DESIGN AND OPERATION OF A GEOPRESSURED-GEOTHERMAL HYBRID CYCLE POWER PLANT

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DISCLAIMER

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1.0 SUMMARY

Geopressured-geothermal resources can contribute significantly to the national electricity supply once technical and economic obstacles are overcome. From an economic standpoint, the cost of building and operating power plants, along with the cost of wells and the productive life of the reservoirs, are primary concerns. From a technical standpoint, operation of a power plant with the corrosive, highly saline brine and impure wellhead gas presents special problems.

Power plant performance under the harsh conditions of a geopressured resource was unproven, so a demonstration power plant was built and operated on the Pleasant Bayou geopressured resource in Texas. This one megawatt facility provided valuable data over a range of operating conditions. In addition, an extended run at maximum power production demonstrated that power can be produced reliably with no serious operating problems.

This power plant was a first-of-a-kind demonstration of the hybrid cycle concept. A hybrid cycle was used to take advantage of the fact that geopressured resources contain energy in more than one form -- hot water and natural gas. Studies have shown that hybrid cycles can yield thirty percent more power than stand-alone geothermal and fossil fuel power plants operating on the same resource. In the hybrid cycle at Pleasant Bayou, gas was burned in engines to generate electricity directly. Exhaust heat from the engines was then combined with heat from the brine to

generate additional electricity in a binary cycle. Heat from the gas engine was available at high temperature, thus improving the efficiency of the binary portion of the hybrid cycle.

Hydraulic energy is also available from a geopressured resource due to the high pressure of the wellhead fluid. This energy can be recovered using a pressure reduction turbine. A pressure reduction turbine was not included in the Pleasant Bayou experiment.

There was only one significant problem encountered during the test. Carbon deposits from the gas engine exhaust caused fouling of the heat exchange surface, thus degrading performance. Possible solutions to the problem of excessive fouling in the exhaust gas exchanger include replacing the gas engine with a gas turbine, using an engine which more efficiently completes combustion, or filtering the exhaust stream.

The hybrid power system demonstration at Pleasant Bayou was successful in all respects. Design power output was achieved, and 3,445 MWh of power were sold to the local utility over the course of the test. Plant availability was 97.5% and the capacity factor was over 80% for the extended run at maximum power production. The hybrid cycle power plant demonstrated that there are no technical obstacles to electricity generation at Pleasant Bayou.

Furthermore, several concerns about operating a commercial power plant on the Pleasant Bayou resource were favorably resolved. Scale and corrosion inhibitors were shown to be effective throughout the operating range of brine temperatures. Heat exchanger fouling due to scale deposition from the high salinity brine was not a problem. Although uninhibited brine is highly corrosive, inhibitors reduced corrosion to such low levels that carbon steel can be used for brine piping and heat exchangers. By using carbon steel as the primary material of construction, the cost of the power plant can be kept in line with other binary cycle power plants which are commercially competitive.

The U.S. Department of Energy (DOE) and Electric Power Research Institute (EPRI) co-funded this hybrid cycle demonstration power plant on a geopressured resource. Management and technical support for the program was provided to DOE by the Idaho National Engineering Laboratory (INEL). The Ben Holt Co., under contract to EPRI, designed the facility and procured new and refurbished equipment. Construction and operation were under a separate contract funded by DOE. For this work, Holt teamed with Eaton Operating Company (Houston, Texas) and Institute of Gas Technology (Chicago, Illinois).

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2.0 INTRODUCTION

2.1 Objectives of the Hybrid Power System Experiment

Primary goals of the hybrid power system (HPS) experiment were to demonstrate, for the first time, the generation of electricity from a geopressured resource and to gain operating data over an extended time period.

The goal of the initial test period was to operate the HPS over a wide range of operating situations, including off-design conditions to obtain data helpful for the design of future commercial operations. A period of operation at maximum power output followed. This longer period of operation constituted an evaluation of the reliability of the HPS and provided the opportunity to develop and document those features of design, operation, and maintenance that are important for achieving high reliability.

Objectives of the project were to demonstrate the hybrid cycle concept for electricity generation and to obtain data regarding operation over time of a power plant using a geopressured resource. Electricity was produced from a gas engine burning methane and from a binary cycle operating on heat from engine exhaust and from geothermal brine.

Demonstration of the hybrid concept on a geopressured well has the benefit of testing what is estimated to be the thermodynamically optimum way to produce electricity from geopressured resources. Much was learned about potential problems such as scaling, corrosion, flow instabilities, and gas engine life with impure wellhead gas.

2.2 Concept

Hybrid cycles have a thermodynamic advantage over stand-alone binary cycle and fossil fuel power plants. In the hybrid cycle used at Pleasant Bayou, the advantage occurred because heat which was rejected from the gas engines was utilized in the binary cycle. Because this heat was available at a higher temperature than heat from the geothermal brine, the thermodynamic efficiency of the binary cycle was increased.

2.3 Description and Potential of Geopressured-Geothermal

A geopressured-geothermal resource contains hot, high pressure brine in which gas, primarily methane, is dissolved in solution. Some of these reservoirs also contain natural gas which is not in solution. Much of this free gas has been commercially exploited by the petroleum industry. The remaining brine and natural gas solution has not been. A geopressured resource provides a natural location for hybrid cycle power plants because both fossil fuel and hot water are provided simultaneously. A hybrid cycle power plant on a geopressured-geothermal resource will efficiently produce power from a domestic energy source which has not been previously utilized.

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3.0 BACKGROUND

DOE has sponsored several programs over the last thirteen years to develop the geopressured-geothermal technology. The goals of these programs were to confirm the existence of the resource, establish its magnitude, measure its characteristics, and develop a technology to recover its energy. Under DOE's "Wells of Opportunity Program" (1977-1982), nine wells which commercial industry was ready to abandon were taken over by DOE. Several of the wells were tested for short periods of time. In the "Design Well Program" (1979-1985), four wells were drilled. Tests were completed on two of the wells. The two remaining wells, Gladys McCall Well No. 1 in Cameron Parish, Louisiana and Pleasant Bayou Well No. 2 in Brazoria, Texas, were tested in DOE's follow-on program (1985-1990) by Eaton Operating Co.

As part of the current program, The Ben Holt Co. built and successfully operated a hybrid cycle power plant at the Pleasant Bayou site. This plant efficiently recovered the energy of a geopressured-geothermal resource. Design of this plant and procurement of equipment for the Pleasant Bayou facility were completed under a separate contract with EPRI. Much of the equipment used at Pleasant Bayou was from DOE's Direct Contact Heat Exchange facility (DCHX) in East Mesa, California.

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4.0 LESSONS LEARNED

The primary lesson learned as a result of this test is that a hybrid cycle can be used to generate power from a geopressured-geothermal resource. At Pleasant Bayou, the binary cycle turbine and the gas engines achieved their design performance at design conditions although parasitics were somewhat higher than design. An availability of 97.5% and a capacity factor of 80.2% were achieved for the extended run at maximum power production. These are excellent results, especially for a test facility built with primarily used equipment. Even better results can be expected with current technology and new equipment.

Before the demonstration at Pleasant Bayou, serious concerns about the viability of power production from a geothermal-geopressured resource existed. These concerns included scaling and corrosion due to the high salinity brine, engine operation on impure wellhead gas, and mechanical problems associated with the large temperature difference in E-3-N. All of these issues were favorably resolved.

Equipment and piping did not corrode during the nine-month test. Wear was not extensive for the length of operation. As a result, carbon steel can be used throughout a commercial plant except for those vessels and pipes which come in contact with the high temperature exhaust gas.

Both brine heat exchangers exceeded design specifications. No significant fouling over an extended time was detected on either exchanger. In addition, minimal scale was found when the heat exchangers were inspected at the conclusion of the test.

During the design phase, there were many mechanical design concerns about E-3-N. These concerns were due to high temperature operation and to the large temperature difference between the inlet exhaust gas and the outlet isobutane temperature. The unique exchanger design which was explained in detail in Section 7.7 successfully solved the thermal stress problem. This exchanger was built of 304 SS and showed no sign of corrosion. Also, there was no sign of wear between the tubes and the tubesheet support due to vibration.

The turbine operated 2902 hours. Vibration monitors provided insight into turbine operation and prevented catastrophic turbine failure.

Some questions arose as a result of this test. Exhaust gas fouling was unacceptably high. Several possible solutions exist. A gas turbine could be installed rather than a gas engine to cut down on particulate emission. A blower which periodically removes the soot or a low pressure drop filter which removes contaminants before they enter the exchanger could be utilized.

Emissions from the engine are also an environmental concern. Research is being conducted in this field in order to reduce emissions from natural gas diesel engines used for public transportation. PG&E and Cummins Power have developed a test engine which emits 2 grams of NOx per horsepower hour with an efficiency of 36%. This is an improvement over the specied emission of 23.5 g/hp-h for the Caterpillar engines used in this test. Although this low-NOx engine is not yet commercially available, rapid development of low-NOx natural gas engines is expected to continue. Since these engines also have a low level of particulate emission, exhaust gas fouling will be reduced.

Isobutane emission is also an environmental concern. Isobutane emission can be greatly reduced by minimizing the number of connections. Joints should be welded whenever possible. Since a commercial power plant must be reliable, maintenance on the working fluid loop will be minimized, thereby reducing isobutane emission.

Turbine design output was achieved at design turbine back pressure. However, turbine back pressure was higher than design at a given wet bulb temperature. This was due to a higher concentration of light ends in the isobutane than design and to a higher noncondensable concentration. Venting the accumulator to atmosphere occasionally would result in an unacceptable emission of isobutane. Rather, the accumulator can be vented to an auxiliary system that removes noncondensables from the system and returns isobutane.

The test at Pleasant Bayou showed the technical feasibility of a commercial power plant. The economic feasibility remains to be assessed. Choosing a working fluid would be part of an economic study. Propane produces more power per pound of brine, but it also has a higher vapor pressure, so equipment cost is higher. An economic analysis based on the relative price of electricity and natural gas would determine whether a hybrid power cycle or a binary power cycle in which the gas is sold to a distributor should be used. An economic analysis would assess if a pressure reduction turbine should be used to recover hydraulic energy. A commercial power plant would have a negotiated power sales contract, so that power plant would be paid a higher price for power than was received at Pleasant Bayou.

An economic analysis which uses data from the test facility to estimate the cost of both construction and operation of a commercial power plant would be a valuable next step. Development of an invaluable energy resource from which power can be produced safely and with minimal environmental impact should proceed.

5.0 ADVANTAGES OF THE HYBRID CYCLE

The hybrid concept can be used to improve the utilization efficiency of energy resources. More electricity can be generated from two energy sources in a hybrid cycle than by using each separately to generate electricity. This occurs because heat which would be wasted from one energy source is utilized in combination with heat from the other source.

Under EPRI contract RP1673-4, The Ben Holt Co. evaluated methane/hot water hybrid cycles for hydrothermal and geopressured-geothermal applications. Hybrid cycles were calculated to generate as much as thirty percent more electricity than if the methane was used in a fossil fuel power plant and the hot water in a binary cycle power plant. Results from that evaluation are summarized in Table 5-1. This table is based on optimized hybrid cycles where enough methane is combusted so that exhaust heat provides all necessary energy to vaporize the working fluid. This requires a methane to hot water ratio higher than is found in a geopressured resource. For example, with a brine temperature of 280°F and a gas turbine heat rate of 14.166 Btu/kwh, 7,100 lb/hr of fuel gas were used with 500,000 lb/hr of brine. At Pleasant Bayou, 470 lb/hr of fuel gas were used with 170,000 lb/hr of brine. The fuel gas to brine ratio is about 5 times greater in this optimized case than at Pleasant Bayou.

TABLE 5 - 1

SUMMARY OF HYBRID CYCLES POWER PRODUCTION

Gas Turbine Heat Rate = 9,850 BTU/KWH

Brine Temp. Difference (°F)	Hybrid (MW Net)	Binary + Fossil (MW Net)	Difference (MW)	(%)
280	24.11	20.09	4.02	20.0
330	20.58	17.49	3.09	17.7
360	18.37	15.93	2.44	15.3

Gas Turbine Heat Rate = 11,350 BTU/KWH

Brine Temp. Difference (°F)	Hybrid (MW Net)	Binary + Fossil (MW Net)	Difference (MW)	(%)
280	19.42	15.40	4.02	26.1
330	16.48	13.39	3.09	23.1
360	14.77	12.33	2.44	19.8

Gas Turbine Heat Rate = 14,166 BTU/KWH

Brine Temp. Difference (°F)	Hybrid (MW Net)	Binary + Fossil (MW Net)	Difference (MW)	(%)
280	17.07	13.05	4.02	30.8
330	15.05	11.96	3.09	25.8
360	13.81	11.38	2.44	21.4

NOTE: Brine Flow Rate = 500,000 lb/hr for all cases.

Hybrid cycles have another important benefit in that they can be used to provide a base load of power in case of an interruption in supply of one of the energy sources. For instance, the binary cycle portion of a geothermal hybrid plant could continue to operate even if the fossil fuel portion of the hybrid plant was shut down due to lack of fuel. The efficiency of the binary cycle would drop if this occurred, but electricity generation could continue.

Development of a resource in stages is another potential benefit of hybrid cycles. A developer could install a binary cycle on a geothermal resource with the potential for adding a gas engine or gas turbine and utilizing the waste heat. Cash flow from the binary cycle electricity sales could contribute to the financing of the conversion to hybrid.

Converting a binary cycle to hybrid also has an important advantage if the geothermal resource is unknown. A binary cycle could be installed first, and if the geothermal resource has limited production or lower than design temperature, the fossil fuel portion of the plant could be designed to compensate. In any case where a binary cycle is to be converted to hybrid, it is important to select the binary cycle turbine, circulating pump, and other equipment such that they will be adequate for the hybrid service.

5.1 Geopressured Application - General

Geopressured resources provide a natural location for hybrid cycle power plants because both the fossil fuel (methane) and hot water are produced simultaneously. A third form of energy, hydraulic, is also available due to the high pressure of the wellhead fluid. However, recovering the hydraulic energy is not a necessary part of a hybrid cycle.

Net power provided by a hydraulic turbine is small compared to total energy output. For example, adding a hydraulic turbine to the hybrid demonstration plant would increase net power from 982 kW to 1062 kW, an increase of only 8% (based on the same quantity of brine and gas going through the hydraulic turbine as goes to the hybrid cycle plant). However, the capital and operating costs of the hydraulic turbine can be low in comparison, making this an attractive option to be considered.

An additional reason that geopressured resources provide a good location for hybrid cycle power plants is that the geothermal brine temperature from geopressured resources tends to be relatively cool at 300°F or less. As seen from Table 5-1, hybrid cycles give a larger percentage improvement for lower temperature resources than for hotter resources. In fact, electricity generation from brine at such low temperatures is probably not economic in a stand-alone geothermal plant.

5.2 Geopressured Application - Pleasant Bayou Experiment

The hybrid cycle experiment at Pleasant Bayou was not meant to be an optimized hybrid cycle experiment. No methane is used other than the gas produced with the brine, so the cycle is not an optimized cycle such is those shown in Table 5-1. In addition, equipment from the DCHX facility was used for the binary cycle, so mechanical limitations prevented the use of a cycle optimized for the Pleasant Bayou condition.

However, the experiment will generate more net electricity than would a gas engine plus a binary cycle operating on the same resource, provided that in both instances the same equipment limitations are imposed.

5.3 Different Concepts

Early in the EPRI program, several different hybrid concepts were considered. These include a binary cycle with a gas turbine, a binary cycle with a gas engine, and a gas engine with a steam cycle. A binary cycle with a gas engine is the concept used at Pleasant Bayou. A binary cycle with a gas turbine is similar except that the natural gas is burned in a gas turbine rather that in an engine. In a steam cycle with a gas turbine, the brine is flashed and steam is run through a turbine to generate power. Exhaust heat can be used to generate additional steam or to superheat the flashed steam. Based upon previous work by The Ben Holt Co. (EPRI RP 1673-1, Assessment of Advanced Geothermal Energy Conversion Concepts), a binary cycle is more efficient for brine at 278°F.

In an earlier phase of the EPRI hybrid cycle evaluation program, United Technologies Research Center studied hybrid cycles using gas engines and gas turbines (Unpublished report to EPRI, Project 1671-2; and EPRI Proceedings, Fifth Annual Conference, AP-2098, p. 5A-11). Cycles using gas turbines were found to get a slightly higher net power output for a binary cycle at Pleasant Bayou. In the early design stages of the hybrid demonstration at Pleasant Bayou, consideration was given to the use of a gas turbine instead of a gas engine.

Gas turbines have the advantage of high exhaust gas mass flow rates. Large quantities of excess air are combined with the fuel in the turbines to keep the combustion gas temperatures below the failure temperature of the inlet turbine blades. The result is a large amount of heat which can be extracted from the exhaust gas.

Gas engines, however, can make up some of the difference in waste heat because they have jacket cooling. In some heat recovery cycles, this jacket cooling can provide useful heat into the bottoming power cycle. Table 5-2, which was taken from the UTRC study, compares gas engine and gas turbine characteristics.

A gas engine was selected for the hybrid test at Pleasant Bayou for two major reasons. First and foremost was that at the time the design was made, a company had agreed to contribute a gas engine to the project. Second, gas engines have proven reliable in similar applications throughout the oilpatch, burning methane or fuel oil to generate electricity required during drilling operations. Gas turbines do not have the field record of large numbers of relatively small turbines operating in remote locations with an impure supply of methane. Thus, a gas engine was selected for use at Pleasant Bayou.

TABLE 5 - 2

GAS ENGINE AND GAS TURBINE CHARACTERISTICS

	Gas Engine	Gas Turbine
Type	Turbo-charged, Spark-ignition	Simple-cycle
Speed, RPM	400-600	
Pressure Ratio	8.25:1	12-14:1
Energy Balance (based on LHV of fuel)		
- Electrical Output	0.36	0.30
- Exhaust Gas Energy	0.28	0.70
- Jacket Water & Charge Air Energy	0.18	0
- Lube Oil, Radiation, Unaccounted	0.18	0
Turbine Inlet Temperature, °F		<2000
Exhaust Temperature, °F	915	1050
Jacket Water Temp., °F	180-200[1]	180-200
Fuel		
- LHV (Btu/SCF) - Typical	900	900
- Minimum	600	550
- Supply Pressure, psig	50	150-250

1 Jacket water temperatures as high as 240°F are achievable in engines with ebullient cooling.

(Khalifa, "Hybrid Power Plants for Geopressured Geothermal Resources", EPRI RP 1671-2, October 1981)

6.0 DESIGN OF A HYBRID POWER SYSTEM FOR PLEASANT BAYOU

6.1 Concept and Flow Diagram

Hybrid cycles have a thermodynamic advantage over stand-alone binary cycle and fossil fuel power plants. In the hybrid cycle used at Pleasant Bayou, the advantage comes about because heat which is rejected from the gas engine is utilized in the binary cycle. Because this heat is available at a higher temperature than heat from the geothermal brine, the efficiency of the binary cycle is increased.

A simplified process flow diagram of the hybrid cycle power plant is shown in Figure 6-1. Wellhead production was estimated at 20,000 Bbl/day of brine containing 22 SCF/Bbl of gas. The power plant operated on one half of the total flow produced. Unused hot brine was reinjected and methane not burned in the gas engines was sold. A complete process flow diagram is in Appendix A.

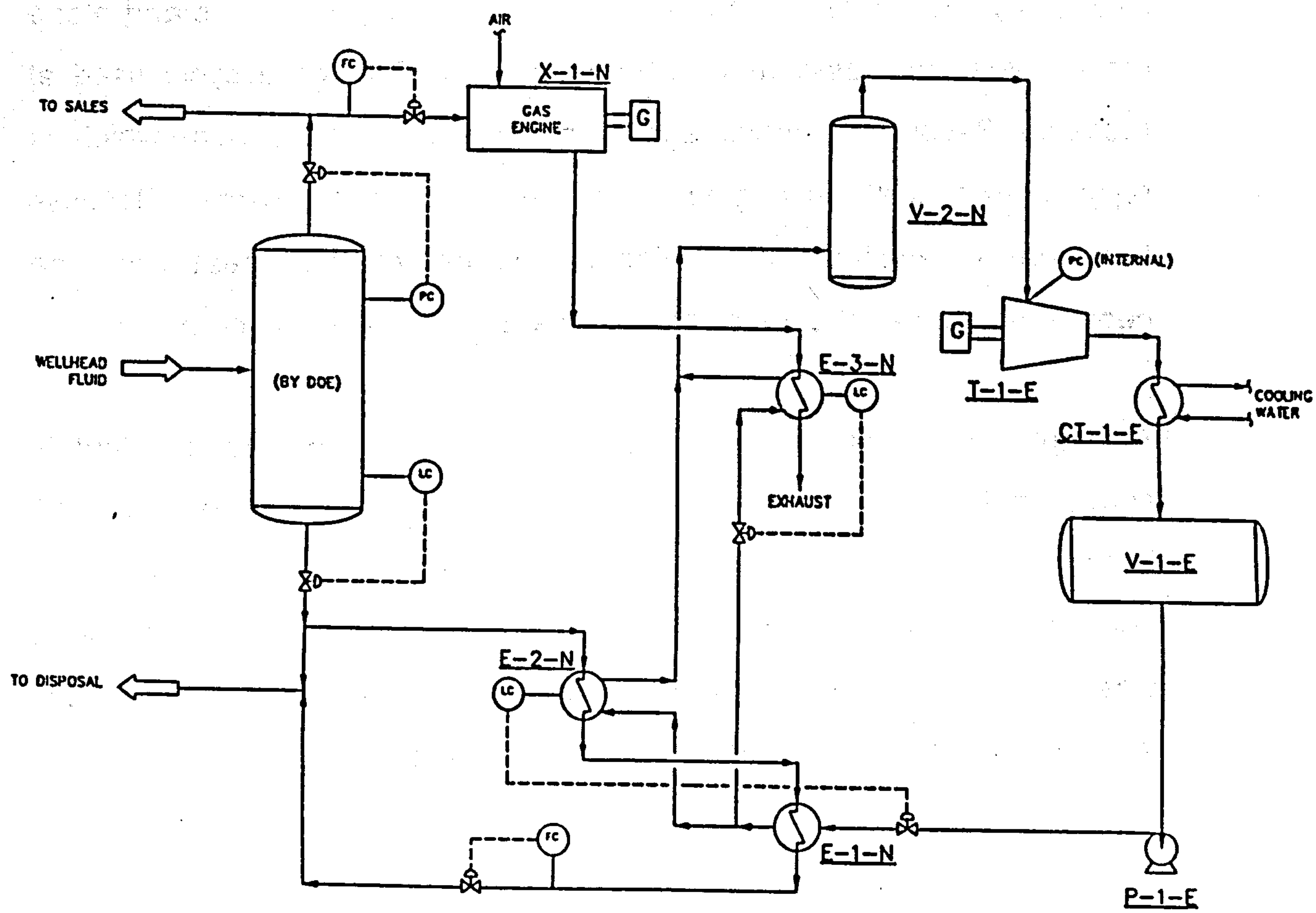

Figure 6-1. Simplified Process Flow Diagram with Major Controls Shown

Power production and parasitic loads at the design condition are summarized in Table 6-1.

TABLE 6 - 1

SUMMARY OF DESIGN POWER PRODUCTION AND PARASITIC LOADS

Power Production:		
	Gas Engines	650 kW
	Binary Cycle Turbine	541 kW

	Total Production	1191 kW
Parasitic Loads:		
	Condenser	75 kW
	Circulating Pump	74 kW
	Miscellaneous	60 kW

	Total Loads	209 kW
	Net Power	982 kW

The load labeled "condensers" includes four water pumps (1 for each Baltimore Aircoil Company [BAC] unit) and eight fan motors. Fans are approximately 85% of the 75 kW. The circulating pump load is the isobutane pump used to pump the condensed isobutane liquid into the high-pressure exchangers.

Miscellaneous loads total 60 kW and include the utility cooler, lube oil pumps, air conditioning, pressurizing air for the trailers, instrument air, control power and lighting. These parasitic loads are a higher percentage of generator output than would be expected for a commercial power plant.

The binary cycle portion of the hybrid plant uses isobutane as the working fluid. Isobutane is pumped to a pressure of 330 psia by P-1-E, a multi-stage vertical turbine pump. Isobutane is then heated to its bubble point by warm brine in E-1-N, a shell-and-tube heat exchanger with counter-current flow. After leaving E-1-N, the isobutane flow splits with some of the isobutane being boiled by exhaust gas from the engine and the remainder boiled by hot brine.

Isobutane vapor from E-2-N and E-3-N is combined, passed through an entrainment separator, and expanded through a turbine to generate electricity. Exhaust isobutane leaving the turbine is condensed in four Baltimore Aircoil condensers. Condensed isobutane enters the accumulator V-1-E before being pumped back through the loop, thus completing the cycle.

Wellhead gas is burned in a gas engine. The hybrid cycle design is based on the use of a Caterpillar model 399 engine which was to have been contributed to the project. These engines require jacket cooling which is generally done by circulating water through the jacket. Jacket cooling can also be accomplished by putting water into the jacket where it boils to make steam. This second method of cooling is called ebullient cooling. Use of an ebullient-cooled engine is best for the hybrid cycle since the jacket heat is available at a higher temperature. However, the company which was to have contributed the engine did not have any ebullient-cooled engines available, so the design was based on an engine with a water-cooled jacket.

Combustion of the gas in the engine yields 650 kW at design. In heat exchanger E-3-N, exhaust gas from the engine at 1130°F is used to boil 14% of the isobutane. The remainder of the isobutane is boiled in E-2-N by hot brine from the wellhead separator. The brine, which leaves the separator at 278°F, is cooled to 220°F in E-2-N. The brine at 220°F enters E-1-N where it preheats the full flow of isobutane.

Even though the heat from the exhaust gas vaporizes only 14% of the isobutane, the addition of this heat is important to the overall cycle efficiency.

Figure 6-2 is a temperature-enthalpy diagram of the binary cycle portion of the hybrid plant showing the cooling curves for brine and exhaust as solid lines. Also shown is a cooling curve for the brine if no exhaust gas is available. Note from Figure 6-2 that the reject brine for the case with no exhaust gas (dotted line) is at a higher temperature than the reject brine when exhaust gas is used. Heat exchange limitations cause this higher rejection temperature since, for the same heat exchange surface, the cooling brine will have approximately the same pinch temperature for each case. The pinch occurs at the bubble point of the isobutane where the isobutane heating curve is closest to the brine cooling curve. Rejecting brine at a higher temperature means that less heat is provided to the cycle by the brine. Thus, for the case where there is no exhaust, less heat is provided by brine and no heat is provided by exhaust, so substantially less power would be produced. For the geopressured pilot plant at Pleasant Bayou, only eight percent of the total heat is from the exhaust gas, but the improvement in overall efficiency is still substantial.

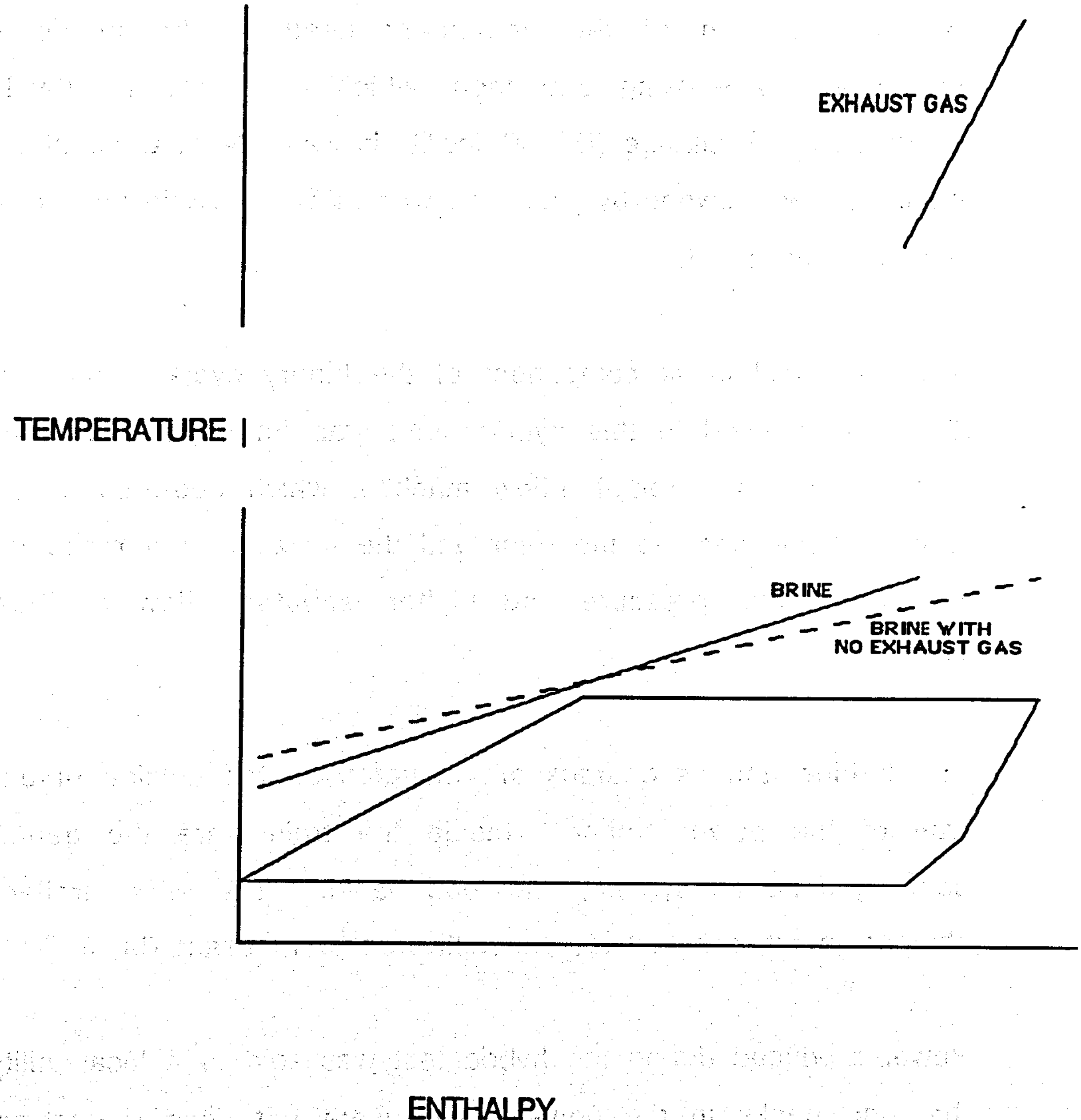

Figure 6-2. Heat Curve for Binary Cycle Portion of Hybrid Power Plant

6.2 Use of Existing Equipment

A major portion of the equipment used in the hybrid cycle experiment is existing equipment which was used in the Direct Contact Heat Exchange (DCHX) facility in East Mesa, California. This equipment was owned by DOE and was made available for use in the hybrid power plant.

The key mechanical component of the binary cycle is the turbine. The turbine used in this hybrid plant was from the DCHX facility. That turbine is a radial inflow machine which operates at 25,000 rpm. Modifications to the rotor and the nozzles were made due to the lower inlet pressure and higher isobutane flow at Pleasant Bayou.

The turbine and its gearbox are mounted on the outside of an end wall of the power trailer. Inside the trailer are the generator, controls, lube oil system, and load banks. The entire trailer was shipped intact, refurbished, and delivered to Pleasant Bayou.

Power produced during the hybrid test was sold to a local utility, so the load banks in the power trailer were not used during normal operation. They were used only during start-up.

The condensers from the DCHX test were reused with little modification. There are four Baltimore Aircoil evaporative condensers which condense isobutane on the insides of the tubes. Cooling water is sprayed on the outside of the tubes. Heat is removed from the isobutane primarily by evaporation of the cooling water. Fans are used to force air up through the tube bundles.

Also reused from the DCHX test was the module which contains the accumulator and the isobutane circulating pump. The accumulator was modified by removing an internal baffle which was used for separating water from isobutane in the DCHX. Six stages were removed from the isobutane pump in order to satisfy the flow and pressure requirements of the hybrid test.

Heat exchange in the DCHX test occurred entirely in the direct contact heat exchanger. This exchanger was not reused, but several instruments from the exchanger were used.

The control panel in the DCHX test was also mounted in a trailer. This control trailer also includes a data-logging computer and office space. The trailer was used in much the same manner as it was before, but the control panel was modified to account for the different process and instrumentation in the hybrid plant.

Another module from the DCHX test which was reused was the air skid. On this skid are the instrument air compressor with its receiver, two air conditioner units, and a fan which maintains positive air pressure in the two trailers. The air intake to this fan is from a stack 40 feet high. The high stack ensures that isobutane-free air is used to purge the trailers in the event of a spill. Isobutane, with a molecular weight of 58, is heavier than air and will tend to stay near the ground.

6.3 Comparison to Optimized System

Isobutane is not the optimum working fluid for a standard binary cycle on a resource with a temperature as low as at Pleasant Bayou (278°F). Propane could be used instead of isobutane to generate more power from a given amount of brine. But propane has a higher vapor pressure than isobutane, so the pressure ratings of most of the reused equipment would be exceeded.

A comparison was made of the difference in power production between propane and isobutane at Pleasant Bayou. Propane yielded approximately 5% more net power than isobutane. This relatively small advantage was not considered enough to merit the purchase of all new equipment. It is a straight forward calculation to estimate how much power can be produced from a different working fluid, so there is little compromised by using isobutane. The primary goals of the test were to demonstrate the hybrid cycle on a geopressured resource and to gain operating data over an extended period. Using isobutane allowed these goals to be met even if the net power production was slightly lower than if propane was used.

An optimized system would also recover the jacket heat from the gas engine. Since an ebullient-cooled engine was not available for this project, engine jacket heat was not recovered in this test. Using a gas engine with ebullient cooling or a gas turbine with a higher exhaust gas flow rate would yield more net power than did this hybrid cycle demonstration plant.

6.4 Piping and Instrumentation Diagram

The piping and instrumentation diagram (P&ID) is in Appendix B. The diagram shows dashed lines around modules which were reused intact. On this and other drawings, the equipment number includes "-N" at the end for new equipment or "-E" for existing equipment.

Also shown on the P&ID are the interface points between the hybrid power plant and the remainder of the geopressured test facility. Operation of the geopressured program for DOE was by a team of three companies: The Ben Holt Co. (Holt) of Pasadena, California; Eaton Operating Company (Eaton) of Houston, Texas; and Institute of Gas Technology (IGT) of Chicago, Illinois. Holt had the responsibility for the hybrid cycle power plant. Drilling and reworking of wells were by Eaton. Fluid handling, gas drying, and production data collecting and evaluating were by IGT.

Hot brine, dried methane, and cooling water makeup were provided to the battery limits of the power plant by IGT and Eaton. Spent brine and cooling water blowdown were taken by IGT at the plant boundary and disposed of.

7.0 EQUIPMENT DESIGN AND SELECTION

Specifications for all new equipment are included in Appendix C.

7.1 Turbine Generator

Electricity production from the binary cycle turbine at design is 541 kW at the generator terminals. Maximum capacity of the generator is 900 kW. A 900 kW load bank is included in the power trailer.

At the heart of the binary cycle is the turbine. The turbine itself is of radial inflow design, and had 13 blades on the rotor and variable nozzles. Rotor diameter was 7.75 inches during the DCHX test, but the rotor was trimmed down to 6.60 inches for the hybrid test. Since four rotors failed during testing at the DCHX, the turbine rotor was a serious cause for concern throughout the hybrid cycle project.

Mafi-Trench manufactured the turbine housing and the original rotor. Mafi-Trench also provided the first two replacement rotors used during the test. The Mafi-Trench rotors were made from aluminum, and the longest period of operation on one rotor was approximately 300 hours. This rotor did not fail structurally, but wore against the housing due to a thrust bearing failure.

The fourth rotor tested was made by Barber-Nichols. Titanium was used since the gear requires a low-mass rotor. The titanium wheel failed due to fatigue after a short period of operation.

The final rotor tested in the DCHX program was a 15-5 hardened stainless steel rotor made by Barber-Nichols. The rotor was made quite thin in order to keep the mass low enough that the gear was not overstressed. The high strength and good fatigue characteristics of the stainless steel allow the thin wheel to stand up to operating stresses. Operating time on the stainless rotor was approximately forty hours. Because of the history of problems with the turbine in the DCHX program a finite-element analysis was made by Structural Sciences Research Inc. to determine maximum stresses and critical frequencies in the rotor. The analysis was done based on design drawings. Maximum stress according to the analysis was approximately 69,000 psi. The yield strength of the steel is 145,000 psi, but the preferred allowable stress is 60% of the yield strength or 87,000 psi. That rotor as designed should have been capable of withstanding centrifugal forces and the reaction forces to isobutane flow to generate power. There is an additional stress from operation at a speed which excites a turbine blade at its natural frequency.

Because the anticipated stress was close to the preferred allowable yield stress, the rotor was removed from the turbine housing and inspected. In places, the actual rotor thickness was less than the values shown on the drawings and used in the calculations. Therefore, the decision was made to replace the rotor. When the new rotor was fabricated, particular attention was paid to ensure that the thickness met design specifications.

As part of this project, a detailed analysis of the rotor as built was also conducted along with a study of the stability of the high speed bearings. It was found that the lateral undamped critical speed of a stainless steel turbine rotor was too close to the 25,000 rpm operating speed. A lighter rotor was required. Titanium was selected and a new wheel was fabricated by Barber-Nichols in June 1989.

Bearing stability was also a concern. Operation with an unstable bearing may result in bearing wear which could cause vibration, rubbing of the rotor on the casing, and eventually failure of the bearings and rotor. A solution to this problem would have required a redesign of the bearings, construction of two custom bearings, putting the turbine/gear unit into a shop, dismantling the gear case to install the new bearings, and reinstalling the turbine/gear unit in the plant. However, this problem was predicted to occur only when the turbine was running at lower speeds. Due to the high cost of reworking the bearing and the probability that there would not be a problem during normal operation, it was decided to operate the plant with the existing bearings.

To protect the turbine and gear, vibration monitors and switches were installed. Two Bently-Nevada probes were used to measure shaft displacement in the gear box. These probes were placed at a 90° angle so that vibration in either axis could be detected. The high vibration switch was set at 4.5 mils. If vibration exceeded this level, the turbine would shut down to prevent damage. Other work done on the turbine included machining the exducer, installing a new spring behind the seal plate, and remachining the backing plate.

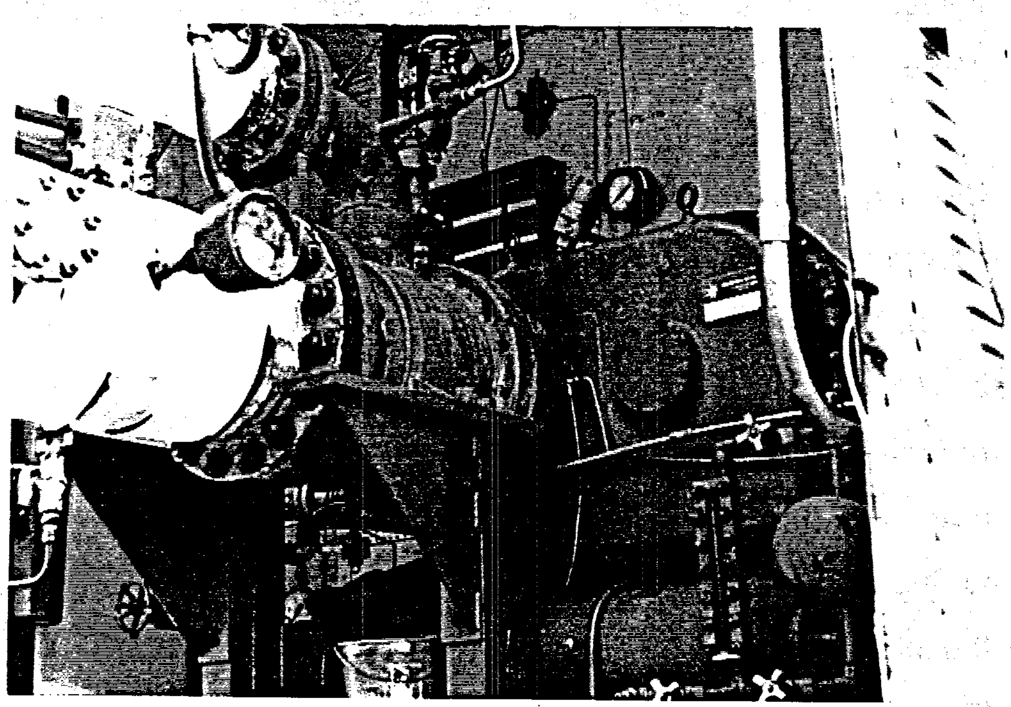

Figure 7-1a. Turbine-Generator, T-1-E

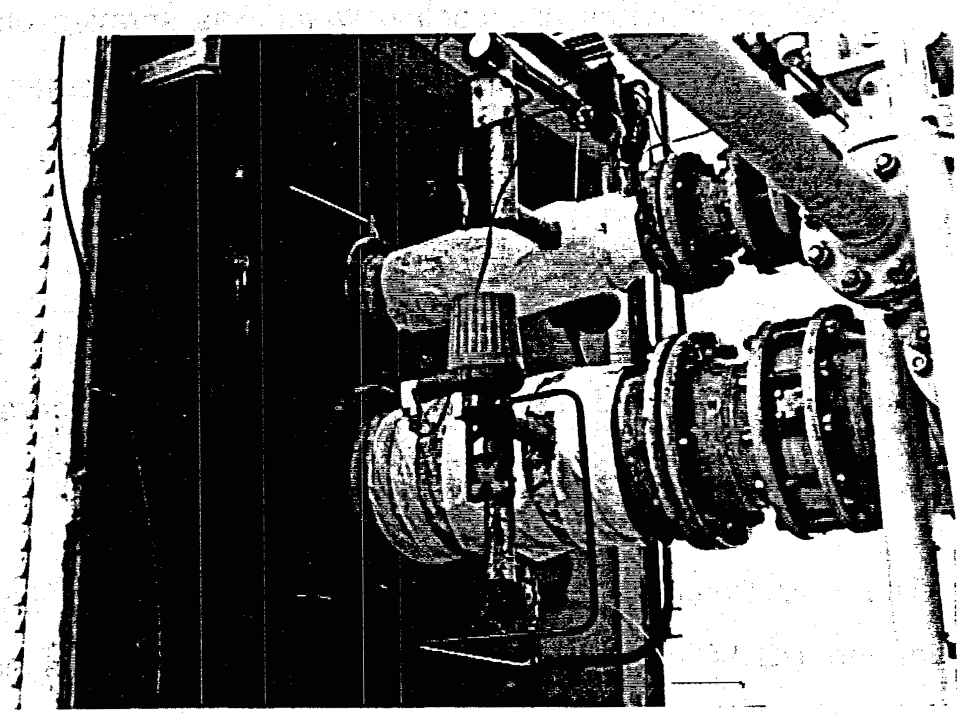

Figure 7-1b. Turbine Inlet & Outlet Piping

7.2 Condensers, CT-1-E

Isobutane exhausting from the binary cycle turbine was desuperheated and condensed in evaporative condensers made by Baltimore Aircoil. Isobutane was circulated through the inside of the exchanger tubes and cooling water was sprayed on the outside of the tubes. Heat was removed from the isobutane primarily by evaporation of the cooling water. Fans are used to force air up through the tube bundles.

Total design duty for all four condensers was 17 MMBtu/hr. At design, condensed isobutane exits the condensers at a design temperature of 94°F with a 64°F wet bulb.

The four Baltimore Aircoil evaporative condensers which were used at the DCHX facility showed evidence of substantial corrosion in the tube bundles. Some corrosion was expected since water vapor and noncondensable gases were mixed with the isobutane which was condensed in these exchangers during the DCHX test.

During refurbishment and construction, condenser coils were hydrotested at 350 psig, or 1.5 times their design pressure, in accordance with code. Approximately 15% of the condenser tubes were plugged prior to the beginning of operation due to hydrotest failures. Although plugging of condenser tubes hurt performance and operation of the power plant, testing occurred over a range of ambient conditions which allowed the power plant to be tested throughout a desired range of condensing conditions.

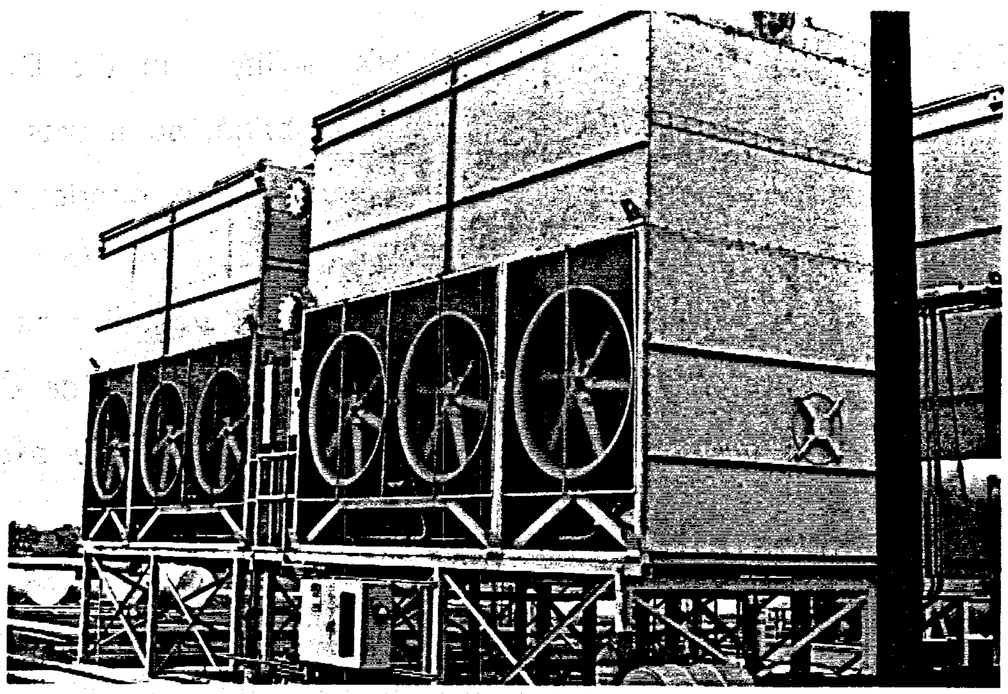

Figure 7-2. Condensers, CT-1-E

7.3 Accumulator

Accumulator V-1-E is a 3600 gallon tank with a diameter of five feet and a length of 25 feet. This tank provided surge capacity to account for changes in isobutane density as operating conditions change. It also provided suction head for the isobutane circulating pump.

This accumulator was from the DCHX facility. In the DCHX test, isobutane was mixed with the geothermal brine, so it was inevitable that some water would be carried over to the condensers. An internal baffle which was used for separating water from isobutane in the DCHX test was removed before this vessel was used at Pleasant Bayou. Water was not in contact with isobutane during the hybrid test since heat exchange was in shell-and-tube exchangers. Thus, the baffle was no longer needed.

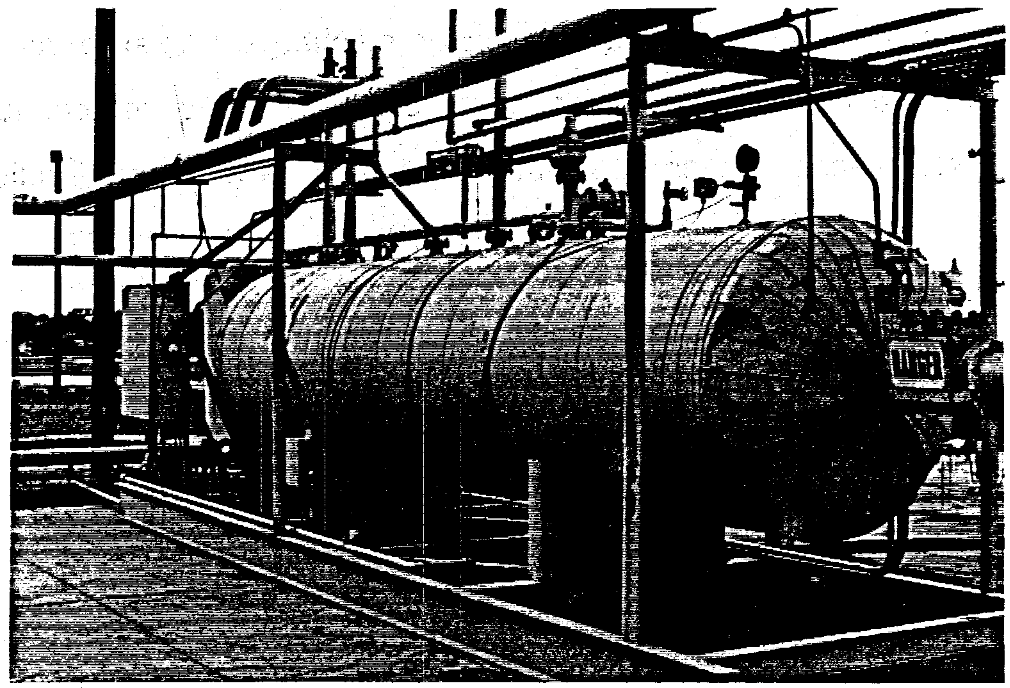

Figure 7-3. Accumulator, V-1-E

7.4 Isobutane Circulating Pump, P-1-E

Design isobutane flowrate in the hybrid test was only 8% higher than in the DCHX test. In addition, the pump design discharge pressure was 330 psia in the hybrid test versus 485 psia in the DCHX test. Thus, the existing isobutane circulating pump could be reused with modifications. Due to the lower discharge pressure required, 6 out of the original 21 stages were removed. This vertical turbine pump was placed in a can so that there would be adequate suction head.

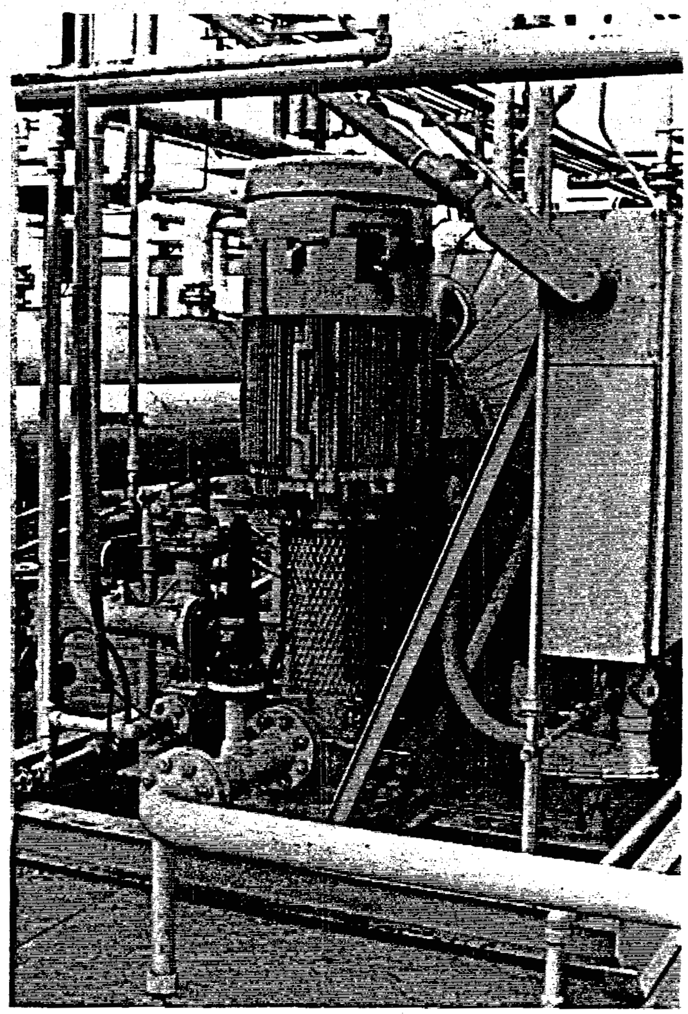

Figure 7-4. Isobutane Circulating Pump, P-1-E

7.5 Brine-to-Isobutane Heater, E-1-N

Isobutane preheat occured in the brine-to-isobutane heat exchanger, E-1-N. This is a shell-and-tube exchanger with single tube and shell passes with true counter-current flow. The exchanger is of fixed tubesheet design and is made of carbon steel. A specification sheet with pertinent design data is included in Appendix C.

Figure 7-5a. All Three Heat Exchangers (From the left: E-1-N, E-2-N, E-3-N)

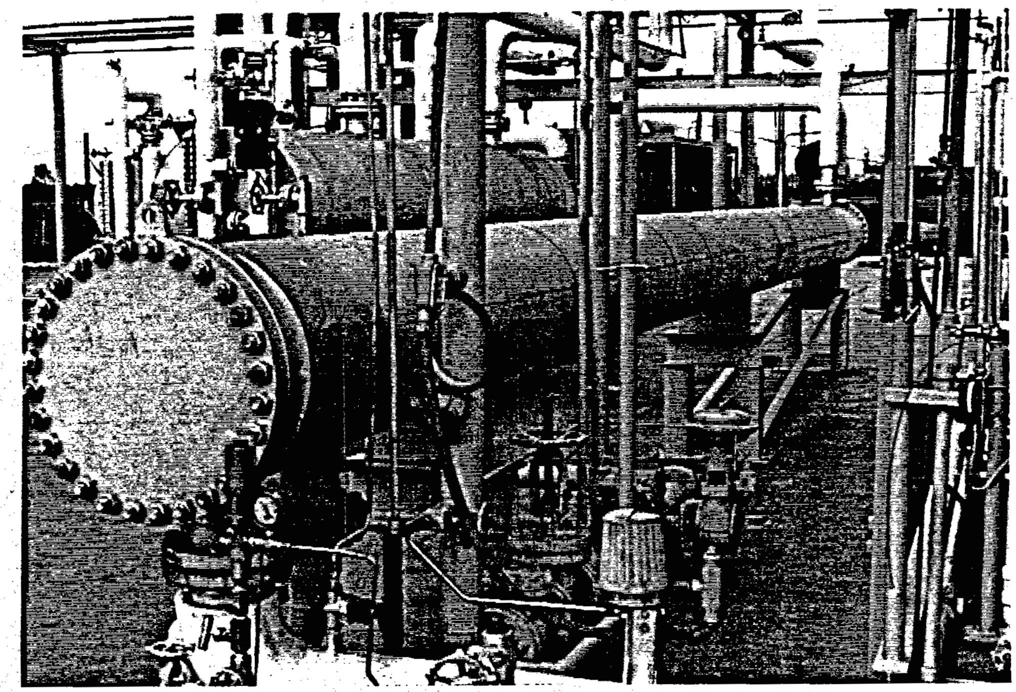

Figure 7-5b. Brine-to-Isobutane Heater, E-1-N

7.6 Brine-to-Isobutane Boiler, E-2-N

At design eighty-six percent of the isobutane is vaporized in the brine-to-isobutane boiler, E-2-N. This heat exchanger is a reboiler with isobutane on the shellside and brine on the tubeside. In order to maintain a high velocity and thereby reduce fouling, brine on the tubeside makes eight passes through the U-tube bundle. A demister is included in the vapor outlet to minimize liquid carryover. Like E-1-N, this heat exchanger is made of carbon steel. A specification sheet with pertinent design data is included in Appendix C.

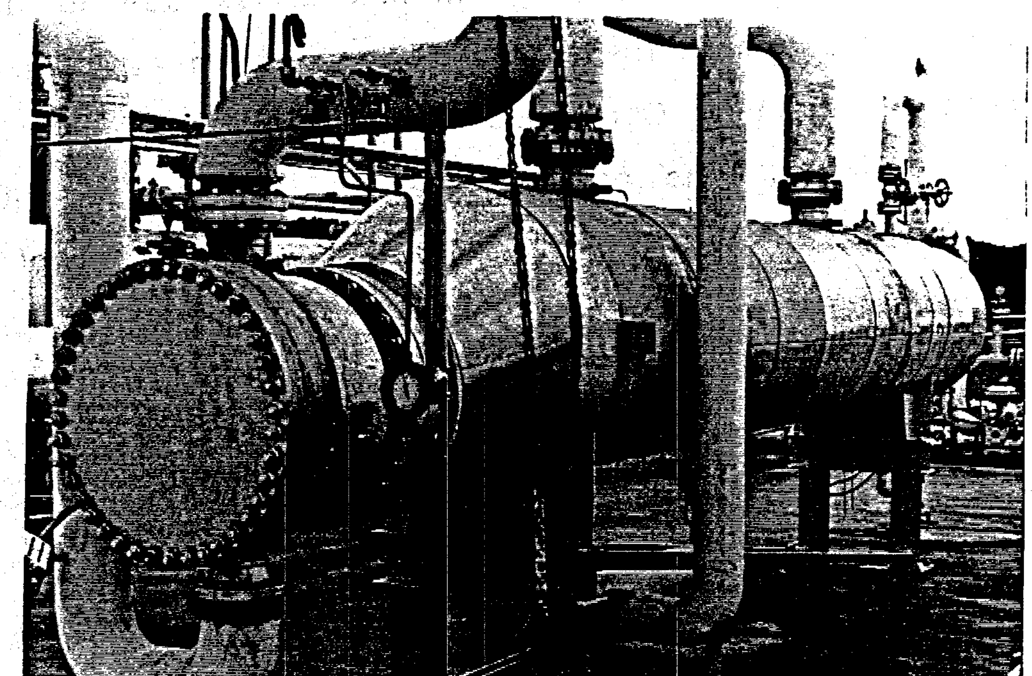

Figure 7-6. Brine-to-Isobutane Boiler, E-2-N

7.7 Exhaust Gas-to-Isobutane Boiler, E-3-N

Exhaust gas from the gas engine is used to vaporize fourteen percent of the isobutane. The exhaust gas enters the exhaust gas-to-isobutane boiler, E-3-N, at 1130°F and exits at 300°F. E-3-N, like E-2-N, is a reboiler with isobutane on the shell side. Exhaust gas enters the bottom of the U-tube bundle and makes two passes before being exhausted to the air.

The primary design concern with this heat exchanger was that the large difference between the 1130°F gas and the 210°F isobutane could cause problems with thermal stress due to differential thermal expansion. The solution to the problem was to use a split channel. Appendix C contains the specification sheet for the heat exchanger with the pertinent process and design information. Sections 7.7.1 through 7.7.3 discuss in detail the design of this heat exchanger.

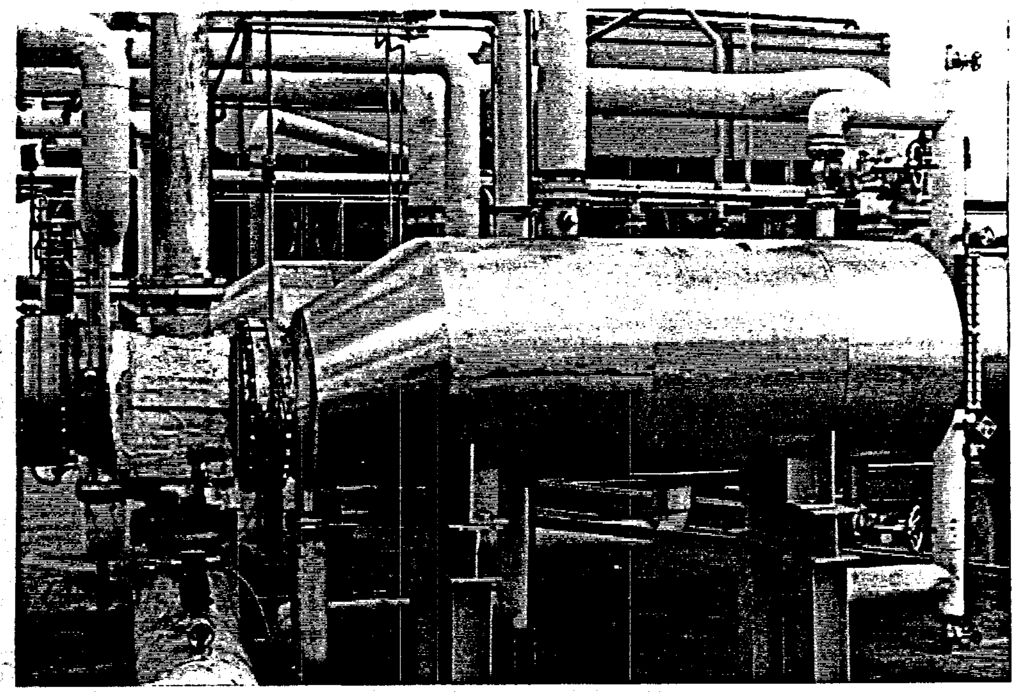

Figure 7-7. Exhaust Gas-to-Isobutane Boiler, E-3-N

7.7.1 Design Considerations

Design of the exhaust gas-to-isobutane heat exchanger, E-3-N, was complicated by the high exhaust gas temperature. Exhaust gas enters the heat exchanger at 1130 °F and cools to 300 °F while vaporizing isobutane which is at a constant temperature of 210 °F.

Several different design alternatives were considered before a final design selection was made. Requests for quotations were issued three different times for this exchanger, and a variety of designs from heat exchanger manufacturers were proposed. Four of the designs considered, but rejected, are shown in Figure 7-8.

7.7.2 Rejected Alternatives

Alternative A in Figure 7-8 is a vertical exchanger with one pass of exhaust gas on the tubeside. This alternative is attractive because the hot gas would enter the bottom of the exchanger and immediately cool down considerably by transferring heat to a boiling pool of isobutane. All the tubes would be wetted the same amount, so all tubes would have about the same thermal growth, thus minimizing stress on the tubesheet.

The problem with the vertical, single tube-pass design in Alternative A is that the tubes will grow considerably more than the shell. This growth must be accounted for by a shell expansion joint, a floating tubesheet, or some other means of flexibility. It was decided that a shell expansion joint would probably be best for the hybrid experiment at Pleasant Bayou. However, expansion joints in large exchangers have been troublesome in past experience and it would be preferable to avoid them. Since a goal of the experiment is to use the same type of equipment which will be used on large commercial facilities, a vertical, single tube-pass exchanger with a shell expansion joint was ruled out.

Alternative B in Figure 7-8 is a vertical exchanger with a U-tube bundle instead of a single tube-pass design. U-tubes have the ability to flex when the inlet side of the tube grows more than the outlet. As before, all tubes are wetted approximately the same amount, so all tubes should grow the same. With all tubes growing the same amount and U-tubes allowing for differential growth, the stress on the tubesheet is minimized. Once again, exhaust gas enters in the bottom of the exchanger so the gas cools quickly after entering the exchanger.

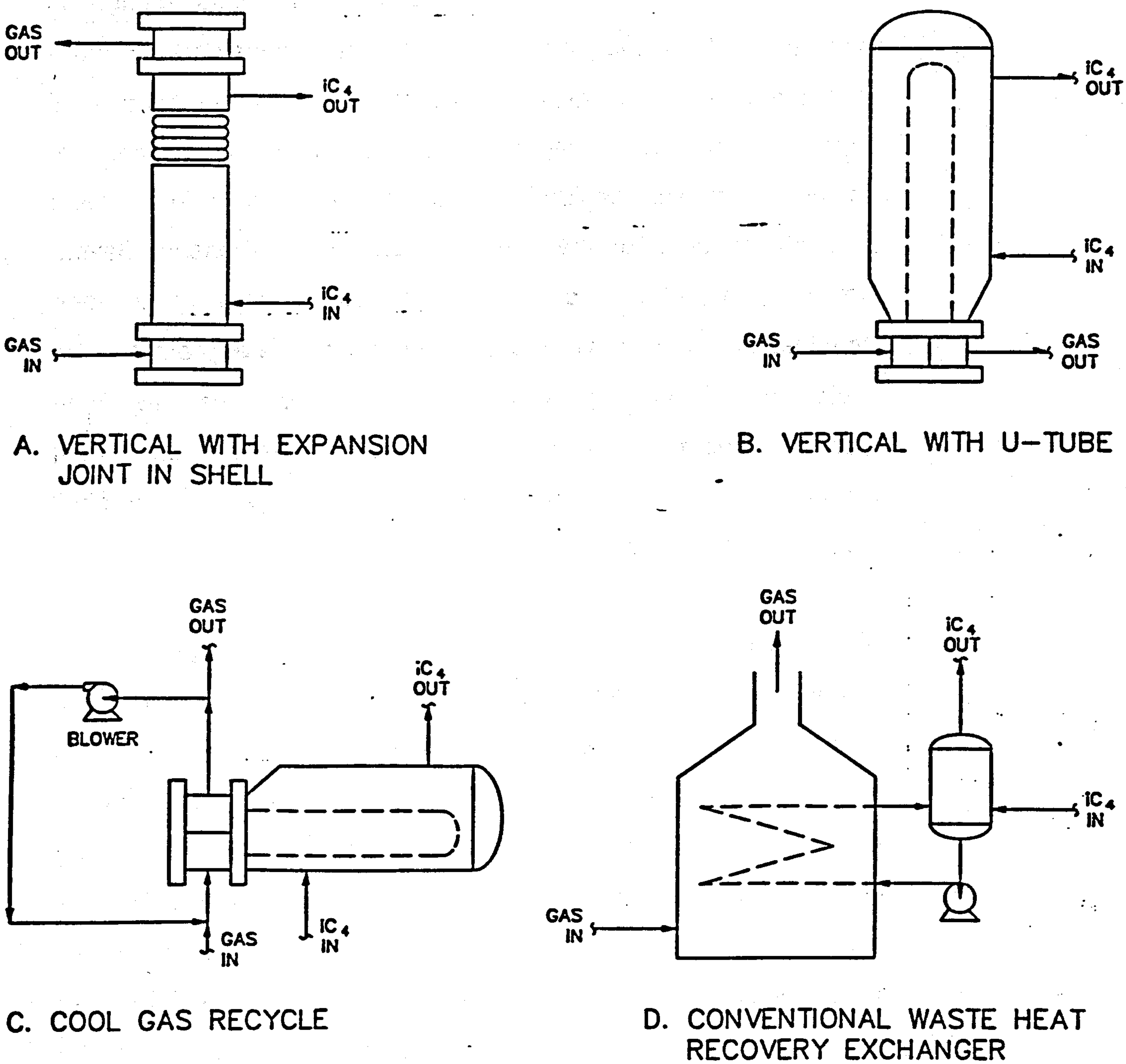

Figure 7-8. Rejected Alternatives for Exhaust Gas-to-Isobutane Heat Exchanger

A serious drawback to the U-tube design for E-3-N is that the gas enters and leaves through the same tubesheet and the same channel. The inlet gas is at 1130°F and the exhaust is at 300°F. During operation, the inlet side of both the tubesheet and the channel will grow more than the outlet. Tremendous stress will develop because the temperature difference is so large. Manufacturers were concerned that failure in the tubesheet, the channel, or the tubesheet-to-channel joint was likely.

Horizontal heat exchangers were also considered. The primary concern with a horizontal exchanger is that the liquid isobutane level is variable. If the liquid level were to drop too low, tubes containing hot inlet gas may be above the liquid. The dry tubes would be in a region where the heat transfer coefficient is low. Thus, these tubes would grow much more than the wetted tubes below them. The resulting stresses on the tubesheet would be high, even for a U-tube bundle.

One means of avoiding the problem of excessive thermal stress is to reduce the temperature of the inlet exhaust gas. One means of accomplishing this which was considered is to recycle a portion of the 300°F gas leaving the exchanger as shown in C of Figure 11-4. The 300°F gas can be combined with the 1130°F inlet gas to drop the entering gas temperature to a temperature of 800°F or less. This would avoid most of the thermal stress problems.

Lowering the gas temperature reduces thermal stress, but it also reduces the LMTD so the heat exchanger area increases. In addition, increased mass flow of exhaust gas through the exchanger increases pressure drop, so a large exchanger diameter is required to stay within pressure drop specifications.

Recycling the outlet gas requires a blower which adds capital cost, operating complexity, and parasitic power load to the system. The alternative of recycling the outlet gas was therefore discarded as too costly.

Another design option which was considered is a conventional waste heat recovery exchanger shown as D in Figure 7-8. In this design, isobutane flows inside tubes which pass through a square duct through which the exhaust gas flows. One advantage of this design is that the exhaust gas has a low pressure drop.

The major disadvantage of a conventional waste heat recovery exchanger is that not all of the isobutane is vaporized inside the exchanger. A separator on the exchanger outlet is required to collect the liquid isobutane which then must be pumped back through the coil. The additional cost and operating complexity caused by this extra equipment makes this an expensive alternative.

7.7.3 Selected Design

The design selected to handle the high temperature difference problems is a horizontal reboiler type exchanger with a U-tube bundle. Figure 7-9 shows the details of the exchanger which was built for this project.

U-tubes are used because their flexibility allows for differential growth of the tubes. The problem of some tubes being above the liquid level is minimized by directing incoming isobutane liquid across all tubes containing the hot inlet gas.

Isobutane liquid enters the shell of the exchanger adjacent to the hot gas inlet. A vertical baffle directs liquid upward across the hot half of the tube bundle as shown in Figure 7-9. A horizontal baffle keeps the liquid in the bottom, hot half of the exchanger. Liquid isobutane washes over the vertical baffle and falls back down across the inlet tubes, thus making sure that all tubes contact liquid in this zone of maximum heat transfer.

The problem of differential expansion across the tubesheet and channel is solved by having a two-piece channel. Separate inlet and outlet channels are bolted onto the tubesheet without being connected in any way. The inlet channel can therefore grow more than the outlet channel without putting too much stress on the connections to the tubesheet.

With separate channels tubesheet can grow without putting excess stress on the channels. The tubesheet will not expand as much as the channels because boiling isobutane rapidly removes heat from the tubesheet. The heat transfer coefficient of the boiling isobutane is much higher than that of the exhaust gas on the other side of the tubesheet, so the tubesheet will tend to stay much closer to the isobutane temperature than to the temperature of the gas.

7.8 Gas Engines, GE-1-N and GE-2-N

Most of the hybrid cycle power output is generated from burning methane in a gas engine. Two Caterpillar 398 engines were selected for use in this project. These engines were 12 cylinder naturally-aspirated internal combustion engines with spark-ignition. Water jacket cooling was used with the coolant outlet temperature maintained at 190°F. Design electricity production was 650 kW. The engines were skid mounted with all necessary controls and auxiliary equipment.

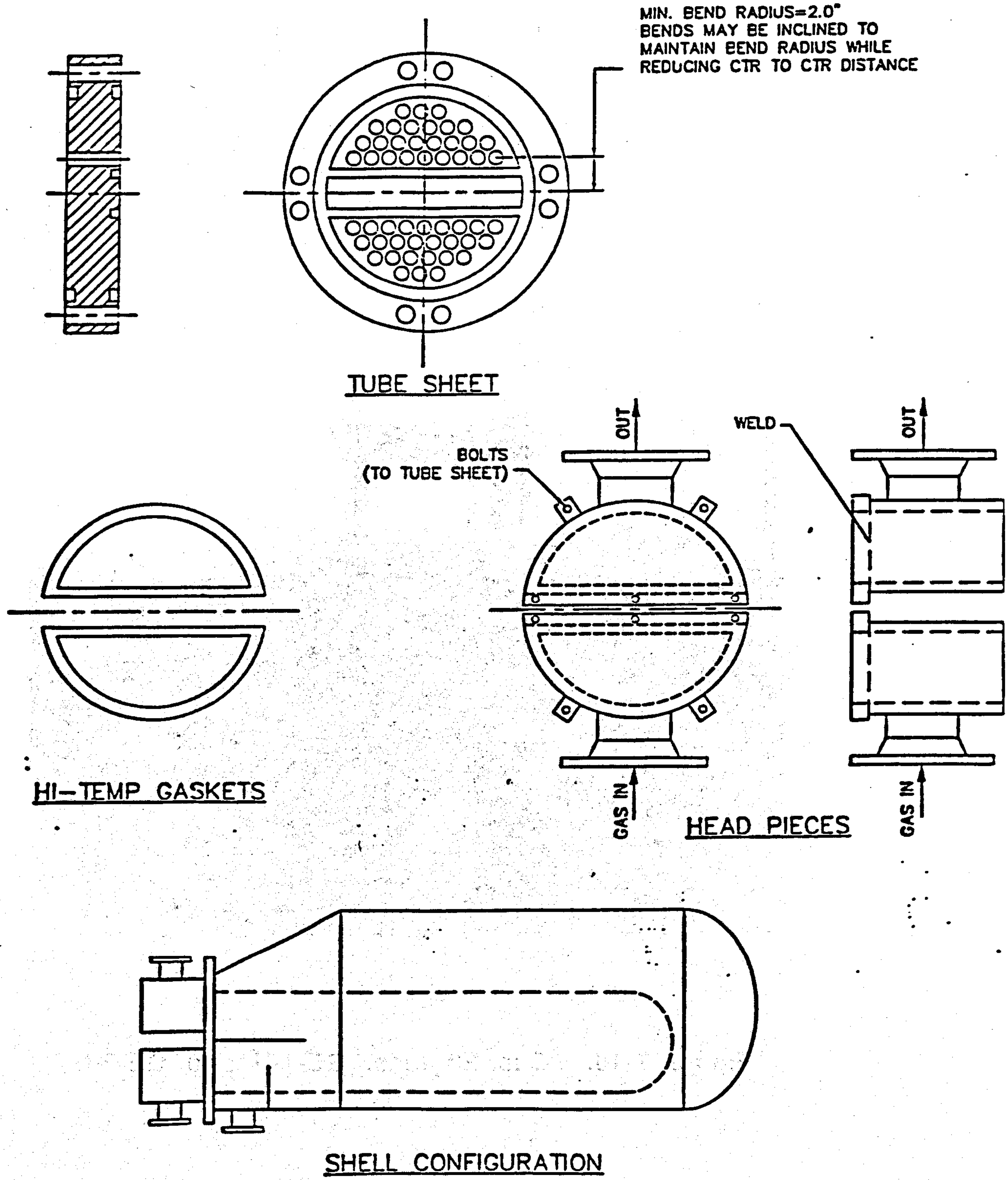

Figure 7-9. E-3-N Design Details

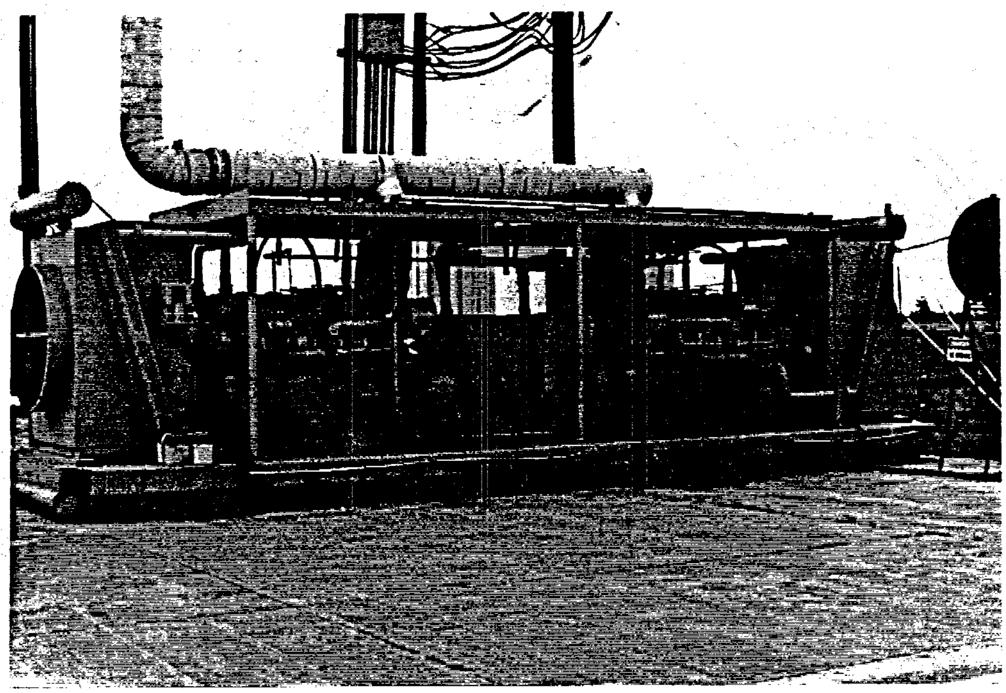

Figure 7-10. Gas Engines, GE-1-N and GE-2-N

7.9 Air System

A schematic of the instrument air system is provided in Figure 7-11. Instrument air is provided by a compressor on the air skid.

Also on the air skid is a fan which is used to provide positive air pressure for the two trailers. Air intake to the fan is through a 40 foot high stack to ensure that isobutane-free air is used to pressurize the trailers.

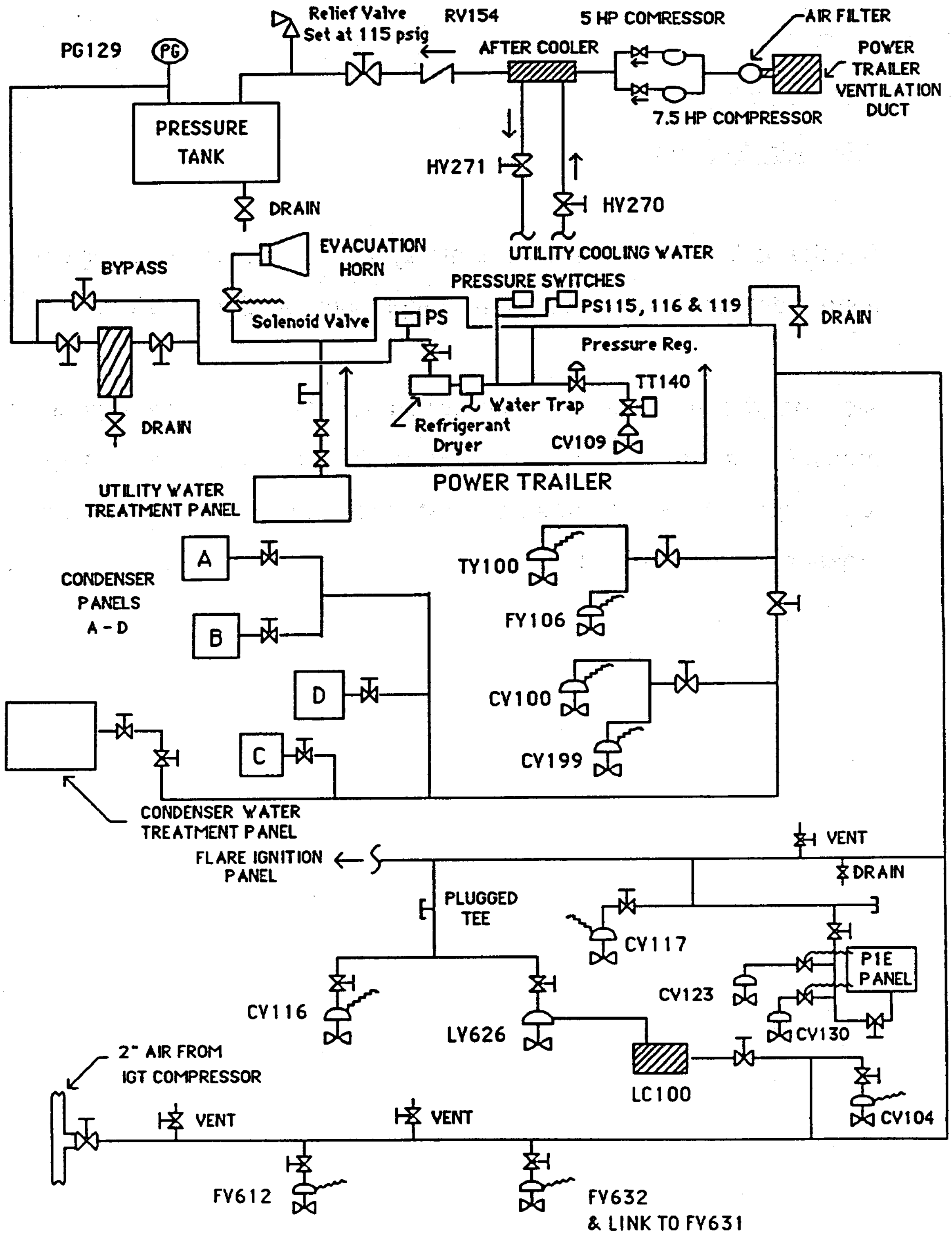

Figure 7-11. Instrument Air

7.10 Gas-Freeing Compressor

A two stage Corken D-390 compressor was purchased. This compressor has a capacity of 14 actual cubic feet per minute and a 7.5 HP motor. It was used to evacuate different sections of the hybrid cycle plant during periods of maintenance. Isobutane could be transferred into the accumulator so that equipment and piping could be safely worked on. It was also used on start-up to remove air from the process lines.

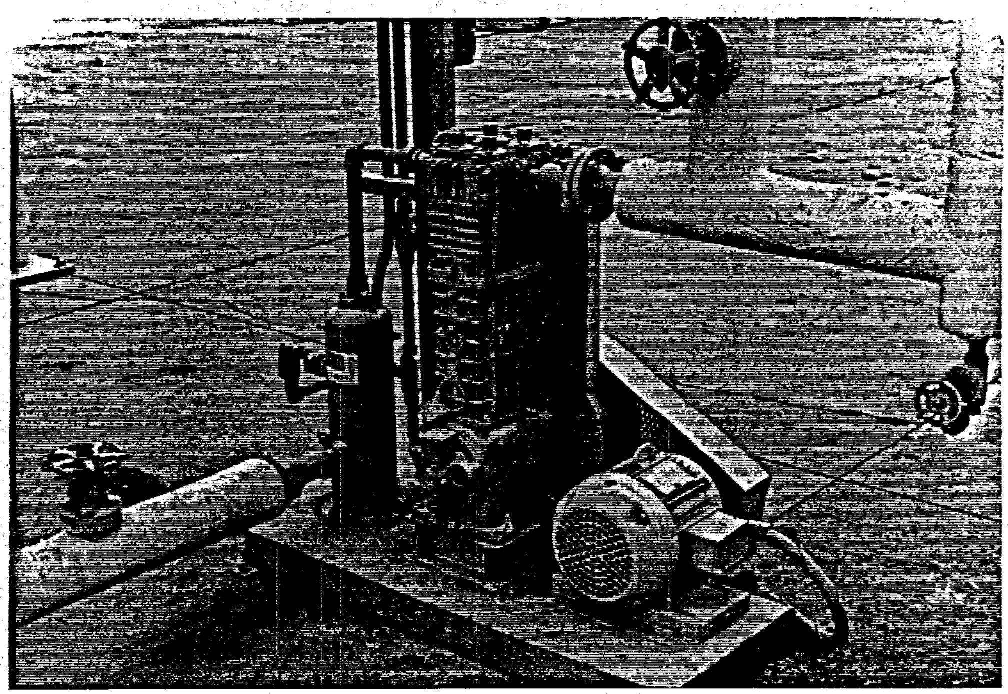

Figure 7-12. Gas-Freeing Compressor

7.11 Fire Protection System

The DCHX test facility had a complete fire protection system which was moved to Pleasant Bayou for reuse. Two fire monitors and a 750 gpm firewater pump could not be transferred and replacements were purchased. A 30,000 gallon firewater pond was built at the facility and a larger flare than had been used at the DCHX facility was added.

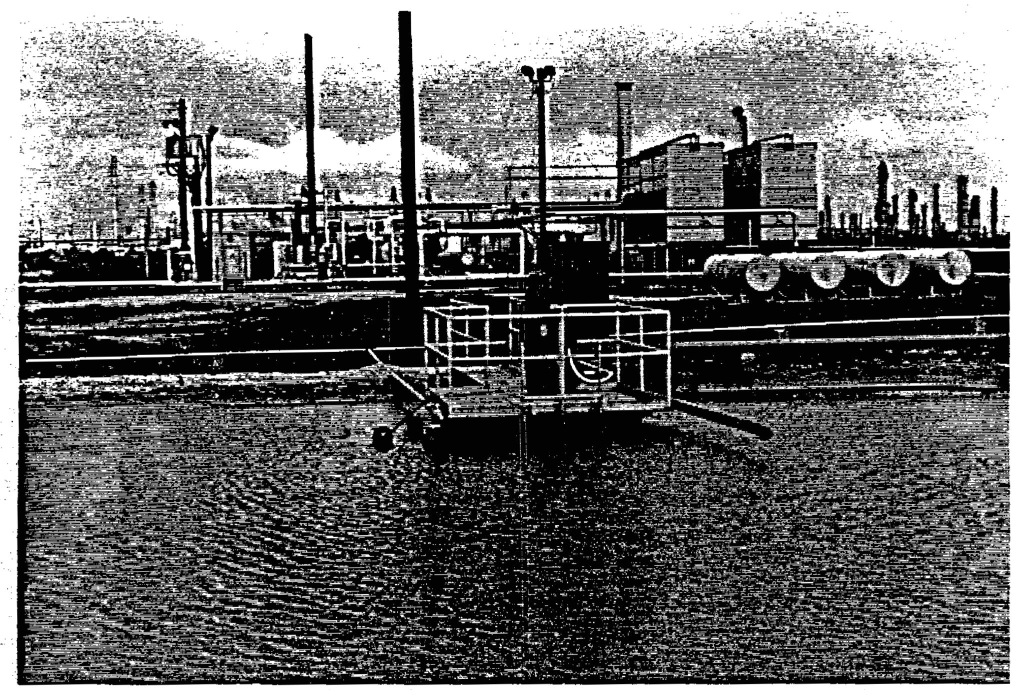

Figure 7-13a. Fire Protection System

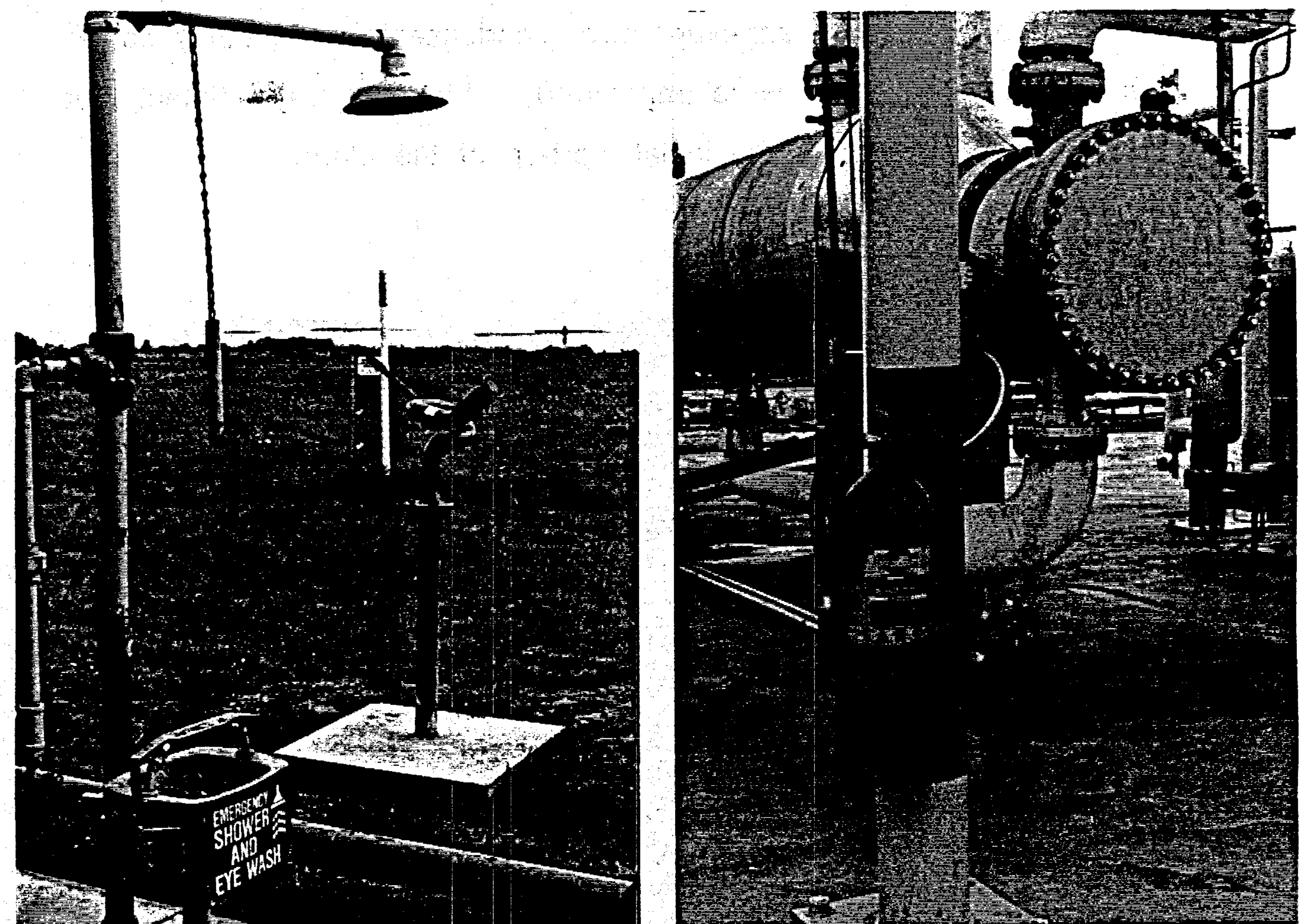

Figure 7-13 b & c. Fire Protection System

7.12 Load Banks

Electricity produced during operation of the DCHX test was dissipated in load banks. The load banks consist of six electric water heaters rated at 150 kW each. Heated water from the load banks was cooled in an evaporative condenser on the utility cooler skid. The load banks were transferred to Pleasant Bayou intact, but were used only during the initial start-up of the plant.

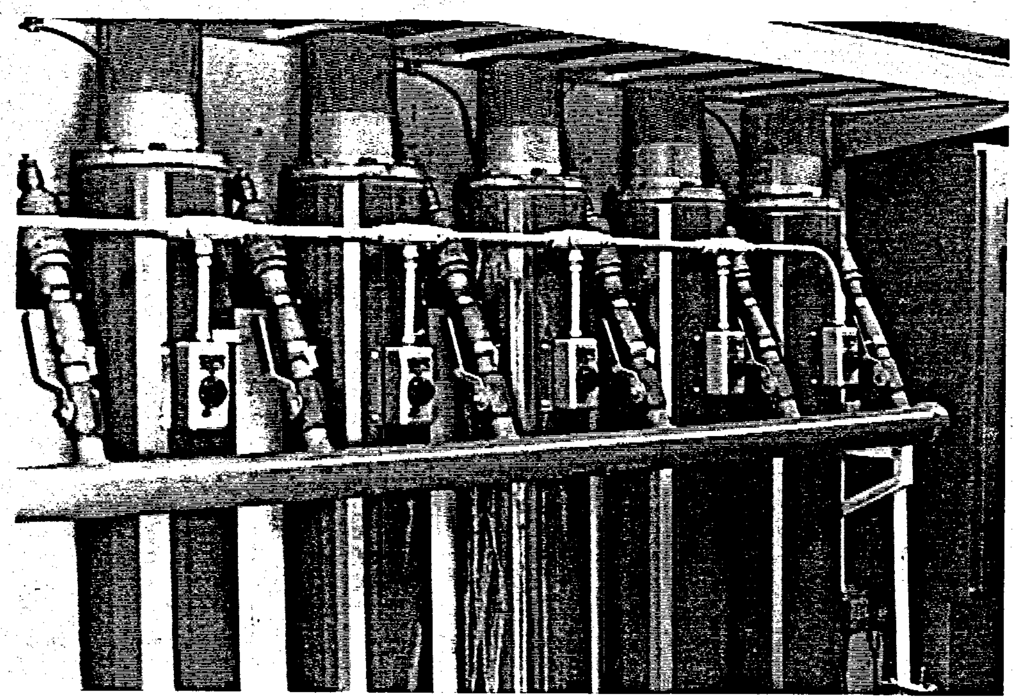

Figure 7-14. Load Banks

7.13 Control System

Control of the system was relatively simple. Isobutane flow was controlled by level control in each of the two reboilers; E-2-N and E-3-N. Brine flow was manually set such that the proper conditions at the outlet of E-1-N were met. Brine was put through the system at as high a rate as possible such that the limitations were on the isobutane side. A process flow diagram which shows the major controls is seen in Figure 6-1.

Existing controllers from the DCHX facility were used where feasible. The existing control trailer was refurbished and the control panel was reworked for the new service.

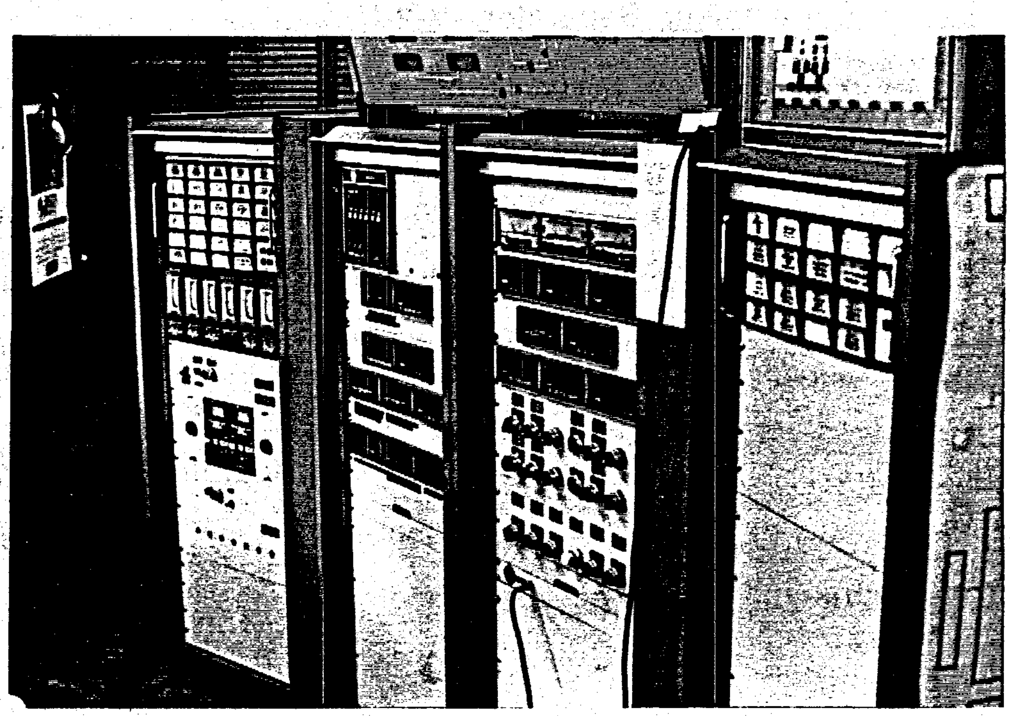

Figure 7-15. Control Panel

7.14 Electrical System

The main single line drawing is in Appendix D. At design, 650 kW of electricity was produced by the gas engine and 541 kW by the binary cycle turbine. Parasitic load was originally estimated to be 209 kW. These loads are presented in Table 6-1 and are described in the text at the beginning of that section. Actual loads were significantly higher than estimated. However, parasitic loads are a much lower percentage of gross output for commercial binary cycle plants. Power which was produced in excess of the amount consumed was sold to Houston Lighting and Power (HL&P).

7.15 Liquid Entrainment Separator, V-2-N

Protecting the turbine from incoming slugs of liquid is critical. Demisters were installed in E-2-N to provide this protection, but the limited liquid-vapor disengaging space raised concerns that the demisters would be inadequate. Therefore, a liquid entrainment separator was added immediately upstream of the turbine. Since E-3-N was purchased after the entrainment separator, no demisters were installed in E-3-N. The liquid entrainment separator was of a cyclone design, and was effective in protecting the turbine.

Figure 7-16. Liquid Entrainment Separator

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8.0 ENVIRONMENTAL, SAFETY AND QUALITY ASSURANCE PROCEDURES

8.1 Environmental Concerns

There are several potential emission sources in the hybrid power system at Pleasant Bayou. These include emissions from the evaporative condensers, gas engines, brine system, and isobutane loop. No emissions occurred which would impede the development of a commercial geopressured power plant.

Evaporative condensers operate on the same principle as conventional cooling towers, so cooling tower blowdown is a liquid waste stream from the plant. However, a clean water supply was available and only small amounts of corrosion inhibitor were added to the cooling water, so cooling water blowdown was not a concern. A permit was obtained from the Texas Railroad Commission (TRC) for disposal of the "non-contact" cooling water into the adjoining waterway (Chocolate Bayou). Proper documentation was also furnished to the Environmental Protection Agency (EPA). Daily checks were made of the pH, temperature, phosphate concentration and residual chlorine concentration of the water being discharged. Quarterly reports were furnished to the Texas Railroad Commission. No problems occurred which resulted in excessive emission of pollutants to the bayou.

Cooling tower emissions were negligible due to the clean water supply. Plume visibility and fogging were also not problems. All of the brine was reinjected so brine disposal posed no environmental concerns. Since the brine is primarily a sodium chloride water solution with a composition similar to that of the tidal basin water, a brine spill would not be catastrophic.

Another potential environmental concern was exhaust emissions from the gas engines. Since the wellhead gas is primarily methane with low sulfur and nitrogen content, it is a clean burning fuel. A standard exemption No. 6 to the Texas Air Control Board (TACB) permitting requirements was obtained on the basis that the engine horsepower was less than 825 HP each, and that the exchaust stack was more than twice the height of nearby obstructions to windflow (45').

Caterpillar specifies the emissions for this engine as 750 g/hr unburned hydrocarbons, 1000 g/hr carbon monoxide and 10850 g/hr of nitrogen oxide. These emissions are based on burning commercial natural gas with 2% excess oxygen. Emission levels were not measured in the demonstration plant, but this issue should be addressed in the design of a commercial facility. Also, since a hybrid cycle is more efficient than stand-alone geothermal and fossil fuel burning plants, less pollutants are emitted per kW of power produced. Unburned carbon caused fouling of heat exchanger

E-3-N and could be an environmental concern due to particulate emissions. However, operation in this manner causes a heat transfer problem which must be overcome. Most likely, once the gas is cleaned up enough to protect the heat exchanger surfaces, the particulate emission problem will be solved.

Isobutane emission was the only significant environmental concern at Pleasant Bayou. Due to the short-term nature of this test and the small amount of emissions, relative to much larger plants, an exemption was obtained to the TACB standards that allowed up to 144 lbs/day of isobutane to be emitted. Approximately 99 lbs/day of isobutane were emitted to the atmosphere from January 29, 1990 through June 11, 1990. Isobutane emission was higher through much of January due to a leak through the turbine seal assembly.

Lower isobutane emission can be achieved in a commercial binary plant in several ways. The equipment would be new and designed for the specific facility, so there would be fewer leaks and less maintenance required. In a plant designed today with keen awareness of environmental concerns, welded connections would replace flanges to reduce emission at joints. Many of the over 860 flanged connections at Pleasant Bayou could be eliminated. Special care in assembling flanged joints could further reduce isobutane emissions. Relief valves could vent to a common header so that fugitive vapors could be recovered or burned in a flare.

8.2 Safety Systems

A summary of actions taken to comply with OSHA Standards (July 1986 Issue) follows.

OSHA Subpart C - General Safety & Health Provisions

1) Material Safety Data sheets were provided for isobutane, cooling tower chemicals and for all chemicals used in the project.

OSHA Subpart D - Walking-Working Surfaces

1) A concrete paved area was provided for the operating area of the plant. This area was maintained clean and free of debris. There were no requirements for material handling of production items. Maintenance work was largely at grade level on the concrete pad.
2) A firewater pond was located approximately 200 feet from the facility. A path with gravel surface was provided for foot traffic.
3) Four storage tanks for isobutane (classified as Liquid Petroleum Gas tanks) and a transfer pump were located beside the foot path.
4) A single elevated platform (5 feet high) existed between four water-cooled condensers. This platform was provided with standard railing to protect open areas.

5) Entrance to a generator mounted in a semitrailer was provided with permanent stairs provided with a handrail to the 4-foot height.

6) A mobile home trailer served as a control room. Access was provided by stairs to the three foot height at two doorways.

OSHA Subpart E - Means of Egress

1) Egress from the control trailer was provided by an exit near each end of the plant with stairs to an open area.

2) Egress from the 25-foot long open platform at the water-cooled condensers had a ladder at each end of the platform.

3) A single door and stairs were provided at the power trailer. Area of the room served by the door was 7 feet by 15 feet. There was no combustible or hazardous materials near the door. This room had electrical switchgear enclosed in metal cabinets and at the far end a generator, gear reducer and lube oil system.

4) All sides of the plant area were open without obstruction if evacuation had been necessary.

OSHA Subpart G - Occupational Health & Environmental Control

1) No work involving abrasives, dusts, or open chemicals was performed. Training was provided for maintenance work prior to introduction of isobutane where isobutane might be vented to the atmosphere from malfunctioning

equipment. Ventilation air for the control room was obtained from a stack 25 feet in the air to ensure isobutane free air.

2) Noise exposure from operation of the generating equipment was a concern.

   (a) Several control valves produced noise and a noise survey was done after the plant started. Ear protection was required around noisy valves.

   (b) Operation of a 500 kw turbine, its gear reducer and generator produced noise. A semitrailer body and partition enclosed the generator. Personnel did not normally enter the trailer during operation and daily exposure was less than 1/2 hour per day. Ear protection was provided each operator and was available at the entrance. Levels of 90 to 95 dBA were expected inside the trailer which is within Table G-16 (29 CFR 1910) requirements. Further reduction of the noise at the generator was not feasible.

   Noise from the gear reduction unit was generated in one end of the enclosed semitrailer. Noise was reduced by the trailer. Employees did not perform any duties near the gear unit.

   Noise from the turbine was generated at the turbine housing and transmitted radially and also along the discharge piping system. Radial noise was mitigated by the enclosure of the semitrailer. Noise transmitted down the discharge pipe was partially mitigated by insulation over the pipe. Operators were not required to approach or work near the turbine or discharge piping during normal duties. Most of their time was spent inside the controls trailer at a distance of 50 feet from the turbine. Daily exposure was well below the Table G requirements. Ear protection for exposure near the turbine and training in proper use was provided to each employee before operations began.

(c) Radioactive materials or electromagnetic radiating devices were not used at the site during operations. X-raying of pipe welds was performed by and under the direction of licensed nondestruction examination subcontractors, Eaton Operating Company (EOC) supervisor and safety personnel (29 CFR 1910.96 & .97)

OSHA Subpart H - Hazardous Materials

1) Compressed gas cylinders were used in operation. Cylinders for maintenance welding by subcontract firms were monitored and appropriately handled.

2) Small quantities of flammable materials were limited to maintenance solvents (paint thinner, diesel, etc.) and were stored away from site in EOC's storage area.

3) Explosives and blasting agents were not allowed on the HPS area; however, they may have been used in well maintenance.

4) Isobutane, classified as a Liquified Petroleum Gas under 29 CFR 1910.110, was used as a working fluid in the power generation cycle.

5) A makeup supply was stored in four small tanks (1000 gallons each). These tanks were permitted by California Occupational Safety and Health Administration and were equipped with relief valves set at 275 psi. Vapor pressure of isobutane at 100°F is 72 psi. A concrete foundation supported the tanks. Spacing of three feet was provided between tanks for fire protection. The tanks were insulated and provided with shutoff, excess flow valves and secured to the pad. Maximum filling density allowed (Table H-27 in 29 CFR 1910) was 49%. Upon delivery of isobutane to the site, the vendor had responsibility for connecting his truck to the system and operating the valves on the truck. He was not allowed to operate the plant valving.

6) An accumulator in the process area of 3475 gallon capacity contained the working fluid. It was manufactured to ASME Section VIII standards per the Tanks Data Sheet for a design working pressure of 225 psi, and was equipped with relief valves set at 225 psi. Design operating pressure of the system was 100 psia. Maximum

filling density allowed (Table H-27 in 29 CFR 1910) was 52%.

7) Odorizing materials were not used as they would create operating problems in the binary cycle. Small amounts of breakdown products would accumulate in the system and cause corrosion of equipment. [29 CFR 1910.110(b)].

8) All isobutane piping was carbon steel, designed for an operating pressure of 500 psi which was above the operating pressures of the system. Cast iron materials were not used.

9) Relief valves were sized to provide for safe release of pressure to an above-ground-flare. Relief valves were provided between block valves.

10) Stress analysis for thermal expansion was performed on all lines subject to temperature changes. Piping was anchored and guided according to piping codes ANSI B31.1 and B31.3.

11) Hose for unloading petroleum products delivery trucks was provided by the transporting carrier.

OSHA Subpart I - Personal Protective Equipment

1) Requirements for personal protection were the OSHA 29 CFR 1910 standards as follows:
   (a) All areas of the plant outside the HPS trailer required a safety hard hat.
   (b) Full length trousers were required.

(c) Appropriate shoes were required.

(d) Safety or prescription safety glasses were required in activities where high pressure fluids were being released.

(e) When handling chemicals for treating cooling towers, a face shield and hard hat and rubber gloves were required.

2) Elevated electrical work was done only from non-conducting ladders.

OSHA Subpart J - General Environmental Controls

1) Sanitation

(a) Restrooms with lavatory were provided on site at the project office facility.

(b) An eating area was provided in the control trailer for employees.

2) Safety stencils for marking physical hazards was used.

(a) The color red was used to indicate fire protection equipment.

(b) The color yellow was used to indicate caution.

3) Safety signs were located as follows:

(a) **"NO SMOKING"** signs on the open sides of the operating area.

(b) **"HARD HAT AREA"** signs on the open sides of the operating area.

(c) **"DO NOT ENTER"** signs on the open sides of the operating area.

(d) **"HEARING PROTECTION REQUIRED"** on 4 sides of the turbine.

(e) **"SAFETY SHOWER"** at the safety shower.

(f) **"DANGER - CORROSIVE CHEMICALS"** at the chemical addition area for the cooling towers.

OSHA Subpart K - Medical and First Aid

1) Medical Services:
   (a) Hospital
   (b) Ambulance
   (c) Paramedics (Fire Dept.)
2) First Aid supplies were maintained in a cabinet in the control trailer.
3) A safety shower and eye wash were provided at the power trailer.

OSHA Subpart L - Fire Protection

1) See Fire Protection System, Section 8.2.1

OSHA Subpart M - Compressed Gas & Compressed Air Equipment

1) Two compressors and a dryer system provided 100 psig air for instrumentation and control of the plant.
2) A single air receiver provided 500 gallons of surge capacity. Pressure rating of the receiver was 115 psi.

3) A relief valve was directly connected to the receiver.

4) Drains were provided on the air receiver, the dryers and on piping.

OSHA Subpart N - Materials Handling and Storage

1) Chemicals for treating the cooling tower water were received in 55 gallon drums which were moved into position with a standard barrel hand cart.

OSHA Subpart O - Machinery and Machine Guarding

1) Rotating machinery at the site included pumps, compressors, fans, a generator, and two gas fueled motor generator sets. No machining was performed on site.

2) Approved guards were provided on all equipment.

OSHA Subpart P - Hand and Portable Powered Tools

1) When compressed air was used for cleaning, it was reduced to 30 psig.

2) Power and pneumatic hand tools were provided for routine maintenance.

OSHA Subpart Q - Welding, Cutting and Brazing

1) Welding and cutting were only performed by trained personnel.

2) Prior to starting any work, a "hot work checkout" procedure was followed and if conditions were proven safe, a "hot work permit" was approved and issued.

OSHA Subpart R - Special Industries (Not Applicable)

OSHA Subpart S - Electrical

1) Electrical design and installation were in compliance with the National Electrical Code.
2) Particular attention was paid to grounding of equipment and classification of areas.
3) Connection to the power distribution system of Houston Lighting & Power (HL&P) was designed and coordinated with HL&P engineers for high voltage equipment and safety relays.
4) Single line drawings are included in the Appendix and show the basic configuration.

OSHA Subpart T - Commercial Diving Operations (Not Applicable)

OSHA Subpart Z - Occupational Health & Environmental Control

1) Certain of the chemicals in Tables Z-1, Z-2 or Z-3 of Subpart Z of 29 CFR 1910, Hazardous Chemicals, may have been used at the site.

2) None of the materials in Sections 1910.1001 to 1910.1047 of 29 CFR 1910, Toxic Chemicals, were on site.

3) Geothermal brine from the well was completely contained in the pipe and exchanger system

4) Hazardous communication program

   (a) Material safety data sheets were provided for isobutane and cooling water treatment chemicals.

   (b) There were no trade secrets involving chemicals or hazards at the site.

   (c) Site personnel was trained in the hazardous communications program.

Carcinogen Policy and Model Standards

1) No known carcinogens were provided or used in the HPS system.

2) There was a "No Smoking" policy in the HPS area.

8.2.1 Fire Protection System

Isobutane was the working fluid in the binary cycle portion of the hybrid plant and methane is burned in the gas engines. Since both isobutane and methane are flammable, a primary safety consideration in the plant was fire protection. The primary means of fire protection was fire prevention. Ignition sources such as flames and arcs were not allowed in the process area.

The fire protection system was designed to keep equipment cool in the event of a fire. No attempt would have been made to put out the fire, since it is safest for the isobutane to continue to burn as long as no equipment is heated to the point of failure. If the flame were to be extinguished with isobutane continuing to leak into the air, a cloud of isobutane could build up and cause an explosion.

Both the control trailer and the power trailer were pressurized by a fan blowing fresh air into the trailers on a continuous basis. The intake to the fan was through a stack 40 feet high. The stack was high in the air because isobutane is heavier than air, so any isobutane which leaked out would tend to stay near the ground.

Providing the trailers with hydrocarbon-free air was important since both trailers contain electrical equipment which can have arcs which are capable of igniting isobutane. Electrical equipment which was not pressurized by this system was located a safe distance away from any piping or equipment which contained isobutane. This distance is a minimum of fifty feet according to code. In addition, smoking was not allowed in the process area.

A gas-freeing compressor was added to the system so that hydrocarbon could be evacuated from any piping or equipment which needed to be worked on. Equipment must be hydrocarbon-free before any hot work such as welding takes place.

Reused from East Mesa were hydrocarbon detectors which can indicate an isobutane leak. In addition to the detectors and spray system, a safety shower and eye wash station were moved from East Mesa to Pleasant Bayou and reused.

The firewater distribution system consisted of a fire pump spray nozzles, and two new fire monitors.

The fire pump was electrically connected to commercial power with a separate breaker at the main bus. Switches to activate the fire pump were located at the control trailer and at the firewater pump. The pump was capable of providing 750 gallons per minute at 125 psig from a 75,000 gallon pond. This allowed a 100-minute water supply at design flow conditions.

The condenser supports were protected by water spray which was automatically activated. A glove valve was preset to the proper flow and the main gate valve was preset in the full open position.

Water monitors were automatically activated by turning on the fire pump in the event of a fire. The nozzles used on the monitors could be adjusted from a straight stream to a wide fog. The monitors were capable of rotating 360° in horizontally and up to 90° of elevation. The monitors were also capable of being manually operated.

There were nine fire extinguishers distributed in the plant; there were four on the pad, two in the power module, two in the control module, and one at the storage module. In each case, the minimum extinguisher rating was 1A:80B:1C.

An evaluation of the new service and of applicable NFPA and Texas state regulations was made. As a result, the following modifications and improvements to the existing fire protection system were made. The two new monitors were moved to a more appropriate location. A small hose house with a 2-1/2" hose and nozzle were installed instead of a hose reel. The hose house was located near the new fire hydrant.

The underground firewater piping main was S/80 PVC with cast iron fittings. Fittings were restrained with thrust blocks. The fire protection system was tested per NFPA 24 and approved by the Liverpool Fire Marshall, the local authority having jurisdiction.

8.2.2 Code Compliance

As stated earlier, the DCHX facility was built to all applicable codes and regulations. All water and brine piping was built and inspected to the specifications of ANSI B31.1, Power Piping. (ANSI is the American National Standards Institute.) Isobutane piping was built and inspected to ANSI B31.3, Chemical Plant and Petroleum Refinery Piping. All new piping also conformed to these codes, with methane piping falling under ANSI B31.3. Reinstallation of existing piping was in accordance with the ANSI codes.

All pressure vessels, new and existing, were stamped in accordance with ASME Section VIII. New heat exchangers were hydrotested in the shop, and the existing accumulator was hydrotested in the field during construction. The coils in the Baltimore Aircoil condensers were hydrotested during refurbishment and again immediately prior to start of testing.

Electrical installations were per National Electric Code (NEC) area classifications. The power trailer in the DCHX was built to Class 1, Section 1, Group D, Division 2. The hybrid plant was also built to NEC standards.

The firewater pump satisfies the requirements of National Fire Protection Association (NFPA) Section 20. All other components of the firewater system were designed to NFPA 58 and all applicable NFPA codes.

8.3 Quality Assurance

A quality assurance program was established by The Ben Holt Co. and implemented consistently throughout the construction and operation of this facility. This program was documented in a Quality Assurance Manual which was approved by DOE. The program describes quality assurance procedures and assigns responsibility for the following activities: design calculations, drawings, specifications, material control, welding, inspection, testing, and data compilation. This quality program ensured that designs were accurate, that manufactured equipment met specifications, and that field fabrication met all applicable codes. DOE's quality assurance inspectors confirmed the quality of this installation.

After construction, quality of a power plant is measured by high availability and high capacity factors. Routine maintenance and operator vigilance is important in maintaining quality. An availability of 97.5%, a capacity factor of 80.2%, and an excellent safety record in a test facility attest to the success of the quality assurance program.

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9.0 CONSTRUCTION

9.1 Refurbishment

Refurbishment of equipment used in the DCHX was completed under the EPRI contract, except for work that had to be done immediately prior to start-up. Table 9-1 is a summary of refurbishment work done on equipment from DCHX facility.

TABLE 9-1

REFURBISHMENT SUMMARY

Item	Condition and General Action		Specific Actions Taken
Control Trailer	Excellent. Trailer was hauled to Instrument Specialists, Inc., in Long Beach, CA. for conversion to new service.		Instruments and controllers rearranged for new process. New alarm panel and transducers added.
Power Trailer with Turbine-Generator	Excellent. The former application required higher pressure and temperature at turbine inlet. Trailer was hauled to Barber-Nichols Engineering Co., in Arvada, CO for refurbishment. (Barber-Nichols had built and operated the system in its former application in the DCHX.)		New turbine wheel. New seal assembly installed on turbine (25,000 rpm). Gearbox checked out.
	Old turbine inlet:	443 psia, 233 deg. F	Lube system checked and oil replaced.
	New turbine inlet:	280 psia, 210 deg. F	Replaced battery in governor. Electrical system: No work required on generator, load banks or wiring and switching for loadbanks. Wiring and switching for electricity sales was checked.

General Note on Condition:

The refurbished equipment is from DOE's 500-kWe direct contact heat exchanger test at East Mesa DCHX. At the conclusion of that test, all piping and vessels were purged with nitrogen and a small positive pressure of nitrogen was maintained in the system for the entire time it was stored. The dry climate in East Mesa also facilitated corrosion protection. Although storage at Pleasant Bayou did affect equipment condition, much of the equipment, including both trailers, was in good condition and could be reused, sometimes with little or no refurbishment.

TABLE 9-1

REFURBISHMENT SUMMARY
(Page 2)

Item	Condition and General Action	Specific Actions Taken
Evaporative Condensers ("Baltimore Aircoils")	Good, despite some signs of substantial corrosion in tube bundles.* Inspection, testing and refurbishment was performed at Lewis Welding in El Centro, CA. (Work covered whole system: coils, fans, pumps, motors and chemical treatment system.) ------ *Corrosion was probably due to geothermal fluid that mixed with isobutane working fluid due to the direct contact heat exchange process being tested at East Mesa.	Coils hydrotested at 350 psig (1 1/2 times design service pressure). Only one tube leaked. No leak in second hydrotest after tube plugged. Coils hydrotested prior to startup. 15 tubes leaked. 58 tubes plugged. Chemically cleaned prior to start-up. Fans lubricated and fan motors checked to assure no shorts and proper current drawn. One belt replaced. Circulating water pumps (4 at 5 HP each) disassembled, cleaned and new seals installed, but shipped as a reserve pump. Backup (75 HP) circulating water pump, not refurbished New metering pump for chemical treatment system installed.
Accumulator Tank (Hot Well)	Good. Thin layer of corrosion on interior walls of vessel. No significant loss of wall thickness. Tank refurbished at Lewis Welding in El Centro, California.	Internal baffle(for isobutane/ water separation in former use) removed. Sand blasted clean (interior). Interior walls coated with diesel oil to preserve surface.

TABLE 9-1

REFURBISHMENT SUMMARY
(Page 3)

Item	Condition and General Action	Specific Actions Taken
Isobutane Circulation Pump	Good. Required modification for new service. Refurbished by Afton Pump Company (the manufacturer).	Inspected and cleaned. Stages removed to convert to new (lower pressure) service (21 reduced to 15).
Utility Cooler Skid (Load Bank Cooler)	Cooler: bad. System: good. Cooler replaced. Balance of system cleaned up by Lewis Welding in El Centro, CA.	Old evaporative cooler discarded. New cooler, also Baltimore Aircoil, purchased as replacement. Piping, equipment and instruments cleaned for reuse. Water chemical injection system inspected and found in good condition.
Air Skid	Good. Refurbished at Lewis Welding in El Centro.	Compressor rebuilt. Balance checked and found in good condition.
Air Stack	Good. Transported to Pleasant Bayou from Lewis Welding.	Kept for reuse as elevated air intake for pressurized trailers.
Isobutane Storage	Excellent. Transported to Pleasant Bayou from Lewis Welding.	Four 900-gal. tanks drained of isobutane, inspected and shipped.
Isobutane Transfer Pump	Good. Checked and shipped from Lewis to Pleasant Bayou.	Shaft rotated. Motor checked.
Piping	Good. Held at Lewis for later shipment just prior to installation.	Steel pipe saved for reuse. Sandblasted prior to shipment. Plastic Pipe discarded.

TABLE 9-1

REFURBISHMENT SUMMARY
(Page 4)

Item	Condition and General Action	Specific Actions Taken
Supports	Good. Disassembled by Lewis and shipped to Pleasant Bayou.	Trailer supports shipped to site. Pipe supports to be reused for pipe sections installed in same service.
Platforms	Marginal. Shipped to Pleasant Bayou.	Removed from around evaporative condensers and shipped with the rest.
Air Piping	Good, but risky to reuse and inexpensive to replace.	Discarded.
Insulation	Good. Left on equipment.	Gaps in the insulation were repaired during installation.
Paint	Good for storage at East Mesa. Better protection needed for some items at Pleasant Bayou.	Done.
Other Protection	Good. Sealing and drying measures adopted at Pleasant Bayou.	Oil coating on surfaces. Plastic seals over flanges with desiccant enclosed. Heaters in trailers and storage container.

9.2 Installation

In August of 1986, the site was graded and a 100 foot by 120 foot concrete pad was poured. This provided a foundation for major equipment and a work area. A grounding loop and major electrical conduits were installed underneath the pad. In October of 1986, most of the refurbished equipment was off-loaded at the Pleasant Bayou site. This required the construction of a temporary board road to provide access. In December of the same year, the remainder of the equipment was off-loaded and painted.

As the design and procurement effort progressed, early in 1987, it became apparent that additional equipment and modifications to existing equipment were required. An existing flare at Pleasant Bayou was evaluated to determine whether or not it could be used for isobutane from the HPS. A larger flare was required due to the high heat content of liquid isobutane. A new flare was purchased and installed on the other side of the firepond from the power plant.

Vibration monitors were added to the isobutane turbine. These monitors were made by Bentley-Nevada to detect irregular vibrations at the turbine shaft. They are designed to shut the turbine down before catastrophic failure occurs.

The interface with the local utility resulted in additional equipment requirements. Houston Lighting and Power required a visible disconnect switch in addition to the lock-out breakers.

Because of corrosion in the condensers and other equipment, a chemical wash was made immediately prior to start-up of the facility.

Site construction began in December of 1988. Subcontract labor under Holt supervision was used to reduce construction costs. Installation of major equipment and piping occurred during the first several months of 1989. Instrumentation and electrical work was completed in July, and insulation was installed in August of 1989. The hybrid power system was mechanically complete at the end of August 1989.

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10.0 PLANT OPERATION

10.1 Start-Up

Operational integrity of each of the major subsystems was verified before brine and isobutane circulation through the plant started. The air compressors were run and tank air pressure was maintained between 85 and 100 psi. It was confirmed that all pneumatic control valves were responding properly to control signals. The cooling water system including the fans and circulating pumps was checked out. Operation of the fire water system including the pump, monitors and condenser spray nozzle throttle valve was confirmed.

The gas freeing system compressor was used to evacuate the piping and equipment before isobutane was added to the system. This reduces the noncondensables content in the isobutane loop thereby decreasing turbine back pressure and increasing turbine output. It also removes oxygen from the system to eliminate a potential explosion hazard.

10.2 Daily Operation

Pleasant Bayou Hybrid Power System was operated in accordance with the Standard Operating Procedures, Revision 0, August 7, 1989, written by The Ben Holt Co. for this facility. Additional operating procedures were written after a few months of operation which detailed procedures for shutting down and starting up the plant after a turbine trip and an electrical trip. The Pleasant Bayou HPS Shutdown and Start-up Checklist Procedures are included in Appendix E.

The plant ran twenty-four hours a day, seven days a week. Operators worked rotating eight hour shifts. Departing operators would advise the arriving operators of any changes in plant operation and specifically of any equipment or instrument which required special attention. They would both walk through the plant listening and watching for any changes.

10.2.1 Documentation

10.2.1.1 Daily Log. Plant operators maintained a log in which they recorded any changes noted in the system. They made an entry in this log at least once a shift. Weather conditions, a general description of plant operation, any changes which were observed, any items which should be watched, and any recommendations for maintenance or other work were reported.

10.2.1.2 Management Report Data Sheet. This form (Figure 10-1) was filled out every two hours during normal operation and more frequently when tests were conducted. This data sheet contains all the process information needed to characterize plant performance. This form was sent to the home office daily so that data reduction could be completed in a timely manner.

FIGURE 10-1
GEOPRESSURED HYBRID POWER SYSTEM - MANAGEMENT REPORT DATA

	UNITS	INST.#											
AMBIENT TEMP	°F												
WET BULB TEMP	°F												
POWER													
T-1-N GROSS	KW	JI-100											
GE-1-N GROSS	KW												
GE-2-N GROSS	KW												
PARASITIC	KW	JI-101											
NET SALE TO HL&P	KW												
NET SALE TO HL&P	RDG												
	KW-HR												
BRINE													
TO E-2-N	PSIG	PI-606											
TO E-1-N	PSIG	PI-611											
FROM E-1-N	PSIG	PI-106											
ISOBUTANE													
IN V-1-E	PSIG	PG-130											
OUT OF P-1-E	PSIG	PI-105											
OUT OF E-1-N	PSIG	PI-602											
OUT OF E-2-N	PSIG	PG-114											
OUT OF E-3-N	PSIG	PI-615											
INTO T-1-E	PSIG	PI-107											
OUT OF T-1-E	PSIG	PI-108											
TO OR 102	PSIG	PG-104											
FROM OR 102	PSIG	PG-105											
GAS													
TO E-3-N	PSIG	PI-614											
BRINE													
TO E-2-N	°F	TI-101											
TO E-1-N	°F	TR-113											
FROM E-1-N	°F	TR-102											

FIGURE 10-1
GEOPRESSURED HYBRID POWER SYSTEM - MANAGEMENT REPORT DATA

	UNITS	INST.#												
ISOBUTANE														
IN V-1-E	°F	TI-104												
OUT OF P-1-E	°F	TI-105												
OUT OF E-1-N	°F	TR-112												
OUT OF E-2-N	°F	TI-111												
OUT OF E-3-N	°F	TI-603												
INTO T-1-E	°F	TI-107												
OUT OF T-1-E	°F	TI-108												
GAS														
TO E-3-N	°F	TI-601												
FROM E-3-N	°F	TI-602												
BRINE	M#/HR	FI-100												
IC4 FROM P-1-E	M#/HR	FI-102												
IC4 TO T-1-E	M#/HR	FI-101												
IC4 TO E-3-N	M#/HR	FR-627												
SEP FLOW	GALS	FQI-633												
GAS TO GE-1-N	#/HR	FR-607												
V-1-E	INCHES	LG-105												

REMARKS

10.2.1.3 Geopressured Hybrid Power System Data Sheet. Data Sheet forms are shown in Figure 10-2 and supplement the Management Report Data Sheet. All field gage readings are recorded on this sheet, as are readings of electronic instruments tied to the computer. This form allows a more detailed look at plant operation including the performance of utility systems. It was also filled out every two hours. The form is arranged according to actual instrument location in the field so that it can be filled out quickly. This form was sent to the home office weekly.

10.2.2 Water Treatment

Conductivity and pH were measured every four hours, two hours after the start of each shift, and two hours before the end of each shift. Samples were taken from each of the condensers through a small brass valve installed in the water line. Sulfuric acid was added as needed to control the pH of water in the condensers to between 7.7 and 8.2. One pump was used to supply all four condensers with sulfuric acid from a 55 gallon drum. Approximately 1.5 to 3 gallons/day of Drewgard 187 were added into the same water line to control conductivity. Twelve ounces of biocide were added manually three times a week to each of the four condensers. Six ounces of biocide were added three times a week to the utility cooler.

We alternated between Drew Biosperse 212 and Drew Biosperse 4505 to ensure that resistant microorganisms did not develop.

FIGURE 10 - 2

GEOPRESSURED HYBRID POWER SYSTEM DATA SHEET

OPERATORS ______________________

____

DATE BEGINNING 0700 ______________ ______________________

	0700	0900	1100	1300	1500	1700	1900	2100	2300	0100	0300	0500
SWITCH HOUSE												
Net Power In KW-HR												
Net Power Out KW-HR												
Power KW												
Amps L1-L2												
L2-L3												
L3-L1												
Volts L1-L2											x	x
L2-L3											x	x
L3-L1											x	x
Battery Bank DC Volt.	x		x	x	x		x	x	x		x	x
POWER TRAILER												
Load Bank Out TI 104												
Gen Amps												
Gen Volts												
Gen Hz												
Power Factor												
Woodward Output V	x		x		x		x		x		x	
Load Bank 1 Volts	x		x		x		x		x		x	
Load Bank 2 Volts	x		x		x		x		x		x	
Load Bank 3 Volts	x		x		x		x		x		x	
Oil Cooler Temp in												
Temp Out												
Seal Press												
Oil Filter D/P												
Brg Press												
Wheel Press												
Speed, RPM												
T1E Elapsed Time												
P1E Elapsed Time												
MUSTANG PANEL												
Gen. 1 Volts												
Amps												
Hz												
KW												
Gen. 2 Volts												
Amps												
Hz												
KW												

UNITS:

TEMP (T)	°F
PRESS (P)	PSIG
FLOW (F)	M#/HR
(or) as indicated	

FIGURE 10 - 2

GEOPRESSURED HYBRID POWER SYSTEM DATA SHEET

OPERATORS ______________________

DATE BEGINNING 0700 ______________

	0700	0900	1100	1300	1500	1700	1900	2100	2300	0100	0300	0500
MUSTANG PANEL (Cont.)												
Eng. 1 Elapsed Time	x		x		x		x		x		x	
Oil Press	x		x		x		x		x		x	
Water Temp	x		x		x		x		x		x	
Water Level	x		x		x		x		x		x	
Eng. 2 Elapsed Time	x		x		x		x		x		x	
Oil Press	x		x		x		x		x		x	
Water Temp	x		x		x		x		x		x	
Water Level	x		x		x		x		x		x	
Oil Tank Level, Inches	x		x		x		x		x		x	
Nat Gas Tank Press.	x		x		x		x		x		x	
Nat Gas Flow FR-607	x		x		x		x		x		x	
COMPRESSOR SKID												
Air Tank Press. PG129												
Check for Water												
UTILITY COOLER												
Spray Press PG107	x		x		x		x		x		x	
Spray Temp TG112	x		x		x		x		x		x	
LO Out TG113	x		x		x		x		x		x	
V110 E Press PG143	x		x		x		x		x		x	
V110 Level LG102	x		x		x		x		x		x	
Circul. Temp. TG103	x		x		x		x		x		x	
P107 Dsch Prs PG141	x		x		x		x		x		x	
Acid Level	x		x	x	x		x	x	x		x	x
Inhibitor Level	x		x	x	x		x	x	x		x	x
pH												
Conductivity												
TURBINE												
Seal Drain Level												
Gear Box Press												
Turbine Screen Δ P												
Gear Box Temp. Out												
A-1 Bladder												
N2 Bottle												
N2 Regulator												
N2 Bladder												

UNITS:

TEMP (T) °F
PRESS (P) PSIG
FLOW (F) M#/HR
(or) as indicated

FIGURE 10 - 2

GEOPRESSURED HYBRID POWER SYSTEM DATA SHEET

OPERATORS ______________________

____

____

DATE BEGINNING 0700 ______________

	0700	0900	1100	1300	1500	1700	1900	2100	2300	0100	0300	0500
CONDENSERS												
Acid Level	x		x	x	x		x	x	x		x	x
Inhibitor Level	x		x	x	x		x	x	x		x	x
TG109	x		x		x		x		x		x	
PG118	x		x		x		x		x		x	
TG110	x		x		x		x		x		x	
PG121	x		x		x		x		x		x	
TG111	x		x		x		x		x		x	
PG122	x		x		x		x		x		x	
TG106	x		x		x		x		x		x	
PG103	x		x		x		x		x		x	
pH												
Conductivity												
GENERAL PLANT												
Sep Level LGR620	x		x		x		x		x		x	
Sep Flow FQI 633 Gals												
Comp.Dsch.Prs.PG623	x		x	x	x		x	x	x		x	x
VIE Level LG105, In.											x	
VIE Press PG130												
OR102 Press PG-105												
OR102 Press PG-104												
Nat. Gas Supply Press	x		x	x	x		x	x	x		x	x
Fire Pond Water Leve	x		x	x	x		x	x	x		x	x
Well Water Pressure			x		x		x		x		x	
E-1-N												
Brine D/P PDI635												
Iso Out PG602												
Brine In PG611												
Brine Out PG												
E-2-N												
Level LGR605												
Iso Out PG114												
Brine D/P PDI634												
Brine In PG606												

UNITS:

TEMP (T) °F
PRESS (P) PSIG
FLOW (F) M#/HR
(or) as indicated

FIGURE 10 - 2

GEOPRESSURED HYBRID POWER SYSTEM DATA SHEET

OPERATORS ______________________

____

DATE BEGINNING 0700 ______________ ______________________

	0700	0900	1100	1300	1500	1700	1900	2100	2300	0100	0300	0500
E-3-N												
Level LG101												
Iso Out PG615												
Iso Out TG603												
Gas In PI614												
ISO STORAGE TANKS												
Level V104-1	x		x	x	x		x	x	x		x	x
Level V104-2	x		x	x	x		x	x	x		x	x
Level V104-3	x		x	x	x		x	x	x		x	x
Level V104-4	x		x	x	x		x	x	x		x	x
CONTROL TRAILER												
Ambient Temp												
Wet Bulb Temp												
FIC 102 % Flow	x		x		x		x		x		x	
FIC 601 % Flow	x		x		x		x		x		x	
LIC 604 % Level	x		x		x		x		x		x	
PIC 103 % Press	x		x		x		x		x		x	
PIC 109 % Press	x		x		x		x		x		x	
HIC 630 Open %	x		x		x		x		x		x	
Vanes % Open												
PDI 105												
PI 106												
PI 108												
FI 102												
TI 105												
TI 104												
TI 109												
TI 108												
TI 101												
FI 100												
TI 141												
TI 601												
TI 602												

UNITS:

TEMP (T) °F
PRESS (P) PSIG
FLOW (F) M#/HR
(or) as indicated

FIGURE 10 - 2

GEOPRESSURED HYBRID POWER SYSTEM DATA SHEET

OPERATORS ____________________

____

DATE BEGINNING 0700 ____________ ____________________

	0700	0900	1100	1300	1500	1700	1900	2100	2300	0100	0300	0500
CONTROL TRAILER (Cont.)												
PI 105												
PI 104												
TI 111												
JI 101, KW												
EI 100, VOLTS												
II 100, AMPS												
JI 100, KW												
TI 107												
PI 107												
FI 101												
PI 116												
Turbine Speed RPM												
VIB. A, MILS												
VIB. B, MILS												

UNITS:

TEMP (T) °F
PRESS (P) PSIG
FLOW (F) M#/HR
(or) as indicated

10.3 Data Acquisition System

A Hewlett-Packard 9825 computer was used to display and record process information. The computer automatically converted instrument signals to conventional units such as gpm or degrees Fahrenheit. This computer was from the ten-year-old DCHX facility and significantly lagged state of the art. An improved computer system would be capable of performing more on-line data reduction. This flexibility would allow process calculations to be output in an easily readable format. On-line plots of system parameters would make trends more apparent. This would save time and help fine tune operation.

10.4 Automation

After the test period, only one operator per shift was needed. During the day shift, the plant manager and a maintenance technician were also present. Eaton and IGT operators were also present around the clock. Under normal operating conditions, the geopressured hybrid power system ran with little operator intervention. No controls on the process loop required manual adjustment. The most time consuming tasks during the demonstration were data recording and water treatment. Both of these tasks can be easily automated.

Automation devices were kept to a minimum to reduce costs since it was a short-term demonstration plant with full-time operator surveillance. More sophisticated controls on utility systems and an improved data acquisition system would further automate operation.

For safety reasons, it was felt that an operator should always be present. An operator who regularly checks the plant and maintains equipment as necessary will also prevent problems before they become serious. An alert, well-trained operator can recognize and react quickly to unsafe situations which may not be incorporated into the control logic. Although safety concerns dictate that an operator is present whenever isobutane is on the site, this individual could oversee a plant which produces significantly more power.

11.0 TEST RUNS

11.1 Test 1 - Design Isobutane Flow

In this test, the isobutane flow rate was set as close as possible to its design value of 107,000 lb/hr. Exhaust gas flow was as close as possible to its design rate of 153 scf/min. The brine flow was then adjusted to the value required to maintain levels in the reboilers. The goal of this test was to determine the actual brine flow which corresponds to the design isobutane flow for the hybrid cycle plant as it was actually built.

This test was run on November 12, 1989. Management Data Sheets for this test and all the other tests are included in Appendix F. With the isobutane flow at 105,500 lb/hr, a brine flow of 126,250 lb/hr was required. The brine to isobutane ratio of 1.20 is lower than the design value of 1.58 due to the brine temperature being 297 °F versus a design value of 278 °F. With a wet bulb temperature of 66 °F, 463 kW was produced by the turbine and 620 kW by the engines.

11.2 Test 2 - Design Brine Flow

The goal of this test was to establish performance at the design levels of both brine and exhaust gas input. The design flow of 10,000 bbl/day of brine was to be directed through the brine-to-isobutane boiler and heater. Exhaust gas flow was also to be set as close to design rate as possible. Isobutane flow was automatically adjusted to maintain the proper liquid levels in the reboilers.

Due to the higher brine temperature, the brine flow rate was less than the design rate and was still adequate to heat the design flow of isobutane. At design brine flow, the corresponding isobutane flow would have exceeded equipment limits. Therefore, this test was not conducted.

11.3 Test 3 - Maximum Brine

With exhaust gas flow set at the maximum available from the gas engines, brine flow was increased until isobutane flow rate was the limiting factor. The goal of this test was to determine the maximum isobutane flow condition and probably the maximum power case. In Test 6, brine and isobutane flow rates were lowered to determine if maximum brine flow is indeed the condition which results in maximum net power generation.

This test was run on December 29, 1989. It was repeated on January 3, 1990 because one of the gas engines shut down during the first test (see Appendix F for test data). The maximum brine flow was 145,000 lb/hr with a corresponding isobutane flow of 116,000 lb/hr. Table 11-1 lists important system parameters from the test.

TABLE 11-1

TEST 3 - MAXIMUM BRINE

	UNITS	1/3/90
Wet Bulb Temperature	°F	64
Brine Inlet Temperature	°F	296
Brine Outlet Temperature	°F	151
Turbine Back Press	psia	73.7
Turbine Power	kW	511
Engine Power	kW	680
Net Sales	kW	917.5
Brine Flow	Mlb/hr	144.6
IC4 Flow	Mlb/hr	116
Gas Flow	lb/hr	488.3
Brine Utilization	Wh/lb	3.53
IC4 Utilization	Wh/lb	4.4
Gas Utilization	kWh/lb	1.424
UE-1-N	Btu/hr-sq ft-°F	145.7
UE-2-N	Btu/hr-sq ft-°F	207
UE-3-N	Btu/hr-sq ft-°F	18.6
Turbine Efficiency	%	71.9

11.4 Test 4 - Low Exhaust Gas

In this case, heat from the exhaust gas was recovered at levels below the design value. This test was run with gas flow to the engines at 75%, 50%, and 25% of design flow, as well as with the gas engines off (zero gas flow).

The goal of this test was to determine the impact of exhaust gas on system performance. Isobutane flow was automatically adjusted to correspond to constant brine flow. Gas normally burned in the gas engine was sold as pipeline gas (as was normally done with gas not used in the HPS).

This test was run on 1/3, 4/2 and 5/9/90 (data in Appendix F). The best results are from the test on 5/9 and are shown in Table 11-2. Turbine output dropped as the flow rate of gas to the engine decreased. Although wet bulb temperature increased during the test period, the decrease in turbine output cannot be accounted for by variation in wet bulb temperature alone. Brine flow was held constant during the test. Isobutane flow decreased as less heat from exhaust gas was available. Turbine output does vary with diurnal temperature, but brine-to-isobutane flow ratio does not.

The inlet temperature of exhaust gas entering E-3-N decreased as gas flow to the engine decreased. At lower gas flows, the compression ratio is higher so the outlet temperature is lower.

TABLE 11-2

LOW EXHAUST GAS TEST

5/9/90

		100%	75%	50%	25%	0%
Wet Bulb	°F	63	73	74.5	76	77
Turbine Output	kW	529	498	487	473	462
Brine Flow	Mlb/hr	149.5	149.2	148.7	149.2	149.7
IC4 Flow	Mlb/hr	122.7	122	114.6	110	109
Gas to Engine	lb/hr	489.6	365	270.2	134.5	0
IC4 to E-3-N	Mlb/hr	11	6.7	1.3	0.1	0
Brine/IC4		1.2	1.23	1.3	1.36	1.37
E-3-N Inlet Temp.	°F	1008	962	936	738.3	432.3
E-3-N Outlet Temp.	°F	362	325	287	233	98

11.5 Test 5 - Low Brine Flow

Three different runs were made to determine the performance of the hybrid plant at brine flow rates lower than design. Tests were made with brine flows at approximately 75%, 50%, and 25% of maximum brine flow. These runs were numbered 5A, 5B, and 5C respectively.

Test 5A and 5B were run on November 4, 1990 and Test 5C on November 6, 1989. System performance at 100% design isobutane was measured in Test 1 on November 12, 1989. The turbine was unstable at the 25% flow and only one point was obtained. Table 11-3 shows system performance at 100%, 75%, 50% and 25% points. As expected, the hybrid power system operates better at full design capacity.

TABLE 11-3

TEST 5 - LOW BRINE FLOW

		100%	75%	50%	25%
Date		11/12	11/4	11/4	11/6
Wet Bulb	°F	66	69	67	77
Turbine Back Press	psia	73.7	71.7	69.7	69.7
Turbine Gross	kW	464	420	191	78
Engine Gross	kW	620	404	288	150
Net Sale	kW	780	529	300	40
Brine Flow 43,400	lb/hr	125,800	119,000	81,000	
IC4 Flow 42,600	lb/hr	106,000	100,500	73,600	
Gas Flow thru E-3-N	lb/hr	475.9	430.6	345.2	200
Brine Utilization	Wh/lb brine	3.69	3.53	2.35	1.79
Isobutane Utilization	Wh/lb iso.	4.37	4.18	2.59	1.83
Gas Utilization	kWh/lb gas	1.30	0.938	0.834	0.75

11.6 Test 6 -Maximum Power

The purpose of this run was to find the brine and isobutane flow rates at which the hybrid system produces the most net electricity for sale. It was expected that this would be the same condition as the maximum brine and isobutane flow case found in Test 3. However, higher generator power production or reduced parasitic power load may have resulted in more net power at a lower flow. This is possible because turbine efficiency may have been substantially lower at the maximum isobutane flow than at a lower isobutane flow rate. Another possibility was that the electricity consumption for a parasitic load, such as the isobutane circulating pump, may have increased substantially with above-design isobutane flow rates.

This test was conducted on January 4, 1990. Brine flow was set at 145,000 lb/hr as found in Test 3. Flow to the gas engines was constant. At higher isobutane flows, the turbine trips. As isobutane flow was lowered, turbine output decreased (Figure 11-1). Although not as dramatically, net sales also decreased (Figure 11-2). Consequently, the hybrid power system was run at maximum isobutane flow for the remainder of the test.

FIGURE 11 -1
TEST 6 - MAXIMUM POWER

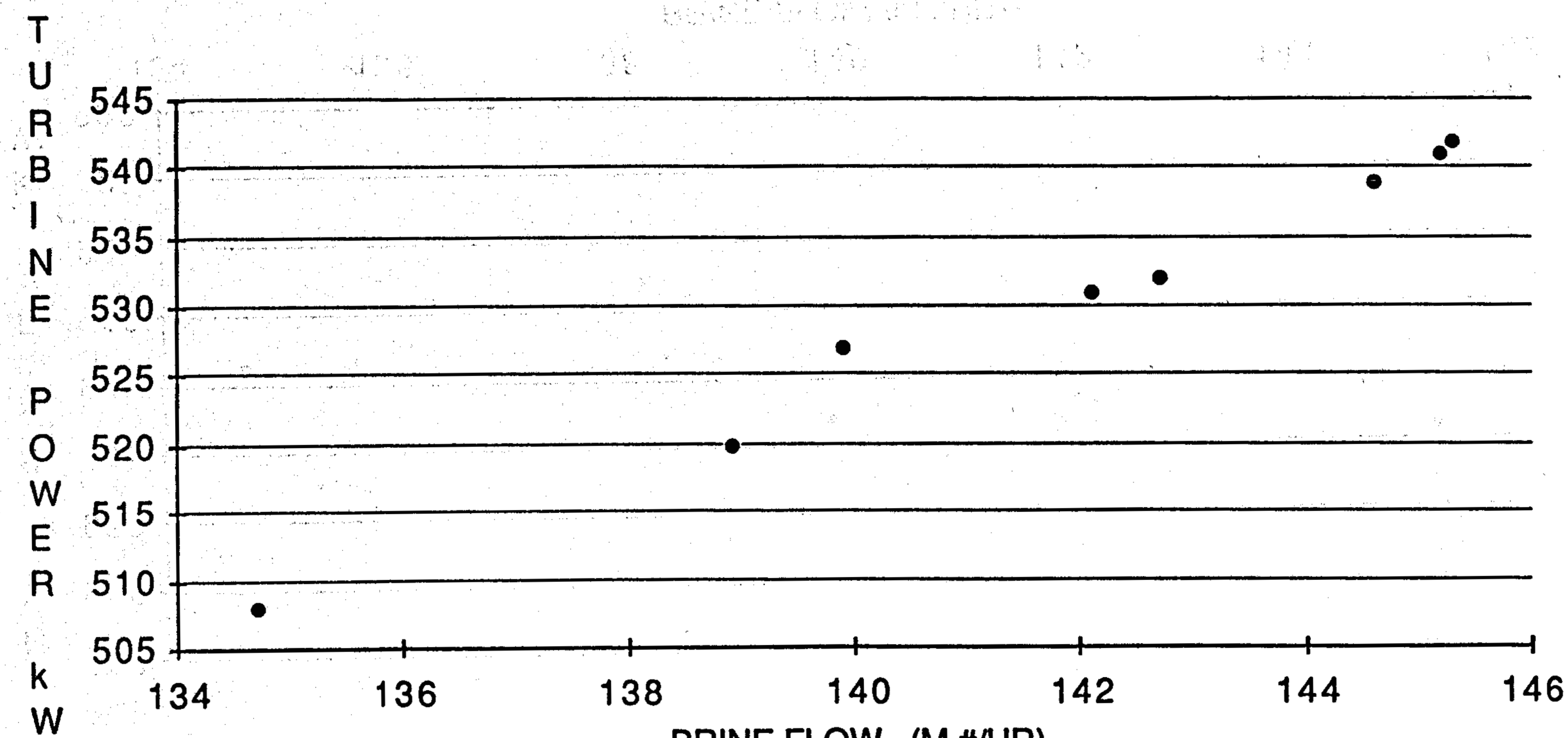
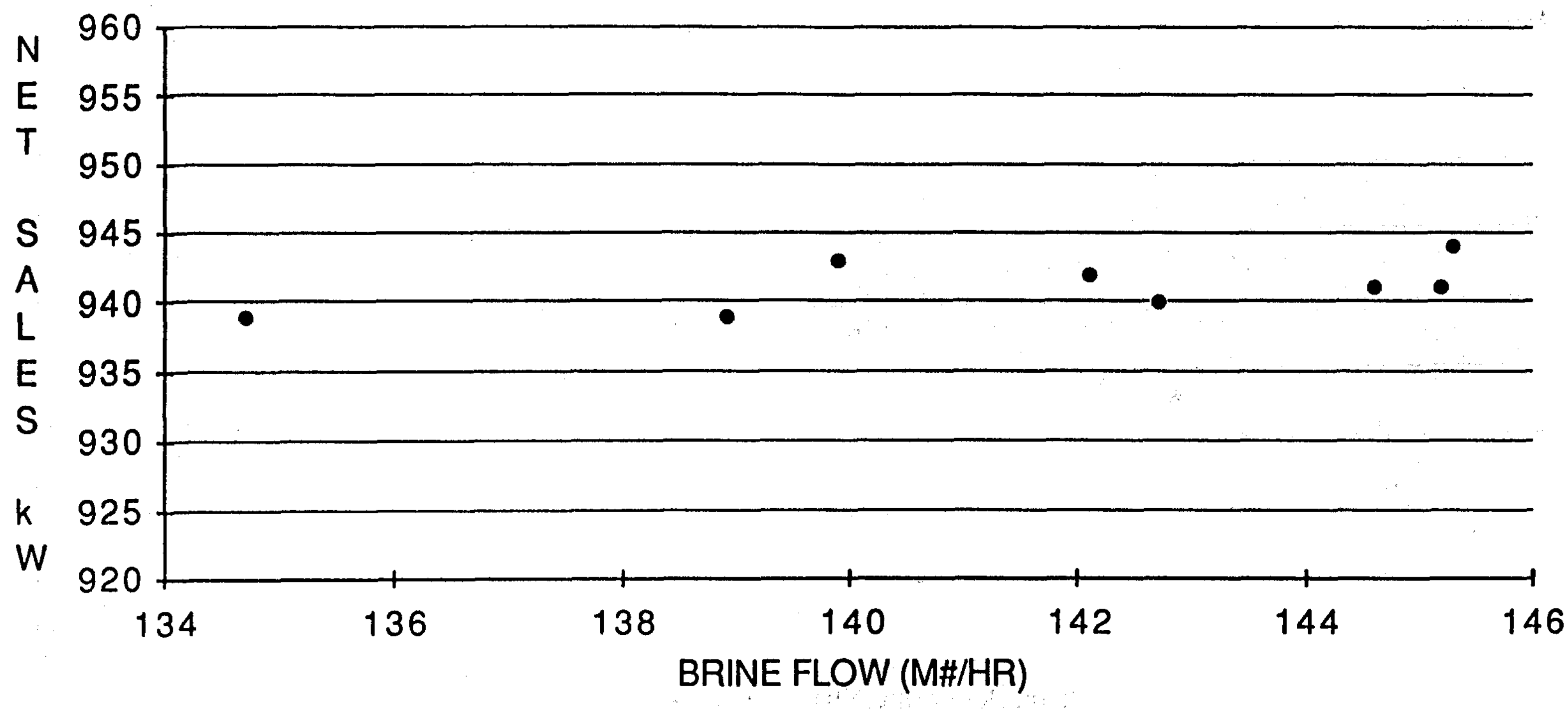


FIGURE 11 - 2
TEST 6 - MAXIMUM POWER



11.7 Test 7 - 100% Load Rejection

The goal of this test was to determine system response and operational characteristics to the HPS being suddenly taken off the grid while operating at full capacity. Wellhead brine flow was maintained, but the gas engines instantaneously shut down and separator gas was diverted to the pipeline.

This test was run on November 15, 1989. At 0835 hours the plant lost power from HL & P. All three generator breakers tripped. The utility breaker opened and the primary utility protection lockout breaker tripped. This facility shut down safely as designed. There were no surges in flow rate or temperature. No unsafe conditions were detected. In fact, there were a total of 24 outages due to utility upsets. The HPS shut down safely with each upset.

11.8 Test 8 - Gas Engines Only

The goal of this test was to determine maximum power output using gas engines only. Brine flow was maintained and exhaust gas was diverted to the stack. These results can be used for evaluating economics of power production from a geopresured resource using only gas engines.

This test was run on October 25, 1989. Gas utilization was 0.78 kWh/lb gas of net power production. However, the gas utilization was 1.28 based on gross engine production.

12.0 CONTINUOUS OPERATION

12.1 History of Plant Operation

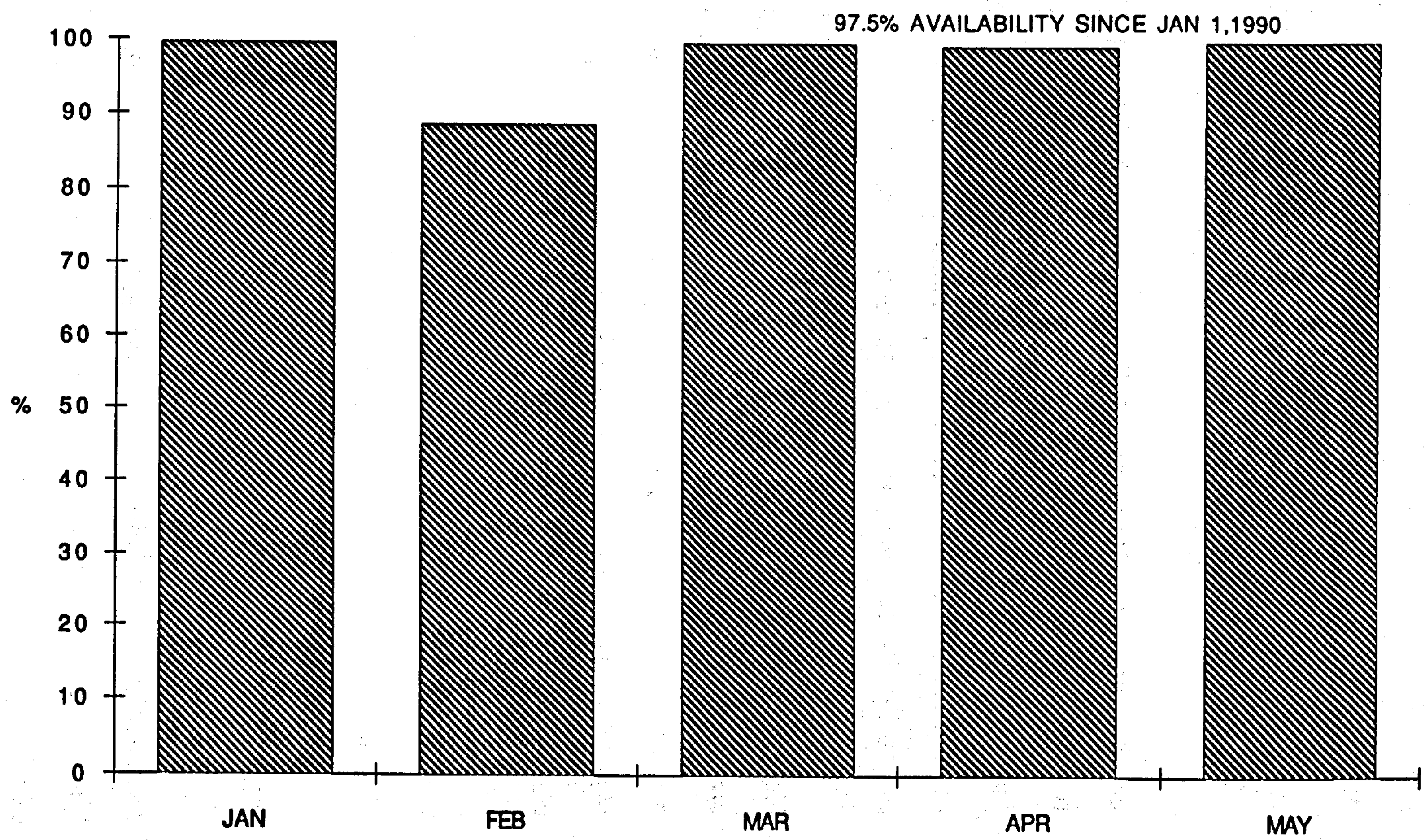
Brine and isobutane circulation through the hybrid power system began on September 3, 1989. The turbine and gas engines were started for the first time on October 19, 1989. E-3-N was put into service on November 6, 1989 and tests were conducted primarily in November and December of 1989. Production Well Pleasant Bayou Number 2 was shut in for maintenance from November 17 through November 24, 1989. From this time until the well was shut in on May 30, 1990, the HPS ran at or near design output except for an occasional outage. The plant was shut down on May 30, 1990 when it became apparent that the brine injection well required rework.

Over the course of the test, 1,443,250 STB of brine and 39,250 MCF of gas flowed through the geopressured hybrid power system.

12.2 Availability and Capacity Factor

Availability is defined as the percentage of time that a plant is on line producing power. Plant availability during the continuous operating period of January 1, 1990 through May 29, 1990 was 97.5%. Figure 12-1 shows monthly availability. Lower availability

FIGURE 12 - 1
PLEASANT BAYOU GEOPRESSURED HYBRID POWER SYSTEM
AVAILABILITY

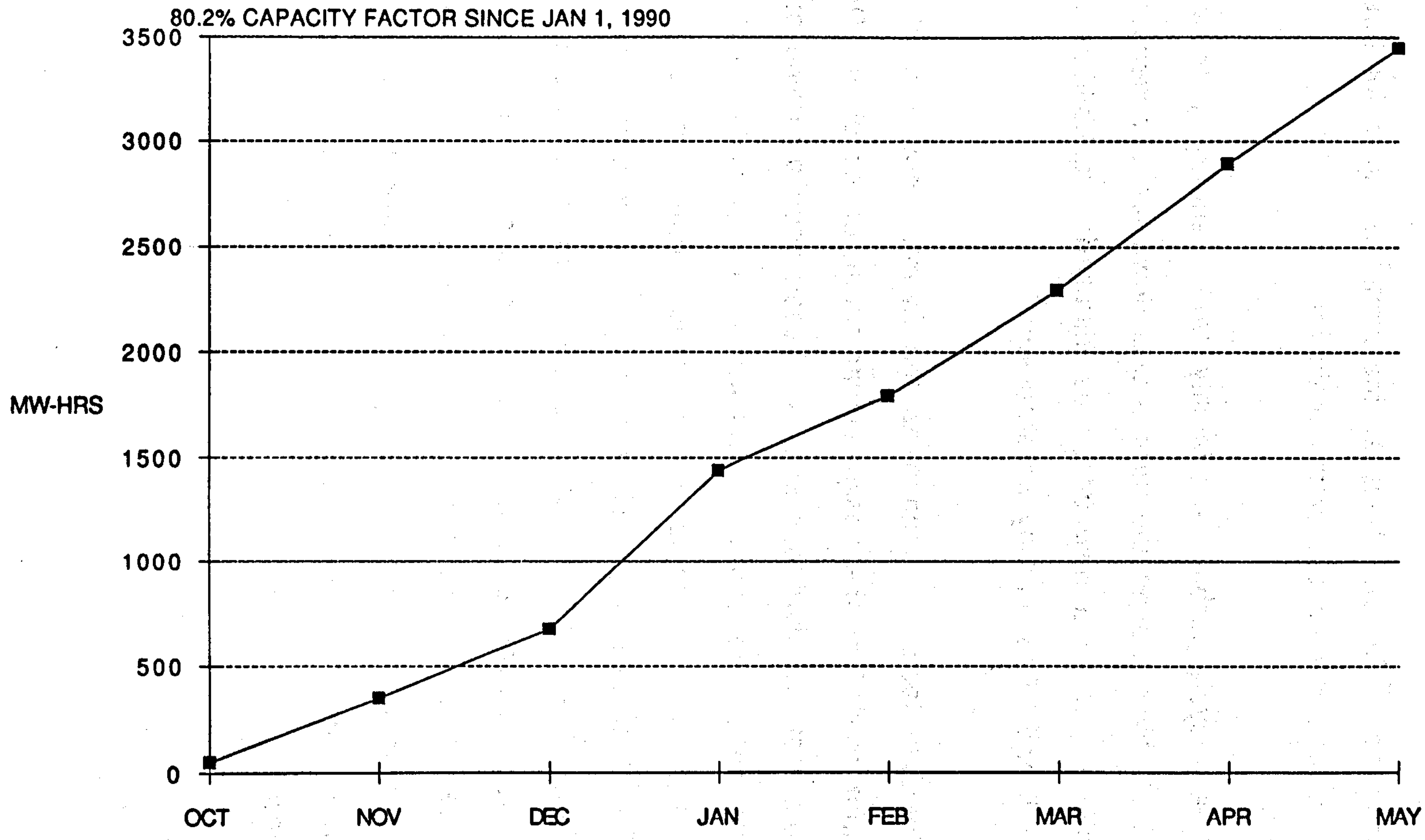


occurred in February because the plant was down for three days due to a ground fault trip of the main breaker.

Binary cycle turbine availability from January 1 to May 29 was 62.9% even though the turbine was down for four weeks due to seal failure. Once a new seal was installed, availabilities of 89.6% in April and 87.4% in May were achieved.

Capacity factor is defined as the average power produced by the plant divided by the design power output of the plant. Design power output of the plant was 905 kW, based upon a turbine output of 541 kW, an engine output of 650 kW, and a parasitic load of 286 kW. The capacity factor for the continuous operating period was 80.2% (See Figure 12-2.). Since wet bulb temperature was significantly higher than design wet bulb temperature for most of this time period, power production was correspondingly lower. Also, capacity factor was seriously impacted by the four-week outage of the binary turbine in February. The three-day outage of the total plant due to the ground fault also hurt capacity factor significantly.

FIGURE 12-2
PLEASANT BAYOU GEOPRESSURED HYBRID POWER SYSTEM
3,445 MW-HRS OF POWER EXPORTED



12.3 Plant Outages

Appendix G lists every turbine or gas engine outage. It includes the time the unit went down, the time it was back on line, and the reason for the outage. Several common reasons for an outage are discussed below.

12.3.1 HL&P Trips

The plant went down 24 times due to trips caused by the temporary connections to the utility. Although these trips were inconvenient, the engines were usually back on line within an hour and the turbine within two hours. Commercial plants are wired so that occasional power blips will not cause the plant to go off line.

12.3.2 Binary Cycle Turbine

Turbine T-1-E was built by Mafi-Trench, operated by Barber-Nichols at the DCHX, and reworked by Barber-Nichols for this application. During the first several months of operation, high vibration was a recurring problem. This was true especially when the turbine was brought from a stop to full speed. Once the turbine was operating at full speed and synchronized, vibrations stabilized at an acceptable level. Shaft displacement measured 1.5 to 1.7 mils during normal operation, and 3.5 to 4 mils during start-up. The high vibration switch which shuts the turbine down was set at 4.5 mils.

Late in February, during a roll-down after an electrical outage the turbine seal failed due to a loss of seal oil. The vibration monitoring system shut down the turbine and prevented serious damage to the turbine seal, bearing and rotor. The automatic high vibration switch was the only indication of the overheated seal. In addition to safely shutting down the turbine, the vibration probes allowed better assessment of turbine operation.

Table 12-1 shows each turbine repair date, the problem which necessitated the repair, and the action taken by Barber-Nichols. After the turbine was reworked at the end of March, the turbine ran consistently without a turbine-related trip until the plant shut down at the end of May.

WIth the resources available to a commercial power plant, many of the turbine problems encountered at the demonstration plant could be avoided. A commercial power plant turbine would be designed for its specific operating conditions and fabricated to these designs. A commercial facility would also stock spare turbine parts to minimize down time after a turbine failure.

TABLE 12-1

TURBINE MODIFICATIONS AND REPAIRS

5-08-89	Vibration monitors installed on high speed shaft.
6-09-89	New titanium wheel fabricated.
8-02-89	New backing plate fabricated.
8-21-89	Modifications made to ensure proper wheel pin clearance.
8-23-89	Modifications made to ensure proper wheel exducer clearance.
8-30-89	High pressure at the shaft behind the wheel was forcing isobutane into the lube oil, so a new spring behind the seal plate was installed.
10-16-89	Seal shims were modified so that there was a 0.115" crush on each.
11-16-89	Vanes were sticking, so the turbine nozzle was hardened and the exducer and rotating ring were coated with nickel and teflon.
1-22-90	Seals leak caused isobutane losses. Mating ring replaced.
2-26-90	Cleaned up and relapped seal noses and mating ring.
3-13-90	Problems with front bearing, so bearing rebabbitted and seal parts refinished.
3-23-90	High vibrations, so seal and mating ring sent to Barber-Nichols. Front bearing and seal parts reworked.

12.3.3 Gas Engines

Gas engines GE-1-N and GE-2-N ran well. Outages were of a short duration with repairs made and the engines back on line in a few hours. Two of the most common problems with the engines were regulator diaphragm failure and magneto failure which would cause the voltage and current to oscillate.

Gas engines require regular maintenance. Maintenance and repairs which were necessary at Pleasant Bayou were largely unrelated to operation on a geopressured-geothermal resource.

12.3.4 Weather

Weather caused a variety of problems with the geopressured HPS. Most of these problems can be avoided in a commercial installation.

The turbine was down for six days at the end of December due to an atypical cold spell in which the temperature dropped to as low as 10°F. Water in the makeup line to the utility cooler froze, causing a high lube oil temperature shutdown of the turbine. In addition, the instrument air pressure indicator failed which caused the rest of the plant to shut down. Makeup water to the condenser also froze in the line. It took several days to obtain PVC fittings to repair the water lines since freeze damage was widespread throughout the Houston area. This problem can be overcome for cold-weather installations. Temperatures this cold are often seen at the (Mammoth-Pacific) binary cycle geothermal plant at Mammoth Lakes, California. This plant continues to produce power during inclement weather since critical systems have been adequately winterized.

Potential for freezing at Pleasant Bayou was acknowledged as a risk during the HPS design phase. However, the decision was made not to include freeze protection due to the relatively high cost for a power plant which was to operate for only one winter. Indeed, the cost for repairs due to freeze-related damage was less than the estimated cost of freeze protection for the power plant and water lines.

A relatively minor problem is that belts on the main air compressor would slip during heavy rains. This problem did not bring the plant down, but it was inconvenient. A small cover over the compressor or a change to HTD drives would solve this problem.

Lightning strikes took the plant down on March 30, April 10, and twice on May 22. The plant was back on line within two hours after each lightning strike. Outages due to lightning may be an unavoidable part of operating at a site in Texas.

12.3.5 Well

Production Well Pleasant Bayou Number 2 was shut in on November 16, 1989 after it became clear that the surface scale inhibitor system was plugged. The well was operational again on November 24, 1989. Both the production and injection well were shut in on May 30, 1990 due to a significant increase in injection pressure. Many commercial plants have multiple wells so that power production may continue even if the capacity of one well decreases.

13.0 SYSTEM PERFORMANCE

13.1 Actual Process Flow Diagram

Table 13-1 shows a comparison of design and typical state points. The stream numbers are labelled as in the process flow diagram (Volume II Section A). The brine inlet to the binary cycle was 18°F to 20°F hotter than design. This reduced the amount of brine required to heat and vaporize the isobutane from 170,000 to 145,000 lb/hr.

Actual parasitic load ranged from 260 to 305 kW instead of the design value of 209 kW. Table 13-2 shows a breakdown of the design and actual parasitic loads. Power drawn by the circulating pump was higher than design since the pump outlet pressure was higher than design. Pump power could have easily been reduced to close to the design value by removing additional stages (six out of the 21 DCHX stages were removed). However, extra stages were left on to make sure there was adequate pumping capacity to meet potential special conditions during the test.

TABLE 13 - 1

COMPARISON OF DESIGN AND TYPICAL STATE POINTS

DESIGN

STREAM NO.	3	4	5	6	7	8	9	10	11	12	13	14	15	16
FLUID	BRINE	BRINE	BRINE	GAS	GAS	EXHAUST	EXHAUST	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE	ISOBUTANE
FLOW, MLBS/HR	170	170	170	0.47	0.47	6.6	6.6	107	107	92	15	107	107	107
TEMP., °F	278	220	164	278	278	1130	300	96	210	210	210	210	128	94
PRESS., PSIA	595	570	520	595	595	16	15	330	300	280	280	280	70	68

ACTUAL WET BULB TEMP - 64°F
TYPICAL (1/14 1300)

STREAM NO.	3	4	5	6	7	8	9	10	11	12	13	14	15	16
FLOW, MLBS/HR	146	146	146	0.5	0.5			109	109	99	10	109	109	109
TEMP., °F	297	216	150			1003	328	95	210	217	212	216	127	93
PRESS., PSIA	515	505	500					383	315	295	315	282	73	71

	DESIGN	ACTUAL
POWER PRODUCTION		
GAS ENGINE	650	680
BINARY CYCLE	541	520
PARASITIC	(209)	(280)
NET POWER	982	920

TABLE 13 - 2

DESIGN VS. ACTUAL PARASITIC LOADS

	Design	Actual
Circulating Pump	74	85
Condensers	75	86
Miscellaneous	60	
Measured		52
Non-Measured		14-59
Total	209	
Measured Only		223
Both		237-282

Estimates used for design condenser parasitics were significantly lower than measured power drawn since detailed equipment specifications were not available when the estimate was made. Miscellaneous parasitics were also higher than design as shown in the breakdown in Table 13-3. Individual equipment power factors were not used in Table 13-3, but a power factor of .92 for the circulating pump and .84 for the condenser pumps and fans was used to calculate the parasitic loads given in Table 13-2. A meter summed the parasitic loads and this value was recorded on the Management Report Data Sheets. However, some of the parasitic loads such as heating and air conditioning were not measured by this meter. As a result, turbine output plus the output of the engines minus parasitic load does not equal net sales. Net sales is lower due to these unmeasured parasitics.

Turbine output was approximately 540 kW at the design turbine back pressure of 70 psia. Turbine output varies with turbine exhaust pressure. A detailed discussion of this is contained in Section 14.2 Turbine Performance. Combined gas engine output was consistently 680 kW. Gas flow to the engines and subsequently power production were higher than design. Both the turbine and gas engine met their designed performance at design conditions.

Table 13-4 summarizes the plant material and energy balance. The flows and duties are averages for normal operation for the period from January through May. The mass balance difference is calculated by subtracting the measured flow to the turbine from the measured flow to the exchangers. The energy balance differences are calculated by subtracting the energy from the heat source minus the energy into the isobutane.

TABLE 13 - 3

		(Page 1)		
		MEASURED PARASITIC LOADS		
NO.		DESCRIPTION	kW	TOTAL kW
CIRCULATING PUMP				
P-1-E		Isobutane Circ. Pump	91.9	91.9
CONDENSERS				
CT-1A-E-M1		'A' Condenser Double Fan	14.6	
CT-1A-E-M2		'A' Condenser Single Fan	6.2	
P-103		'A' Condenser Circ. Pump	4.4	
CT-1B-E-M1		'B' Condenser Double Fan	14.9	
CT-1B-E-M2		'B' Condenser Single Fan	6.3	
P-104		'B' Condenser Circ. Pump	4.4	
CT-1C-E-M1		'C' Condenser Double Fan	14.6	
CT-1C-E-M2		'C' Condenser Single Fan	6.2	
P-112		'C' Condenser Circ. Pump	4.4	
CT-1D-E-M1		'D' Condenser Double Fan	14.8	
CT-1D-E-M2		'D' Condenser Single Fan	6.3	
P-111		'D' Condenser Circ. Pump	4.4	
P-109		Water Conditioner Pump	0.6	
				102.1
MISCELLANEOUS				
T-1-E-M1		Turbine Lube Oil Pump	9.5	
T-1-E-M2		Turbine Lube Oil Pump	9.5	
CT-2-N		Utility Cooler Fan	15.5	
P-106		Utility Cooler Circ. Pump	1.0	
P-107-E		Utility Closed Loop Pump	8.3	
		Control Power	1.3	
K-1-E-2		Instrument Air Compressor	7.3	
K-1-E-1		Instrument Air Compressor	0.0	
P-2-E		Isobutane Transfer Pump	0.0	
T-1-E		Oil Heater	0.0	
LP-B		Flare Panel	0.0	
				52.4
TOTAL MEASURED				246.4

		(Page 2)		
	NON-MEASURED PARASITIC LOAD			
NO.		DESCRIPTION	kW	TOTAL kW
		Firewater Pump	0.0	
		Water Well	3.1	
K-2-N		Gas Freeing Compressor	0.0	
LPA		Elect. Bldg. Panel	1.0	
		Area Flood Lights	1.1	
LP		Power Trailer Panel	8.5	
TOTAL WITHOUT HEAT OR A/C				13.7
		Power Trailer A/C	5.8	
		Control Trailer A/C	7.3	
TOTAL WITH A/C				26.8
		Power Trailer Heater	20.7	
		Control Trailer Heater	24.8	
TOTAL WITH HEATERS				59.2

AMPS - Data taken 1-17-90 for "measured" and 1-18-90 for "non-measured".
KW - Equals Avg. Amp X 480V. X 1.7321 (for three phase) X % run time.
- Note that equipment power factors are not included.

TABLE 13 - 4

MASS AND ENERGY BALANCE

Isobutane Mass Balance

Average Flow	=	118,826 lb/h
Mass Balance	=	4.27% ± 0.34%

Energy Balance

	E-1-N	E-2-N	E-3-N	Overall Plant
Duty (Btu/lb °F)	4,055,000	10,300,000	1,039,000	20,630,000
Energy Balance	-2.83% ± 3.3%	-5.06% ± 3.50%	-16.04% ± 16%	-2.93% ± 2.42%

13.2 Brine Utilization

Figure 13-1 shows brine utilization, kW produced by the turbine per 1000 lb/hr of brine, for 1990. Brine utilization ranged from 4.4 Wh/lb to 3.2 Wh/lb. Variations in this plot track variations in wet bulb temperature. As seen in Figure 13-1, brine utilization decreased due to warmer weather in April and May. At the design wet bulb temperature, brine utilization was 3.6 Wh/lb of brine versus a design of 3.18. Total Wh/lb brine produced by both the turbine and the gas engines averaged 8.13; the design value was 7.0. Improved performance was due primarily to higher brine temperatures.

13.3 Gas Utilization

Figure 13-2 shows gas utilization, defined as kW produced by the gas engines per lb/hr of gas. This value held constant at approximately 1.32. Lower utilization values occurred when an engine was run at less than full capacity. Warmer weather in April and May decreased gas utilization. This gas utilization figure is an indicator of engine performance. However, if this figure is used to predict the performance of a hybrid cycle it is important to remember that the exhaust gas produced by the engine also increases binary cycle output and therefore brine utilization.

FIGURE 13-1

BRINE UTILIZATION

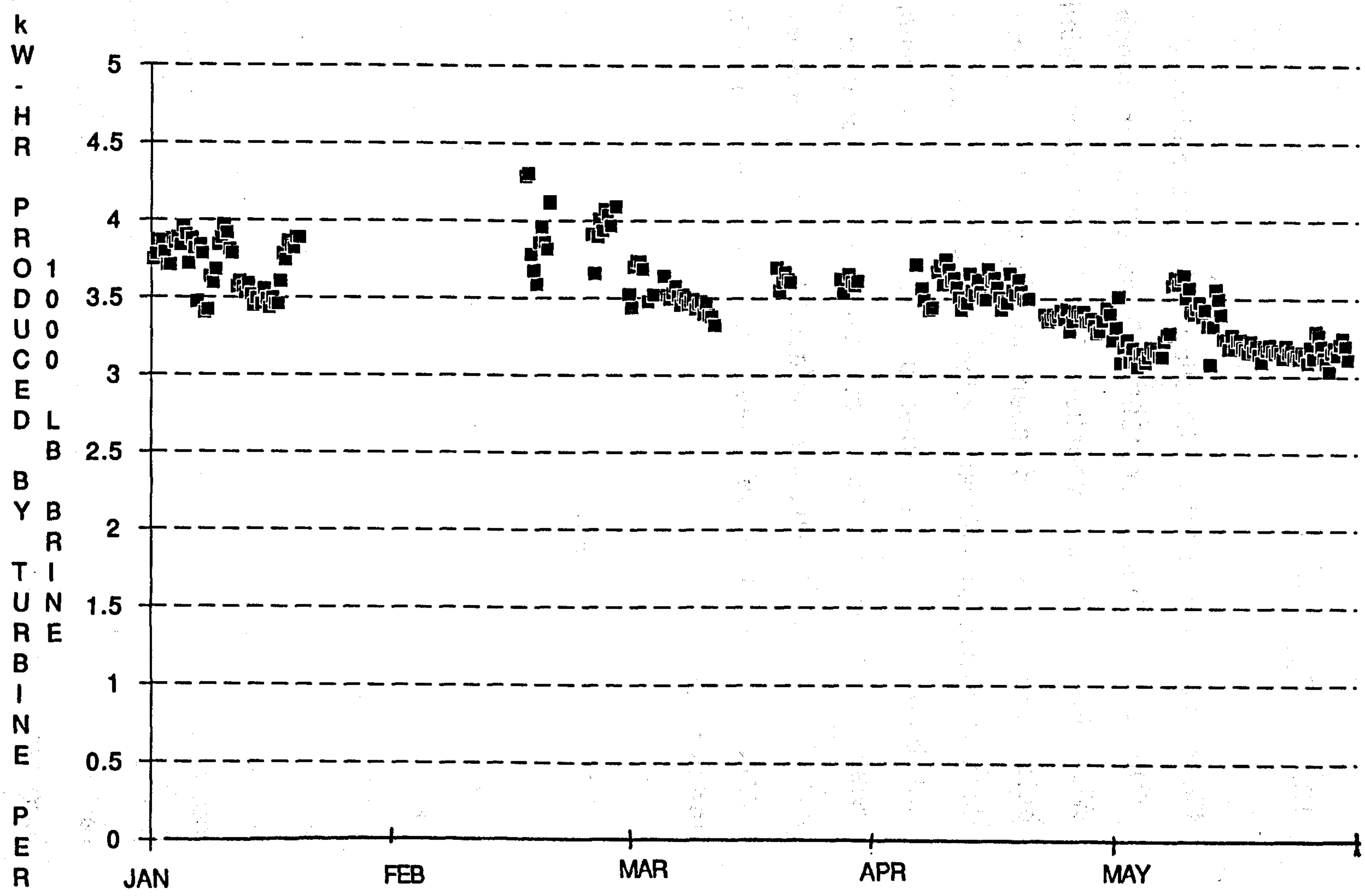
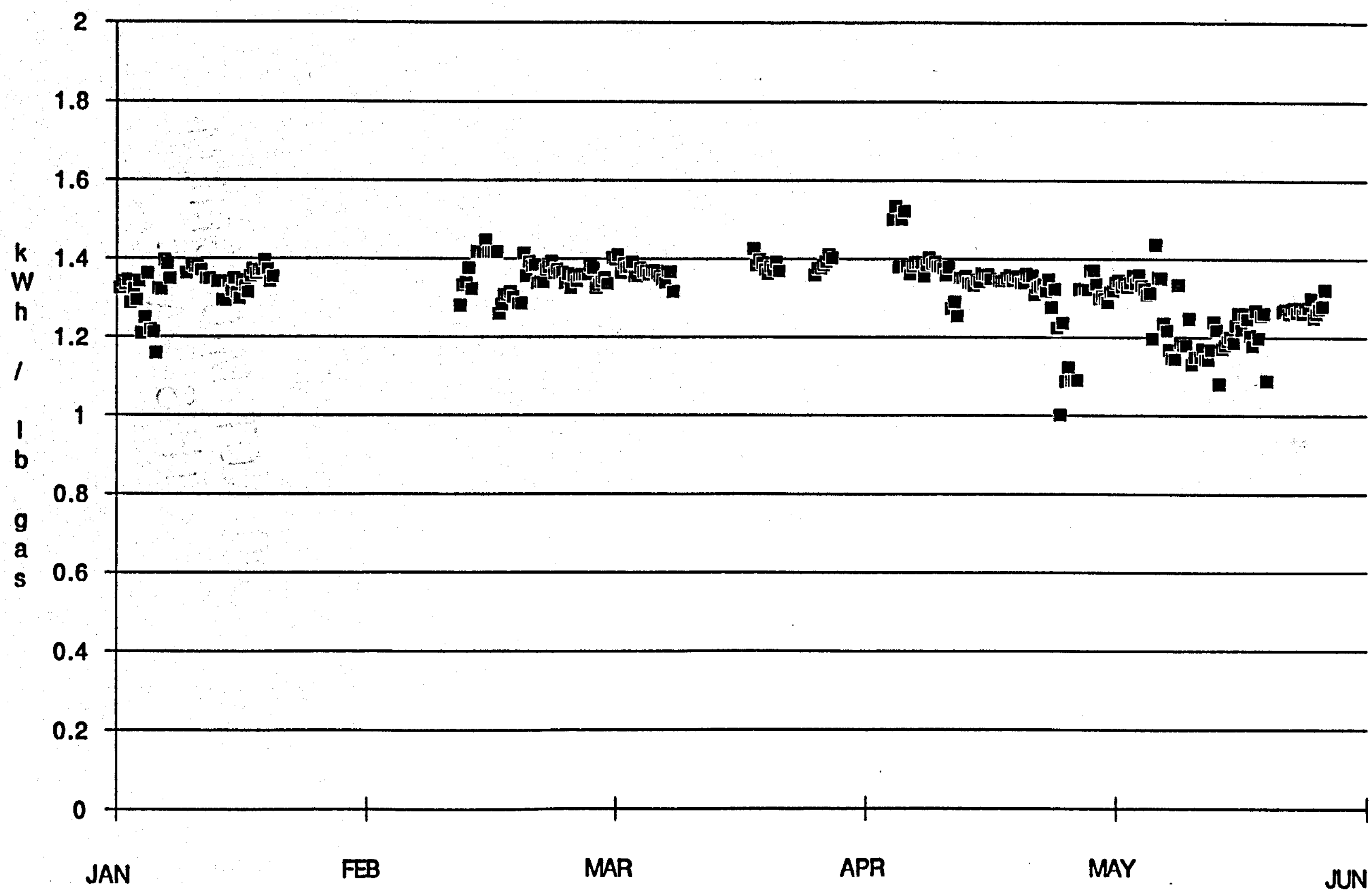


FIGURE 13-2

GAS UTILIZATION



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14.0 COMPONENT PERFORMANCE

14.1 Heat Exchangers

14.1.1 Calculation Method

Heat exchanger performance was determined by first calculating the duty. Temperatures in and out plus the flow rate lead directly to an estimate of the heat exchanged (the duty). Fluid properties such as latent heat and heat capacity were calculated by a computer program written to perform these calculations. In the hybrid plant, both tubeside and shellside fluid temperatures were monitored, so the duty was calculated both ways as a check for accuracy.

The critical value in estimating heat exchanger performance is the overall heat transfer coefficient. In addition to the duty, the logarithmic mean temperature difference (LMTD) was calculated. The calculation of LMTD is straightforward, requiring inlet and outlet temperatures of both hot and cold fluid. The overall heat transfer coefficient was found by dividing the duty by the exchanger area and the LMTD. No correction to the LMTD was required since the brine to isobutane heater is a counter-current flow exchanger, and in both the brine-to-isobutane boiler and exhaust gas-to-isobutane boiler, isobutane is vaporized at a constant temperature.

Fouling resistance was obtained by comparing the measured overall heat transfer coefficient to a calculated overall heat transfer coefficient. The overall heat transfer coefficient was calculated based on calculated film heat transfer coefficients of the shellside and tubeside, allowing for resistance due to conduction through the tubes.

Boiling heat transfer coefficient was calculated using a correlation based on external mass flow. This was based on the assumption that heat must be absorbed by the liquid by forced convection before passing into the vapor bubbles (Kern, Process Heat Transfer, McGraw Hill, 1950). A correlation such as Motinski's (Perry, Chemical Engineers' Handbook, Fifth Edition, McGraw Hill, 1973, pp. 10-22) based on heat flux and fluid properties more adequately describes the physics of the situation, but predicts heat transfer coefficient higher than manufacturer's design value as shown in Table 14-1. Since the goal of the test was to trend fouling in the exchangers, a correlation was used with coefficients which could be adjusted to match design values. The detailed equations are in Appendix H. A listing of the computer program which was used to make these calculations is in Appendix I, along with a sample output.

TABLE 14 - 1

SHELLSIDE HEAT TRANSFER COEFFICIENTS

	E-2-N			E-3-N		
	h_o	Ucalculated	Umanuf	h_o	Ucalc	Umanuf
Equations Used	427	207	208	200	18.4	18.44
Motinski	662	256	208	771	19.8	18.44

Since fouling factors are calculated as a small difference between large numbers, absolute accuracy of the calculation is relatively poor. However, process conditions were constant during the five month continuous operation test. Note that the control system varied the brine flow to maintain constant isobutane operating conditions. Turbine inlet pressure was 280 psia and the flow rate 119,000 lbs/hr throughout the test period. Since process conditions were constant during the test and because the calculation is always done on the same basis, fouling factor trends are calculated with good accuracy.

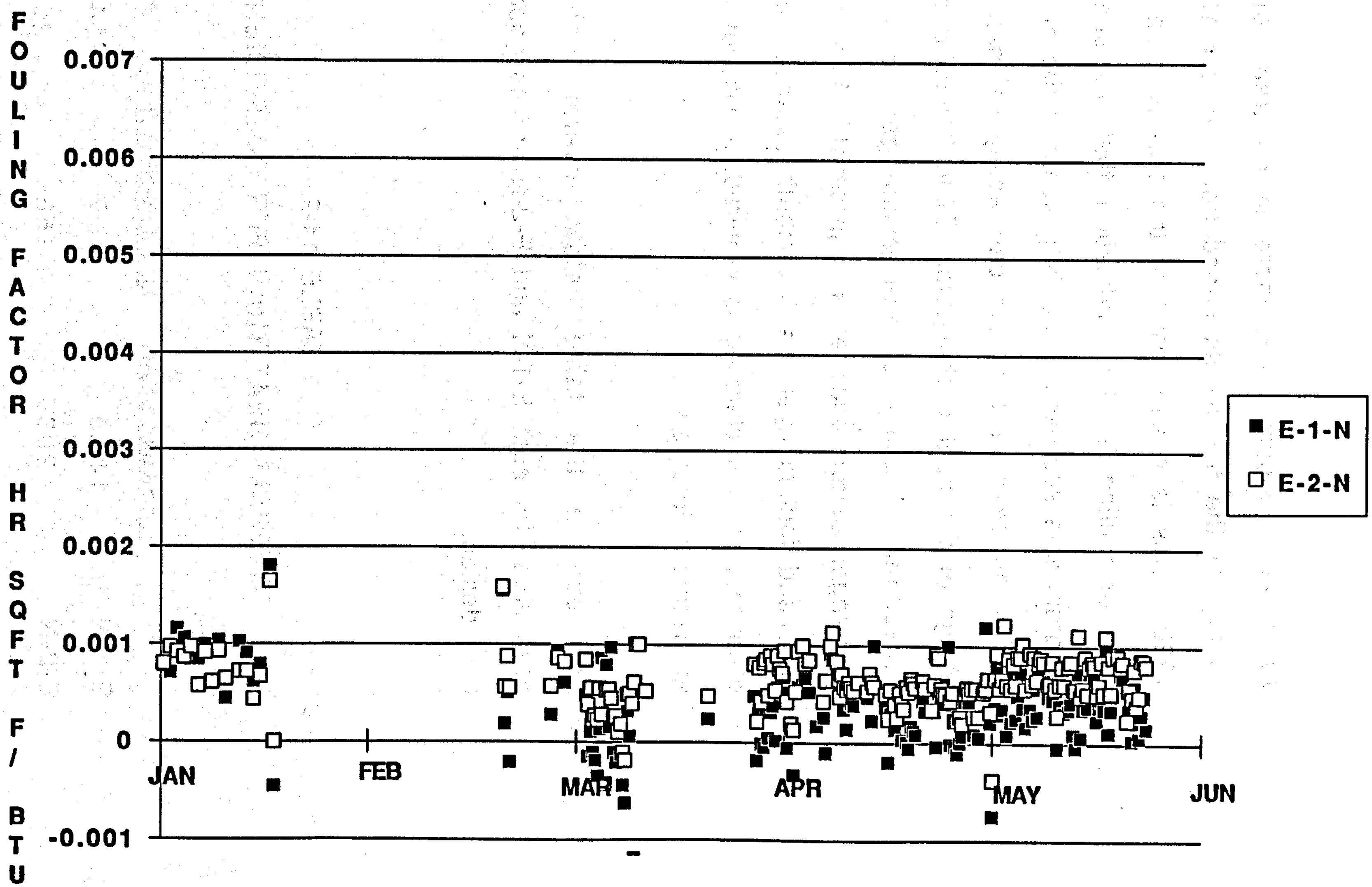
Oil leaked from the turbine, entered the isobutane stream, and accumulated in the two boilers. Based on the estimates of oil visible when the exchangers were inspected at the conclusion of the test, approximately 2 inches of oil accumulated in the bottom of E-3-N and less in E-2-N. This would not significantly reduce heat transfer area. There is no way to determine if this was a gradual leak or a catastrophic event. The oil may have entered the isobutane stream during problems with the turbine seal in January. Fouling factors were calculated throughout the test to trend fouling. Existence of oil in the exchangers was not known at that time. This oil did not significantly degrade heat transfer.

14.1.2 Heat Exchanger Fouling - Brine Exchangers

Figure 14-1 shows calculated fouling factors for E-1-N and E-2-N. As seen in Figure 14-1, there is an offset from zero and some scatter in the data. However, a significant increase in fouling would show as an upward trend in the data.

FIGURE 14-1

FOULING FACTORS E-1-N & E-2-N



As seen in Figure 14-1, there is no trend of increased fouling for the five month period from January 1990 to May 1990. This is a key result of the test program. The low level of fouling is clear indication that the scale inhibitor program was successful. Fouling on the order of 0.001 hr ft^2 °F/Btu as seen in this test can easily be handled in the design of the heat exchangers. Even if fouling does occur, occasional cleaning of the exchangers can keep the exchanger performance at a high level. With the lack of increased fouling over the five-month extended period, it is clear that even if cleaning is required, it will not need to be at frequent intervals.

As seen in the table below, overall heat transfer coefficients for both E-1-N and E-2-N are as good or better than design.

TABLE 14-2

OVERALL HEAT TRANSFER COEFFICIENTS

	DESIGN-CLEAN	DESIGN-SERVICE	ACTUAL
E-1-N	148.5	97.7	140 - 165
E-2-N	208	156	200 - 230

Figure 14 - 2 shows the normalized brine pressure drop in E-2-N. Pressure was read from a differential pressure gauge and then normalized to account for varying flowrates andchanges in the number of tubes. (Tubes leaked in E-2-N on two occasions, so several tubes were plugged.) Pressure drop is plotted for those days in which brine circulated through the exchanger starting in September. By January, the pressure drop had leveled off. One possible explanation is that a thin layer of scale built up on the inside surface of the tubes, but the scale layer did not get thick enough to severely restrict flow. Inspection of the tubes at the conclusion of the test indicated that this was the case.

14.1.3 Heat Exchanger Fouling - Exhaust Gas Exchanger

Fouling in E-3-N, the exhaust gas exchanger, was significant as shown in Figure 14-3. Fouling increased uniformly while the engines were running. Black carbon powder, probably resulting from incomplete combustion of the fuel, deposited on the inside of the tube surface. This creates an additional resistance to heat transfer which degrades performance. As operation continues, the deposition layer becomes thicker and heat transfer continues to degrade. When the engines shut down, the exchanger cools and the powder falls off the tubes. When the engines are restarted, the powder is blown out. As a result, heat exchanger performance improved dramatically after each restart of the engines. On several occasions, operators observed soot coming out of the stack.

Actual overall heat transfer coefficients ranged from 10 to 16.5 Btu/hr ft^2 °F. This was lower than the design values of 18.44 clean and 16.5 service. Overall heat transfer coefficient was lower than design even with a clean exchanger, and fouling exaggerated the problem.

FIGURE 14-2
NORMALIZED PRESSURE DROP
E-2-N

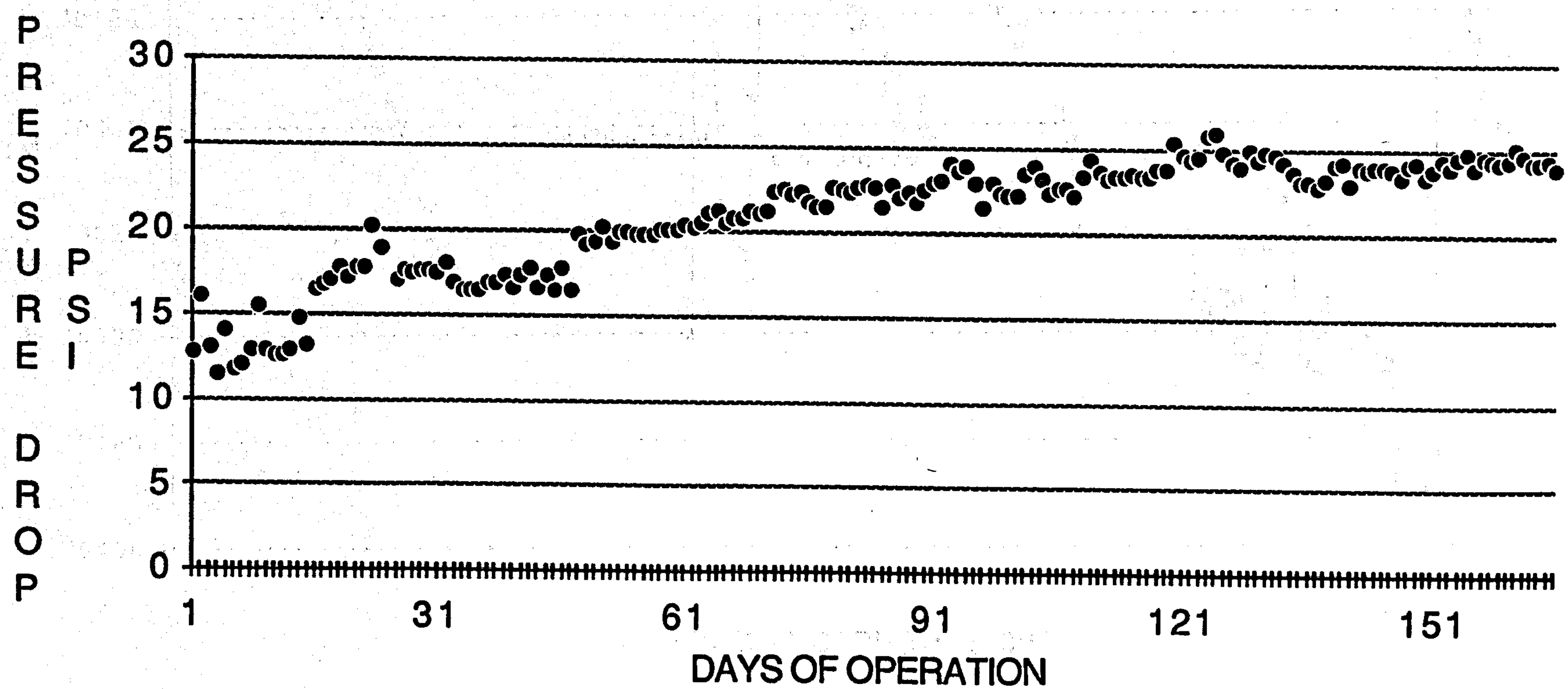
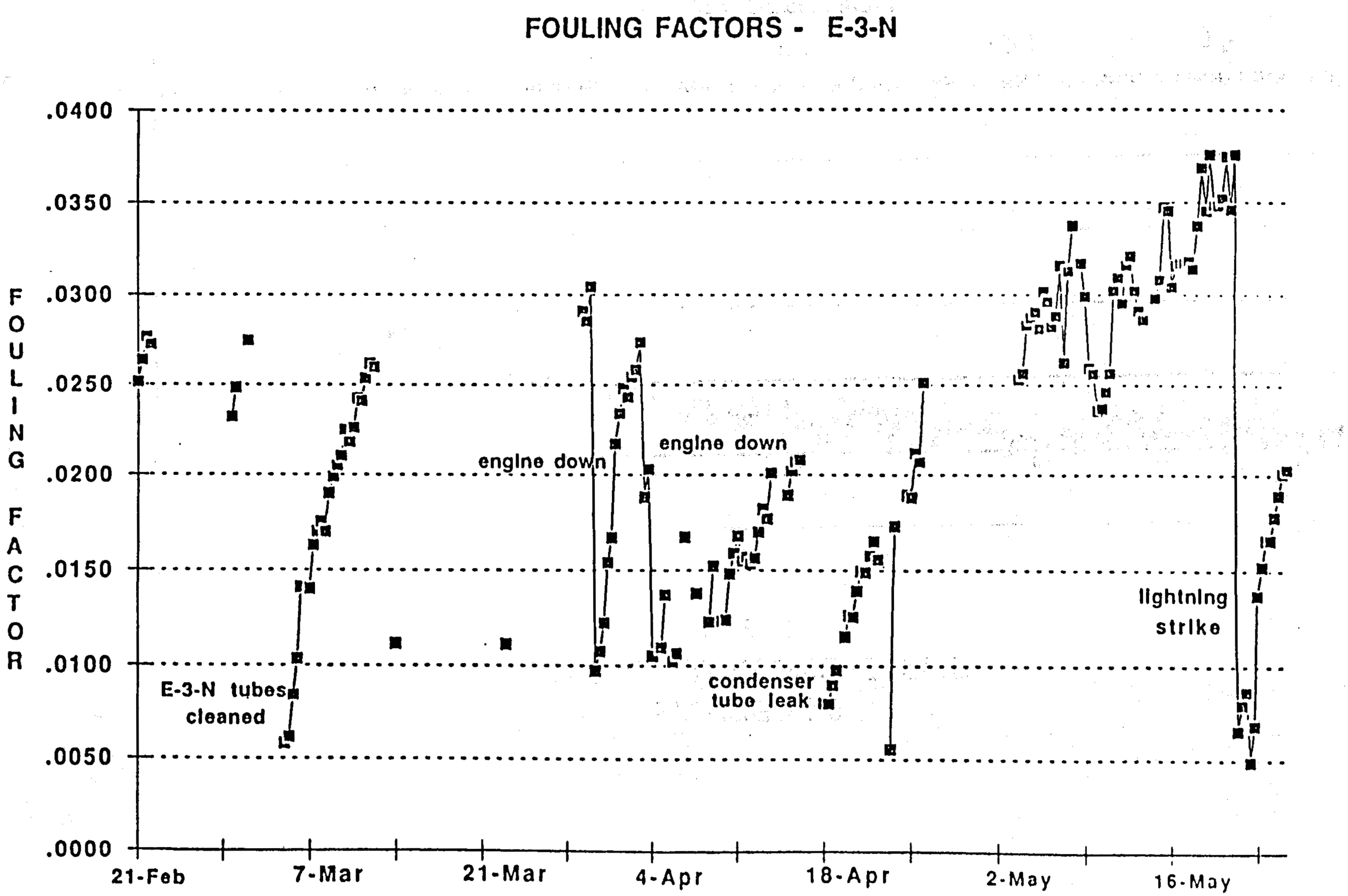


FIGURE 14 - 3

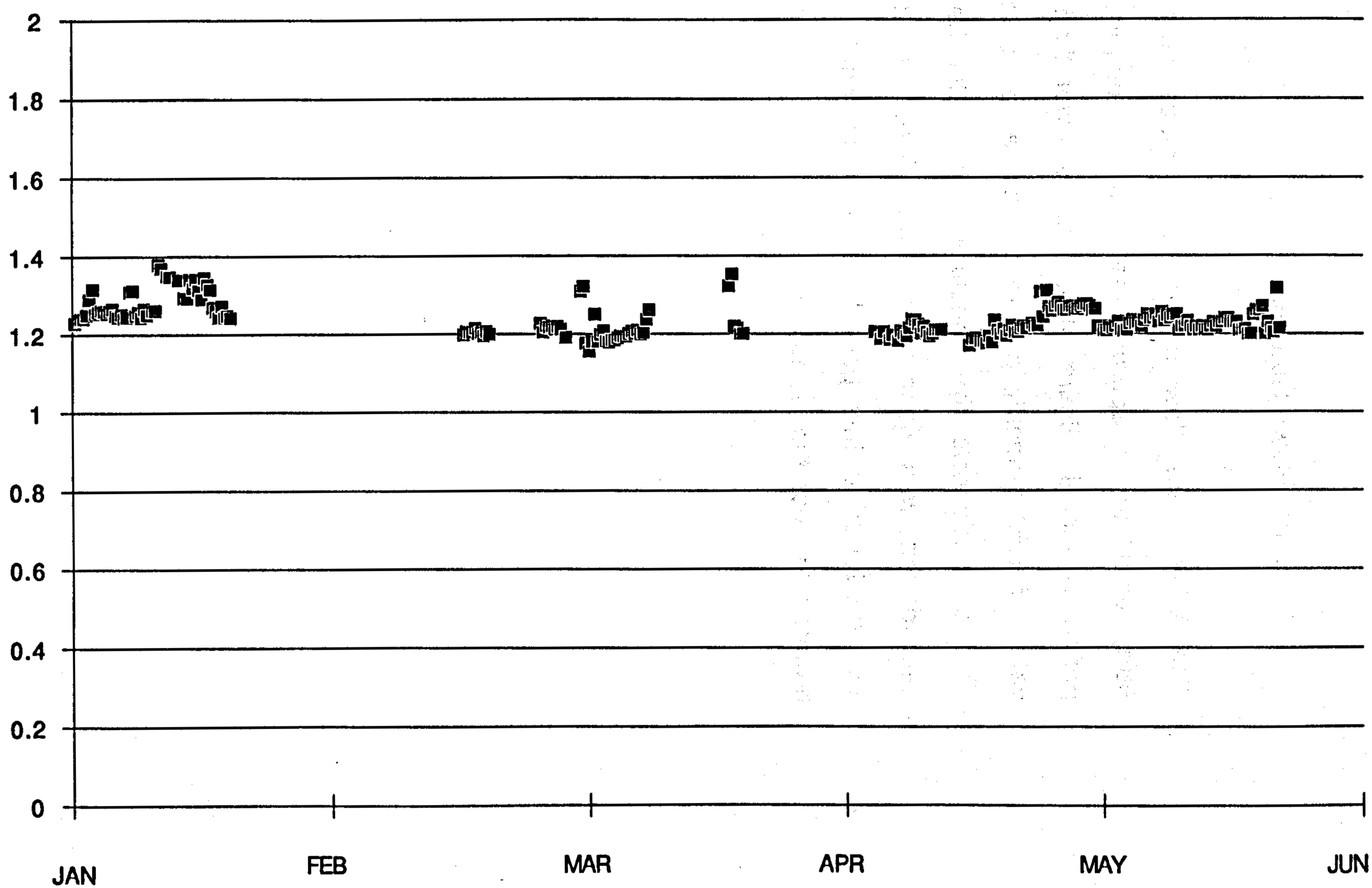

FOULING FACTORS - E-3-N
FOULING FACTOR
.0400
.0350
.0300
.0250
.0200
.0150
.0100
.0050
.0000
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
2-May
16-May
E-3-N tubes cleaned
engine down
engine down
condenser tube leak
lightning strike

14.1.4 Brine Flow/ Isobutane Flow

The brine mass flow to isobutane mass flow ratio was fairly constant at approximately 1.25 throughout the test period as seen in Figure 14-4. This is lower than the design value of 1.58 primarily due to the higher brine temperature. This plot supports the conclusion that little heat transfer degradation was seen during this test. If fouling had increased during this period, more brine would have been required to heat the isobutane.

FIGURE 14-4

BRINE FLOW / ISOBUTANE FLOW



14.1.5 Post-Test Evaluation

A thorough inspection of all three exchangers was conducted at the end of the test. Channel covers at both ends of E-1-N were opened and samples of the scale on the inlet and outlet headers were collected. Chemical analysis of these samples showed that they were primarily oil and rust. The result of the chemical analysis is included in Appendix J. There was little scale on the inside of the tubes. This is a fixed tube exchanger so the tubes could not be pulled out without destroying the exchanger. The internal diameter of three tubes was measured using a caliper and a micrometer. The measured diameters of 0.496", 0.502" and 0.503" were close to the 0.495" diameter specified on the drawing, indicating that little corrosion had occurred.

Due to a tube leak, the head had been pulled off of E-2-N a few days before the plant had shut down. At that time no scaling was apparent on the tubes. During the post-shutdown inspection, the tube bundle was pulled completely out of the exchanger. Four tube samples were cut out and these tubes plugged. The bundles were in good shape and showed no sign of warpage. Several gallons of a thick black oily substance was in the shellside of this exchanger. Samples of this were taken. Analysis results indicated that this sample was primarily rust, oil and water. The oil is most likely turbine lube oil which leaked into the isobutane system through the turbine seal.

The internal diameter of the tube samples was 0.61". An internal diameter of 0.62" is called out on the drawing, so little if any corrosion had occurred.

The only significant corrosion formed was on the ferrules which had been inserted into the tubes. An electron microgragh which is included in Appendix J shows that corrosion was on the outside of the ferrule. Corrosion occurred in the gap between the ferrule and the tube but not on the surface of the ferrule exposed to brine flow. Since no corrosion was seen on the inside of the ferrule or on the tube just downstream of the ferrule, it is concluded that ferrules are not necessary to protect the tubes.

Corrosion coupons were put in the system on December 11, 1990 and removed on January 16, 1991. Metal loss rates were measured by IGT as:

Coupon location	Mils per year loss rate
Upstream of separator chokes	6.5
Downstream of separators	3.2
Near disposal well	3.8

This metal loss rate is acceptable. This conclusion is supported by corrosion coupon data.

As was done for E-2-N, the channel cover was taken off of E-3-N and the tube bundle taken out of the shell. Black soot was apparent on the inner surface of the tubes. Samples were taken of the soot on the inlet and the outlet header. Analysis showed that the outlet header sample was primarily iron rust, carbon particles, and moisture. The inlet sample was primarily iron rust and siliceous dirt. This sample contained gasket fragments. Particles of rust from upstream piping and equipment may have contributed to E-3-N fouling. Damage to an exhaust gas exchanger from rust can be minimized by reducing engine down time.

Approximately ten gallons of oil poured out of E-3-N when the shellside was opened. The turbine lube oil appeared to be clean with some small black particles visible. IGT measured the specific gravity of the oil from the exchanger as 0.852 and the specific gravity of turbine lube oil as 0.861. IGT also analyzed the two oils using a capillary column gas chromatograph with a flame ionization detector. Their results show that the oils are nearly identical in composition except that the turbine gearbox oil contains 0.2% isobutane and the oil from E-3-N contains 1% isobutane. It is apparent that some turbine gear oil had leaked into the isobutane loop and accumulated in the boilers. Probably, the trace amount of oil in E-2-N is also turbine lube oil.

Although all heat exchangers were cleaned before start-up, rust may have been present due to exposure at Pleasant Bayou. Also, since E-2-N leaked during the test, some water may have gotten into the isobutane system. After the plant was shut down, isobutane was evacuated from the system and the exchangers sat for three weeks before the exchangers were inspected.

Results of the visual inspection, chemical analysis of the scale and electron dispersion spectroscopy of the tube samples all support the conclusion that the exchangers maintained their mechanical integrity throughout the test. No corrosion of the tubes was measured and no wear due to erosion or vibration was found. Little scale was observed on the brine tubes. The presence of turbine lube oil in the boilers apparently did not degrade performance.

14.2 Turbine

14.2.1 Operation

The turbine operated 2902 hours at Pleasant Bayou. Some problems with high vibration occurred early in the test and the primary seal failed in February. After these problems were solved, a binary cycle availability of 88.5% was achieved for the months of April and May.

14.2.2 Performance

Figure 14-5 shows the turbine output as measured at the generator terminals for 1990. Turbine output varies with wet bulb temperature so fluctuations in turbine output are expected. At a higher wet bulb temperature, the condensing temperature of isobutane in the condenser is higher, so its vapor pressure is higher, thus driving turbine output lower. Figure 14-6, which is a plot of turbine output versus back pressure for the month of January, shows that the design turbine output of 541 kW was achieved at the design turbine back pressure of 70 psia. However, Figure 14-7 shows that at the design wet bulb temperature of 64°F the turbine output is approximately 20 kW lower than design. This occurs since the accumulator pressure was approximately five psi higher than design as shown in Figure 14-8. Table 14-2 shows a comparison of the isobutane which was delivered at Pleasant Bayou compared to the standard composition of commercial isobutane which was used as the design basis.

FIGURE 14-5

TURBINE OUTPUT

measured at generator terminals

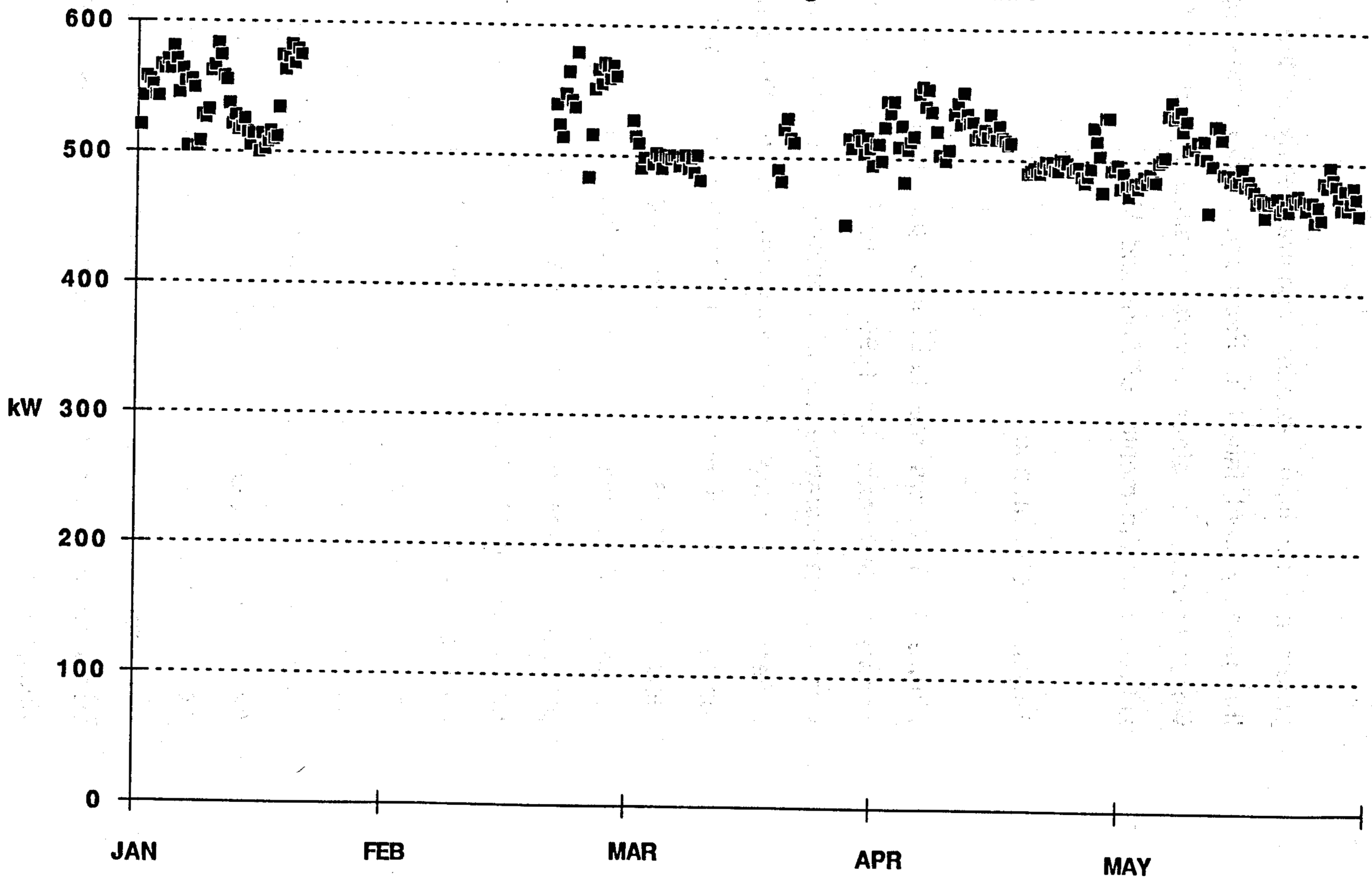


FIGURE 14 - 6
GEOPRESSURED HYBRID POWER SYSTEM
JANUARY 1990

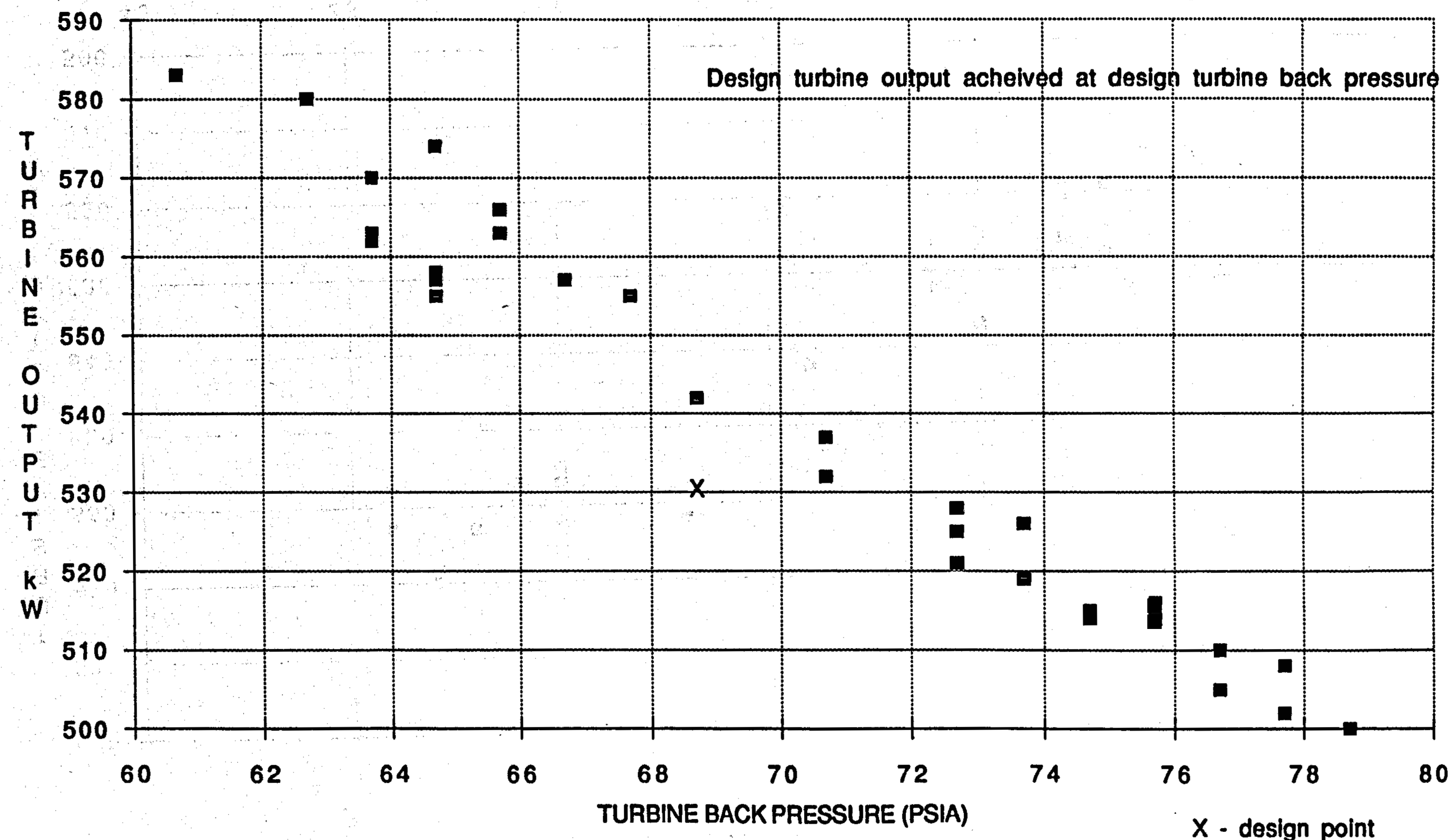


FIGURE 14 - 7
GEOPRESSURED HYBRID POWER SYSTEM
JANUARY 1990

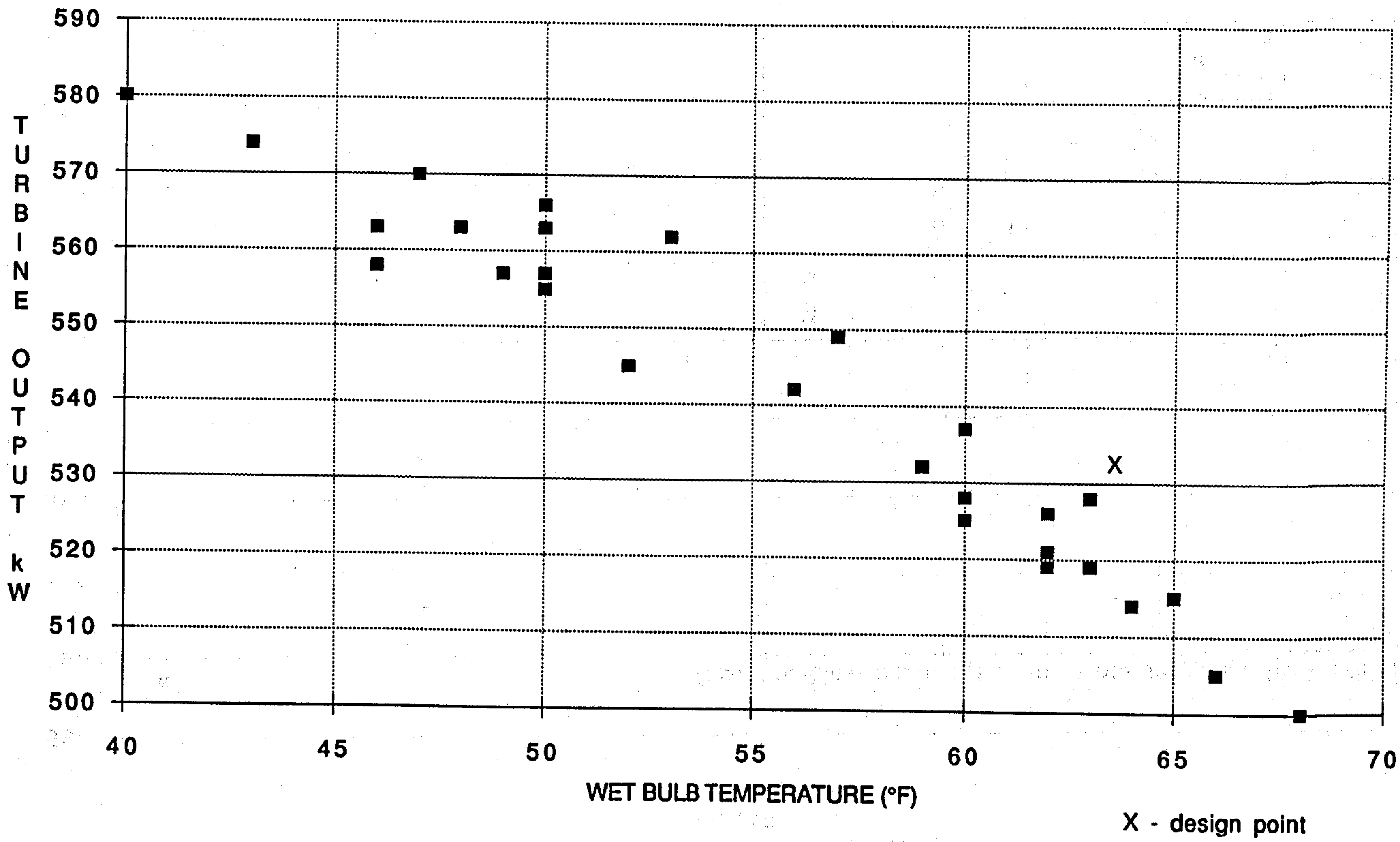


FIGURE 14-8
GEOPRESSURED HYBRID POWER SYSTEM
JANUARY 1990

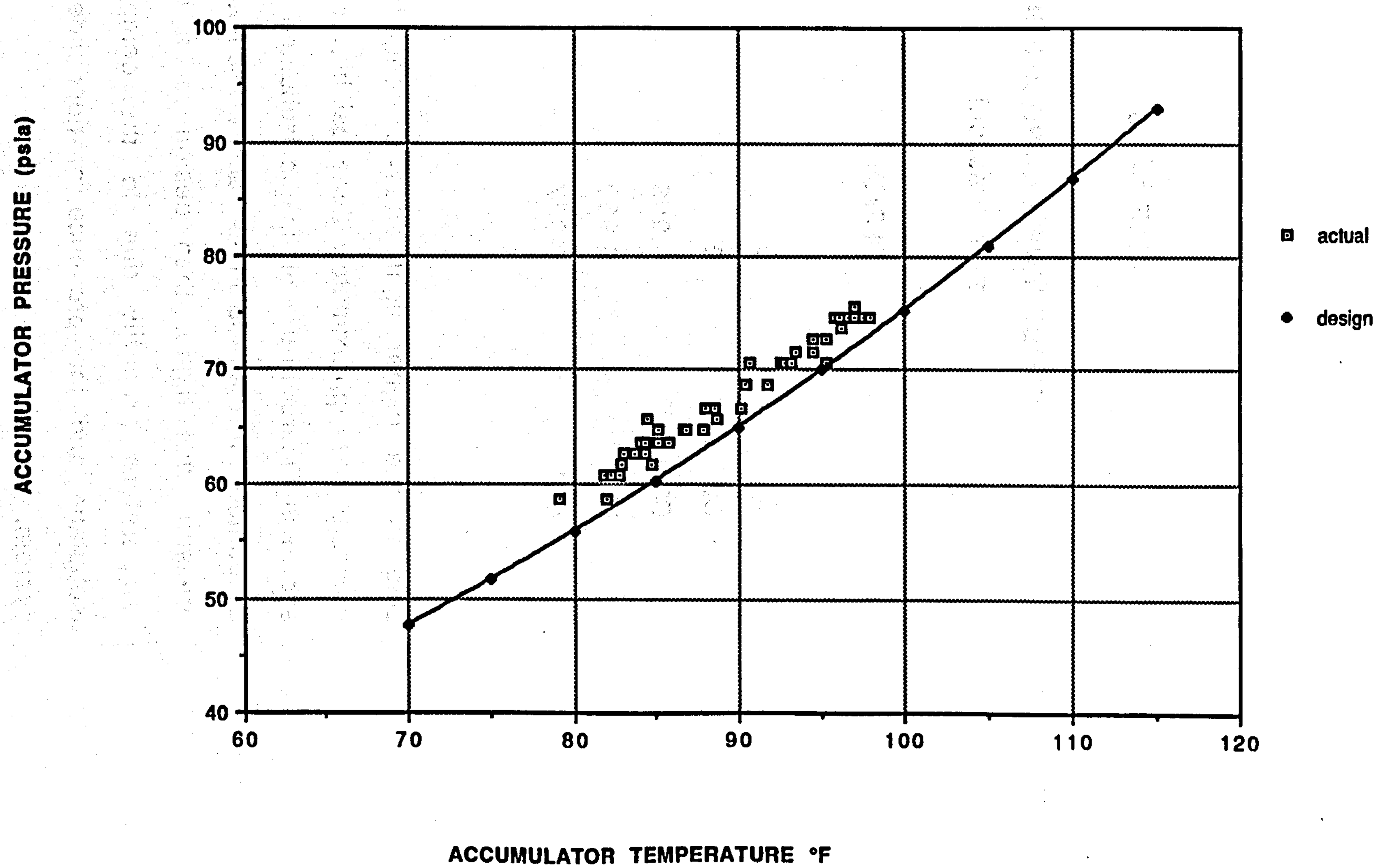


TABLE 14 - 3

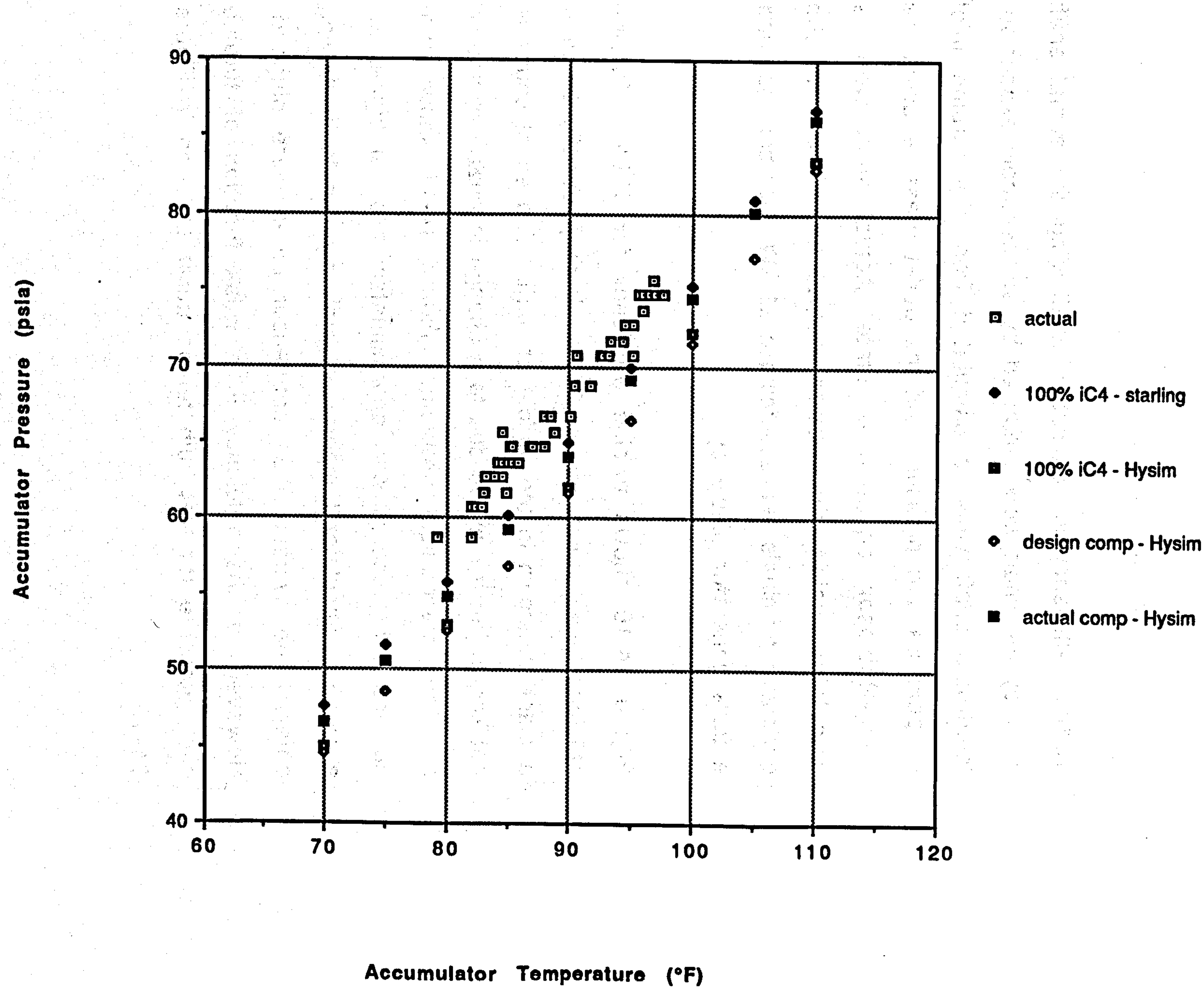
ISOBUTANE COMPOSITION

(mole fraction)

	DESIGN	ACTUAL
C1	0	0.0007
C2	0	0.0002
C3	0.003	0.0228
iC4	0.960	0.9603
nC4	0.037	0.0160

Due to the higher light ends content, the accumulator pressure was approximately three psi higher than design as shown in Figure 14-9. Air in the isobutane system probably accounted for the additional back pressure. Turbine back pressure was higher than design for a given wet bulb temperature primarily due to the composition of the isobutane and the presence of noncondensables in the system.

FIGURE 14-9


Accumulator Pressure (psia)
90
80
70
60
50
40
60
70
80
90
100
110
120
Accumulator Temperature (°F)
actual
100% iC4 - starling
100% iC4 - Hysim
design comp - Hysim
actual comp - Hysim

Turbine efficiency is calculated by dividing the actual shaft work by the shaft work produced by an isentropic expansion. Isentropic shaft work is calculated from the turbine inlet temperature and pressure and the outlet pressure using the Peng-Robinson equation of state. Actual shaft work is calculated using the power output measured at the generator terminals and assuming a 21 kW gear box loss and a 95% generator efficiency.

Figure 14-10 shows turbine efficiency for 1990. Turbine efficiency was approximately 70%. It dropped slightly after a plant shutdown in the middle of April. The exact cause is not known but it may be due to a change in nozzle clearance or other mechanical problem. Figure 14-11 shows that accumulator pressure was approximately two psi higher for a given accumulator temperature, probably due to air having entered the system when condenser tubes were plugged. However, turbine efficiency is a weak function of turbine back pressure (or wet bulb temperature) as seen in Figure 14-12.

FIGURE 14-10

TURBINE EFFICIENCY

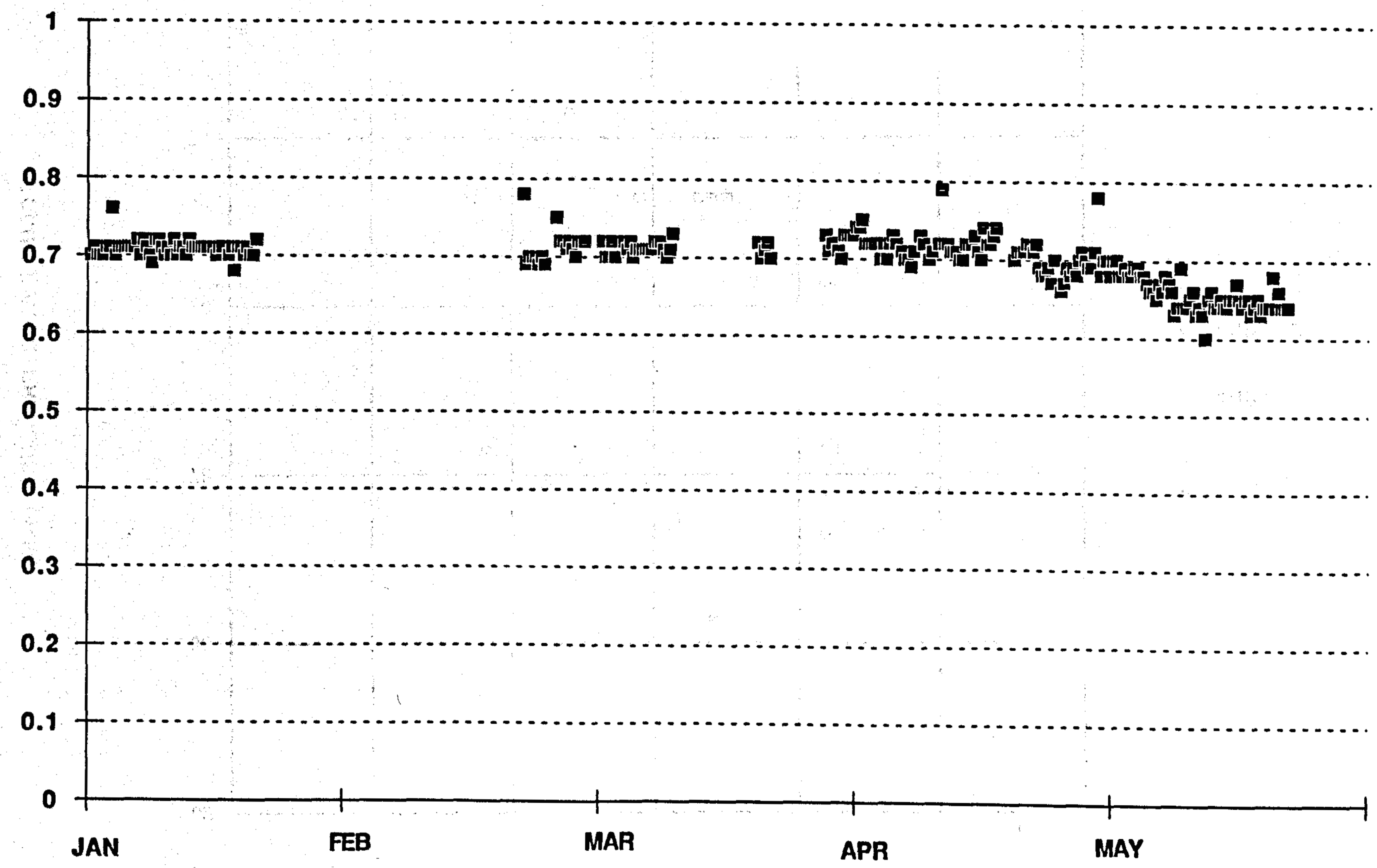


FIGURE 14-11

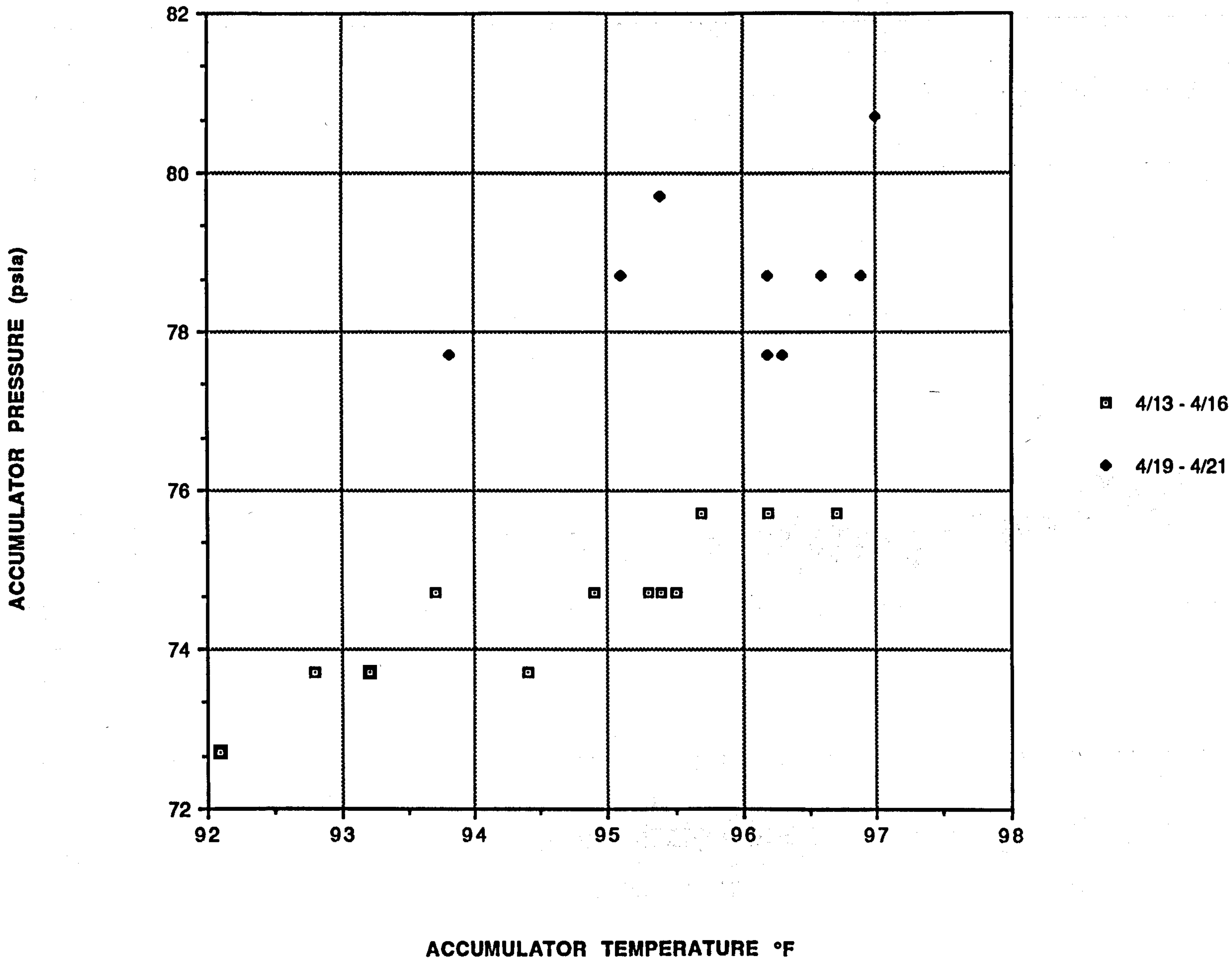
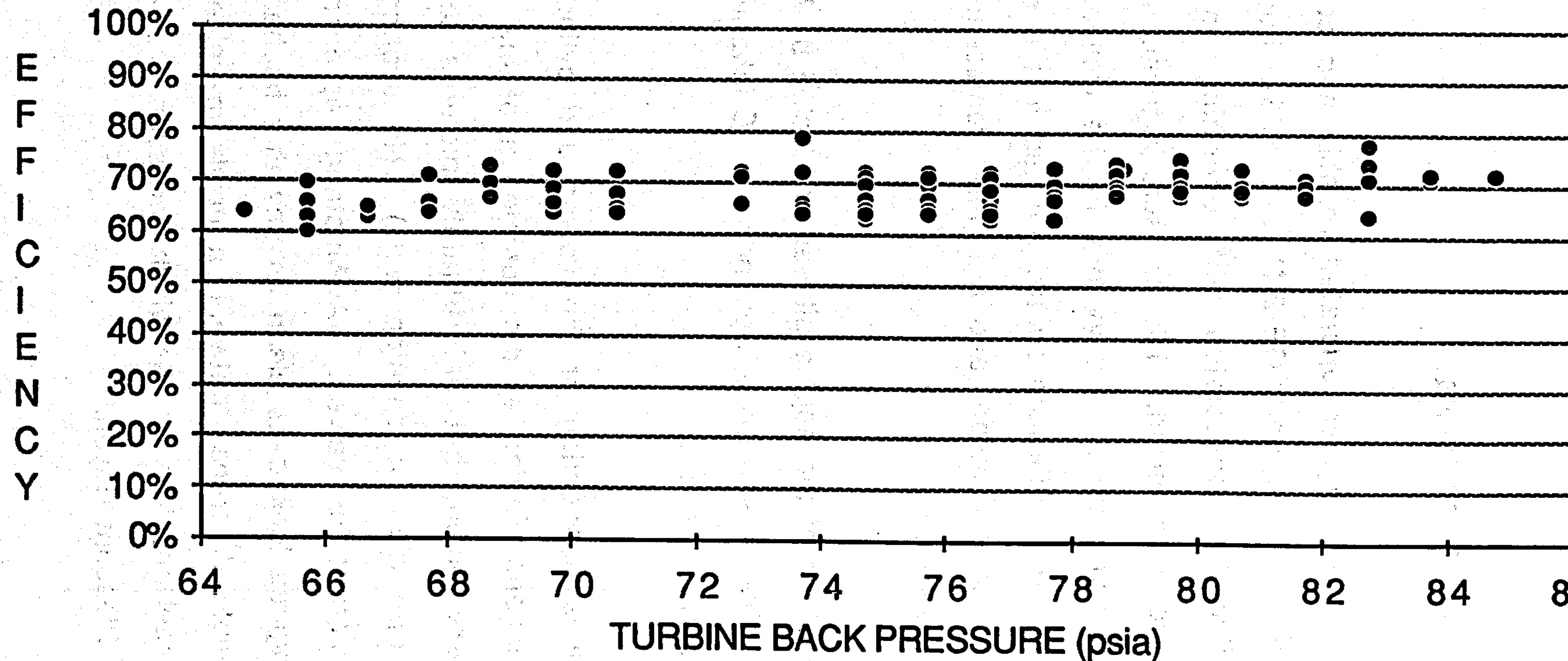

ACCUMULATOR PRESSURE (psia)
82
80
78
76
74
72
92
93
94
95
96
97
98
ACCUMULATOR TEMPERATURE °F
4/13 - 4/16
4/19 - 4/21

FIGURE 14-12
TURBINE EFFICIENCY VS. TURBINE BACK PRESSURE
MARCH 29 - MAY 16, 1990



14.3 Gas Engines

The gas engines operated reliably and consistently. GE-1-N ran 4585 hours and GE-2-N ran 4832 hours. Few operational difficulties associated with operating on impure wellhead gas were experienced. The pressure regulator diaphragm was gradually dissolved by the heavy oils in the wellhead gas and had to be replaced. Attention should be paid to the diaphragm material used in this application, and a regular replacement schedule should be followed.

Analysis of the engine oil was conducted by Mustang Power. A copy of this is shown in Appendix J. Contaminant levels were within normal levels.

Visual inspection of the valves and cylinders was conducted at Mustang Engine at the completion of the test. (Pictures of this were taken, but unfortunately pictures taken through the bore scope did not develop well.) No scoring was evident on the cylinders or valves. A Mustang representative stated that the engines looked as clean as any that he had seen. There was no visible difference between a newly machined engine of the same model and the engines which had seen over 4500 hours of operation at Pleasant Bayou.

14.4 Condenser

Design duty for the four Baltimore Aircoil condensers was 17 MMBtu/hr. Because this condenser had been used at the DCHX facility where water was present in the isobutane loop, the condensers were corroded. Two tubes were plugged during the initial refurbishment of the equipment. The condenser was hydrotested once again immediately prior to plant start-up and fifteen tubes leaked. This resulted in the loss of these tubes and an additional 43 tubes which blocked access to the leaky tubes. When the power plant began operation, 15.1% of the condenser surface area had been lost. At the end of January, a tube leak caused two more tubes to be plugged. Again in the middle of April, two tubes were plugged. By the end of the test, 16.7% of the condenser area had been lost.

Despite the loss of surface area, the condenser performed as designed. A condenser duty of 18 to 19 MMBtu/hr was achieved at the design approach temperature. (Approach temperature is defined as condenser outlet temperature minus wet bulb temperature). Isobutane flows were higher than design yet the condenser was able to adequately cool the isobutane. It was difficult to detect any change in cooling capacity or approach temperature before and after the two tubes were plugged in April.

14.5 Isobutane Circulating Pump

The isobutane circulating pump was originally used at DCHX and modified for use at this facility. Pump outlet pressure as originally configured was higher than required at Pleasant Bayou. Table 14-3 shows the design pump conditions, actual pump conditions for January 17 at 0700 hours, manufacturer's predicted pump performance based on actual conditions, and manufacturer's predicted performance based on design conditions. At the DCHX facility, this vertical turbine pump had 21 stages. Six of these stages were removed for the Pleasant Bayou test, although additional stages could have been removed with the pump still meeting design requirements. The extra stages resulted in a non-optimum design which wasted power, but gave flexibility for a range of operating conditions. Table 14-3 shows the high actual power versus the design value. As seen by a comparison of the two actual flow cases in Table 14-3, pump output was close to what was specified by the pump manufacturer. Pump outlet pressure was slightly higher than predicted and overall efficiency was only slightly lower than specified. Pump outlet pressure and power requirements were steady over the course of the test. The pump performed well, but was not ideally suited for this application.

TABLE 14 - 4

PUMP PERFORMANCE

Flow	Design	Actual	Pump Curve Actual Flow	Pump Curve Design
Flow (lb/hr)	107,000	119,000	119,000	107,000
Inlet Pressure (psia)	70	74.7	74.7	70
Outlet Pressure (psia)	330	378.7	375	402
Work-100% (Btu/hr)	171,537	200,099	198,124	195,726
Overall Efficiency	67.9%	64.4%	66.6%	68.4%
Parasitic Load (kW)	74	91	87.2	83.8

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15.0 CONCLUSIONS

The test of the Geopressured Hybrid Power System at Pleasant Bayou was successfully completed. The Ben Holt Co. and the other project participants demonstrated for the first time the generation of electricity from a geopressured-geothermal resource. An innovative hybrid cycle was used to efficiently recover this energy. Valuable operating data and experience were gained over the nine month demonstration period.

Test results indicate that a commercial hybrid cycle power plant on the Pleasant Bayou geopressured-geothermal resource is technically feasible. Historically, there have been several concerns about operation on a geopressured well. Excessive scaling could have rendered heat exchangers ineffective; severe corrosion could have required the use of expensive, exotic materials; and impure well head gas could have caused severe problems with operating gas engines.

The test of the Geopressured Hybrid Power System at Pleasant Bayou showed that these problems have been overcome. The plant achieved an availability of 97.5% and a capacity factor of 80.2% for the five month continuous operation test. 3445 MWh of power were exported to the local utility.

Both brine-to-isobutane heat exchangers exceeded design specifications. No significant fouling over an extended operating period was detected on either exchanger. In addition, minimal scale was found when the heat exchangers were inspected at the conclusion of the test. Scale and corrosion inhibitors were effective throughout the range of brine temperatures. Corrosion was minimal in carbon steel piping and heat exchanger tubes.

Fouling in the exhaust gas heat exchanger was a problem. Excessive fouling in this exchanger has several possible solutions. A gas turbine may be installed instead of a gas engine to cut down particulate emissions. In a larger plant, a larger gas engine which more efficiently completes combustion could be employed. As another alternative, a blower which periodically removes the soot could be provided. A low pressure drop filter may be all that is required. Although this question must be addressed, it is an engineering design issue rather than a technology development issue.

Gas engines ran well on the impure well head gas. The turbine accumulated 2902 hours of operation with a single rotor. This is a significant improvement over the DCHX test in which five turbine rotors operated for a total of only 1074 hours.

This successful demonstration of electricity generation using the hybrid concept has shown that there are no technical obstacles to commercial utilization of the Pleasant Bayou geopressured-geothermal resource.

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