately 82 percent. With this steam flow, the selection of minimum pipe size was based on velocity. As can be seen in Table 7, a check of pressure loss with the minimum pipe size 15.24 cm (6 in.) main header and 7.62 cm (3 in.) branch) indicates a loss of approximately 1448 kPa (210 psi). For the two pipe sections considered, one nominal pipe size above and below the minimum was also evaluated in order to see the effect on total system cost due to decreasing pressure loss by increasing pipe size.

3. Thermal Expansion

For the pipe sizes considered, the three methods of compensating for thermal expansion shown in Figure 16 were evaluated.

o Pipe expansion loops.

o Metal bellows expansion joints.

o Barco joints (swivel ball joints).

In order to simplify the piping support system, movement of the pipe at any location due to thermal expansion was limited to approximately 40.64 cm (16 in.). This requires a method of accommodating the expansion at intervals of approximately 122 m (400 ft). The cost of each of these techniques is listed in Table 7.

4. Insulation

In order to complete the piping study, insulation costs were developed based on the following assumptions.

o Wind speed - 4.9 m/sec (11 mph).

o Ambient temperation - 18.3 C (65 F).

o Energy Cost - $0.68/W ($0.20/Btu/hr).

A preliminary evaluation was performed comparing head loss cost and capital cost for the following seven types of insulation.

Thermo 12
Epitherm 1200
Super Caltemp
Kaylo 10

Table 7 Comparison of Alternatives

	Main Header						Branch		
	Farthest Array			Closest Array					
Pipe Size, cm (in.)	10.16 (4)	15.24 (6)	20.32 (8)	10.16 (4)	15.24 (6)	20.32 (8)	5.08 (2)	7.62 (3)	10.16 (4)
Pipe Cost ($1000)	318.6	402.7	487.4	37.7	47.6	48.1	128.1	144.0	166.4
Expansion Method ($1000)									
Pipe Loops	51.9	84.4	133.4	3.7	6.0	8.1	25.4	33.1	44.5
Bellows	51.6	55.4	76.2	3.7	4.0	5.4	23.3	39.3	44.2
Barco Joints	15.2	31.1	45.5	1.1	2.2	3.3	8.9	12.7	19.5
Insulation Cost ($1000)									
Bellows or Barco Joints	54.5	66.5	92.8	6.4	7.8	10.8	24.1	27.2	33.2
Pipe Loops	63.4	80.4	114.4	7.0	8.8	12.4	28.9	33.8	42.5
TOTAL COST ($1000)									
Pipe Loops	433.9	597.5	715.2	48.4	62.4	78.6	182.4	210.9	253.4
Bellows	424.7	524.6	656.4	47.8	59.4	74.3	180.3	210.5	253.1
Barco Joints	388.3	500.3	625.7	45.2	57.6	72.2	161.1	183.9	219.1
TOTAL PRESSURE DROP, kPa (psi)									
Pipe Loops	11470 (1664)	1544 (224)	386.1 (56)	1269 (184)	172.4 (25)	41.37 (6)	475.8 (69)	62.06 (9)	13.79 (2)
Bellows	10600 (1537)	1420 (206)	358.5 (52)	1207 (175)	165.5 (24)	41.37 (6)	420.6 (61)	55.16 (8)	13.79 (2)
Barco Joints	10510 (1525)	1393 (202)	344.8 (50)	1186 (172)	158.6 (23)	34.48 (5)	420.6 (61)	55.16 (8)	13.79 (2)

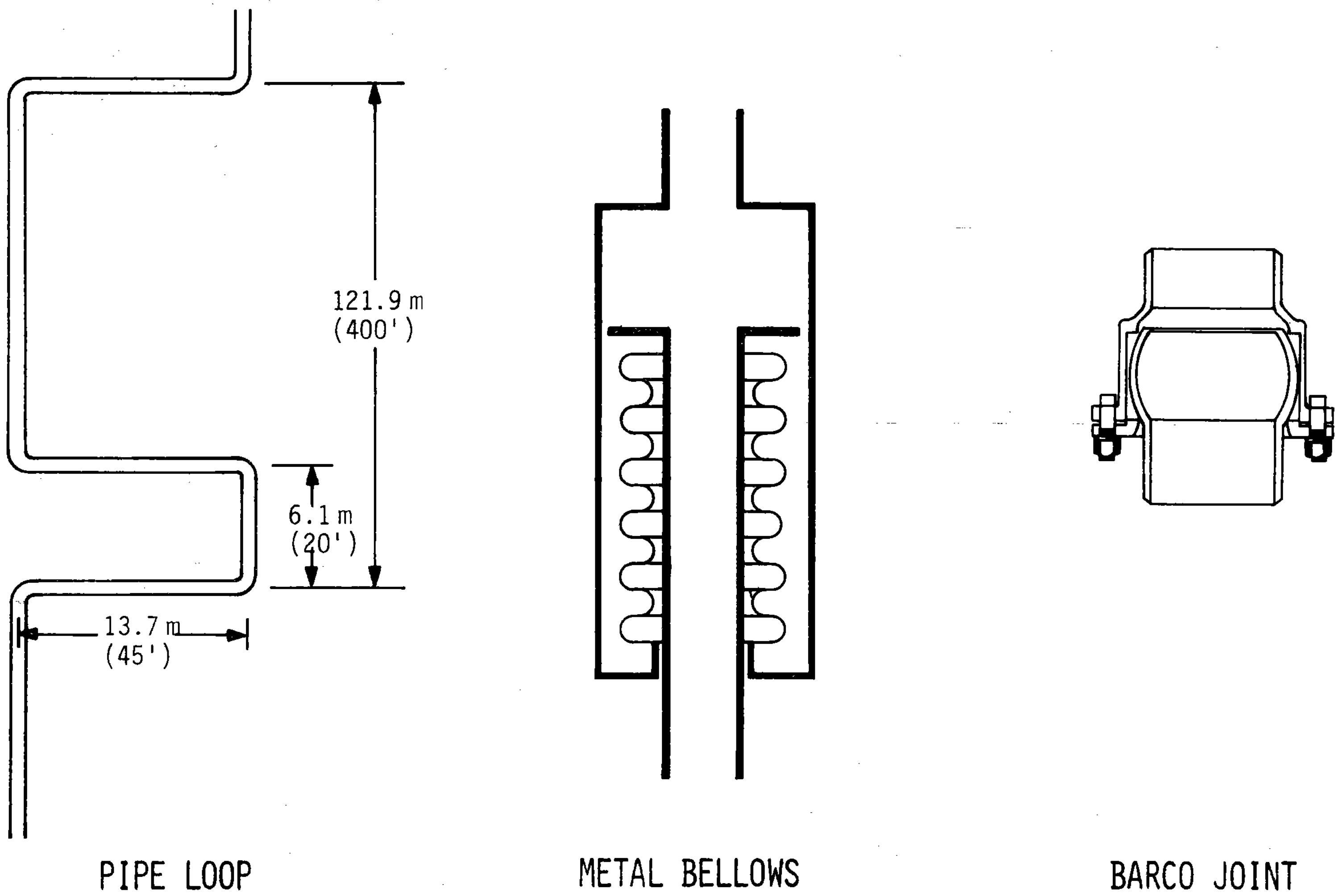

Figure 16 Thermal Expansion Devices

Kaowool 2600
Micro-lok 650
Celotex 1500

The three least expensive types of insulations (Epitherm 1200, Kaowool 2600, and Micro-lok 650) were further evaluated to determine the most economical insulation type and thickness for each size pipe. The results of this analysis for a representative pipe size 15.24 cm (6 in.) is shown in Table 8. For this case it is apparent that the evaluated cost decreases sharply with increasing insulation thickness until a thickness of 8.89 cm (3.5 in.) is reached. For all pipe sizes, 8.89 cm (3.5 in.) of Micro-lok 650 was either the optimum or the point at which additional thickness resulted in insignificant cost savings. These results appear as the insulation cost in Table 7.

5. Conclusions

The principal conclusion of the study is that the most economical piping system would be--

15.24 cm (6 in.) main header with barco joints and 8.89 cm (3.5 in.) of Micro-lok insulation.

7.62 cm (3 in.) injection piping with barco joints and 8.89 cm (3.5 in.) of Micro-lok insulation.

Table 8 Insulation Comparative Cost (Pipe Size - 15.24 cm (6 in.) SCH 80)

Insulation Type and Thickness, cm (in.)	Heat Loss W/m (Btu/hr/ft)	Heat Cost $/m ($/ft)	Capital Cost $/m ($/ft)	Total Cost $/m ($/ft)
EPITHERM 1200				
5.08 (2.0)	187.9 (195.5)	128.29 (39.10)	22.21 (6.77)	150.50 (45.87)
6.35 (2.5)	158.0 (164.4)	107.88 (32.88)	25.03 (7.63)	132.91 (40.51)
7.62 (3.0)	138.0 (143.5)	94.16 (28.70)	28.58 (8.71)	122.74 (37.41)
8.89 (3.5)	118.3 (123.1)	80.78 (24.62)	39.44 (12.02)	120.22 (36.64)
10.16 (4.0)	109.9 (114.3)	75.00 (22.56)	45.41 (13.84)	120.41 (36.70)
11.43 (4.5)	102.6 (106.7)	70.02 (21.34)	50.04 (15.25)	120.05 (36.59)
12.70 (5.0)	97.1 (101.0)	66.28 (20.20)	54.76 (16.69)	121.92 (37.16)
MICRO-LOK 650				
5.08 (2.0)	198.8 (206.8)	135.70 (41.36)	23.52 (7.17)	159.23 (48.53)
6.35 (2.5)	167.1 (173.8)	114.05 (34.76)	27.99 (8.53)	142.03 (43.29)
7.62 (3.0)	145.8 (151.7)	99.55 (30.34)	32.19 (9.81)	131.73 (40.15)
8.89 (3.5)	122.4 (127.3)	83.53 (25.46)	36.35 (11.08)	119.89 (36.54)
10.16 (4.0)	115.3 (119.9)	78.68 (23.98)	40.49 (12.34)	119.17 (36.32)
11.43 (4.5)	108.4 (112.8)	74.02 (22.56)	44.98 (13.71)	119.00 (36.27)
12.70 (5.0)	102.3 (106.4)	69.82 (21.28)	49.12 (14.97)	118.94 (36.25)
KAOWOOL 650				
5.08 (2.0)	161.4 (167.9)	110.18 (33.58)	32.38 (9.87)	142.56 (43.45)
6.35 (2.5)	135.7 (141.2)	92.66 (28.24)	40.65 (12.39)	133.31 (40.63)
7.62 (3.0)	119.6 (124.4)	81.63 (24.88)	48.26 (14.71)	129.89 (39.59)
8.89 (3.5)	101.8 (105.9)	69.49 (21.18)	56.24 (17.14)	125.73 (38.32)
10.16 (4.0)	94.4 (98.2)	64.44 (19.64)	67.72 (20.64)	132.16 (40.28)
11.43 (4.5)	88.1 (91.6)	60.11 (18.32)	78.78 (24.01)	138.88 (42.33)
12.70 (5.0)	82.7 (86.0)	56.43 (17.20)	89.80 (27.37)	146.23 (44.57)

III. SYSTEM PERFORMANCE AND ECONOMICS

The efficient design of a receiver requires a complete thermal analysis of the power inputs as well as losses to the receiver. The receiver design should provide the maximum amount of power with minimum amount of losses to provide power at the most economical rate.

A. COLLECTOR/RECEIVER MODULE PERFORMANCE

In determining the collector/receiver module performance, various computer programs were used. The receiver reflected loss and heat flux characteristics were calculated by TRASYS. TRASYS also calculates the radiation conductor paths which can be input into a program, called MITAS, that calculates radiation, convection and conduction losses. Aperture spillage and collector field efficiencies were calculated using Sandia's DELSOL and MIRVAL computer programs. The systems annual performance was determined by using another Sandia program known as STEAEC.

1. Collector Field Performance

MIRVAL calculated the collector field efficiencies for all combinations of the following sun azimuth and elevation angles.

Azimuth angles 0°, 30°, 60°, 75°, 90°, 110°, 130°

Elevation angles 5°, 15°, 25°, 45°, 65°, 89.5°

The results of MIRVAL's calculations are shown in Table 9. These collector field efficiencies include tower shadowing, spillage,

Table 9 Collector Field Efficiencies

		SUN AZIMUTH (SOUTH = 0°)						
		0°	30°	60°	75°	90°	110°	130°
SUN ELEVATION (Horizontal = 0°)	5°	.250	.240	.239	.233	.220	.150	.125
	15°	.575	.542	.506	.488	.461	.380	.330
	25°	.717	.682	.638	.613	.582	.516	.450
	45°	.818	.791	.747	.716	.683	.640	.592
	65°	.795	.785	.757	.735	.715	.684	.654
	89.5°	.730	.730	.729	.729	.725	.705	.690

heliostats shadowing/blocking, reflectivity, tracking errors, slope errors cosine, and stmospheric attenuation.

2. Cavity Heat Flux Characteristics

A simplified cavity plan view and foldout, showing active and inactive surface for the cavity, is shown in Figures 17 and 18. The foldout also shows nodal breakdown for the cavity, Preheat panels are located in the roof and a portion of the north wall, the remainder of the active wall area consists of boiler panels. The boiler panels can accept a peak flux of 69.4 W/cm^2 (220,000 $Btu/hr\text{-}ft^2$) while the preheat panels can only accept a peak heat flux of 34.7 W/cm^2 (110,000 $Btu/hr\text{-}ft^2$). Figure 19 shows the incident heat flux and the heat flux after reflections for noon day 58. The heat fluxes in parenthesis represent the flux on a node after reflection inside the cavity while the flux without parenthesis represents the incident heat flux. Both heat fluxes are in $watts/cm^2$. The heat fluxes in Figure 19 are the result of a simple aiming strategy that was required to reduce the peak heat flux to within acceptable limits. The aiming strategy is shown in Table 10. The coordinate system for the aiming strategy is in meters with the center point of the aperture being (0.0, 0.0, 0.0).

Table 10 Aiming Strategy

Aim Point Numbers	Aim Points			Rows
	X	Y	Z (m)	
1	0.0	0.0	0.0	1-11, 21-29
2	0.0	0.0	1.5	12-13
3	0.0	0.0	1.25	14
4	0.0	0.0	1.0	15-16
5	0.0	0.0	-1.0	17-18
6	0.0	0.0	-0.5	19-20

3. Receiver Thermal Losses

Thermal losses from solar central receivers consists of spillage, solar reflection, infrared radiation, convection, and conduction.

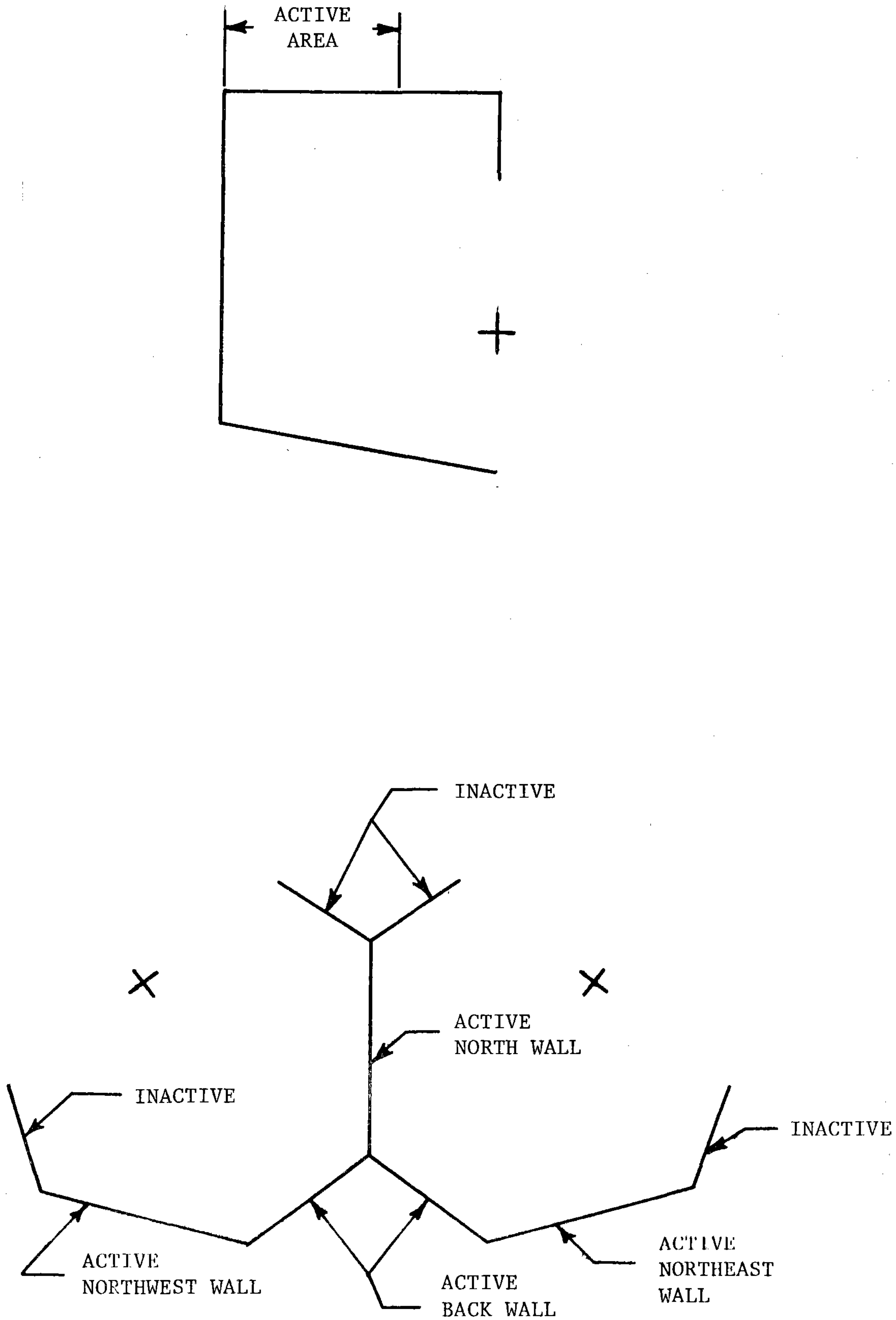

Figure 17 Receiver Plan View and Cross Section

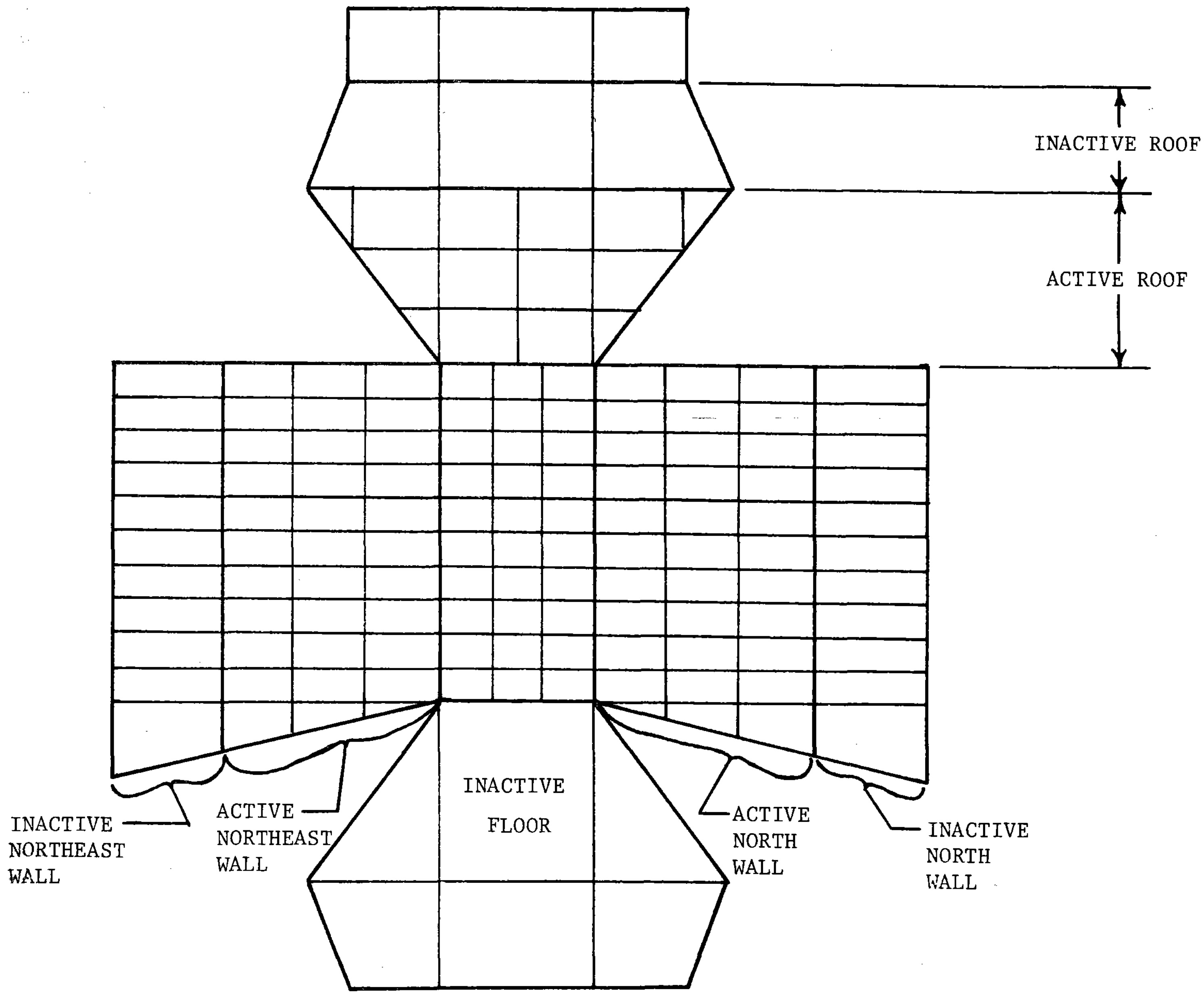

Figure 18 Northeast Cavity Foldout

NORTHEAST WALL				BACKWALL			NORTH WALL			
IN-ACTIVE	ACTIVE						ACTIVE			IN-ACTIVE
0.0 (0.21)	1.29 (1.63)	23.1 (22.6)	41.9 (40.9)	49.8 (48.3)	51.0 (49.3)	43.2 (41.9)	31.3 (30.8)	19.9 (19.7)	2.86 (3.22)	0.01 (0.25)
0.0 (0.22)	2.79 (3.12)	31.9 (31.0)	49.3 (47.8)	56.6 (54.6)	58.8 (56.7)	48.9 (47.2)	35.5 (34.8)	23.8 (23.4)	3.84 (4.21)	0.03 (0.25)
0.02 (0.23)	4.88 (5.11)	36.1 (34.9)	51.8 (50.1)	60.3 (58.1)	62.1 (59.7)	52.0 (50.1)	36.4 (35.6)	24.5 (24.0)	4.40 (4.73)	0.03 (0.25)
0.11 (0.26)	7.42 (7.51)	38.0 (36.7)	54.4 (52.6)	66.1 (63.6)	66.1 (63.4)	55.7 (53.6)	36.3 (35.5)	23.1 (22.6)	4.55 (4.84)	0.03 (0.24)
0.23 (0.29)	9.86 (9.81)	40.2 (38.7)	57.7 (55.7)	71.1 (68.3)	69.7 (66.8)	58.6 (56.3)	36.2 (35.3)	21.5 (21.1)	4.60 (4.85)	0.04 (0.24)
0.31 (0.30)	11.0 (10.8)	39.6 (38.1)	54.5 (52.5)	66.1 (63.4)	64.8 (62.1)	53.9 (51.8)	33.0 (32.2)	19.5 (19.1)	4.45 (4.68)	0.07 (0.23)
0.29 (0.28)	9.41 (9.32)	32.3 (31.1)	41.4 (40.0)	48.7 (46.8)	48.7 (46.7)	40.4 (38.8)	25.3 (24.8)	15.6 (15.3)	3.80 (4.03)	0.08 (0.22)
0.18 (0.23)	5.86 (5.92)	19.9 (19.3)	23.8 (23.1)	27.2 (26.3)	28.1 (27.1)	23.3 (21.5)	15.3 (15.2)	10.2 (10.2)	2.52 (2.78)	0.06 (0.20)
0.07 (0.18)	2.36 (2.56)	8.69 (8.63)	9.47 (9.43)	10.4 (10.2)	11.2 (11.0)	9.18 (9.06)	6.57 (6.73)	4.92 (5.09)	1.07 (1.37)	0.02 (0.17)
0.01 (0.14)	0.44 (0.71)	1.99 (2.23)	2.02 (2.29)	2.43 (2.63)	2.63 (2.83)	1.91 (2.13)	1.11 (1.48)	1.06 (1.39)	0.19 (0.50)	0.0 (0.15)
0.0 (0.12)	0.01 (0.29)	0.21 (0.52)	0.45 (0.77)				0.23 (0.60)	0.05 (0.40)	0.0 (0.31)	0.0 (0.13)

Figure 19 Northeast Cavity Heat Fluxes, Noon Day 58

	ROOF					
INACTIVE	0.03 (0.19)		0.29 (0.30)		0.38 (0.30)	
ACTIVE	0.28 (0.67)	4.94 (5.45)	11.2 (11.5)	11.3 (11.6)	8.28 (8.61)	1.06 (1.45)
		19.9 (20.0)	25.5 (25.5)	23.9 (23.8)	17.9 (18.0)	
		29.3 (29.3)	29.0 (29.1)	27.0 (27.0)	22.4 (22.5)	

NOON

DAY 58

INSOLATION 950 W/m^2

FLOOR INACTIVE		
0.0 (0.15)	0.01 (0.19)	0.0 (0.14)
0.0 (0.11)	0.01 (0.13)	0.0 (0.11)

TOTAL INCIDENT POWER

15.619 MWI

TOTAL POWER AFTER

REFLECTED LOSSES

15.376 MW_t

Figure 19 continued

Spillage losses were calculated using the Sandia program DELSOL. The design point (noon, day 58) spillage loss was 1.3% while the annual loss was 1.9%.

Solar reflection losses were based on TRASYS grey-body calculation. The solar reflection loss for the design point is 1.56%.

The infrared radiation, convection, and conduction for the design point, were calculated based on an ambient air temperature of 4.4 C (40 F). The infrared radiation loss was determined to be 1.51%. The convection loss was also based on the wind velocity in the cavities being 20% of the freestream. The freestream velocity, at the receiver height, was 4.9 m/sec (16.1 ft/sec). The convection loss was calculated to be 2.41%. The conduction loss was found to be 0.4% based on 10.16 cm (4 in.) of mineral wool insulation.

Overnight cooldown was analyzed using the finalized "wet" receiver heat capacity, a 286 C (546 F) receiver temperature and a -6.7 C (20 F) ambient air temperature at shutdown, on the night of December 21. The winter solstice represents the longest night-time duration and assuming a constant -6.7 C (20 F) temperature would provide a more severe cooldown condition than some shorter but colder night. Figure 20 shows the cooldown rate and after 14.5 hours the receiver only experiences a 70.6 C (127 F) temperature drop. The final fluid conditions are sufficient for a rapid morning startup.

Based on loss data obtained during the twin-cavity design, an annual receiver performance analysis was performed using STEAEC. The results of this analyses are presented in Table 11.

Table 11 Annual Receiver Performance

Yearly Energy to Collector Field, MWHt	90899.6
Yearly Energy to Receiver, MWHt	62155.4
Yearly Energy to Working Fluid, MWHt	55894.3
Yearly Energy at Base of Tower, MWHt	55869.7
Yearly Receiver Energy Loss, %	10.1

4. <u>Aperture Sizing</u>

The apertures for the twin-cavity receiver were optimized to provide the maximum amount of energy to enter the cavities while

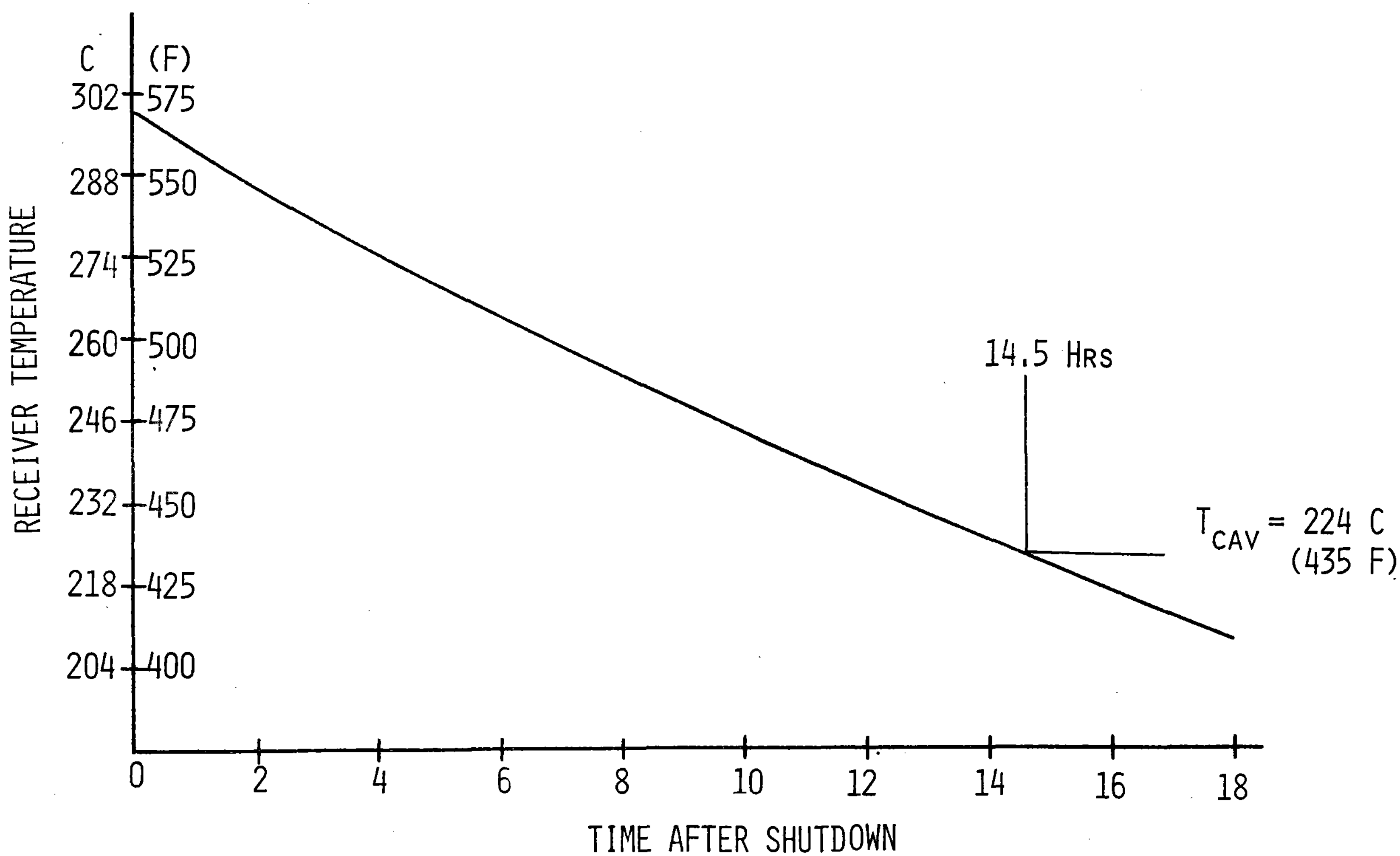

Figure 20 Receiver Overnight Cooldown

minimizing their losses. Based on the thermal losses out the aperture and spillage the apertures were found to optimize at 5.5 m x 5.5 m (18 ft x 18 ft). Figure 21 illustrates the aperture sizing process for the range of sizes studied.

B. ENERGY CONVERSION PERFORMANCE

1. Insolation Models

To perform yearly energy production calculations, the SOLMET typical meterological year (TMY) insolation and weather data base was used. As no TMY exists for Bakersfield, California area, the TMY data tape for Fresno, California was selected. Fresno is approximately 100 miles northeast of the site, but was chosen as being representative of the San Joaquin Valley region. The typical meterological years selected for each month for the Fresno data are shown in Table 12.

Table 12 Typical Meterological Years for Fresno, CA

January 1964	July 1954
February 1975	August 1973
March 1968	September 1968
April 1953	October 1966
May 1968	November 1974
June 1962	December 1968

This SOLMET TMY data yields an average daily direct normal insolation value of 6.21 $kWh/m^2/day$. This value compares favorably with insolation data compiled by Randall and Watson: "Final Report: Hourly Insolation and Meterological Data Bases Including Direct Insolation Estimates" (ATR-78(7592)-1, Aerospace Corp., 1977), which show average daily direct normal insolation values for Fresno between 6.0 and 6.86 $kWh/m^2/day$.

2. Solar System Performance

The conceptual design described in Section III has been modeled for design point and annual performance using three computer models--STEAEC, MIRVAL and TRASYS. Using the collector, receiver and piping performance parameters discussed in Section III.A., performance stairsteps were determined on an annual basis and at the design point (950 W/m^2 Insolation, Day 58) for the selected

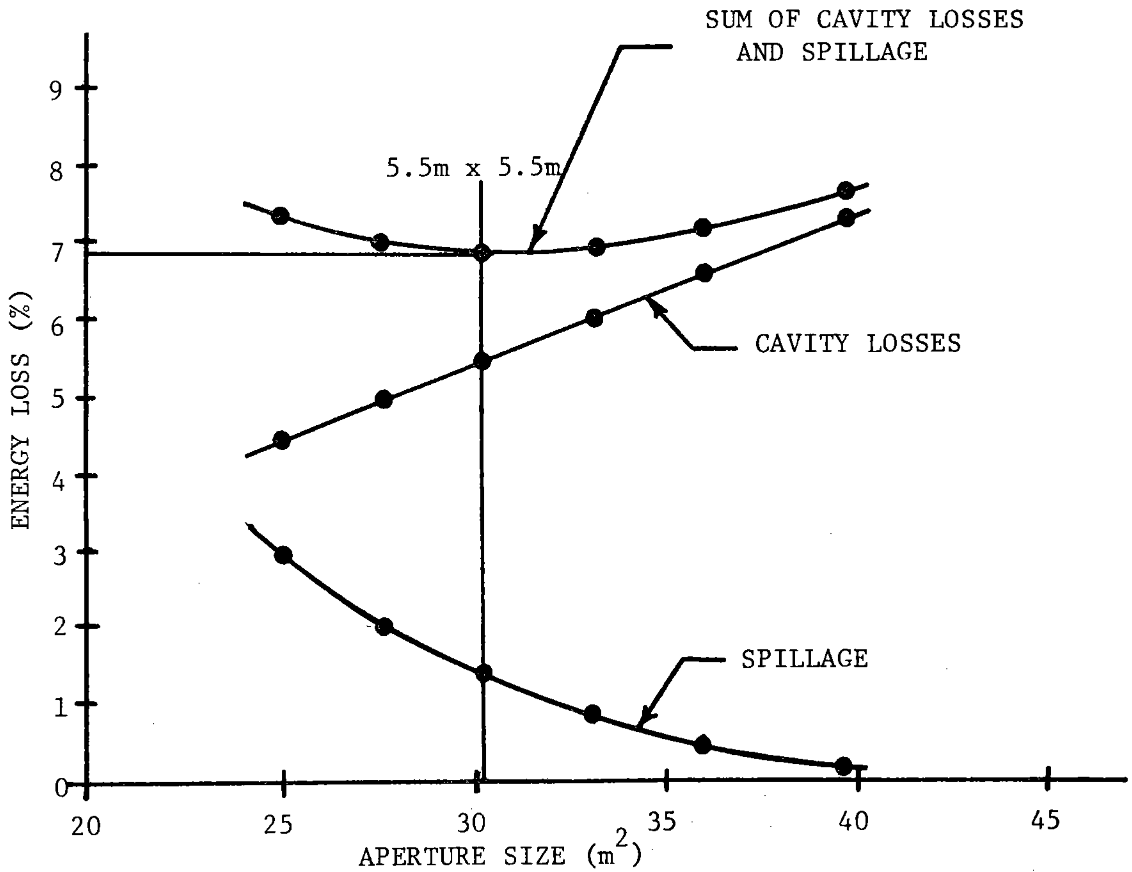

Figure 21 Aperture Sizing

Kern River Site. These performance stairsteps are shown in Figures 22 and 23, respectively. The annual energy derived from the solar subsystem, as shown, is 55,870 MWHt (190,684 MBtu) at an annual system efficiency of 61.46%. The design point stairstep shows an overall system efficiency of 78.67%, producing 30.0 MWt (102.6 MBtu/hr) at 950 W/m^2 insolation.

C. SOLAR RETROFIT SYSTEM ECONOMICS

To enable preliminary assessments of the selected STEOR system configurations, preliminary capital and operating and maintenance cost estimates have been made, the economic environment peculiar to the site owner has been defined, fuel cost projections have been researched and an economic methodology has been developed. In the following sections each of these will be discussed, along with the results of preliminary cost effectiveness assessments.

1. Capital Cost and O&M Cost Estimates

Based on the conceptual design described in Section III, preliminary capital costs for the major subsystems have been estimated and are shown in Figure 24. As shown in the figure, the major portion of the capital cost (>60%) is in the collector subsystem, using an installed heliostat cost of $\$230/m^2$, at DOE/SLL direction. The receiver cost has been based on the preliminary design of the 2 cavity configuration. The tower cost, for a 90 m steel tower, was calculated using the tower cost model developed by Sandia-Livermore based on the work performed by Stearns-Roger detailed in "Tower Cost Data for Solar Central Receiver Studies" (Contract 18-8446). For this analysis, indirects and contingencies have been estimated as a percentage of the plant cost, exclusive of the collector field.

Operations and Maintenance costs have been estimated at just under $150,000 per year. This includes heliostat maintenance and washing at $\$1.10/m^2$/year, receiver maintenance of 1% of the receiver subsystem cost, allowance of $36,000/yr for heliostat removal and reenplacement for oil well operations, and $20,000 per year for steam line placements and maintenance. Also, yearly electrical energy requirements for the solar retrofit operation has been identified as approximately 835,000 $kWhr_e$ for feedwater pump operation and 125,000 kWh_e for heliostat field operation (including stow operations(.

The capital, operating and maintenance cost estimates, fuel and electric requirements for the existing process are shown in Table 13 (1980 $).

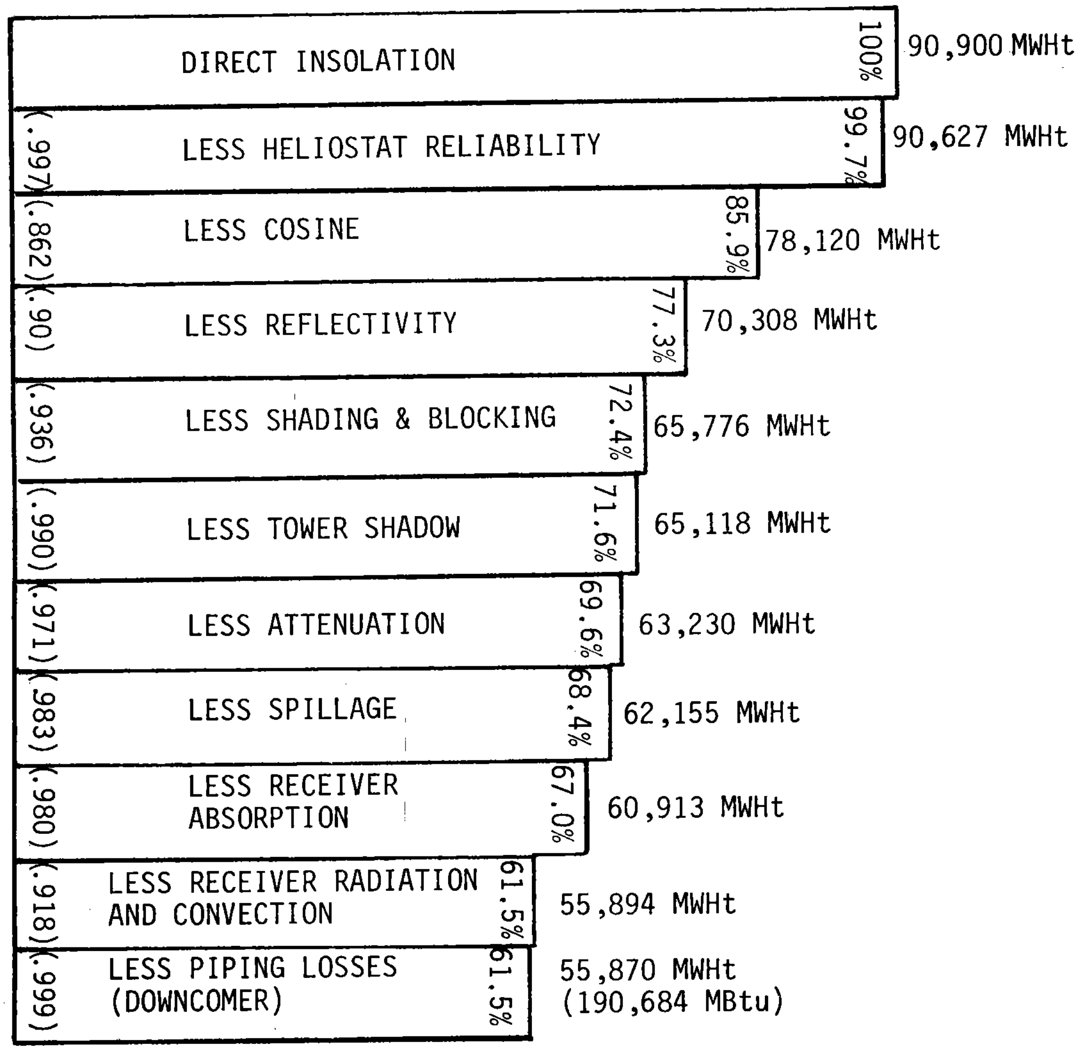

Figure 22 Annual Efficiencies, Fresno Insolation

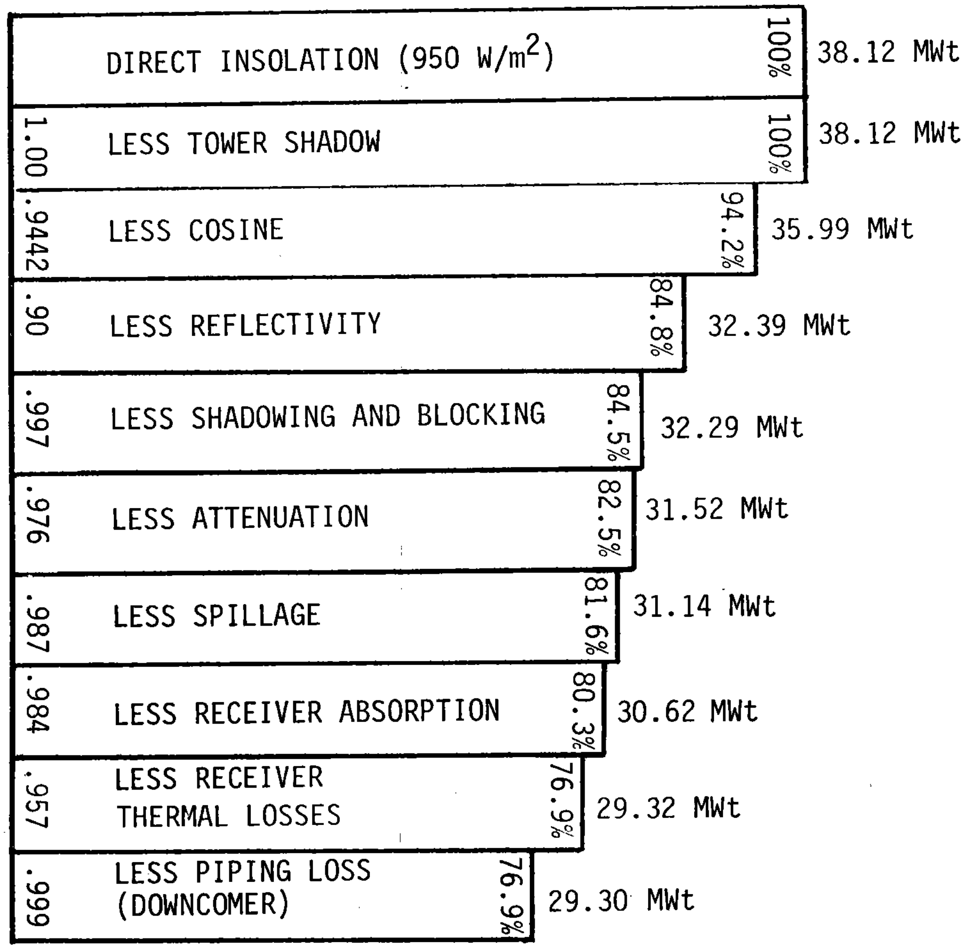

Figure 23 Design Point Efficiencies, 950 W/m² Insolation (Day 58, Noon)

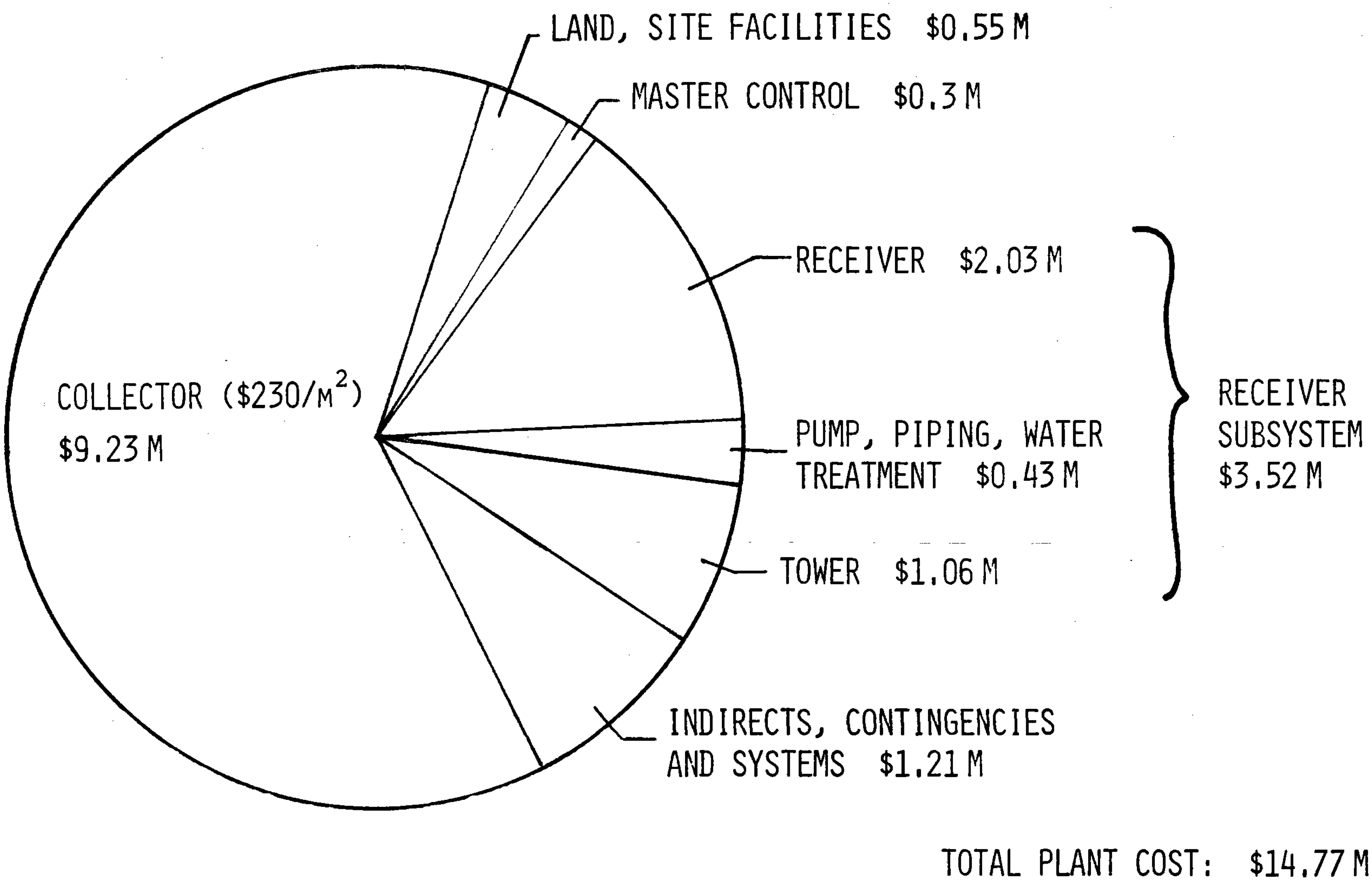

Figure 24 STEOR Capital Cost Estimates

Table 13 Cost and Performance Summary

	STEOR	Thermoflood-25
Capital Cost	\$14,767,000	\$667,000
Yearly O&M	\$146,300	\$147,300
Yearly Electrical Req.	960,000 kWh_e	1,690,000 kWh_e
Yearly Fuel Req.	-0-	70,810 MWt
Yearly Performance	55,870 MWt	55,444 MWt

2. Economic Environment for Assessment

The baseline (Exxon) economic parameters for evaluation of the STEOR system are shown in Table 14.

Table 14 Baseline Solar Economic Parameters

System Life	26 years
Initial Year of Operation	1985
Rate of Return	15%
Depreciation Life	11 years
Depreciation Method	ADR
Investment Tax Credit	28.1%
Composite Tax Rate	50.86%
Insurance and Property Tax	2.25%

The investment tax credit rate shown of 28.1% is made up of several separate, but interrrelated tax credits. Simplified, this credit is made up of 10% Federal investment tax credit, 10% energy tax credit under the 1978 Energy Tax Act and 8.1% California tax credits. Associated with these credits and the other baseline parameters, a fixed charge rate ($\overline{FCR}$) on capital can be calculated to be 0.092. However, there exists varying interpretations and expectations of the various tax credits, yielding possible tax credit levels of 30.4% and 33.1%. These three levels will be used in the assessment to determine the sensitivities in the assessments.

In order to quantify the value of the fuel displaced by the STEOR system, it is necessary to come up with realistic fuel costs and escalation rates. Table 15 details the fuel costs and escalation rates used in these preliminary assessments.

Table 15 Fuel Cost/Escalation Assumptions (1980 $)

	Exxon	DOE
Rate of General Inflation	7%	8%
Capital Escalation Rate	7%	8%
O&M Escalation Rate	8%	8%
Fuel Cost (Oil)	$3.83/MBtu*	$4.00/MBtu
Oil Escalation Rate	10%*	12%

*From National Energy Plan - II (NEP II), not an Exxon forecast

The fuel cost of $3.83/MBtu reflects the NEP-II forecast of $24.00/bbl oil in 1982 (1980 $), de-escalated to 1980. The DOE fuel costs were provided by Sandia-Livermore in Technical Memo #6 in order to ensure a consistent assessment between alternative technologies.

3. Economic Assessment of Selected STEOR Configuration

The methodology used in the assessment of the solar retrofit economics differs from the traditional required revenue methodology that has been used for solar thermal systems in the utility environment. For this EOR application, the after-tax levelized energy cost was calculated. An after-tax fixed charge rate was calculated by:

$$FCR_{AT} = (1 - \tau(DPF_{SD,11}) - \alpha)\ CRF_{.15,26}$$

where τ is the tax rate for depreciation; $DPF_{SD,11}$ is the depreciation factor for sum-of-the-years digits for 11 year depreciation life; α is the investment tax credit level and CRF is the capital recovery factor at 15% rate of return over the 26 year system life.

The levelized energy cost is then calculated by

$$\overline{EC} = (FCR \times CI_{pv}) + (1 - \tau)(CRF_{.15,26})(OM_{pv} + ELECT_{pv} + FUEL_{pv})$$

where τ is the composite tax rate and the subscripted variables are the present values of the capital investment (CI), operations and maintenance cost (OM), electricity cost (ELECT) and fuel costs (FUEL) over the life of the system at the first year of operation.

Using this methodology, the capital costs, the economic parameters and the fuel costs discussed in the previous sections, preliminary economic analyses of the STEOR conceptual design have been made for the baseline 26 year system lifetime and for varying system lifetimes. Figure 25 depicts the levelized energy cost (in 1980 $) for the STEOR system using the three alternative tax credit levels as a function of system operating period. Also shown are the levelized energy costs associated with a conventional oil-fired steamer for the two fuel cost/escalation scenarios, identified as NEP-II fuel cost and DOE fuel costs. As shown in the figure, using NEP-II fuel cost forecasts, the STEOR system (using $230/m^2 heliostat cost), shows a breakeven with the conventional steamer between 21 and 28 years, depending on the level of tax credits assumed. However, using the DOE-supplied fuel cost and escalation, the breakeven system life is reduced to between 14 and 18 years, again depending on the level of tax credits.

Table 16 summarizes the levelized energy costs for both the solar and conventional systems at the projected 26 year system life for the two fuel cost assumptions and three tax credit cases. Under the conventional steamer levelized energy costs, the annualized costs (AC_{oil}) of the oil burned only is shown, depicting the large percentage of the total energy cost due to fuel cost in the conventional system.

Table 16 STEOR Economic Analysis Summary (26 Year System Life)

Conventional Oil-Fired Steamer		Solar Thermal EOR System	
$3.83/MBtu, 10%	$4.00/MBtu, 12%	28.1% Credits	$8.08/MBtu
$7.84/MBtu ($\overline{AC}_{oil}=\$6.41$/MBtu)	$10.04/MBtu ($\overline{AC}_{oil}=\$8.61$/MBtu)	30.4% Credits	$7.47/MBtu
		33.1% Credits	$7.16/MBtu

In summary, these preliminary analyses have shown that the STEOR system that has been developed is a cost-effective application of the solar central receiver concept. These analyses will be further refined and expanded in the remainder of Task 5; however, we do not expect any significant changes in the cost effectiveness of the STEOR concept.

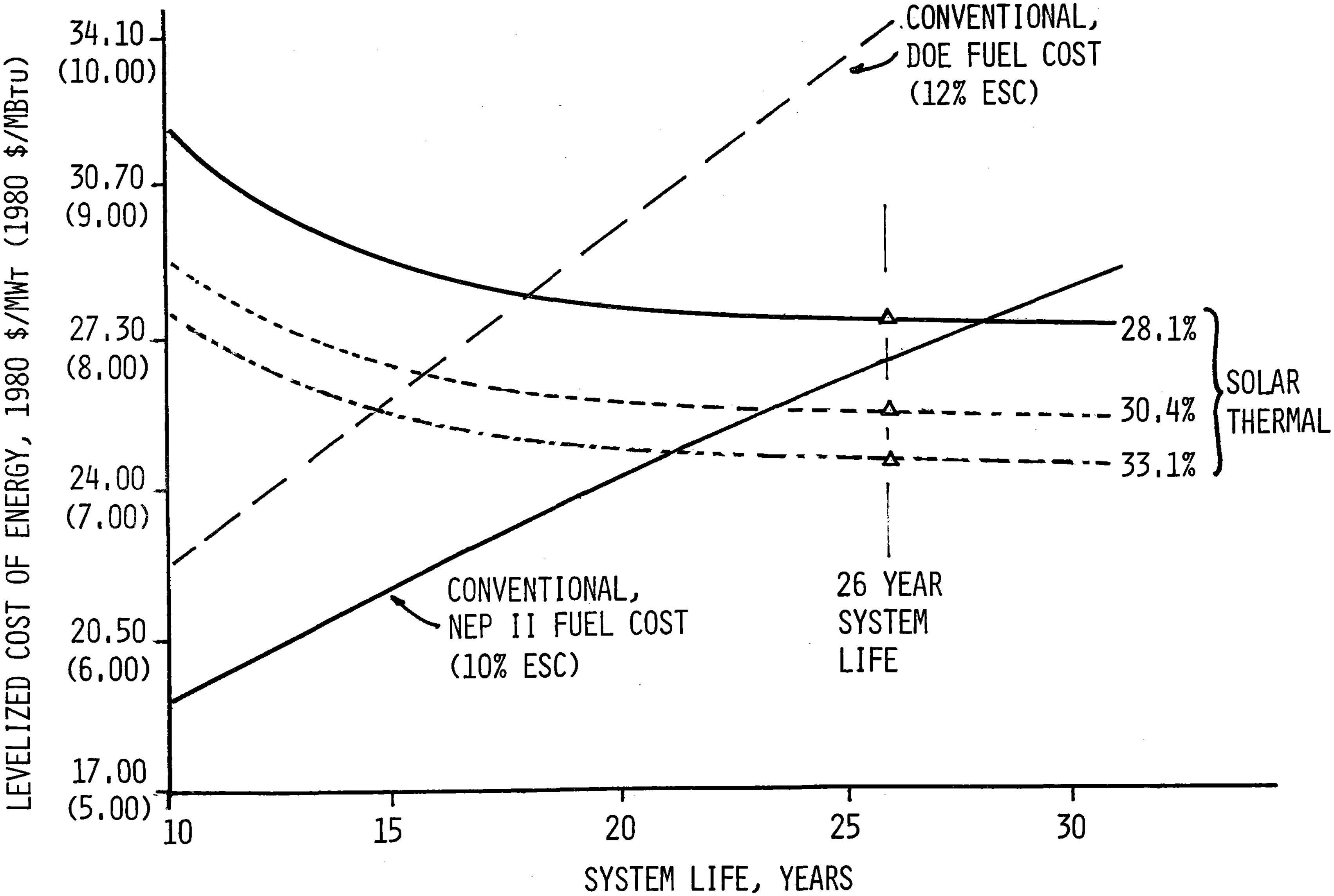

Figure 25 Solar Thermal/Conventional Breakeven Analysis

APPENDIX A

REPOWERING/INDUSTRIAL RETROFIT

SOLAR THERMAL ENHANCED OIL RECOVERY PROJECT

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