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A Study of Pumps for the Hot Dry Rock Geothermal Energy Extraction Experiment (LTFT)

Charles A. Tatro

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A STUDY OF PUMPS FOR THE HOT DRY ROCK GEOTHERMAL ENERGY EXTRACTION EXPERIMENT (LTFT)

by

Charles A. Tatro

ABSTRACT

A set of specifications for the hot dry rock (HDR) Phase II circulation pumping system is developed from a review of basic fluid pumping mechanics, a technical history of the HDR Phase I and Phase II pumping systems, a presentation of the results from experiment 2067 (the Initial Closed-Loop Flow Test or ICFT), and consideration of available on-site electrical power limitations at the experiment site.

For the Phase II energy extraction experiment (the Long Term Flow Test or LTFT) it is necessary to provide a continuous, low maintenance, and highly efficient pumping capability for a period of twelve months at variable flowrates up to 420 gpm and at surface injection pressures up to 5000 psi. The pumping system must successfully withstand attacks by corrosive and embrittling gasses, erosive chemicals and suspended solids, and fluid pressure and temperature fluctuations.

In light of presently available pumping hardware and electric power supply limitations, it is recommended that positive displacement multiplex plunger pumps, driven by variable speed control electric motors, be used to provide the necessary continuous surface injection pressures and flowrates for LTFT. The decision of whether to purchase the required circulation pumping hardware or to obtain contractor provided pumping services has not been made.

EXECUTIVE SUMMARY

Specific requirements for the Hot Dry Rock (HDR) Program's Phase II surface circulation pumping system are developed from a discussion of: pump mechanics, the Phase I circulation pumping system, Initial Closed-Loop Flow Test (ICFT) experimental results, and the available electric power supply at the experimental site. System specifications are presented and summary recommendations are made for the procurement of necessary pumping hardware.

The overall objective of the HDR Geothemral Energy Development Program is to develop and demonstrate the technology required for economical commercial extraction of thermal energy from naturally heated crustal rock at accessible depths where the rock contains insufficient in-situ fluid to be an ecomonical source of steam or hot water. Hydraulic fracturing is used to connect the injection and production wellbores at suitable depths. The total available energy as heat in hot dry rock at depths up to 10km has been estimated at 5.9×10^6 Quads for the conterminous United States but existing technology limitations place constraints of the amount of this thermal resource that can be economically exploited.

Phase I (Research) and Phase II (Engineering) systems have been developed at the Fenton Hill site. The goal of the Phase II system is to produce 20MWt continuous for up to twelve months during the Long Term Flow Test (LTFT). The surface pumping system will have to provide up to 420 gpm at 5000 psi for LTFT. The geothermal fluid for LTFT will contain CO_2, H_2S, O_2, dissolved species, suspended solids, and dissolved solids. High pressure geothermal energy extraction pumping systems are not yet widely available so petroleum industry hardware is generally modified as needed to suit the geothermal application of interest. The pumping system for LTFT must continuously circulate the geothermal fluid while maintaining sufficient pressure to prop open reservoir fractures. As reservoir parameters mature during LTFT, the pumping system must have the flexibility to meet variable capacity, variable pressure requirements.

Multiple stage centrifugal turbine pumps and reciprocating plunger pumps are most suitable for HDR fluid circulation. Centrifugal turbine pumps are composed of numerous impeller stages mounted on a single shaft. Each impeller imparts radial velocity to the fluid thereby increasing its pressure. Capacity and pressure characterstics of centrifugal pumps are intimately related and maximum efficiencies rarely exceed 75%. Efficiency losses are dominated by disk-fluid viscous interaction. Cavitation damage in centrifugal turbine pumps can occur if insufficient fluid pressure (called Net Postive Suction Head or NPSH) is supplied to the pump. Centrifugal pump performance and maintenance is dominated by impeller wear rings, shaft packing assemblies, and mechanical seals. Fluid pressure, temperature, and chemistry determine the materials selected for pump impellers, packing, and sealing mechanisms.

Reciprocating plunger pumps do work on a fluid by squeezing the fluid. These positive desplacement pumps leave mechanical efficiencies ranging from 85-95%. They also produce fluid pressures that are independent of capacity. They also produce undesirable pressure pulsation which must be reduced or eliminated to prevent damage to associated equipment. Plunger pumps also contain packing assemblies, which seal the fluid chamber from the external world along the reciprocating plunger, and seals in the form of spring-loaded check valves, two for each plunger. The packing and seal mechanisms are high maintenance items and directly effect duty rating of the pump. Pulsation dampening equipment is usually installed on both the suction and discharge sides of multiplex plunger pumps to reduce fatigue stress and to insure adequate NPSH. For LTFT it is desirable to have pumps capable of continuous duty operation, rather than intermittant duty rated. Continuous duty rated pumps are larger and more expensive than pumps of the same intermittant duty rating.

The pumps used for the Phase I experiments and also specified in the inital Phase II system design were multistage centrifugal turbine pumps of various sizes. The Phase I system provided 300 gpm at 1375 psi for injection via three series boosts of 175 psi, 600 psi, and 600 psi. Mechanical seal problems were encountered, packing materials degraded at low flow rates, and there was a gradual deterioration of pump impellers possibly due to insufficient NPSH. The design of the pumping system for Phase II circulation included fourteen individual centrifugal pumps to produce 1000 gpm at 3000 psi. This pumping system design was flexible yet complicated and only 55-65% efficient. The electrical power requirements of such a pumping system could not be met by available electric power at the site.

Phase II reservoir parameters were evaluated during a 30 day experiment (the Initial Closed-Loop Flow Test or ICFT) conducted in May and June of 1986. ICFT was designed to obtain data necessry for specification of the final surface system for LTFT. For the Phase II surface circulation pumping system, the most important parameters are surface injection pressure and flow rate, and fluid geochemistry. The pumping system must be able to supply a maximum of 420 gpm (10BPM) at 5000 psi although system impedance will decrease during LTFT thereby reducing these maximum pumping requirements. From ICFT fluid chemistry data, it is expected that H_2S, CO_2, suspended solids, and dissolved species will have the greatest effect on surface system components. The surface circulation system utilized during ICFT was supplied by a contractor, B.J. Titan Services, in accordance with specification HDRS-3635C. The contractor supplied positive displacement triplex plunger pumps, controls, personnel, and supplies for the 30 day experiment. The contractor supplied 400% capacity on site and experienced both power end (diesel engine) and pump problems during the test. Valve seats showed H_2S embrittlement and cracking and pulsation dampeners degraded due to CO_2 in the fluid.

Currently available electric power at the Fenton Hill site is 1000 KVA 3 phase WYE configuration which can probably supply 900 kWe continuously. 150 kWe are necessary for site nonpumping requirements, leaving 750 kWe available for pumping. Pumping power at maximum injection pressure is 914 kW (1225 HHP) at 100% pumping system efficiency. For overall pumping system efficiencies fo 75%, almost 1.5 MWe are required. Pump capacity must be continuously variable from 1 to 10 BPM through the use of vairable speed motor controls. Electric motors may be controlled either by variable voltage DC drives and associated controls or by variable frequency AC drives and controls. Power conversion efficiencies for both types of controls are high (94 to 98%) and maintenance requirements are nominal.

Diesel-electric generating units may also be utilized to augment existing utility supplied AC power at the site.

Specificaitions for the Phase II LTFT pumping system include parameters necessary for outside bid procurement and are contained in fourteen subheadings. For the LTFT, it is felt that positive displacement plunger pumps will provide the necessary performance characteristics at high efficiencies. Available power for pumping at the site will have to be augmented by diesel-electric generator units unless the local utility can supply 2MWe. Fluid chemistry will determine pump material selection and is predictable from ICFT experimental results. Little of the already purchased pumping hardware is expected to be utilized for LTFT. It would be prudent to consider contracting out LTFT pumping services unless further site plans necessitate permanent pumping hardware for future geothermal tests.

1.0 INTRODUCTION

1.1 Outline of Topics Addressed in This Study

This paper discusses the specific requirements for Los Alamos National Laboratory's (LANL's) hot dry rock (HDR) Phase II surface injection (circulation) pumping system. First, the mechanics of centrifugal and reciprocating plunger pumps are briefly outlined. A technical history of the Phase I surface circulation (pumping) system follows as a precursor to the development of specific requirements for the Phase II pumping system design. Next, results of the Initial Closed-Loop Flow Test (ICFT) are presented. ICFT data and experimental results which will directly affect the Phase II Long Term Flow Test (LTFT) pumping system are discussed, including chemical and physical properties of the geothermal working fluid critical to the pump system design. A discussion of available electric power at the Fenton Hill geothermal site is included as is pertinent to prime mover specification for the pumping system.

At this point, a fairly comprehensive set of Phase II LTFT surface pumping system specifications is drawn up based on the technical considerations of the preceding chapters. A summary of these specifications serves as a basis for recommendations made in regard to the procurement of necessary pumping system hardware for the Phase II long term energy extraction experiment (also known as the LTFT). It is hoped that this paper will also serve as a guide for specification development and/or hardware procurement of geothermal pumping systems for other geothermal projects.

1.2 The Hot Dry Rock (HDR) Energy Extraction Project at Los Alamos National Laboratory

The objective of the Hot Dry Rock (HDR) Geothermal Energy Development Program at Los Alamos National Laboratory (LANL) is to develop and demonstrate the technology required for economical commercial extraction of thermal energy from naturally heated rock at accessible depths in the earth's crust in locations where the rock contains insufficient in-situ fluid to be an economical source of steam or hot water. The HDR energy extraction system is composed of two (or more) separate wells drilled into a hot region of the earth's crust. The wells are then connected at a desired depth by hydraulic fracturing. The connection created between the wells is comprised of numerous rock fractures of varying apertures.

The fractures act as flow paths between the two wells, thereby creating a giant crustal heat exchanger known as a geothermal reservoir. Cold water from the surface is pumped down one well (the injection side) and flows through the reservoir fractures where it absorbs energy as heat from the surrounding rock. This hot water is then recovered through the other well (the production side) under sufficient pressure to prevent boiling. The useful heat in the water is then extracted in a closed loop heat exchanger or by flashing the hot water to produce steam to spin a steam turbine. A simplified schematic diagram of the HDR energy extraction system is shown in Figure 1.1.

The basic requirement for the establishment of an HDR geothermal system is the availability of hot, low permeability crustal rock suitable for hydraulic fracturing. Rock temperatures above 392°F (200°C), existing at depths of less than 20,000 ft (6 km) are the most suitable (G. Heiken et. al., 1982).

The total available energy as heat in hot dry rock at depths up to 10 km in the earth's crust has been estimated at 5.9 x 10^6 Quads for the conterminous United States (G. Heiken et. al., 1982). Current annual energy use in the United States is approximately 70 Quads. Although the magnitude of available energy as heat in crustal hot dry rock makes energy extraction attractive, severe downhole environments - particularly temperature and pressure - and existing technology limitations, place constraints on the amount of this thermal resource that can be economically exploited.

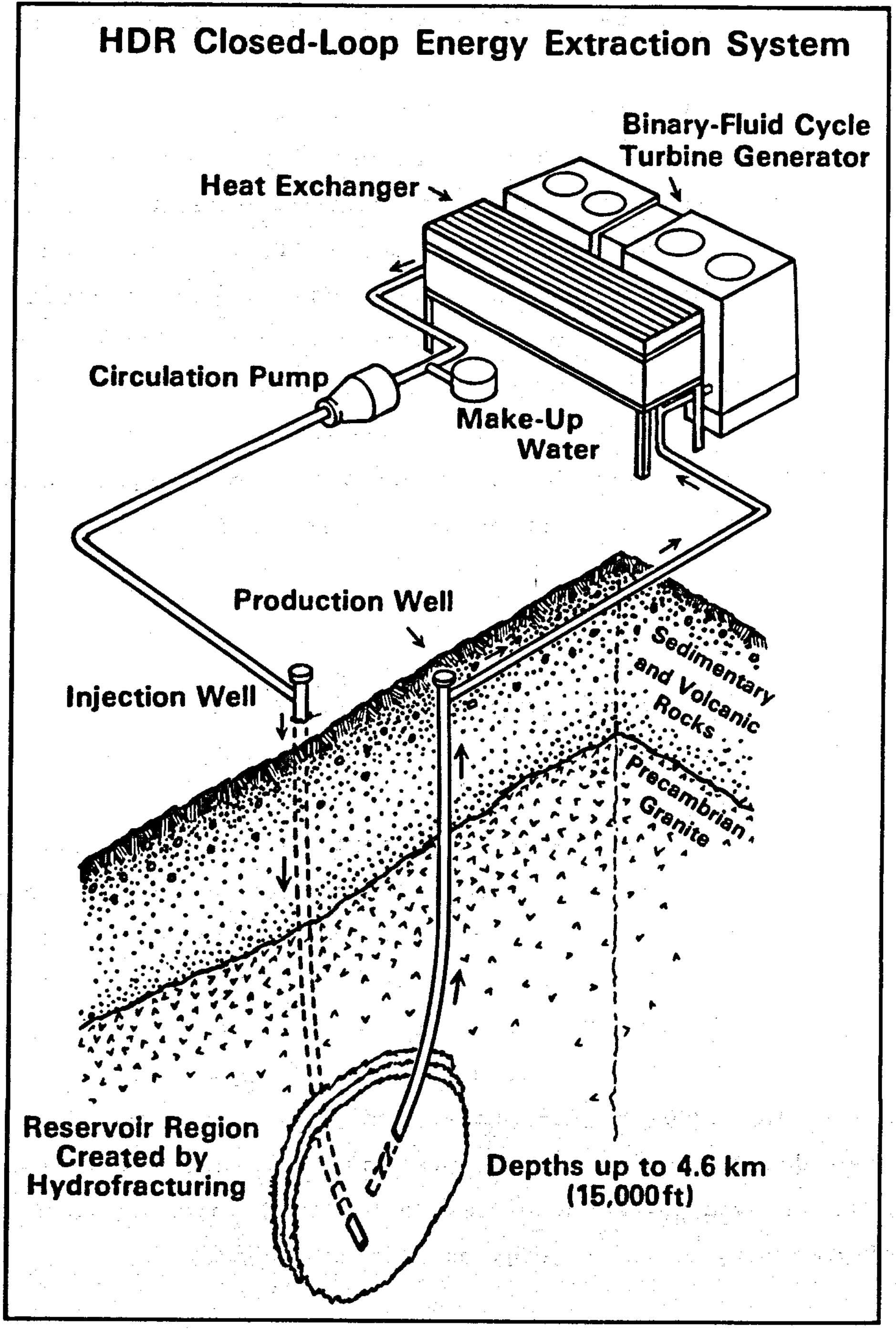


Figure 1.1

Simplified Schematic of a Closed Loop HDR Energy Extraction System.

1.3 The HDR Phase I (Research) and Phase II (Engineering) Systems

A prototype (Phase I) closed loop HDR energy extraction system similar to the system represented in Figure 1.1 was developed and successfully operated for over a year at LANL's Fenton Hill site but the temperature and flow rate of the geothermal fluid produced (less than 5 MWt) were not sufficient to demonstrate the economic feasibility of electric power generation on a commercial scale. In order to demonstrate the commercial viability of hot dry rock energy extraction, the development of a larger, hotter, Phase II engineering system has been completed at Fenton Hill with a goal of producing 20 MWt for a period of up to one year with minimal thermal draw-down. A comparison of the Phase I and Phase II system parameters is shown in Table 1.1.

1.4 The Phase II Injection Pumping System and the Long Term Flow Test (LTFT).

As Table 1.1 indicates, successful implementation of the commercial scale (Phase II) system will place especially strenuous demands on the surface pumping system. With the injection well of the commercial size system approaching a true vertical depth of 12,000 ft (4400 m) and a bottom hole temperature of 455°F (235°C), the surface pumping system will have to provide working fluid flow rates of up to 420 gpm (26 l/s) at surface pressures reaching 5000 psi (35 MPa). The surface pumping system must be able to provide the necessary pressure and flow rates with minimal down time for the one-year Long Term Flow Test (LTFT) in order to demonstrate commercial viability of this energy extraction scheme.

The aforementioned pressures and flow rates must be provided by a pumping system which also successfully deals with, material embrittlement due to dissolved CO_2 and H_2S; possible abrasion due to suspended solids, corrosion due to heat and pressure; and the possible precipitation of calcium-based solids.

TABLE 1.1

Comparison of the Phase I and Phase II HDR Systems at Fenton Hill, N.M.

System Parameter	Phase I*	Phase II**
Depth to Most Useful Reservoir	9620 ft (2.93km)	11,580 ft (3.5km)
Reservoir Temperature	387°F (197°C)	455°F (235°C)
Est. Effective Heat Transfer Area	480,000 ft^2	1,000,000 ft^2
Est. Reservoir Modal Volume	9,330 ft^3 ($264m^3$)	12,450 ft^3 ($354m^3$)
Production Temperature	270°F (172°C)	374°F (190°C)
Production Flow Rate	95 gpm (6 l/sec)	290 gpm (18.3 l/s)
Energy Extraction Rate	3.5 MW(t)	10 MW(t)
Water Loss	7 gpm (0.44 l/s)	77 gpm (4.9 l/s)
Surface Injection Pressure	1300 psi (9 MPa)	4600 psi (31.75 MPa)
Overall System Impedance	15 psi/gpm(1.6 GPa)	19psi/gpm(2GPa/m^3)
Reservoir Rock Type	Granitic Precambrian Crystalline Rock	
Reservoir Fracture Initiation Pressure	3000psi (21MPa)	4800psi (33MPa)

* Value at the end of a 286-day flow test, March-December 1980.

** Value at the end of the ICFT, June 1986.

1.5 Geothermal Circulation Pump Technology

Generic high pressure circulation systems for geothermal energy extraction applications are not yet widely available. Geothermal pumping systems are generally designed and developed (at substantial cost) to meet the specific requirements of each individual geothermal system. The great variety of oil field exploration and production equipment has historically served as the basis for geothermal hardware development. Off-the-shelf petroleum industry hardware is modified as needed to suit the geothermal application of interest. Hot dry rock energy extraction systems are no exception to this rule. Although enormous technological developments have been made in the geothermal field, the diverse operating requirements - especially temperature, pressure, and chemical properties of the geothermal fluid - make the development of available off-the-shelf geothermal circulation equipment economically unfeasible at current levels of demand.

The purpose of the pumping system in the HDR Phase II energy extraction loop is really two-fold. The pumping system must continuously circulate the geothermal fluid at sufficient flow rates, and it must also provide the necessary pressure to prop open the reservoir fractures, thereby minimizing reservoir impedance. The pumping system must also have the flexibility to meet variable capacity, varying pressure requirements as geothermal reservoir parameters change during the Phase II LTFT.

2.0 MECHANICS OF CENTRIFUGAL PUMPS AND RECIPROCATING PLUNGER PUMPS

2.1 Introduction

There are two classes of pumps suitable for HDR geothermal fluid circulation. They are: multiple stage centrifugal turbine pumps (Figure 2.1) and reciprocating plunger pumps (Figures 2-2 and 2-3). Although there are many other types of pumps, they do not offer high flowrate and high pressure simultaneously at reasonable efficiencies or they are not compatible with geothermal applications and fluids. Each type of pump has its own merits and shortcomings with regard to geothermal applications. The most important operating characteristics of either pump type are: total dynamic head or pump head, H [ft] or [m], flow rate or capacity, Q [gpm] or [l/sec], hydraulic horsepower, P [hp] or [W], and overall pump efficiency, n [%]. The pump head (H) is the developed pressure difference between the suction inlet and the discharge flange as given by:

$$H = \left[\frac{P}{\gamma} + \frac{V^2}{2g} + Z\right]_{\text{discharge}} - \left[\frac{P}{\gamma} + \frac{V^2}{2g} + Z\right]_{\text{suction inlet}} \qquad (2.1)$$

where the term P/γ is the pressure head or flow work, $V^2/2g$ is the velocity head or the kinetic energy of a unit weight of fluid moving with velocity V, and Z is the elevation or potential head with respect to some chosen datum (Z is usually negligible).

Pump capacity (Q) is the volume of fluid per unit time delivered by the pump. Hydraulic horsepower (HHP) is the amount of energy imparted to the fluid per unit time and is given by:

$$HHP = \frac{(Q)\ (s)\ (H)}{3960} \qquad (2.2)$$

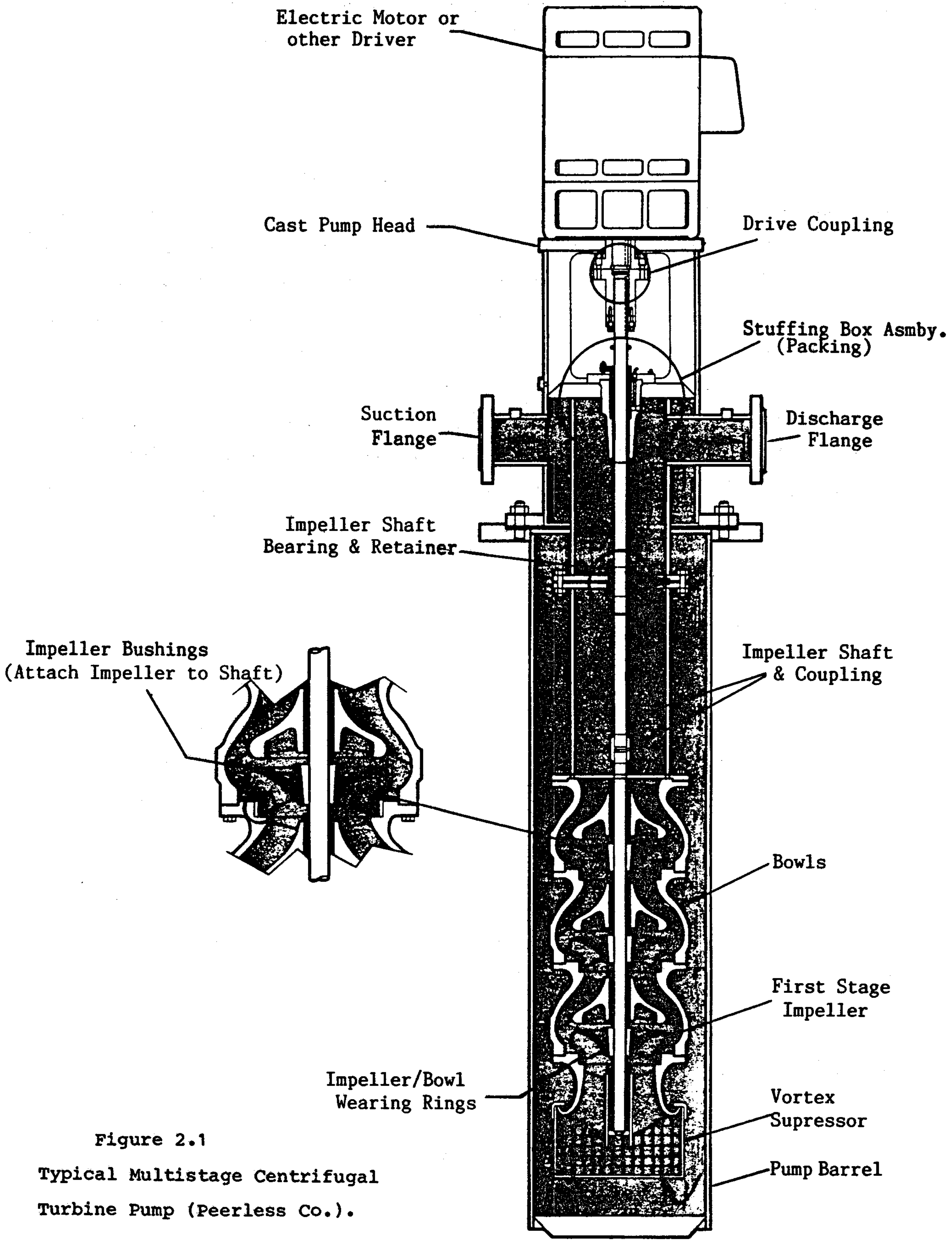


Figure 2.1

Typical Multistage Centrifugal Turbine Pump (Peerless Co.).

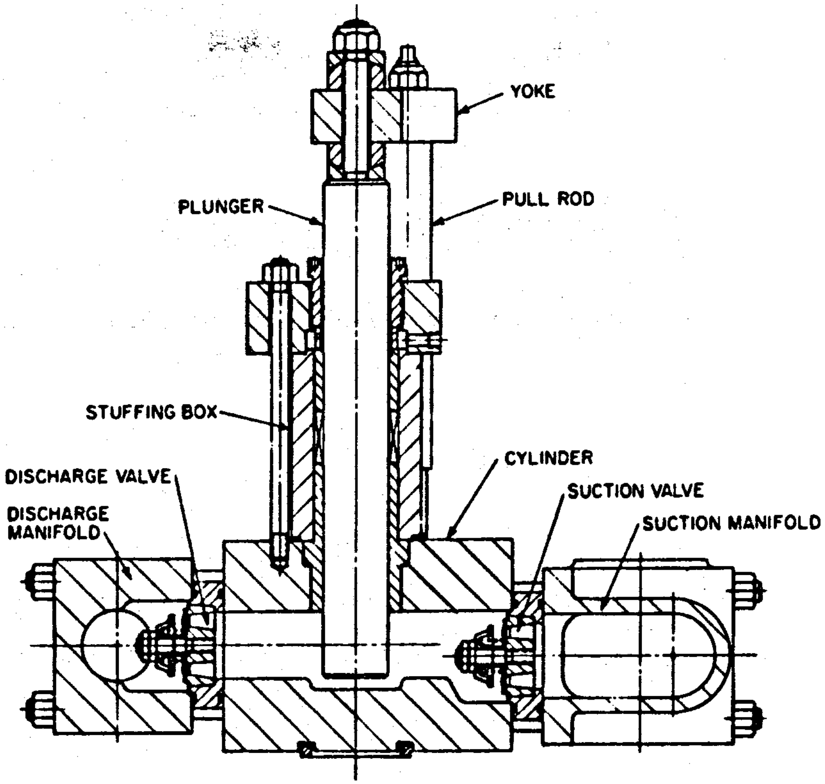


Figure 2.2

Liquid End, Vertical Power Pump (Ingersoll Rand Co.).

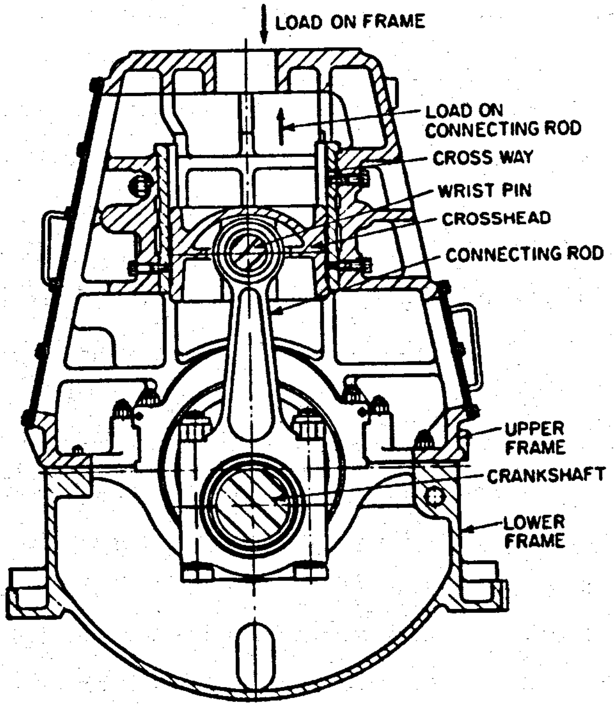


Figure 2.3

Power End, Vertical Power Pump (Ingersoll Rand Co.).

where s is the specific gravity of the fluid and Q and H are given in [gpm] and [ft], respectively. Overall pump efficiency (n), is the hydraulic horsepower (HHP) divided by the mechanical input power to the pump shaft,

also called the brake horsepower (BHP); $n = \frac{HHP}{BHP}$. (2.3)

Pump efficiencies are discussed further in sections 2.4 and 2.8.

2.2 Basics of Centrifugal Turbine Pumps

Centrifugal pumps impart radial and tangential velocity to the liquid via a set of rotating vanes called an impeller. This fluid kinetic energy is then transformed into an increase in pressure as the fluid exits through a diffuser. Bernoulli's equation for any point along a streamline relates the decrease in a fluid's velocity to a corresponding increase in the pressure of the fluid (I. Karassik, et. al., p. 2-3). This pressure increase, or head (H), represents the net work done on a unit weight of fluid. Centrifugal pumps are designed to operate at the point of best efficiency as noted in Figure 2.4. Figure 2.4 shows the general characteristics of a centrifugal pump. The shape of the head, efficiency and power curves are typical of centrifugal pumps. Pump performance falls off rapidly away from the maximum efficiency (design) point.

The brake horsepower vs. capacity (P-Q) curve in Figure 2-4, depicts the steadily increasing power requirement for higher flow rates. The head vs. capacity (H-Q) curve is fairly flat but falls off markedly beyond the best efficiency point. Therein lies one of the most fundamental drawbacks of using centrifugal pumps for the Phase II injection pumping system. In the Phase II HDR energy extraction system it is necessary to provide variable capacities at a stable injection pressure. Reductions in efficiency and total pump head result at pump capacities above the best efficiency point. To surmount this problem would require an over designed centrifugal pump operated below its maximum efficiency. In addition, present capabilities

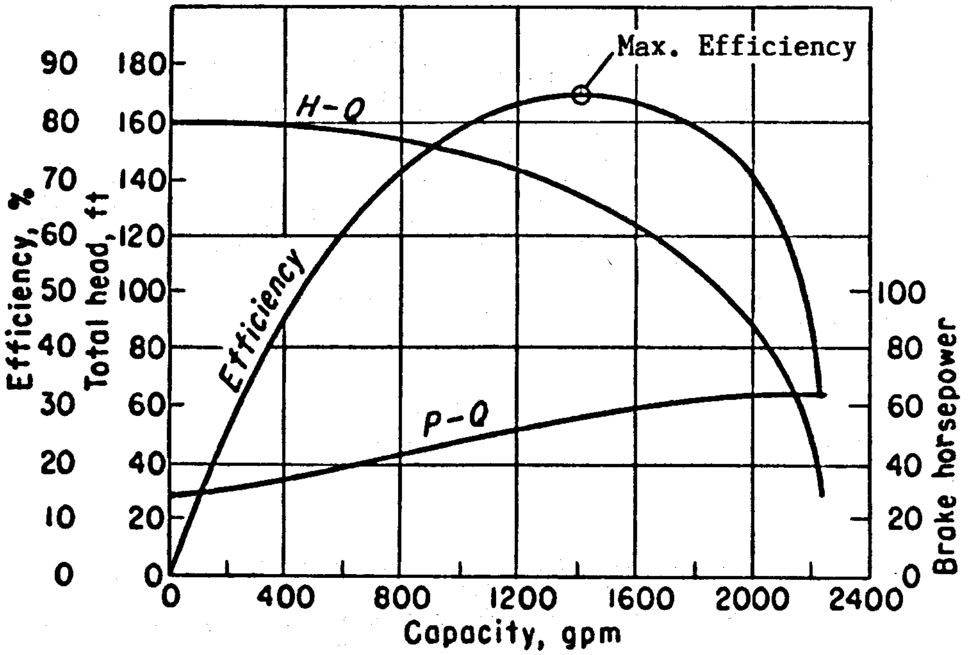


Figure 2.4

Typical Characteristic Curves for a Centrifugal Pump.

of multistage centrifugal turbine pumps limit the maximum pressure that can be developed at the 420 gpm flow rates necessary for the Phase II LTFT. Present centrifugal turbine pumps can develop up to 2300 psi total dynamic head in one pump at the flow rates mentioned above (Goulds Proposal #82-6-618, p. 2). Goulds proposal was to take fluid at 3000 psi and boost this to 5300 psi with one pump.

2.3 Affinity Laws for Centrifugal Pumps

The relationship between the several variables involved in centrifugal pump performance can be expressed by the pump affinity laws (also called the pump laws). These laws relate pump impeller diameter, D, pump capacity, Q, total head, H, pump brake horsepower, BHP, and pump speed, N [RPM] for all types of centrifugal pumps.

When comparing centrifugal pumps of the same impeller diameter, D, the relations are:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{2.4}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{2.5}$$

$$\frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{2.6}$$

where subscripts 1 and 2 denote the two pumps of interest. When comparing the two geometrically similar pumps at the same speed, N, the relations become:

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \tag{2.7}$$

$$\frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2 \tag{2.8}$$

$$\frac{BHP_1}{BHP_2} = \left(\frac{D_1}{D_2}\right)^3 . \tag{2.9}$$

As can be seen from equations 2.4-2.6, a change in the speed of a given pump results in a corresponding change in its output capacity. However, the same shaft speed increase changes the total developed pump head by the square of the speed change ratio. (If $N_2 = 2N$, then $H_2 = (2)^2 N_1 = 4N_1$.) Even more dramatic is the increase in the BHP required by the pump. BHP increases as the speed ratio cubed (Eqn. 2.6). Equations 2.7-2.9 show the same relationship with respect to different size pump diameters at the same shaft speed, N.

Efficiencies of centrifugal pumps remain nearly constant for small shaft speed changes and for small changes in impeller diameter. These laws tell the centrifugal pump user that a change in the pump speed will not only affect the flow rate but it will markedly change the developed head and required brake horsepower. For the HDR LTFT, it is desirable to change the flow rate with little or no change in injection pressure (developed head). This is one shortcoming of centrifugal pumps in regard to the LTFT. Centrifugal pumps will not provide fixed capacity variable pressure performance, or fixed pressure variable capacity operation because developed pressure and capacity are intimately related.

2.4 Mechanical Efficiencies of Centrifugal Pumps

Overall pump efficiency is simply the ratio of hydraulic horsepower (HHP) to brake horsepower (BHP) as presented in Eqn. 2.3. The difference between HHP delivered and BHP required is primarily due to hydraulic losses and leakage flow losses, although impeller disk friction and mechanical friction also incur small efficiency penalties. Overall efficiency, n, can also be expressed by:

$$n = \frac{1}{\frac{1}{n_H n_v} + \frac{P_{DF}}{HHP} + \frac{P_M}{HHP}} \qquad (2.10)$$

where n_H is the hydraulic efficiency which can be approximated by (I. Karassik, et.al., p. 2-17):

$$n_H = 1 - \frac{0.8}{Q^{.25}} \quad . \qquad (2.11)$$

n_v is the volumetric efficiency and is given by:

$$n_v = \frac{Q}{Q + Q_L} \tag{2.12}$$

where Q_L is the internal flow leakage through the wearing rings or impeller vane clearances and thrust equalization holes and Q is the pump output. P_{DF} is the power lost due to disk-fluid viscous interaction and P_M represents mechanical friction losses due to bearings and stuffing boxes. P_{DF} and P_M are insignificant (less than 2 percent of total HHP) at flow rates above 200 gpm. Centrifugal pump peak efficiencies range from 60-75% when operating at their design point.

2.5 Cavitation and Net Positive Suction Head (NPSH) Requirements

Cavitation is the occurrence of local boiling of the pumped fluid due to low-pressure regions in the flow. This local boiling creates regions of vapor and bubbles where the pressure is below the vapor pressure of the liquid. Damage to the surrounding structure is believed to be caused by pressure waves or possibly fluid jets emanating from the collapsing bubbles when they again encounter regions of increased pressure. Another important consequence of cavitation is that the cavitating region, through vigorous mixing with the main stream causes losses in total pressure and thereby a decrease in efficiency. The low pressure regions can also cause flow pattern distortions, thereby enlarging the low pressure regions and decreasing the static pressure of the flow causing sudden head drops and efficiency losses.

When the pumped fluid contains dissolved gasses, extra care must be taken to provide the NPSH required to prevent the separation of dissolved gas species as well as the flashing of water vapor. Dissolved gasses are often liberated just before liquid vaporization begins. The first turbine stages in multistage centrifugal pumps are most prone to cavitation damage. NPSH is the minimum pressure required at the pump suction flange to prevent cavitation in a pump and is determined by manufacturer testing of the pump at the stated installed operating conditions. To prevent cavitation, available NPSH at the pump suction flange must always be greater than or equal to the manufacturer's specified NPSH.

2.6 Multistage Impeller/Bowl Wear Surfaces

Multistage centrifugal pumps are generally constructed with removable or replaceable leakage joints, called wearing rings, between the moving impellers and the fixed bowls or casing. Several types of wearing ring configurations are shown in Figures 2.5 through 2.7. These moving surfaces prevent fluid backflow from the high pressure side of the impeller to the low pressure side, thereby increasing pump efficiency. Wearing ring degradation is strongly affected by the suspended solids content of the fluid handled but wearing surfaces are also subject to corrosion due to high pressure gasses dissolved in the fluid. These problems can be overcome by using a clean and/or deaerated fluid flush to displace the pumped fluid in the region between the rings. Wearing rings may be constructed of bronze, cast iron, stainless steel, surface-hardened steel, plastic, or other materials depending upon the chemical characteristics of the fluid handled. It is not the intent of the wearing rings to be weight bearing or alignment surfaces for the pump impellers. They are primarily for leakage control around the impellers.

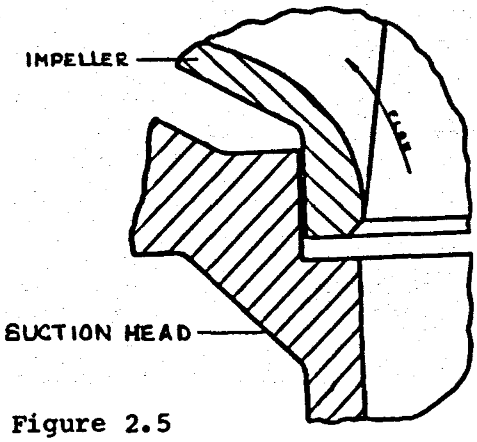


Figure 2.5

Plain Flat Leakage Joint- no rings.

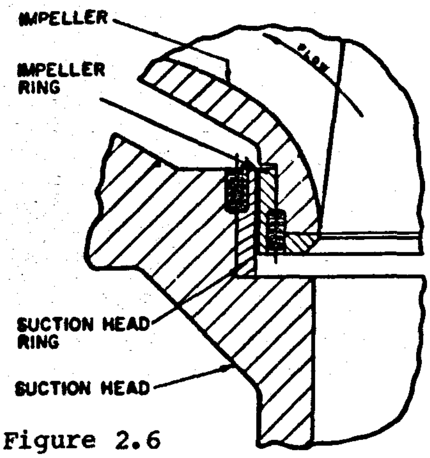


Figure 2.6

Double Flat Ring Construction.

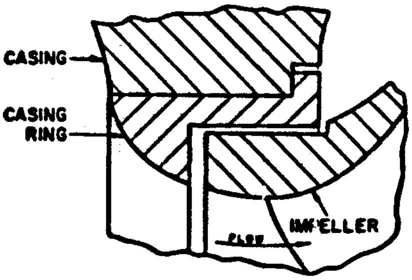


Figure 2.7
L-Type Casing Wearing Ring.

2.7 Shaft Packing and Mechanical Seals

Pump shaft packing configurations basically consist of mechanical packing material contained in the packing box, bushings or a bottom ring, an adjustable gland ring, and lubrication supplied either by normal leakage or by a higher pressure fluid injected into the stuffing box through a lantern ring. Figure 2.8 shows a typical stuffing box arrangement. The stuffing box is a fixed packing arrangement around the rotating pump shaft provided to seal against leakage out of the pump along the shaft.

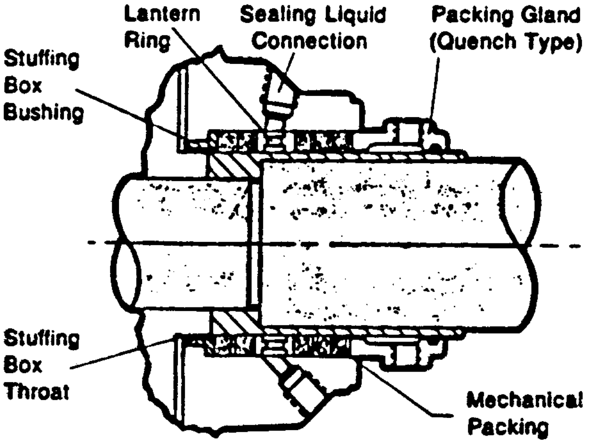


Figure 2.8
Typical Stuffing Box Arrangement (Description of Parts).

Mechanical seals also provide an area in which to seal against leakage along the shaft, however, the mechanical seal forms a running (rotating), seal between the pump shaft and other stationary parts utilizing one or more O-ring seals and spring-loaded mating surfaces. Figure 2.9 depicts a basic mechanical seal. The only mechanical wear takes place between the two mating surfaces because the O-rings are free to move. The spring assembly provides self-adjustment as the surfaces wear, and the fluid provides a thin lubrication film between the mating surfaces. Mechanical seals can be of several types (single, double, balanced, unbalanced, tandem, etc.) and are used in place of shaft packing assemblies or in conjunction with them. Mechanical seal life is effected most strongly by suspended solids content, dissolved gasses, and temperature of the fluid handled. Fluid pressure, temperature, and chemistry determine the type of seal selected and the materials used in construction.

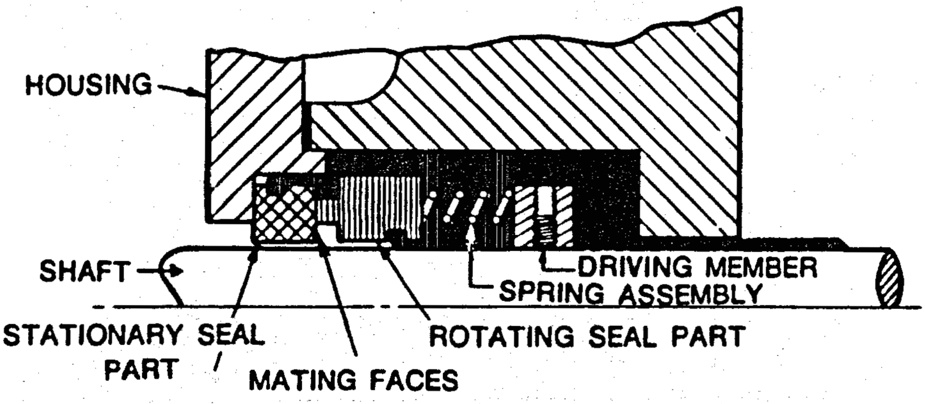


Figure 2.9

Basic Mechanical Seal.

Shaft packing assemblies are prone to degradation from suspended solids, dissolved gasses, and local heat build-up due to insufficient water leakage through the packing. Some continuous leakage is necessary for proper packing effectiveness. Packing and seal mechanisms are the major maintenance items in centrifugal pumps.

2.8 Basics of Reciprocating Plunger Pumps.

Plunger pumps, sometimes called power pumps, do work on a fluid by virtue of the fluid's negligible compressibility. These positive displacement pumps use a moving cylinder (plunger) to decrease the volume of a cavity containing the fluid being pumped. One-way check valves at each end of the cavity provide outlet and inlet flow paths as the plunger moves into and out of the fluid cavity. The outlet valve opens as the plunger enters the fluid cavity and fluid flows out under pressure. As the plunger retreats, the outlet valve closes, and NPSH on the inlet side of the pump causes a new slug of fluid to enter through the inlet valve. Figure 2.10 shows a schematic of a reciprocating plunger pump. Plunger pumps are built in vertical or horizontal configurations and with two to nine plungers. Figures 2.2 and 2.3 show the construction of a vertical plunger pump. Figure 2.2 shows the fluid end, and Figure 2.3 shows the power end. Pump capacity (Q) is related to the number of plungers and the pump speed.

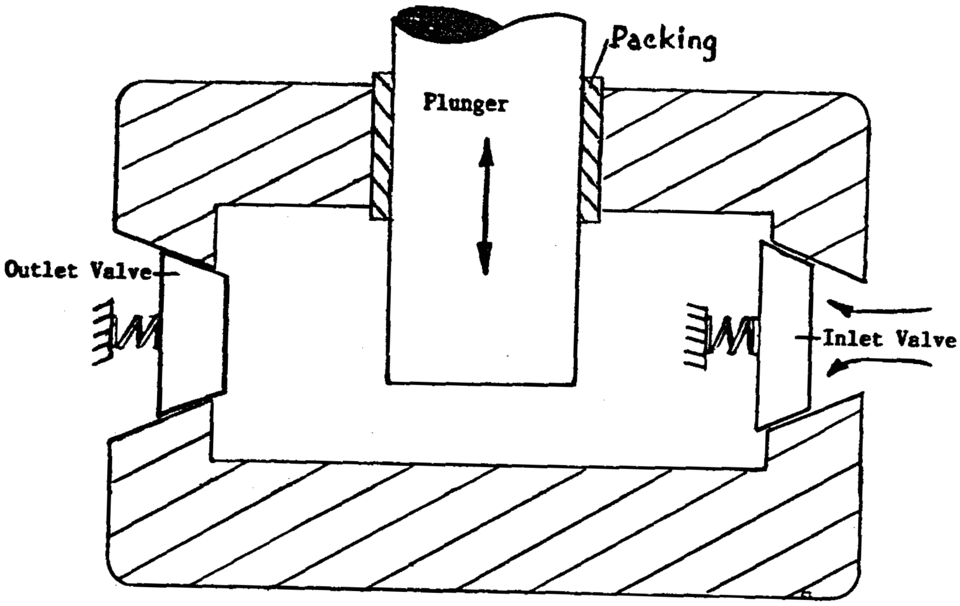


Figure 2.10
Reciprocating Plunger Pump Schematic.

Neglecting slip losses, Q [gpm] is given by:

$$Q = \frac{(A)\ (m)\ (N)\ (L)}{231} \tag{2.13}$$

where A [in^2] is the cross-sectional area of the plunger, m is the number of plungers, N [rpm] is the speed of the pump, L [inches] is the plunger stroke length, and 231 [in^3/gal] is a conversion factor. Plunger pumps and long stroke intensifiers are capable of producing continuous flow rates at pressures as high as 30,000 psi. Maximum developed pressure is dependent on the power delivered to the crankshaft and on the geometric configuration of the fluid end.

The brake horsepower (BHP) required to produce a certain flow rate for a given developed pressure is expressed by:

$$BHP = \frac{(Q)\ (p)}{(1714)\ (n)} \tag{2.14}$$

where Q is the flow rate [gpm], p is the developed pressure [lbs/in^2], and n is the overall pump efficiency [%]. Overall efficiencies of power pumps (90-95%) are significantly better than those of centrifugal pumps (60-75%) and are only affected slightly by developed pressure at constant speed (I.J. Karassik, et. al., p. 3-5). Therefore, hydraulic horsepower (HHP) ratings for power pumps are very close to their rated mechanical input or BHP.

Power pump slip (S) is the capacity loss expressed as a percentage of the suction capacity and is often given by:

$$S = 1.0 - VE \tag{2.15}$$

where VE is the volumetric efficiency of the pump [%]. When pumping water below 6000 psi, VE is very close to unity due to water's negligible compressibility and assuming minimal valve and stuffing box leakage.

Volumetric efficiency is the ratio of discharge volume to the suction volume expressed as a percentage. Figure 2.11 gives volumetric efficiency curves as a function of the ratio "r," and the discharge pressure. "r" is the total internal volume of the pump between the intake and outlet valves divided by the output capacity of the pump, neglecting slip losses.

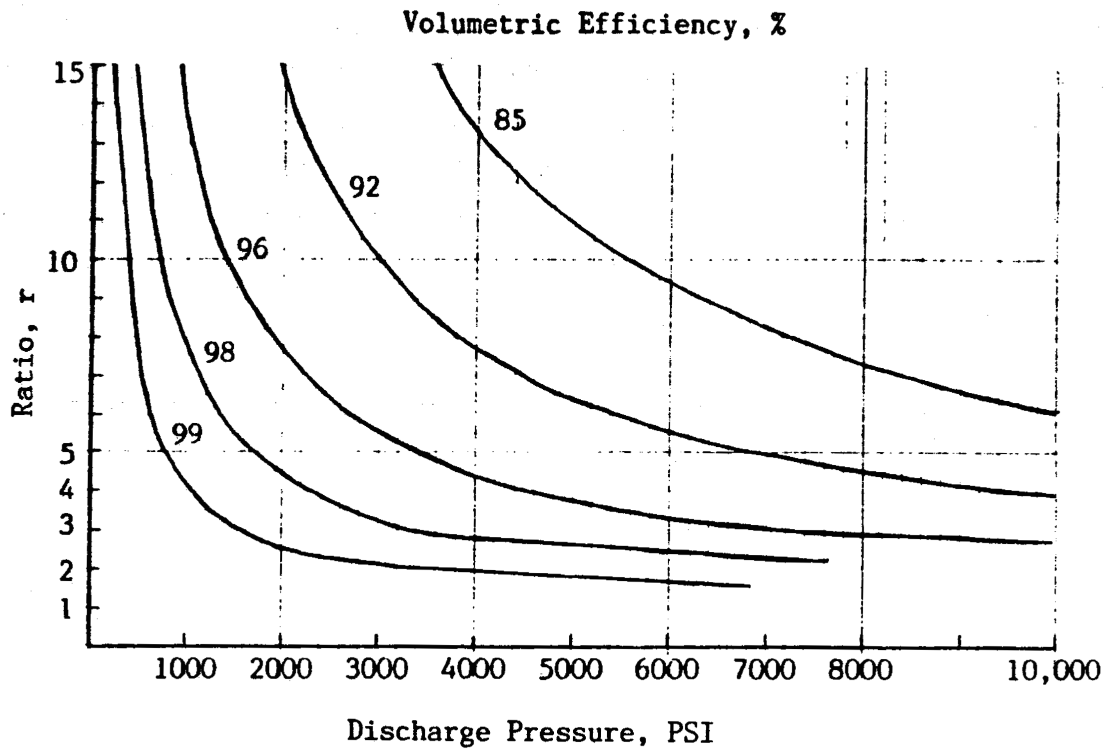


Figure 2.11
Volumetric Efficiency of Plunger Pumps (Ingersoll Rand Co.).

Volumetric efficiency is decreased when dissolved gases or entrained air are present in the fluid. Volumetric efficiencies of positive displacement pumps are very high. Slip losses for pumping low viscosity fluid (water) are negligible. Overall mechanical efficiency is therefore high (>90%). Also, the output capacity of a power pump can be varied almost continuously with little change in pump performance. This fact alone makes power pumps the preferred choice for fixed pressure, varying flow rate applications like LTFT. It is possible that as LTFT proceeds, system impedance will decrease thereby dictating a type of pumping system that will provide variable capacities at steadily decreasing pressures. Plunger pumps will also meet this performance requirement.

Power pump design speeds (ND) are between 300 and 800 rpm. To maintain good packing lifetimes, pump speeds are often limited by plunger stroke speeds of 140 to 150 ft/min. Valve types and available NPSH also limit pump speed.

2.9 Plunger Pump Packing and Valve Assemblies

Power pump packing assemblies (stuffing boxes) seal the high-pressure fluid end from the outside world and are situated along the plunger as shown in Figure 2.12. The plunger packings perform the same duty as those in a centrifugal pump except that in a plunger pump they are subjected to higher pressures on the fluid side and they must seal reciprocal motion rather than shaft rotation. Packing materials can be reinforced asbestos, teflon, neoprene, or others and are selected based on the fluid's chemical composition, the discharge pressure, and the fluid temperature. In many cases it is necessary to inject a clean lubrication fluid under high pressure into the packing area to reduce packing wear from abrasives or corrosives in the pumped fluid. Power pump packing assemblies must be replaced periodically as part of normal pump maintenance and it is therefore advantageous to utilize a pump design with easily accessible packing assemblies.

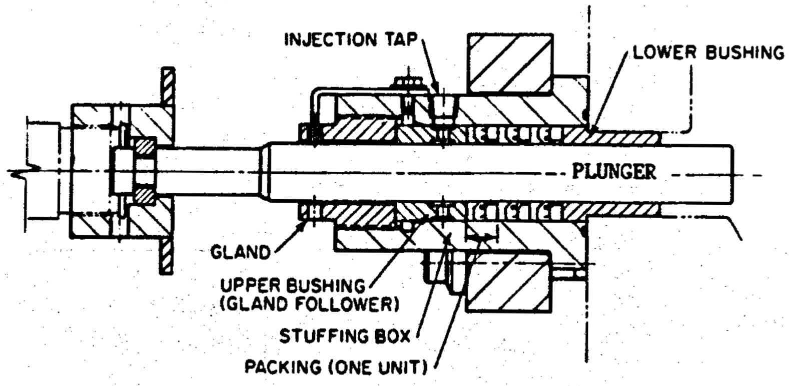


Figure 2.12

Typical Plunger Pump Packing Assembly (Ingersoll-Rand Co.).

Plunger pump check valve assemblies are of different types depending on the type of fluid handled and the operating pressure of the pump. The main parts of a check valve are illustrated in Figure 2.13. They are the valve seat, the valve plate, and the retainer assembly. Figure 2.14 shows

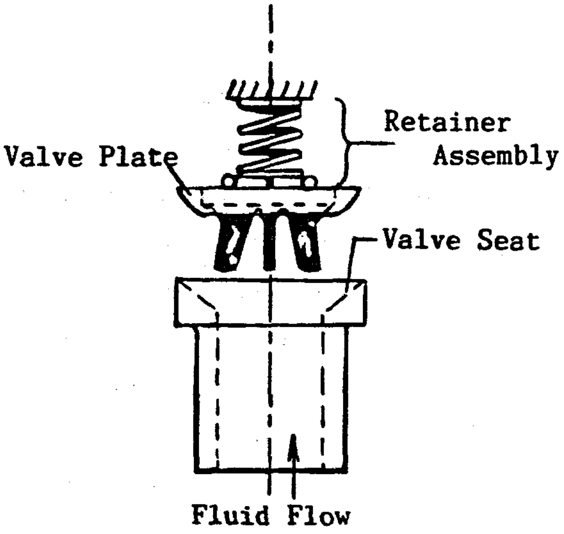


Figure 2.13

Plunger Pump Valve Assembly.

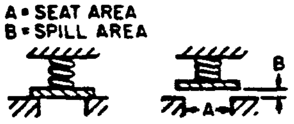
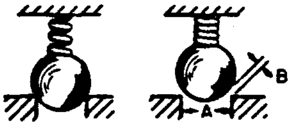
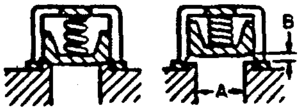
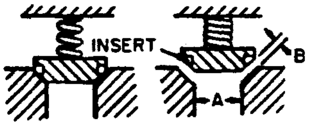
TYPE	SKETCH	PRESSURE	APPLICATION
PLATE		5,000	CLEAN FLUID. PLATE IS METAL OR PLASTIC
WING		10,000	CLEAN FLUIDS. CHEMICALS
BALL		30,000	FLUIDS WITH PARTICLES. CLEAR, CLEAN FLUID AT HIGH PRESSURE. BALL IS CHROME PLATED
PLUG		6,000	CHEMICALS
SLURRY		2,500	MUD, SLURRY. POT DIMENSIONS TO API-12. POLYURETHANE OR BUNA-N INSERT

Figure 2.14

Check Valves and Their Applications.

several types of valves and their applications. The valve seat is the surface on which the valve seals and is usually integrally cast in the fluid end casing then hardened or, more commonly, consists of a separate hardened ring or other shaped surface fitted into the pump casing. Valve seal surfaces and valve seats are prone to erosion and corrosion cracking because they serve as the pressure seals between the plunger chamber and the intake and discharge manifolds. Valve seats are of a greater hardness than are the sealing surfaces of the valve plate, having a 10 to 15% harder surface finish. Just as in centrifugal pumps, plunger packing and valve assemblies require the most maintenance during the pump's lifetime.

2.10 Pulsation Dampening Equipment

One drawback of plunger pumps is their cyclical discharge rate which produces wide variations in discharge pressure and capacity about the mean, especially in pumps with 2, 3, 4, or 6 plungers. Table 2.1 summarizes the effect of the number of plungers on power pump capacity variations.

TABLE 2.1

Plunger Pump Discharge Pulsation Characteristics

Pump Type	Number of Plungers	% Above Mean Capacity	% Below Mean Capacity	Total Variation
Duplex	2	24	22	46
Triplex	3	6	17	23
Quadruplex	4	11	22	33
Quintuplex	5	2	5	7
Sextuplex	6	5	9	14
Septuplex	7	1	3	4
Nonuplex	9	1	2	3

Reciprocating pump pulsations at certain frequencies or harmonics can excite fundamental vibration modes (resonances) in the associated piping, thereby creating excessive noise and possible equipment damage. For the HDR injection well at Fenton Hill it has been determined that pulsations greater than 2 percent and less than -7 percent of the injection pressure could be harmful. Pulsation dampening equipment should be installed on both the suction and discharge sides of a plunger pump. Suction side pulsation dampeners provide a constant NPSH to the pump inlet valves, thereby protecting the pump fluid end from cavitation damage and increasing valve seat lifetime. Discharge side dampeners protect the outlet valve assemblies as well as the high pressure fluid plumbing connected to the pump. Most dampeners are nitrogen-charged bladder bottles utilizing rubber as the bladder material. Some dampeners are also spring-assisted bladders with nitrogen charges. Good pulsation dampening equipment can suitably attenuate capacity and pressure variations even on duplex and quadruplex plunger pumps.

2.11 NPSH Required

Plunger pump speeds, and therefore capacities, are limited by the available NPSH. At high plunger speeds, fluid separation from the plunger can occur creating low pressure regions which induce cavitation. Minimum NPSH is related to the pump speed by:

$$\text{NPSH [PSI]} = \frac{14.72 - N^2 d\ (LR - R^2)}{6861.18} \left(\frac{A_p}{A_s} \right) \tag{2.17}$$

where N is the pump speed [rpm], d is the length of the pipe where flow resistance is measured [ft], L is the length of the pump's power end connecting rod [ft] - not including the plunger, R is the power end crank radius [ft], A_p is the plunger end surface area [in^2], and A_s is the cross-sectional area of the suction pipe [in^2]. Here it has been assumed that NPSH equals suction head minus piping friction loss. NPSH requirements for certain pump speeds are usually given by the manufacturer.

2.12 Continuous Duty and Intermittent Duty Ratings

Every plunger pump design has associated with it an intermittent duty rating and a continuous duty rating. Intermittent duty rating covers high capacity pumping at or near maximum rated pump pressure for short durations (several hours to a few days) after which pump and power end undergo major overhaul. Continuous duty ratings cover long duration (months or years) pumping requirements at fluid pressures well below the maximum rated pump pressure. Continuous duty ratings are directly related to plunger pump size and weight. For a given size and weight, a pump's continuous duty rating can be three to four times less than its intermittent duty rating.

3.0 TECHNICAL HISTORY OF THE PHASE I AND PHASE II CIRCULATION PUMPING SYSTEMS

3.1 Introduction

This chapter discusses the Phase I and the Phase II surface pumping systems, including main injection or circulation pumps and drivers as well as fluid makeup pumps and drivers. The main injection pumps circulate water at high pressure through the closed loop energy extraction system which includes the injection well, the geothermal reservoir, the production well, and the surface system. Produced hot water, under enough pressure to prevent flashing, is circulated through a heat-exchanger and is then routed back to the main circulation pumps. The makeup pumping system supplies water to compensate for small fluid losses in the surrounding reservoir rock.

3.2 The Phase I Surface Pumping System

The Phase I surface system was designed to provide up to 300 gpm of geothermal fluid (water) with a 1200 psi differential pressure and a 1450 psi maximum pressure. The water was specified at 176°F with up to 400 ppm total dissolved solids. The main circulation pumps installed initially were two Goulds centrifugal seven stage vertical turbine pumps each capable of furnishing 300 gpm of water at 600 psi total dynamic head. These two Goulds pumps were connected in series to provide up to 1200 psi total dynamic head. Inlet pressure to the Goulds' was maintained at 175 psi to produce a 1375 psi injection pressure. Each pump was driven by a Louis-Allis Co. 200 hp electric motor.

The makeup water pumping system initially consisted of a single 40 hp two-stage centrifugal pump, also manufactured by Goulds, capable of producing 130 gpm at 190 psi. As this pump's performance was inadequate, a single Myers two-stage centrifugal supercharge pump was installed which supplied 125 gpm at 134 psi when driven with a 15 hp electric motor.

After Run Segment 2 of Phase I (the 75 day Energy Extraction Experiment, Jan.-Apr. 1978) two additional Goulds seven stage centrifugal pumps were installed as back-up system circulation pumps for those already on-line. These additional Goulds pumps were built to the same specifications as the first two and were also driven by 200 hp Louis Allis motors. At the same time, four new Myers makeup pumps were installed, each driven by a 15 hp AJAX electric motor. With these pumps connected in parallel, the makeup system can supply 225 gpm at 160 psi. This makeup system was used for the Phase II ICFT conducted May-June 1986 and is currently in place at the Fenton Hill site.

3.3 Phase I Surface System Performance

Throughout the Phase I energy extraction experiments, the main Goulds circulation pumps were continuously plagued by mechanical seal deterioration problems due to suspended solids in the geothermal fluid. The mechanical seals eroded away and there was no way to determine whether a mechanical seal would last 90 minutes or 90 days. The circulation pumps also tended to heat up at low pumping flow rates thereby reducing pump packing life. Five separate energy extraction experiments were conducted between September 1977 and December 1980 (Phase I, Run Segments 1 through 5). During Run Segment 5 (the final 286 day flow test) there was a gradual decrease in the performance of the main circulation pumps due to corrosion or erosion of pump impellers, especially the first and second stage impeller surfaces. This damage was possibly attributable to cavitation arising from insufficient positive suction pressure (NPSH) on the pump, although manufacturer's specifications were followed to assure sufficient NPSH.

The initial Phase I makeup water pump (the 40 hp Goulds pump mentioned earlier) performed rather pitifully. The pump did not self-prime properly due to inadequate suction draw. It is thought that inadequate suction piping provided insufficient NPSH, resulting in poor performance. It was replaced with a single Myers pump (Section 3.2). This single Myers pump was subsequently replaced with four new Myers makeup pumps to achieve a flow rate of 270 GPM. There have been no significant problems with these four Myers pumps currently installed at Fenton Hill other than periodic maintenance/replacement of the pump seals.

3.4 Phase II Surface System Design

The surface system design for the Phase II energy extraction loop was initially designed to have a heat rejection capability of 50 MWt at a design flow rate of 1000 gpm and a reservoir injection pressure of 3000 psi (G.M. Cremer, et.al., p. 58). The design of the Phase II surface system was to include four Myers supercharger makeup pumps, six first stage pumps, and four second stage pumps as pictured in Figure 3.1. The four Myers supercharger pumps, each driven by a 15 hp motor, have already been described in section 3.2. The six each first stage pumps were designed to provide 1400 psi water to the second stage pumps in several different flow configurations. The four Goulds pumps and motors in place from the Phase I experiment, were to be used as first stage pumps to increase the fluid pressure from 175 psi to 1375 psi (1200 psi total dynamic head). In addition, for low flowrate applications, two additional 100 hp Goulds 29 stage vertical turbine pumps capable of producing 40 gpm at 1200 psi total dynamic head were included in the first stage. This was done to alleviate the packing problems that plagued the 300 gpm Goulds pumps when they were used for low flowrate applications during the Phase I experiments.

The second stage pumps were designed to raise the first stage discharge pressure (1400 psi) to the 3000 psi necessary for injection. Four each Peerless industrial 12 stage centrifugal turbine pumps, each driven by a Siemens-Allis 300 hp electric motor, were purchased during 1980. The Peerless pumps were manufactured in two sets of 2-each (HP-1 and HP-2) to be connected in series as shown in Figure 3.2. This was the conceptual

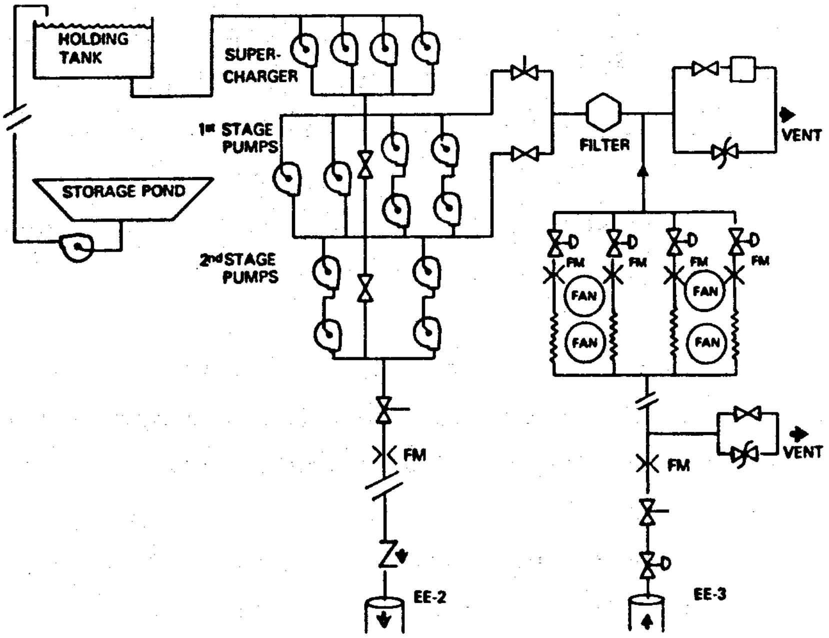


Figure 3.1

Phase II Surface System Design Schematic - 1980.

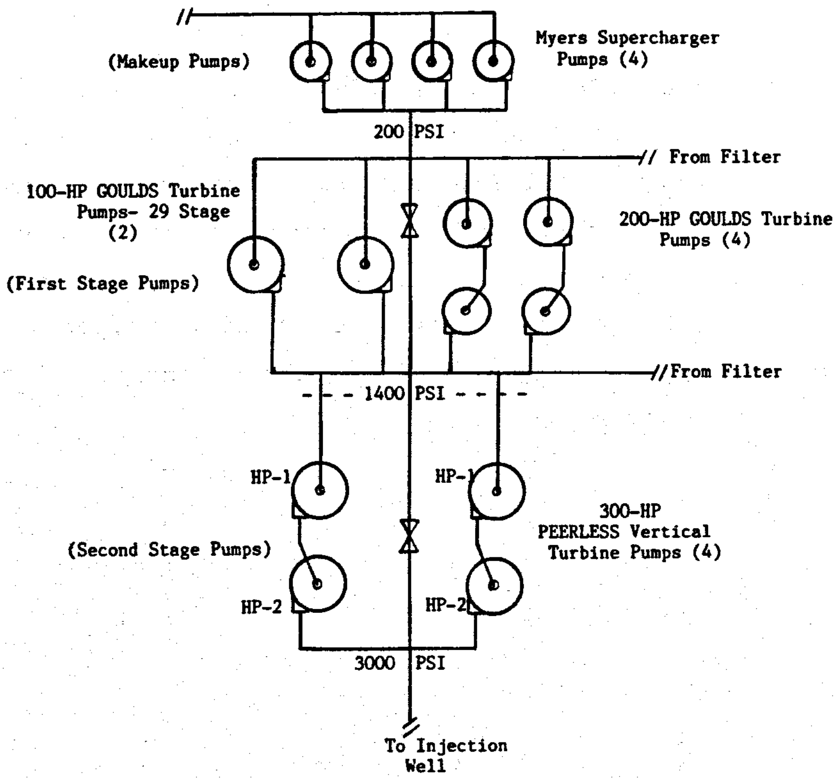


Figure 3.2

Phase II Circulation Pump System Design - 1980.

design for the Phase II circulation pumping system. In 1981, design efforts were directed at an "interim system" for Phase II able to handle 300 gpm at 3000 psi to extract 20 MWt. This design (see Figure 3.3) utilized two of the Goulds and two of the Peerless pumps already purchased. Installation of this "interim" circulation system was partially completed during 1982. This hardware was eventually to be utilized in the final Phase II surface system as shown in Figure 3.2.

Current opinion regarding the Phase II LTFT surface circulation system favors a reduction in the number of pumps from the system design shown in Figure 3.2. The most advantageous design would utilize a minimum number of circulation pumps each capable of meeting the pressure and flow rate specifications of 200-420 gpm variable flowrate at 5000 psi injection pressure. This specification represents realistic energy extraction goals for reservoir parameters determined from the recent ICFT. These flowrate requirements are substantially reduced from the original 1000 gpm requirement and injection pressures have been increased from those originally specified in the Phase II surface system design.

The available stock of HDR pumping hardware, if it were to be used to construct the surface circulation system for the Phase II LTFT, would not meet the current pressure and flowrate requirements. In addition, the available electric power at Fenton Hill is currently inadequate to meet the pumping requirements even with highly efficient (75%) centrifugal pumps. A new design for the Phase II circulation pumping system will favor a positive displacement pumping system rather than a centrifugal system.

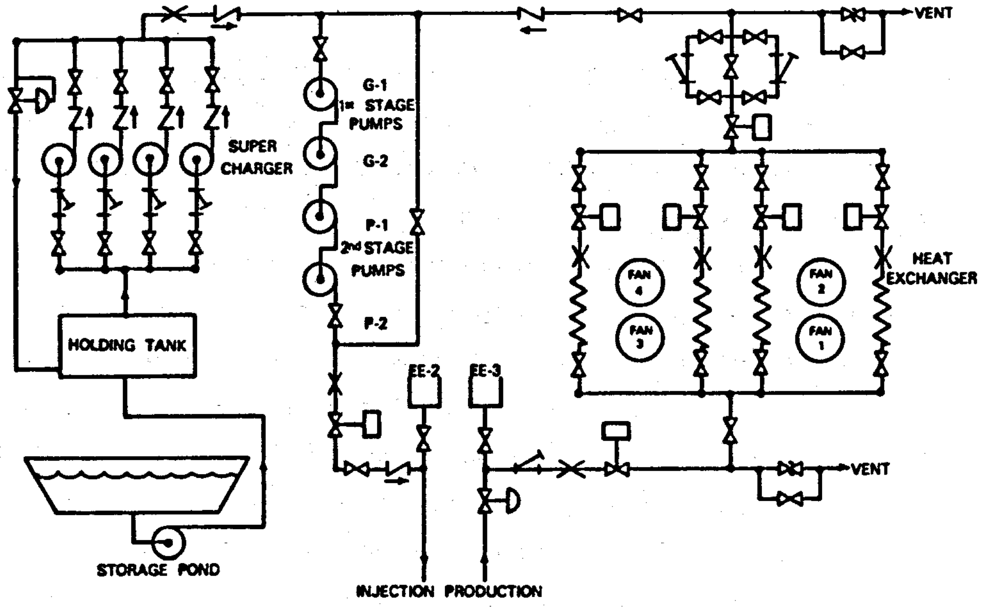


Figure 3.3

Phase II "Interim" Surface System Design - 1981.

4.0 RESULTS OF THE PHASE II INITIAL CLOSED-LOOP FLOW TEST (ICFT)

4.1 Introduction

This chapter presents results of the ICFT which are pertinent to specification of the main circulation pumping system for the Phase II LTFT energy extraction experiment scheduled for late FY'87. The ICFT (Exp. 2067), conducted between May 19 and June 18, 1986, was designed to determine the Phase II reservoir parameters necessary for specification of the final surface system and flow loop for the Long Term Flow Test (LTFT). The ICFT was also designed to prove the feasibility of the Phase II reservoir as an energy producer, and to evaluate various completion schemes for the injection well (EE-3A) and the damaged production well (EE-2). ICFT goals and objectives can be summarized as follows: 1) to evaluate reservoir characteristics such as reservoir volume, effective heat transfer area, flow impedance, and water loss; 2) to determine the characteristics and to predict the long term trends of fluid geochemistry such as, dissolved gasses, corrosion and scaling tendencies, suspended solids content, dissolved solids content, and other parameters; 3) to maximize the energy extraction rate and to predict surface production temperature, production flow rate, and thermal energy extraction rate; and 4) to evaluate the condition and completion of both the injection and production wells.

For design of the Phase II LTFT surface circulation pumping system, the most important ICFT determined parameters are: surface injection pressure and flow rate, and fluid geochemistry. These parameters are discussed in this chapter, as well as a brief description of the surface circulation pumping system used for the ICFT.

4.2 ICFT Pressure and Flowrate Data

ICFT Experimental data for surface injection pressure, production pressure, injection flowrate, production flowrate, system impedance, and energy extraction rate all as functions of time are given in Figures 4.1 - 4.4.

By plotting both injection pressure and production flow rate against time (Figure 4.5), one can see the correlation between injection pressure and production flow rate. Maximizing the output flow rate will result in maximum energy extraction, a primary goal of LTFT. Therefore, it is necessary to provide a surface pumping system capable of producing at least 5000 psi. The pumping system should be capable of injecting up to 420 gpm (approximately 10 barrels per minute) at maximum injection pressure. Figure 4.3 leads one to predict that the overall system impedance would probably decrease to around 12-15 psi/gpm or less at the high (420 gpm) injection flow rates planned for LTFT. At the 420 gpm flowrate, the energy extraction rate approaches 19 MWt assuming a 160°C temperature difference through the heat exchanger. Figure 4.4 shows the steadily increasing energy extraction rate during ICFT. This was due to production wellbore heating during ICFT, resulting in hotter production temperatures, and due to the increased injection (and therefore production) flow rates during the last half of the experiment (Figures 4.6 and 4.2, respectively). Figures 4.7 and 4.8 show injection well and production well pressure and flow behavior during ICFT.

4.3 ICFT Fluid Chemistry Data

Presented below are fluid geochemistry results from ICFT believed to have the greatest impact on the surface pumping system design for LTFT. Table 4.1 shows results for some of the gas samples analyzed by the gas chromatograph during ICFT. Figure 4.9 shows daily H_2S gas concentration in percent volume of total dry gas during ICFT. Concentration measurements made to detect H_2S concentration ranged in value from 150 ppm to 1125 ppm of the total flow (Table 4.2) but showed no discernible increase or decline as the experiment proceeded. From this data, one is led to believe that H_2S concentrations as high as 1200 ppm (0.12% by weight of total production flow) may be periodically encountered during the LTFT and surface system

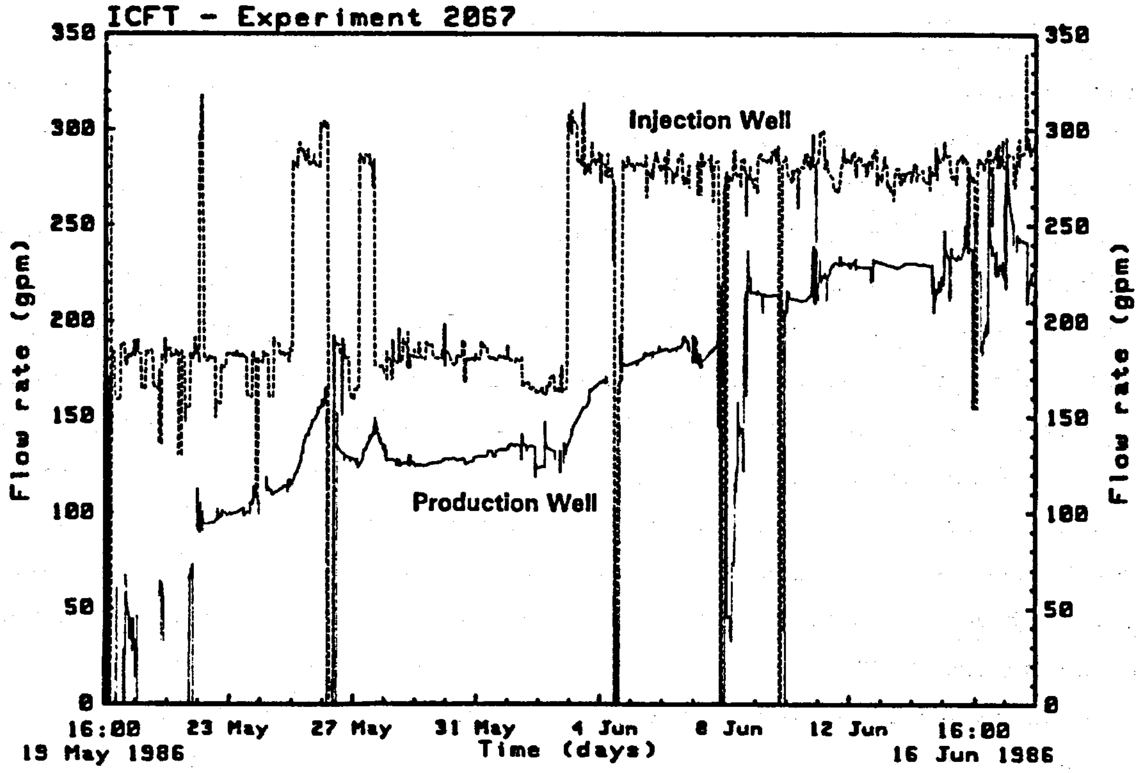


Figure 4.1

Injection & Production Pressure During ICFT.

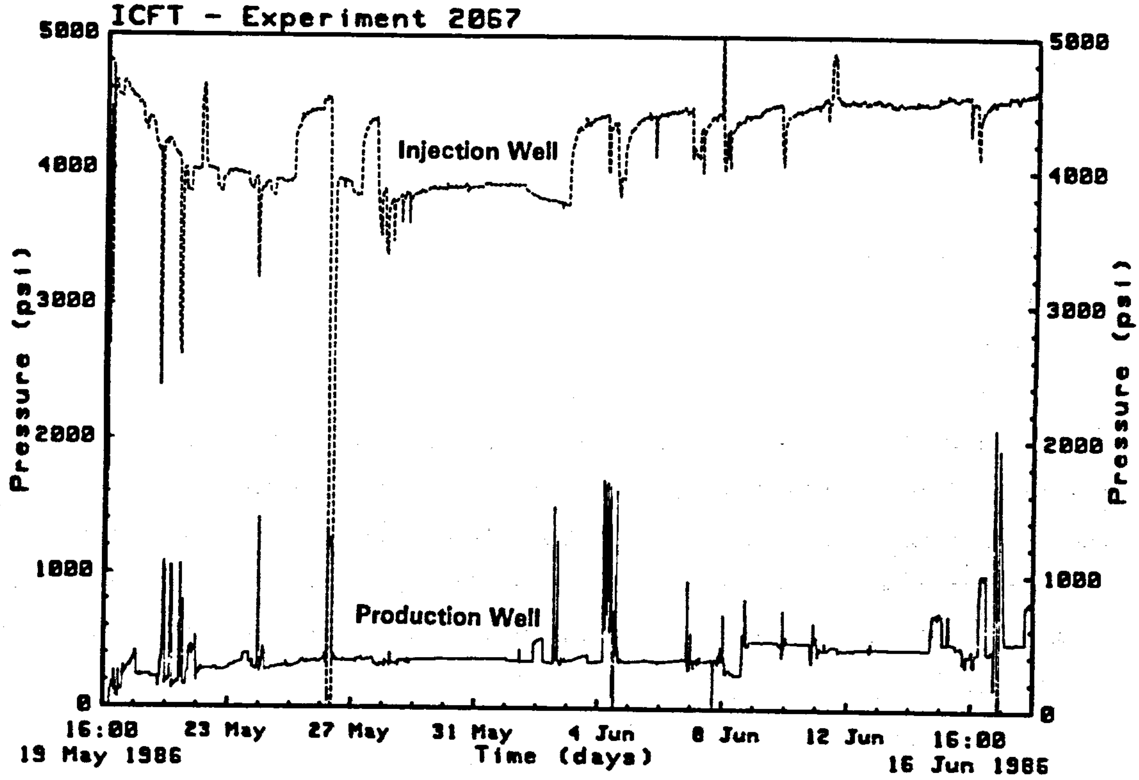


Figure 4.2

Injection & Production Flowrate During ICFT.

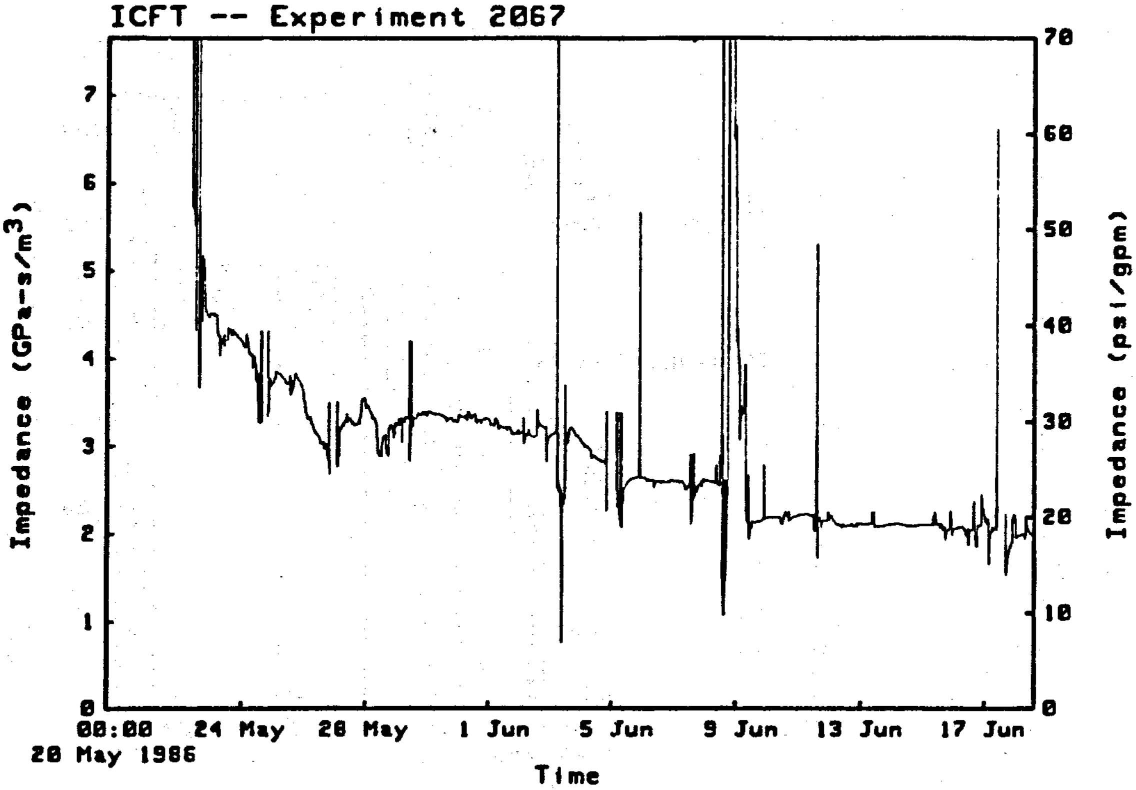


Figure 4.3

Corrected System Impedance During ICFT.

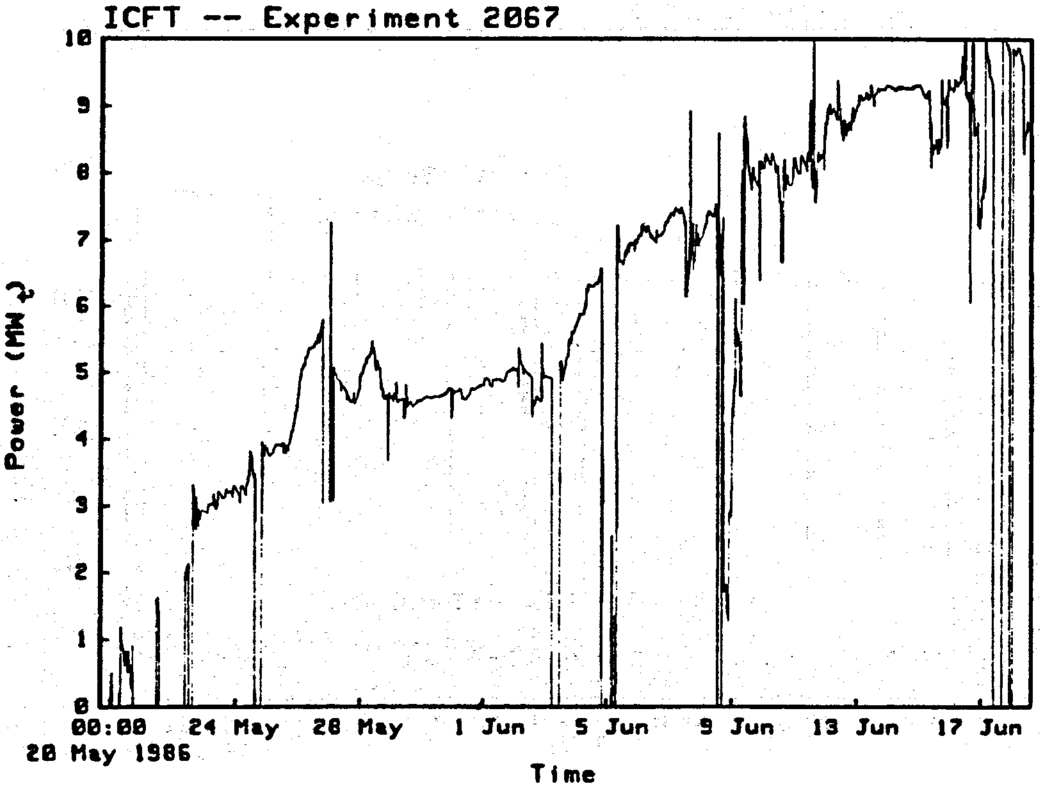


Figure 4.4

Energy Extraction Rate During ICFT.

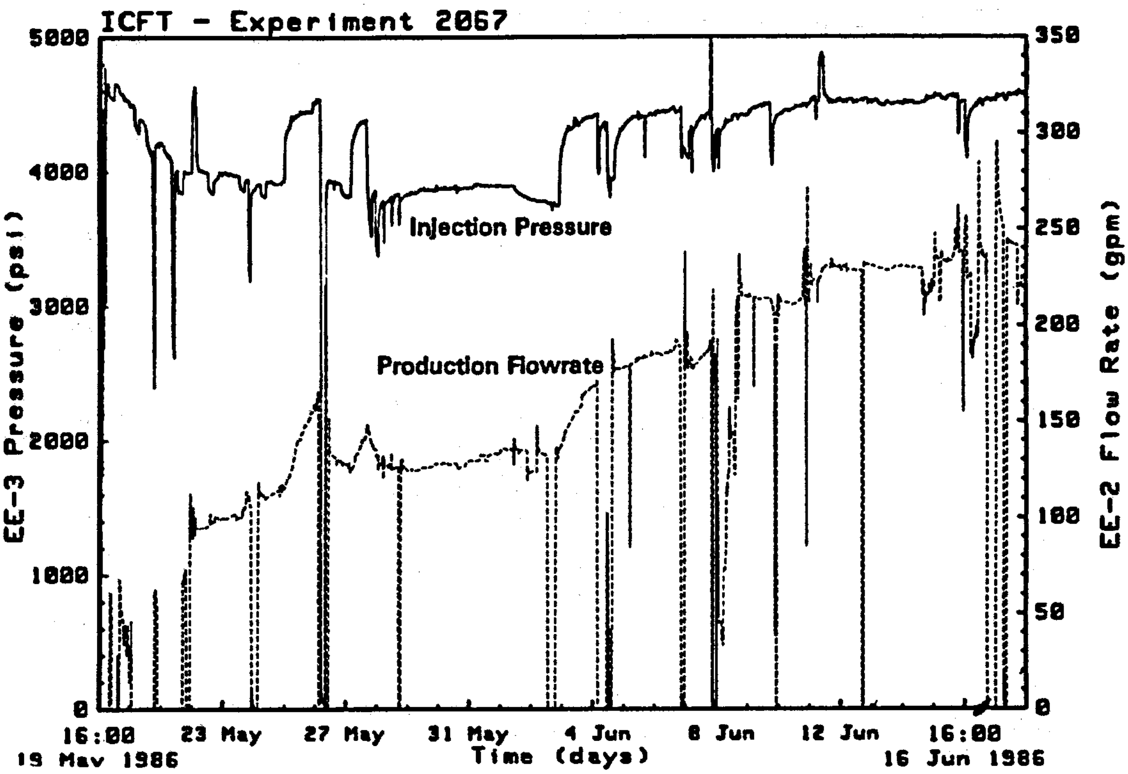


Figure 4.5

Injection Pressure & Production Flowrate During ICFT.

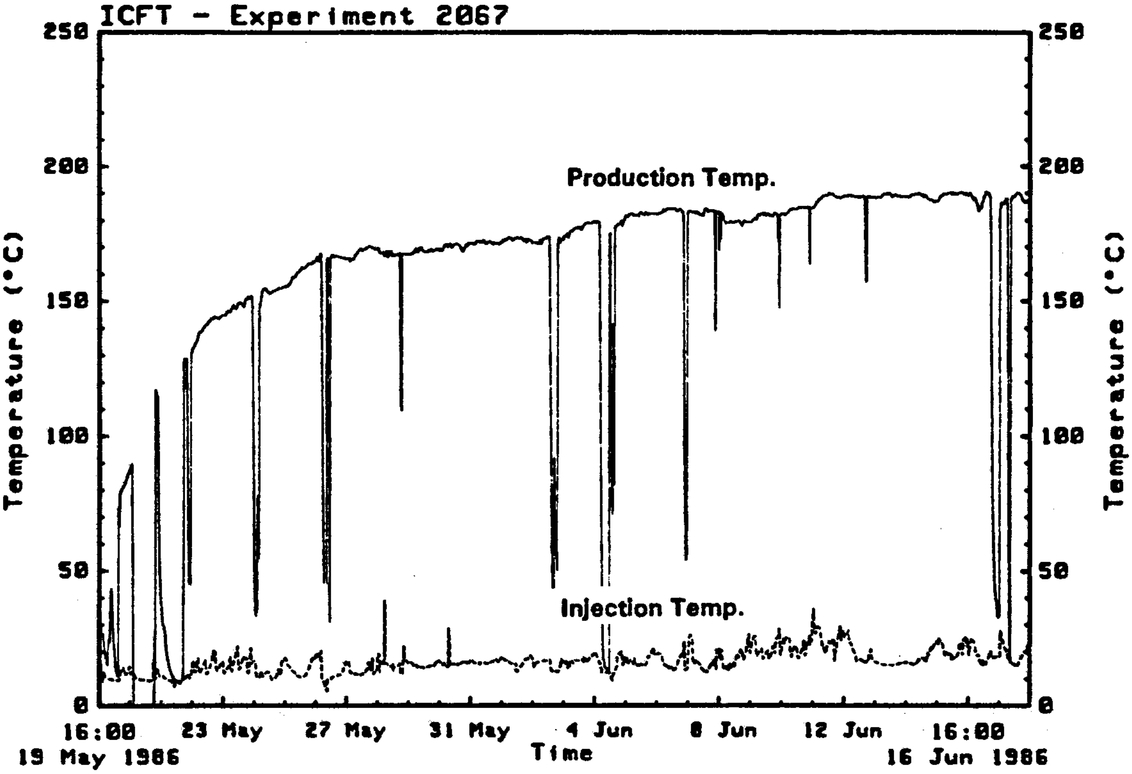


Figure 4.6

Injection & Production Temperature During ICFT.

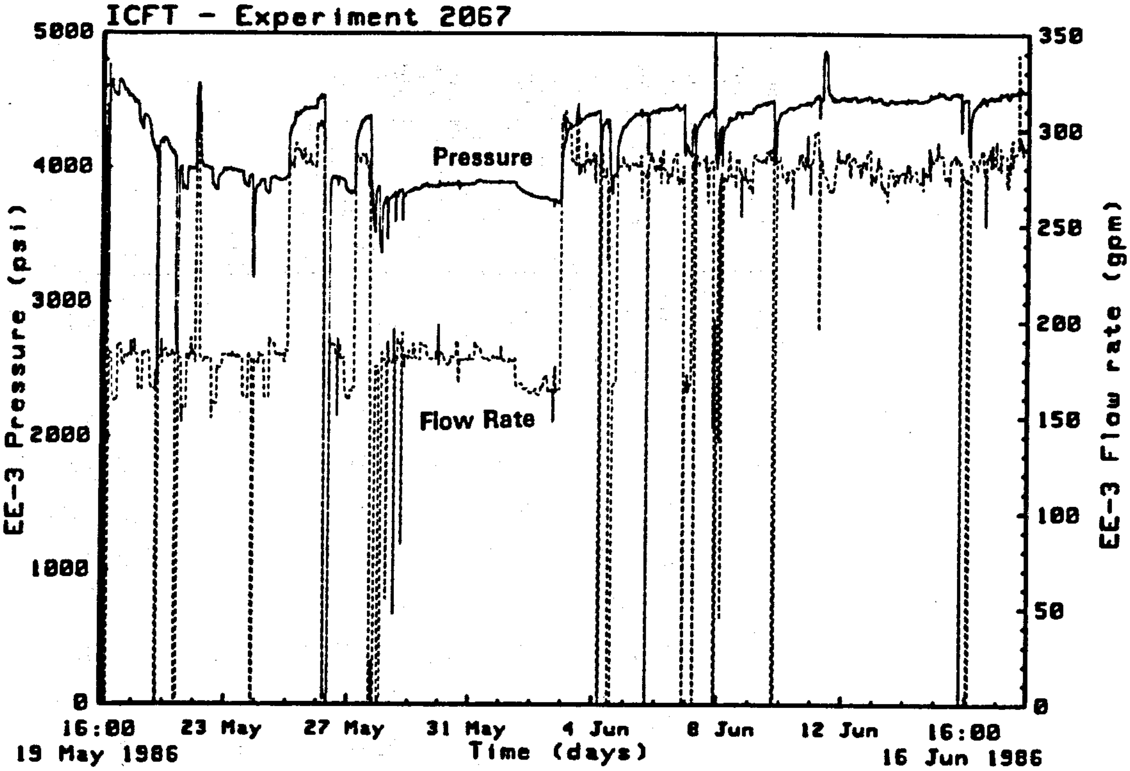


Figure 4.7

Injection Well Pressure & Flowrate.

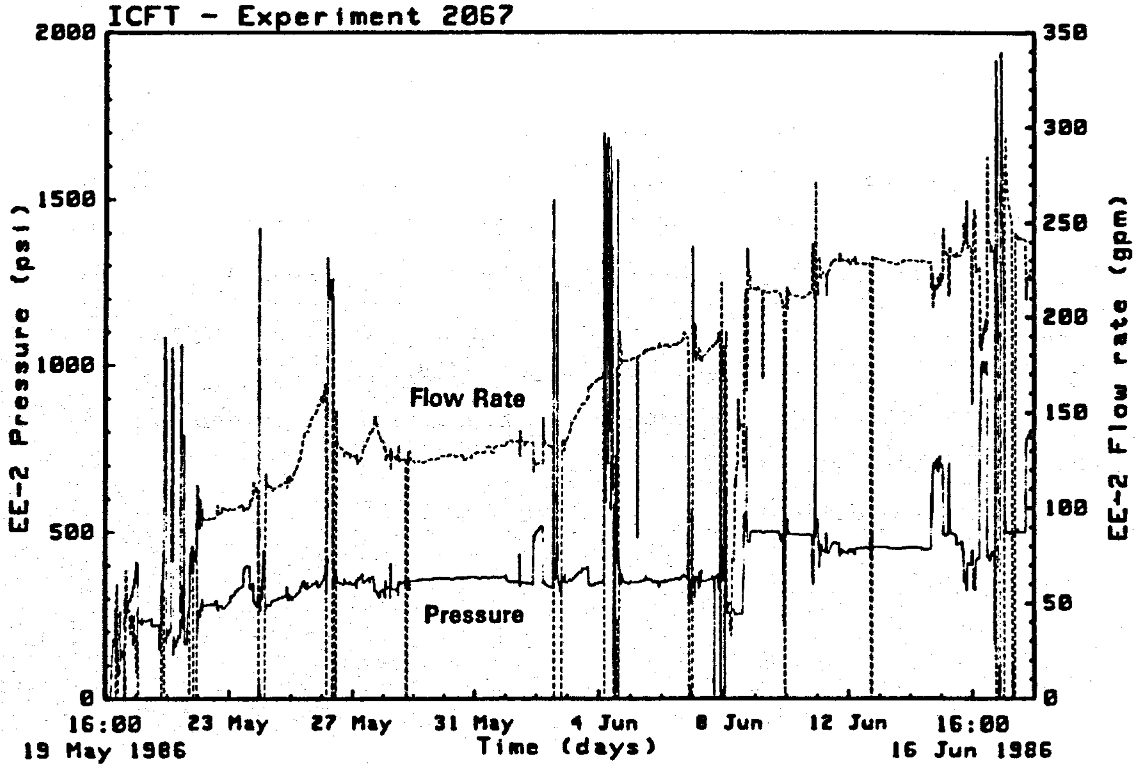


Figure 4.8

Production Well Pressure & Flowrate.

TABLE 4.1

Selected Gas Samples from ICFT

(all in % volume of dry gas)

Sample	Date	H_2	CO_2©	CH_4	H_2S	O_2	N_2
G003	5/20/86	ND	98.72	ND	0.05	0.24	0.98
G009	5/20/86	ND	99.67	ND	0.26	0.06	0.12
G019	5/21/86	ND	99.34	ND	0.17	0.05	0.45
G023	5/22/86	ND	99.07	ND	0.16	0.03	0.75
G029	5/28/86	ND	97.07	ND	0.11	0.25	2.58
G033	6/02/86	0.26	79.64	0.17	0.03	0.53	19.32
G035	6/03/86	ND	98.05	ND	ND	0.08	1.97
G036	6/04/86	ND	97.37	ND	0.07	0.14	2.42
G039	6/06/86	ND	96.41	ND	0.17	0.08	3.33
G045	6/07/86	ND	97.54	ND	0.16	0.08	2.21
*G060	6/08/86	ND	56.61	ND	0.03	0.12	43.18
G073	6/09/86	ND	20.83	0.05	ND	0.06	79.10
G085	6/10/86	ND	25.01	ND	ND	0.06	74.93
G104	6/11/86	ND	59.03	ND	0.11	0.06	40.80
G110	6/12/86	ND	72.89	ND	0.09	0.06	26.95
G118	6/13/86	ND	77.68	ND	0.10	0.07	22.16
G120	6/16/86	ND	84.36	0.04	0.20	0.12	15.28
G122	6/17/86	ND	83.02	0.04	0.19	0.15	16.60
G124	6/18/86	ND	86.82	0.04	0.05	0.13	12.96

• Denotes N_2 Injection Experiment Begun 6/08/86.

© The amount of CO_2 in the production fluid varied between .2% and .8% of total fluid weight.

ND Means "Not Detected."

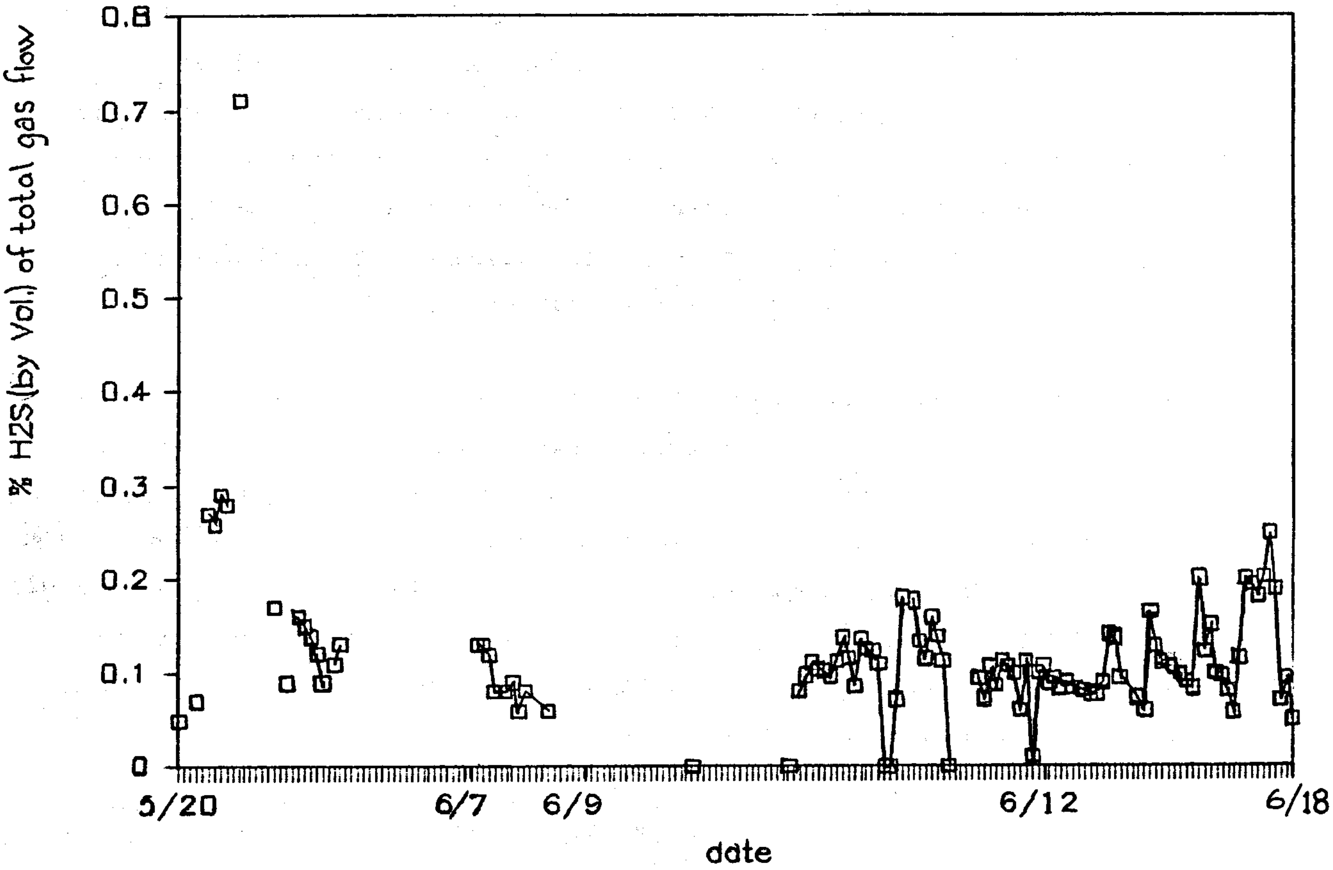


Figure 4.9

H_2S Gas Volume During ICFT.

TABLE 4.2

H_2S Concentration During ICFT

Sample	Date	H_2S [ppm of total flow]	
G028	5/28/86	824	
G030	6/02/86	1000	(Gas Pocket)
G036	6/04/86	510	
G038	6/05/86	625	
G045	6/06/86	625	
G074	6/09/86	188	
G078	6/09/86	150	
G085	6/10/86	170	
G109	6/12/86	150	
G120	6/16/86	725	
G122	6/17/86	1125	
G124	6/18/86	925	

equipment must be designed with this in mind unless a gas separator is installed. Besides the concern for H_2S in the geothermal fluid, CO_2, N_2, and O_2 are present in appreciable quantities and must also be considered in the design of surface system components. H_2, CH_4, and C_2H_6 are present only in very small amounts (less than 0.3% by volume for H_2, and less than 0.17% by volume for both CH_4 and CH_6) and present no significant design hurdles at the moderate fluid pumping temperature (150°F).

Because CO_2 is the most prevalent dissolved gas in the geothermal fluid (Table 4.1) care must be taken to prevent steam flashing and CO_2 separation in the surface system. This may be accomplished by maintaining the surface system pressure above the CO_2 separation pressure. Concentrations of dissolved CO_2 in the geothermal fluid could be as high as 0.5% by weight based upon ICFT fluid chemistry results. Figure 4.10 shows the minimum pressure required to prevent steam flashing and CO_2 separation at different temperature and dissolved CO_2 concentrations.

The geothermal fluid also contains: various dissolved species, such as arsenic, Ca, Na, Cl, K, SO_4, HCO_3, F and SiO_2, which may precipitate out of the fluid as the pressure and temperature are reduced; suspended solids composed of quartz sand, fine granite particles, metal particles; and other miscellany. (Concentrations of selected geothermal fluid species for samples taken during ICFT are given in Appendix B, p.112.)

For LTFT it is expected that some of these species will reach their saturation concentrations in the fluid, therefore presenting potential corrosion and scaling problems for surface circulation system hardware.

4.4 ICFT Circulation Pumping System

The injection pumping system for ICFT was provided as a contracted service by B.J. Titan Services (Bid #5-XS6-3635C). B.J. Titan has extensive experience in long term, high rate pumping of petroleum wells. Titan

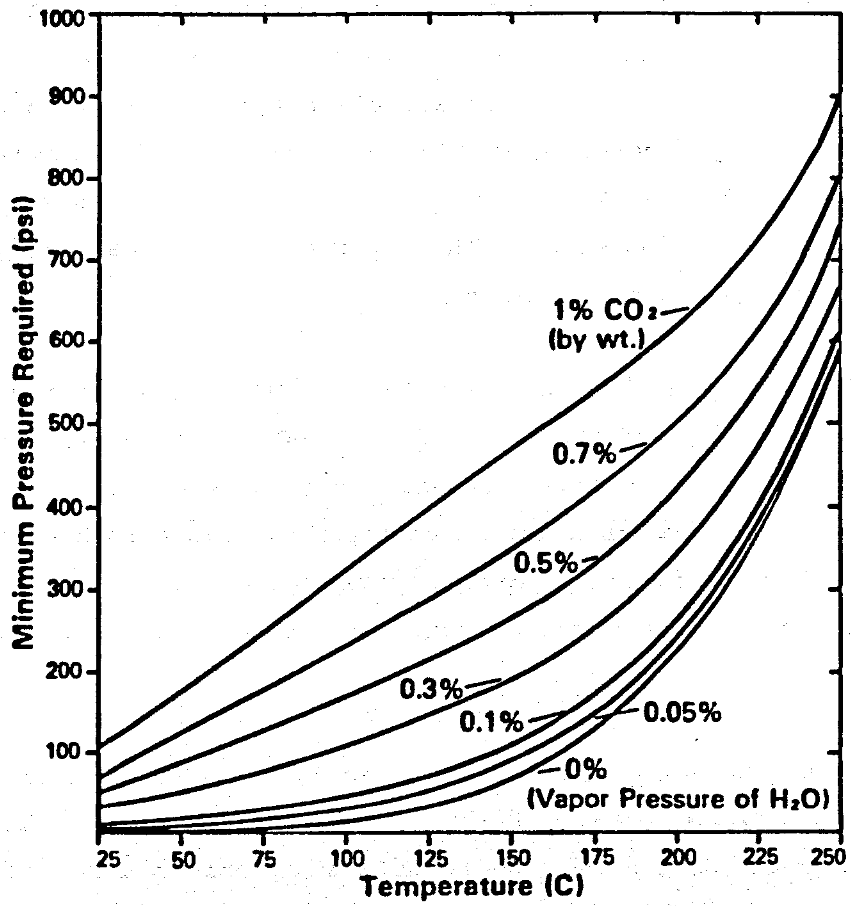


Figure 4.10

Minimum Pressure Required to Prevent Steam Flashing & CO_2 Separation for Different Temps. & Dissolved CO_2 Concentrations (Bruce Robinson).

supplied equipment, personnel, parts, and supplies for ICFT in accordance with specification HDRS-3635C. The specification called for a continuous pumping rate of up to 5 BPM below 5000 psi (usually below 4500 psi) and a continuous high pumping rate operation of 1 to 3 days duration at 5000 psi and up to 10 BPM. The pumps were to be remote controlled, variable speed (positive displacement) plunger pumps, continuous duty rated for 5 BPM at 5000 psi with 100% equipment backup and able to pump at rates as low as 1 BPM for up to one-half hour. Pump discharge pulsation was not to exceed pressure variations of +2% or -7% of discharge pressure with pulsation dampeners. Supply water to the contractor's pumps was provided by LANL's Myers centrifugal pumps operating at 160 to 175 psi. Fluid temperature was specified between 32°F and 125°F. The pumped fluid is water with traces of CO_2, H_2S, sulfates, carbonates and other species (Na, K, Ca, SiO_2, Cl, and F), and up to 200 ppm suspended solids.

The pumps utilized by B.J. Titan were OPI 1300WS. These are horizontal triplex single-acting power pumps rated at 1300 hp (1000 HHP) with an 8 inch stroke and 5.75 inch plunger diameters driven by diesel engines. The fluid end is machined from an alloy steel forging. Plungers are mild steel with hard overlay surfaces. Packings are either chevron adjustable, non-adjustable, or spring-loaded. Specifications for these pumps are given in Table 4.3.

Four separate pump/diesel units were initially brought on site although each unit could provide the necessary injection flow rate. These pumps performed very well during the 30-day ICFT with only moderate fluid end maintenance required on valves, pulsation dampeners, and fluid end hardware. All of the pumps were built in 1982 or before. Diesel fuel in the engine oil was a recurrent power end problem. Two (2) fluid end stay bolts failed on one pump due to fatigue. One pump developed a crack in the suction head, another pump developed a leak in the suction manifold, and two pumps experienced problems with pulsation dampening equipment, especially on the suction side. Overall, B.J. Titan was pleased with pump performance, experiencing no packing or high-pressure iron problems.

TABLE 4.3

Performance Data for 1300WS O.P.I. Triplex Pumps.

MAXIMUM PRESURE:	7,000 P.S.I.
MAXIMUM RATE:	20.9 B.P.M. @ 2150 P.S.I.
STROKE LENGTH:	8 "
PLUNGER DIAMETER:	6"
DISPLACEMENT PER REV.:	.069 Barrels per Revolution
RATED HYDRAULIC HORSEPOWER:	1000 HHP
MAXIMUN SPEED:	300 R.P.M. MAXIMUM

WHEN THE PUMP SHAFT IS TURNING AT:	THE PUMP CAN DISPLACE (- B.P.M. @ - P.S.I.)
50 R.P.M.	3.5 B.P.M. @ 7000 P.S.I.
100 R.P.M.	6.9 B.P.M. @ 6465 P.S.I.
200 R.P.M.	14.2 B.P.M. @ 3175 P.S.I.
250 R.P.M.	17.7 B.P.M. @ 2550 P.S.I.
300 R.P.M.	20.9 B.P.M. @ 2150 P.S.I.

Valve bodies performed well, although valve seats showed H_2S embrittlement corrosion due to dissolved H_2S (and also possibly due to dissolved CO_2) in the geothermal fluid. Also one valve seat barrel cracked due to sulfide stress corrosion. H_2S embrittlement also caused several failures of the valve snap rings, which secure the rubber valve seals on the valve bodies. It should be noted, however, that B.J. Titan had 400% pumping capacity on site and that each pump rarely operated more than four hours continuously and then at less than full rated load. These pumps were not really operated under continuous duty long term conditions during ICFT.

Figure 4.11 shows the locations of corrosion/cracking experienced during ICFT. The valves were spring loaded lift type with guided disk vanes, and are typically used when pumping relatively clean fluids at high pressures (up to 10,000 psi) for short durations. Typical applications would include acid treatments and sand fractioning jobs in the oilfield.

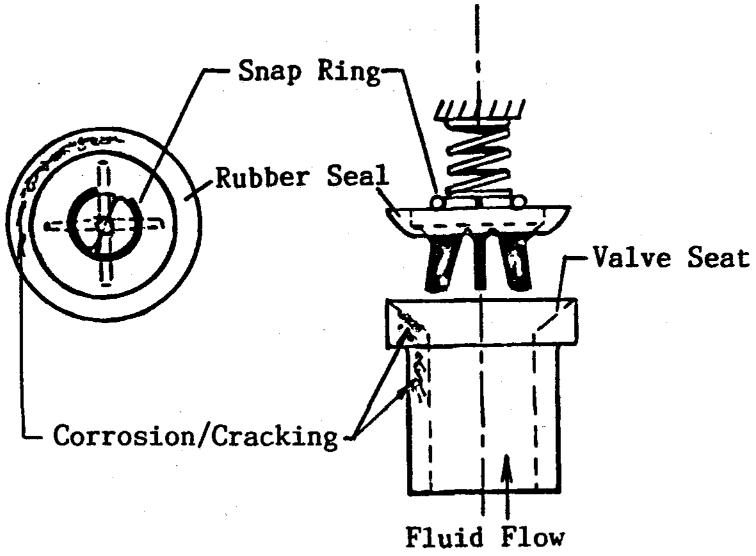


Figure 4.11

Location of H_2S Corrosion/Cracking on Plunger Pump Valve Assemblies During ICFT.

The contractor also experienced failure of three steel-reinforced high pressure hoses used on the suction side of the pumps. These hoses have a working pressure rating of 250 psi and are static test pressure rated at 400 psi. Two of the hose failures were attributed to hose wear at locations where the hose rested on the ground or on wooden blocks. Movement of the hoses during pumping first caused the outer rubber hose casing to wear away, exposing the inner steel reinforcement, which then began to wear away also. The hoses subsequently failed when enough reinforcement had worn away and the hose yielded to suction pressure, typically between 150 and 165 psi. The other (third) hose failure has been attributed to the temperature excursion experienced when suction side fluid temperatures reached 280-300°F for a short time. This was enough to cause one steel-reinforced hose to fail.

The failure of the discharge (high pressure) pulsation dampeners was thought to be caused by either CO_2 or H_2S induced blistering of the dampener bladder material. Blistering was observed on both the fluid side and the N_2 side of the bladders. B.J. Titan believes that dissolved CO_2 in the high pressure fluid migrated into the bladder material causing blistering of the bladder and eventual bladder failure. There were two discharge side pulsation dampeners that failed due to blistering. The discharge dampeners utilized high-pressure nitrogen (N_2) charged bladders. There were also two suction side dampeners that failed. These units were cylindrical N_2 charged bladders with spring assist. The failures were believed to be due to bladder fatigue failure although the units have not yet been dismantled to ascertain the exact cause.

B.J. Titan recommends that extra bladders be available for replacement in discharge dampening equipment used during LTFT, because of the adverse effect of gas migration/blistering on the bladders experienced during ICFT. B.J. Titan also recommends the use of large pulsation dampening equipment which can be readily maintained on-site for LTFT.

5.0 FENTON HILL ELECTRIC POWER LIMITATIONS

5.1 Available Electric Power at Fenton Hill

The Fenton Hill geothermal site is serviced by Jemez Mountain Electric Coop., Inc. which feeds primary electric power to the site through the Jemez Springs Substation, 25 miles away. The available electrical power at Fenton Hill is 1000 KVA, 3 phase WYE configuration at either 24.9 KV and 240V or 480V. The secondary system rating of 1000 KVA is not a continuous load rating, however, only a peak value. The existing electrical system can probably supply 900 KWe continuous power. If one were to use a large electric motor to drive the circulation pumping system, the maximum starting current that could be drawn (assuming a 90% power factor for the transformer at Fenton Hill) would be 1084 Amps. This current limitation necessitates voltage reducing starters for any electric motor over 250 hp since starting current is typically 3-5 times the operating load current.

Of the 1000 KVA supplied to the site, less than 160 KWe average continuous power is needed to meet normal operating requirements aside from fluid circulation. During ICFT, electric power consumption averaged 132 KWe for the 35 day billing window containing ICFT as compared with 60 KWe average hourly consumption for the previous month and 52 KWe for the same month during 1985. ICFT power consumption does not include circulation pumping power because injection pumping was provided by diesel engine driven plunger pumps. It does, however, indicate the magnitude of summer time on-site power consumption aside from fluid circulation. Winter electrical demand will be higher due to electric space heating in on-site buildings.

Assuming the 150-170 KWe are necessary for nonpumping requirements and that 900 KWe is the realistic total available continuous power (1 MWe peak for short duration), then approximately 730-750 KWe are available for fluid circulation (845-871 BHP at 100% electrical motor efficiency).

5.2 Power Requirements for LTFT Fluid Circulation

To provide suitable energy extraction rates during LTFT, it is necessary to inject at least 200 gpm of geothermal fluid at minimum surface injection pressures of 4500 psi. Table 5.1 shows the circulation pumping power requirements for LTFT.

TABLE 5.1

LTFT Circulation Pumping Power Requirements

Flowrate	Injection Pressure	Power Required
200 gpm (nom)	4500 psi	525 HHP / 392 KW
420 gpm (max)	5000 psi	1225 HHP / 914 KW

The nominal pumping power requirement is 0.39 MW and the maximum power required is 0.91 MW. Centrifugal type pumps for large capacity moderate pressure applications such as this are limited to 75% overall mechanical efficiency. Plunger or power pumps operating in the same capacity and pressure ranges have mechanical efficiencies of 90-95%. Therefore, plunger pumps require less supplied power to produce the necessary HHP for fluid circulation. Table 5.2 shows the BHP required at the pump shaft to produce 1 HHP for different pump efficiencies.

TABLE 5.2

BHP Necessary to Produce 1 HHP for Given Pump Mechanical Efficiencies (n_{me})

Pump Efficiency (n_{me}) [%]	BHP to Provide 1 HHP
60	1.67
65	1.54
70	1.43
75	1.33
80	1.25
85	1.18
90	1.11
95	1.05

For example, a centrifugal turbine pump with a 65% mechanical efficiency would require 2156 BHP (1.61 MW) input to produce 1400 HHP (1.05 MW) while a plunger pump with an 85% efficiency would require only 1652 BHP (1.23 MW) to produce the same HHP.

To carry the comparison and analysis one step further, one must also consider the efficiency of the pump driver, i.e. an electric motor, a diesel engine, or other prime mover such as a turbine. Large electric motors are characterized by efficiencies between 85 and 95% and 3 phase AC power factors of 85-90%. For analysis, assume an electric motor efficiency (n_{elec}) of 90% with a power factor (p.f.) of 95%. Electric motor efficiency, motor power factor, and mechanical efficiency are multiplied together to give overall electrical-to-HHP pumping system efficiency. Therefore a pumping system with n_{me}=75%, n_{elec}=90%, and p.f.=95%, yields an overall system efficiency (n_{sys}) of 64%. This pumping system would require 1.16 KW of electric power to deliver 1 HHP (.746 KW) to the fluid.

Figures 5.1 through 5.4 show the electric power required to produce the necessary LTFT flowrate and injection pressure for several overall pumping system efficiencies. Figure 5.4 shows that even with an overall system efficiency of 75%, 1.2 MWe are required to produce a 400 gpm flowrate at 5000 psi. Recall from section 5.1 that only 0.75 MWe are currently available at Fenton Hill.

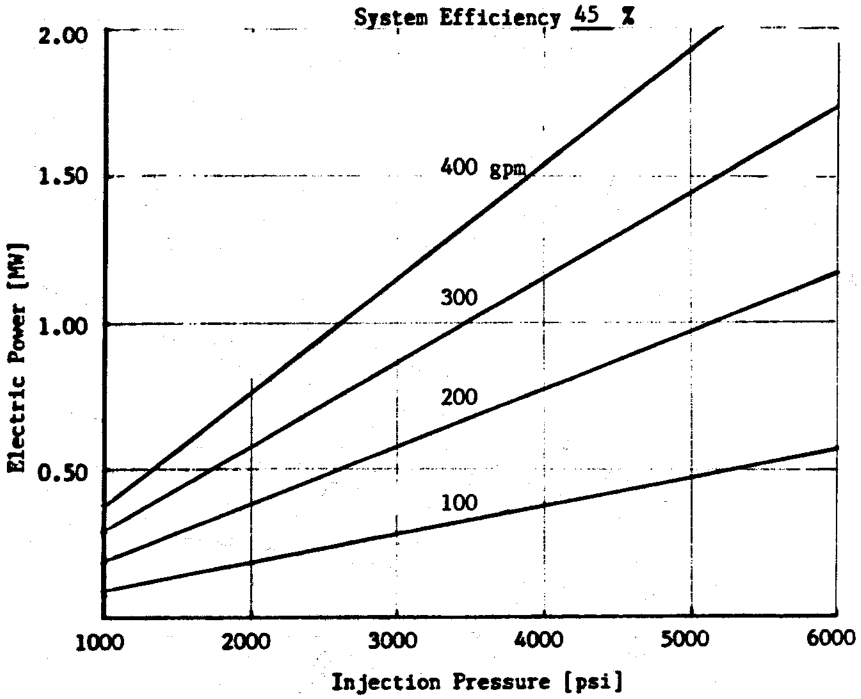


Figure 5.1

Electric Power Required for

LTFT Circulation at 45% System Efficiency.

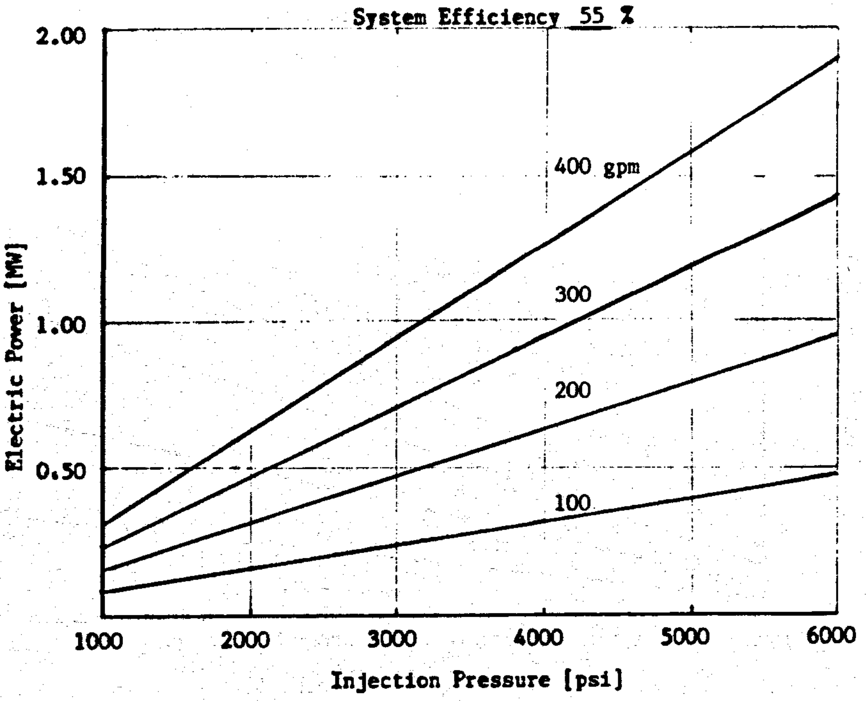


Figure 5.2

Electric Power Required for LTFT Circulation

at 55% System Efficiency.

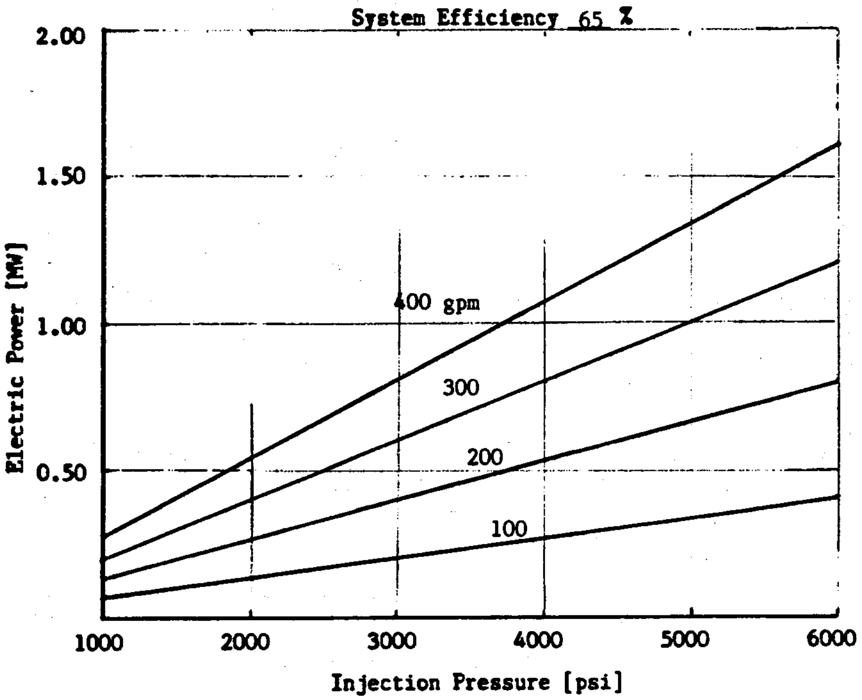


Figure 5.3

Electric Power Required for LTFT Circulation at 65% System Efficiency.

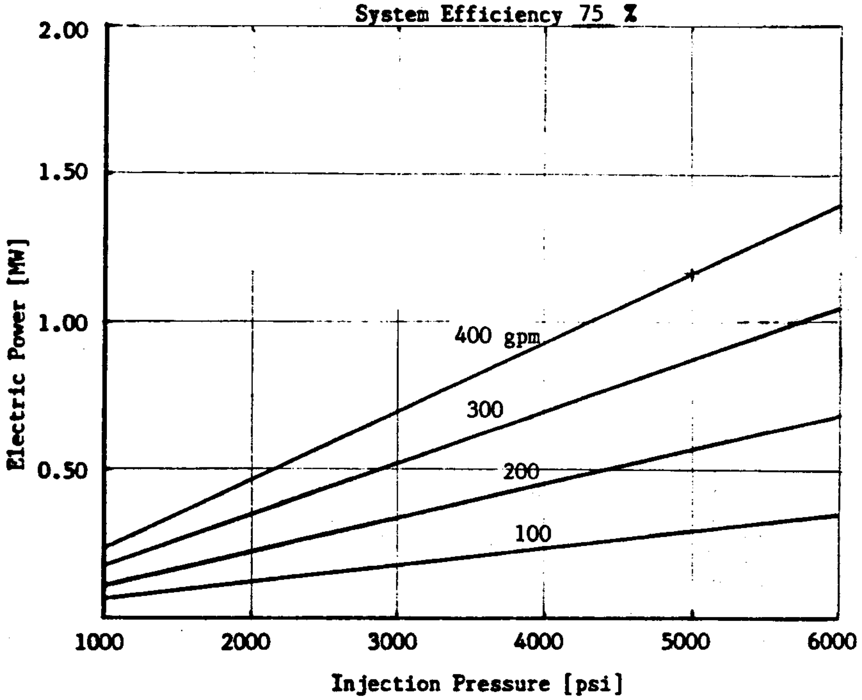


Figure 5.4

Electric Power Required for LTFT Circulation at 75% System Efficiency.

5.3 Variable Speed Electric Motor Controls

For LTFT, it is necessary to provide variable pump capacity which means having the capability to change the speed of the drive motor. DC electric drive motors may be controlled by using an AC to DC converter to convert 3 phase AC electric power into variable voltage DC power for precise DC motor speed control. However, since fixed frequency AC electric motors are cheaper, simpler, and more durable, it is generally advantageous to convert the fixed frequency AC power (supplied by the utility) into AC voltage of a different frequency using a frequency inverter.

Both converters and inverters utilize thyrister switching circuits composed of silicon controlled rectifiers or SCRs - to transform the 3 phase AC power into either DC voltage or variable frequency AC power. SCRs are merely 4 layer p-n-p-n controlled switching devices as shown in Figure 5.5.

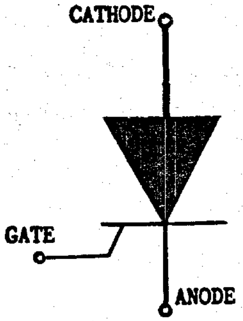


Figure 5.5
Graphical Representation of an SCR.

Forward current (anode to cathode) is controlled by low level gate voltage and reverse current (cathode to anode) is blocked in the same manner as that of a silicon diode up to some reverse breakdown voltage. Power conversion efficiencies of SCR inverters are extremely high due to the relatively low losses in solid state rectifiers, and because only one stage of power conversion is necessary in going from fixed frequency AC power to variable frequency AC power. Power conversion efficiencies for SCR inverters are typically 94 to 98%. Because they are solid-state switching devices, SCR inverters are highly reliable, have low maintenance, are fault tolerant, and are easily interfaced to computers for fault diagnosis and control.

5.4 Diesel Engine and Diesel-Electric Pump Drives

Instead of using utility supplied AC power, diesel engines can be used to drive plunger pumps. Mechanical transmissions allow shaft output power from the diesel engine to drive the pump most efficiently. Mechanical transmission efficiencies are high, ranging from 87 to 95 percent. Diesel engine/transmission drivers have good performance histories in long term power delivery applications and are readily maintained.

Diesel engine driven electric generators (sometimes called diesel-electric units) produce on-site electrical power. These units are standard items in the oilfield for supplying pump rig and site power. These units are also readily available, durable, modular, and easily maintainable.

A diesel engine or a diesel-electric unit should be considered to supplement the currently available electric power at Fenton Hill. This would enable LTFT to utilize existing AC electricity during nominal pumping applications. For pumping operations requiring more power, the diesel engine or diesel electric unit would supplement utility AC power.

6.0 SPECIFICATIONS FOR THE PHASE II CIRCULATION PUMPING SYSTEM

6.1 Scope

An extended energy extraction experiment (the LTFT) is planned to evaluate the commercial thermal production potential of the Phase II HDR geothermal reservoir over a twelve month period. The function of the surface pumping system is to circulate geothermal fluid through the hot dry rock reservoir region located approximately 12,000 feet beneath the earth's surface. The HDR site is located at Fenton Hill in north central New Mexico at an elevation of 8700 feet. The pumping system, as specified in the following sections, shall consist of pumps, their prime movers, variable speed controllers, and all the necessary documentation, instrumentation, and spare parts for twelve months continuous service.

6.2 Pumping Requirements

The pumps shall be of reciprocating multiplex design continuous duty rated to provide a total of 10 BPM (420 gpm) at 5000 psi (1225 HHP continuous). Total capacity shall be continuously variable from 1 to 10 BPM. The pumps shall be designed for continuous duty operation over a period of one year with only brief shutdown periods to replace expendable fluid end and wear parts. This fluid end maintenance should not require more time than the use of two men during an eight hour shift during any six month period. The pumps will accept 32°F to 150°F water from the heat exchanger through a 6 inch diameter suction line pressurized by one (1) to four (4) Myers centrifugal makeup water feed pumps operating between 160 and 175 psi. The pumps must be supplied with suction stabilizers, such as Fluid Kinetics or a University approved equivalent, designed to eliminate all acceleration head losses at the pump's maximum operating speed and able to provide 1000 psi suction side pressure. Cyclic fatigue loading of the injection system by the pumps requires that discharge pressure pulsation not exceed +2% or -7% of the discharge pressure. The bidder will include documentation of suitable pump performance in his bid. If discharge pulsation dampeners are required they will be Fluid Kinetics or University approved equivalent with bladders capable of extended life in high pressure fluid environments containing dissolved CO_2 and H_2S (See fluid chemistry, section 6.7).

6.3 Pump Construction

The pumps shall be constructed in accordance with API Standard 674, May 1980, except for modifications as agreed to between the University and the pump supplier. The supplier shall furnish a history of the pump's performance in continuous duty high pressure installations.

Pump materials should be capable of suitable tensile and yield strength while handling chlorides, H_2S, and other dissolved gasses which may lead to extreme stress corrosion and cracking of valve seats and working barrels. The high pressure working barrel components, discharge manifolds, and valves must be fabricated from materials such as forged Armco "Nitronic 50," 4140 steel, or University approved equivalent. Working barrels preferably will be individual for each plunger. No weld repair will be allowed on high pressure forgings.

Valves and seats will preferably be clamped between the manifolds and working barrels and should be removable as a complete unit. Valve materials should be at least equal to the working barrels and/or discharge manifolds.

Plungers shall be finished with a hard surfacing material with at least 57c on a brinell hardness scale finished to at least a 16 RMS. Plunger stuffing boxes should include a self-adjusting (spring loaded or other) main packing to eliminate daily manual adjustment. A leak-off header will be provided to carry away leakage from the main packing and shall be furnished with an orifice and pressure switch to indicate failure of the main packing. Plunger lubricators shall be furnished with the pumps, each having a separate reservoir and equipped with a device such as "Lube Sentry" with alarms to indicate low oil level and no flow conditions.

Pump power end lube systems shall be full pressure systems with rifle drilled crankshaft and connecting rods. The main lube oil pump will be directly driven from the main pump crankshaft. The lube oil system will include: a 25 micron cartridge type filter, a low oil pressure alarm switch, a high oil temp. alarm switch, pressure gauges on both sides of filter, a dial thermometer, and an oil-to-air heat exchanger with a motor driven fan. Oil cooling capability shall match the continuous BHP load rating of the frame.

6.4 Electrical Power and Drivers

At present, the available installed electrical power at the Fenton Hill site is 1000 KVA. Approximately 150 KWe continuous will be needed for site housekeeping and data acquisition which leaves 750 kWe available for circulation pumping equipment. Maximum line current is 1084 Amps.

Maximum circulation pumping requirement (420 gpm at 5000 psi) is 1225 HHP or 914 kW. Available electric power limitations necessitate the use of diesel engine or diesel-electric prime movers for the pumps. The driver must be capable of continuously variable controlled speed, either by electrical or mechanical means. The total speed range must be equal to or greater than 10 to 1. If diesel-electric, the unit must have a continuous duty operation power factor greater than 0.8 and no more than a 40°C temperature rise at 8700 ft. altitude.

6.5 Skid and Housing

The skids will be of 3 runner construction with an oilfield tail roll type loading feature designed utilizing I-beam structural members whose size and cross section will be selected to limit skid deflection to 0.25 inches at any point when the skid is supported on both ends. Beam deflection calculations will be included with the bid to verify compliance. Cross members will be located throughout the skid to provide support for necessary equipment. The skid shall include an adequate sized floor plate about the top of the skid as a walking deck. All welds shall be ground smooth and all sharp corners shall be removed by rounding with a grinder. The skid will be sandblasted and coated with a zinc primer coat.

The housing shall incorporate sound attenuating material and will completely enclose the equipment, providing a weatherproof area extending the full skid length. The noise level shall not exceed 90dBA at any point 10 feet from skid and housing. Each pump shall meet the criteria of OSHA 1910.95. The enclosure shall enclosure shall include adequate access doors and also internal and external lighting.

6.6 Instrumentation and Controls

All instrumentation and controls shall be monitored and operated locally on the equipment within the skid and housing and also remotely in a data/control center. Provision shall be made for remote monitoring and operation of instrumentation and controls via electrical contacts on an equipment junction box (or boxes) for the necessary user supplied data center interconnections. Everything monitored and/or controlled locally can also be monitored and controlled remotely via the data center interconnections.

The following functions are to be monitored:

Plunger pump suction pressure and fluid temperature
Plunger pump discharge pressure
Plunger pump discharge flowrate
Power end lubricating oil pressure and temperature
Fluid end lubricating oil pressure.

The user will provide transducers to measure pres. and temp. Local indication of these parameters shall be furnished by the vendor. Flow will be measured with a turbine type flow meter and indicated locally with a tachometer, as well as providing a 10-20 milliamp signal to the data center. All gauges used for local monitoring are to be of superior quality to enhance monitoring confidence. All measurements needed for proper operation of a particular unit (voltages, rpm, hydraulic pres., fan speed, bearing temp., accumulated running time clock, etc.) are to be fully described and provided as part of the bid.

6.7 Circulating Fluid

Circulating fluid will be water with traces of CO_2, H_2S, O_2, sulfates, and carbonates. Water pH will be between 5 and 9. The water will be filtered to remove suspended particles larger than 0.005 inches. CO_2 gas is expected to be about 0.1% by weight of the production well water and will be reduced by the addition of fresh makeup water which is projected to be between 10 and 100% of the water supplied.

It is expected that most fluid constituents will reach their equilibrium values during the energy extraction experiment. An oxygen stripper and/or a gas separator will be used to reduce the levels of O_2 and H_2S in the water.

Water contaminants are not expected to exceed the concentrations given in Table 6.1 below.

TABLE 6.1

Circulating Fluid Contaminant Concentrations

SiO_2	-	500 ppm	Cl	-	5000
Na	-	1600 ppm	F	-	10 ppm
K	-	200 ppm	H_2S	-	<5 ppm
Ca	-	120 ppm	O_2	-	<1 ppm
HCO_3	-	1000 ppm	Suspended Solids	-	800 ppm
SO_4	-	250 ppm	silica	-	500 ppm

These are considered to be maximum possible concentrations for the geothermal fluid. Pump materials should be selected for maximum continuous duty life under these conditions.

6.8 Testing

Each major component such as the pump, reduction gear, motors, controls, etc., shall be tested at each manufacturer's facility and will be witnessed.

The pump shall be subjected to a 3-hour mechanical run test at the manufacturer's facility at which time it will operate for at least one hour at full pressure and one hour at full flow. The fluid end shall be hydrotested to at least 1-1/2 times the maximum discharge pressure. These tests will be witnessed and certified reports will be furnished.

The completed packaged unit will be tested at full operating speed to prove alignment and compatibility of the components. All alarms and switches must be tested to prove their functions during this test. This test will be witnessed.

6.9 Startup Assistance

The manufacturer of this equipment shall provide on-site startup and check-out assistance at Fenton Hill. This assistance shall be designed to educate Los Alamos personnel on the operation, capabilities, maintenance, and safety requirements of the units. Startup assistance shall also include the actual operation of the equipment in its specified application. Vendor is to quote on five (5) days for this startup assistance.

6.10 Manuals

The manufacturer of the equipment shall provide complete operation manuals to include electric motor manuals, pump manuals, assembly drawings, all hydraulic-lubricating oil-electrical schematics, and vendor data on all associated components installed on the equipment. Three (3) manuals shall be provided per unit.

6.11 Maintenance Schedule

The vendor of the equipment shall provide a complete maintenance schedule for the purpose of allowing Los Alamos personnel to initiate a standard scheduled maintenance program. It is also required that the vendor be able to perform all of these maintenance functions on a maintenance contract program if instituted, in which case thrity-six hour response time by the vendor is a requirement.

6.12 Safety

Safety is of prime importance at Los Alamos and cannot be overemphasized. The bid package must contain a section wherein safety is exclusively treated. The bidder shall familiarize all operational personnel with all safety problems unique to the equipment during start-up. These safety practices shall also be documented in the equipment manuals. Generally the bidder's system shall meet all industry (API, ASME, ANSI) standards applicable.

6.13 Performance Warranty

Manufacturer shall warrant the equipment for 100% of cost on parts and labor for one year after such date that equipment is accepted. Should the equipment require any warranty work, the service must be performed at he Fenton Hill site if possible. The bidder shall evaluate the cost of providing this performance warranty and will list this cost as a separate charge which may or may not be included in the total bid package.

6.14 Bid Document Requirements

The bid package shall include the following documentation in addition to the individual items required in the specifications:

Complete Preliminary Assembly Drawings (3 each)
Skid Deflections and Vector Analysis (3 each)
Pump Performance Curves (3 each)
Piping and Instrumentation Schematic (3 each)
Prime Mover Specifications (3 each)
Terms of Payment (3 each)
Total Cost of Equipment (3 each)
Delivery Schedule (3 each)
Any Exceptions or Exclusions to the Specifications (3 each).

The bid will be awarded based on a competitive cost review and a technical evaluation. After review and evaluation a recommendation will be prepared for award. The ESS-4 Geological Engineering group will be available to discuss recommendations prior to the award of the contract.

7.0 SUMMARY AND RECOMMENDATIONS

7.1 Equipment Selection

At present it is felt that positive displacement multiplex plunger pumps with both suction and discharge pulsation dampeners are the best choice for the LTFT surface circulation system. Their superiority over multistage centrifugal turbine pumps is clearly evident. Plunger pumps have much better mechanical efficiencies and when fitted with suction side pulsation dampeners are not subject to cavitation problems until driven above rated speed. Plunger pumps have no rotating mechanical seals or wearing rings. The Phase I centrifugal pumps experienced mechanical seal degradation due to suspendid solids in the geothermal fluid. Plunger pumps are capable of variable capacity with less pressure variation than centrifugal pumps. A centrifugal pump's developed head is inversely related to its capacity. With proper material selection, plunger pumps can perform continuous duty high pressure pumping tasks with only minor fluid end maintenance. Fluid end maintenance on plunger pumps is less time consuming than for multistage centrifugal pumps because the fluid end components are readily accessable. Plunger pumps may be specified and purchased outright for LTFT or they will be supplied and maintained by any qualified bidder if it is decided to contract out LTFT pumping services.

In light of presently available electic power limitations at the Fenton Hill site, it will be necessary to drive the pumps with either diesel engines or with electric motors supplied by diesel-electric power units and controlled by SCR converters (for DC drive motors) or inverters (for AC drive motors). Injection pumping power requirements are substantially greater than the available installed power supply at the site, although preliminary discussions have begun with the local utility to supply the necessary LTFT electrical demand of approximately 2MWe. Although it is technically feasible to provide pumping power from the extracted thermal power of the geothermal reservoir, the costs are enormous and the reservoir is too small (10-20 MWt) to attract commercial involvement and support for such a scheme.

7.2 Materials Concerns

Fluid chemistry is one of the most unique boundary conditions for the specification of the pumping system, as it is for any geothermal installation. At Fenton Hill, dissolved H_2S, the CO_2/Carbonate equilibrium, and dissolved O_2 in the fluid are concerns that must be addressed to insure maximum surface equipment lifetimes. Gas separators and materials having high resistances to hydrogen attack (corrosion, blistering, and embrittlement) should be used. Only long duration experiments (like LTFT) will prove the capability of equipment and materials in this HDR geothermal system.

7.3 Geothermal Reservoir

The results form ICFT indicate that overall system impedance and total water loss will probably decline during LTFT. A decline in total system impedance would relax the 5000 psi maximum injection pressure currently specified, thereby reducing the stated power requirements and the size (or number) of pumps utilized. Fluid chemistry parameters will not change significantly during LTFT except that concentrations of some species will approach equilibrium values dictated by reservoir temperature and pressure. Fluid chemistry parameters dictate materials selection for the entire surface system. After startup, the closed-loop HDR system generally exhibits decreased injection pressures due to buoyancy effects caused by injection of relatively cool fluid down the injection well and the production of hot fluid in the production well.

7.4 Already Puchased Hardware

There are currently four (4) Siemens-Allis 300 hp electric motors available for use which were purchased in 1980. These electric motors, although intended to be vertically mounted drivers for the Peerless pumps, may be able to be used to drive one plunger pump (rated at 600 BHP) if two motors could be coupled together through a variable speed transmission. These electric motors seem to be the only possible equipment already available which might be able to be modified for use in the Phase II LTFT injection pumping system.

7.5 Future Goals

It would be prudent to consider the possibility of contracting out the twelve-month LTFT. This one year long experiment would lend itself well to outside service bids. But if future plans for the Fenton Hill site include further goethermal reservoir or energy extraction experiments, then it would enhance the site's capability to have permanent circulation pumps available and working for future tests and therefore actual procurement of pumping equipment would be advisable.

APPENDIX A

ICFT EXPERIMENTAL RESULTS

ICFT Gas Data

ICFT Fluid Geochemistry Data

ICFT GAS SAMPLES - ALL IN % VOL. OF DRY GAS

EXP.2067 GAS SAMPLES

SAMPLE #	DESCRIPTION	DATE MM/DD/YY	TIME HH:MM	H2 %	CO2 %	C2H6 %	H2S %	H2S ppm	O2 %	N2 %	CH4 %	
6001	Exp.2067	05/20/86	08:32	ND	99.80	ND	ND	---	0.03	0.17	ND	
6002	Exp.2067	05/20/86	09:02	ND	99.92	ND	ND	---	ND	0.08	ND	
6003	Exp.2067	05/20/86	09:32	ND	96.72	ND	0.05	---	0.24	0.98	ND	
6004	Exp.2067	05/20/86	10:02	ND	99.92	ND	ND	---	ND	0.08	ND	
6005	Exp.2067	05/20/86	10:32	ND	99.93	ND	ND	---	ND	0.07	ND	
6006	Exp.2067	05/20/86	11:02	ND	99.86	ND	0.07	---	ND	0.07	ND	
6007	Exp.2067	05/20/86	11:32	ND	99.93	ND	ND	---	ND	0.07	ND	
6008	Exp.2067	05/20/86	12:02	ND	99.64	ND	0.27	---	ND	0.09	ND	
6009	Exp.2067	05/20/86	12:32	ND	99.67	ND	0.26	---	0.06	0.12	ND	
6010	Exp.2067	05/20/86	13:02	ND	99.57	ND	0.29	---	ND	0.14	ND	
6011	Exp.2067	05/20/86	13:32	ND	99.60	ND	0.28	---	ND	0.13	ND	
6012	Exp.2067	05/20/86	14:02	ND	99.89	ND	ND	---	ND	0.11	ND	
6013	Exp.2067	05/20/86	14:32	ND	89.49	ND	0.71	---	2.11	7.70	ND	← Gas Pocket
6014	Exp.2067	05/20/86	15:02	ND	99.40	ND	ND	---	0.32	0.29	ND	
6015	Exp.2067	05/20/86	16:02	ND	99.86	ND	ND	---	ND	0.14	ND	
6016	Exp.2067	05/20/86	16:32	ND	99.84	ND	ND	---	ND	0.16	ND	
6017	Exp.2067	05/20/86	17:02	ND	99.86	ND	ND	---	ND	0.14	ND	
6018	Exp.2067	05/21/86	11:58	ND	99.48	ND	ND	---	0.04	0.48	ND	
6019	Exp.2067	05/21/86	12:28	ND	99.34	ND	0.17	---	0.05	0.45	ND	
6020	Exp.2067	05/21/86	12:58	ND	99.30	ND	ND	---	0.03	0.66	ND	
6021	Exp.2067	05/22/86	10:42	ND	97.92	ND	0.09	---	0.09	1.90	ND	
6022	Exp.2067	05/22/86	12:43	ND	97.59	ND	ND	---	0.43	1.98	ND	
6023	Exp.2067	05/22/86	17:44	ND	99.07	ND	0.16	---	0.03	0.75	ND	
6024	Exp.2067	05/22/86	19:14	ND	98.91	ND	0.15	---	0.04	0.90	ND	
6025	Exp.2067	05/22/86	20:44	ND	98.80	ND	0.14	---	0.05	1.01	ND	
6026	Exp.2067	05/22/86	21:44	ND	98.63	ND	0.11	---	0.06	1.20	ND	
6027	Exp.2067	05/23/86	00:44	ND	98.05	ND	0.09	---	0.15	1.71	ND	
6028	Exp.2067	05/28/86	10:30	---	---	---	---	824	---	---	---	
6029	Exp.2067	05/28/86	12:13	ND	97.07	ND	0.11	---	0.25	2.58	ND	
6030	Exp.2067	06/02/86	08:36	0.27	78.81	0.1	0.13	1000	0.55	19.96	0.17	← Gas Pocket
6031	Exp.2067	06/02/86	09:03	ND	87.85	ND	ND	---	0.53	11.53	0.09	
6032	Exp.2067	06/02/86	10:41	ND	87.73	ND	ND	---	0.33	11.83	0.11	
6033	Exp.2067	06/02/86	13:11	0.26	79.64	ND	0.08	---	0.53	19.32	0.17	
6034	Exp.2067	06/02/86	14:11	ND	93.73	ND	0.10	---	0.63	5.50	0.04	
6035	Exp.2067	06/03/86	15:26	ND	98.05	ND	ND	---	0.08	1.87	ND	
6036	Exp.2067	06/04/86	13:36	ND	97.37	ND	0.07	510	0.14	2.42	ND	
6037	Exp.2067	06/04/86	17:36	ND	97.62	ND	0.11	---	0.08	2.19	ND	
6038	Exp.2067	06/05/86	10:00	---	---	---	---	625	---	---	---	
6039	Exp.2067	06/05/86	12:41	ND	97.27	ND	0.11	---	0.09	2.54	ND	
6040	Exp.2067	06/05/86	16:41	ND	96.77	ND	0.11	---	0.15	2.98	ND	
6041	Exp.2067	06/05/86	20:40	ND	97.01	ND	0.11	---	0.11	2.76	ND	
6042	Exp.2067	06/06/86	00:41	ND	96.87	ND	0.10	---	0.12	2.91	ND	
6043	Exp.2067	06/06/86	04:41	ND	96.94	ND	0.09	---	0.11	2.86	ND	
6044	Exp.2067	06/06/86	08:40	ND	97.57	ND	0.10	---	0.09	2.24	ND	
6045	Exp.2067	06/06/86	12:41	ND	96.41	ND	0.07	625	0.14	3.38	ND	
6046	Exp.2067	06/06/86	16:41	ND	97.48	ND	0.17	---	0.08	2.27	ND	
6047	Exp.2067	06/06/86	20:40	ND	97.47	ND	0.15	---	0.09	2.30	ND	
6048	Exp.2067	06/07/86	00:40	ND	97.50	ND	0.18	---	0.08	2.25	ND	
6049	Exp.2067	06/07/86	04:40	ND	97.55	ND	0.16	---	0.08	2.21	ND	
6050	Exp.2067	06/07/86	08:40	ND	97.54	ND	0.16	---	0.08	2.21	ND	
6051	Exp.2067	06/07/86	12:41	ND	97.01	ND	0.10	---	0.11	2.78	ND	
6052	Exp.2067	06/07/86	16:40	ND	91.72	ND	ND	---	0.25	7.95	ND	
6053	Exp.2067	06/08/86	15:14	ND	96.83	ND	0.11	---	0.11	2.95	ND	← N_2 Injection

ND - BELOW THRESHOLD FOR DETECTION

SAMPLE #				H_2	CO_2	C_2H_6	H_2S	H_2S ppm	O_2	N_2	CH_4
6054	Exp.2067	06/08/86	15:44	ND	97.09	ND	0.13	---	0.09	2.70	ND
6055	Exp.2067	06/08/86	16:14	ND	96.61	ND	0.13	---	0.05	3.10	ND
6056	Exp.2067	06/08/86	16:44	ND	95.90	ND	0.12	---	0.06	3.90	ND
6057	Exp.2067	06/08/86	17:15	ND	55.21	ND	0.06	---	0.14	44.56	ND
6058	Exp.2067	06/08/86	17:45	ND	62.49	ND	ND	---	0.15	37.31	ND
6059	Exp.2067	06/08/86	18:14	ND	64.22	ND	0.05	---	0.13	35.58	ND
6060	Exp.2067	06/08/86	18:44	ND	56.61	ND	0.03	---	0.12	43.18	ND
6061	Exp.2067	06/08/86	19:14	ND	63.91	ND	0.06	---	0.05	35.95	ND
6062	Exp.2067	06/08/86	19:44	ND	42.74	ND	0.05	---	0.13	57.05	ND
6063	Exp.2067	06/08/86	20:44	ND	29.14	ND	ND	---	0.11	70.71	ND
6064	Exp.2067	06/08/86	21:44	ND	45.19	ND	ND	---	0.07	54.69	ND
6065	Exp.2067	06/08/86	22:44	ND	43.82	ND	0.05	---	0.07	56.01	0.05
6066	Exp.2067	06/08/86	23:44	ND	48.47	ND	ND	---	0.05	51.43	0.04
6067	Exp.2067	06/09/86	00:44	ND	48.80	ND	ND	---	0.05	51.11	0.04
6068	Exp.2067	06/09/86	02:44	ND	47.78	ND	ND	---	0.05	52.13	0.04
6069	Exp.2067	06/09/86	04:44	ND	47.21	ND	ND	---	0.06	52.73	ND
6070	Exp.2067	06/09/86	06:44	ND	36.64	ND	ND	---	0.06	63.25	0.05
6071	Exp.2067	06/09/86	08:44	ND	21.61	ND	ND	---	0.06	78.27	0.06
6072	Exp.2067	06/09/86	10:44	ND	20.63	ND	ND	---	0.06	79.26	0.05
6073	Exp.2067	06/09/86	13:15	ND	20.80	ND	ND	150	0.06	79.10	0.05
6074	Exp.2067	06/09/86	13:44	ND	22.00	ND	ND	188	0.06	77.90	0.05
6075	Exp.2067	06/09/86	14:44	ND	21.90	ND	ND	180	0.06	78.00	0.06
6076	Exp.2067	06/09/86	16:44	ND	21.70	ND	ND	---	0.06	78.20	0.06
6077	Exp.2067	06/09/86	18:44	ND	22.10	ND	ND	---	0.06	77.80	0.05
6078	Exp.2067	06/09/86	19:44	ND	22.80	ND	ND	150	0.06	77.10	0.05
6079	Exp.2067	06/09/86	20:44	ND	22.80	ND	ND	---	0.06	74.10	0.06
6080	Exp.2067	06/09/86	22:14	ND	25.70	ND	ND	---	0.06	74.10	0.05
6081	Exp.2067	06/10/86	00:14	ND	31.70	ND	ND	---	0.08	68.21	0.06
6082	Exp.2067	06/10/86	07:14	ND	21.83	ND	ND	---	0.06	78.04	0.06
6083	Exp.2067	06/10/86	09:14	ND	23.42	ND	ND	---	0.07	76.52	ND
6084	Exp.2067	06/10/86	11:10	ND	23.19	ND	ND	---	0.06	76.70	0.05
6085	Exp.2067	06/10/86	12:10	ND	25.01	ND	ND	170	0.06	74.93	ND
6086	Exp.2067	06/10/86	14:10	ND	25.99	ND	ND	---	0.07	73.89	0.06
6087	Exp.2067	06/10/86	16:10	ND	24.88	ND	ND	---	0.05	75.06	ND
6088	Exp.2067	06/10/86	18:10	ND	26.54	ND	ND	---	0.06	73.39	ND
6089	Exp.2067	06/10/86	20:10	ND	27.12	ND	ND	---	0.07	72.82	ND
6090	Exp.2067	06/10/86	22:10	ND	28.13	ND	ND	---	0.07	71.76	0.05
6091	Exp.2067	06/11/86	00:10	ND	31.61	ND	ND	---	0.07	68.27	0.05
6092	Exp.2067	06/11/86	02:10	ND	30.04	ND	ND	---	0.07	69.50	ND
6093	Exp.2067	06/11/86	04:10	ND	31.45	ND	ND	---	0.07	68.42	0.05
6094	Exp.2067	06/11/86	04:40	ND	43.38	ND	0.06	---	0.05	56.44	0.04
6095	Exp.2067	06/11/86	06:10	ND	46.23	ND	0.11	---	0.06	53.61	ND
6096	Exp.2067	06/11/86	08:10	ND	62.39	ND	0.14	---	0.05	37.42	ND
6097	Exp.2067	06/11/86	09:10	ND	32.58	ND	0.09	---	0.10	67.19	0.05
6098	Exp.2067	06/11/86	11:04	ND	66.33	ND	0.12	---	0.05	33.50	ND
6099	Exp.2067	06/11/86	13:03	ND	49.92	ND	0.07	---	0.07	49.94	ND
6100	Exp.2067	06/11/86	14:33	ND	74.51	ND	0.18	---	0.04	25.27	ND
6101	Exp.2067	06/11/86	16:33	ND	70.61	ND	0.14	---	0.05	29.20	ND
6102	Exp.2067	06/11/86	18:03	ND	32.81	ND	ND	---	0.09	67.06	ND
6103	Exp.2067	06/11/86	20:03	ND	56.17	ND	0.10	---	0.06	43.67	ND
6104	Exp.2067	06/11/86	22:03	ND	59.03	ND	0.11	---	0.06	40.80	ND
6105	Exp.2067	06/12/86	00:03	ND	68.39	ND	0.11	---	0.05	31.44	ND
6106	Exp.2067	06/12/86	02:03	ND	71.23	ND	0.09	---	0.06	28.63	ND
6107	Exp.2067	06/12/86	04:03	ND	71.73	ND	0.09	---	0.06	28.12	ND
6108	Exp.2067	06/12/86	06:03	ND	70.63	ND	0.08	---	0.06	29.23	ND
6109	Exp.2067	06/12/86	09:48	ND	30.87	ND	0.14	250	0.14	68.74	0.11

SAMPLE #			H_2	CO_2	C_2H_6	H_2S	H_2S PPM	O_2	N_2	CH_4
6110	Exp.2067	06/12/86 11:48	ND	72.89	ND	0.09		0.06	26.95	ND
6111	Exp.2067	06/12/86 13:48	ND	37.67	ND	ND	---	0.10	62.23	ND
6112	Exp.2067	06/12/86 15:48	ND	59.21	ND	0.06	---	0.06	40.65	ND
6113	Exp.2067	06/12/86 17:48	ND	74.89	ND	0.13	---	0.06	24.92	ND
6114	Exp.2067	06/12/86 19:48	ND	75.39	ND	0.11	---	0.07	24.43	ND
6115	Exp.2067	06/12/86 21:48	ND	74.52	ND	0.10	---	0.07	25.32	ND
6116	Exp.2067	06/12/86 23:48	ND	73.82	ND	0.08	---	0.12	25.98	ND
6117	Exp.2067	06/13/86 01:48	ND	74.26	ND	0.12	---	0.07	25.55	ND
6118	Exp.2067	06/13/86 03:48	ND	77.60	ND	0.10	---	0.07	22.16	ND
6119	Exp.2067	06/13/86 07:48	ND	81.54	ND	0.12	---	0.06	18.28	ND
6120	Exp.2067	06/16/86 08:57	ND	84.36	ND	0.20	725	0.12	15.28	0.04
6121	Exp.2067	06/16/86 14:41	ND	84.73	ND	0.25	---	0.13	14.86	0.04
6122	Exp.2067	06/17/86 07:35	ND	83.02	ND	0.19	1125	0.15	16.60	0.04
6123	Exp.2067	06/17/86 09:45	ND	49.92	ND	0.07	---	0.30	49.60	0.11
6124	Exp.2067	06/18/86 08:30	ND	86.82	ND	0.05	925	0.13	12.96	0.04

COMMENTS

SAMPLE #

6001 First gas sample, Exp. 2076
6002
6003
6004
6005
6006
6007
6008
6009
6010
6011
6012
6013
6014
6015
6016
6017
6018 Possibly contaminated with air.
6019
6020
6021 Possibly contaminated with air.
6022 Possibly contaminated with air.
6023
6024
6025
6026
6027 Possibly contaminated with air.
6028 After gamma experiment.
6029 Possibly contaminated with air.
6030 No water phase. Hit gas pocket?
6031 Manual inj.,Collected at separator.
6032 No water phase. Hit gas pocket?
6033 No water phase. Hit gas pocket?
6034 No water phase. Hit gas pocket?
6035 Cold Trap Sealed. Sampling pump added.
6036 GC recalibrated.
6037
6038 After alternate vents/shutins.

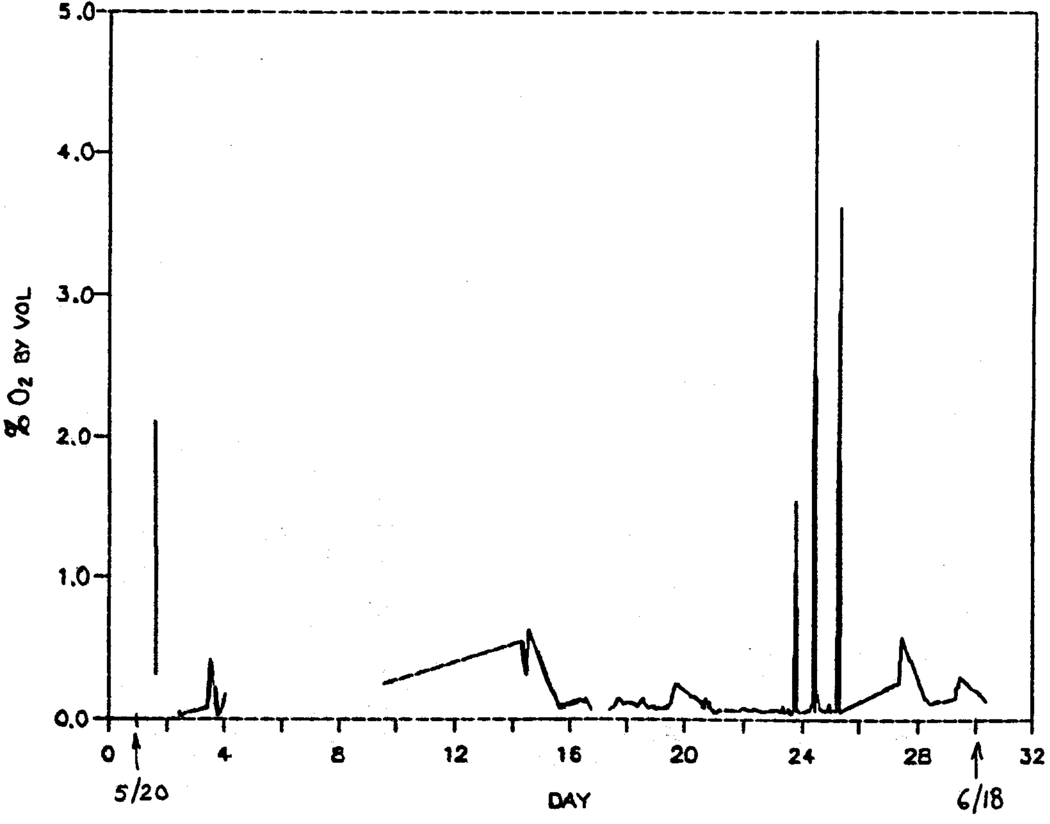
SAMPLE

6052 Possibly contaminated with air.
6053 N2 injected EE-3A at ~11:00
6054
6055 Possible start of nitrogen purge.
6056 Possible start of nitrogen purge.
6057 Nitrogen purge.
6058 Nitrogen purge.
6059 Nitrogen purge,venting w/partial flow to HX.
6060 Nitrogen purge,venting w/partial flow to HX.
6061 Nitrogen purge,venting w/partial flow to HX.
6062 Nitrogen purge,venting w/partial flow to HX.
6063 Nitrogen purge,venting w/partial flow to HX.
6064 Nitrogen purge,venting w/partial flow to HX.
6065 Nitrogen purge,venting w/partial flow to HX.
6066 Nitrogen purge,venting w/partial flow to HX.
6067 Nitrogen purge,venting w/partial flow to HX.
6068 Nitrogen purge,venting w/partial flow to HX.
6069 Nitrogen purge,venting w/partial flow to HX.
6070 Nitrogen purge,venting w/partial flow to HX.
6071 Stopped venting,gas purge mode.
6072
6097
6098 Lowered pressure,only gas in sampling line.
6099 Lowered pressure,only gas in sampling line.
6100 Increased pressure to 500 PSI. H2O & gas.
6101
6102 Decreased pressure to 390 PSI. Gas only.
6103 Increased pressure to 430 PSI.
6104
6105
6106
6107
6108
6109 Reduced Pressure. Mostly gas.

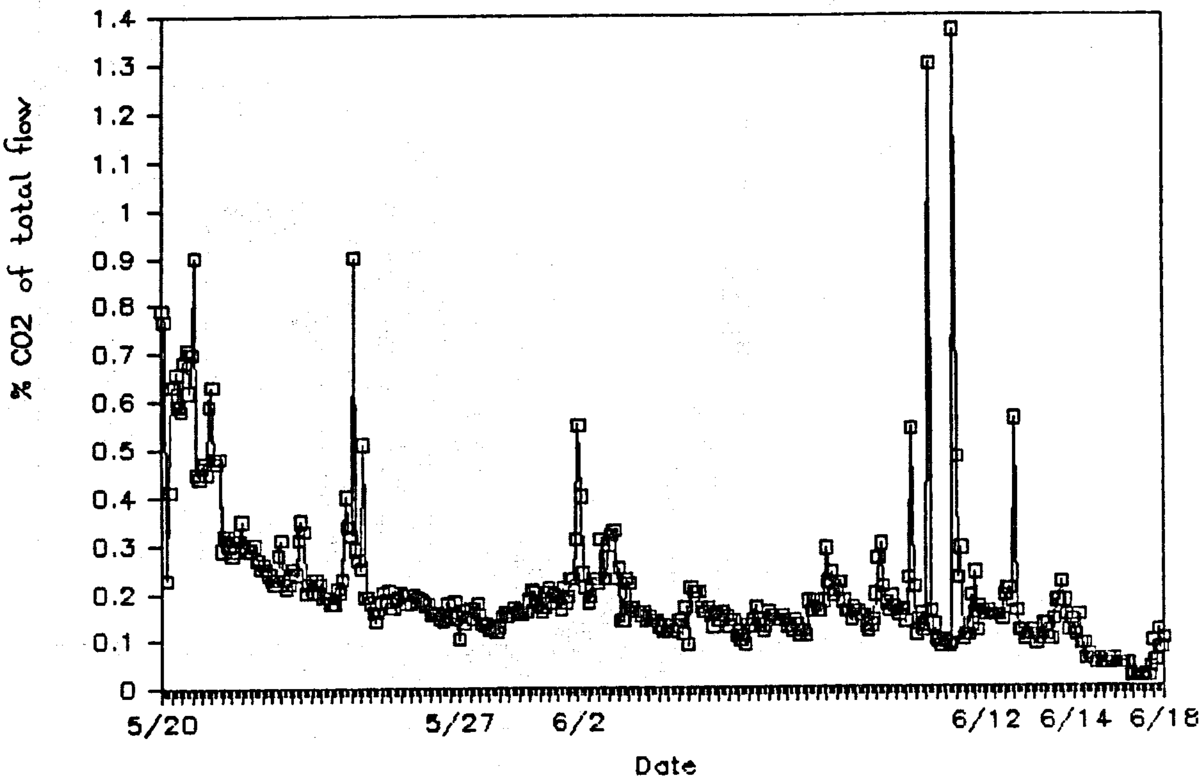
SAMPLE *	COMMENTS - CON'D
6111	Reduced Pressure. Mostly gas.
6112	
6113	
6114	
6115	
6116	
6117	
6118	
6119	Gamma tracer injected 12:24. Gas sampling interrup
6120	
6121	
6122	
6123	Reduced Pressure. Mostly gas.
6124	Last gas samples, Exp. 2067

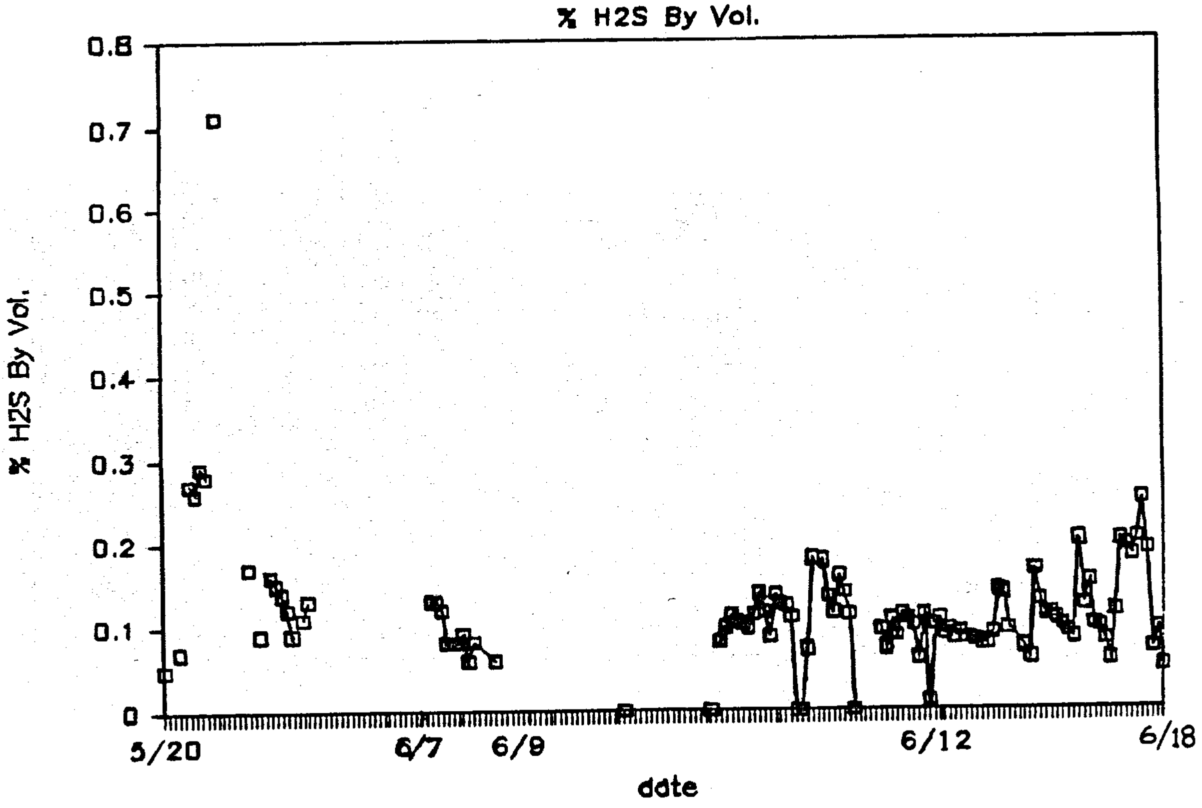
ICFT PRODUCTION

% O2 DRY GAS VS TIME

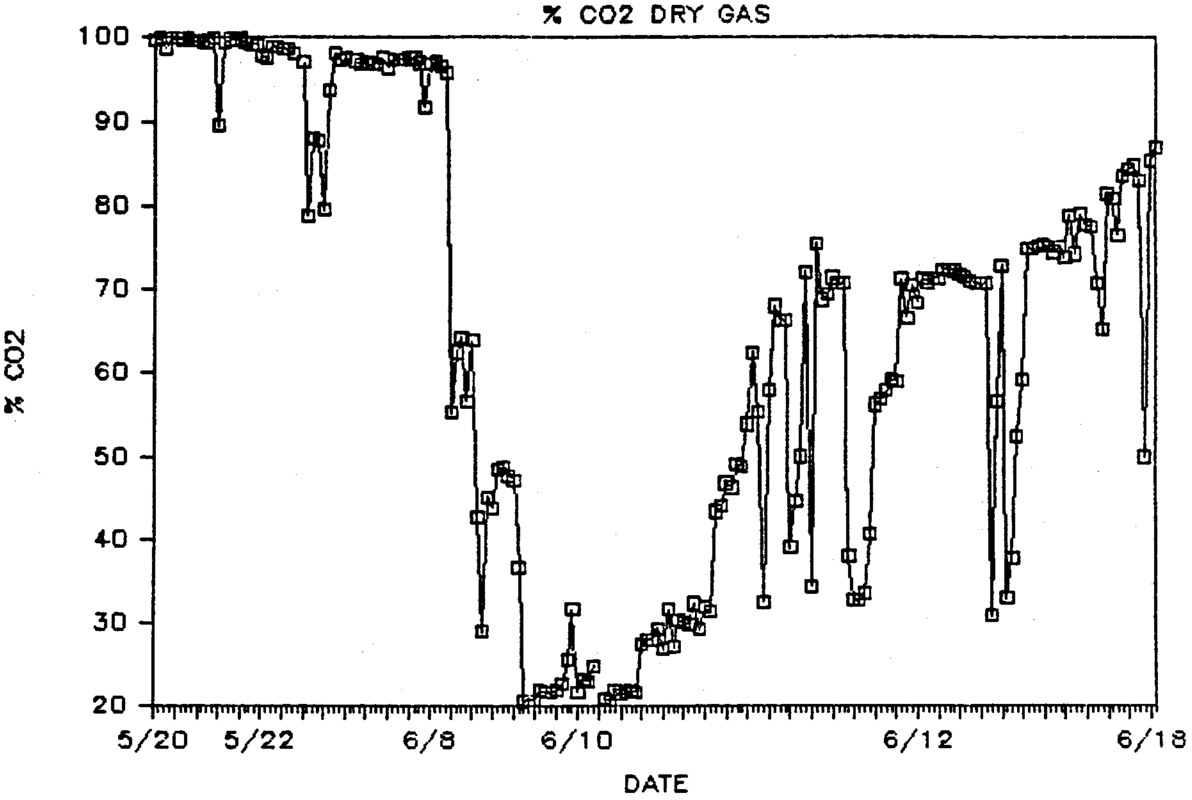


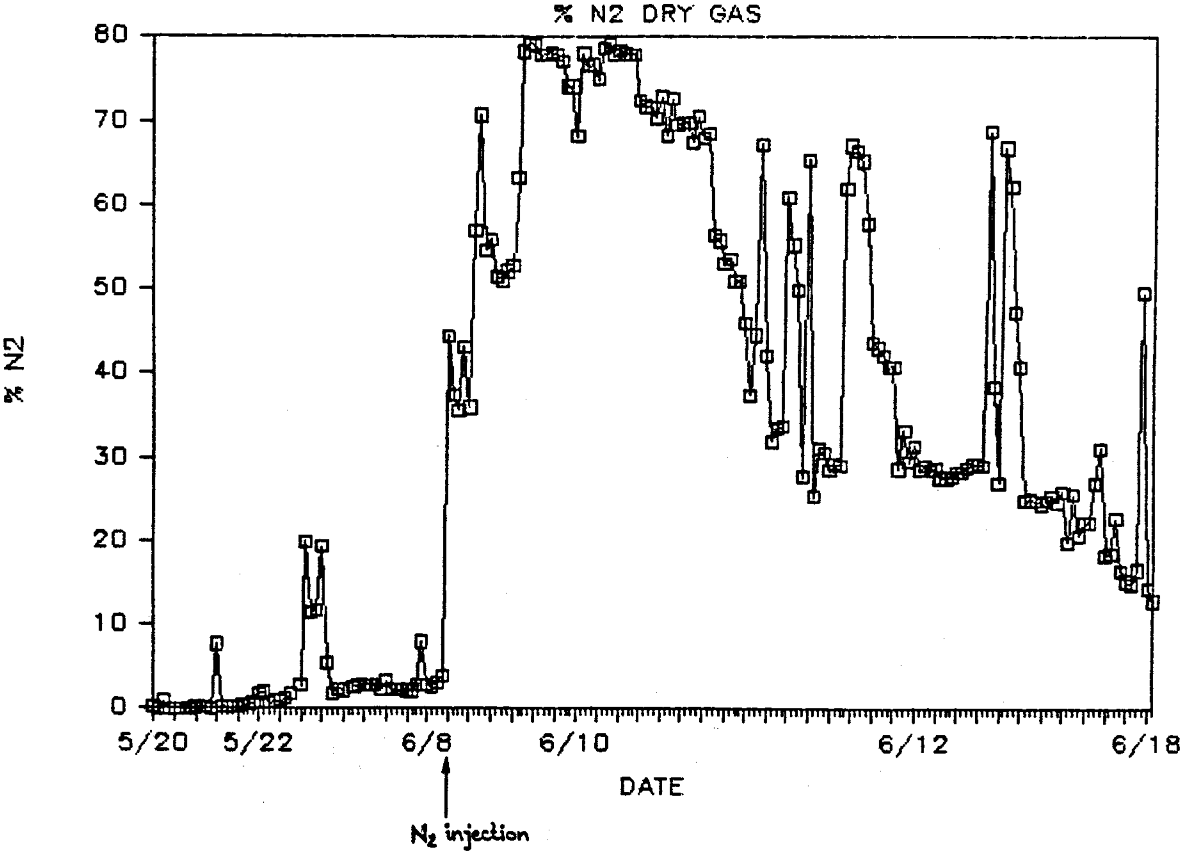
ICFT


% CO2 of total flow
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5/20
5/27
6/2
6/12
6/14
6/18
Date


% H2S By Vol.
% H2S By Vol.
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5/20
6/7
6/9
6/12
6/18
date

ICFT

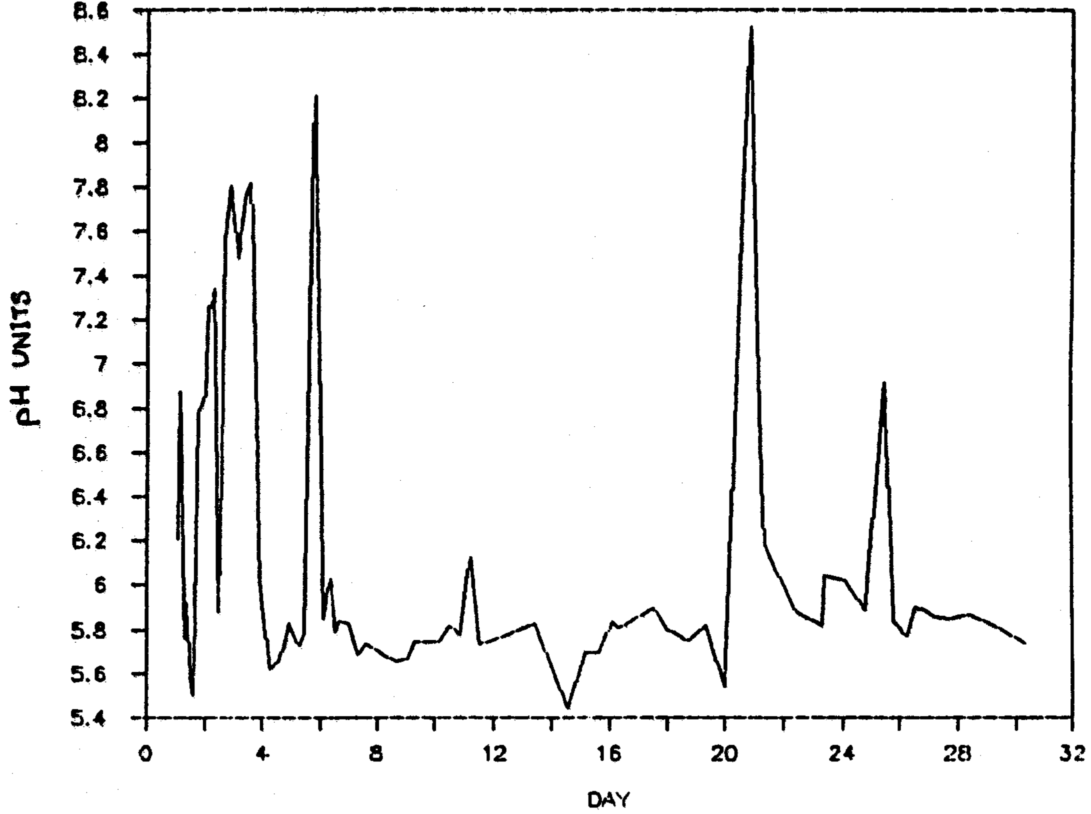

% CO2 DRY GAS
100
90
80
70
60
50
40
30
20
% CO2
5/20
5/22
6/8
6/10
6/12
6/18
DATE

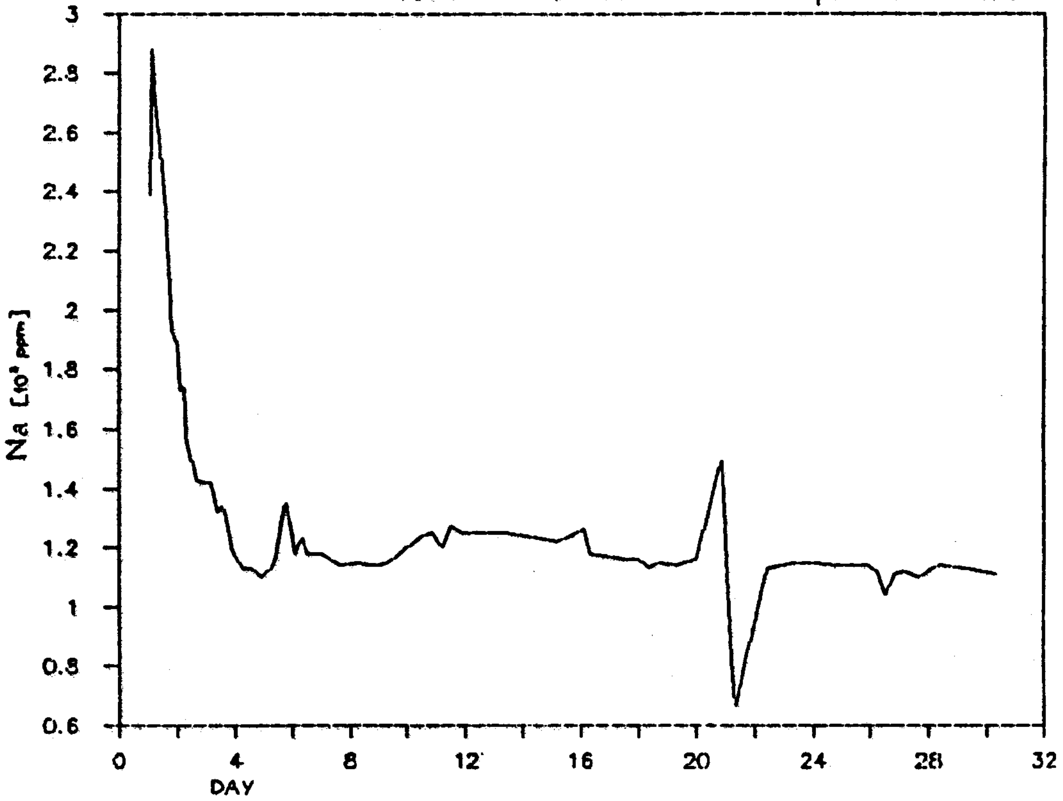

% N2 DRY GAS
80
70
60
50
40
30
20
10
0
% N2
5/20
5/22
6/8
6/10
6/12
6/18
DATE
N2 injection

ICFT FLUID CHEMISTRY

SAMPLE #	DATE DD-MMM-YY	Time	Ca ppm	Cl ppm	Cond. (L) µmho/cm	F ppm	HCO3 ppm	K ppm	Na ppm	pH (L)	SiO2 calcul	SO4 ppm
P-001			---	---	---	---	---	---	---	---	---	---
P-002	20-May-86	01:15	69	3605	12700	6.62	781	262	2390	6.21	437	109
P-003	20-May-86	03:00	100	4558	15790	6.29	742	412	2880	6.87	467	123
P-004	20-May-86	08:10	88	4365	14670	5.38	630	330	2630	5.76	464	86.9
P-005	20-May-86	10:00	83	4460	14500	---	649	319	2590	5.92	471	94.5
P-006	20-May-86	12:00	78	4180	13720	5.68	555	295	2440	5.58	462	91.8
P-007	20-May-86	14:00	67	3950	13040	---	541	285	2340	5.50	462	99.0
P-008	20-May-86	16:00	62	3585	12220	---	530	262	2220	5.86	462	106
P-009	20-May-86	18:00	58	3480	11570	---	482	245	2090	6.78	462	113
P-010	20-May-86	20:00	57	3210	10850	---	462	275	1930	6.80	475	128
P-011	20-May-86	22:00	52	3100	10670	---	458	233	1920	6.81	475	121
P-012	21-May-86	00:00	50	3040	10460	---	465	233	1890	6.86	479	121
P-013	21-May-86	02:00	46	2810	10100	---	436	227	1730	7.26	492	125
P-014	21-May-86	04:00	45	2705	9810	---	436	204	1740	7.26	488	131
P-015	21-May-86	06:00	46	2728	9620	---	428	204	1740	7.26	492	131
P-016	21-May-86	08:00	45	2600	9440	---	415	210	1570	7.34	492	133
P-017	21-May-86	12:00	39	2300	8430	---	412	192	1500	5.88	447	136
P-019	21-May-86	16:00	44	2270	8550	---	406	167	1430	7.57	477	158
P-022	21-May-86	22:00	79	2280	8200	---	445	163	1420	7.81	488	210
P-024	22-May-86	03:15	41	2195	8050	---	356	167	1420	7.48	505	156
P-025	22-May-86	05:10	44	2253	7780	---	370	166	1400	7.59	496	165
P-027	22-May-86	10:00	38	1978	7300	---	387	160	1320	7.76	445	137
P-028	22-May-86	14:00	41	2000	7500	11.9	375	154	1340	7.82	501	155
P-030	22-May-86	22:00	34	1810	6810	---	344	141	1190	6.03	449	159
P-032	23-May-86	06:00	45	1790	6770	---	383	130	1130	5.62	458	162
P-034	23-May-86	14:08	31	1734	6310	---	388	134	1130	5.66	439	158
P-036	23-May-86	22:00	33	1738	6500	---	393	130	1100	5.83	449	163
P-038	24-May-86	06:00	35	1706	6670	---	400	127	1130	5.73	460	167
P-039	24-May-86	10:00	32	1730	6510	---	389	133	1170	5.78	456	168
P-041	24-May-86	18:00	36	2024	7460	---	123	155	1350	8.21	484	207
P-043	25-May-86	02:00	124	1833	6350	---	644	108	1180	5.85	432	189
P-045	25-May-86	08:00	59	1800	6750	---	408		1230	6.03	469	181
P-046	25-May-86	12:00	42	1814	6460	10.4	408	114	1180	5.79	452	183
P-047	25-May-86	16:00	36	1824	6380	---	398	123	1180	5.84	454	183
P-049	26-May-86	00:00	45	1807	6290	---	447	119	1180	5.83	462	186
P-051	26-May-86	08:00	41	1786	6210	---	438	131	1160	5.69	456	183
P-052	26-May-86	15:00	35	1698	6230	---	415	118	1140	5.74	454	168
P-053	27-May-86	08:30	35	1600	6430	---	454	113	1150	5.68	454	176
P-055	27-May-86	16:00	26	1585	6160	---	442	114	1140	5.66	454	173
P-057	28-May-86	00:00	39	1615	6350	---	510	101	1140	5.67	452	183
P-059	28-May-86	08:00	50	1625	6500	---	544	116	1150	5.75	452	186
P-063	29-May-86	02:00	32	1604	6320	---	478	105	1210	5.75	452	184
P-065	29-May-86	12:00	28	1577	6250	---	487	110	1240	5.82	460	185
P-067	29-May-86	20:00	24	1582	6470	---	465	110	1250	5.78	452	185
P-069	30-May-86	04:00	23	1578	6290	---	481	102	1200	6.13	460	186
P-071	30-May-86	12:00	34	1611	6450	---	508	125	1270	5.74	456	192
P-073	30-May-86	20:00	25	1610	6760	---	505	137	1250	5.75	452	192
P-074	01-Jun-86	10:00	24	1637	6670	---	514	137	1250	5.83	484	199
P-075	02-Jun-86	14:30	28	1699	6650	---	520	137	1230	5.44	452	202
P-077	03-Jun-86	04:00	26	1648	6660	---	461	130	1220	5.70	447	204
P-079	03-Jun-86	16:00	26	1746	6840	---	466	115	1240	5.70	452	216
P-081	04-Jun-86	02:00	23	1678	6490	---	444	128	1260	5.84	447	196
P-083	04-Jun-86	08:00	22	1695	6350	---	462	129	1180	5.81	441	195
P-085	05-Jun-86	12:00	23	1565	6100	---	423	125	1160	5.90	454	191
P-087	06-Jun-86	00:00	26	1598	6330	---	455	117	1160	5.80	462	199
P-089	06-Jun-86	08:00	22	1588	6280	10.6	477	127	1130	5.78	462	199
P-091	06-Jun-86	16:00	23	1580	6250	---	470	124	1150	5.75	462	201
P-093	07-Jun-86	08:00	22	1615	6480	---	487	129	1140	5.82	469	209
P-095	07-Jun-86	23:45	24	1597	6220	10.6	488	125	1160	5.54	458	206
P-097	08-Jun-86	20:00	27	2072	7820	---	183	154	1490	8.52	477	264
P-099	09-Jun-86	08:00	19	1003	4050	---	306	75	666	6.18	282	120
P-100	10-Jun-86	10:30	23	1665	6310	---	359	122	1130	5.88	460	220
P-101	11-Jun-86	08:00	24	1654	6250	---	367	123	1150	5.82	437	229
P-102	11-Jun-86	10:00	23	1652	6200	11.4	370	124	1150	6.04	471	233
P-104	12-Jun-86	02:00	23	1678	6260	---	360	124	1150	6.02	467	230
P-106	12-Jun-86	19:00	22	1642	5430	---	381	129	1140	5.89	454	230
P-108	13-Jun-86	11:10	22	1621	6100	---	386	126	1140	6.92	443	232
P-110	13-Jun-86	18:05	21	1621	6040	---	383	130	1140	5.84	443	229
P-112	13-Jun-86	21:55	20	1621	6200	---	376	127	1140	5.82	439	223
P-114	14-Jun-86	05:00	19	1590	6200	---	351	119	1120	5.77	449	204
P-116	14-Jun-86	13:00	17	1583	5600	---	322	115	1040	5.90	441	197
P-118	14-Jun-86	21:00	18	1557	5850	---	322	128	1110	5.89	454	191
P-120	15-Jun-86	05:00	18	1540	5990	---	321	122	1120	5.86	458	187
P-122	15-Jun-86	17:00	19	1560	5900	---	376	122	1100	5.85	447	209
P-124	16-Jun-86	09:00	20	1560	5400	10.2	399	117	1140	5.87	404	219
P-125	17-Jun-86	07:00	---	1570	6160	---	458	120	1130	5.82	ERR	227
P-126	18-Jun-86	07:30	---	1556	6390	---	447	123	1110	5.74	0	234

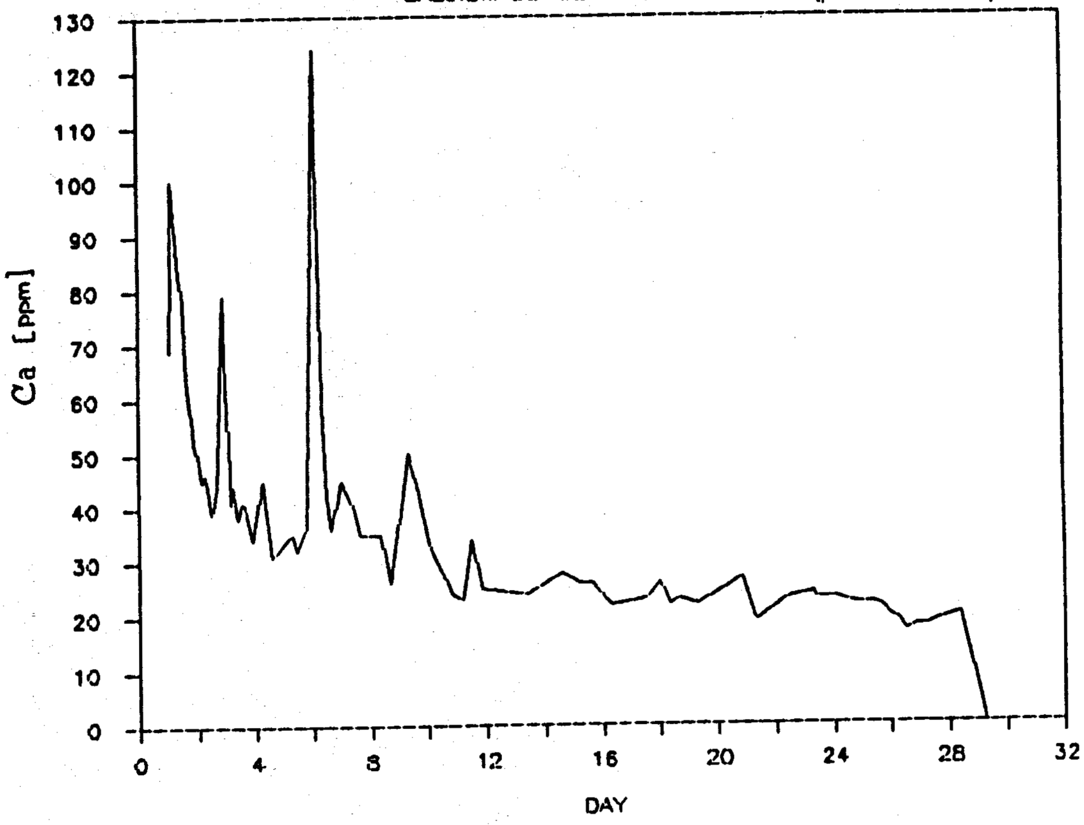
ICFT - production fluid


pH VS TIME

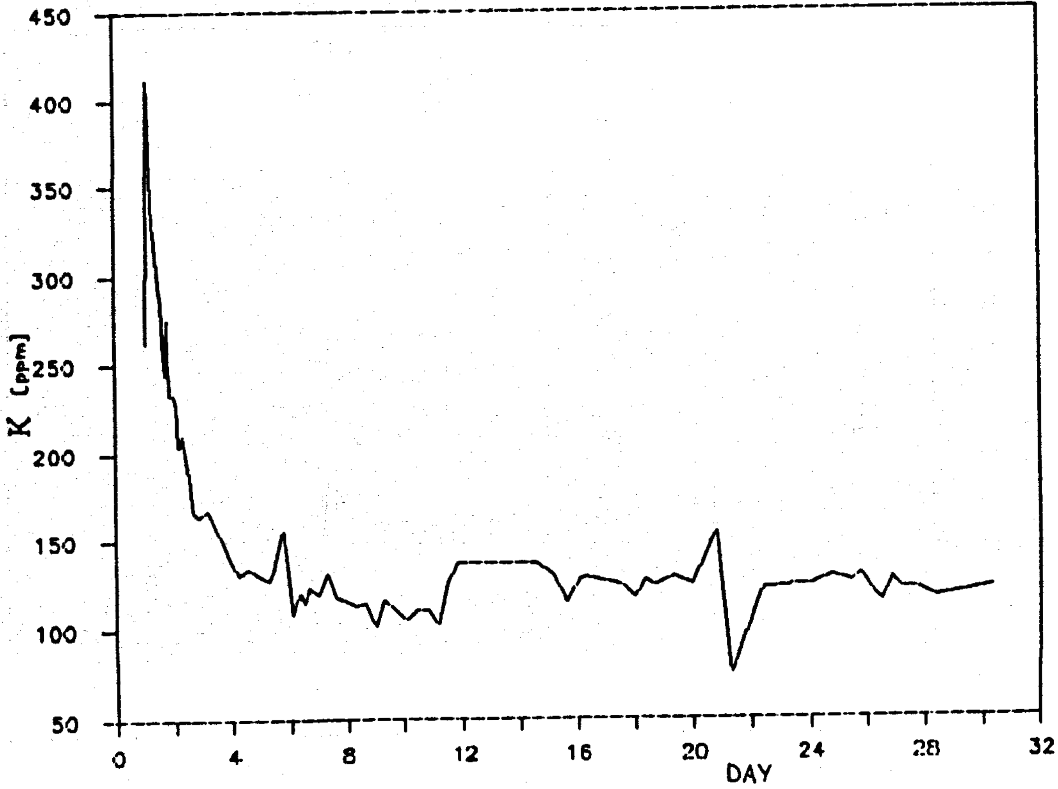

SODIUM CONCENTRATION VS TIME (production fluid)

ICFT

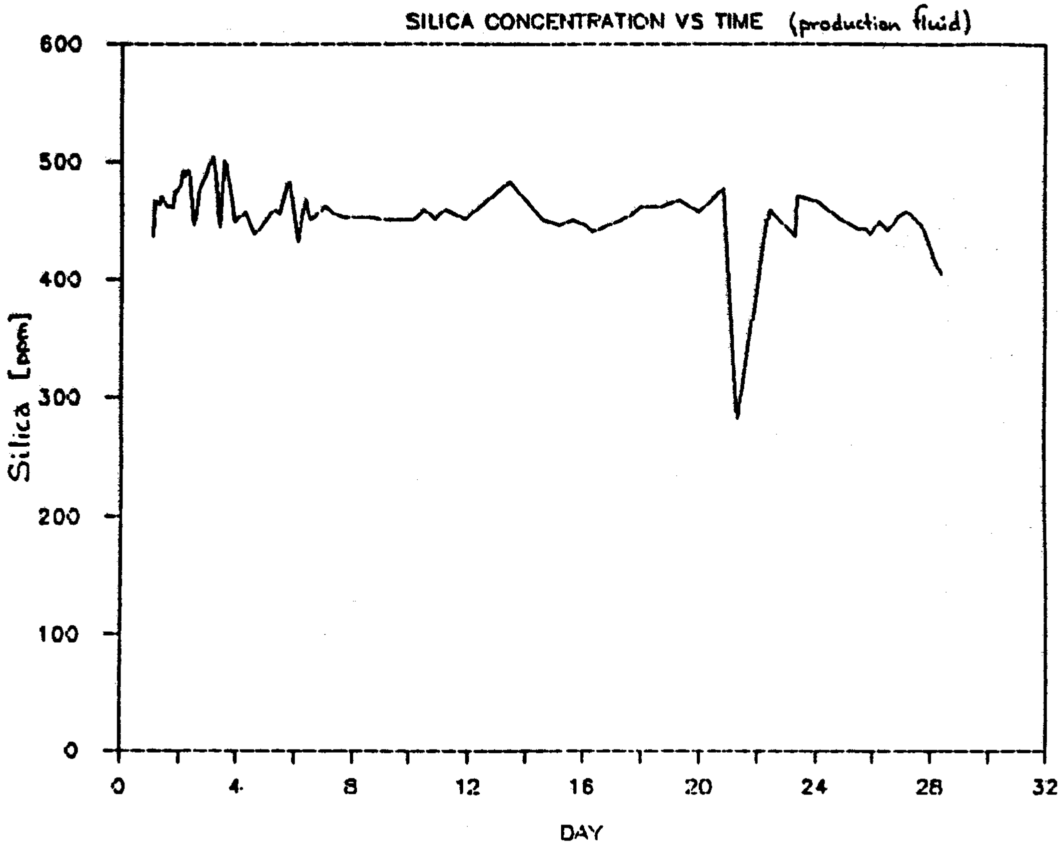
CALCIUM CONCENTRATION VS TIME (production fluid)

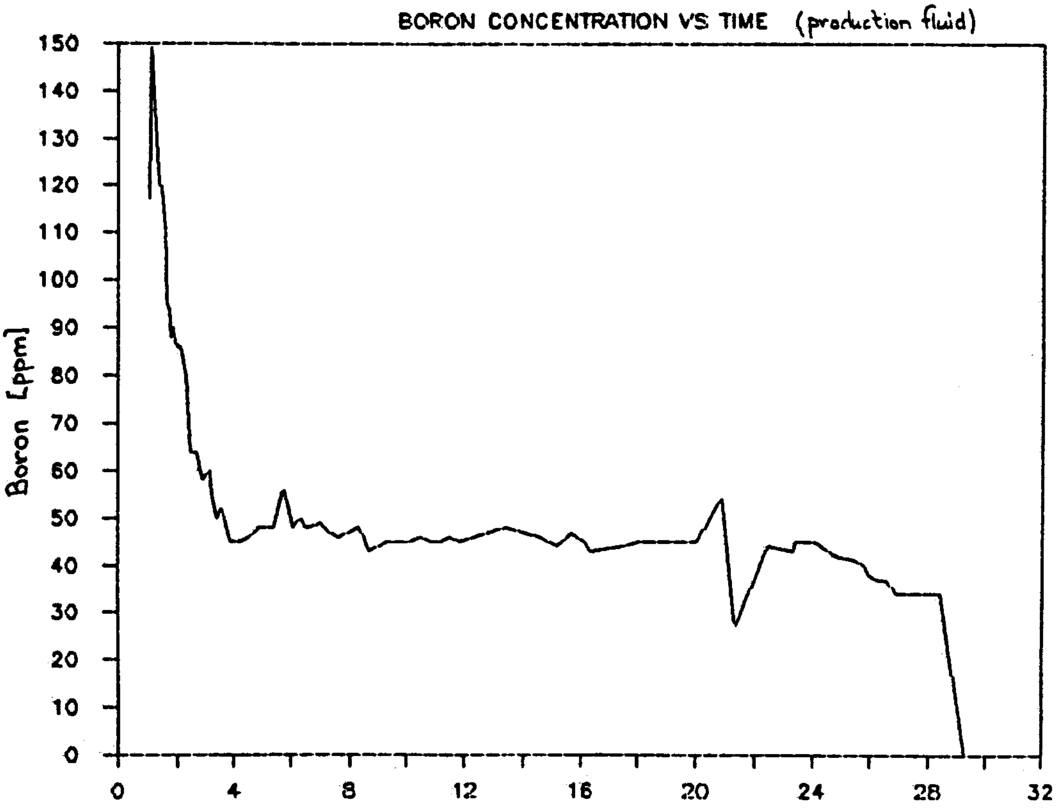


POTASSIUM CONCENTRATION VS TIME (production fluid)



ICFT


SILICA CONCENTRATION VS TIME (production fluid)
Silica [ppm]
600
500
400
300
200
100
0
0
4
8
12
16
20
24
28
32
DAY


BORON CONCENTRATION VS TIME (production fluid)
Boron [ppm]
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32

SYMBOLS USED

A	Cross-sectional area [in^2]
A_p	Plunger end surface area [in^2]
A_s	Cross-sectional area of suction pipe [in^2]
BHP	Brake horsepower
d	Pipe length [ft]
D	Pump impeller diameter [in]
EE-2	Production well
EE-3A	Injection well
g	Acceleration due to gravity [ft/sec^2]
H	Developed pump head [ft]
L	Stroke length [in]
m	Number of plungers
n	Overall pump efficiency [%]
n_H	Pump hydraulic efficiency [%]
n_V	Pump volumetric efficiency [%]
N	Pump speed [rpm]
ND	Pump design speed [rpm]
p	Developed pressure [psi]
P	Pump hydraulic horsepower [hp]
P_{DF}	Powere loss due to disk-fluid viscous interaction [hp]
P_M	Power lost due to mechanical friction [hp]
Q	Pump capacity [gpm]
Q_L	Pump internal flow leakage [gpm]
r	Internal pump volume divided by its output capacity
R	Plunger pump power end crank radius [ft]
s	Fluid specific gravity
S	Pump slip [% of total suction capacity]
V	Fluid velocity [ft/sec]
VE	Volumetric efficiency [%]
Z	Elevation above datum [ft]
γ	Fluid density [lb/ft^3]

UNITS

BPM	Barrels per minute (1 barrel = 42.2 U.S. gallons)
dBA	Decibels on the A scale
gpm	Gallons per minute
hp, HP	Horsepower
KV	Thousand volts
KVA	Thousand volt amperes
KW	Thousand watts
KWe	Thousand watts electric
l/s	Liters per second
MPa	Million pascals
MWe	Million watts electric
MWt	Million watts thermal
ppm	Parts per million concentration
psi	Pounds per square inch
rpm	Revolutions per minute
V	Volts

ABBREVIATIONS

ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
HDR	Hot Dry Rock
ICFT	Initial Closed-Loop Flow Test
LTFT	Long Term Flow Test
NPSH	Net positive suction head
OSHA	Occupational Safety and Health Administration
RMS	Root mean square
SCR	Silicon coltrolled rectifier

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