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Assessment of Central Receiver Solar Thermal Enhanced Oil Recovery Systems

Thermal Power Systems
5031 W. Red Rock Drive
Larkspur, Colorado 80118

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185
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ASSESSMENT OF CENTRAL RECEIVER SOLAR THERMAL ENHANCED OIL RECOVERY SYSTEMS

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Prepared for Sandia National Laboratories
under Contract No. 98-3601

ABSTRACT

In November 1982, ARCO Solar, Incorporated, with the cooperation of ARCO Oil And Gas Company, completed installation and began operation of a central receiver solar thermal pilot plant to produce steam for enhanced oil recovery. The highly automated plant can produce approximately one megawatt of thermal power in the form of 80 per cent quality steam, which is delivered to a distribution header for injection into heavy oil formations.

An engineering evaluation of data from the ARCO plant has been performed, with the the conclusion that central receiver solar systems can be very effective sources of power to generate steam for the enhanced recovery of heavy oil. The highly automated pilot plant exhibited outstanding reliability of the solar power conversion components while operating routinely with a single attendant, demonstrating the capability for very low operating and maintenance costs for these systems relative to the use of conventional oil-burning steam generators.

This document reports the operating and performance characteristics of the ARCO solar thermal enhanced oil recovery (STEOR) system over a full year of operation. System sizing and performance projection for a much larger commercial plant is also presented.

SOLAR THERMAL TECHNOLOGY
FOREWORD

The research and development described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100 deg C in low-temperature troughs to over 1500 deg C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To be succesful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Component and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assesssing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

This report describes the operation and performance of the ARCO Solar thermal enchanced oil recovery plant. The ARCO facility, a privately funded 1 MWt pilot plant, uses central receiver technology to generate steam for the enhanced recovery of heavy oil. Plant data for a full year of operation are analyzed, and performance projections are provided for a much larger commercial-size plant.

ACKNOWLEDGEMENTS

This document is presented in fulfillment of P.O. 98-3601, a consulting contract issued by the Sandia National Laboratories. Project management at Sandia Laboratories was provided by Alan Skinrood and Scott Faas. Much of the information contained herein was derived from data provided by ARCO Solar, Incorporated, obtained from operation of the ARCO Fairfield solar thermal enhanced oil recovery facility. This facility was designed, installed and operated by ARCO Solar, Incorporated, with no government funding involved. The courtesies and assistance of ARCO Solar management and personnel made this data transfer and report possible, and is very much appreciated.

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EXECUTIVE SUMMARY

The thermal process of injecting steam into the ground for enhancing the production of heavy crude oil has long been viewed as an attractive application of central receiver solar thermal technology. This process requires large quantities of sub-saturated steam at pressures in the general range of 300 to 800 psig (temperatures from 420 to 520 deg F). A central receiver plant can be utilized in a variety of configurations. A simple water/steam receiver system with no thermal storage can be installed to generate steam on the basis of insolation availability, or more sophisticated systems with thermal storage and electrical cogeneration capability can be beneficially used.

ARCO Solar, Incorporated installed and began operation of a pilot solar thermal enhanced oil recovery (STEOR) system in 1982, on a site within an existing steam injection operation of the Arco Oil and Gas Company. This report documents an operational and performance evaluation of that pilot system, and was made possible by an agreement between ARCO Solar, Incorporated and the Sandia National Laboratories.

The ARCO STEOR system is located in Kern County, California, which is the world's most prodigious area of heavy crude oil production by the steam injection process. The plant was designed to produce a maximum 1 MW of thermal power in the form of steam at up to 1000 psig and 80 per cent quality for injection into an existing field distribution header. The design point flowrate of 3500 lb/h is about 10 per cent of the normal steam flow supplied by two gas-fired steam generators to the header. The system is powered by 30 heliostats of 52.8 m2 reflecting area, designed and fabricated by ARCO Solar, Incorporated. The collector field focuses upon a receiver which is a natural circulation water/steam boiler with a 10 ft x 10 ft absorbing zone. The receiver steam, flowing in a closed loop, is condensed by delivering its energy to a secondary circuit which generates steam for oil field injection. The system operates in an automatic mode under command of a computerized master control system, with a single attendant on duty to monitor the operation and perform routine inspection, maintenance and repair functions. First heat was applied to the receiver in November 1982 and the plant was in routine daily operation six months thereafter.

Data recorded during operation over a twelve month period was reduced, analyzed and evaluated to assess plant performance over a long term production period. Particular attention was devoted to studies of insolation, equipment maintenance and repair, operational factors, energy and steam production and evaluation of system losses. The refined data resulting from pilot plant operation was correlated with the output of a

computer simulation of the system, which was then used to project the required size and the performance characteristics of a solar plant equivalent to a 50 MBtu/h oil fired steam generator.

The ARCO Solar, Inc. STEOR installation provided a valuable experience base for the continuing development of central receiver technology as an energy source of the future. This system demonstrated outstanding reliability and operational characteristics, not only relative to the developmental nature of the project, but also as compared to conventional oil field steam generators which are typically inoperative 30 per cent of the time for maintenance and repair. Steam was delivered to the oil field on 230 of the 366 days of the evaluation year. The plant was idled only 20 full days of the year by problems within STEOR system hardware, and was down for five days for a mandatory annual inspection. Two days were lost due to maintenance activities in the oil field. Weather was the major reason for non-production, as the lack of insolation prevented operation on 70 of the 136 inoperative days. The facility was unattended for various reasons on 39 days.

Total energy production for the year was 688 MW-h during 1280 hours of steam injection, for an average power output of .54 MW. The system delivered 2,796,620 pounds of steam to the oil field at an average flowrate of 2,185 lb/h. Analytical projections were made to estimate the year's performance if the system had been operated to its full potential (i.e., full operator availability and reduced equipment outage). Using actual average operating insolation and system performance values extrapolated over an additional 41 days of operation (271 days total) plant energy potential was determined to be 789 MW-h contained in 3,223,860 pounds of injected steam, which is 51 per cent of maximum theoretical performance based upon 366 days of operation with no down time due to weather or other causes. Insolation during the year was significantly below average for the area, as was the case at the Solar I facility (approximately 170 miles east of the Fairfield site). It would be expected that system operation over a multi-year period would result in even better average performance than the projections have indicated.

A transient computer model of the ARCO STEOR system was used to simulate operation for several days during the pilot plant evaluation year. The simulated performance correlated very closely with actual data produced on each of those days. The math model was then used to perform a preliminary sizing study for a larger system representative of a commercial plant. It was determined that a 50 million Btu/h oil fired EOR steam generator could be replaced with a central receiver system powered by 585 heliostats of 148 m2 size. The capital cost for such a system was estimated to be about 25 million dollars, based on heliostats at $160/m2.

The primary conclusion of this project is that the ARCO Solar, Incorporated pilot plant demonstrated that central receiver solar technology can provide an effective source of energy for thermal enhanced oil recovery operations. The system is reliable, and the solar-specific equipment performed well. Furthermore, the successful use of a highly automated control system proved that such systems can be operated with only minimal human supervision, and very likely can be developed as an unattended facility. This type of system with its direct steam generating receiver is capable from a technical perspective of immediate utilization in large commercial heavy oil recovery projects, particularly as a means of expanding production without using air pollution offsets, or to create offsets by retiring existing oil fired steam generators. In order to enhance operational flexibility and economic potential, the development of designs using thermal storage and electrical cogeneration capability should be pursued for future use.

I INTRODUCTION

This report presents the results of 1) an engineering evaluation of operational and performance characteristics of a central receiver solar thermal enhanced oil recovery (STEOR) pilot system which was designed, constructed and operated by ARCO Solar, Incorporated, and 2) an extrapolation of the ARCO experience to generate size and performance projections for a larger plant representative of a commercial installation.

The ARCO Solar STEOR facility is situated on the Fairfield lease, a producing heavy oil field which is owned and operated by ARCO Oil and Gas Company. The Fairfield lease is located in the western extreme of Kern County, California (Figure I-1), and is a part of the oil producing region generally known as the Midway-Sunset field. This area was first developed as a source of light crude oil around the turn of the century. Subsequently, the light crude was largely depleted and the Midway-Sunset field is now produced predominantly by use of the steam injection process. Production of the Fairfield lease is totally dependent upon steam injection.

The Fairfield STEOR project was sponsored and financed by ARCO Solar, Incorporated, with the cooperation of ARCO Oil and Gas Corporation who furnished the site and technical support necessary for interfacing the STEOR output with the ongoing steam EOR activities within the Fairfield lease.

A. BACKGROUND

A large portion of the known petroleum reserves in the United States and throughout the world is in the general category of "heavy" oil, which is crude oil that is highly viscous (below 20 deg API) and cannot be extracted from the ground by conventional pumping alone. Crude oil in its natural state is highly variable in composition and viscosity, even within a common formation. Production from a newly developed field will preferentially deplete the lighter crude first, simply because it will migrate to the production wells more rapidly than the heavier fluid. Over a period of years production rates fall as the viscosity rises, until it is no longer profitable to produce the field in the conventional manner. At this point a large fraction of the resource usually remains in place, requiring more advanced secondary or tertiary techniques for economic production.

Many techniques for the enhancement of heavy crude oil production have been conceived, including the injection of chemicals, gases, water and steam. The choice of method for a specific production application may depend upon a combination of factors, such as the physical nature of the

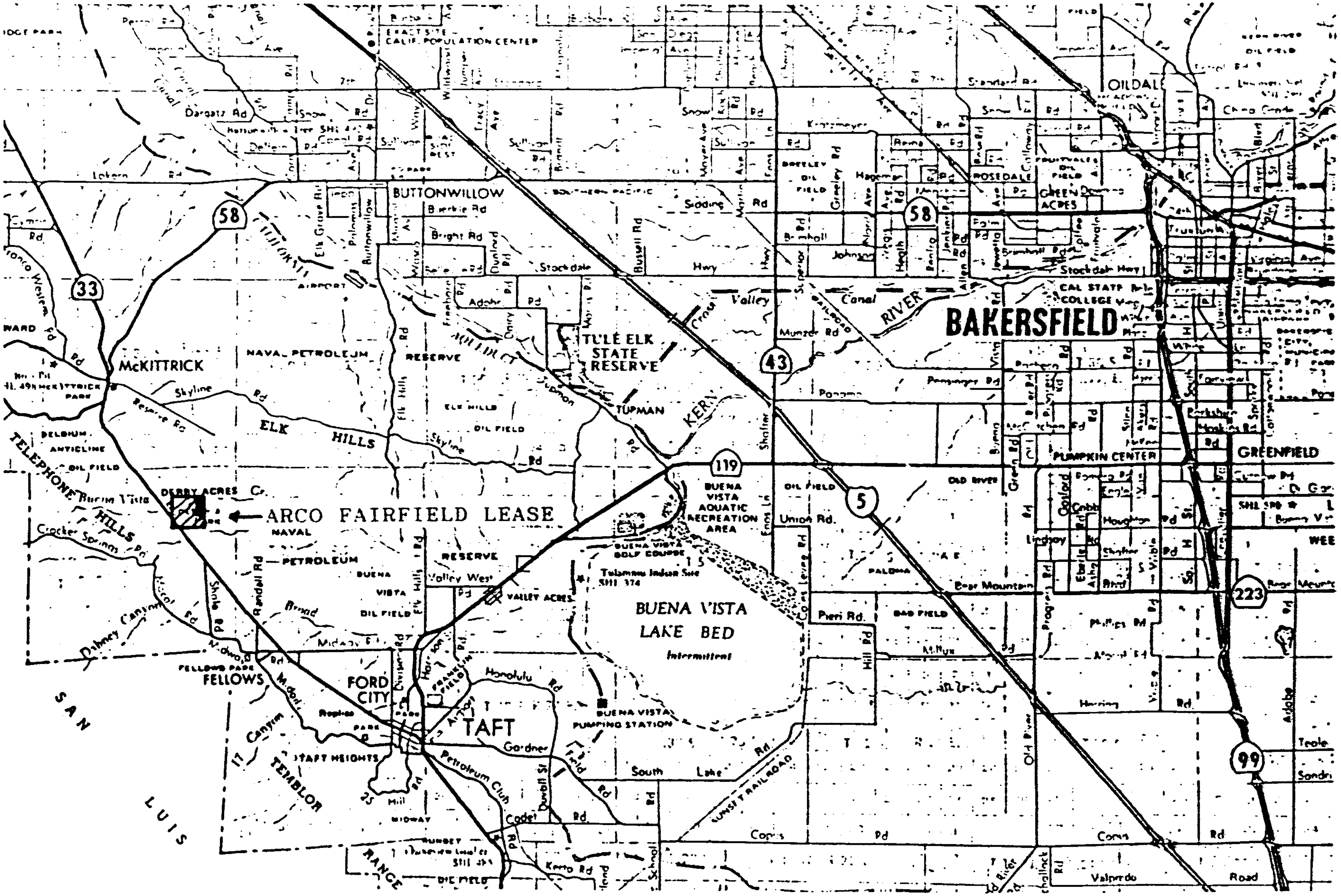


FIGURE I-1 ARCO FAIRFIELD STEOR SITE LOCATION formation, composition and viscosity of the crude oil and the local availability and cost of materials for use in the process.

The method most widely used for enhanced oil recovery (EOR) operations throughout the world today is the injection of steam into the formation, which reduces the viscosity of the oil by heating and dilution and also provides pressure to assist migration of oil through the formation to the production well sites. Steam is injected either continously into dedicated injection wells interspersed throughout the oil field or intermittently into production wells, as dictated by the relative effectiveness of each mode in a specific production environment.

Most of the oil field steam generators in use today are fired with crude oil, due largely to its ready availability. Natural gas is used by producers who have access to an adequate source because of its cost advantage in today's climate of energy economics. Regardless of which fuel is used, however, the energy consumption related to this means of oil production is very high. Up to one third the energy content of the oil produced is used to generate steam for the process. In the case of crude oil fired units, the raw combustion products are very high in atmospheric pollutants resulting from the high content of natural contaminants (such as sulfur). This can necessitate the use of expensive stack gas treatment equipment which reduces system operating efficiency.

The region of most extensive steam EOR production in the world today is Kern County, California, where an estimated 80 per cent of the world's steam EOR operations are conducted. Located in the southern tip of the San Joaquin Valley, the county's major city is Bakersfield, which is the center of the area's petroleum and agriculture industries. The extensive use of oil field steam generators, coupled with the presence of mountains on three sides, has created a very severe air polution problem in the county. In order to prevent further deterioration of the atmospheric environment, the concept of "emissions offsets" is being enforced in Kern County. Simply put, this regulation prevents an operator from increasing the total emissions produced by his operations unless he removes from service (or has done so in the past) equipment producing an equivalent emissions load. This restriction together with the absence of adequate natural gas in the area effectively precludes the expansion of existing oil production operations and the development of new fields using conventional steam EOR methods.

The use of solar energy to replace the fossil fuels presently used to generate EOR steam can potentially increase the net production of crude oil from steam injection EOR operations by up to 50 per cent while concurrently making a substantial reduction in the air polution problem.

B. SYSTEM DESCRIPTION

The ARCO STEOR facility was designed to produce steam at up to 1000 psig for use in enhanced oil recovery operations. The process must be controlled to produce wet steam at a maximum quality of 80 per cent (water content of 20 per cent). The feedwater generally available to supply the steam EOR operations is usually very high in dissolved solids content, and there must be sufficient water in the steam to prevent deposits from forming in the steam generation and distribution system.

Project management was provided by the ARCO Power Systems division of ARCO Solar, Incorporated. ARCO Power Systems also performed the analysis, design, construction, startup and early operation of the plant. Major subcontractors were Struthers-Wells Corporation, which supplied the receiver and mechanical equipment components, Electronic Metal Products Corporation, which fabricated the heliostat pedestals and mirror support structures, and Microflect Corporation, which supplied the tower upon which the receiver was mounted.

Since the intent in constructing this facility was to demonstrate state-of-the-art solar power conversion technology capable of immediate entry into commercial markets, a water/steam receiver was selected over the use of sodium/potassium salts, sodium or other thermal absorption media. A receiver must operate at high radiant heat flux intensities for high efficiency, which is not considered to be compatible with the dissolved solids content of the available water. This problem was circumvented by using a dual water/steam circuit process, which will be described in detail.

The steam produced by the ARCO STEOR facility is piped into an existing distribution header on the Fairfield lease where it is mixed with the output of two conventional gas-fired steam generators and routed to the various reservoir injection wells. The STEOR pilot plant can supply up to about 10 per cent of the steam normally flowing in the header. Operating pressure in the header is in the range of 400-500 psig, so the STEOR system output is normally set at 600 psig.

This project was conceived early in 1981. By June of 1981 the system design was completed and bid solicitations for key items of hardware were issued. Supplier contracts

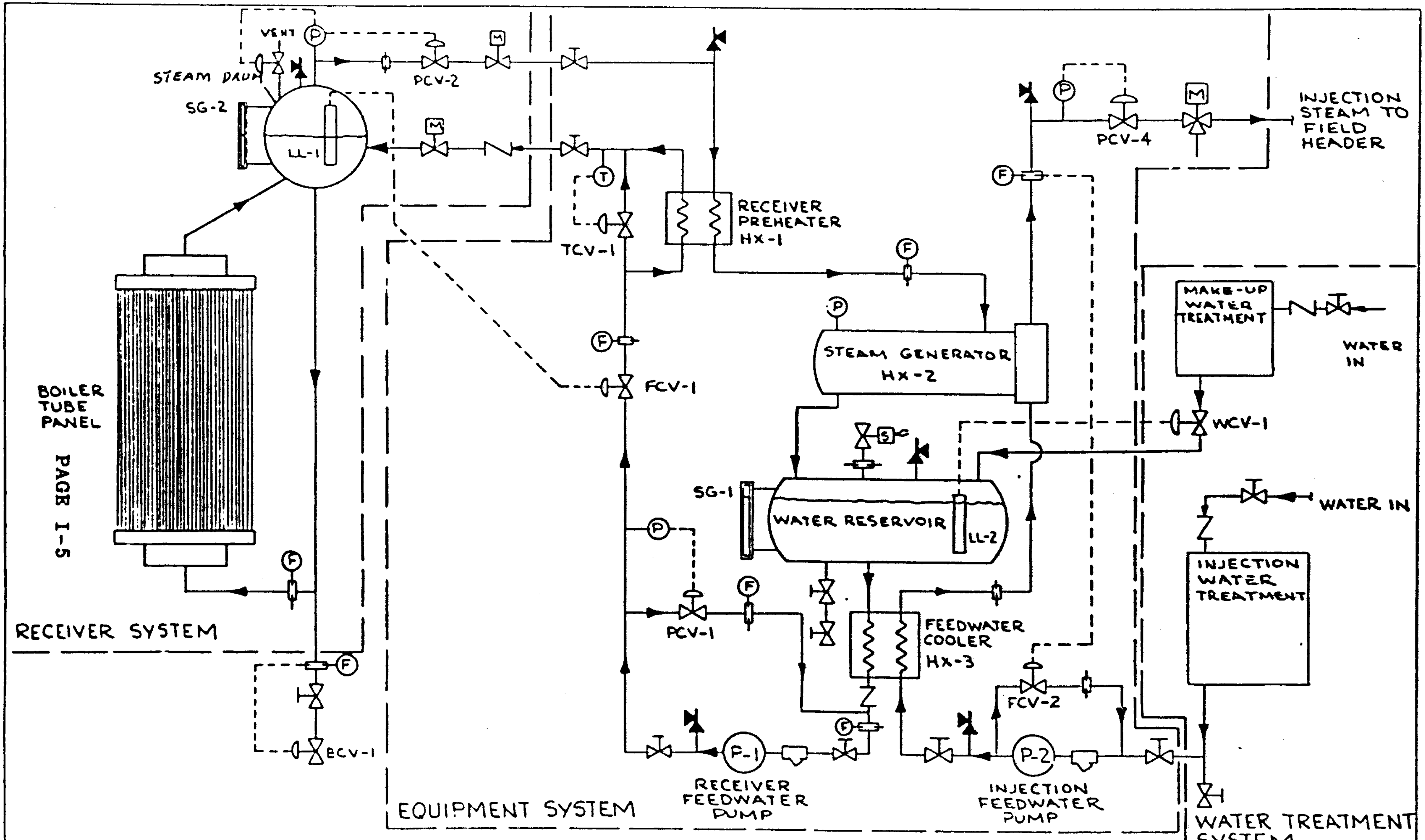


FIGURE I-2 SOLAR THERMAL ENHANCED OIL RECOVERY – SYSTEM SCHEMATIC were solidified during the last quarter of 1981, and on-site construction activities began in January 1982 with preparations for assembly of heliostat rack assemblies. Installation of the heliostat field and receiver tower was completed in May 1982. The receiver, heat exchangers, pumps and water equipment were delivered to the site in mid-August, and their installation, checkout and activation were completed in time to deliver the first solar produced steam to the Fairfield lease on 19 November 1982.

The ARCO STEOR system consists of 4 major elements: the collector, the receiver, the mechanical equipment, and the control subsystems. Two separate water/steam circuits are used, as shown in the schematic of Figure I-2. The receiver circuit, exposed to high heat flux intensities in the receiver boiler, operates in a closed loop with a small make-up water addition to compensate for leakage and blowdown losses. The injection circuit, subject to much lower heat flux levels in the condenser/boiler, requires less costly water treatment and supplies steam to the oil field distribution header.

1. COLLECTOR SUBSYSTEM
   The collector field, shown in the photograph of Figure I-3, consists of 30 heliostats arranged in a 90 degree north quadrant. The heliostats are located in circular arcs (centered at the receiver tower) having radii of 100, 162.2, 197.5, 255.5 and 308.9 feet.

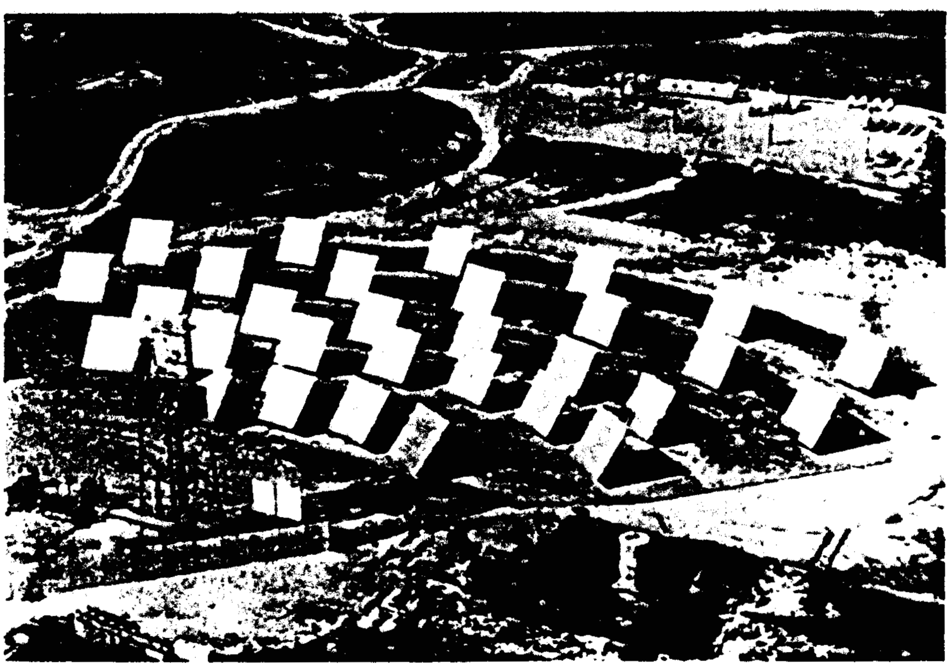


FIGURE I-3 AERIAL VIEW OF ARCO FAIRFIELD STEOR FACILITY

The heliostats (Figures I-4 and I-5) have a total area of 568 square feet (52.8 m2) on the 12 mirror modules having nominal dimensions of 4 feet by 12 feet. Mirror reflectivity is .83 in a clean condition.

A mirror module consists of two facets 4 feet by 6 feet in size. Facets for all heliostats are curved for a focal length of 250 feet. In order to use existing tooling, it was not possible to incorporate a continous curvature into the entire mirror module. The two facets on each module are canted slightly relative to one another to provide approximate beam alignment on the receiver during most of the operating day. Two different facet alignments were used, one having a focal length of 125 feet (used for the first three rows) and one having a focal length of 200 feet (used for the last two rows). This compromise in design resulted in quite significant aperture spillage during early morning and late afternoon operation, particularly in the late spring through early fall period. The mirror modules on each row of heliostats are canted to the slant range for the row, using on-axis canting strategy.

2. RECEIVER SUBSYSTEM

The receiver is a natural circulation steam generator configured to accept and convert the concentrated radiant energy projected from the collector field. It is mounted atop a 65 foot tower, as seen in Figure I-6, to provide clear beam paths from all the heliostats and minimize field cosine losses. The absorbing surface is a 10 foot square wall of 1 inch diameter vertically positioned boiler tubes. The entire receiver is insulated to restrict heat losses and includes an insulated door which slides up to cover the boiler panel during shutdown.

There are only three control elements associated with the receiver, as shown in Figure I-2. The control valve PCV-2 throttles receiver steam output to maintain receiver pressure in response to set point commands issued by the control computer and a steam drum pressure transducer. FCV-1 insures proper liquid level in the steam drum in accordance with level sensor LL-1 and set point commands from the control computer. TCV-1 maintains feedwater temperature by controlling bypass flow around HX-1 in response to the temperature sensor in downstream of HX-1 and setpoint commands from the control computer.

The water/steam mixture in the boiler panel collects in an upper header and flows up to the drum through riser tubes. Steam collects in the top half of the drum and exits the receiver while water in the lower part of the

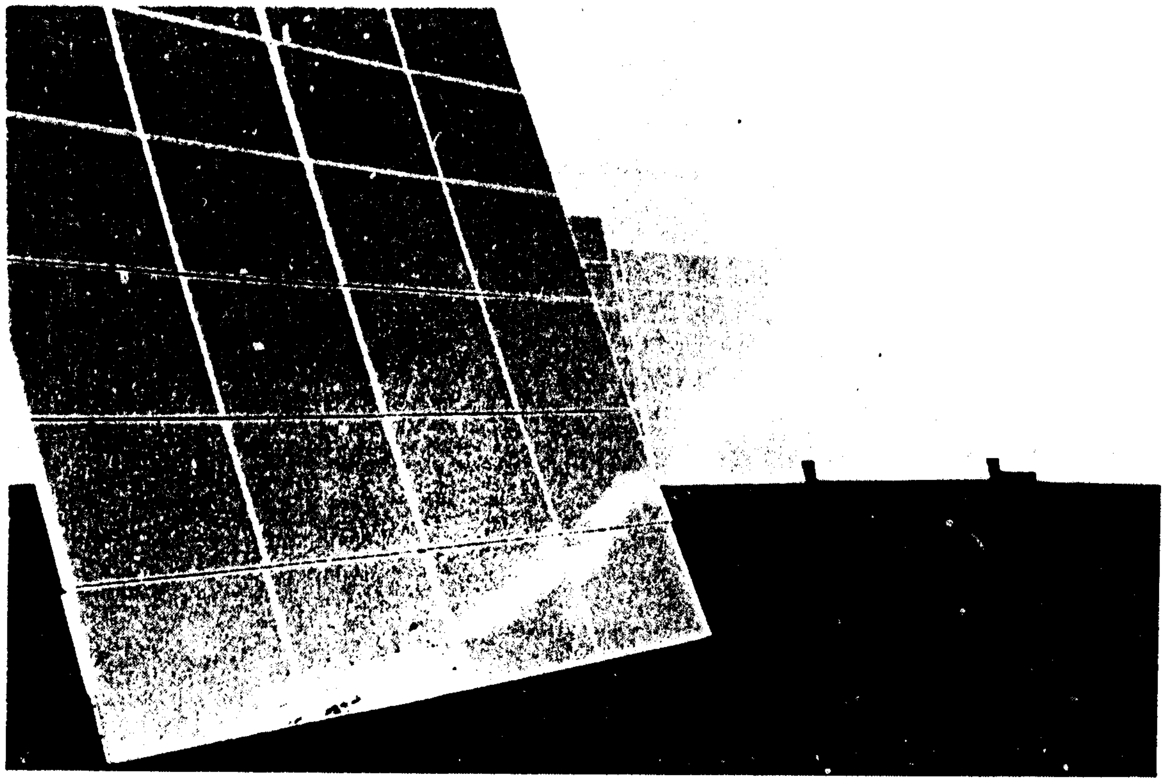


FIGURE I-4 FRONT VIEW OF HELIOSTATS

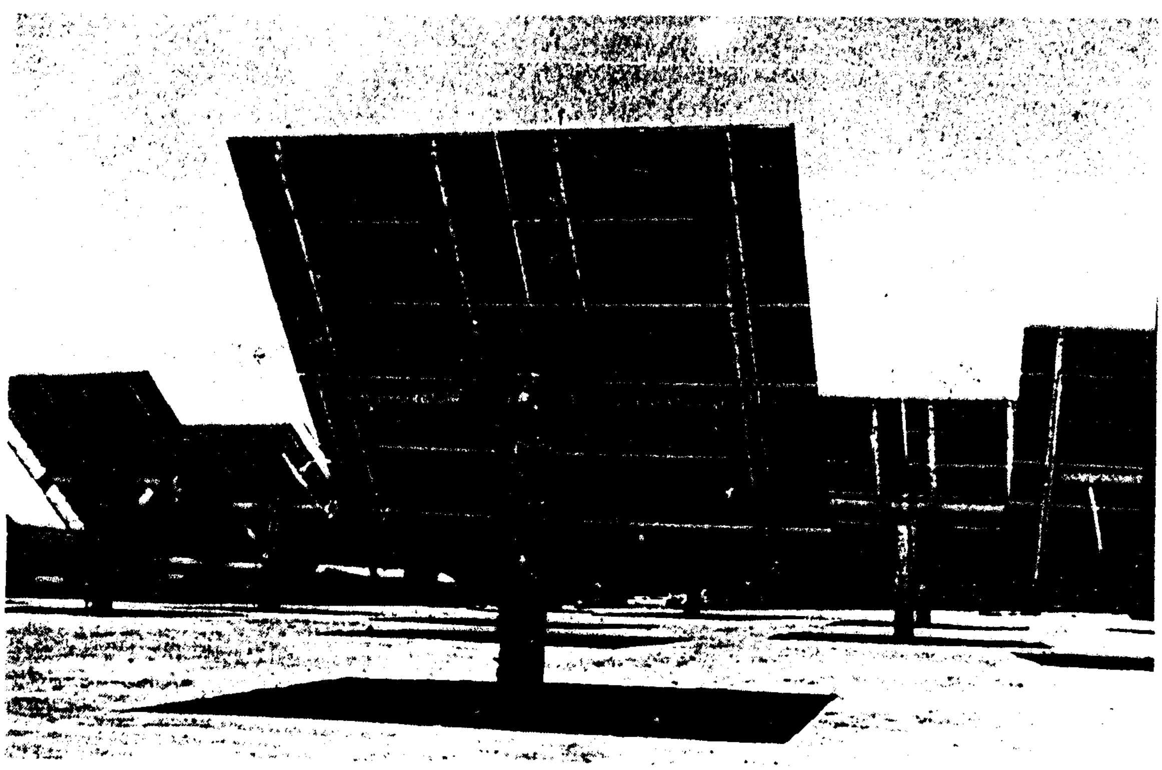


FIGURE I-5 REAR VIEW OF HELIOSTATS

FIGURE I-6 RECEIVER OPERATING DURING SYSTEM STARTUP drum recirculates through the downcomer and lower header back to the boiler panel. The recirculation flow is driven by the density difference between the water/steam mixture in the boiler panel and the single-phase water in the downcomer. Since this density difference is a function of heat absorbed, the recirculation flow automatically adjusts to variations in energy input, which completely eliminates the need for an active flow control system.

3. MECHANICAL EQUIPMENT SUBSYSTEM

This subsystem includes all water/steam treatment, transfer, heat exchange, pumping, valving and associated hardware (everything except the receiver subsystem in Figure I-2). All this equipment is installed on a concrete pad at ground level, as seen in Figure I-7. Referring to Figure I-2, HX-1 is the feedwater preheater for the receiver circuit which receives heat from the receiver output steam. A bypass line on the feedwater side includes a temperature control valve for maintaining desired drum inlet temperature. HX-2 is a "condenser/boiler" which generates injection circuit steam while condensing the receiver steam. The condensate reservoir provides a continuous supply of water for the receiver feedwater pump. HX-3 is a dual function heat exchanger which preheats the injection circuit water while lowering the receiver condensate temperature to a level acceptable for reliable pump operation. P-1 and P-2 are the receiver and injection circuit feedwater pumps.

FIGURE I-7 MECHANICAL SUBSYSTEM

The receiver makeup water treatment system includes series anion/cation demineralizers and chemical additions to remove all oxygen and control pH of the water. The injection circuit treatment system includes parallel mixed-bed demineralizers (with automatic re-generation capability) and chemical additions for oxygen and pH control.

4. MASTER CONTROL SUBSYSTEM

The master control subsystem consists of a master control computer, a collector field computer, a data display computer, a supervisory control console and a data acquisition system. These major control system elements and their interrelationship are illustrated in Figure I-8. The control system computers are shown in Figure I-9. The master control computer, on the right, is a Hewlett Packard 9826 with approximately 1 megabyte of RAM memory and a single 5 1/4 inch flexible disk drive used for permanent storage of operating data. The heliostat field computer is a Hewlett Packard 9825 and is on the left in the photograph. The computer in the center, also a Hewlett Packard 9825, controls the data display monitors which are located above the master control computer.

The supervisory control panel (Figure I-10) contains all control stations necessary to operate the receiver and mechanical equipment subsystems. It provides capability for manual control through operator input, or automatic control (the normal mode) under command of the master control computer.

In the normal operating mode all control and data acquisition elements (including the collector field and data display computers) are slaved either directly or indirectly to the master control computer. The master control subsystem provides total "hands-off" control capability in all operational regimes from startup through shutdown. Key operating parameters are continually monitored and potentially hazardous anomolies will trigger warnings and/or safe shutdown of the system as required. The master control subsystem also drives the data acquisition equipment for both real time display and data logging.

The routine daily operating sequence begins with recurring calculations of radiant power available to the receiver from the collector field, based on actual direct normal insolation and analytical simulation of system performance characteristics. The collector field is directed to track for a standby aim point just to the east of the receiver boiler panel. After the minimum startup power has been available for the specified continuous time span (to preclude false

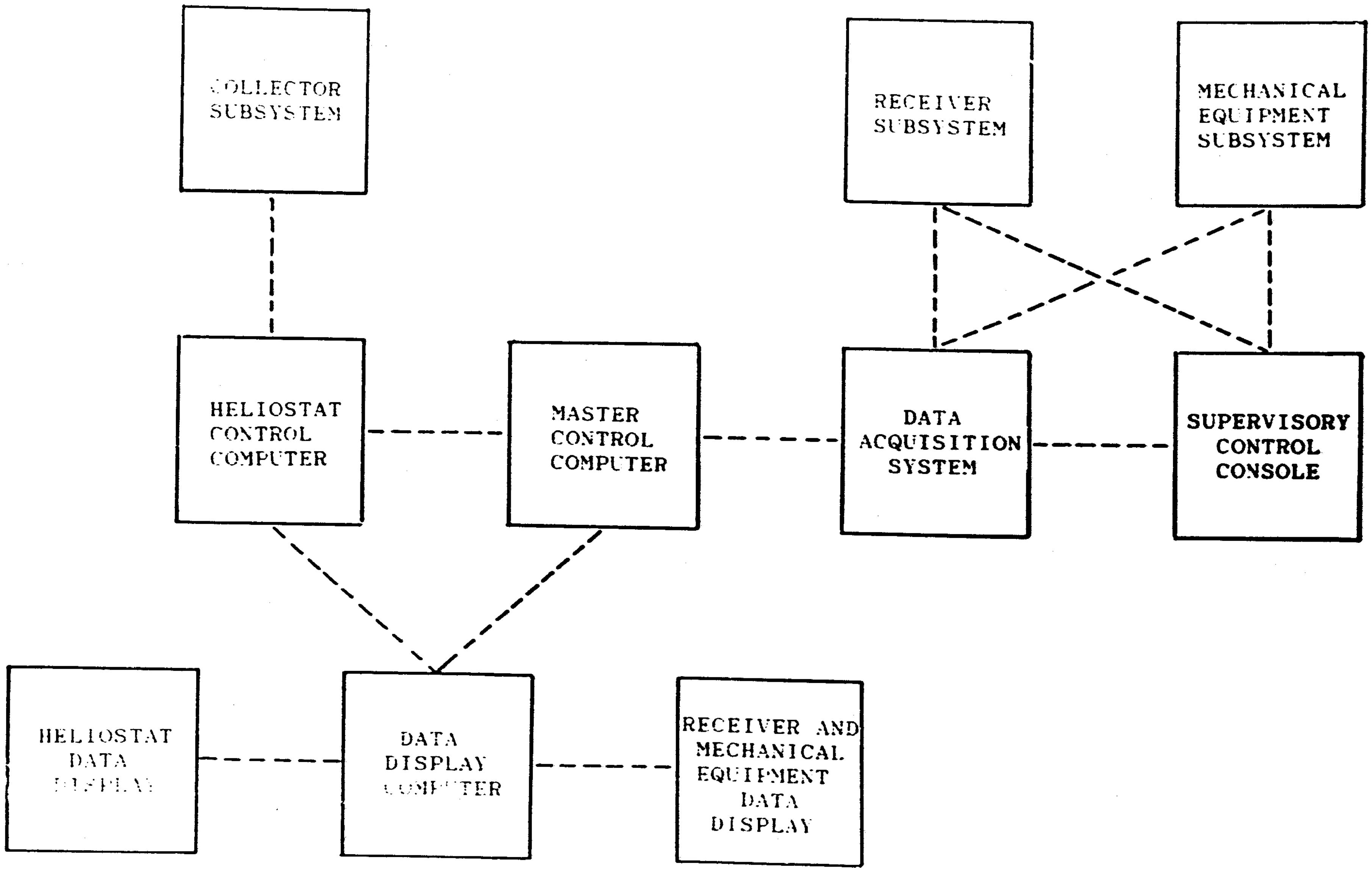


FIGURE I-8 STEOR CONTROL SUBSYSTEM SCHEMATIC

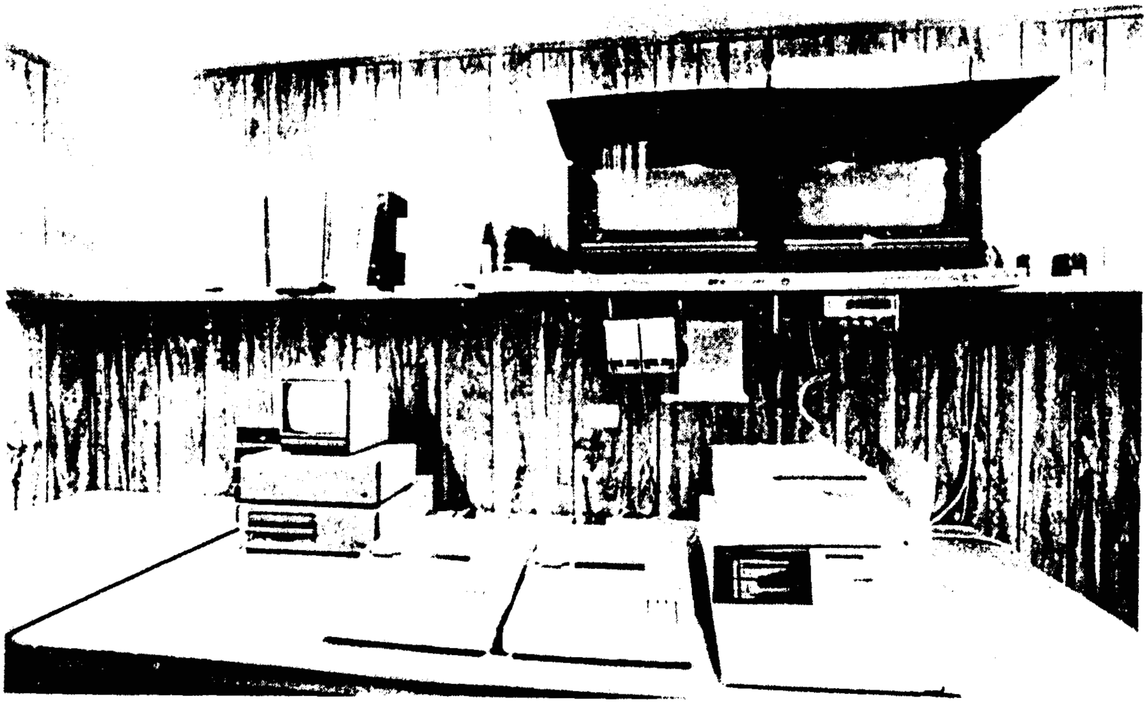


FIGURE I-9 STEOR SYSTEM CONTROL COMPUTERS

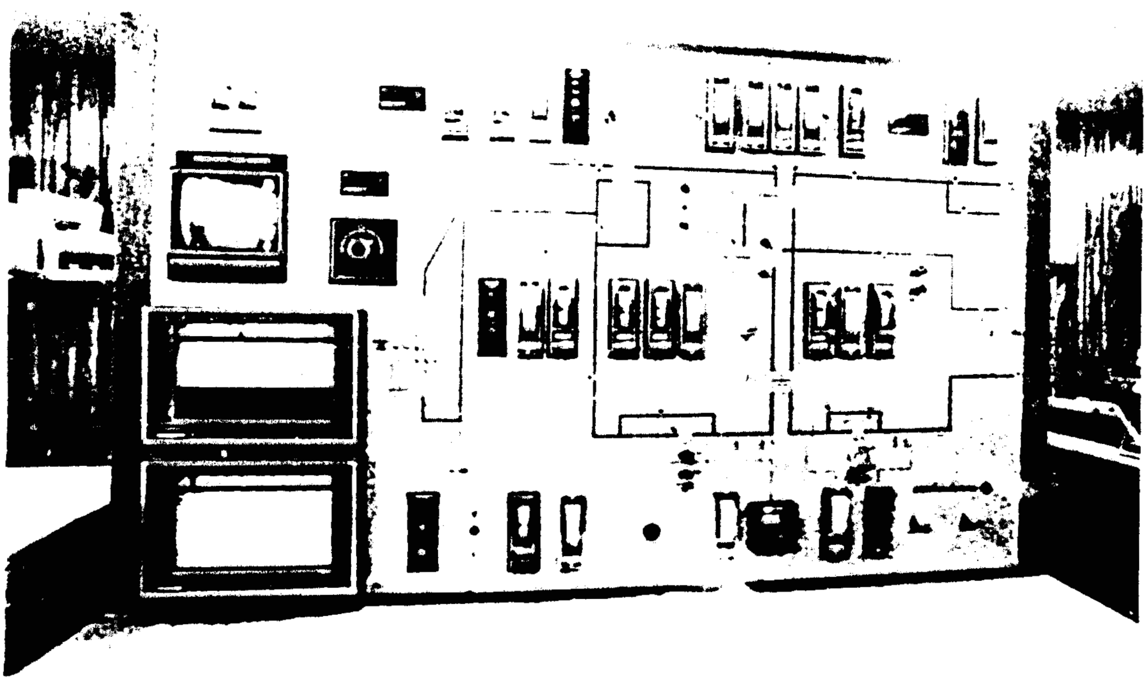


FIGURE I-10 SUPERVISORY CONTROL PANEL

starts in the presence of intermittent cloudiness), the master control computer triggers the startup sequence. The initial procedures are to initialize valve positions, start the feedwater pumps and ramp up pressures, open the insulated door of the receiver and direct heliostats onto the boiler panel in a prescribed sequence to begin system heatup. Two distinct heatup procedures have been used. The original heatup procedure entailed a sequential process of first heating the receiver to its specified temperature and pressure, then releasing receiver steam to begin heating the remainder of the flow circuitry and establish the required injection steam temperature. In order to reduce temperature gradients on heat exchangers and other pressure vessels, a parallel heatup procedure was instituted. In this mode, receiver steam is admitted to the entire flow circuitry soon after the heliostats are brought onto the receiver and the entire water/steam circuitry is heated concurrently. In both modes, once the injection circuit outlet temperature reaches the required value, steam is directed to the oil field distribution header. System operation continues until the master control computer determines that the system is receiving insufficient solar power to produce the minimum required injection steam conditions, at which point the shutdown sequence is executed. Throughout all phases of operation the master control system correlates system data values with defined warning and shutdown limits, and will initiate corrective action, issue alarms or trigger an immediate shutdown sequence as dictated by the particular situation.

Although this control system has demonstrated the capability for unattended operation, certain provisions of the California boiler regulations require that an operator be on site during operation of a drum-type boiler. For this reason, (as will be seen in Section II) this plant was not operated on days when an operator was not available onsite. On routine operating days, the operators duties were generally limited to periodic observations of key operating parameters, replenishment of water treatment chemicals once a day and performance of miscellaneous maintenance functions on a non-interference basis.

II OPERATIONAL HISTORY

Heat was initially applied to the receiver on 8 November 1982. Rated steam was supplied to the oil field distribution header for the first time on 19 November 1982. The next six months involved the many system operational checkouts and debugging normally entailed in the startup of a new process heat installation. The major activities during this period included the following.

1) Locating and fixing leaks in flanges,valves and fittings
2) Verification of instrumentation calibrations and functional checks
3) Checkout and adjustment of control actuators
4) Tuning of automatic control supervisory stations
5) Functional verification of water treatment equipment and adjustment of chemical metering rates
6) Development and checkout of the computerized master control system and software

Although these activities were significantly hampered by adverse weather conditons during the December-February period, the system was fully functional and routinely operating under automatic computer control by the end of May 1983. Through the remainder of 1983 and into early 1984, efforts were made to operate the system whenever weather permitted. Toward this end, a split-shift schedule was adopted to allow personnel coverage from sunrise to sunset during the summer and early fall months. Five periods of scheduled shutdown totaling 26 days were implemented.

NOV 6 - NOV 10	for annual receiver inspection,	5 days
NOV 24 - NOV 27	for Thanksgiving holidays,	4 days
DEC 24 - JAN 3	for Christmas holidays,	11 days
APR 20 - APR 22	for Easter weekend,	3 days
MAY 26 - MAY 28	for Memorial Day weekend,	3 days
	Total scheduled shutdown	26 days

By the end of May 1984 a gradual reduction in operation of the STEOR system had begun to occur. This resulted from the need to divert more manpower to the Arco Solar/PG&E enhanced photovoltaic power plant final installation and checkout at the Carissa Plain. Routine weekend operation of STEOR was terminated at the end of April 1984. Weekday shutdowns began to occur in May due to the increasing diversion of available manpower to the Carissa Plain project.

The selection of an operational period to be used for a meaningful evaluation of STEOR performance was driven largely by the circumstances discussed above. It was desirable that the evaluation period encompass a continuous year of operation in order to assess effects of seasonal weather conditions and to determine equipment responses to daily operational and thermal cycling. The time frame selected as most closely meeting these requirements is the 12 month period from June 1983 through May 1984.

An important term used in this report is "operational day" (may also be called "injection day"), which is defined as a day during which a measurable quantity of steam produced by the STEOR system was injected into the oil field distribution header. There were days when sufficient insolation was present to initiate startup operations, but shutdown was triggered by the onset of clouds or other causes prior to the attainment of rated steam output conditions. Such days are categorized as non-operational.

A. ACTUAL HISTORY

A summary of the actual STEOR operating history is presented in Table II-1. Of the 366 total days, there were 230 operational days, according to the daily log records. Recorded data were found for 213 of those days. The master control system commanded data to be recorded on 5 1/4 inch flexible discs at six minute intervals, with each disc capable of storing about eight operating days of data. When a disc was filled, an appropriate notification was displayed on the master control monitor each time a data dump was attempted. The message remained for a short period of time, then was replaced by another pertinent status message. Subsequently a printout, and later an audible warning of a full disc condition were added. Nonetheless, a total of 17 days of data were lost due to the failure to execute prompt disc replacements.

In the absence of a complete set of data for every day the system was operated it was considered important to devise a reasonable method for extrapolating the data to arrive at a fair approximation of total actual monthly and yearly performance for the system. This was done by multiplying each totalized data value for each month by an adjustment factor defined as

$$\frac{\text{total number of operational days}}{\text{number of days of data available}}$$

As an example, Table II-1 shows that of the 30 days in June 1983, there were 28 operational days, and data exists for 26 of those days (two days of no data). The total time of operation on the 26 days of data was 173.7 hours, and the adjusted operating time for the month is

Hours of operation = (173.7)(28/26) = 187.0 hours

This method was used to arrive at adjusted values for the various energy, steam output and operational times which represent a best estmate of actual system performance over the operational year. The adjusted values, rather than

TABLE II-1
ARCO SOLAR STEOR OPERATIONAL SUMMARY
ADJUSTED HISTORY

MONTH	NUMBER OF DAYS			OPERATING STATUS NO OPERATION DUE TO			HOURS OF DAYLIGHT		HOURS OF OPERATION
	TOT.	STM. INJ.	NO DATA	SYSTEM	WEATHER	OPERATOR	MONTHLY TOTAL	OPERATING DAYS	
JUN 83	30	28	2	2	0	0	440.2	399.3	187.0
JUL	31	30	0	1	0	0	446.7	421.5	187.5
AUG	31	17	3	7	7	0	417.9	229.9	84.5
SEP	30	23	1	1	6	0	366.2	282.4	144.0
OCT	31	26	7	1	4	0	340.8	290.0	129.0
NOV	30	4	0	5	16	5	297.3	41.7	16.5
DEC	31	6	0	3	8	14	289.5	59.1	21.5
JAN 84	31	8	0	4	15	4	298.7	81.1	32.2
FEB	29	22	4	0	6	1	307.3	237.1	92.2
MAR	31	26	0	0	4	1	366.6	307.8	147.9
APR	30	22	0	1	4	3	392.7	283.8	136.0
MAY	31	18	0	2	0	11	438.4	248.0	102.2
TOTAL	366	230	17	27	70	39	4402.3	2881.7	1280.5

actual data from the discs, are presented and discussed in the body of this report. The actual data as reduced from discs are included in Appendix A.

Referring to Table II-1, 70 of the 136 non-operational days were due to weather, 39 resulted from the absence of an operator and 27 were equipment related. Two of the equipment outage days (one day in July 1983 and the other in April 1984) resulted from maintenance operations performed on the oil field steam distribution header, and did not involve STEOR system equipment. The highest monthly operating time was logged in July 1983 and the least in November 1983.

The "monthly total" hours of daylight represents the integral time between sunrise and sunset for all days of each month, and the "operating days" column under "hours of daylight" represents the integral time of steam delivery to the oil field distribution header (does not include system startup time). The total operational time for the year of 1280.5 hours was 44 per cent of the available daylight time for all 230 operational days, or an average of 5.6 hours for each day on which some steam was delivered to the field. The normal startup time (from the beginning of receiver heatup to the delivery of rated steam to the field header) on a good sunny morning was about two hours, and averaged about 2.5 hours. The length of daylight for an average operational day was 12.5 hours, therefore, the average totally idle time on an operational day was about 4.4 hours. This includes time waiting for minimum heatup power after sunrise, residual daylight time after shutdown, downtime for clouds and fog, and downtime due to equipment problems.

B. OPERATIONAL POTENTIAL

As shown in Table II-1, the STEOR system could not be operated on 39 days of the year due to the absence of an operator at the facility. Also, of the 27 days down due to system equipment problems, two were attributable to the oil field system and a number of others can be categorized as infant mortality, design wring-out, and the fact that component selections were based on limited life pilot plant economics rather than long life commercial plant economics. Furthermore, much of the maintenance and repair work could have been performed at night and/or more efficiently in the economic environment of a commercial operation. In view of these kinds of considerations, it is estimated that the average annual number of complete days due to equipment outage could reasonably be no more than 12 for a more mature, commercial installation (see Section IV).

The operational history was re-assessed for a scenario based upon actual weather conditions, but the presumptions that an operator was on-site every day of the operational year and that the number of equipment outage days was 12 rather than 27. This would infer that an additional 54 days could have been made available for system operation during the evaluation year. This exercise provides important insight relating to the operational potential of a future commercial STEOR installation in the vicinity of the Arco Fairfield lease.

Table II-2 presents an estimated operational potential for the Arco STEOR system considering a redistribution of the 54 days of operator and equipment induced down days. Some of the days (13) were assigned as weather outage in approximate proportion to the actual occurrance of weather outages for each month, and the remainder were assigned as operational days. The number of equipment outage days was held at 12 for the year. A comparison of Tables II-1 and II-2 shows that the relative proportions of weather outage to operational days remains nearly constant (70/230 = .300, 83/271 = .306). The operational hours of daylight and the hours of operation were increased in proportion to the increase in operational days for each month; therefore, the average daily operating time as previously discussed remained unchanged. In subsequent sections of this report, system performance will be presented for both the adjusted actual operating history and this estimated operational potential.

C. INSOLATION CHARACTERISTICS

Direct normal insolation was measured with an Eppley Normal Incident Pyroheliometer (NIP) located on the roof of the control room at the STEOR, and within 500 feet of all 30 heliostats in the field. During the evaluation year, reasonable efforts were made to keep the instrument properly aligned and the viewport clean. During the year 1983 there were several publicized accounts of abnormally low insolation noted in various parts of the country (including the Solar 1 site at Barstow, approximately 170 miles east of the Arco STEOR site), and there is speculation that this resulted from a cloud of particulate matter dispersed into the upper atmosphere by a large volcano which erupted in Mexico in 1982. There is no question that the insolation measured at the STEOR site during 1983 and early 1984 was significantly below expectations.

During November through February, insolation in the Bakersfield area suffers considerably from combinations of rain, cloudiness and fog which commonly occur during these months. It is common for direct normal insolation to be essentially zero for days at a time during this period. The months of April through September comprise the prime season for solar operations, with weather-induced shutdown occurring only ocasionally during these months.

TABLE II-2
ARCO SOLAR STEOR OPERATIONAL POTENTIAL
WITH FULL OPERATOR AVAILABILITY

MONTH	NUMBER OF DAYS			OPERATING STATUS NO OPERATION DUE TO			HOURS OF DAYLIGHT		HOURS OF OPERATION
	TOT.	STM. INJ.	NO DATA	SYSTEM	WEATHER	OPERATOR	MONTHLY TOTAL	OPERATING DAYS	
JUN 83	30	29	3	1	0	0	440.2	413.6	193.7
JUL	31	31	1	0	0	0	446.7	435.6	193.8
AUG	31	22	8	2	7	0	417.9	297.5	109.4
SEP	30	24	2	0	6	0	366.2	294.7	150.3
OCT	31	26	7	1	4	0	340.8	290.0	129.0
NOV	30	8	4	3	19	0	297.3	83.4	33.0
DEC	31	15	9	1	15	0	289.5	147.8	53.8
JAN 84	31	12	4	2	17	0	298.7	121.7	48.3
FEB	29	23	5	0	6	0	307.3	247.9	96.4
MAR	31	27	1	0	4	0	366.6	319.6	153.6
APR	30	25	3	0	5	0	392.7	322.5	154.5
MAY	31	29	11	2	0	0	438.4	399.6	164.7
TOTAL	366	271	58	12	83	0	4402.3	3373.7	1480.3

A summary of insolation data recorded during the evaluation year at the STEOR site is presented in Table II-3. It is important to note that STEOR measurements were recorded only during system operation, and therefore do not represent true average data for the months and year. The highest daily peak value recorded was 982 W/m2, which occurred on 27 March 1984. The average of the peaks for all operational days was only 853 W/m2, and the average insolation during all hours of operation was 717 W/m2. Since operational days were generally characterized by clear skies, the daily peaks on these occasions could reasonably be expected to reach 950 W/m2 in this locale.

TABLE II-3
ARCO STEOR SITE INSOLATION CHARACTERISTICS
DURING SYSTEM OPERATION

	INSOLATION (W/M2)			DAILY DIRECT NORMAL INSOLATION (KW-HR/M2)	
MONTH	MAX PEAK	AVG PEAK	AVG DAILY	STEOR	ERSATZ
JUN 83	942	858	742	6.9	9.1
JUL	931	894	817	6.7	9.1
AUG	885	834	736	5.3	8.4
SEP	908	848	671	6.4	7.4
OCT	916	801	653	4.6	6.1
NOV	909	755	601	4.1	4.2
DEC	896	832	656	4.0	2.8
JAN 84	891	797	645	4.0	3.1
FEB	911	803	619	4.1	4.1
MAR	982	868	690	5.9	5.3
APR	964	898	770	6.6	6.8
MAY	952	911	815	7.1	8.0
AVERAGE	924	853	717	5.8	6.2

Insolation trend data are shown in Table II-4. This clearly shows that the quality of insolation was improving throughout the 1984 portion of the evaluation year. From June 1983 through January 1984 (eight months of operation) there were 21 days during which insolation exceeded 900 W/m2, while during the next four months there were 34 days in excess of that value.

TABLE II-4
INSOLATION TREND DATA

MONTH	DATA DAYS	NUMBER OF DAYS INSOLATION ABOVE 850	875	900	925	950	975
JUN 83	26	18	10	3	2	0	0
JUL	30	28	25	15	3	0	0
AUG	14	7	4	0	0	0	0
SEP	22	12	8	1	0	0	0
OCT	19	3	1	1	0	0	0
NOV	4	2	1	1	0	0	0
DEC	6	4	1	0	0	0	0
JAN 84	8	2	2	0	0	0	0
FEB	18	6	6	3	0	0	0
MAR	26	16	11	7	5	2	1
APR	22	20	17	13	4	1	0
MAY	18	15	14	12	9	2	0
TOTAL	213	133	100	56	23	5	1

Referring back to Table II-3, it is noted that the mean daily direct normal insolation (DDNI) for the year <u>during operation</u> was 5.8 kW-h/m2, which is slightly below the ERSATZ value of 6.2 kW-h/m2 for Bakersfield, California. The ERSATZ data is direct normal insolation which has been analytically derived from total hemispherical insolation measurements, and was compiled by the Solar Energy Research Institute from aproximately 23 years of insolation history (see <u>Direct Normal Solar Radiation Manual</u>, SERI document No. SP-281-1658, October 1982). Since the STEOR data was measured only during system operation, it does not include data for days when the system was down due to weather, equipment problems or operator absence. Since the operational days were predominantly sunny, it would be expected that the true average insolation for the STEOR evaluation year is below the 5.8 kW-h/m2 value. In an attempt to estimate the lower boundary it can be assumed that (refering to the adjusted operational history) the direct normal insolation during the 70 days of weather outage was always zero, producing an DDNI of zero for this entire period. It is further assumed that the 65 days of system and operator outages experienced the same average insolation experienced during the 230 days of system operation. Therefore, the lower bound would be

$$\text{DDNI(Min)} = \frac{(5.8)(230) + (0)(70)}{300} = 4.5 \text{ kW-h/m2}$$

The real value of average integrated direct normal insolation probably lies somewhere between 4.5 and 5.8 kW-h/m2, perhaps close to the average of about 5.2 kW-h/m2. The important conclusion of this discussion is that the Arco STEOR site did experience insolation significantly lower than the ERSATZ yearly average of 6.2 kW-h/m2.

III PERFORMANCE DATA

The STEOR system was instrumented beyond the normal requirements of automated operation to obtain sufficient data for engineering evaluation purposes. Approximately 150 data channels were sampled and logged on 5 1/4 inch flexible discs during system operation. These data include temperatures, pressures, flows, liquid levels, insolation, wind velocity and direction, valve positions, heliostat status and other parameters. Copies of the data discs were obtained through the cooperation of Arco Solar, Inc. and used as the basis for this evaluation.

The HP9826 master control computer also controlled the processing, display and storage of data through the use of software subprograms. Data were sampled from the HP3497A DAC unit at discrete intervals (approximately 5 per minute). During the time from initiation of the system startup sequence until completion of shutdown, data were dumped to disc at six minute intervals. Each disc contains up to eight days of data.

System performance was evaluated in terms of quantities of steam delivered and its thermal energy content. All flowrates were measured by means of calibrated orifice flowmeters. The determination of energy content requires,as a minimum, both flowrate and temperature of the fluid. In the case of energy content of injection steam, which was at all times sub-saturated, steam quality was also required. Steam quality is the ratio of mass of vapor to total steam mass and was measured by two methods. An automated method which produced the detailed steam quality histories included on the data discs entailed the use of a specially calibrated orifice flowmeter in the steam line. A manual method was also used several times per day, which utilized electrical conductivity measurements of the injection feedwater and the liquid portion of the injection steam to determine quality. Electrical conductivity measurements provide a very accurate indication of the total dissolved solids (TDS) content (in parts per million) of a water sample, and steam quality is calculated as follows.

$$\text{Quality} = \frac{(\text{TDS of steam liquid} - \text{TDS of injection feedwater})}{(\text{TDS of injection feedwater})}$$

This method represents a very reliable method of determining steam quality and is more accurate than that obtained by the orifice method. The conductivity method consistently resulted in peak quality values of about 75 per cent, whereas the orifice method resulted in peak values of 65 to 70 per cent. An attempt was made to normalize the logged (flowmeter) data to a daily peak of 75 per cent for use in calculating injection steam energy. This procedure does not alter the value of injection steam energy more than about 5 per cent in most cases, but should result in a more accurate value. On many operational days the flowmeter produced isolated spikes of above 75 per cent (and even above 100 per cent) at unlikely times, such as soon after the start of injection to the oil field when steam quality was characteristically low. An adequate screening process could not be devised to filter out such questionable data, so for these cases no correction factor at all was applied to the recorded value of injection steam quality.

A. SYSTEM PERFORMANCE

This section discusses system performance in terms of net steam energies and quantities as produced by the receiver and as delivered to the oil field distribution header relative to gross solar energy potentially available to the collector field. As a point of reference, estimates of energy incident at the receiver aperture plane will also be included. Since the various energy loss parameters must be evaluated indirectly by calculation rather than by direct measurements, they will be discussed in section III-A-3 of this report.

1. TOTALIZED ENERGY

Recall from Section II that the term "adjusted" as used with history or performance herein relates to an extrapolation of the 213 operational days for which recorded data is available to the 230 total days of operation as verified by facility log records. The data extrapolation was done on a monthly basis and represents the best available knowledge of system output for the operational year of June 1983 through May 1984.

A monthly summary of adjusted system performance is presented in Table III-1. The four energy parameters are defined below.

QSUN - total energy potentially available to the collector field, calculated as the product of insolation and total heliostat reflective area, integrated over the applicable time period.

QINC - Total energy incident at the receiver aperture plane, calculated as the product of insolation, total heliostat reflective area, field cosine and heliostat reflectivity, integrated over the applicable time period. Although this is a purely calculated number, it should be accurate within a range of about +/- 5 per cent. A major uncertainty is the value used for mirror reflectivity, which was a constant 74.7 per cent for all calculations. This represents a cleanliness factor of .9 used with the 83 per cent reflectivity mirrors. The actual reflectivity probably ranged between 70 and 80 per cent, depending on the state of cleanliness. Heliostats were normally washed at four to six week intervals. Upon occasion one or more heliostats were taken out of EOR service for various reasons (i.e. to support other test activities, be washed, for maintenance or repair). An accurate record of off-line time was not maintained, so this factor could not be considered in the computations for QINC and subsequent system performance calculations.

QREC - Net energy into receiver steam generation at rated pressure

QINJ - Net energy into injection steam delivered to oil field

The values for receiver steam generated represent net quantities at rated pressure. During June through August 1983 while system startup was conducted sequentially, rated receiver steam pressure is defined as the normal operating pressure. For the remainder of the evaluation year system startup was conducted in the parallel mode, for which rated receiver steam pressure is defined as the pressure existing at the time injection to the oil field header is initiated.

TABLE III-1
ARCO SOLAR STEOR PERFORMANCE SUMMARY
ADJUSTED HISTORY

MONTH	ENERGY (MW-HR)				STEAM GENERATED (LB)	
	QSUN	QINC	QREC	QINJ	RECEIVER	INJECTED
JUN 83	307.4	188.0	106.8	90.0	385,380	368,426
JUL	316.9	198.7	119.7	111.0	464,300	440,220
AUG	142.1	91.0	48.7	45.1	188,570	185,190
SEP	231.8	153.7	82.7	78.9	323,631	328,691
OCT	187.9	131.2	76.9	72.1	293,090	289,260
NOV	25.7	18.3	9.8	9.1	36,800	37,360
DEC	38.4	27.7	10.5	8.9	38,450	38,300
JAN 84	50.5	36.3	18.0	16.9	68,790	72,350
FEB	143.6	101.7	50.1	47.8	191,500	192,490
MAR	244.0	164.9	81.0	76.8	310,740	313,080
APR	229.0	148.7	79.2	75.6	305,790	307,060
MAY	201.6	125.5	59.4	56.1	225,640	224,190
TOTAL	2118.8	1385.7	742.8	688.3	2,832,680	2,796,620
FRACTION	1.00	0.65	0.35	0.32		

The Performance Data tabulated in Table III-1 represent the adjusted monthly totals as derived by extrapolating the actual data recorded over the total known operational days for each month (Section II-A). Overall net power conversion efficiency for the year was 32 per cent, as derived by comparing the total injected thermal energy (QINJ) to the total integrated insolation (QSUN) available during operation. The 688.3 MW-h net power produced 2,796,620 lb of steam delivered to the oil field. Net output from the receiver (after attaining rated steam pressure) was 742.8 MW-h. The difference in these values, 54.5 MW-h, was dissipated in raising system temperatures to maximum operating levels and in heat loss to the environment. The calculated value for energy incident at the receiver aperture plane (QINC) is included only for reference, but the value shown is probably quite representative of the actual.

July 1983 was by far the most productive month in terms of net energy (111 MW-h) and steam (440,220 lb) delivered to the oil field. This resulted from the cumulative effects of several positive factors which characterized this month.

1) Most operational days (30)
2) Best weather (3 days of partial cloudiness)
3) Highest system availability (31 days, 1 day lost due to oil field repair)
4) High average daily insolation (6.7 kW-h/m2)

The months of November and December virtually tied for the least productive, closely followed by January. This is largely a result of the frequent occurences of fog, cloudiness and rain which is characteristic of this period in the south San Joaquin Valley. About half the days during these three months were non-operative due to weather alone. Additional factors of significance contributing to low output during this time were

1) November:	5 days for planned annual inspection
	5 days due to absence of operator
2) December:	3 days for equipment repair
	14 days due to absence of operator
3) January:	4 days for equipment repair
	4 days due to absence of operator

The 23 days down due to absence of operator resulted primarily from declared holidays, and the 12 equipment down days represent nearly half of the total system outage days for the year. The total system energy energy contribution for the November - January quarter was 34.9 MW-h, only five per cent of the year's total and 31 per cent of the July output.

The data from Table III-1 were extrapolated to determine the performance potential for the system with continual daily operator and an improved equipment availability. These results are shown in Table III-2. Overall power levels are 15 percent above the adjusted actual values, and, since all performance parameters were extrapolated by the same factor the operating efficiency is unchanged. The performance increase is simply the integral effect of the ratio of estimated attainable to actual operational days for each month and does not include any attempt to increase system output by reducing partial- day down time, increasing system operating efficiencies or consideration of improved weather patterns.

TABLE III-2
ARCO SOLAR STEOR PERFORMANCE POTENTIAL WITH FULL OPERATOR AVAILABILITY

MONTH	ENERGY (MW-h)				STEAM GENERATED (lb)	
	QSUN	QINC	QREC	QINJ	RECEIVER	INJECTED
JUN 83	317.5	194.2	110.4	93.0	399,144	381,584
JUL	327.5	205.3	123.7	114.7	479,777	454,894
AUG	175.3	112.2	60.1	55.6	244,032	239,658
SEP	241.4	160.1	86.1	82.2	337,702	342,982
OCT	187.9	131.2	76.9	72.1	293,090	289,260
NOV	51.4	36.6	19.6	18.2	73,600	74,720
DEC	96.0	69.3	26.3	22.3	96,125	95,750
JAN 84	75.8	54.5	27.0	25.4	103,185	108,525
FEB	148.7	105.3	51.9	49.5	200,205	201,240
MAR	253.4	171.2	84.1	79.8	322,692	325,122
APR	260.2	169.0	90.0	85.9	347,489	348,932
MAY	324.8	202.2	95.7	90.4	363,531	361,195
TOTAL	2459.8	1611.1	851.7	788.9	3,260,570	3,223,860
FRACTION	1.00	0.65	0.35	0.32		

The importance of deriving a reasonable estimate for performance potential of the pilot plant is in its use to establish a relationship between the somewhat idealistic design point specifications for this type of installation and realistic long-term performance expectations. Such a correlation is neccesary to accurately assess the influence of weather and equipment induced down time upon the size and cost of future commercial systems.

The Fairfield STEOR simulation code was used to calculate an idealized set of performance data, assuming system operation all day each day during the evaluation year. Monthly insolation averages as measured during system operation through the evaluation year and a heliostat reflectivity degradation of ten per cent were used as the basis for calculating input energy. The results of these calculations represent the ultimate performance capability for the STEOR system had it operated every day of the year without any downtime whatsoever and are shown in Table III-3. The overall power conversion efficiency prediction of 37 per cent might seem to contradict the corresponding value of 32 per cent from actual system operational measurements. However, this is to be expected since many of the actual operating days were foreshortened by weather or other causes, and some system startups were initiated from a cold condition. Both situations result in lowering the overall average operating efficiency and neither existed in the calculation of the idealized performance data of Table III-3.

TABLE III-3
ARCO SOLAR STEOR PERFORMANCE PREDICTIONS
MAXIMUM IDEAL DAILY OPERATION
USING MEASURED INSOLATION

MONTH	ENERGY (MW-HR)				STEAM GENERATED (LB)	
	QSUN	QINC	QREC	QINJ	RECEIVER	INJECTED
JUN 83	394.2	234.3	143.4	125.7	545,500	527,300
JUL	421.3	253.0	155.3	142.6	598,900	575,200
AUG	375.7	235.6	146.0	130.5	558,800	536,300
SEP	345.3	226.2	145.8	134.4	563,900	543,700
OCT	313.7	213.3	137.3	123.4	525,500	503,100
NOV	257.1	178.8	114.6	99.0	433,200	416,400
DEC	282.1	197.2	132.1	116.9	503,700	480,500
JAN 84	285.5	198.1	129.6	115.0	494,000	471,700
FEB	295.2	200.4	130.2	116.9	496,300	474,900
MAR	378.5	245.8	161.8	146.0	620,400	594,800
APR	391.2	243.0	158.1	143.4	604,500	582,700
MAY	429.4	258.2	159.3	146.9	619,600	597,400
TOTAL	4169.2	2683.9	1713.5	1540.7	6,564,300	6,304,000
FRACTION	1.00	0.64	0.41	0.37		

A comparison of the total energy in steam injected (QINJ) during the evaluation year (688.3 MW-h) from Table III-1 with the maximum ideal yearly value (1540.7 MW-h) from Table III-3 shows that the Fairfield STEOR facility produced 45 per cent of the ideal net energy. A similar comparison of QINJ from Tables III-2 and III-3 show that with continual operator coverage, the Fairfield STEOR system could potentially produce 51.2 per cent of the maximum idealized energy and steam, considering the actual weather conditions and reasonble allowance for hardware outages.This is called the "annual performance factor" (APF) and is a very important correlation to emerge from this evaluation of the Fairfield data, as it can provide helpful guidance for the sizing of larger STEOR systems of a similar design (as will be done in Section V). The APF value of 51.2 per cent is probably conservative, because it represents a year during which insolation was significantly below average. An increased average insolation would result in higher daily output; and since the energy loss for startup would be unaffected, the net performance efficiency and hence the APF would increase.

This evaluation of totalized energy data for the STEOR facility illustrates the seasonal nature of performance to be expected from solar powered processes in the south San Joaquin Valley. During the eight months of most reliable insolation (March through October), potential totalized performance should average 62 per cent of the idealized output, whereas during the four worst months (November through February) only 26 per cent of idealized output could be expected. The March-October energy represents 85 per cent of the annual potential output, while the November-February energy is only 15 per cent of the annual total.

2. POWER OUTPUT CHARACTERISTICS

The instantaneous net power production by the ARCO STEOR system was highly variable, which is characteristic of a central receiver solar thermal power system with no thermal storage capability. Output is most directly affected by direct normal insolation and sun position, which are in a constant state of transience throughout each day. Factors such as mirror reflectivity, receiver absorptivity, and steam leakage also have a significant influence on power production, but change much more slowly with time.

System design point net power output was calculated at 1.06 MW prior to construction of the facility. The pertinent design point conditions are listed below.

Operating Time and Day:	Noon on Winter Solstice
Insolation:	1000 W/m2
Mirror Condition:	Clean (.83 reflectivity)
Receiver Absorptivity:	.95 (newly painted)

It is noted that the design point conditions were selected on the basis of defining maximum "theoretical" power production for the STEOR system. These conditions never existed concurrently during the evaluation year, and some never occurred individually. The system was down due to weather on the winter solstice, and the nearest operational day was December 10, when the peak insolation was 853 W/m2. The maximum insolation value recorded at the Fairfield site was 982 W/m2, on 27 March 1984. The highest insolation recorded between 17 July 1983 and 20 March 1984 was 916 W/m2, on 25 October 1983. Mirror reflectivity was never measured in the field, although some indirect measurements on samples were made on occasion. The local environment was very dusty, with the presence of volatile hydrocarbons in the air. The heliostats were washed seven times during the evaluation year, at an average interval of seven weeks. It is estimated that actual reflectivity ranged from 98 to 80 per cent of the clean value (.83), and averaged about 90 per cent (.747). The receiver boiler panel was painted with Pyromark approximately one year prior to the beginning of the evaluation year. Degradation (as visually observed) occurred over a period of time and some repainting was attempted during the summer of 1983, with less than complete success. The maximum expected absorptivity of a Pyromark surface in the field is about .95. It is estimated that the actual absorptivity was approximately .9 during the year.

Equivalent "design point" power outputs were calculated for days other than the winter solstice (maintaining the remaining three criteria), to provide a frame of reference for comparing actual performance to the maximum theoretical for various times of year. The winter solstice potential output of 1.05 MW is reduced to .91 MW on the summer solstice as shown in Figure III-1. Actual measured values of daily peak net power output from the STEOR system attained a maximum of about 80 per cent of theoretical, due to degraded insolation, heliostat reflectivity and receiver absorptivity as cited in the previous paragraph.

Plots which describe system performance during two complete operational days are presented in Figures III-2 through III-11. Performance characteristics for additional days are contained in Appendix B. The operating days of 22 June 1983 and 20 March 1984 were selected for this discussion because they illustrate typical system performance characteristics, and due to their proximity to the summer solstice and vernal equinox.

FIGURE III-1

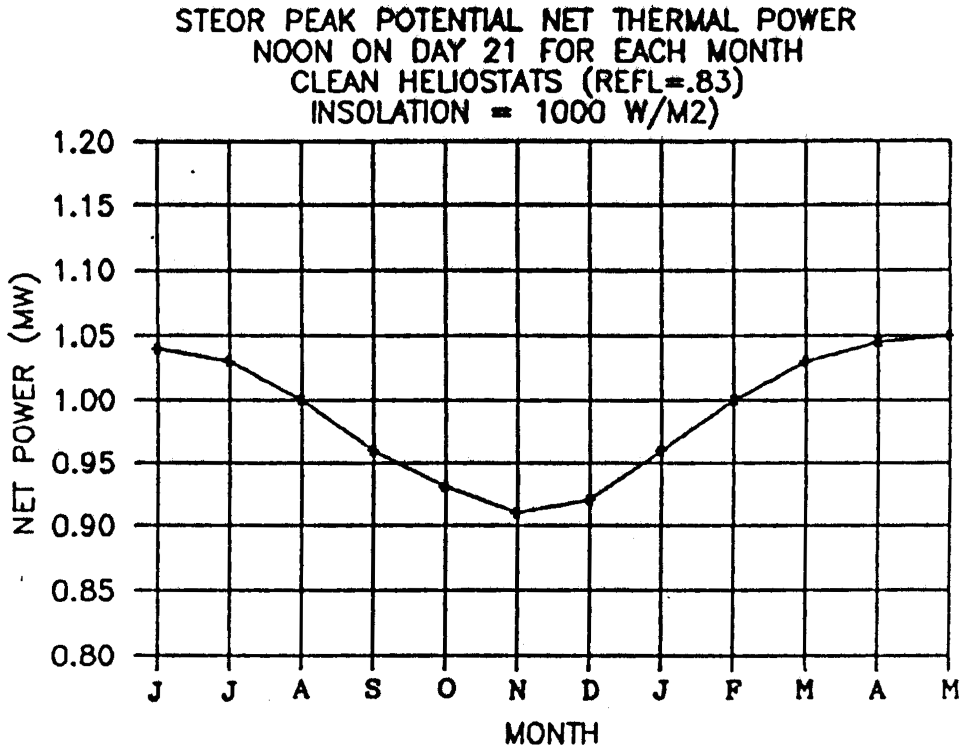
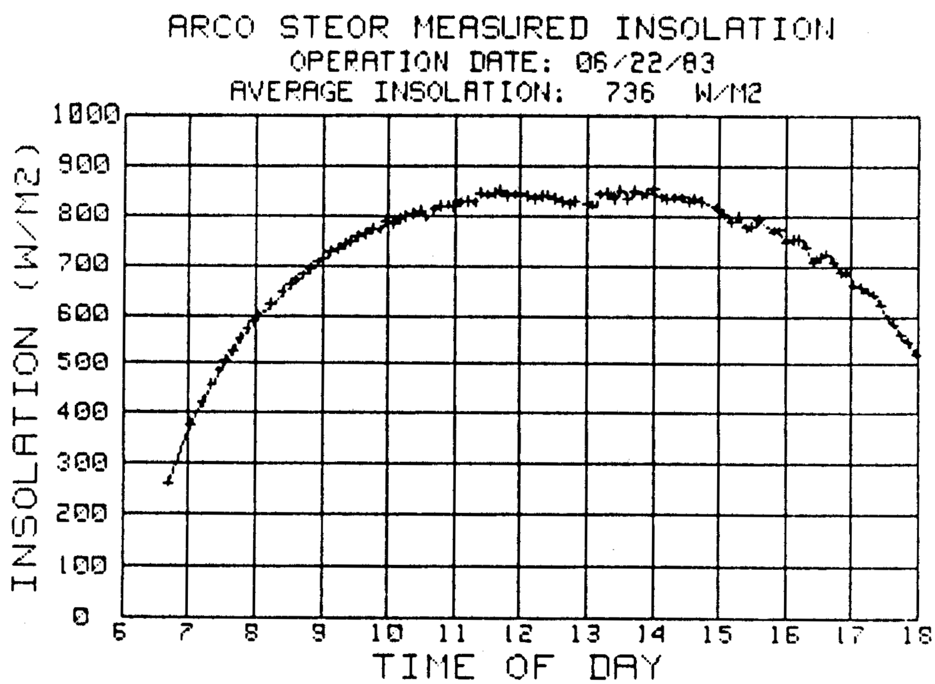


FIGURE III-2



June 22, 1983 was a good clear day early in the evaluation year and produced one of the longest periods of system operation. The startup sequence was initiated at aproximately 6:30 AM and shutdown occurred at 6:00 PM. Measured insolation data are plotted in Figure III-2. The peak and average values for the day were 851 and 736 W/m2, respectively, just slightly below the June averages of 858 and 741 W/m2. The slight perturbations seen in the curve are quite possibly due to jet aircraft contrails which frequently appeared, as the Fairfield site lies beneath a major north-south commercial airlane.

Receiver and injection circuit steam flowrate predictions (using the system simulation model) and measured data are shown in Figures III-3 and III-4, respectively. The initial injection circuit flow of approximately 1000 lb/h during start-up is water rather than steam. The point at which the injection flowrate suddenly escalates to follow the receiver flowrate marks the attainment of steam generation at rated temperature and the point at which injection to the oil field header begins. Several obervations of interest can be made concerning Figure III-4. Log entries indicate that two emergency shutdowns were commanded by the master control system, the first at just after 7:00 AM and the second just before 1:00 PM. It was quickly determined that the shutdowns were caused by erroneous data spikes indicating low condensate reservoir liquid level, and in both cases the system was re-started within a few minutes. Clear evidence of these shutdowns is seen in the sudden drops in flowrates at the indicated times. A second observation pertains to the serial start-up procedure used during this period (whereby receiver pressure is brought up to maximum operating value before steam flow from the receiver is initiated), as compared to the parallel start-up procedure used after the end of August (receiver steam flow is initiated early to heat the receiver and injection circuits simultaneously). Receiver flow does not begin until two thirds the way through the start-up transient. The reason for the oscillations in the early receiver flowrate is the normal response lags in the steam drum liquid level and pressure controllers, which are not included in the system simulation model.

Figures III-5 and III-6 depict thermal power imparted to the two flow circuits. Again, the control overshoots during start-up are evident in the measured data. After the onset of steam flow to the field at about 9:45 AM, there is a finite difference between power in the receiver and injection circuits which gradually diminishes with time. This difference represents energy delivered by the receiver which is

FIGURE III-3

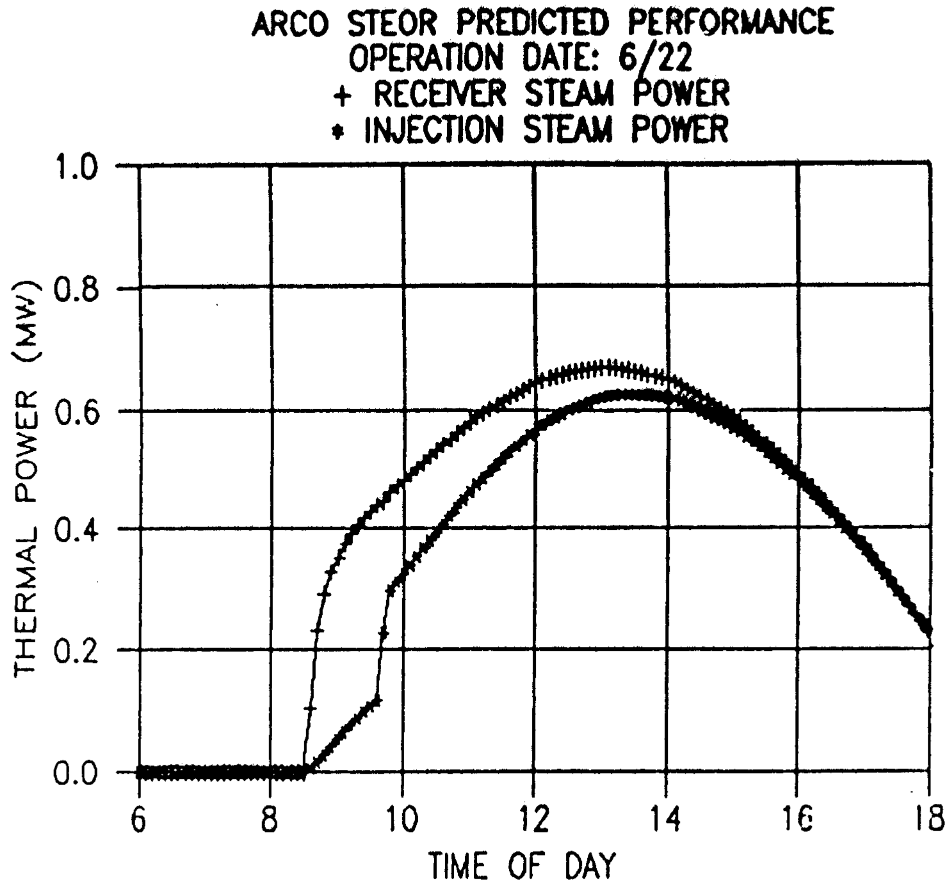


FIGURE III-4

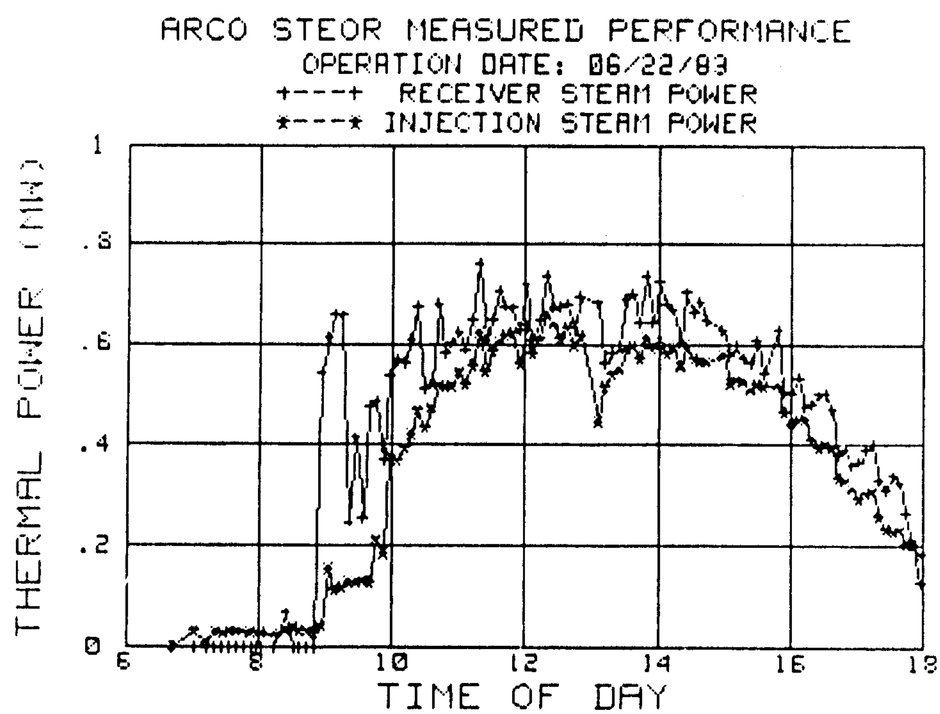


FIGURE III-5

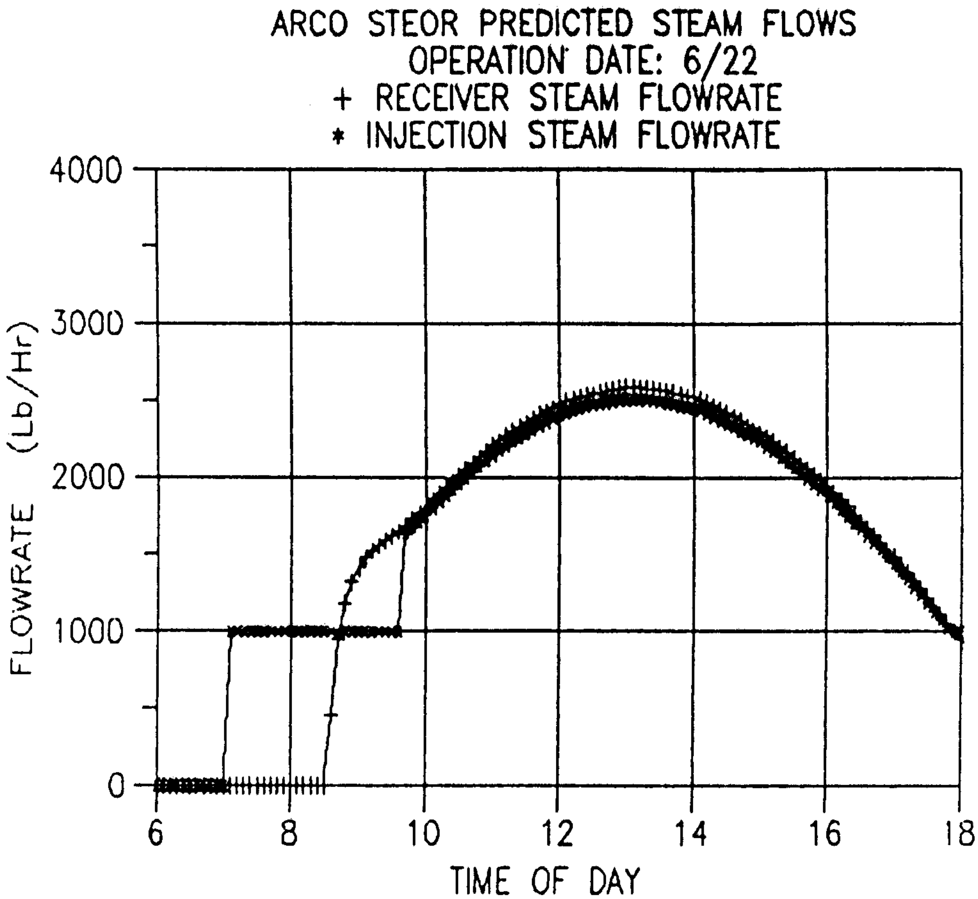
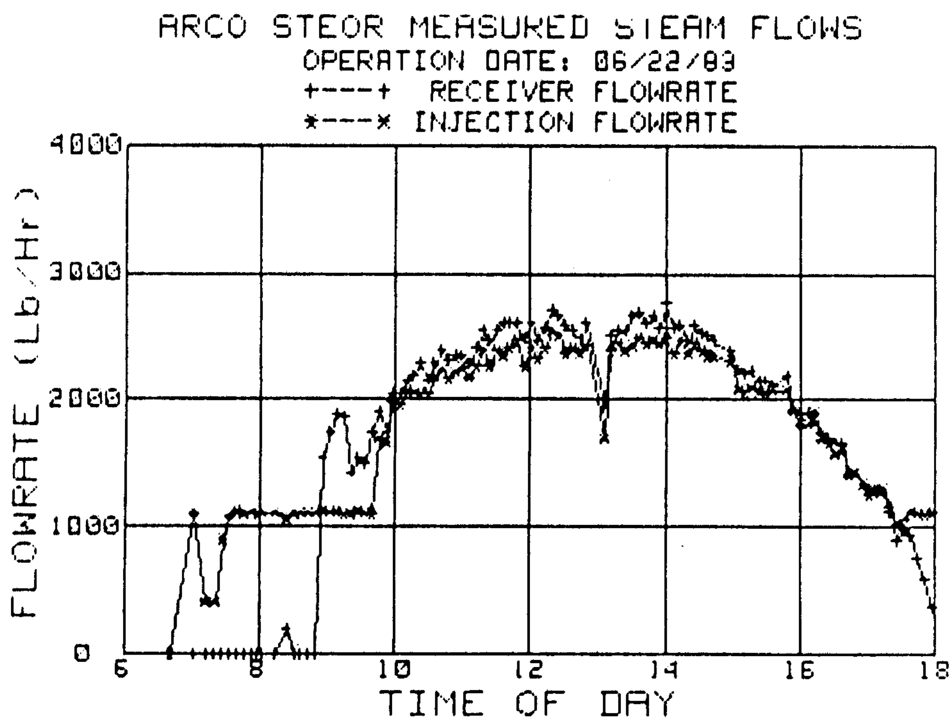


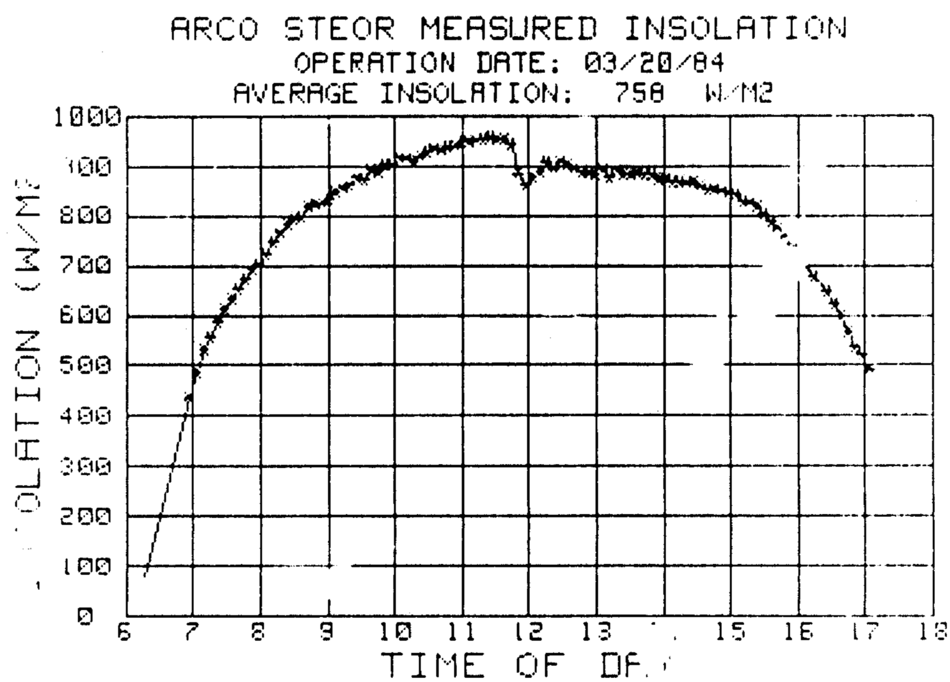
FIGURE III-6



continuing to heat the system flow circuit hardware to maximum temperatures. Injection steam power will always be slighty less than receiver steam power due to small thermal losses throughout the system.

Theoretical daylight on June 22 was 14.34 hours, with sunrise at 5:47 AM and sunset at 8:08 PM. Data indicates the system startup sequence was initiated at 6:40 AM and shutdown occurred at 6:00 PM. The extreme sun angles and characteristic atmospheric haze in the area prevent effective operation during the first and last hours on most days of the year. Also it was quite common for a thin cloud line to form in the late afternoon over the nearby mountain range to the west of the facility causing premature shutdown, although there is no indication of that on this day. Total system startup time was three hours, some of which is attributable to the aforementioned false shutdown. The net duration of steam injection to the field was 8.25 hours.

FIGURE III-7



Insolation data recorded on 20 March 1984 is shown in Figure III-7. This was one of the best operating days of the evaluation year. Insolation reached 956 W/m2, the third highest peak value recorded during the year. Some very slight cloudiness is evident beginning

FIGURE III-8

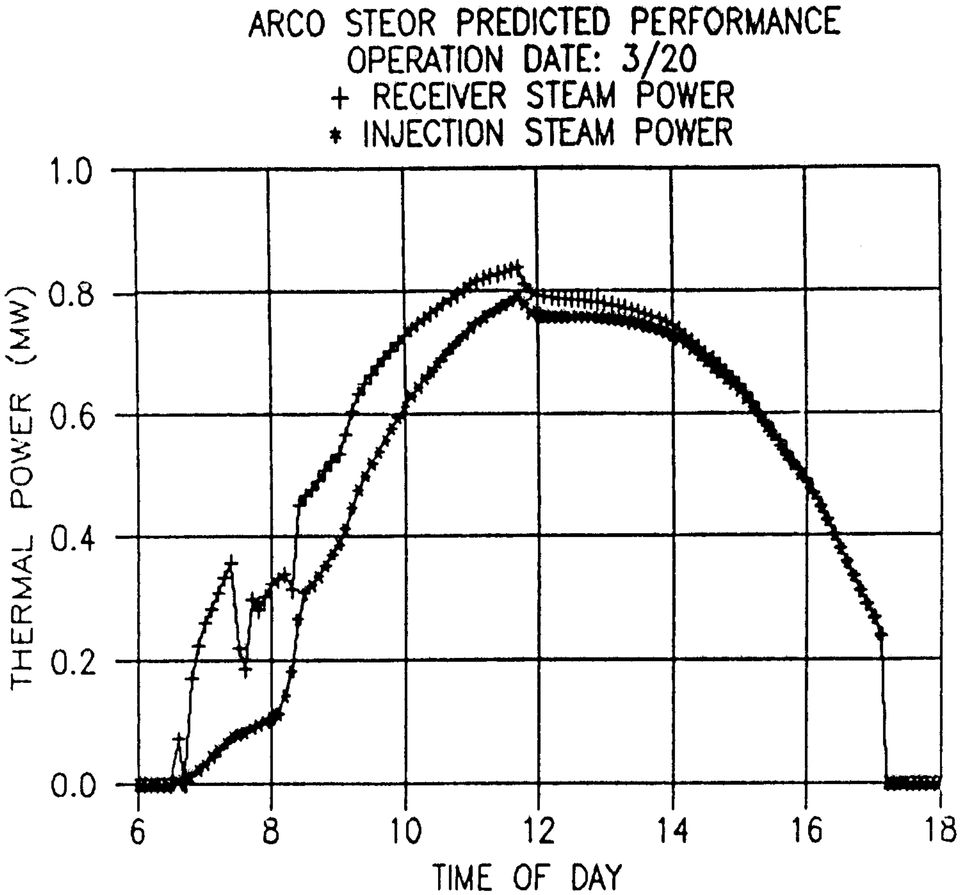


FIGURE III-9

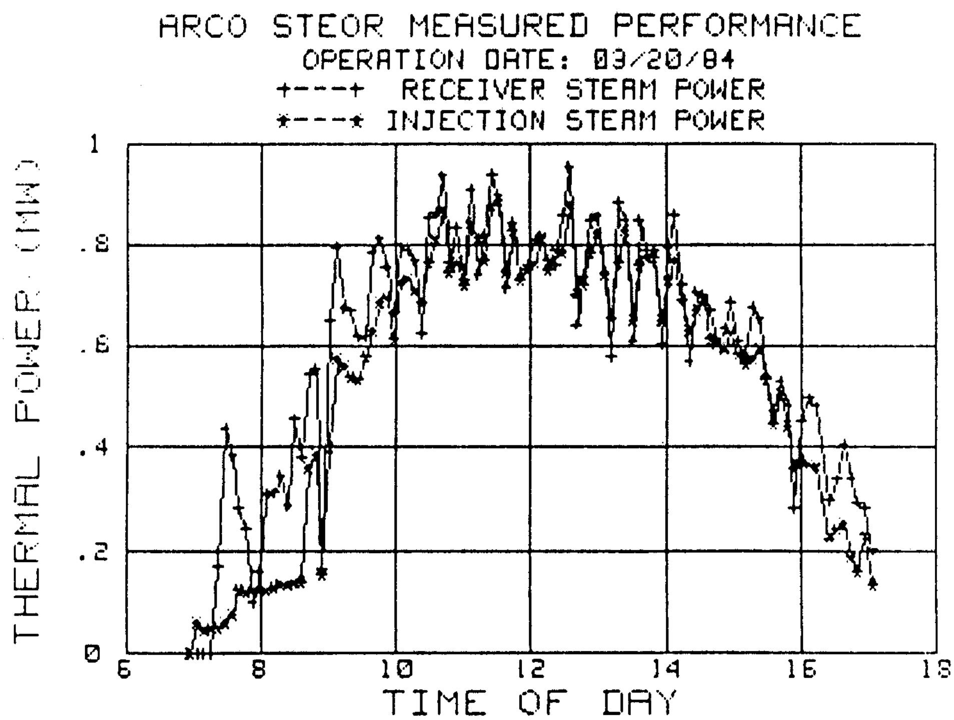


FIGURE III-10

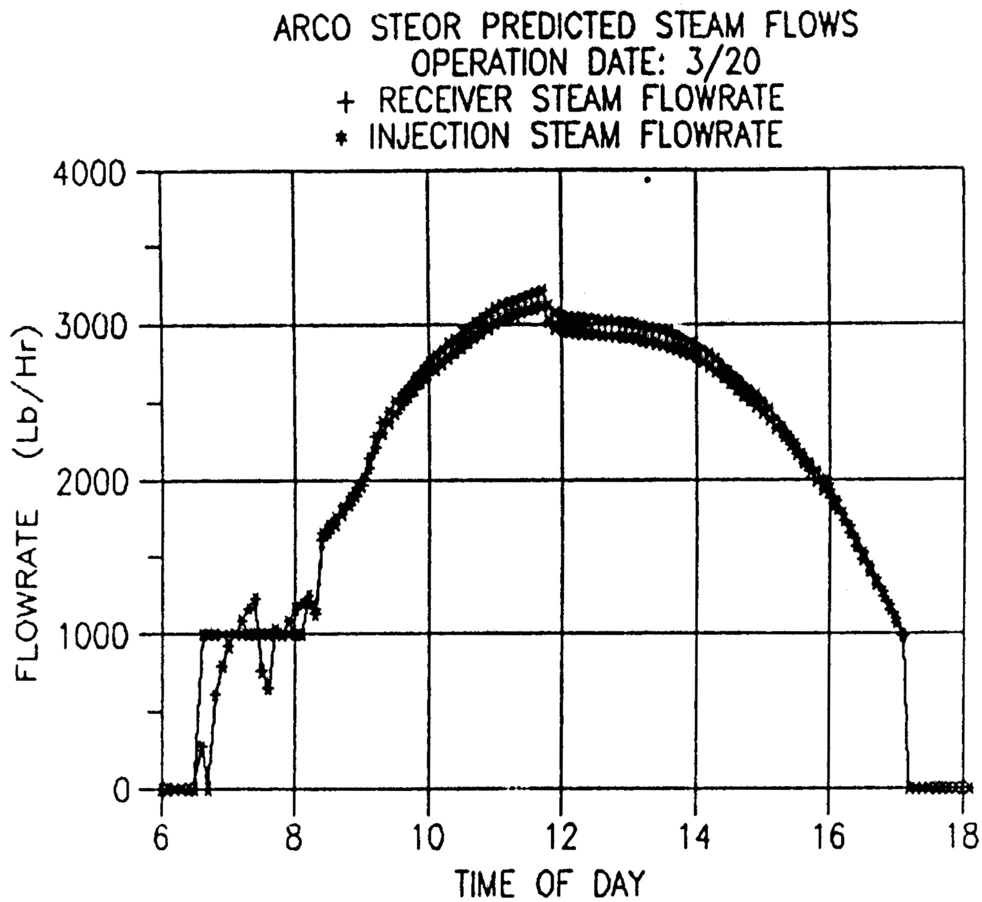
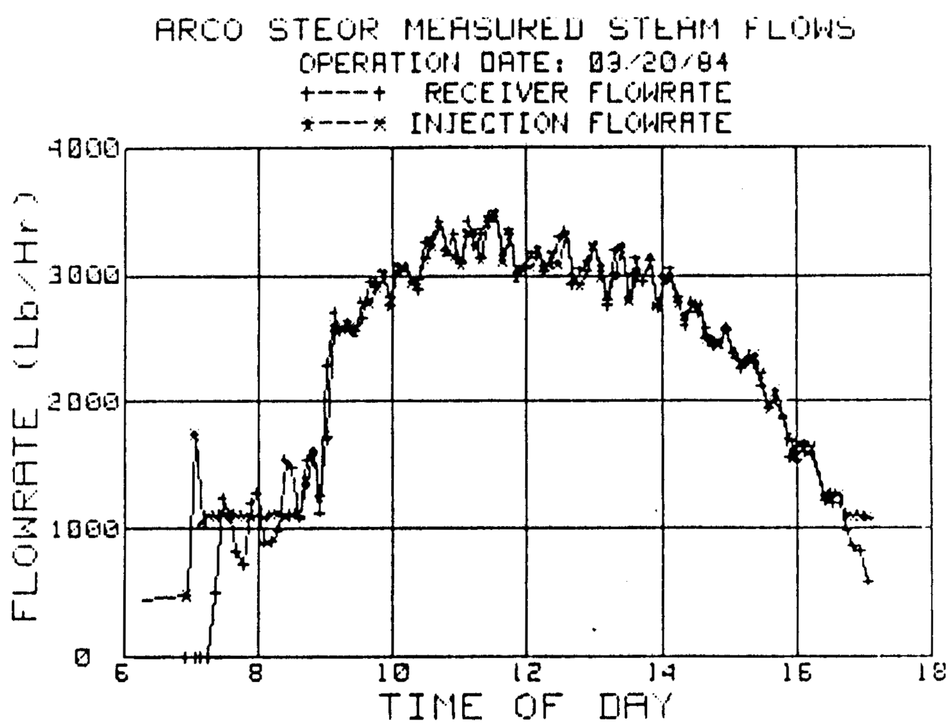


FIGURE III-11



shortly before noon but seems to have dissipated by 3:00 PM. Sunrise occurred at 6:05 AM and sunset at 6:02 PM, providing nearly 12 full hours of daylight.

Predicted and actual steam flowrates are shown in Figures III-8 and III-9, and steam power characteristics are plotted as Figures III-10 and III-11. The mid-day cloudiness had barely perceptible effect upon system performance. Startup was initiated at 6:56 AM and shutdown occurred at 5:08 PM. Steamflow to the field is indicated at 9:00 AM. The injection duration of 8 hours 8 minutes was only 7 minutes less than the injection time on 22 June 1983 when there was two hours more daylight. This was due to a quicker startup (by one hour) and injection continuing one hour closer to sunset as compared to the 22 June operation. Total steam injected this day was 21,840 lb representing 5.5 MW of power, as compared to the 16,740 lb and 4.21 MW injected on 22 June. This higher performance resulted from the higher insolation and average field cosines on March 20.

Figure III-9 illustrates the parallel startup procedure used beginning early September 1983. Receiver steam flow is initiated very early in the startup, as compared to the serial procedure shown in Figure III-4. This allows the entire system to heat up concurrently and reduces thermal gradients in equipment throughout the water/steam circuits, without affecting system startup time. The effect should be increased gasket life and reduced cyclic stresses in pressure vessels.

3. EVALUATION OF SYSTEM THERMAL LOSSES

Although it was not possible to install sufficient instrumentation to measure most energy losses directly, a good accounting was made using analytical techniques. The same algorithms for calculation of losses in the system simulation model were inserted into the data reduction software, and operated upon actual insolation, temperatures and other data to produce estimates of the major categories of energy losses. The total system energy loss as considered herein is the difference between the integrated insolation energy incident upon the 30 heliostats if all were pointed at the sun, and the net energy imparted to the steam injected into the oil field header. Five different loss parameters were evaluated.

QFLS - The collector field loss, which includes the degradations imposed by the field cosine factor and mirror reflectivity.

QAPL - Receiver aperture spillage loss, or the energy radiated from the heliostats that is not incident upon the receiver boiler panel.

QRCL - Receiver energy loss, consisting of radiant energy reflected from the boiler panel, radiant energy emitted from the boiler panel, energy convected from the boiler panel directly to the atmosphere and energy conducted through insulation and support structure associated with the boiler panel and steam drum.

QSTL - System startup loss, which includes energy used in heatup of system fluids and hardware and energy contained in injection circuit water/steam dumped prior to the attainment of rated injection conditions.

QESL - Equipment system loss, which is the energy consumed by final heatup and losses from the pad-mounted water/steam system after the beginning of steam injection to the oil field. This is the one loss parameter which can be quantified from system data measurements, being simply the difference between receiver steam energy (QREC) and injection steam energy (QINJ).

A complete summary of system energy inputs, losses and outputs for the adjusted operating year is presented in Table III-4, and for the potential operating year (reduced down time as discussed in section II-B) in Table III-5. The only parameters in Table III-4 derived solely from measured data are QSUN (total available energy), QREC (net receiver steam energy), and QINJ (net energy in steam injected). The summation of all five loss parameters should be equal to the difference between QSUN and QINJ. For the total operating year this would be

Energy Losses = 2118.8 - 688.3 = 1430.5 MW-h

The total losses of 1430.5 MW-h represent 67.5 per cent of the available input energy, QSUN. A summation of the calculated losses for the year in Table III-4 produces a value of 1473.1 MW-h, or 69.5 per cent of QSUN. This is a very good correlation of measured and calculated data, and is in fact within the bounds of expected accuracy of the instrumentation used to obtain the measured data. Although this does not demonstrate that a comparable correlation exists for each individual loss factor, it does provide confidence in the analytical techniques used to calculate the losses.

TABLE III-4
ARCO SOLAR STEOR ENERGY BALANCE SUMMARY
ADJUSTED HISTORY

MONTH	ENERGY (MW-HR)								
	QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QESL	QINJ
JUN 83	307.4	-119.3	188.0	-14.0	-52.6	-30.5	106.8	-16.8	90.0
JUL	316.9	-118.2	198.7	-12.0	-51.0	-30.0	119.7	-8.7	111.0
AUG	142.1	-51.2	91.0	-5.3	-24.0	-16.2	48.7	-3.6	45.1
SEP	231.8	-79.1	153.7	-8.5	-38.9	-27.8	82.7	-3.8	78.9
OCT	187.9	-56.7	131.2	-4.4	-30.7	-25.0	76.9	-4.8	72.1
NOV	25.7	-7.3	18.3	-0.5	-3.9	-4.6	9.8	-0.7	9.1
DEC	38.4	-10.7	27.7	-0.7	-4.9	-9.5	10.5	-1.6	8.9
JAN 84	50.5	-14.2	36.3	-1.0	-7.9	-8.9	18.0	-1.1	16.9
FEB	143.6	-42.0	101.7	-3.1	-22.2	-23.1	50.1	-2.3	47.8
MAR	244.0	-79.0	164.9	-7.8	-40.8	-34.3	81.0	-4.2	76.8
APR	229.0	-80.3	148.7	-8.8	-37.8	-25.1	79.2	-3.6	75.6
MAY	201.6	-76.1	125.5	-9.2	-33.1	-26.3	59.4	-3.3	56.1
TOTALS	2118.8	-734.3	1385.7	-75.2	-347.9	-261.2	742.8	-54.5	688.3
TOTAL FRACTION	1.00	-0.35	0.65	-0.04	-0.16	-0.12	0.35	-0.03	0.32
STEP FRACTION	1.00	-0.35	0.65	-0.05	-0.25	-0.19	0.54	-0.07	0.93

TABLE III-5

ARCO SOLAR STEOR ENERGY BALANCE SUMMARY

WITH FULL OPERATOR AVAILABILITY

MONTH	ENERGY (MW-HR)								
	QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QESL	QINJ
JUN 83	317.5	-123.5	194.2	-14.5	-54.5	-31.6	110.4	-17.4	93.0
JUL	327.5	-122.1	205.3	-12.4	-52.7	-31.0	123.7	-9.0	114.7
AUG	175.3	-66.2	112.2	-6.8	-31.0	-20.9	60.1	-4.5	55.6
SEP	241.4	-82.6	160.1	-8.9	-40.6	-29.0	86.1	-3.9	82.2
OCT	187.9	-56.7	131.2	-4.4	-30.7	-25.0	76.9	-4.8	72.1
NOV	51.4	-14.6	36.6	-1.0	-7.8	-9.1	19.6	-1.4	18.2
DEC	96.0	-26.9	69.3	-1.7	-12.3	-23.7	26.3	-4.0	22.3
JAN 84	75.8	-21.4	54.5	-1.4	-11.9	-13.3	27.0	-1.7	25.4
FEB	148.7	-43.9	105.3	-3.2	-23.2	-24.2	51.9	-2.4	49.5
MAR	253.4	-82.1	171.2	-8.1	-42.4	-35.6	84.1	-4.4	79.8
APR	260.2	-91.3	169.0	-10.0	-43.0	-28.5	90.0	-4.1	85.9
MAY	324.8	-122.7	202.2	-14.8	-53.4	-42.3	95.7	-5.3	90.4
TOTALS	2459.8	-853.9	1611.1	-87.3	-403.5	-314.3	851.7	-62.8	788.9
TOTAL FRACTION	1.00	-0.35	0.65	-0.04	-0.16	-0.13	0.35	-0.03	0.32
STEP FRACTION	1.00	-0.35	0.65	-0.05	-0.25	-0.20	0.53	-0.07	0.93

a. COLLECTOR FIELD LOSSES

The collector field loss (QFLS) is 734.3 MW-h for the year, representing 35 per cent of available insolation energy. The calculation of this parameter included a degradation of ten per cent on the mirror reflectivity of .83, so that the net specular reflectivity of .747 results in 548.5 MW-h, or 75 per cent of the field loss. The remaining 25 per cent (185.8 MW-h) is due to the field cosine factor averaged over the year. Blocking and shadowing within the collector field are small except at very low sun elevation angles, and were neglected. Mirror reflectivity will vary with time as a function of weather conditions and washing schedule. Based upon the overall performance correlations, it appears that the assumed average degradation of 10 per cent was a good approximation. The field cosine factor varies continuously during each day and throughout the year in accordance with sun position. This can be observed in Table III-4 where QFLS ranged from a low of 28 per cent of QSUN in December to a high of 39 per cent in June.

b. APERTURE SPILLAGE LOSS

This calculation was based upon curve fits of receiver radiant heat flux distributions predicted by a separate math model. Although spillage can be relatively high at extreme sun angles (up to 30 per cent at early morning and late afternoon near the summer solstice) the aggregate input power for those conditions is a small portion of the operating total. During the central six to eight hours throughout the year, spillage losses were projected to be small, which was qualitatively verified visually. The yearly totalized energy spilled was calculated to be 75.2 MW-h, or 3.5 per cent of the available solar input. Like the field loss parameter, the spillage varied during the year from a maximum of 4.6 per cent for June to a minimum of 1.8 per cent in December.

c. RECEIVER LOSSES

Thermal losses from the receiver comprised the second largest category of system energy loss, next to collector field losses. The totalized value of 347.9 MW-h represents 16 per cent of QSUN. A more descriptive expression for receiver loss is its proportion of net energy incident upon the absorber surface, which is

$$\frac{QRCL}{QINC-QAPL} = \frac{347.9}{1385.7-75.2} = .265$$

The value of 26.5 per cent is significantly larger than one would expect for a commercially sized utility installation, which should be about 15 per cent of energy incident on the absorber. This effect is caused by the fact that the pilot plant receiver has an absorber area inordinately large in proportion to the design point power input. For a very small system, such as this, the heliostat beams project a large pattern on the receiver plane, relative to slant range, because off-axis aberrations are independent of slant range. This effect was compounded for the STEOR plant due to the use of non-optimum mirror module focal design. Therefore, the design point average heat flux over the absorber surface for this receiver is approximately .1 MW/m2, about 1/3 the value at which a commercial receiver would be sized. In the absence of these non-linearities in scaling of imaging characteristics, the STEOR receiver would have an absorber area 1/3 the actual area of 100 sq ft. Since a large portion of receiver losses (convection and emitted radiation) are a function of receiver area, the overall receiver energy loss is understandably larger than one might expect. A partially mitigating factor is that the STEOR receiver operates at a relatively moderate temperature (550-600 deg F, as compared to 1000 deg F for utility receiver designs) which can explain why the estimated STEOR receiver energy loss is only 60 per cent greater rather than three times the magnitude that would otherwise be expected.

d. STARTUP LOSSES

All energy calculated as absorbed by the receiver prior to the beginning of steam injection each day is categorized as startup loss. Although the totalized value of 261.2 MW-h is only 12 per cent of the available energy (QSUN), it represents 38 per cent of the net energy injected into the oil field. Since most of any reduction in this loss factor would add to the net steam injected, a reduction of energy expended in ramping the system up to injection conditions could increase the overall system efficiency and output significantly. As in the case involving receiver losses, there are characteristics unique to this pilot plant which inevitably worked toward increasing the duration and energy required to get the system into operation on a daily basis. Some of the most applicable factors are discussed below.

MINIMUM GAGE AND SIZING

Due to the small size of this system, much of the design of high pressure steam generation and transport components was influenced by minimum wall thickness and diameter considerations, as dictated by either the ASME boiler code or by engineering judgment. For instance, a decision was made to use nothing smaller than 1 inch diameter for water and 1 1/2 inch diameter for steam piping and tubing, although fluid velocity and pressure drop considerations would have permitted smaller sizes. Also the headers, risers and downcomer in the receiver were all oversized to insure adequate flow distribution and circulation within the boiler circuit. These kinds of design characteristics result in an increased system heat capacity which requires proportionally more energy for startup.

RECEIVER STEAM DRUM WATER INVENTORY

Electrical power backup for the collector field and feedwater pumps was not provided in the STEOR system design. To insure a safe transition of concentrated solar heat flux from the receiver in the event of a utility power failure, the receiver steam drum was purposely oversized to provide sufficient water to maintain a full absorber panel under the most adverse combination of insolation and sun position drift rate. This consideration dictated a steam drum capacity and weight of two to three times that which would normally be specified for this system.

SYSTEM THERMAL ISOLATION TECHNIQUES

Temperatures in most of the water/steam components (receiver boiler, heat exchangers, condensate reservoir and piping) would cool to near ambient overnight, typically reaching 100-150 deg F by morning. Only the receiver steam drum, being relatively compact and more easily isolated, remained relatively hot (325-350 deg F) for daily system startup. The standard industrial techniques used for the design of structural mountings, supports, penetrations and surface insulation are not adequate for properly restricting thermal losses during overnight shutdown. More attention to the analysis and design of these features can potentially produce significant reductions in system startup energy requirements with commensurate increase in useful power production.

e. EQUIPMENT SYSTEM LOSSES

This component of energy loss represents about three per cent of total available insolation energy and just under 8 per cent of net energy delivered to the oil field. This loss results from the same system insulation and structural heat leaks discussed above, the only differentiation being whether the system is operating or dormant. Therefore any improvements in the restriction of overnight thermal losses will also reduce this loss parameter.

4. ENERGY DISTRIBUTION DIAGRAMS

Performance trends for Arco Solar's Fairfield STEOR pilot plant can readily be illustrated through the use of system energy distribution diagrams. These diagrams approximate system energy balances but are not the true equivalent because most of the energy losses are calculated rather than measured.

The distribution of energy for the entire evaluation year of June 1983 through May 1984 is shown in Figure III-12. This is a visual representation of the totalized adjusted energy categories for the evaluation year shown previously in Table III-4. In Section III-A-1 it was stated that the overall energy conversion efficiency (ratio of QINJ/QSUN for the year) of 32 per cent was affected by the significant number of foreshortened operating days through the year, which tend to reduce the efficiency. This effect is clearly illustrated by comparing Figure III-12 to the subsequent two diagrams.

Figure III-13 shows the total energy distribution for the month of July 1983, which was the most productive month of the year and had only four of 30 operational days severely shortened for any reason. The measured energy injected (111 MW-h) was 35 per cent of the 316.9 MW-h available to the collector field. There is an apparent inconsistency if the difference between QINC and QREC (79.0 MW-h, or 24.9 per cent) is compared with the sum of QAPL, QRCL and QSTL (93.6 MW-h, OR 29.6 PER CENT). It must be remembered that the only energy parameters which are truly based upon measured data are QSUN, QREC and QINJ. A likely source of much of the discrepancy is the assumed mirror degradation factor of 10 per cent. The heliostats were all washed on July 2nd and 3rd, and the clear, calm weather that prevailed during this month was conducive to relatively low contamination effects.

The energy distribution for 20 March 1984 is presented in Figure III-14. This day (approximately coincident with the vernal equinox) represented one of the most productive and longest periods of injection for the entire year. Overall energy conversion efficiency was 41 per cent, as compared to the year's average of 32.5 per cent. Also, there is good correlation between measured (5.55 MW-h) and derived (5.4 MW-h) net energy production (within 1.6 per cent of QSUN).

FIGURE III-12
ARCO FAIRFIELD STEOR SYSTEM ENERGY SUMMARY
EVALUATION YEAR TOTAL

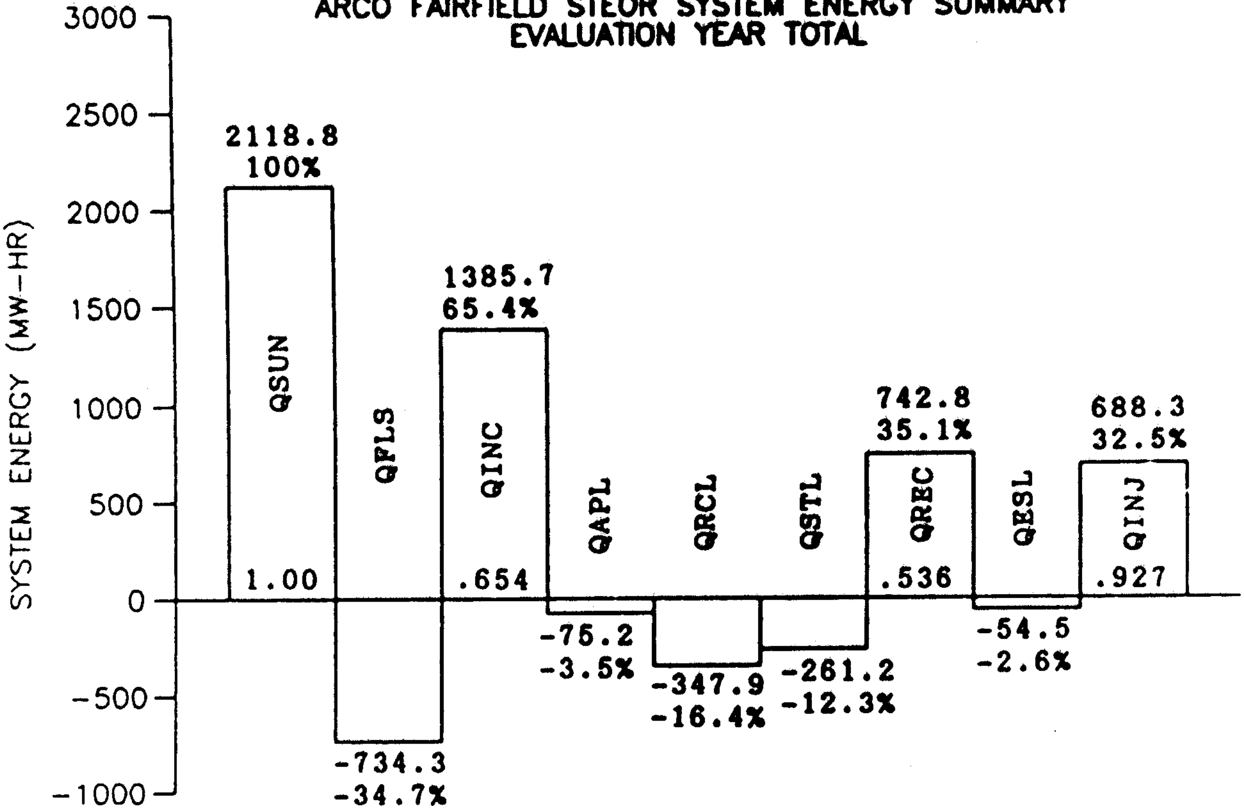


FIGURE III-13
ARCO FAIRFIELD STEOR SYSTEM ENERGY SUMMARY
JULY 1983

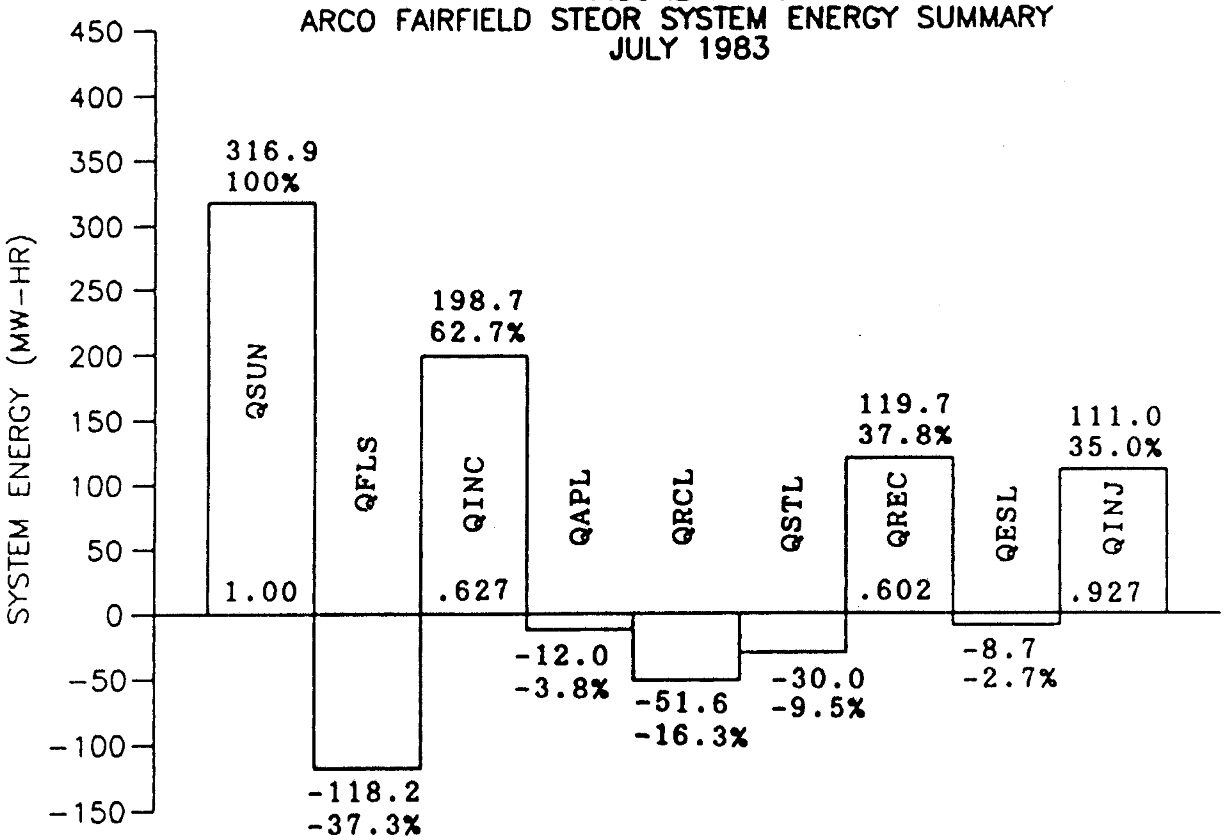
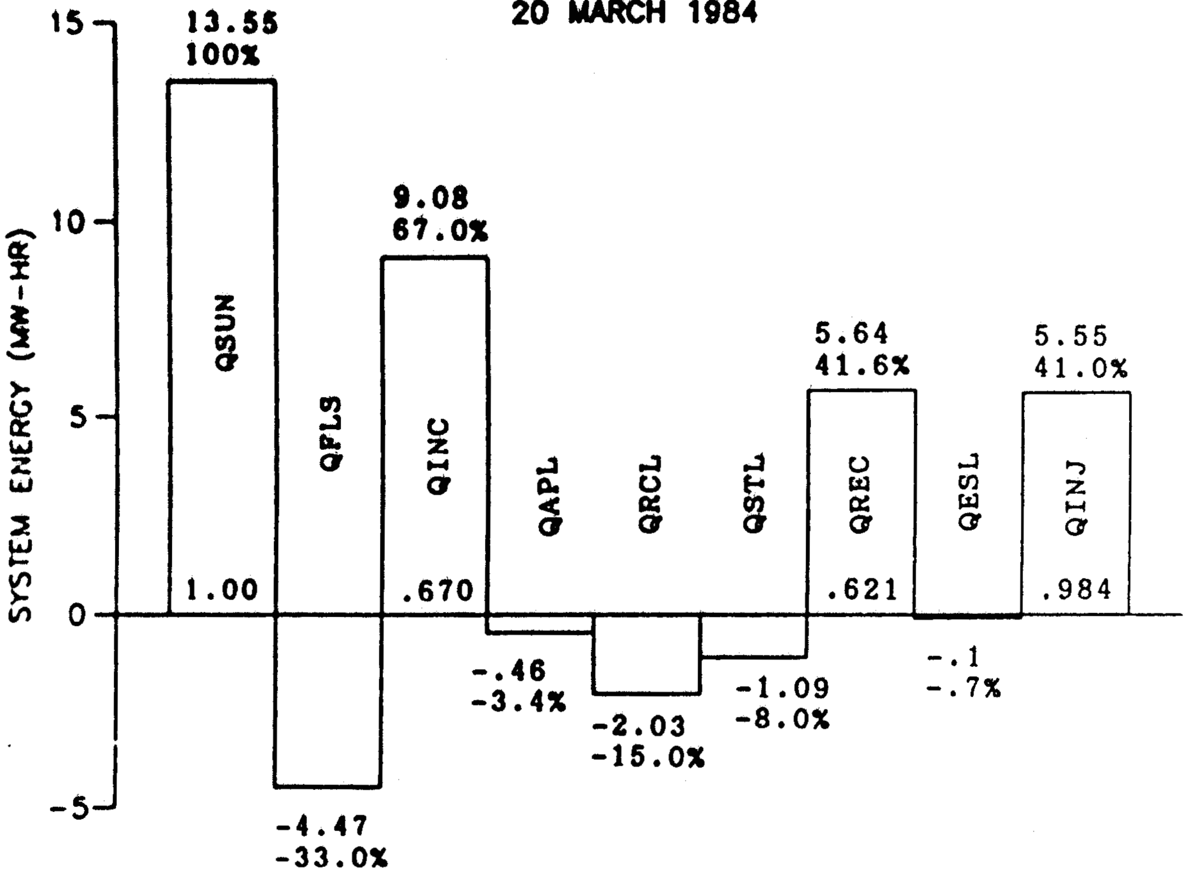


FIGURE III-14
ARCO FAIRFIELD STEOR SYSTEM ENERGY SUMMARY
20 MARCH 1984



The predominant factor producing the high system energy conversion efficiency on 20 March 1984 (41 per cent) as compared to the July 1983 average (35 per cent) and evaluation year average (32.5 per cent) is the lower startup loss fraction. On 20 March the startup loss was 8.0 per cent of QSUN, whereas the July and the year's averages were 9.5 and 12.3 per cent, respectively. These startup loss trends can be directly related to the period of useful steam production which was 8.4 hours for 20 March 1984, and averaged 6.3 and 5.6 hours for July and the entire year, respectively. As discussed in section III-A-3-d, anything which can be done to decrease startup time and increase daily productive operating time will increase system performance efficiency. In addition to those hardware considerations discussed in section III-A-3-d, any reductions in the number of partial day outages due to equipment repair or deficient insolation will also increase system performance efficiency.

IV MAINTENANCE

Maintenance activities at the STEOR facility are categorized into two general classifications, scheduled and unscheduled. Scheduled maintenance involves routine periodic inspections and procedures to detect and correct any hardware deficiencies which might be expected to occur over long periods of operation. Unscheduled maintenance consists of unplanned or irregular procedures usually performed in response to hardware malfunctions resulting in either anomolous operation or immediate shutdown of the system.

Scheduled maintenance normally does not interfere with system operation, as those procedures which require the system to be non-operating can usually be done in the early morning prior to startup, after end-of-day shutdown or during operational outages due to weather or other reasons. There is one notable exception to this, due to the length of time required. The receiver annual inspection requi~es the steam drum to be cooled to ambient temperature, a manway opened and an interior inspection made of the drum internal surfaces by a certified ASME boiler inspector. The manway is then closed and resealed and the system refilled for startup. This procedure will normally consume three days, but because it occurs during the month of November, the chances are high that one or more of those days would be non-operational due to lack of insolation. Heliostat washing can also infringe upon system operation, although it does not require total shutdown. An average of two heliostats are out of operation during this activity, which usually requires two days to complete and is performed at one-to-two month intervals.

It was items of unscheduled maintenance that consumed the most manpower and impacted system operational time most significantly. These usually entailed various instances of hardware failure or malfunction and sometimes required extensive troubleshooting and/or repair procedures to correct. Two items were included that did not involve the STEOR system itself but consisted of repair work performed by oil field personnel on the field steam distribution system. These two items were included to provide a complete accounting of operational/non-operational days, as discussed in Section II.

A chronological summary of all recorded operational outages resulting from system unavailability (due to scheduled maintenance, unscheduled maintenance or other cause) is presented in Table IV-1. Separate accountings were made for complete-day and partial-day outages. There were no operational outages caused by either the master control system or the collector system (although there were instances of individual heliostat malfunctions, to be addressed later). There were 26 days of complete system outage attributed to

TABLE IV-1
STEOR OPERATIONAL OUTAGES RESULTING FROM SYSTEM HARDWARE PROBLEMS

Common Terms:

HX-2	Condenser/Boiler
LL-1	Steam Drum Liquid Level Sensor
LL-2	Condensate Reservoir Liquid Level Sensor

DATE	DURATION		CAUSE OF OUTAGE
	COMPLETE DAYS	PARTIAL DAYS (Hrs)	
1983			
JUN 1-2	1	5	Install new HX-2 flange gasket
14		3	Air compressor elect. wiring
16-17	1	5	Install larger capacity rec. make-up water pump
JUL 13	1		Maintenance on oil field steam header (No STEOR outage)
Jul 19		7	Demonstrate receiver low pressure operation (no maint or repair)
Aug 23-26	4		Fix leak in receiver downcomer flowmeter fitting
Aug 27-29	3		LL-1 and LL-2 recalibration and bleed-in
Oct 12-13		8	Torque & re-torque HX-2 flange bolts
Oct 20-21	1	2	Inj. water low ph. Regenerate resin beds, drain & refill 1000 gal run tank
Nov 6-10	5		Annual receiver inspection
Dec 6-7		8	LL-2 cal. check & bleed
Dec 9	1		Re-work LL-2 installation, cal. & software
Dec 12	1		Re-work LL-2 wiring
Dec 13	1		Replace trim in rec. circuit control valve
Sub-total	19	38	

TABLE IV-1 (Continued)

DATE	DURATION COMPLETE DAYS	DURATION PARTIAL DAYS (Hrs)	CAUSE OF OUTAGE
1984			
Jan 14	1		Replace LL-1 transmitter, cal. & bleed. Bleed LL-2
Jan 22	1		Continued troubleshooting LL-2 anomolies
Jan 27-28	2		Replace LL-2 transmitter, cal. & bleed
Mar 29		7	LL-2 cal. check & bleed. Flushed white crystalline mat'l from sensing line
Apr 2		2	Changed LL-2 transmitter
Apr 25	1		Maintenance on oil field steam header (no STEOR outage)
May 7	1		Relaced LL-2 Sensing lines
May 8	1		Bleed LL-1 sensing lines. Re-calibrate LL-2
May 14		4	Fix leak in sight glass on receiver steam drum
May 16		3	Low inj. feedwater pump. Bleed cylinders
May 17		4	Flush & bleed LL-2 sensing lines
Sub-Total	7	20	
Total	26	58	

some kind of hardware unavailability. There were 15 partial days totaling 58 hours of operational outage. A major portion of all these operational outages can be placed in three specific categories, as illustrated in Table IV-2. Problems with level sensors alone (mostly LL-2) accounted for 11 complete days and 21 hours of partial day outage, amounting to approximately 40 per cent of all system unavailability. The next largest contributors to system outage was the receiver annual inspection and repair of the downcomer leak.

TABLE IV-2
CLASSIFICATION OF HARDWARE PROBLEMS
RESULTING IN SYSTEM OUTAGES

CAUSE	COMPLETE DAYS	PARTIAL DAY HOURS
LEVEL SENSORS	11	21
RECEIVER ANNUAL INSPECTION	5	'
DOWNCOMER REPAIR	4	'
OIL FIELD STEAM LINE	2	'
MISCELLANEOUS	4	37
TOTAL	26	5

A. HELIOSTAT MAINTENACE AND REPAIR

There are only two items of regular maintenance required for heliostats. Lubricant levels in the azimuth and elevation drive cases should be checked every six months and replenished as necessary. Secondly, the mirror surfaces should be washed at intervals of one-to-two months in order to maintain high output performance.

Installation of the STEOR collector field was completed in May 1982, and by the 1st of June was placed in a nightly routine of automated continuous cycling from soon after sunset until just before sunrise. All heliostats were slewed continuously through the entire range of motion in both azimuth and elevation as a means of attaining an accelerated operational history over a short period of time. The number of cycles completed each night varied from 23 in the summer to 34 in the winter, averaging about 28 per night over a year. This procedure continued after the entire STEOR facility became operational, although it was not performed every single night for a variety of reasons. A conservative estimate is that these cycling operations were performed on an average of 240 nights per year. Therefore, each heliostat had logged the equivalent of about 18 years of daily operating cycles by 1 June 1983, and 36 years by 31 May 1984.

Heliostat availability was very high during the operating year. Although no rigorous records were kept of precise duration of each heliostat outage, the number of outages were few, the usual down time was less than an hour, and rarely was a heliostat inoperative as long as a day. Since the Fairfield STEOR heliostats have no battery backup for memory, they lose position during power interruptions of even very short duration. These happenings are not considered as failures or malfunctions, and recovery is a routine procedure which usually consumes no more than 15 minutes to return the unit to operation.

Recorded occurrences of heliostat malfunctions during the evaluation year which required repair or replacement of components are listed in Table IV-3. A reclassification of this information showing the various components replaced is presented in Table IV-4. Repair procedures were performed at a rate of slighty more than one per month. Most of these resulted from malfunctions which became abruptly apparent, such as a total loss of communications or inability to effect motion in either axis. In such cases the isolation and replacement of the faulty module was usually quickly accomplished. Whenever a fault was traced to a pedestal control box or motor assembly, either of those modules could be replaced within 15 minutes and the unit immediately returned to operation.

The most frequent component replaced was the oil seal on the azimuth or elevation drive input shaft. This seal is very similar to a typical automotive wheel bearing seal and required about 20 minutes to replace. Pedestal control box modules were replaced on five occasions, four in response to a communications outages and once as a result of chronic fuse failures. Four drive motor assemblies were replaced due to failures in the Hall Effect encoder module attached to the extended shaft (there were no motor failures). One cable assembly was replaced, bringing the total of heliostat components replaced to 16. In addition, one line driver (a data transfer device which communicates with a group of heliostats and is located in the control room) out of five used required replacement. There was no failure of any of the 120 limit switches installed on the 30 heliostats.

B. RECEIVER MAINTENANCE AND REPAIR

The major item of scheduled receiver maintenance was the annual inspection, which includes an examination of the steam drum internal surfaces for signs of corrosion and

TABLE IV-3
CHRONOLOGY OF HELIOSTAT REPAIR

DATE	UNIT	PROBLEM	RESOLUTION
1983			
Jul 15	A2	Blows fuses	Replaced control box
Aug 15	E3	Oil leak at drive input shaft	Replaced seal
Aug 15	E6	Oil leak at elevation output shaft	Tightened seal flange
Aug 27	(1)	Oil leak at drive input shaft	Replaced seal
Sep 18	C3	Oil leak at drive input shaft	Replaced seal
Sep 23	(2)	Erratic communications	Replaced line driver
Nov 6	E4	No movement in azimuth	Replaced motor ass'y
Dec 22	D3	Lost communications	Replaced control box
1984			
Jan 22	C4	No movement in azimuth	Replaced cable ass'y
Jan 28	C1	Azimuth position errors	Replaced motor ass'y
Feb 17	E1	Elev. position errors	Replaced motor ass'y
Apr 23	D3	Lost communications	Replaced control box
Apr 25	D2	Lost communications	Replaced control box
May 16	C2	Azimuth position errors	Replaced motor ass'y
May 29	E4	Lost communication	Replaced control box

Notes: (1) Replaced on four heliostats, unknown Locations
(2) A control room component which transmits data to a group of heliostats

TABLE IV-4
HELIOSTAT COMPONENT REPLACEMENTS

REPLACED COMPONENT	QUANTITY
Drive input shaft oil seals	6
Control boxes	5
Motor assemblies (includes encoder)	4
Cable assembly	1
Line driver (see note 2 above)	1

deposits. The actual outage time attributed to this procedure was five days. Three days were spent with the drum open for inspection, partly because this was the first known exposure of a natural circulation boiler to a year of routine solar powered operation and partly because of a problem in scheduling the boiler inspector's visit. For subsequent annual inspections, no more than three days of down time should be necessary.

Another item which probably should be scheduled on a somewhat regular basis is repainting of the absorber tube panel. After the receiver had been installed for 18 months and subjected to regular operational cycles for 15 months, substantial degradation was visually apparent. This consisted of some flaking of the paint, appearances of rust from the carbon steel tubes and an apparent lightening of the total surface (absorptivity measurements were not made). The panel was repainted in March of 1984. This procedure was performed on a cloudy day and did not infringe upon operational time.

The item of receiver unscheduled maintenance which consumed the most time involved the leak in the downcomer flowmeter fitting. Of the four days of outage charged to this problem, at least two full days were spent assessing the ramifications of alternative repair approaches regarding the potential necessity for recertification. The actual time required to make the repair was about one hour. One day was expended in locating the leak, cooling and draining the receiver, and about a half day was required to refill the receiver and prepare for startup. This repair and turn-around procedure should require no more than two days of down time to accomplish.

Only two other receiver problems infringed upon potential system operating time. One was a leaking sight glass for visual verification of steam drum liquid level, which penalized operational time by four hours. The other pertained to the steam drum remote level sensors, which required about 2.5 days of total outage time over three separate occasions to investigate and rectify.

C. BALANCE OF PLANT MAINTENANCE AND REPAIR

This part of the system, which includes heat exchangers, pumps, water treatment and other conventional industrial components, was responsible for most of the incurred hardware-induced operating outage time. Seventeen of the 26 complete days and all 58 hours of partial-day of down time is directly chargable to this part of the STEOR system. More specifically, a total of 11 complete days, and 21 hours of partial-day outage was the result of problems within a single functional element herein - the condensate reservoir liquid level remote sensing instrumentation.

In view of general state-of-the-art technology involved, the large amount of system down time caused by remote level sensor problems was excessive. A contributing factor, not recognized until late in the evaluation year, was water chemistry. After a considerable number of recurrent anomolies in this measurement, evidence of a crystalline deposit was found while flushing a sensing line on 29 March 1984. A chemical analysis identified this substance as a sulfite compound, linking its source to the use of excessive hydrogen bisulfite for oxygen removal. One of the most important considerations of water chemistry is insuring a total absence of dissolved oxygen in boiler feedwater, to prevent the extremely rapid tube degradation which can occur at elevated temperatures. This mandates the maintenance of some excess sulfite ion count in the condensate. The margin of detectible sulfite content was apparently too high, and it is possible that the susceptibility to this problem was enhanced by the cyclical temperature characteristics. A program of gradual reduction of hydrogen bisulfite injection rate was initiated. It is considered that this problem, either through more precise control of the hydrogen bisulfite injection rate, the use of a alternative oxygen scavenger or by use of more advanced fiber optics level sensing techniques, can be reduced to an insignificant imposition upon productive operational time.

The entire first day and part of the second day of the evaluation year (June 1 and 2, 1983) were spent replacing the head-flange gasket on the condenser/boiler (HX-2). This was the culmination of a long series of attempts to fix a steam leak in this joint, which was caused by a damaged flange face in the unit as delivered. Although this heat exchanger passed the standard hydrostatic test, the cyclic applications of combined heat and pressure during system operation revealed this problem very early after initial facility activation. The procedure followed on June 1 and 2 entailed the installation of a soft metal gasket with exfoliated graphite on both sides and incrementally torqueing the stud nuts following a prescribed sequence. This was effective in stopping the leak, until some slight leakage again appeared in early October. The stud nuts were re-torqued on October 12 and 13, preventing further leakage for the next five months. Between March 15 and March 20, 1984 five instances of slight leakage were logged, but no additional mention was made until mid-May, when some dripping water was noticed. This seemed to occur only for short periods during the startup transient, and terminated when operating steam conditions were attained.

V PROJECTIONS FOR LARGER EOR SYSTEMS

The experience gained and data produced by the ARCO pilot plant can be very beneficial to the development of larger STEOR installations for commercial use. One of the difficult problems encountered in designing a solar powered system is proper sizing of the facility to insure the desired output capacity, while preventing needless and costly over-design. The operational and performance data presented in Sections II and III, together with effective analysis and design tools, can provide important guidance to the plant-sizing process.

The ARCO STEOR pilot plant experience can also impact the details of system and component design for larger plants, as well as influence the sizing process. In some cases the operational experience illuminates areas for improvement requiring further design or development work. Of equal importance are aspects of the system which proved to be particularly beneficial and warrant strong consideration for use in future systems.

The ARCO Fairfield STEOR data acquired over the period of a year were used as the basis for projecting the size, in terms of heliostats required, and a rough estimate of the capital cost of a larger system which might be representative of a commercial installation.

A. PLANT SIZING

The proper sizing of solar thermal power installations is a difficult task, due largely to the complications and uncertainties of variations in local weather patterns which directly impact system operation and output. Even when a rather complete weather and insolation history is available for a prospective plant site, the problem of constructing a transient math model which realistically simulates the important nuances of that weather history is formidable. Furthermore, the ability to predict the nature and effects of the various operational anomolies which inevitably occur is severely limited. Consequently, the availability of documented operational and performance data from the ARCO facility provides an opportunity to evaluate the performance for larger systems of similar design and functional characteristics which might be considered for future installation in the Kern County area.

There are at least two very possible pitfalls in using the ARCO Fairfield data at face value as guidance in sizing larger systems. First, it has been established that the average insolation during the 12 month data evaluation period was significantly below average for the Bakersfield locale. Effects of differences in actual vs. projected insolation caused by relative variations in atmospheric transmissivity during system operation can be analytically determined with confidence. If the reduced average insolation was caused by total blockage by clouds or fog, resulting in lower than normal operational time, a much more difficult assessment is created. A thorough examination of insolation and weather characteristics compiled by NOAA and the National Weather Service for the evaluation year as compared to "normal" years is required in this case. Otherwise, a collector field sized on the operational history during the evaluation year alone will be conservative to some unknown degree.

The second concern about applicability of the Fairfield data lies in the fact that a pilot plant generally is operated on the basis of different priorities and is subject to different economic criteria than commercial installations. This issue was addressed in Section II regarding operator and hardware availability.

A central receiver STEOR system of the ARCO Fairfield type has been sized to produce the equivalent energy output of a standard 50 million Btu/Hr (input power) crude oil fired steam generator. The net output efficiency (including parasitic steam used for stack gas scrubbing) of these units is about 85 per cent, and normal maintenace/repair needs result in a typical operating availability of 70 per cent. The net annual output for this unit would then be

Actual Yearly Energy = (.85)(.7)(50 MBtu/h)(8760 h/Yr)
= 260,610 MBtu/Yr, or 76,358 MW-h/Yr

In Section III-A-1 it was determined that an ARCO Fairfield type of STEOR plant could operate at an annual performance factor of at least 51.2 per cent. On that basis, an STEOR system which would displace the 50 MBtu/h oil field unit would produce a maximum theoretical yearly output of

Theoretical Yearly Energy = (76,358 MW-h/Yr)/.512
= 149,137 MW-h/Yr

By expressing this performance as a daily average output of 408.6 MW-h/day (146,137/365), an unattainable theoretical criterion is transformed to a performance level which could realistically be produced by the system on a cloudless full day of operation. Through the use of an established system simulation model, the number of heliostats required for this system can be estimated.

Considering the vernal equinox as representative of an average day, a first approximation of collector field size is made using the following equation.

$$Nhe = \frac{QINJ}{(Ins)(Tinj)(Cos)(Ref)(Att)(Fspl)(Reff)}$$

Where: Nhe = Number of heliostats
Ins = Average insolation during the day
Tinj = Time span for injection
Cos = Average field cosine during the day
Ref = Heliostat reflectivity
Att = Atmospheric attenuation
Fspl = Aperture spillage factor
Reff = Receiver efficiency

The procedure then becomes one of generating a heliostat field layout, which is then used in the system simulation model to calculate net system output for the day. If necessary, the number of heliostats are then adjusted and these two steps are repeated until the calculated day's output equals that derived from the theoretical yearly total (408.6 MW-h). As this iterative process closes, system performance should be calculated for several days through the year to determine average performance rather than rely solely on the equinox prediction.

Using this method, it was determined that a collector field consisting of 585 heliostats of 148 m2 each would be required to supplant the 50 MBtu/h steam generator. The collector field was configured to power a north facing receiver atop a 350 foot tower, and is shown in Figure V-1. The field, which has not been optimized, consists of 26 radial rows at radii ranging from 400 feet to 2230 feet from the receiver centerline. The field wedge angle is 120 degrees at row one, decreasing to about 83 degrees at row 26. The entire field would cover slightly less than 100 acres of land.

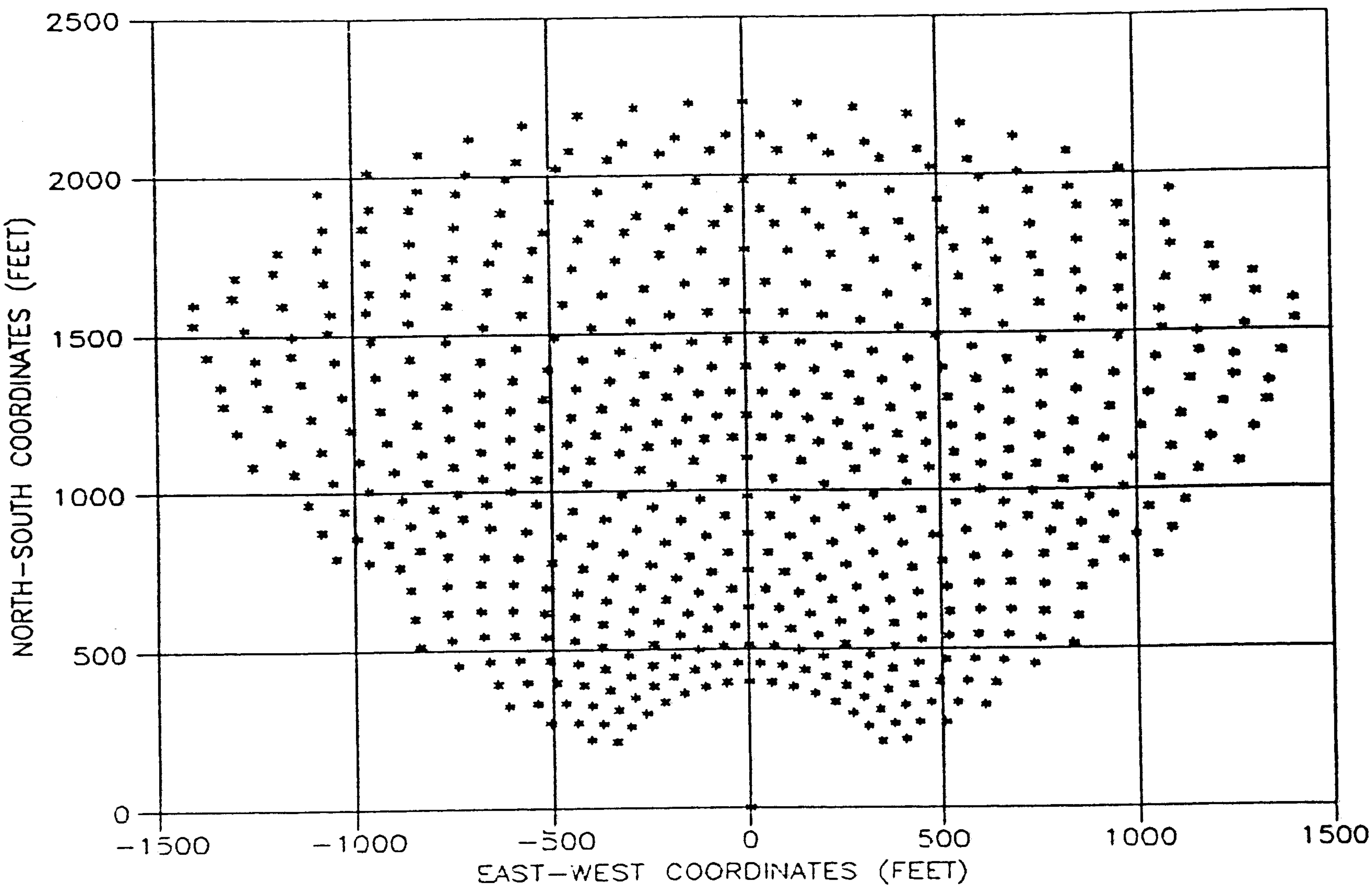
The same system simulation code used for correlating the Fairfield STEOR data was used to generate performance predictions for this large plant, with appropriate changes in input data. Some of the pertinent system design characteristics are given below.

Peak operating insolation:	925 W/m2
Collector field configuration:	Per Figure V-1
Heliostat size:	148 m2
Mirror module design:	4 x 20 ft, continuous spherical curvature per slant range
Mirror reflectivity:	.819 (.91 clean with .9 dust factor)
Receiver size:	170 m2

The above criteria were used to predict ideal performance (clear skies all day and maximum possible operating time)

FIGURE V-1

50 MBTU/HR STEOR HELIOSTAT FIELD
585 HELIOSTATS
HELIOSTAT SIZE: 148 SQ M
TOWER HEIGHT: 350 FT



for the 21st day of each month of the year. An operational output factor for each month (expressed as a ratio of potential QINJ to maximum ideal QINJ) was determined from Tables III-2 and III-3. By applying the output factor to the ideal performance, a value representing expected average injection energy for each month was derived. These relationships are illustrated in Table V-1.

TABLE V-1
50 MBtu/Hr STEOR SYSTEM PERFORMANCE

Month	Operational Output Factor	Energy Produced (MW-Hr)			Steam Produced (MLb)		
		Ideal Day	Ideal Month	Expected Month	Ideal Day	Ideal Month	Expected Month
Jan	.221	381.4	11,823	2,613	1.37	42.5	9.4
Feb	.423	408.2	11,430	4,835	1.47	41.2	17.4
Mar	.547	434.2	13,460	7,363	1.56	48.4	26.5
Apr	.599	429.9	12,897	7,725	1.55	46.5	27.9
May	.615	435.4	13,497	8,301	1.57	48.7	30.0
Jun	.740	433.5	13,005	9,624	1.56	46.8	34.6
Jul	.804	434.8	13,478	10,836	1.57	48.7	39.2
Aug	.426	432.3	13,417	5,716	1.56	48.4	20.6
Sep	.612	422.2	13,088	8,010	1.52	45.6	27.9
Oct	.584	408.6	12,666	7,397	1.47	45.6	26.6
Nov	.184	373.5	11,205	2,062	1.34	40.2	7.4
Dec	.191	361.8	11,216	2,142	1.30	40.3	7.7
Total			151,172	76,642		542.9	275.2

Although appearing under the label of "ideal", the daily energy values of Table V-1 should be attainable, and even exceeded, on good clear days with a peak insolation of 925 W/m2 or above and uninterrupted system operation throughout the day. The term "ideal" in this context applies to consistent recurrence of good clear days peaking at 925 W/m2 every day of each month throughout the year. In this ideal weather environment and in the absence of equipment failure, the 585 heliostat STEOR system would produce 151,172 MW-h of energy in the form of steam injected into the oil field. After applying the operational output factors, which reflect actual weather and equipment induced shutdown time for the ARCO Fairfield pilot plant, the net annual energy which could be realistically expected from the large STEOR system is 76,642 MW-h in the form of 275.2 million pounds of steam injected. This performance is slightly above the 76,358 MW-h previously calculated as the average annual output of a 50 MBtu/h crude oil fired generator. The system would produce 85 per cent of the energy during the eight best months of March through October, at an average of 8124 Mw-h per month, while output would drop to an average of 2272 MW-h per month during the typically poor months of November, December and January.

Predicted thermal power and flowrate characteristics for the large STEOR system on the vernal equinox are shown in Figures V-2 and V-3. Peak steam power produced is 54 MW (184 MBtu/h), which is more than four times the net power produced by a 50 MBtu/h oil fired generator, and injection steam flowrate reaches nearly 200,000 lb/h.

B. PLANT COST ESTIMATE

A preliminary study was performed to estimate the capital cost for design and construction of a 50 MBtu/h STEOR plant. The study was based on a plant using a dual water/steam process of the ARCO Fairfield type, no thermal storage and 585 large area (148 m2) glass heliostats. The study included the evaluation of variations in heliostat capital cost and annual performance factor upon projected cost of the plant.

The plant was divided into four cost categories on the basis of grouping similar types of equipment together. A fifth cost category was added to include indirect costs associated with plant design and construction. The five cost categories are as follows.

1) Collector field - Includes heliostats, control electronics and field wiring
2) Tower
3) Process equipment - Includes receiver, heat exchangers, water treatment equipment, pumps, water reservoirs and all related components such as piping, valves and instrumentation.
4) Controls - Includes master control computer(s), data acquisition and display components, and related components such as supervisory stations, digital/analog converters, and data drivers necessary to communicate data and control signals to and from the collector field and process equipment. This category also includes a beam characterization system to evaluate alignment and tracking characteristics of heliostats.
5) Project engineering and management - includes such functions as engineering analysis, design, contracting, cost control and construction management.

There are no post-construction capitalized costs included for operational and maintenance activities. Also, cost for land was not included on the assumption that these systems would normally be installed on user-owned property. This was not intended to be a sophisticated cost study, and no attempt was made to estimate sublevel

FIGURE V-2

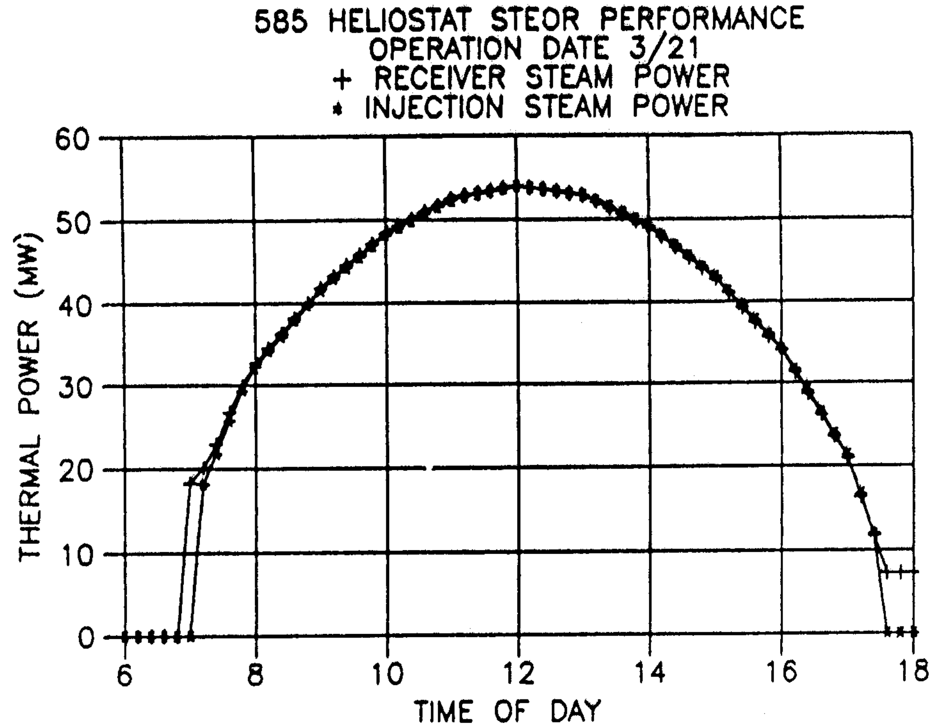
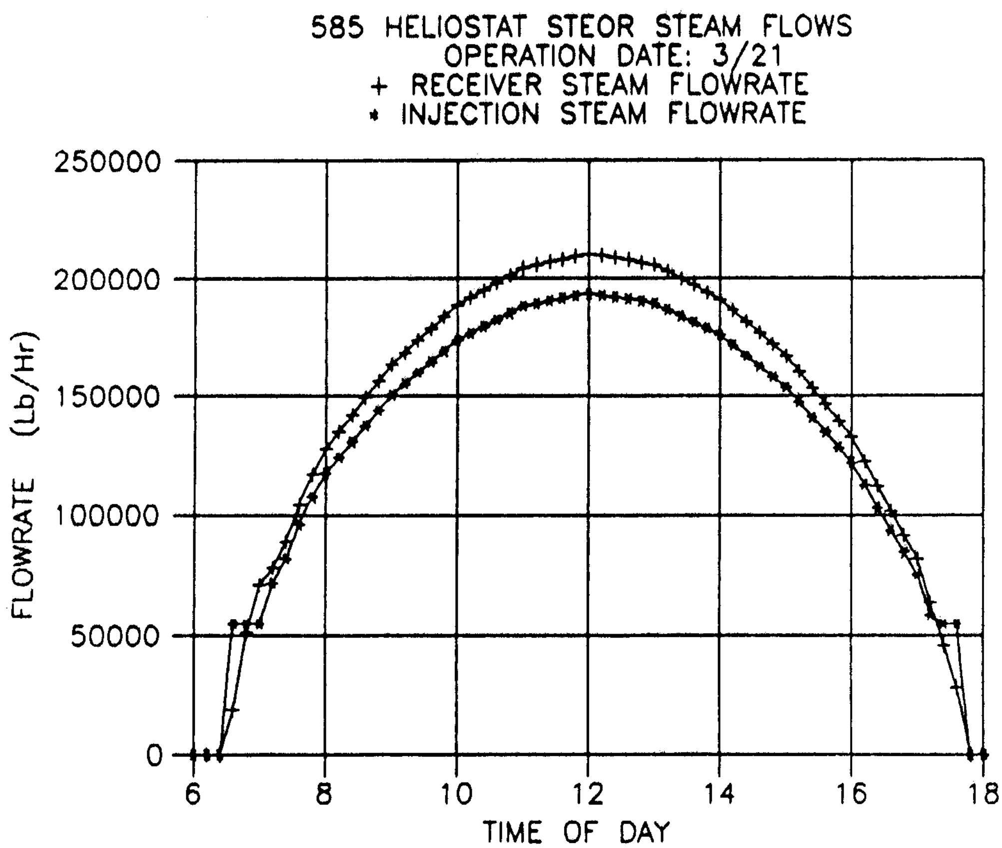


FIGURE V-3



costs below the top categories listed. The estimates are based on a mix of costing techniques from the DELSOL code (ref. DELSOL 3 user's manual by Bruce D. Kistler, SAND 86-8018, Sandia National Laboratories, Livermore CA) and experience in the design and construction of similar systems and subsystems.

The baseline estimated capital cost for the 50 MBtu/h STEOR system is shown in Table V-2. The collector field cost of $13.9 million was based upon heliostats at an installed price of $160/m2. This is lower than current estimates for existing heliostat designs (about $200/m2), and presumes that continued progress will be made in cost reduction - particularly in the area of drives. The tower

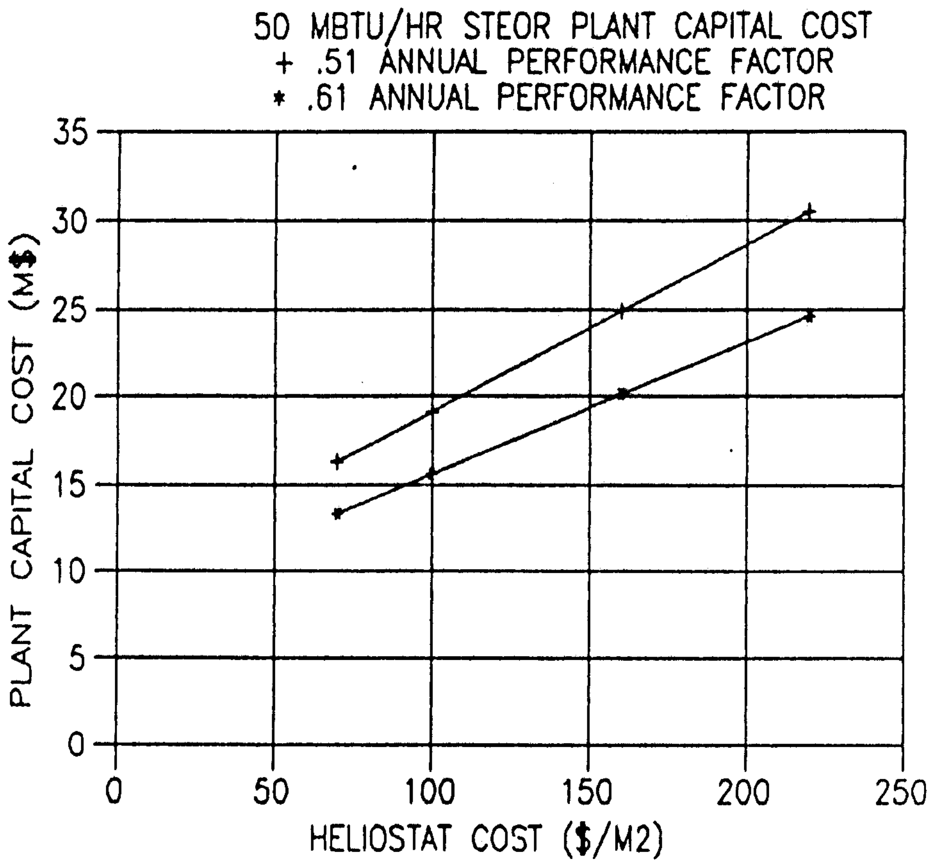
TABLE V-2
585 HELIOSTAT LARGE STEOR PLANT
CAPITAL COST ESTIMATE

COST CATEGORY	COST (M$)
Collector System	13.9
Tower	2.8
Process System	5.5
Master Control System	.4
Subtotal	22.6
Project Engineering and Management	2.3
Total Plant Capital Cost	24.9

cost was determined using the DELSOL algorithm. The process system cost was derived from a combination of costs for existing hardware of a similar nature, techniques from DELSOL, and judgment. The $5.5 million figure is close to the price of five conventional units, which would produce about the same thermal power as the STEOR at peak output conditions. The master control system estimate of $.4 million resulted primarily from experience with previous systems. The subtotal of these four direct cost categories is $22.6 million. Project engineering and management cost was estimated to be ten per cent of direct costs, resulting in a total capital installed cost for the plant of $24.9 million.

The sensitivities of plant cost to heliostat price and annual performance factor were evaluated and are illustrated in Figure V-4. Assuming the successful development of a stretched membrane design which could be produced in quantity for $70/m2, the plant cost could be reduced to $16.3 million. At $120/m2, the most optimistic prediction for glass mirror heliostats, the 50 MBtu/h STEOR would cost $21 million. If a detailed evaluation of insolation history for the selected plant site can justify a higher annual performance factor, then fewer heliostats would be neccessary to produce the same annual output. For a 20 per cent increase in annual performance factor (from 51.2 to 61.4 per cent), the projected plant costs are plotted in Figure V-4.

FIGURE V-4



VI CONCLUSIONS AND RECOMMENDATIONS

The ARCO Fairfield pilot plant served as a very clear and successful demonstration of a steam injection enhanced oil recovery process. The system interfaced very easily with the oil field environment both physically and functionally, and supplied useful steam which supplemented the output of existing gas fired generators for the oil recovery process.

The fully automated control system demonstrated that unmanned operation of a complex solar steam plant is possible with inexpensive computer equipment. Although the ARCO facility was routinely operated in a totally automatic mode, it was not operated without a qualified operater at the site. This was due to a conservative interpretation of provisions of the California boiler regulations (which do not specifically address solar powered systems) that requires the presence of an operator for drum type steam generators. However, based on the ARCO STEOR experience, it is felt that an excellent case can be made for exemption of this type of solar powered boiler for oil field use.

In an overall sense, the technical feasibility of using solar thermal central receiver systems for producing steam for enhanced oil recovery and other process heat applications has been proven. The ARCO STEOR performance and operational experience have produced several conclusions pertaining to this system. These conclusions, and some recommendations related to future systems of similar designs or operational purposes, are discussed in the following paragraphs.

A. COMPATIBILITY WITH OPERATIONAL OIL FIELD ENVIRONMENT

A central receiver system can be easily integrated into an ongoing steam injection oil recovery program. The major potential limitation is availability of sufficient land which is relatively flat. Initial installations would probably be used to supplement oil or gas fired steam generators, wherein some existing pipe runs or other miscellaneous equipment may require relocation (as occurred in the Fairfield installation). Interfacing with an existing steam distribution header is a simple procedure, both mechanically and operationally. Heliostat fields can accomodate the inclusion of oil wells by providing sufficient clearance for periodic well maintenance activites, which would not be a significant spacing penalty for large installations.

Recommendations:

1) Perform more detailed financial assessments to evaluate the economic potential of STEOR systems relative to conventional oil fired units. This would provide an important supplement to the technical information contained herein.

2) Evaluate other potential thermal processes (such as water desalination) which may benefit from the application of a nearly identical central receiver system.

3) Investigate the use of molten salts or other media for the inclusion of thermal storage capability, which could be used to smooth the steam output and/or provide capability for cogeneration.

B. SYSTEM RELIABILITY

The equipment used in these systems is highly reliable. Hardware maintenance and repair as a cause of system down time ranked third behind weather and operator absence. All instances of equipment-related shutdown were associated with conventional process equipment (e.g. level sensors, boiler inspection, water/steam system flanges and fittings, etc.). Total equipment-caused down time of the ARCO STEOR system was 32 days (24 complete days plus 58 hours of partial day outages) as compared to about 110 days for a typical crude oil fired steam generator.

Recommendations:

1) Consider the use of fiber optic or other techniques for remote sensing of liquid levels.

2) Accommodate thermal cycling by using welded joints wherever possible. Where bolted flanges must be used, require rigid final inspection of flange sealing surfaces, provide adequate accessibility for maintenance in the installation design and use gaskets suited to thermal cycling service (preferably with exfoliated graphite).

C. OPERATION AND MAINTENANCE

A solar powered EOR system can be operated by automated computer control and does not require a dedicated control room operator. It is considered that a single technician should be assigned to the facility to periodically check critical operating parameters and perform routine inspection and maintenace procedures on a non-interference basis. The technician would also make minor repairs, which would largely require only the replacement of a modular component. Major repair and maintenance operations would relate almost exclusively to the process equipment (heat exchangers, pumps, valves, control components, etc.) and would be performed in the present manner either by the existing oil field maintenance crew or by contract service personnel.

D. DUAL FLUID SYSTEM DESIGN

The dual water/steam circuit design is a workable method for utilizing high TDS (total dissolved solids) water for injection steam. This is an important factor in EOR operations, because the unavailability and/or cost of sufficient sources of high quality water to feed the open-loop injection steam generation process. This validation of a dual fluid system also has implications regarding the potential use of a heat transfer salt or other fluid in the receiver circuit and the possible inclusion of thermal energy storage capability in future STEOR designs. Such design concepts would entail similar functional and control characteristics as demonstrated by the ARCO system

Recommendations:

1) Investigate the use of molten salts or other media for thermal storage capability, which could be used to smooth the highly variable steam output and/or provide for cogeneration capability.

E. <u>SYSTEM STARTUP RESPONSE</u>
The ARCO STEOR startup losses averaged 38 percent of the net injection steam energy delivered during the evaluation year. A reduction in startup time by a factor of two would have resulted in nearly 20 per cent more steam delivered to the oil field for the same operating history. Startup response is determined by the combined effects of two design characteristics: thermal capacity of the heated fluids and components, and overnight heat losses. The ARCO pilot plant has a high heat capacity relative to energy throughput, partly by choice and partly because it is a small plant; and central receiver scaling characteristics penalize small systems. This problem can be significantly improved in larger installations.

Recommendations:

1) Heat losses must be minimized by innovative design of insulation and structural support for all heated components.

2) Thermal capacity of all heated components, particularly heat exhangers and high pressure fluid storage reservoirs, must be kept to a minimum. Excessive over-design in these areas can be costly to system performance.

APPENDICES

A ARCO STEOR OPERATIONAL DATA SUMMARIES

B STEOR PERFORMANCE SIMULATION MODEL AND PREDICTIONS

APPENDIX A: ARCO STEOR OPERATIONAL DATA SUMMARIES

This appendix consists of a summary of daily and monthly performance parameters from operation of the ARCO Fairfield STEOR pilot plant. Data is presented for 213 of the 230 operational days during during the evaluation year. Data for the remaining 17 days were lost due to problems with replacement of full data discs.

The parameter names used herein are defined below.

QAPL - Energy loss at the receiver aperture due to spillage in MW-h

QFLS - Energy loss due to sun vector cosine and mirror absorption in MW-h

QINC - Energy incident at the plane of the receiver aperture in MW-h

QINJ - Energy in steam at rated temperature from the injection circuit in MW-h

QSTL - Energy expended in heating the water/steam circuitry prior to attaining required injection conditions in MW-h

QRCL - Energy loss from receiver due to reflected insolation, radiation and convection from absorber and conduction through insulation and structure in MW-h

QREC - Energy in steam at rated temperature from the receiver in MW-h

QSUN - Solar energy potentially collectable from system startup to shutdown as determined by the product of insolation and mirror area in MW-h

STM INJ - Mass of steam injected into field header in klb

Most of these parameters result primarily from direct measurements (QINJ, QSTL, QREC, QSUN, STM INJ), while some (QFLS, QINC, QRCL) result primarily from calculation. One parameter, QAPL, is a totally calculated quantity. The parameters obtained primarily or wholly through calculation are included to provide some insight relating to the energy losses they represent.

TABLE A-1
ARCO FAIRFIELD STEOR PERFORMANCE DATA
JUNE 1983

	MAX INS	SYSTEM ENERGY PARAMETERS MW-h								STM INJ
DAY	W/m2	QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	klb
2	803	3.70	1.30	2.40	.07	.38	1.98	.23	.79	.67
5	778	11.05	4.23	6.82	.49	2.00	.86	4.51	3.88	15.30
6	799	7.80	3.01	4.79	.36	1.61	.85	1.92	1.19	6.03
7	774	6.73	2.49	4.24	.23	1.29	.71	2.38	1.74	7.97
8	777	7.60	2.90	4.71	.31	1.34	.88	1.87	1.16	5.12
9	806	11.73	4.53	7.20	.53	2.04	.91	4.77	4.09	16.44
10	819	12.58	4.92	7.66	.61	2.28	.87	5.04	4.06	17.35
11	856	10.68	4.06	6.62	.42	1.87	1.42	3.39	2.78	11.81
12	930	14.78	5.83	8.96	.75	2.49	1.03	5.49	4.76	19.00
13	910	14.23	5.60	8.64	.70	2.39	.91	5.61	4.86	19.27
14	861	11.93	4.58	7.35	.51	1.97	3.21	2.49	1.84	8.71
15	871	10.46	4.06	6.40	.47	1.84	1.16	3.60	2.97	12.19
17	893	5.69	2.21	3.48	.26	1.02	.62	1.92	1.57	6.54
18	942	14.53	5.70	8.83	.69	2.35	.93	5.95	5.00	20.52
19	876	12.15	4.81	7.34	.60	2.08	1.00	4.13	2.75	11.40
20	871	13.18	5.19	7.99	.63	2.23	1.11	4.51	3.86	16.46
21	886	11.74	4.48	7.25	.46	1.81	.99	4.62	4.13	16.29
22	851	12.93	5.09	7.84	.62	2.22	1.01	4.67	4.21	16.74
23	871	13.18	5.19	7.99	.63	2.23	1.11	4.51	3.86	16.46
24	880	11.60	4.48	7.12	.49	1.85	1.30	3.84	3.55	13.73
25	881	13.50	5.31	8.19	.65	2.27	.92	4.98	4.49	17.79
26	891	11.30	4.27	7.03	.42	1.93	.44	4.75	4.47	17.07
27	827	6.06	2.44	3.62	.35	1.13	.81	1.72	1.29	6.20
28	889	12.91	4.99	7.92	.57	2.05	.88	4.54	3.70	15.26
29	873	11.34	4.43	6.91	.53	2.04	1.60	3.35	2.73	11.98
30	897	11.98	4.67	7.32	.56	2.06	.91	4.39	3.89	15.79
TOT		285.36	110.77	174.62	12.91	48.77	28.42	99.18	83.62	342.09
AVG	858	10.98	4.26	4.72	.50	1.88	1.09	3.81	3.22	13.16

SUMMARY

Operational Days:	28 Days
Days Data Available:	26 Days
Average Time of Daylight:	14.26 Hours
Average Time of Injection:	6.68 Hours
Average operating Insolation:	742 W/m2

TABLE A-2
ARCO FAIRFIELD STEOR PERFORMANCE DATA
JULY 1983

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	STM INJ klb
1	878	12.65	4.92	7.73	.59	2.16	.83	4.73	4.36	17.10
2	844	5.11	1.98	3.13	.24	.86	.97	1.34	.95	4.71
3	913	13.39	5.16	8.23	.60	2.15	.85	4.89	4.24	17.53
4	861	10.00	3.81	6.19	.41	1.73	.69	4.06	3.63	14.73
5	889	10.99	4.10	6.88	.39	1.86	.72	4.75	4.54	17.50
6	925	13.29	5.11	8.18	.59	2.24	.79	5.40	4.84	19.82
7	907	9.52	3.47	6.05	.27	1.43	.88	4.00	3.79	14.54
8	906	10.69	3.94	6.75	.35	1.61	.81	4.48	4.00	16.20
9	931	11.30	4.19	7.11	.39	1.83	1.19	4.27	4.06	15.57
10	919	11.15	4.12	7.03	.38	1.78	.80	4.64	4.37	16.91
11	910	11.07	4.10	6.97	.38	1.69	.74	4.69	4.43	17.13
12	907	10.84	4.00	6.84	.37	1.66	.86	4.41	3.93	16.23
14	856	8.67	3.12	5.55	.23	1.30	.82	3.56	3.21	12.71
15	925	10.29	3.78	6.52	.33	1.60	.78	4.35	3.64	15.07
16	902	9.81	3.57	6.24	.30	1.50	.81	4.03	3.76	14.70
17	918	11.06	4.08	6.98	.38	1.66	.70	4.41	4.13	16.07
18	899	11.23	4.17	7.06	.41	1.79	.76	4.53	4.36	16.94
19	906	9.55	3.51	6.04	.32	1.36	3.24	1.47	1.25	5.32
20	914	12.26	4.60	7.66	.48	1.92	.87	4.78	4.39	17.63
21	902	11.64	4.36	7.28	.45	1.67	1.90	3.68	3.45	13.45
22	900	11.61	4.31	7.29	.44	1.84	.75	4.60	4.39	16.97
23	888	13.22	5.05	8.17	.61	2.27	.77	5.09	4.78	18.79
24	888	9.48	3.42	6.06	.29	1.59	.00	4.39	4.27	16.31
25	881	8.64	3.27	5.37	.36	1.33	2.96	2.63	3.30	12.18
26	849	12.06	4.54	7.52	.52	2.07	.96	4.39	4.14	16.08
27	884	11.85	4.39	7.46	.47	1.90	.77	4.57	4.35	17.00
28	864	12.92	4.90	8.03	.59	2.21	.75	4.80	4.55	18.22
29	893	8.29	3.00	5.29	.28	1.25	.71	3.21	2.97	11.80
30	873	6.79	2.51	4.28	.28	1.11	.74	2.23	1.95	8.44
31	883	7.54	2.76	4.79	.28	1.51	1.55	1.28	.94	4.57
TOT		316.91	118.24	198.68	11.98	50.88	29.97	119.66	110.97	440.22
AVG	894	10.56	3.94	6.62	.40	1.70	1.00	3.99	3.70	14.67

SUMMARY

Operational Days:	30 Days
Days Data Available:	30 Days
Average Time of Daylight:	14.05 Hours
Average Time of Injection:	6.26 Hours
Average operating Insolation:	816 W/m2

TABLE A-3
ARCO FAIRFIELD STEOR PERFORMANCE DATA
AUGUST 1983

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h								STM INJ klb
		QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	
1	867	6.38	2.39	3.99	.29	1.06	.83	1.91	1.86	7.46
2	858	11.44	4.19	7.25	.45	1.92	.83	4.28	4.08	15.94
3	885	12.31	4.54	7.76	.52	2.07	.88	4.64	4.37	17.05
4	869	12.16	4.45	7.71	.49	2.08	.81	4.55	4.38	16.96
5	889	8.01	2.75	5.26	.18	1.19	.00	3.77	3.69	14.06
6	744	6.98	2.61	4.38	.33	1.49	2.31	.63	.45	2.10
7	752	5.08	1.82	3.26	.18	1.00	.99	1.23	1.07	4.53
9	806	5.34	1.96	3.38	.23	.87	1.21	1.10	.91	4.04
10	818	5.41	1.87	3.54	.15	.77	1.41	1.20	1.13	4.76
11	877	9.39	3.28	6.11	.29	1.50	.00	4.18	3.72	15.71
12	884	13.42	4.89	8.52	.57	2.20	1.43	4.42	4.26	17.75
13	848	10.39	3.75	6.64	.42	1.75	1.23	3.92	3.36	15.15
16	818	6.96	2.35	4.60	.17	1.11	.68	3.07	2.75	12.19
17	766	3.69	1.24	2.45	.09	.69	.66	1.22	1.11	4.81
TOT		116.96	42.09	74.85	4.36	19.70	13.27	40.12	37.14	152.51
AVG	834	8.35	3.01	5.35	.31	1.41	.95	2.87	2.65	10.89

SUMMARY

Operational Days:	17 Days
Days Data Available:	14 Days
Average Time of Daylight:	13.52 Hours
Average Time of Injection:	4.99 Hours
Average operating Insolation:	736 W/m2

TABLE A-4
ARCO FAIRFIELD STEOR PERFORMANCE DATA
SEPTEMBER 1983

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	STM INJ klb
1	795	5.20	1.75	3.45	.16	1.32	1.47	.64	.40	2.11
2	868	11.22	3.90	7.32	.44	1.94	1.33	4.72	4.54	19.18
3	876	12.93	4.49	8.44	.51	2.22	.78	5.39	5.02	20.44
5	889	12.59	4.33	8.27	.48	2.05	.80	5.41	5.17	20.71
7	835	10.93	3.69	7.25	.38	1.92	.80	4.53	4.31	17.12
8	843	12.88	4.45	8.43	.51	2.31	1.07	4.92	4.46	18.60
9	908	12.94	4.41	8.52	.48	2.27	1.33	4.11	3.50	15.08
10	835	13.18	4.68	8.50	.63	2.20	1.25	4.26	4.08	17.35
11	852	12.36	4.20	8.16	.46	2.03	.92	5.58	5.35	21.54
12	861	12.74	4.34	8.40	.48	2.08	.97	5.38	5.17	20.75
13	877	12.36	4.14	8.22	.42	1.96	3.08	3.90	3.01	12.65
14	810	2.83	1.08	1.75	.18	.48	.95	.58	.31	1.36
15	890	10.67	3.49	7.18	.32	1.69	.38	5.29	5.03	20.08
16	844	11.90	3.95	7.94	.40	1.91	1.00	5.01	4.29	18.07
17	865	12.66	4.21	8.45	.44	2.03	.88	5.57	4.98	21.18
18	881	12.24	4.05	8.20	.41	1.94	.88	5.21	5.16	20.43
19	888	11.81	3.87	7.94	.37	1.90	1.08	4.70	4.27	18.35
20	835	5.39	1.75	3.64	.17	1.46	.58	1.99	1.75	7.74
21	831	5.50	1.81	3.69	.18	1.21	1.73	1.30	.99	3.91
24	821	7.97	2.66	5.31	.29	1.39	2.89	1.07	.73	3.80
25	849	11.14	3.63	7.51	.35	1.79	3.07	2.18	2.11	10.31
27	670	3.60	1.11	2.49	.08	.79	.68	.59	1.02	5.02
TOT		225.04	75.99	149.06	8.14	38.89	27.92	82.33	75.65	315.78
AVG	847	10.23	3.45	6.78	.37	1.77	1.07	3.74	3.44	14.35

SUMMARY

Operational Days:	23 Days
Days Data Available:	22 Days
Average Time of Daylight:	12.28 Hours
Average Time of Injection:	7.14 Hours
Average operating Insolation:	688 W/m2

TABLE A-5
ARCO FAIRFIELD STEOR PERFORMANCE DATA
OCTOBER 1983

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	STM INJ klb
2	784	5.75	1.92	3.83	.16	1.01	1.35	2.07	1.03	4.95
3	787	9.61	2.98	6.63	.24	1.72	1.18	3.83	3.43	14.88
4	836	10.20	3.21	6.98	.29	1.75	.61	4.75	4.69	18.59
5	869	11.24	3.57	7.68	.34	1.94	.72	5.15	5.16	19.90
6	819	6.51	1.97	4.54	.14	1.16	.61	2.65	2.51	10.40
7	831	6.71	2.03	4.68	.15	1.05	2.42	1.19	1.08	4.45
14	826	3.42	1.13	2.29	.13	.63	.00	1.55	1.50	5.85
16	773	8.80	2.65	6.15	.21	1.50	.88	3.59	3.49	13.81
18	748	9.43	2.85	6.57	.24	1.60	1.23	3.58	3.53	13.86
19	796	9.19	2.76	6.43	.22	1.51	.62	4.39	4.00	16.45
21	690	1.37	.42	.95	.04	.24	.00	.76	.78	2.88
22	760	7.36	2.13	5.22	.14	1.11	.62	3.46	3.41	13.30
23	759	7.36	2.13	5.23	.14	1.24	.89	3.59	3.23	13.10
24	819	5.99	1.72	4.27	.11	.92	.72	2.62	2.48	10.07
25	916	9.11	2.62	6.48	.17	1.22	.99	4.36	4.36	16.54
26	861	9.28	2.71	6.58	.19	1.39	.83	4.33	4.30	16.61
27	815	7.13	2.05	5.08	.13	1.01	.84	3.08	2.78	11.37
28	784	3.97	1.13	2.84	.07	.71	1.79	.47	.24	1.38
30	747	4.83	1.36	3.47	.07	.68	2.05	.82	.70	2.99
TOT		137.26	41.34	95.90	3.18	22.39	18.35	56.24	52.70	211.38
AVG	801	7.22	2.18	5.05	.17	1.18	.96	2.96	2.77	11.13

SUMMARY

Operational Days:	26 Days
Days Data Available:	19 Days
Average Time of Daylight:	11.15 Hours
Average Time of Injection:	4.96 Hours
Average operating Insolation:	653 W/m2

TABLE A-6
ARCO FAIRFIELD STEOR PERFORMANCE DATA
NOVEMBER 1983

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h								STM INJ klb
		QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	
3	657	3.34	.97	2.37	.07	.51	1.40	.45	.29	1.53
4	593	3.53	.99	2.54	.06	.72	1.25	.64	.47	2.20
15	909	9.11	2.57	6.54	.17	1.15	1.05	4.30	3.99	16.48
16	861	9.67	2.80	6.88	.21	1.56	.84	4.41	4.36	17.15
TOT		25.65	7.33	18.33	0.51	3.94	4.54	9.80	9.11	37.36
AVG	755	6.41	1.83	4.58	.13	.98	1.14	2.45	2.28	9.34

SUMMARY

Operational Days: 4 Days
Days Data Available: 4 Days
Average Time of Daylight: 10.42 Hours
Average Time of Injection: 4.12 Hours
Average operating Insolation: 601 W/m2

TABLE A-7
ARCO FAIRFIELD STEOR PERFORMANCE DATA
DECEMBER 1983

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	STM INJ klb
1	682	4.41	1.25	3.16	.08	.59	1.66	.78	.65	2.83
5	896	7.13	1.94	5.19	.10	.79	1.54	2.62	2.75	10.41
6	863	8.38	2.37	6.01	.16	1.10	.89	2.20	1.30	6.81
7	866	7.19	2.07	5.12	.15	.92	3.42	.60	.37	2.09
8	833	5.75	1.58	4.18	.09	.88	.20	2.68	2.26	10.10
10	853	5.55	1.54	4.01	.09	.66	1.76	1.60	1.58	6.06
TOT		38.41	10.75	27.67	0.67	4.94	9.47	10.48	8.91	38.30
AVG	832	6.40	1.79	4.61	.11	.82	1.58	1.75	1.49	6.38

SUMMARY

Operational Days:	6 Days
Days Data Available:	6 Days
Average Time of Daylight:	9.85 Hours
Average Time of Injection:	3.59 Hours
Average operating Insolation:	656 W/m2

TABLE A-8
ARCO FAIRFIELD STEOR PERFORMANCE DATA
JANUARY 1984

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h								STM INJ klb
		QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	
5	776	7.52	2.13	5.39	.15	1.15	1.34	3.17	3.23	12.85
6	725	.94	.29	.65	.03	.15	.03	.42	.35	1.49
24	747	7.29	2.08	5.22	.15	1.07	1.78	2.20	2.10	8.61
25	795	8.80	2.51	6.29	.18	1.34	1.18	3.49	3.41	13.74
26	718	5.08	1.44	3.65	.10	1.10	1.92	.48	.31	1.08
29	891	8.26	2.31	5.95	.14	1.07	1.21	3.67	3.44	16.50
30	877	6.41	1.77	4.64	.09	.92	.66	2.29	2.16	9.41
31	843	6.20	1.74	4.46	.11	1.08	.81	2.30	1.94	8.67
TOT		50.50	14.27	36.25	0.95	7.88	8.93	18.02	16.94	72.35
AVG	797	6.31	1.78	4.53	.12	.99	1.11	2.25	2.12	9.04

SUMMARY

Operational Days: 8 Days
Days Data Available: 8 Days
Average Time of Daylight: 10.14 Hours
Average Time of Injection: 4.02 Hours
Average operating Insolation: 645 W/m2

TABLE A-9
ARCO FAIRFIELD STEOR PERFORMANCE DATA
FEBRUARY 1984

DAY	MAX INS W/M2	SYSTEM ENERGY PARAMETERS MW-h								STM INJ KLB
		QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	
2	750	2.92	.85	2.07	.07	.34	1.66	.07	.06	.31
3	756	3.68	1.02	2.66	.05	.61	1.23	.49	.33	1.50
4	718	5.45	1.53	3.93	.09	.80	1.04	1.80	1.62	6.65
5	620	5.56	1.57	3.98	.10	1.11	.89	1.80	1.35	6.41
6	749	5.80	1.65	4.15	.11	.89	.86	1.72	1.60	6.36
7	849	8.02	2.29	5.73	.15	1.13	1.07	2.87	2.69	11.07
8	611	3.31	.96	2.35	.07	.55	1.34	.38	.40	1.60
9	764	2.21	.59	1.61	.02	.32	.93	.38	.53	1.34
10	911	4.88	1.38	3.51	.08	.77	1.74	.76	.52	2.89
12	883	8.47	2.46	6.01	.18	1.17	1.43	2.93	2.85	11.19
18	875	5.68	1.69	3.99	.14	.88	.00	3.01	3.25	12.09
19	902	10.86	3.21	7.65	.25	1.61	1.08	4.50	4.73	18.37
22	876	6.28	1.87	4.41	.15	.97	1.11	2.11	2.20	8.83
23	901	10.09	3.01	7.08	.24	1.44	.75	4.34	4.49	17.50
24	783	7.62	2.25	5.37	.17	1.31	.95	2.83	2.73	11.28
25	835	9.36	2.82	6.54	.23	1.56	.82	3.79	3.36	14.72
26	849	9.60	2.91	6.69	.24	1.55	.85	4.07	4.08	15.71
28	817	7.72	2.30	5.42	.17	1.09	1.32	2.64	2.22	9.67
TOT		117.51	34.36	83.15	2.51	18.10	19.07	40.49	39.01	157.49
AVG	803	6.53	1.91	4.72	.14	1.01	1.06	2.25	2.17	8.75

SUMMARY

Operational Days:	22 Days
Days Data Available:	18 Days
Average Time of Daylight:	10.78 Hours
Average Time of Injection:	4.19 Hours
Average operating Insolation:	619 W/m2

TABLE A-10
ARCO FAIRFIELD STEOR PERFORMANCE DATA
MARCH 1984

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	STM INJ klb
1	805	7.31	2.19	5.13	.16	1.21	.88	2.84	2.72	10.96
3	790	6.75	2.05	4.70	.16	1.07	1.15	2.60	2.34	9.46
4	877	10.87	3.36	7.51	.29	1.83	.73	4.75	4.66	18.36
5	894	11.86	3.69	8.17	.33	1.92	.91	5.02	5.20	19.59
6	871	9.40	2.93	6.47	.26	1.60	.98	3.57	3.24	13.99
8	806	6.54	1.99	4.54	.15	1.00	1.18	2.14	1.85	8.09
9	819	9.67	2.98	6.69	.24	1.46	1.13	3.72	3.67	14.45
10	873	10.93	3.44	7.49	.31	1.75	1.48	3.74	3.60	14.67
11	874	5.92	1.91	4.01	.19	.95	.94	1.25	1.08	4.84
13	821	4.60	1.54	3.06	.18	.80	1.39	.88	.71	3.20
15	899	9.04	2.97	6.07	.32	1.80	1.11	2.09	1.80	8.06
16	890	10.19	3.26	6.93	.30	1.61	.88	4.40	4.35	17.01
17	819	9.35	3.03	6.32	.29	2.06	1.20	3.09	3.02	12.02
18	831	6.05	1.93	4.11	.17	1.08	.97	1.95	1.67	7.49
19	911	12.87	4.20	8.67	.41	1.91	1.06	5.65	5.53	21.96
20	956	13.55	4.47	9.08	.46	2.03	1.09	5.64	5.55	21.84
21	823	6.17	2.07	4.09	.23	1.32	2.11	.43	.32	1.70
22	950	14.04	4.68	9.36	.48	2.32	1.10	5.67	5.65	22.16
23	922	12.22	4.00	8.22	.38	1.82	1.01	5.06	4.92	19.56
24	841	9.32	3.17	6.14	.36	1.91	1.02	2.80	2.39	10.87
25	709	4.89	1.59	3.30	.15	1.02	1.57	.39	.20	1.15
26	851	6.11	1.91	4.20	.13	.96	1.35	.67	.26	1.47
27	982	15.23	5.17	10.06	.57	2.40	1.18	5.88	6.00	23.53
28	936	12.89	4.32	8.57	.45	2.17	1.13	4.72	4.32	18.67
29	873	12.54	4.24	8.30	.46	1.92	5.77	.54	.38	2.08
30	942	5.66	1.98	3.68	.25	.83	1.19	1.50	1.41	5.90
TOT		243.97	79.07	164.87	7.68	40.75	33.44	80.99	76.84	313.08
AVG	868	9.38	3.04	6.34	.30	1.57	1.33	3.11	2.96	12.04

SUMMARY

Operational Days:	26 Days
Days Data Available:	26 Days
Average Time of Daylight:	11.84 Hours
Average Time of Injection:	5.69 Hours
Average operating Insolation:	690 W/m2

TABLE A-11
ARCO FAIRFIELD STEOR PERFORMANCE DATA
APRIL 1984

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h								STM INJ klb
		QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	
2	911	8.66	2.90	5.76	.29	1.46	1.13	2.29	1.68	7.77
3	860	11.16	3.73	7.43	.37	1.75	1.68	3.76	3.38	15.23
4	847	5.60	1.93	3.66	.23	.92	.92	1.67	1.44	6.63
7	927	12.03	4.02	8.00	.39	1.69	1.46	4.74	4.79	18.30
8	809	3.07	1.12	1.95	.16	.52	.86	.51	.34	1.70
9	964	10.21	3.46	6.74	.35	1.53	1.12	3.03	2.71	11.71
10	877	7.25	2.58	4.68	.32	1.43	1.49	1.77	1.71	6.80
11	946	14.19	4.89	9.30	.52	2.19	1.44	5.47	5.65	21.35
12	897	12.84	4.48	8.38	.50	2.12	.87	5.24	5.34	20.45
13	908	12.73	4.50	8.23	.53	2.11	1.31	4.82	4.78	18.81
14	911	13.37	4.61	8.76	.48	2.12	1.68	5.05	5.00	19.43
15	919	9.08	3.08	6.00	.28	1.43	.82	3.73	3.66	14.42
16	931	10.22	3.54	6.68	.37	1.75	.92	3.98	3.84	15.56
17	902	12.00	4.11	7.89	.40	1.97	1.38	4.37	4.34	16.88
18	913	6.43	2.31	4.12	.29	.97	1.66	1.30	1.07	4.89
23	921	13.56	4.88	8.68	.57	2.28	1.44	4.59	4.32	17.50
24	908	12.53	4.56	7.96	.55	2.24	.78	4.01	3.94	15.74
26	916	9.84	3.66	6.19	.47	1.84	1.17	3.09	2.75	12.27
27	888	12.31	4.54	7.78	.56	2.15	.75	4.61	4.16	17.51
28	889	10.32	3.58	6.74	.33	1.82	.69	4.04	3.95	15.79
29	868	10.76	3.86	6.90	.42	1.81	.75	4.13	4.02	16.24
30	839	10.84	3.99	6.85	.48	1.78	.84	2.99	2.72	12.08
TOT		229.00	80.33	148.68	8.86	37.88	25.16	79.19	75.59	307.06
AVG	898	10.41	3.65	6.76	.40	1.72	1.14	3.60	3.44	13.96

SUMMARY

Operational Days:	22 Days
Days Data Available:	22 Days
Average Time of Daylight:	12.90 Hours
Average Time of Injection:	6.18 Hours
Average operating Insolation:	770 W/m2

TABLE A-12
ARCO FAIRFIELD STEOR PERFORMANCE DATA
MAY 1984

DAY	MAX INS W/m2	SYSTEM ENERGY PARAMETERS MW-h								STM INJ klb
		QSUN	QFLS	QINC	QAPL	QRCL	QSTL	QREC	QINJ	
1	861	5.37	2.05	3.32	.29	.98	1.15	1.04	.79	3.93
2	951	14.24	5.30	8.94	.67	2.48	.86	4.97	4.91	19.24
3	946	14.90	5.62	9.28	.74	2.60	.85	5.44	5.52	21.22
9	919	14.08	5.37	8.72	.70	2.36	1.56	4.37	4.13	16.79
10	948	15.79	6.05	9.74	.82	2.66	1.02	5.66	5.21	22.29
11	947	13.42	5.03	8.39	.60	2.25	.92	4.79	4.84	18.68
12	948	8.85	3.07	5.78	.22	1.08	2.34	2.15	2.13	8.30
14	891	7.02	2.53	4.48	.24	.88	3.25	.30	.80	1.12
15	882	5.95	2.08	3.87	.14	.96	.74	2.05	1.52	6.98
16	922	11.74	4.37	7.36	.49	1.85	1.06	2.80	1.48	7.01
17	817	5.56	2.13	3.44	.27	1.00	.87	1.40	1.27	5.35
18	913	13.92	5.29	8.63	.64	2.16	2.82	3.47	3.40	13.27
21	944	14.15	5.40	8.75	.65	2.29	1.43	4.76	4.73	18.35
22	944	16.02	6.30	9.72	.86	2.63	1.11	5.37	5.24	20.89
23	927	15.07	5.87	9.21	.77	2.77	1.20	5.01	4.73	19.31
25	956	13.00	5.01	7.99	.60	2.08	2.13	3.55	3.59	13.71
30	831	4.78	1.79	3.00	.18	.89	1.35	.63	.45	1.99
TOT		193.86	73.26	120.62	8.88	31.92	24.66	57.76	54.74	218.43
AVG	911	11.20	4.23	6.97	.51	1.84	1.46	3.30	3.12	12.46

SUMMARY

Operational Days:	18 Days
Days Data Available:	18 Days
Average Time of Daylight:	13.78 Hours
Average Time of Injection:	5.68 Hours
Average operating Insolation:	815 W/m2

APPENDIX B: STEOR PERFORMANCE SIMULATION MODEL AND PREDICTIONS

A transient math model was used to predict operational and performance characteristics of the ARCO STEOR system. This model contains all major elements of the actual system, including collector field, receiver, heat exchangers and the receiver condensate reservoir. In addition, the model contains sufficient control logic characteristics to produce a realistic simulation of important system startup sequences.

Optical performance of the collector field is calculated in accordance with daily and seasonal sun position variations. A simplified sun vector algorithm is used to determine azimuth/elevation angles and beam cosines for each heliostat. Mirror reflectivity is calculated as the product of the clean surface value (.83) and a dirt attenuation factor. Receiver aperture spillage is approximated by use of an algorithm derived from aperture plane heat flux distributions over the range of daily and seasonal variations, which were calculated previously with a separate computer model. Since the heliostat/receiver distances are small for this installation, atmospheric attenuation of reflected beam power was not considered.

Heat losses due to reflection, reradiation and convection from the absorber panel and losses through receiver insulation and structure are calculated using standard heat transfer relationships. The mass, heat capacity and heat transfer characteristics of elements in the water/steam circuits are modeled to replicate the thermodynamic response to the application and variation of thermal power loads. Heat exchanger calculations are included to predict realistic variations in temperatures, pressures and steam quality throughout the system, particularly during startup transients.

The math model can simulate system startup in both the serial mode (where the receiver is ramped all the way to operating pressure before steam is extracted from the drum) or the parallel mode (where receiver steam bled off early during startup to heat the entire water/steam circuitry simultaneously. When conditions for receiver steam flow have been met, the flowrate is calculated by an energy balance of the receiver. Injection circuit water/steam flowrate is then set to a specified fraction of receiver flowrate, just as is done during actual operation by the master control system. Injection water temperature at the condenser/boiler outlet is calculated during heatup until the saturation temperature corresponding to injection pressure set-point is reached, then a steam quality calculation replaces the temperature calculation.

The system math model was used to simulate actual STEOR system operation for several of the operational days during the evaluation year. The days selected were relatively good operating days, with no cloud induced or other operating interruptions. An insolation algorithm was devised which closely approximated the overall shape of the intensity-time curve throughout the day, so it was necessary to change only the daily peak insolation value and the date to perform these runs. A summary comparison of energy predicted energy production to the actual measured performance is presented in Table B-1. Power and steam flow comparisons for each of these days are included as Figures B-1 through B-32. Predicted performance correlates with actual data very well. The prediction for available sun energy (QSUN) averages about 5 per cent above values derived from measured insolation data, which could be due to an inferior insolation algorithm, differences in actual vs predicted operating durations, or more likely, a combination of these factors. The key point is that the model provides a very good, though slightly conservative, representation of actual system operating performance.

The primary value of this model is for use as a tool in the assessment of potential system design improvements, and ultimately for generating realistic performance characteristics of commercially sized installations of this type (as described in Section V).

The system simulation model was used to evaluate optical enhancements of the STEOR heliostat mirror modules, which are low in performance by today's standards. Table B-2 presents predictions of system performance with these enhancements, which consisted of 1) increasing the reflectivivity from .83 to .91 (clean value), and 2) use of continuous contoured mirror modules focused at actual slant ranges, in addition to the higher reflectivity. These conditions were run for the operational days of 22 June 1983 and 20 March 1984, respectively. In comparason to predictions for the existing system shown in Table B-1, the upgrade in mirror module design could increase system performance by 20 per cent.

TABLE B-1 COMPARISON OF ACTUAL/PREDICTED STEOR SYSTEM PERFORMANCE

DATE	ENERGY (MW-h) QSUN ACT	QSUN PRED	QREC ACT	QREC PRED	QINJ ACT	QINJ PRED	STM INJ (klb) ACT	STM INJ (klb) PRED
6/9/83	11.8	12.6	5.2	4.7	4.1	4.1	16.6	16.1
6/22/83	12.9	13.2	5.1	5.1	4.2	4.4	16.7	17.3
7/6/83	13.3	14.6	5.7	5.6	4.8	5.0	19.8	19.3
7/23/83	13.2	13.8	5.4	5.4	4.8	4.8	18.8	18.4
8/3/83	12.3	13.5	4.9	5.4	4.4	4.8	17.1	18.4
9/18/83	12.2	12.2	5.2	5.2	5.2	4.9	20.4	19.1
3/4/84	11.3	11.8	4.9	5.2	4.7	4.9	18.4	19.1
3/20/84	13.6	13.5	5.6	5.8	5.6	5.7	21.8	21.9
AVERAGE	12.6	13.2	5.3	5.3	4.7	4.8	18.7	18.7

TABLE B-2 STEOR SYSTEM OPTICAL PERFORMANCE ENHANCEMENTS

DATE	CONDITION	QSUN (MW-h)	QRST (MW-h)	QISTM (MW-h)	STM INJ (klb)
6/22/83	"As is" configuration	13.2	5.1	4.4	17.3
	Add .91 reflectivity mirrors	13.4	5.7	5.0	19.6
	Add State-of-art mirror modules	13.6	6.0	5.4	20.8
	Add 950 W/M2 Insolation	15.5	7.0	6.3	24.3
3/20/84	"As is" configuration	13.5	5.8	5.7	21.9
	Add .91 reflectivity mirrors	13.6	6.6	6.4	24.6
	Add State-of-art mirror modules	13.6	6.8	6.7	25.4

FIGURE B-1

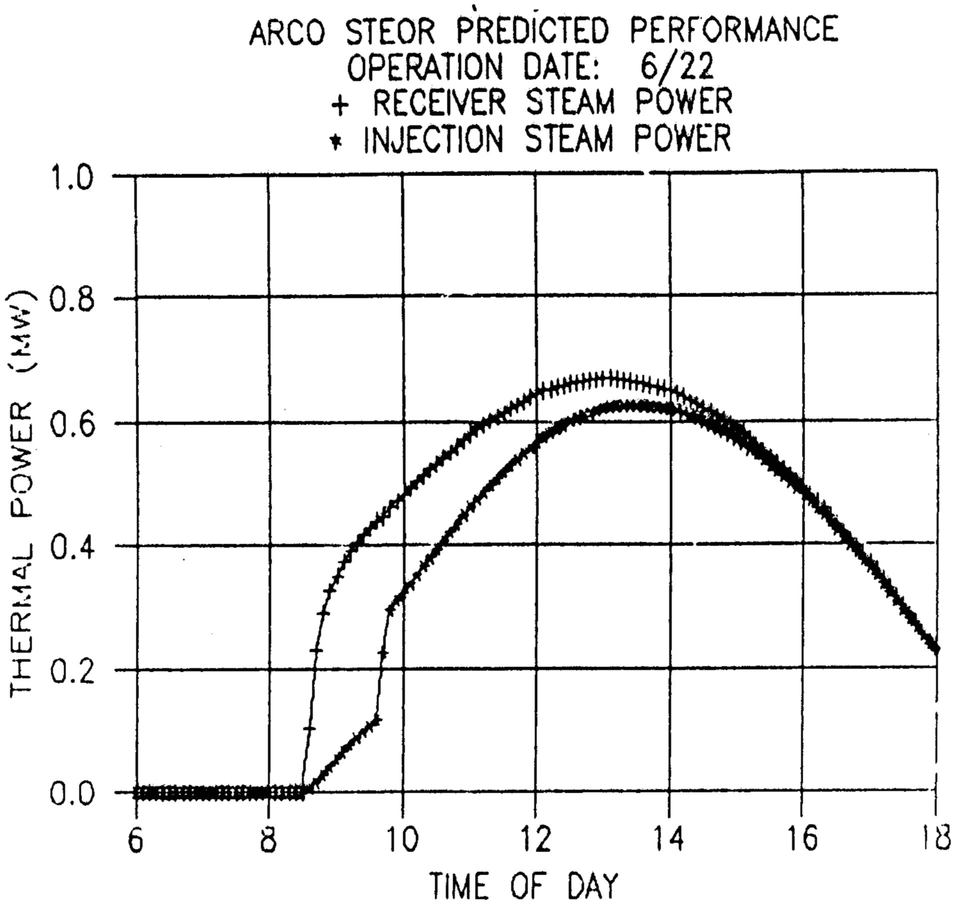


FIGURE B-2

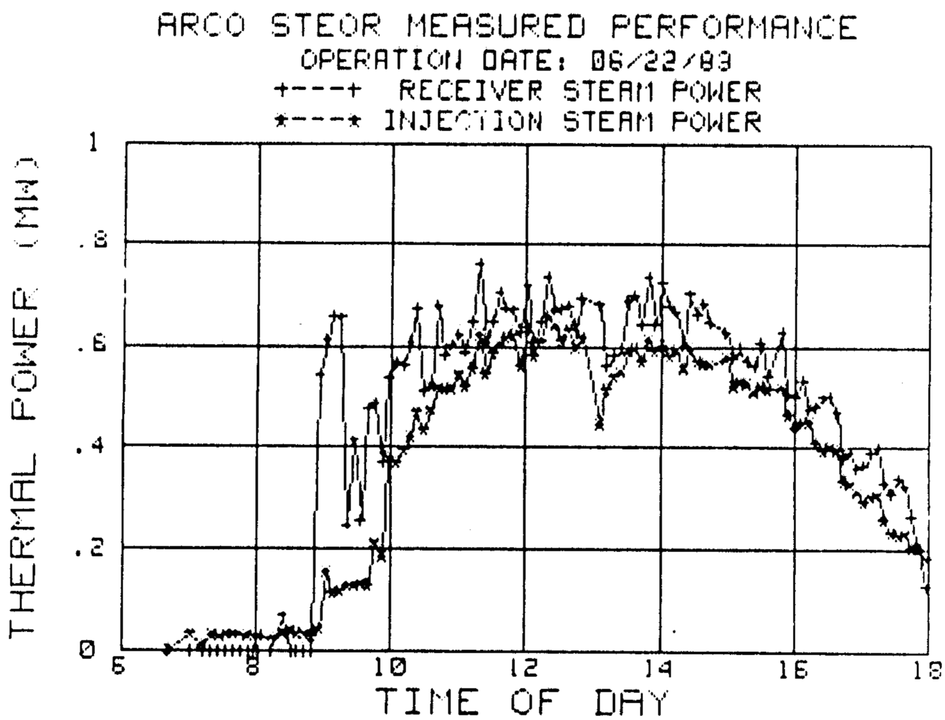


FIGURE B-3

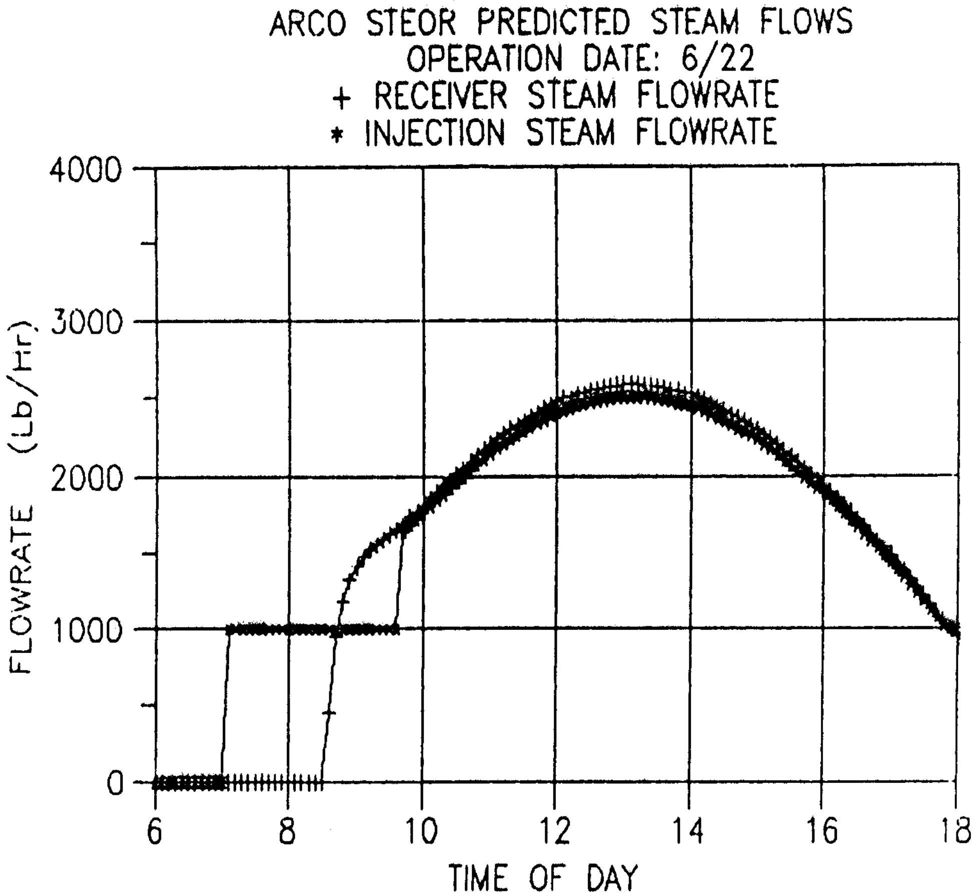


FIGURE B-4

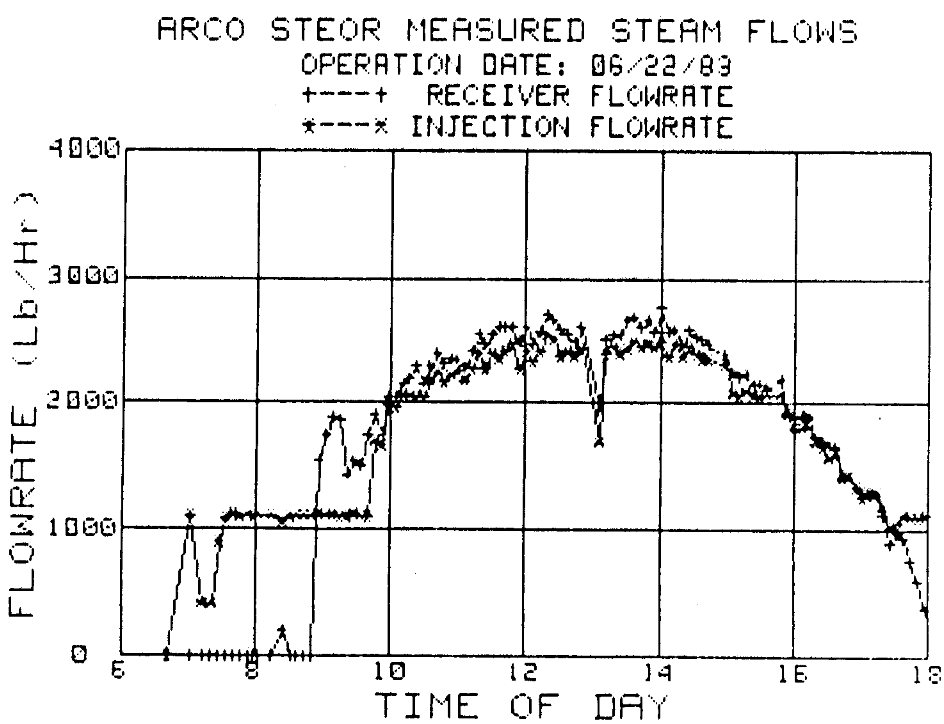


FIGURE B-5

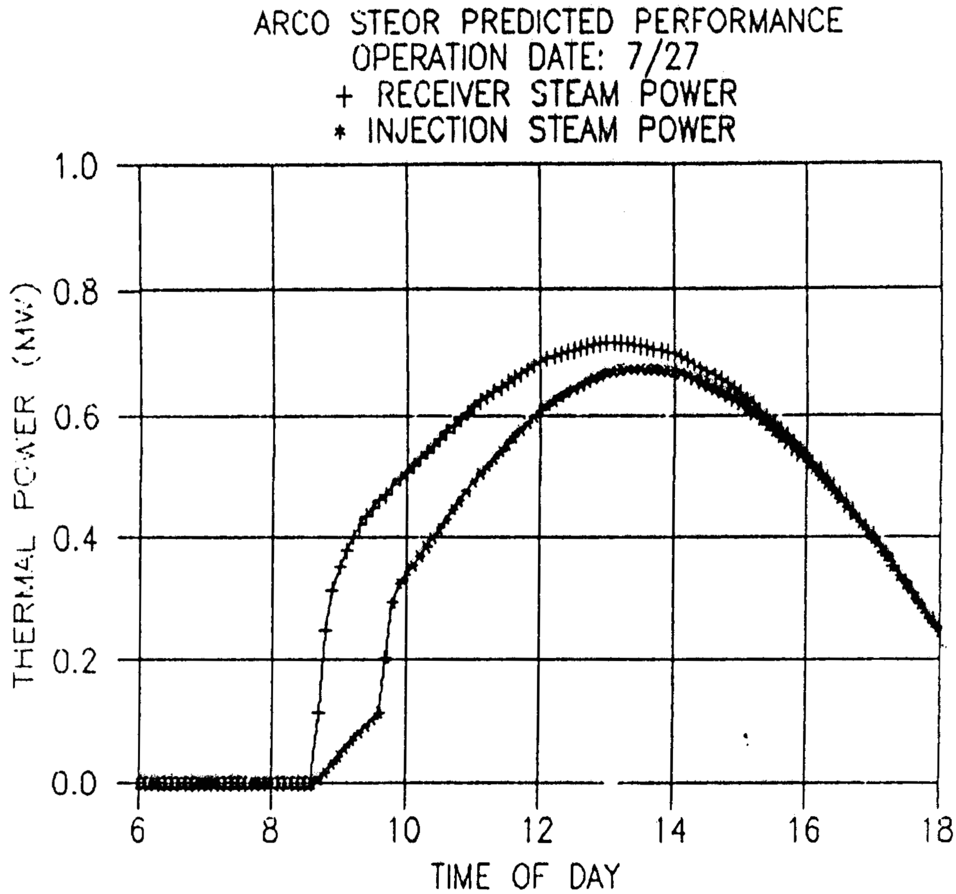


FIGURE B-6

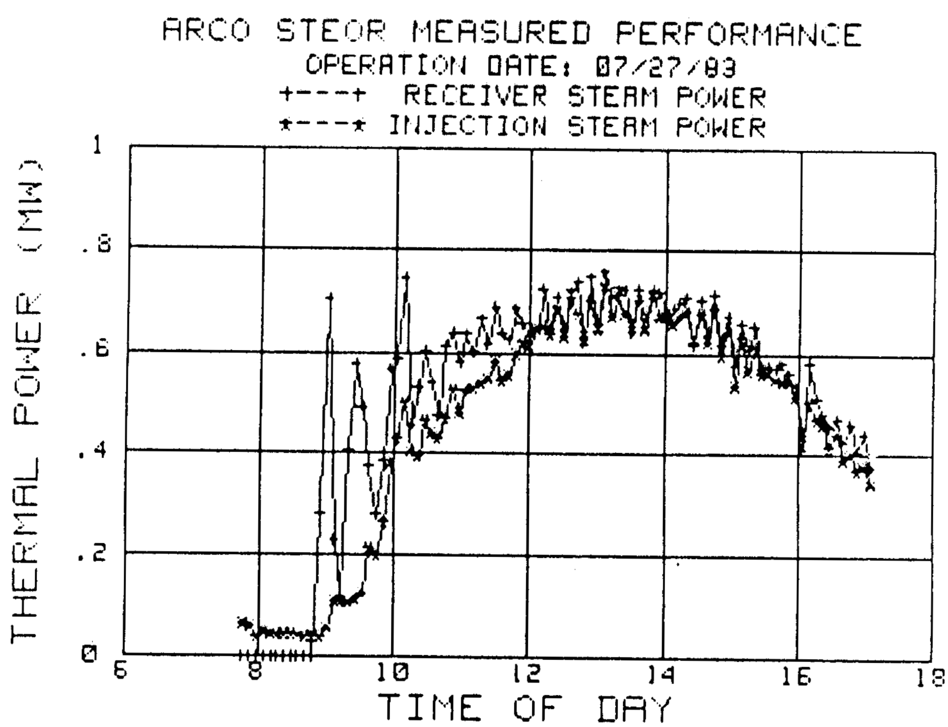


FIGURE B-7

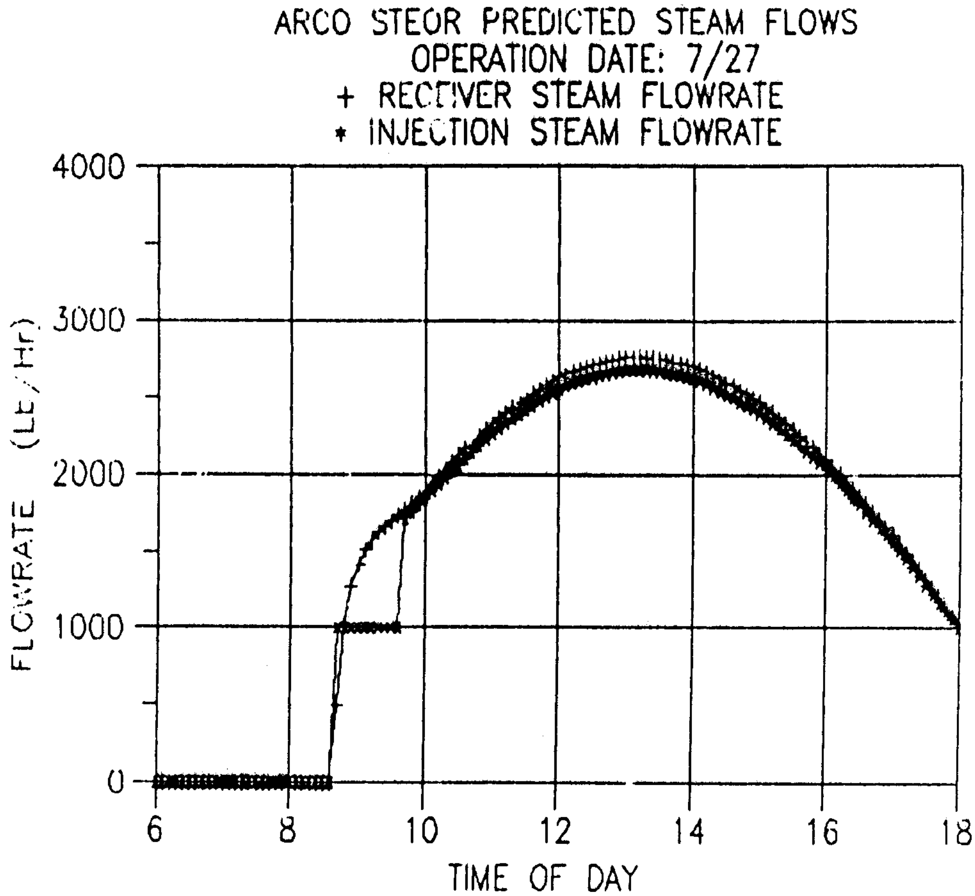


FIGURE B-8

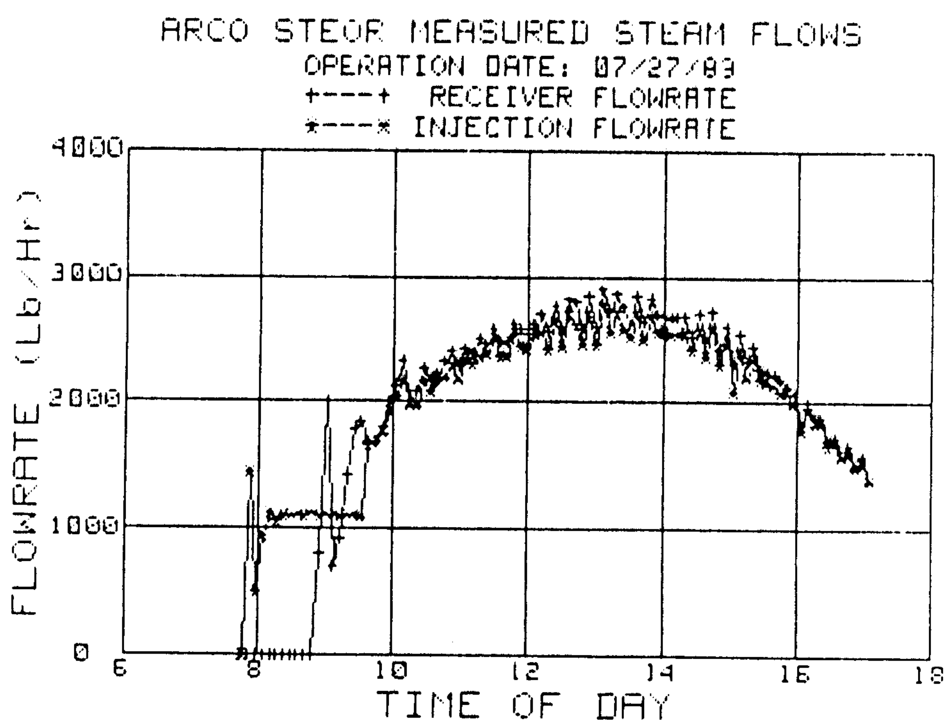
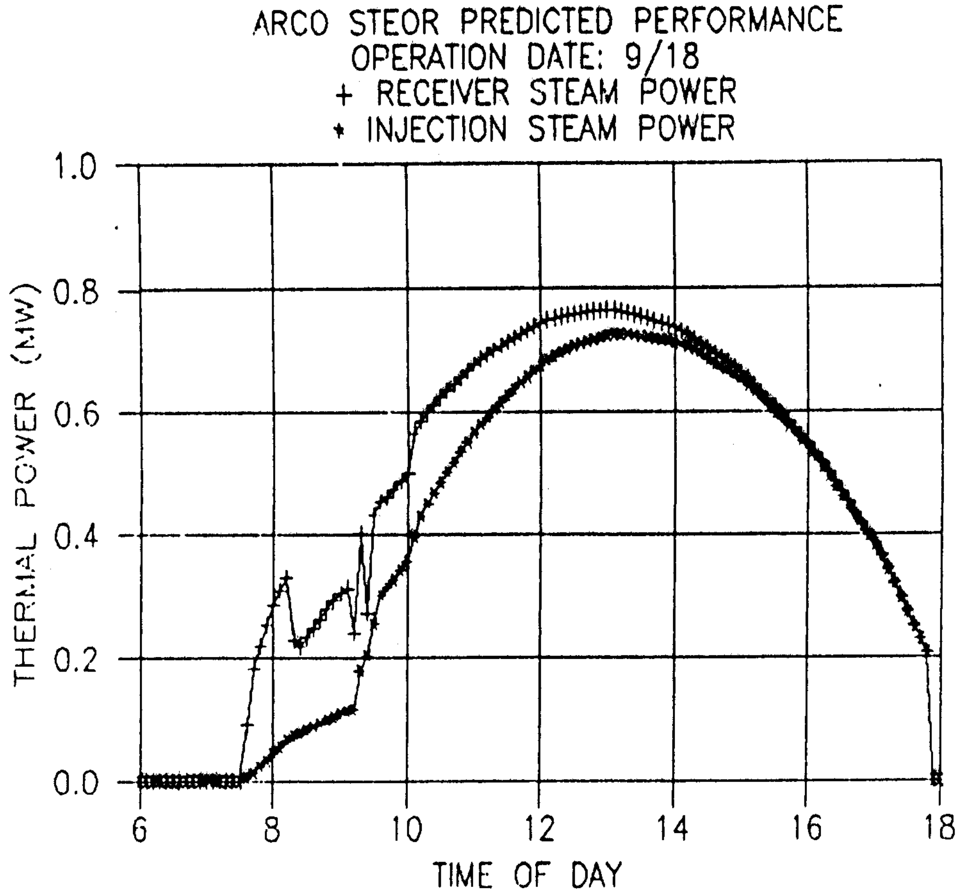


FIGURE B-9



FIGURR B-10

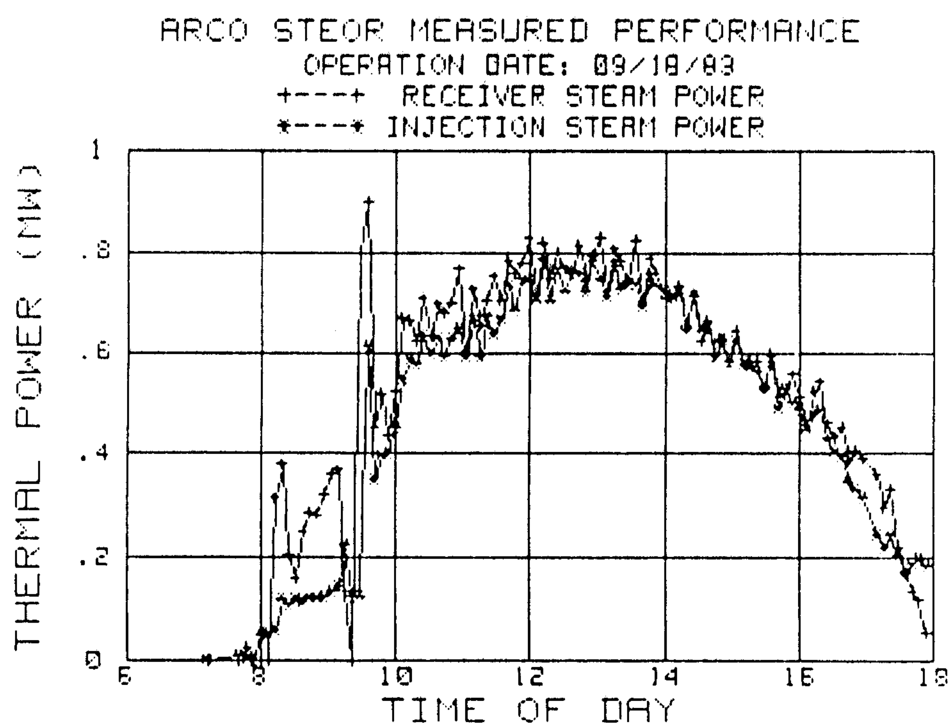


FIGURE B-11

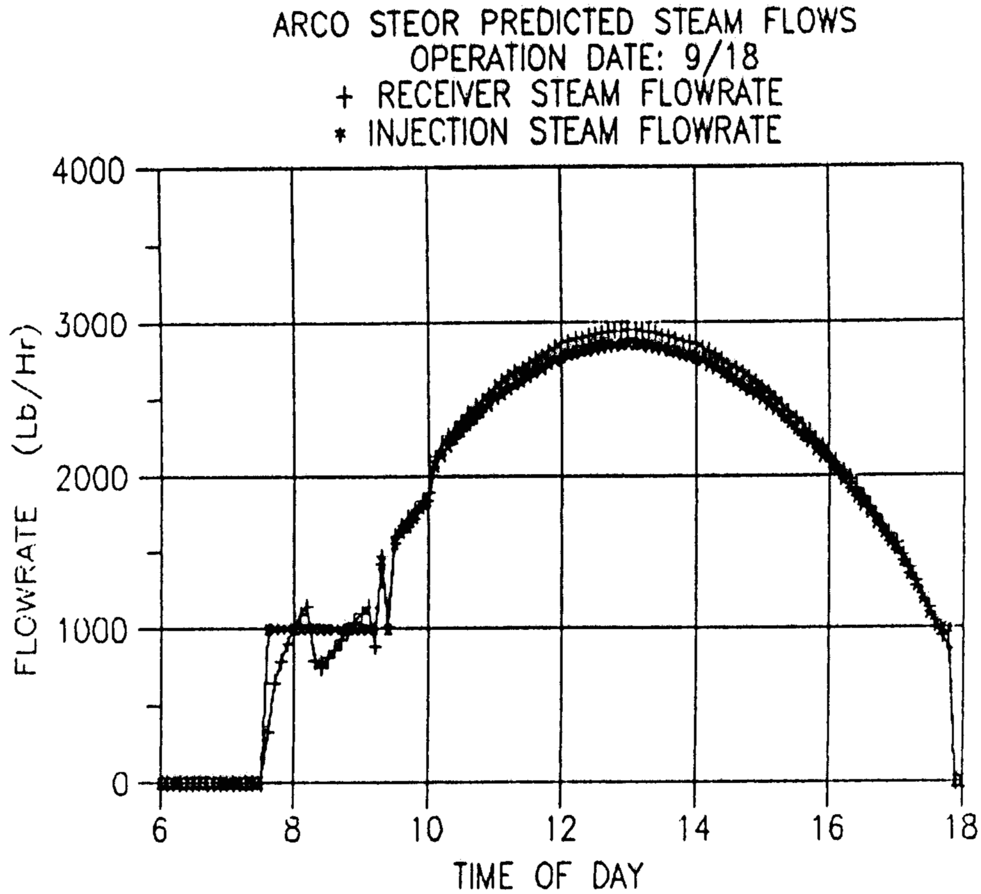


FIGURE B-12

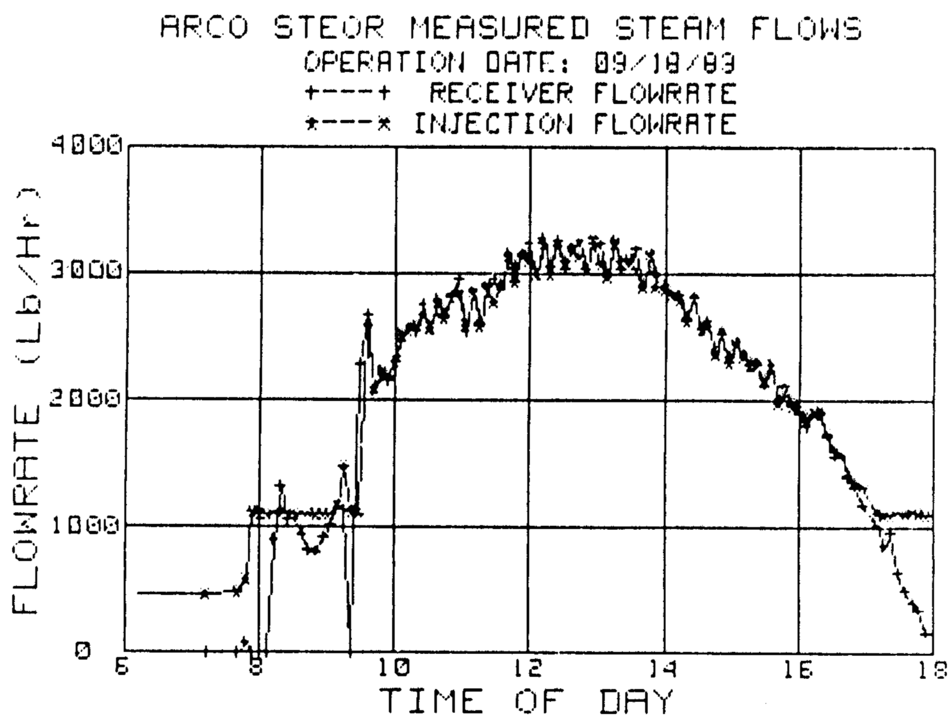


FIGURE B-13

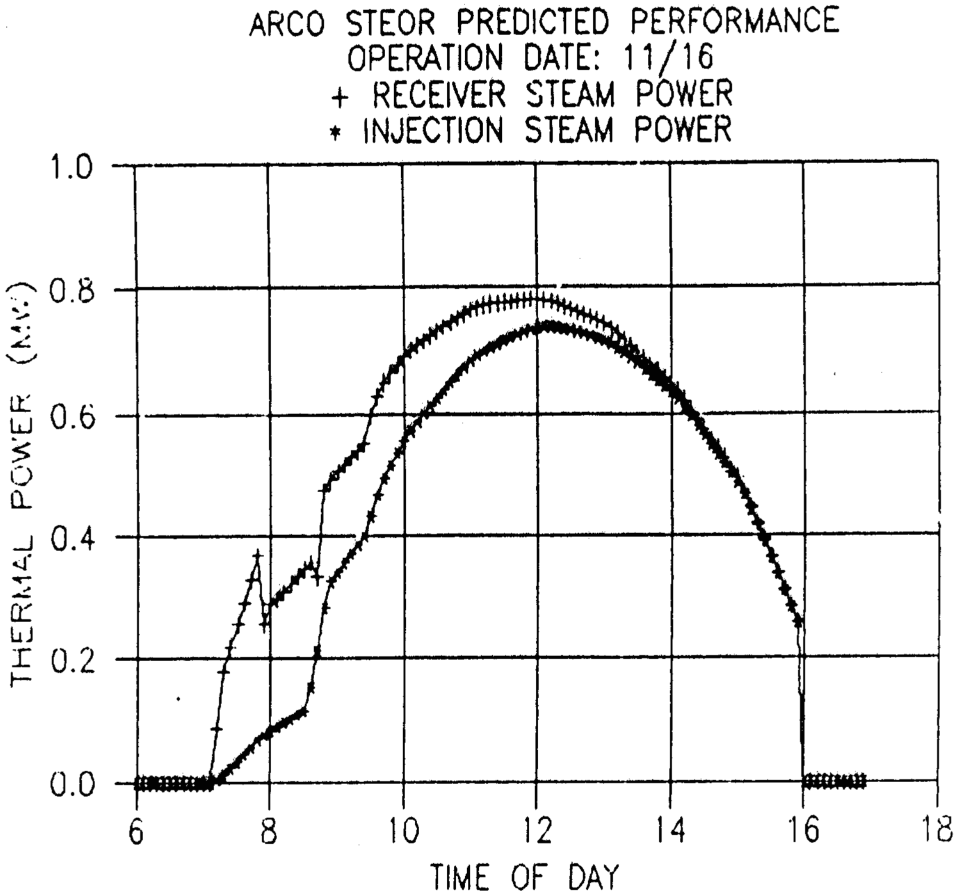


FIGURE B-14

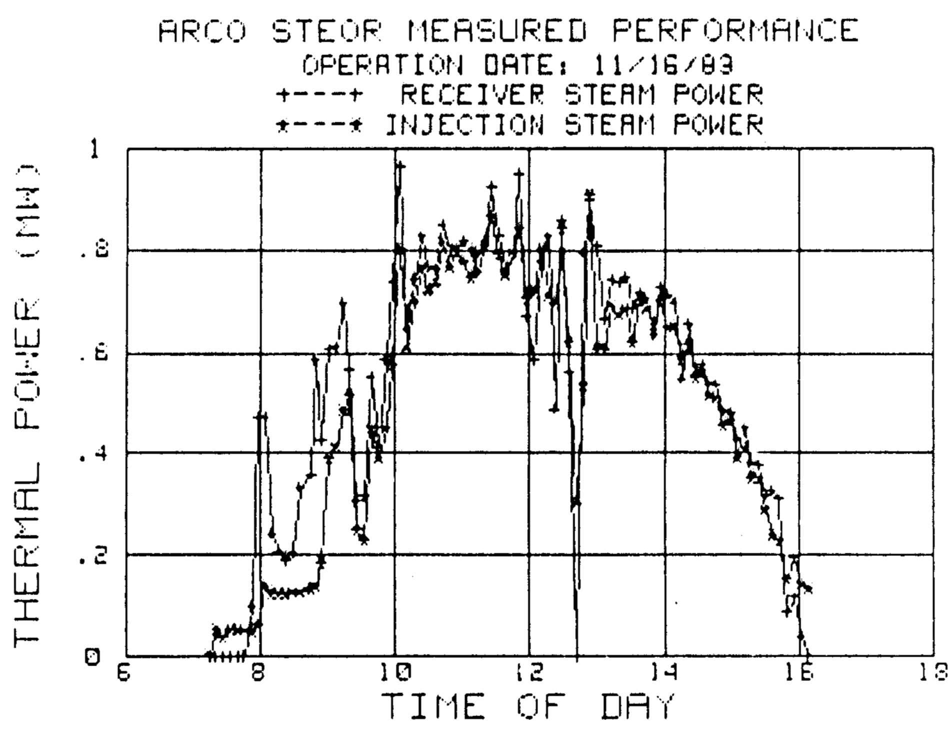


FIGURE B-15

ARCO STEOR PREDICTED STEAM FLOWS
OPERATION DATE: 11/16
+ RECEIVER STEAM FLOWRATE
* INJECTION STEAM FLOWRATE

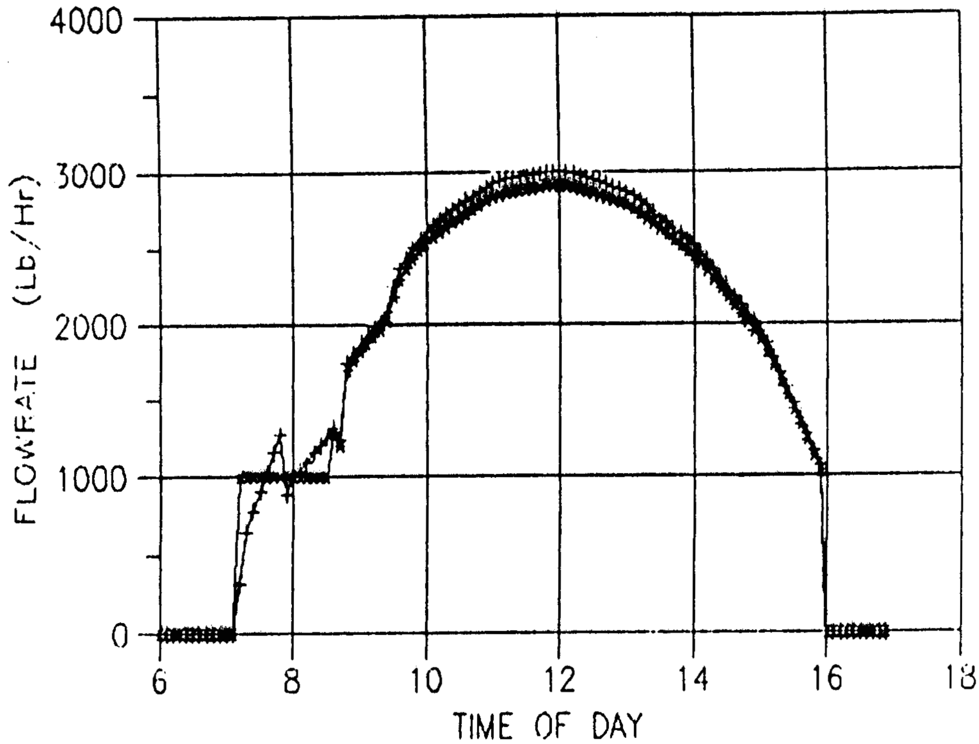


FIGURE B-16

ARCO STEOR MEASURED STEAM FLOWS
OPERATION DATE: 11/16/83
+---+ RECEIVER FLOWRATE
--- INJECTION FLOWRATE

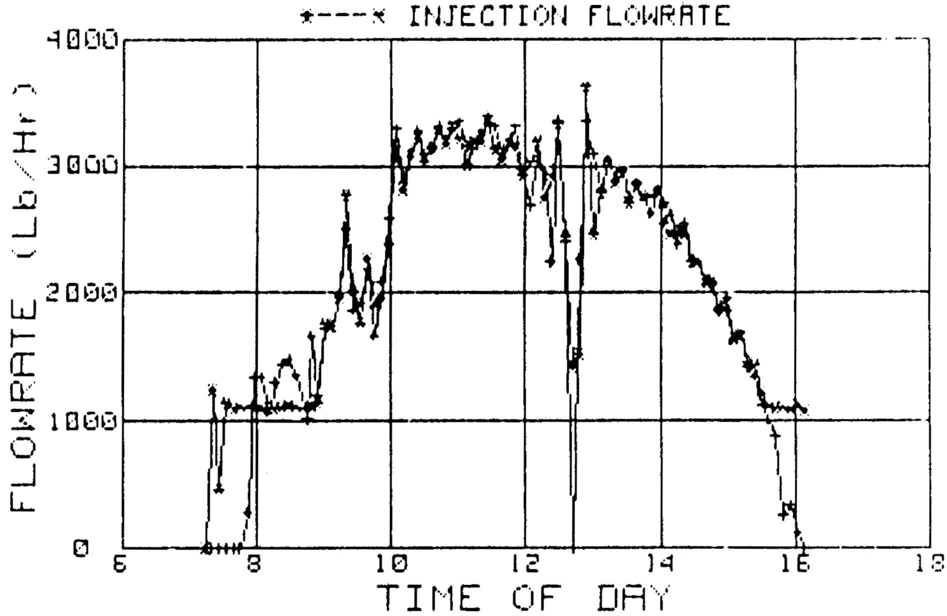


FIGURE B-17

ARCO STEOR PREDICTED PERFORMANCE
OPERATION DATE: 2/23
+ RECEIVER STEAM POWER
* INJECTION STEAM POWER

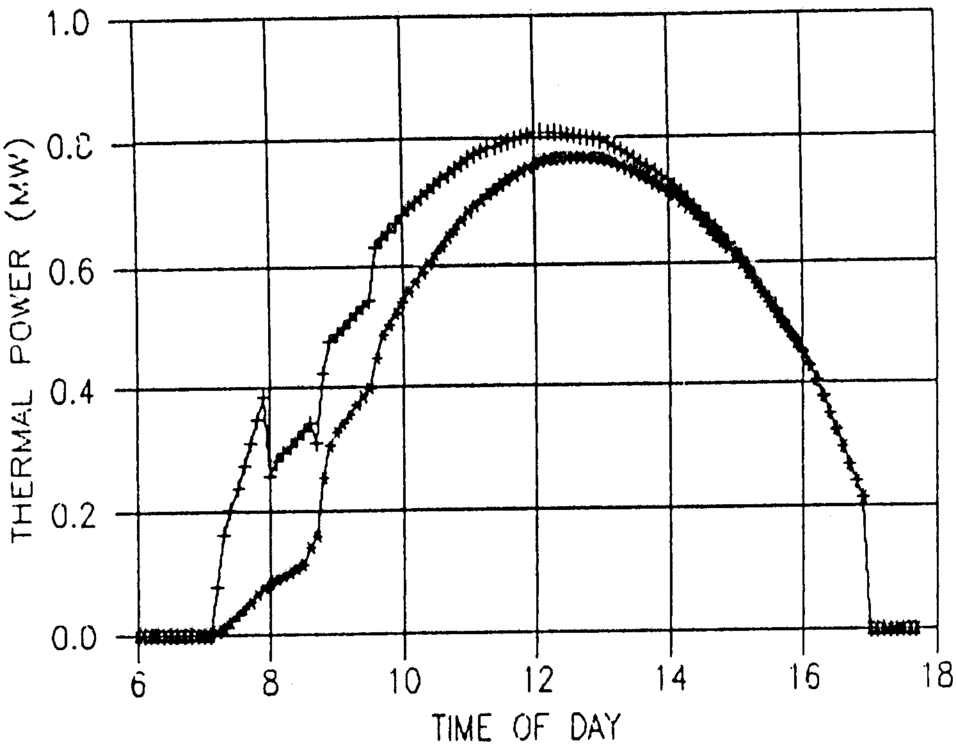


FIGURE B-18

ARCO STEOR MEASURED PERFORMANCE
OPERATION DATE: 02/23/84
+---+ RECEIVER STEAM POWER
--- INJECTION STEAM POWER

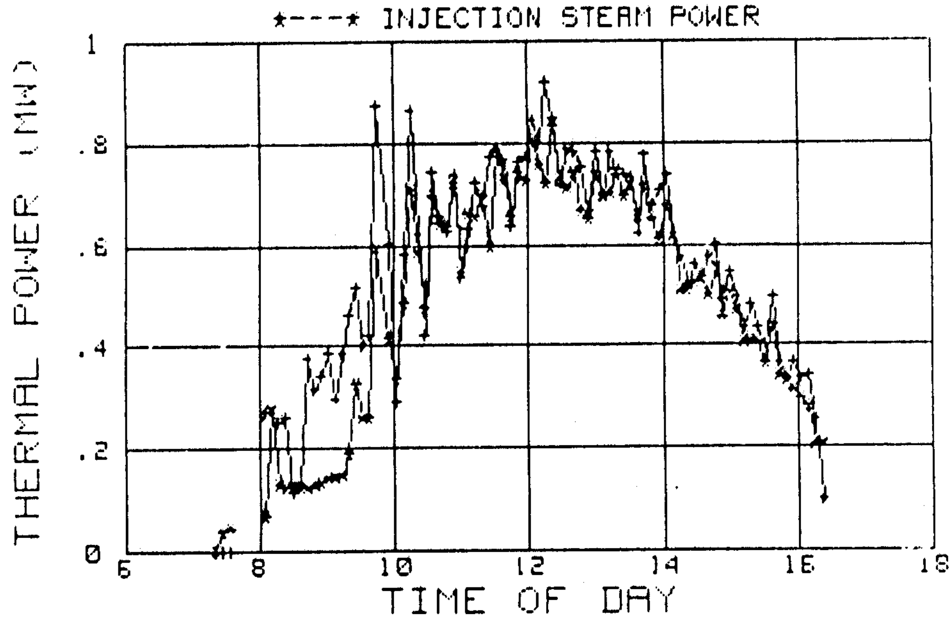


FIGURE B-19

ARCO STEOR PREDICTED STEAM FLOWS
OPERATION DATE: 2/23
+ RECEIVER STEAM FLOWRATE
* INJECTION STEAM FLOWRATE

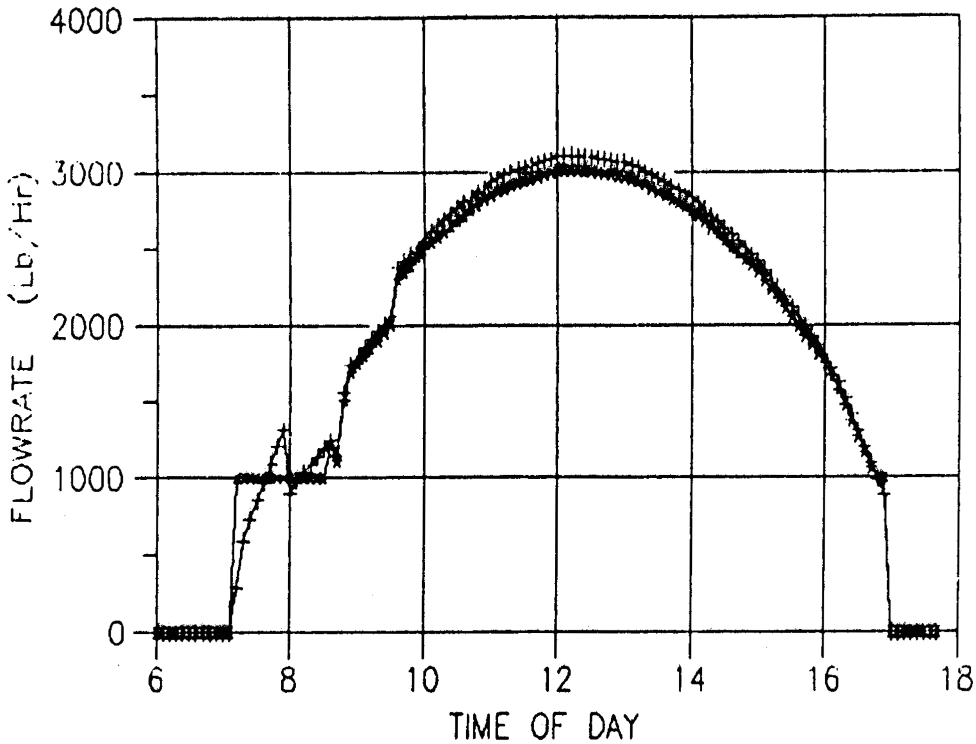


FIGURE B-20

ARCO STEOR MEASURED STEAM FLOWS
OPERATION DATE: 02/23/84
+---+ RECEIVER FLOWRATE
--- INJECTION FLOWRATE

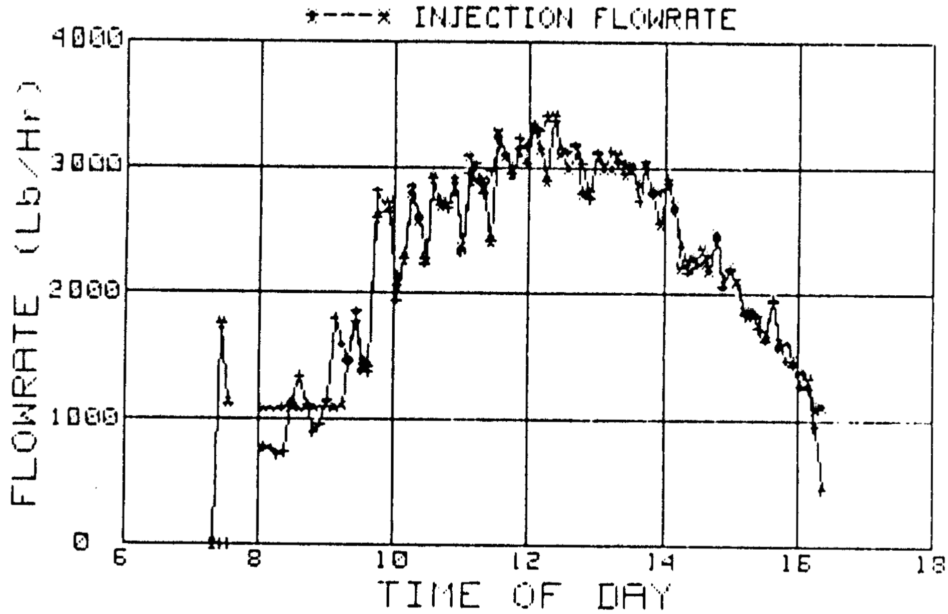


FIGURE B-21

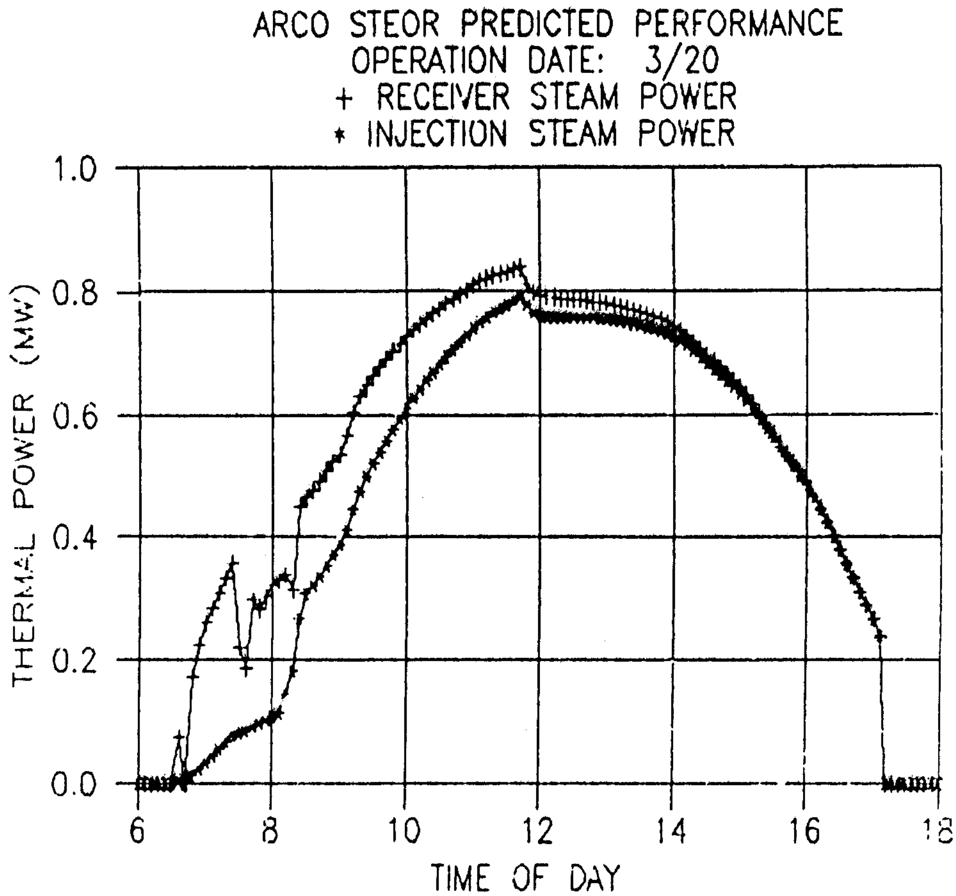


FIGURE B-22

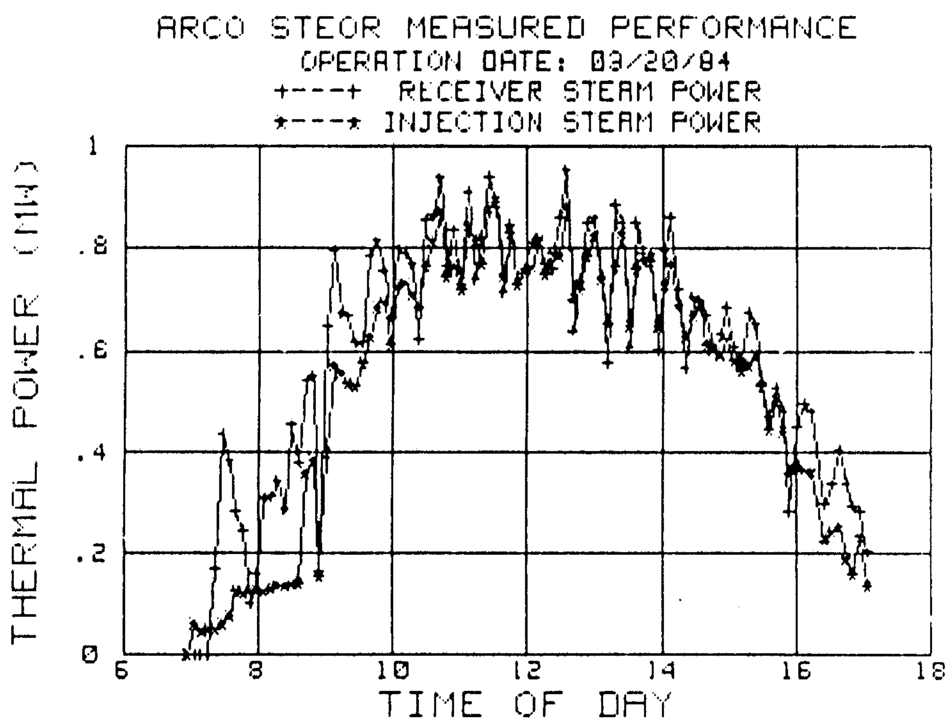


FIGURE B-23

ARCO STEOR PREDICTED STEAM FLOWS
OPERATION DATE: 3/20
+ RECEIVER STEAM FLOWRATE
* INJECTION STEAM FLOWRATE

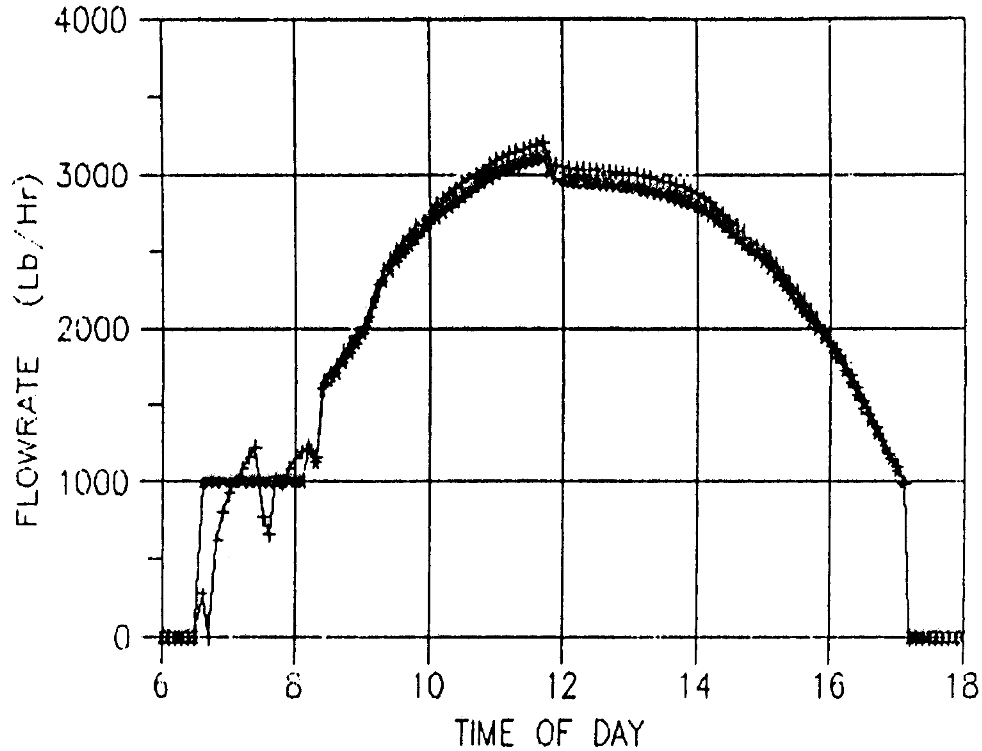


FIGURE B-24

ARCO STEOR MEASURED STEAM FLOWS
OPERATION DATE: 03/20/84
+---+ RECEIVER FLOWRATE
--- INJECTION FLOWRATE

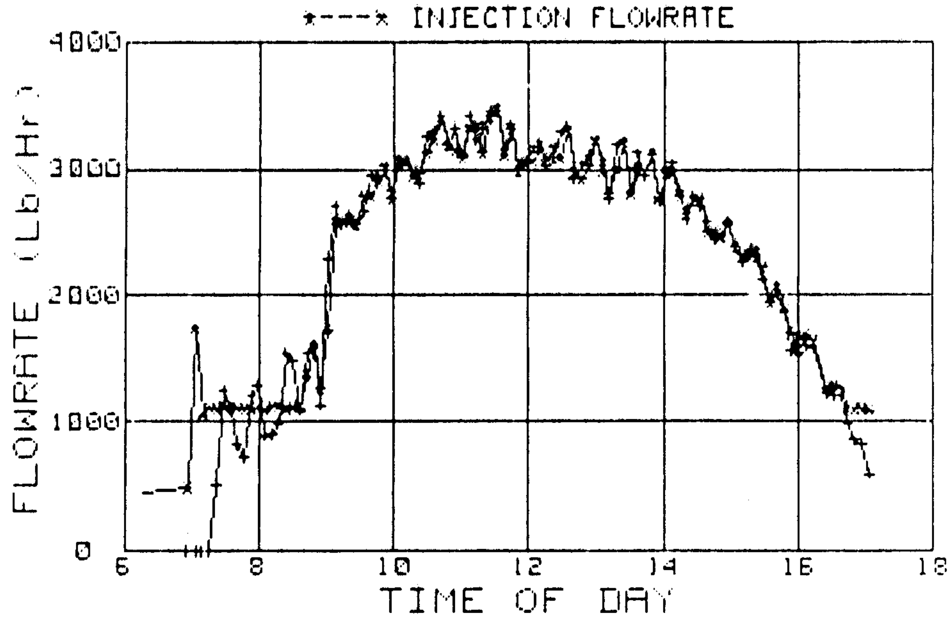


FIGURE B-25

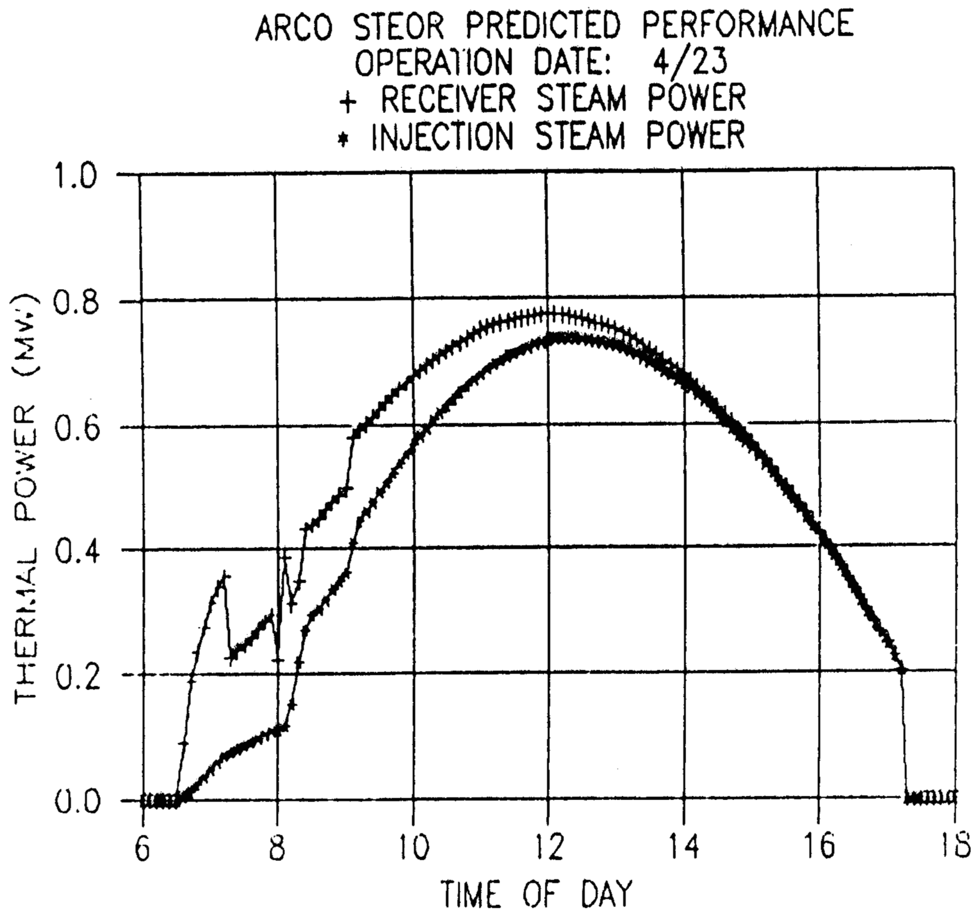


FIGURE B-26

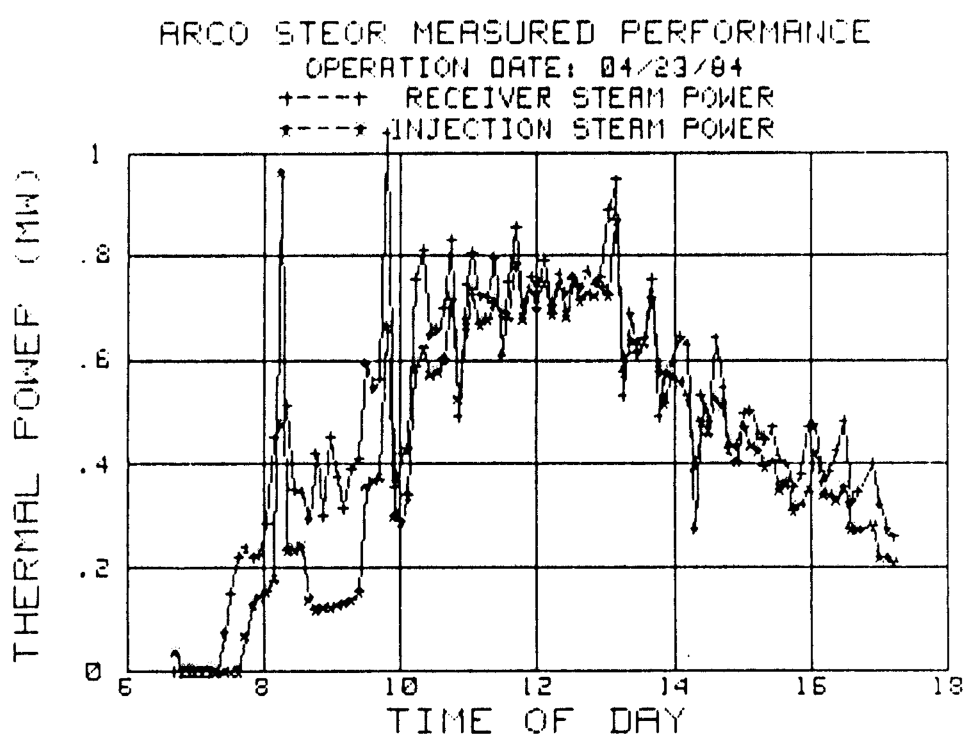


FIGURE B-27

ARCO STEOR PREDICTED STEAM FLOWS
OPERATION DATE: 4/23
+ RECEIVER STEAM FLOWRATE
* INJECTION STEAM FLOWRATE

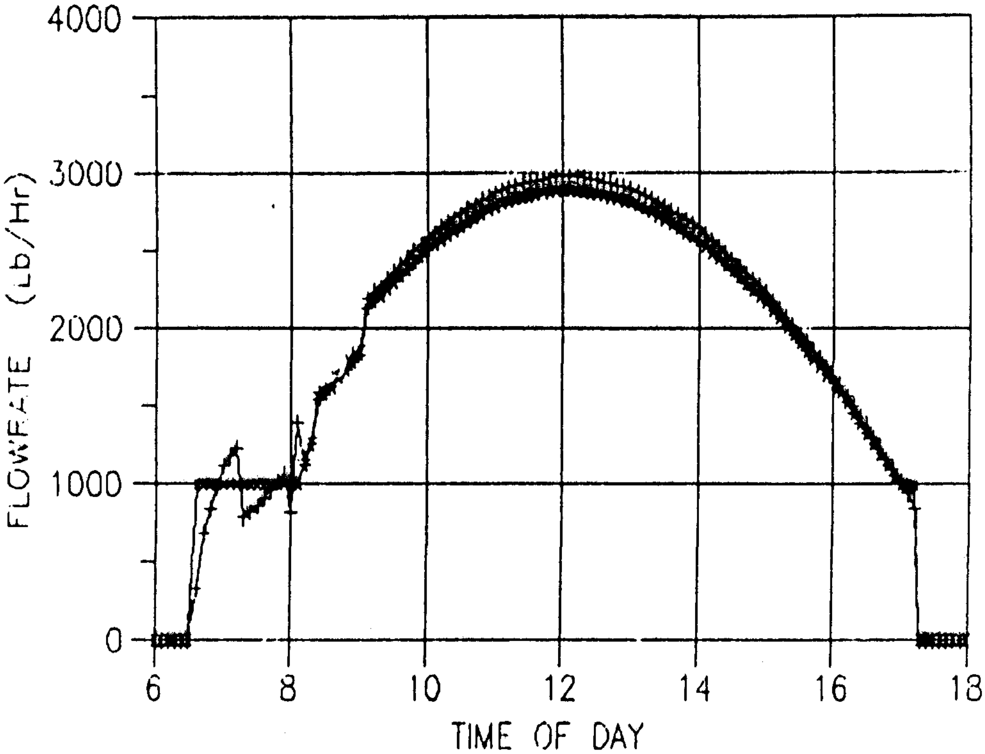


FIGURE B-28

ARCO STEOR MEASURED STEAM FLOWS
OPERATION DATE: 04/23/84
+---+ RECEIVER FLOWRATE
*---x INJECTION FLOWRATE

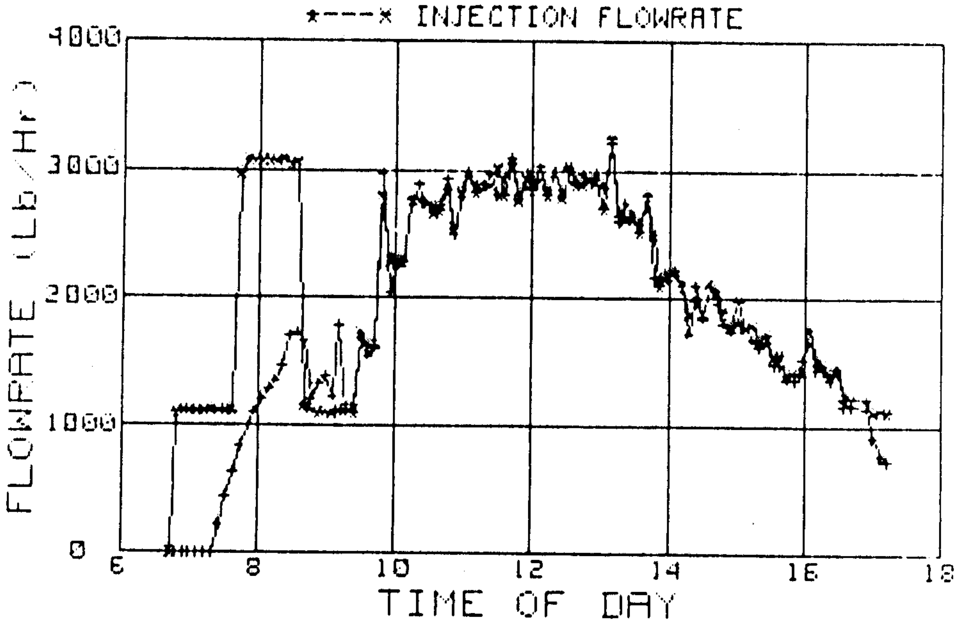


FIGURE B-29

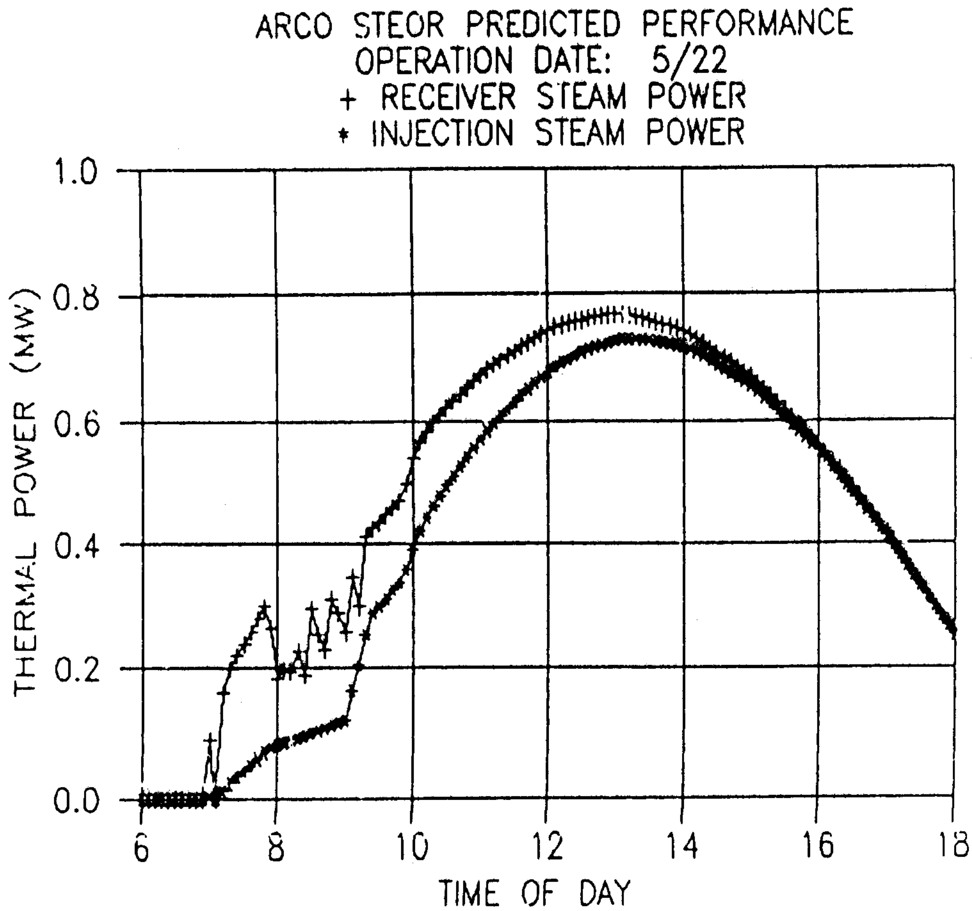
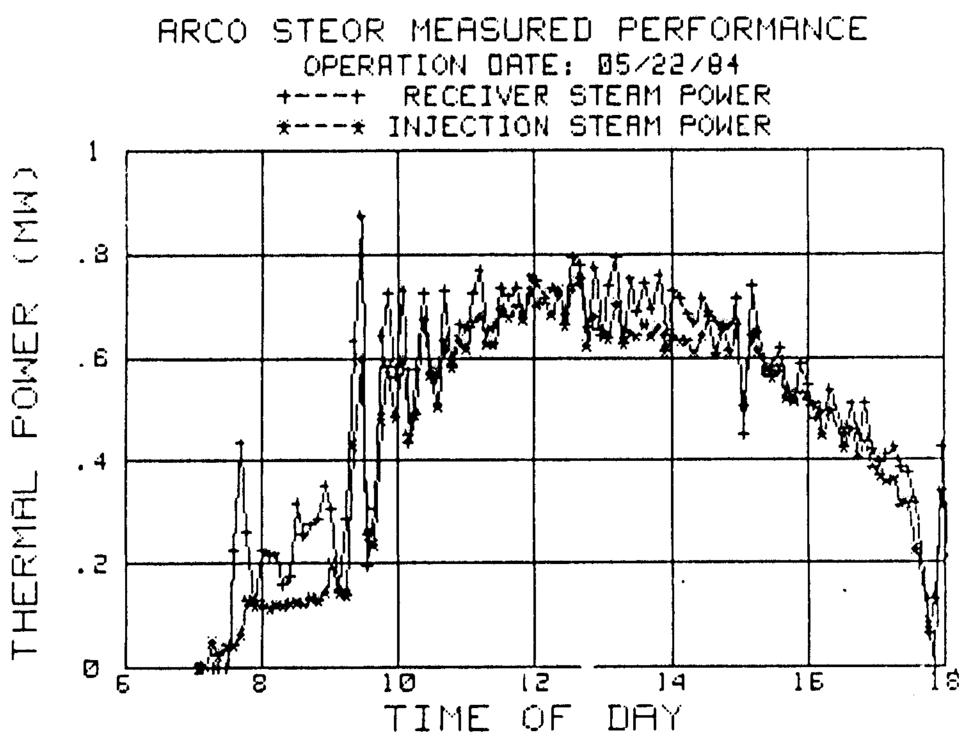


FIGURE B-30



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