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**RESEARCH AND DEVELOPMENT OF A
HIGH-PRESSURE WATERJET CORING DEVICE
FOR GEOTHERMAL EXPLORATION AND
DRILLING**
Final Report

MASTER

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Research and Development of a High-Pressure Waterjet Coring
Device for Geothermal Exploration and Drilling

by

James R. Reichman

Abstract

A study was conducted to determine the feasibility of using high-pressure waterjets for coring for geothermal coring and drilling. The study examined the effects of confining pressure, borehole pressure, and temperature on jet cutting ability. Additionally, a study was made to determine the requirements of a high-pressure drilling system and the compatibility of high-pressure equipment with standard drill rigs. The study concluded that waterjet coring in geothermal formations is a feasible process and that high-pressure equipment can be made rig compatible with little modification of existing equipment.

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Summary

A study was conducted to demonstrate the feasibility of using high-pressure waterjets for coring for geothermal exploration and drilling. The study examined the effect of deep well conditions on waterjet cutting ability for two rock types. The effects of borehole pressure, confining pressure and temperature was studied. Based on these results, a core barrel and coring head were designed. The coring device was tested in granite under submerged conditions. The tests demonstrated that a 2 in. diameter core could be cut in granite at a rate of 37 fph. The O.D. of the hole cut was 3.5 in. The horsepower used in these test was approximately 100. The results of these tests compare quite favorably with conventional coring rates. Based on the tests conducted in this study, coring with waterjets was demonstrated to be a feasible process.

A second portion of the study examined the feasibility of using high-pressure equipment with standard drill components. In this study, new and modified equipment is described conceptually. Additionally, fluid compatibility with high-pressure pumping equipment is discussed as well as the feasibility of developing downhole high-pressure pumps. This portion of the study concludes that high-pressure equipment can be made compatible with standard drilling particularly when only the cutting fluid is pumped at high-pressure.

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1. Introduction

In geothermal exploration for hot dry rocks, coring is an essential part of the operation. Coring is needed to obtain information on the geological formation being drilled. Characteristics such as rock type, jointing, porosity and permeability are essential in evaluating a potential geothermal reservoir. The conventional method of obtaining cores is by using either a diamond or tri-cone coring bit. The central core, with these devices, is formed by cutting a circular slot in the rock. Mechanical coring works well in conventional oil and gas exploration. In geothermal formations, however, cores are usually taken from very hard granitic formations and from great depths. The hardness of the rock and deep well conditions cause the coring process to be very slow. For example, during the summer of 1974, the coring rate for deep (over one mile) exploration holes in Marysville, Montana was only about one-half to two feet per hour (McSpadden, 1975). The reasons for the slow rate of coring are obvious: At great depths it is difficult to maintain proper thrust particularly in very hard formations; the tool bit dulls quickly due to increased wear; and at elevated temperatures the bit life is decreased because of heat build-up in the bearing of the bit. For these reasons, it is advantageous to examine other methods that can mitigate some of the problems encountered in conventional coring. If such a device required little thrust it would not dull as quickly and could maintain its optimum cutting ability substantially longer than a conventional device.

In this study, a waterjet coring method was examined as an alternative to conventional techniques. The advantage of using waterjets to cut rocks results from the fact that waterjet nozzles do not touch the rock to cut it, therefore, minimum mechanical wear occurs during the cutting process. In addition, the thrust requirements are minimal, thus bypassing the difficulty of maintaining a high optimum thrust in a very deep hole.

To evaluate the potential of waterjet coring and drilling, a program was undertaken to examine the feasibility of using a high-pressure waterjet coring device for geothermal exploration and drilling. The

aim of the study was to examine the effect of rock type, borehole pressure, confining pressure, and temperature on waterjet cutting. Based on this information, a laboratory scale coring bit was to be developed and tested which would be capable of coring rocks generally encountered in geothermal drilling. Additionally, the program was to examine the compatibility of high-pressure coring systems with conventional drilling equipment.

The major emphasis of this study was to determine the cutting ability of waterjets under simulated conditions. The rocks that were chosen were a granite and basalt which are typical of rocks encountered in deep geothermal exploration. The waterjet pressures examined ranged up to 60,000 psi. The drilling conditions simulated were borehole pressures up to 5,000 psi, confining pressure up to 10,000 psi and temperatures to 3.5° C. The test conditions are selected to simulate conditions at depths that are encountered in many deep drill holes.

Cutting data obtained under simulated conditions, was used to develop a multiple waterjet nozzle configuration which could cut a circular slot and allow a core to be collected. Such a nozzle and core barrel were designed and fabricated. Testing was conducted on granite blocks and cores up to 12 in. long were cut. The core recovery in all cases was complete. The rate of coring in granite was approximately 37 ft/hr which compares quite favorably to conventional coring rates in a very hard rock (compressive strength in excess of 29,000 psi).

Schemes were developed which could be used for actual coring operations. The equipment necessary for high-pressure drilling was determined. Its compatibility with conventional drilling equipment was examined. The aim of this portion of the study was to determine what areas are crucial for the development of high-pressure drilling and what the limitations of such a system are.

The results of the study demonstrate that waterjets are capable of coring in geothermal formations at a rate that exceeds that achieved by conventional methods. The study also indicates that it is technically feasible to develop the necessary equipment for a waterjet coring system which utilizes pressures up to 50,000 psi. Waterjet coring and drilling

appear to be economically feasible under special conditions where drilling cost is expensive and drilling rate and drill life dominates the drilling cost. Such situations occur frequently in deep drilling in hard, geothermal formations and in off shore drilling.

A detailed description of the results of this study are presented in the following sections of this report. Additionally, areas where it is felt that future work should be done in order to develop a viable high-pressure waterjet coring and drilling systems are discussed.

2. Experimental Apparatus

Testing was conducted at Flow Industries using both standard test facilities and specially designed apparatus. Rock cutting tests with a submerged jet, under standard atmospheric pressure and temperature were conducted using standard laboratory equipment. Confining pressure, borehole pressure and temperature tests were conducted utilizing chambers specially designed for this program. The test equipment used is described below.

2.1 Atmospheric Testing

All testing with a submerged jet under standard atmosphere and temperature conditions including coring tests, were conducted in the Flow Industries cutting booth. In this booth, the specimen to be cut is mounted in a plexiglass tank and remains stationary. The high-pressure nozzle is mounted on a carriage and is capable of controlled motion in the three mutually perpendicular x-y-z directions. Control is achieved by standard hydraulic controls. The speed range in this booth is 0.5 ips to 10 ips for the x-y motion and 0.1 ips to 10 ips for the z motion. This speed range proved to be adequate for the testing conducted under this program. A schematic of the test system is shown in Figure 1.

For coring tests, which were all conducted at atmospheric conditions, the motion of the core barrel was achieved by rotating the core barrel at the end of a high-pressure swivel. The rotation was achieved with a 1.5 kw electric motor and rotational speed was controlled by a speed controller on the motor. With the gear reducers available, rotational rates of 10 to 2000 rpm could be obtained.

2.2 Confining Pressure Vessel

Testing for the effect of confining pressure on waterjet cutting was conducted in a confining pressure vessel specifically designed for this program. The vessel is shown schematically in Figure 2. In this apparatus, the rock is placed in the chamber, a slotted plate placed over the rock sample and then the sample is locked into place. Confining pressures up to 15,000 psi are exerted on the rock by a high-pressure water intensifier pump which is described in Section 2.4. The purpose

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of the slotted plate is to hold the rock in compression in order to keep the confining pressure from fracturing the small rock sample. Additionally, the plate allows several cuts to be made in the sample without any danger of having rock spallation occur between cuts.

Cutting was achieved by using an off-centered nozzle mounted on a swivel. The axis of the swivel was concentric with the axis of the pressure chamber. Several different eccentric nozzle pieces were fabricated so cuts could be made at different radial distances from the center of the rock sample. For the cutting tests the chamber area above the rock was filled with water and cutting was then done. This was sufficient to simulate submerged conditions. This was confirmed by running several tests with the chamber completely submerged in a plexi-glass tank.

2.3 Temperature and Borehole Pressure Chamber

The effects of back-pressure and temperature on waterjet cutting was examined in a chamber which was capable of simulating back-pressures of up to 7,000 psi at ambient temperature. The maximum chamber temperature was 350°C; at this temperature maximum borehole pressure was 5,000 psi. A photograph and a schematic of the chamber are shown in Figure 3.

The chamber consisted of a thick walled cylinder with an I.D. of 3.9 in. and an O.D. of 6.5 in. The top plate of the cylinder had three independently plumbed nozzles so that three cuts on the rock specimen could be made without removing the sample. With these nozzles, feed rate, standoff distance and nozzle diameter could be varied on a single sample. Additionally, the top plate had borehole pressure inlet and exhaust parts. The specimen was moved by being rotated by an external motor. Rotation speeds of up to 100 rpm could be obtained with the seals used. All chamber seals were specified to withstand the maximum 350°C temperature of the chamber.

The chamber was heated by two 1 kw heater-bands wrapped externally around the chamber cylinder. Power to the heater was controlled by a standard temperature controller. The chamber was surrounded by high temperature calcium silicate insulation in order to minimize heat loss.

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The entire temperature vessel and insulation was surrounded by a sheet metal jacket. This jacket served as an explosion jacket for the vessel. Holes were drilled in the sheet metal in order to allow steam to escape should a leak develop in the chamber.

The exhaust water from the chamber went through a condenser which was immersed in a cold water bath. The cooled water then went through a variable back pressure relief valve. This valve could regulate borehole pressure from 250 to 10,000 psi. The entire chamber and condenser were located in a sealed test booth. All controls were located external to the booth.

2.4 Pumps and Nozzles

The high-pressure water for the cutting jets was supplied by either of two pumps. For nozzles up to 0.014 in., a 37.5 kw high-pressure intensifier was used. For nozzle diameters larger than 0.014 in., a 187.5 kw intensifier was used. A schematic showing the principle of operation of the pumps is shown in Figure 4. The pumps are capable of maximum pressures of 55,000 psi. In the test where confining pressure and/or borehole pressure as well as nozzle pressure was required, both pumps were utilized. The 37.5 kw pump was used for secondary pressure while the 187.5 kw pump was used for the nozzle pressure.

The nozzles for the linear cutting tests ranged in diameter from 0.006 to 0.020 in. The nozzle sizes tested were kept to the above range so that when a coring head was developed the pumping requirements for the multi-nozzled head could be met with the pumping capacity of the 187.5 kw pump.

3. Linear Cutting Experiments

Testing was conducted using a single jet to cut various rock samples in order to determine jet cutting effectiveness under conditions that are encountered in geothermal exploration and drilling and to aid in the design of a coring head. As a base, data set, cutting was done under submerged conditions, but at ambient temperature, borehole pressure and confining pressure. Testing under simulated conditions was compared to the base data set to determine what effect temperature, back pressure, or confining pressure had on jet cutting. The conditions simulated in the experiments were:

$$\begin{aligned}0 &\leq P_b \leq 5,000 \text{ psi} \\0 &\leq \sigma_c \leq 10,000 \text{ psi} \\0 &\leq T \leq 315^\circ \text{ C}\end{aligned}$$

In deep geothermal drilling, generally hard impermeable rocks are encountered. For our testing, two rock types were used. The first was St. Cloud Gray Grandiorite (Charcoal Granite) and the second was Dresser Basalt. These rocks have been characterized by the U.S. Bureau of Mines (1974). The properties of these rocks are shown in Tables 1 and 2. The results of waterjet cutting on these two rock types are presented in the following sections.

3.1 Waterjet Cutting at Ambient Conditions

In order to determine the effect of simulated conditions on waterjet drilling, it was necessary to determine the jet cutting effectiveness at standard ambient conditions. As a result, a parametric study was conducted on Charcoal Granite and Dresser Basalt under submerged conditions, but at ambient temperature, borehole temperature and confining pressure. The testing was conducted in the cutting booth described in Section 2.1. The testing examined the effect of pressure, traverse velocity, and nozzle diameter on jet cutting. The results of the parametric study for Charcoal Granite and Basalt are shown in Figures 5 through 7. Figure 5 shows the effect of jet pressure as well as establishing a threshold pressure for the rock. As is expected, the depth of cut goes up approximately

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linearly with pressure. The importance of this plot, however, is in the establishment of an optimum cutting pressure. It has been found by several investigators, Crow (1973) and Veenhuizen and Cheung (1977), that from an energy standpoint it is most effective to operate at three times the stagnation pressure. This would establish an optimum operating pressure of approximately 54,000 psi for the granite and approximately 110,000 psi for basalt. The optimum pressure for granite is an attainable pressure with presently available pumping equipment. The optimum pressure required for the basalt is greatly in excess of what is attainable with presently available pumps. This would indicate that Dresser Basalt is not a good candidate rock for efficient waterjet cutting.

When cutting with waterjets of any specified pressure and horsepower, the parameter that should be optimized is the area removal rate. Optimization of the area removal rate is equivalent to optimizing the jets specific energy which is defined as the area removed divided by the hydraulic horsepower of the jet. Optimization of area removal rate specifies the traverse rate of the nozzle. Figure 6 represents plots of depth of cut versus traverse velocity. As would be expected, the figure indicates that the depth of cut goes down with feed rate. However, by plotting the depth of cut times, traverse velocity 'versus' the traverse velocity, an area removal curve is generated. Curves such as this are plotted in Figure 7 for granite and basalt. Examination of Figure 7 indicates that the higher traverse rates are more efficient. (They have a lower specific energy.) It was found experimentally that for granite a maximum area removal rate occurred at 10 ips.

Also, examined in this portion of the program was the effect of nozzle diameter. These tests demonstrated that depth of cut is proportional to the diameter, consequently when using waterjets to cut rock the choice of nozzles should be to use the largest diameter for the available horsepower. Available horsepower is therefore, the limiting factor in the cutting or drilling rate of rock.

The final cutting parameter examined in this portion of the program was standoff distance. When cutting in the submerged condition under low ambient pressure standoff distances of up to 2 in. did not affect the jet cutting ability. This confirms what was found by Cheung and Hurlburt

(1976). In that study and in this one, it was observed that the water-jet cavitated and the cavitation accounts for the small effect of standoff distance. Once cavitation ceases the effect of standoff distance becomes significant to the jets ability to cut. This will be discussed in greater detail in the next section.

3.2 Effect of Borehole Pressure on Jet Cutting

As mentioned in Section 3.2, waterjet cutting under ambient conditions did not significantly depend on standoff distance. This is attributed to cavitation which occurs in the jet. The phenomena has been seen by several investigators, Cheung and Hurlburt (1976) and Lichtarowicz (1977). Lichtarowicz showed in his study on cavitation erosion that cavitation ceases when back-pressure is raised. Cheung in his study developed a model which predicts a similar effect for back-pressure. Because of this, it was anticipated that back-pressure would have the greatest effect on jet cutting. Once cavitation ceased, jet pressure decay would be similar to any submerged jet which means a very strong effect of distance to jet pressure, Schlichting (1960). As a result, experiments were conducted to determine to what extent borehole pressure effected waterjet cutting ability.

Testing was conducted in the temperature chamber described in Section 2.3. For these tests, the rock specimen was placed in the chamber and the chamber was pressurized by an intensifier pump. Pressure was held constant by means of a back-pressure relief valve. The rock in these tests was not isolated from the borehole pressure so the effective state of stress in the rock was equivalent to ambient conditions. The jet was then started as the rock was rotated. Up to three tests could be made on the rock without opening the chamber. After testing, the rock was removed and measurements were made.

The results of the back-pressure tests are shown in Figure 8. Plotted on this graph is the non-dimensional depth of cut versus the back-pressure of the surrounding fluid. The data is for back-pressures between 1,000 and 3,000 psi, a jet pressure of 45,000 psi and a stand-off distance of 0.15 in. Examination of this figure indicates a very strong influence of back-pressure on jet cutting. At atmospheric pressure, the jet cuts approximately 17 diameters deep, at 1,000 psi the cut is 4

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diameters deep and at 3,000 psi no measureable cut is made. At pressure below 500 psi no noticeable drop in jet cutting ability is observed. Tests that were conducted on basalt at high back-pressure showed that for the jet nozzles used in these experiments no measurable cuts were made. The proposed reasons for the results of the back-pressure tests are presented below.

It has been demonstrated that a submerged waterjet, exiting into a fluid with no back-pressure applied, will cavitate. As back-pressure increases, the point where cavitation occurs moves inward towards the nozzle. As back-pressure further increases, cavitation ceases. The point where cavitation ceases has not been found precisely, however, it appears from experimental tests, Lichtarowicz (1977), that this point is 2 to 3% of the nozzle pressure. As back-pressure is further increased, the jet simply acts as a submerged jet and the governing jet conditions are the Δp across the nozzle.

When cutting hard materials with small diameter nozzles, the existence of cavitation bubbles is important. When cavitation bubbles are present the jet does not spread as much as a standard submerged jet due to bubble sheathing, and the bubble collapse aids in the cutting process. When cavitation ceases altogether or occurs so close to the nozzle exit that utilizing the bubble collapse is impractical, the entire mode of cutting changes. Cutting becomes governed by the jet pressure deliverable to the rock face. In the non-cavitating region, nozzle diameter and jet pressure are the critical control parameters. Jet centerline pressure decay is shown in Figure 9. This curve was taken for a fully submerged large diameter jet operating at low-pressure. The Reynolds number for this jet is approximately equal to our high-pressure jets. The measurements were taken using a flat plate backed by a pressure transducer. Examination of this curve shows that jet pressure decays rapidly and reaches half the initial stagnation pressure at approximately 10 diameters from the jet exit. The high jet pressure decay would not prove a problem for large diameter jets, but for small-diameter jets, cutting materials with high threshold pressures, the decay is important. In the testing conducted in this program, nozzles of up to 0.02 in. diameter

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were used and rocks with threshold pressures of 18,000 and 38,000 psi were used. In order, therefore, to cut a piece of basalt (38,000 psi threshold pressure) with a 50,000 psi waterjet, the standoff distance would have to be 7 diameters. This represents a distance of 0.15 in. between the nozzle exit and the rock surface. This distance is too small to be accurately maintained and jet cutting would be very ineffective. This was borne out by experiments. For the testing in granite using an 0.018 in. nozzle at 45,000 psi and a 3,000 psi back-pressure, the distance at which cutting would cease is approximately 0.18 in. ($x/D = 10$ from Figure 9). This is the approximate standoff distance used in the experiments and would explain why cutting ceased (see Figure 8).

This portion of the program showed that for small diameter jets back-pressure is a critical cutting parameter. At high back-pressures, a jet can cut any given material if the nozzle is made large enough so x/D gives the proper pressure at the rock surface and this pressure exceeds threshold pressure. If this cannot be accomplished because of excessive pumping requirements, then jet coring or drilling would not be practical.

3.3 Effect of Confining Pressure on Jet Cutting

The effect of confining pressure was examined utilizing the apparatus described in Section 2.2. The testing was conducted on Charcoal Granite using confining pressures up to 10,000 psi. The back-pressure for these tests was one atmosphere. No cutting on basalt was tried because of the inability of a submerged jet to effectively cut basalt when back-pressure was applied. The results of the tests are plotted in Figure 9. Each data point represents the average depth of cut for each confining pressure. The error bands represent the data spread for each confining pressure. Examination of the data reveals that back-pressure has little if any effect on the depth of cut. Examination of rock samples shows that as confining pressure increases the amounts of rock removed increases due to increased spallation. Figure 10 shows photographs of a typical cut at no confining pressure and a typical cut of elevated confining pressure. The reasons for this phenomena is discussed below.

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The confining pressure tests indicate no discernable effect due to the application of a confining pressure. The reason for this is that the granite used in these tests is categorized as a very hard rock and as such has dense grain structure and a strong bond between grains. When confining pressure is applied there is very little change in the basic rock structure so little change in jet cutting takes place. This is in contrast to softer rocks such as limestone and sandstone. In this type of rock, confining pressure has a larger effect due to a compaction of the rock. This has been experimentally confirmed by Summers and Bushnell (1976).

A secondary effect of confining pressure was an increase in the amount of spallation that occurs immediately around the cut. It is postulated that this is due to a favorable superposition of stress caused by the confining pressure and the stress relieving of the rock by the waterjet. The spallation therefore, increases with confining pressure due to the increased stress level within the rock.

The maximum confining pressure used during testing was 10,000 psi. This represents an equivalent state of stress in the rock equal to that of a rock being drilled at 20,000 ft. This is because at that depth the confining pressure is approximately 20,000 psi, but the axial stress due to the borehole pressure is approximately 10,000 psi. With these pressures acting on the rock, the result rock stress could be simulated by a zero axial stress and a radial stress of 10,000 psi. Thus, the equivalent rate of stress for these tests is 1 ft/0.5 psi.

3.4 Effect of Temperature on Jet Cutting

The vessel described in Section 2.3 was used for testing the effect of temperature on jet cutting. For these tests, the chamber was filled with water and pressurized sufficiently to assure that no vapor would form in the vessel when heated. Once pressurized, the heaters were used to elevate the temperature in the vessel to the desired level. When the temperature was reached the cut on the specimen was made. No attempt was made to heat the water for the jet. This was the result of a study, Altseimer (1976), which showed that in geothermal drilling the temperature rise in the drill fluid was small (at normal drilling flow rates temperatures

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reached 63° C in the drilling mud). After cutting, the rock was removed from the vessel and measurements were taken. Testing was conducted using temperatures up to 315° C. The results of these tests are shown in Figure 11. Plotted on this graph is the average depth of cut versus temperature. Next to each data point the variation in back-pressure that occurred during the test is indicated.

Figure 11 shows that below approximately 200° C there is no significant change in jet cutting due to an increase in temperature. At temperatures above 200° C, however, there is an increase in cutting effectiveness. This phenomena is expected since elevated temperature weakens the rock. This has been demonstrated by Wingquist (1969). He studied the elastic module of Charcoal Granite at elevated temperature. In this study, up to 200° C, the Young's modulus has dropped to 65% of its initial value, but from 200° to 315° C, the Young's modulus drops to 25% of its value at room temperature. This drop in elastic modulus is an indication of a general weakening of the rock and it is what causes the jet cutting to increase.

The same phenomena that aids in waterjet drilling would also aid in increasing the drilling rates achieved with conventional bits. This may occur initially, but the high rock temperature causes two major problems which ultimately reduces drilling rates. The high borehole temperature causes (1) increased bit wear due to a weakening of the bit material and (2) a deterioration of the bearings. Both of these factors reduce drilling effectiveness and bit life. Since the waterjets do not contact the rock, and high thrust is not applied to the rock, bit life would be extended and maximum drilling effectiveness maintained for a longer time. This could result in higher drilling rates and fewer trips due to bit changes, when compared to conventional drilling methods.

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4. Coring Tests

After completion of the linear cutting tests, the next task was to design a coring head and to demonstrate that waterjets could be used to core rock. In order to demonstrate this, a laboratory scale core drill was designed and tested. The drill used a multiple nozzle coring head to cut a circular kerf wide enough for the barrel to enter. Testing was done using a barrel that cut a 2 in. O.D. core and approximately a 3.5 in. O.D. hole. The results of this portion of the program demonstrated waterjet coring to be a feasible process. The equipment used for the coring program and the results of the tests are presented below.

4.1 Linear Kerfing and Nozzle Configuration

In order to cut a wide kerf (on the order of 0.8 in.) it is necessary to determine the maximum spacing between two parallel cuts so that the material between the two slots are removed. This is necessary in order to determine the minimum number of nozzles that can be used to cut the slot. The slot spacing is a function of the type of rock being cut, soft rocks being less likely to spall than harder rocks. To establish minimum slot spacing, tests were conducted using a single jet to cut a series of parallel slots. In these tests, the slot spacing was decreased until complete material removal was achieved between slots. This procedure was used in testing two distinct types of rocks. The first was Charcoal Granite which is a very hard rock and, because of the existence of microfractures, is a rock which readily spalls. The second rock was Wilkeson Sandstone, a soft rock which the waterjet cuts by erosion of individual grains. The results of this study are plotted in Figure 13. The non-dimensional slot distance is plotted versus traverse velocity. The results indicate that for granite a spacing of 15 diameters between slots will assure breakage. For sandstone, a cut spacing of 7 diameters assures breakage between slots. The results of the slot spacing tests were then incorporated into the design of a 5 nozzle linear kerfing nozzle.

Before the drill was made, a linear block with five nozzles was made. The aim of this was to prove the results of the slot spacing tests and to demonstrate that a wide slot could be cut by simply traversing

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a nozzle manifold across a rock specimen. Additionally, methods of mounting small diameter nozzles in a narrow manifold block were tested. The linear coring nozzle is shown in Figure 14. The actual carrier block was divided into two chambers so that two different coverage patterns could be tried. Each chamber was separately fed and could be tested independently. The five angles that were used are shown in Figure 14. The angles were chosen so that there was maximum hole clearance around the outer diameter of a core barrel and a tight clearance around the core so it could enter the inner barrel and still have maximum core recover. The two outer nozzles had an 0.014 in. diameter and the inner nozzles were 0.013 in. diameter. The angles were chosen so an 0.75 in. slot would be cut with a constant 0.25 in. standoff distance. The remaining 3 nozzles were evenly spaced across the 0.75 in. kerf width. This nozzle configuration worked satisfactorily, cutting a clear slot. The nozzle spacing was 0.1875 which is a non-dimensional distance of 14 between slots. This spacing was in accordance with the results of our slot spacing tests.

In order to mount small nozzles of high quality into a narrow nozzle carrier, a technique was used whereby the orifice nozzles were mounted into a holder and the holder was then mounted into the nozzle carrier. The nozzle holder was externally threaded so the high-pressure water would not dislodge the plug. The plug was then welded into place to assure sealing around the nozzle plug. This method of mounting proved satisfactory for the testing done in this program.

The nozzle configuration shown in Figure 14 was used in the coring head as was the method of mounting the nozzles. The design of the coring head is presented in Section 4.2.

4.2 Coring Head Design

To demonstrate the feasibility of coring with waterjets, a laboratory scale coring barrel and coring head were designed. The coring mechanism consisted of a swivel for core barrel rotation, a manifold block to distribute water to the individual nozzle, high-pressure tubing, a nozzle head, and an inner and outer tube. A schematics of the swivel and core barrel are shown in Figures 15 and 16 respectively.

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In order to simulate an actual coring device, the core barrel was rotated. This necessitated the use of a high-pressure swivel. No commercial high-pressure swivel was available so a swivel was made for this program. The swivel is shown in Figure 15. The swivel is a scaled down version of a swivel developed by Flow Industries, Wang, Robins, Olsen (1976), for a waterjet assisted tunneling program. The swivel is designed for high-pressure and low rpm (up to 75). The swivel was tested for approximately 4 hours and no wear problem arose. A swivel such as this is capable of being used in other than laboratory applications. The feasibility of making such a swivel and its importance to a high-pressure field coring system is discussed in Section 5.

The core barrel shown in Figure 16 consists of a manifold, an inner and outer core barrel, high-pressure tubing connecting the manifold to the nozzle, and a coring nozzle head. The nozzle manifold was drilled so that flow could be supplied to up to eight high-pressure nozzles. Nozzle ports that were not used could be blocked off. High-pressure water was delivered to the nozzle by high-pressure tubing which went from the manifold to the coring head. High-pressure water was supplied to each nozzle by an 0.25 in. O.D. by 0.063 in. I.D. high-pressure tube. The high-pressure tubing was then surrounded by an inner and outer core barrel. Since no thrust is exerted on the rock when it is cut by the waterjets no stiffener rods were required in the core barrel. The coring head had a 3 in. O.D. and a 2 in. I.D. With a standoff distance of 0.25 in., a 1.9 in. diameter core was recovered and a 3.5 in. diameter hole was cut. The nozzle configuration in the coring head was the configuration described in 4.1. A photograph of the core barrel is shown in Figure 17.

The coring barrel and head was used to core up to 12 in. long cores in Charcoal Granite. The results are presented below.

4.3 Coring Tests

The coring device, previously described, was used to cut cores in Charcoal Granite. The cutting was done in a submerged condition at ambient conditions. Initially, the nozzle was fed downward at a constant rate, this method, however, proved impractical due to variations in the

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advance speed of our cutting booth traversing mechanism. To compensate for this, spacers were placed on the bottom of the core barrel. The welded-on spacers can be seen in Figure 17. The use of spacers proved adequate in keeping the coring head from contacting the rock. Even with the spacers, the torque and thrust requirements were minimal (on the order of 2 hp or less for the torque).

Testing was conducted to demonstrate that waterjets could drill a large diameter hole and recover a core. Secondly, tests were conducted to determine the optimum advance rate and rotational speed for coring Charcoal Granite. Cores cut in granite are shown in Figures 18 and 19. In Figure 18 the core was not removed from the hole. Figure 19 shows a hole and the recovered core. In order to remove the core, the coring head is rotated. This rotation with no vertical advance allows the jet to cut under the core. With the resultant stress riser the eccentricities of the core barrel exert enough of a force on the core to break it off at the base. These pictures in Figure 18 and 19 clearly demonstrate that waterjets can cut a core in hard rock. The core recovery in these tests was complete.

Tests were conducted in order to optimize the coring rate in Charcoal Granite. The tests were conducted using 104 hydraulic horsepower. This quantity was fixed throughout the tests. The test pressure was 45,000 psi. The parameters, varied during the tests, were the advance rate and rpm of the core barrel. The general finding of the study were similar to that found by other investigators in waterjet drilling studies, Summers (1976). The findings are that: the optimum traverse velocity from linear cutting corresponds to the optimum rpm. The quality of the hole (hole finish) depends on the ratio of feed rate to rpm; and a feed rate to rpm ratio that is too large results in no core recovery. A summary sheet of three tests showing these results are given in Table 3. The condition where the advance rate equals 37 fph and the rotation speed 75 rpm was the optimum for coring. At the other conditions, either no core was recovered or the core bit ran into the rock face. The optimum conditons for granite compare quite favorably with conventional core bits in a similar rock.

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5. System Feasibility Study

Prior to the start of the experimental program a system feasibility study was conducted to determine if high-pressure (up to 60,000 psi) pumping is compatible with standard drilling equipment and, if not, whether the technology exists to make a compatible system. Hardware and fluid compatibility was studied in this portion of the program. This was done at the start of the program because if high-pressure coring could not feasibly be done in the field then laboratory feasibility would have little meaning.

Before a feasibility study could be initiated, it was necessary to develop several systems that could be used for geothermal coring. Various methods of waterjet coring were examined. The systems that were most compatible with high-pressure were evaluated. This study resulted in two basic high-pressure coring systems; both use a dual-pipe concept. The systems are described in this section.

High pressure waterjet coring appears to be a feasible method of coring in geothermal formations. Field tests of coring systems could be conducted at the present time with only a modest development effort. No extensive development programs are required for such tests. The components necessary for the coring systems can be designed and fabricated using currently available products or state-of-the-art technology. The systems will be compatible with standard rig equipment and will not represent any safety hazard to rig personnel.

5.1 High-Pressure Waterjet Coring Systems

In order to conduct a feasibility analysis of high-pressure waterjet coring systems and components, it was first necessary to narrowly define which systems would be suitable. The following criteria was used to judge the proposed systems:

- (a) The physical size of the system must be compatible with standard drilled hole sizes,
- (b) The pressure losses through the system must be kept to a minimum,
- (c) The system must not represent any safety hazard to personnel,
- (d) The additional power requirements must be minimized,

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- (e) Methods of joining the high-pressure fluid pipe must exist, and the seal life must be acceptable,
- (f) The overall system must be reliable, and
- (g) The system must be easy to operate.

Once the systems that best meet these criteria were chosen, a review of the systems, component by component, could be made to determine compatibility with the high-pressures that would be required to adequately core geothermal formations.

Two systems were selected on the basis of the above criteria for the coring device. Both the schemes are based on modifications of the conventional coring systems and involve a dual-pipe scheme and a two-passage swivel. The systems and their components are described in this section.

5.1.1 Supplying High-Pressure Fluid to Cutting Nozzles

Before it could be determined which system would be considered for high-pressure waterjet coring, it first had to be determined if we would pump all the fluid at high-pressure or only that fluid required for the cutting jets. This question is a fundamental one because it greatly affects the type of system used for coring. If all the fluid is pressurized, the result is a conventional type of drilling system (single pipe); if only the cutting jet fluid is pressurized, then a two-pipe drilling system is required, as well as a new type of drilling operation. To decide which system was better for waterjet coring, we first examined the two approaches to pumping from a technical point of view, and then, from the point of view of rig operations. The methods of fluid pumping were examined from the point of view of the drill pipe that would be used. Principally, we examined what would happen if a single drill pipe was used to carry the high-pressure fluid and what would happen if a two-pipe system was used. This examination yielded a consistent conclusion from both viewpoints.

The use of high-pressure fluids requires special care in the selection of the tubing that would be used to carry the fluids. At the high-pressures required (up to 60,000 psi), the tubing should have an O.D.-to-I.D. ratio of approximately 3:1 if a safety factor of four is to

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be maintained. Then, from a coring standpoint, larger than standard holes must be drilled in order to obtain a given size of core. In addition, the weight of such tubing would be significantly higher than conventional drill pipe, and this tubing would require larger drill rigs to support the string. A standard 5-1/2-in.-O.D. type E drill pipe weighs 24.7 lbs/ft while a high-pressure 5-1/2-in.-O.D. drill pipe would weigh 65 lbs/ft and would have an I.D. of 1.37 in. The small I.D. of the high-pressure drill pipe would result in much greater pressure losses than occur with a conventional drill pipe. Both of these factors lead to higher drilling costs, which are undesirable.

Another aspect of high-pressure drilling is safety to personnel and equipment. If a drill pipe containing high-pressure tubing bursts, it would do so with a large release of energy. A 5-in.-I.D. drill pipe, 30 feet in length, would have an internal force of over 300×10^6 lbs at 60,000 psi. The release of such a force would almost certainly result in damage to equipment and possibly injury to personnel. If a dual-pipe system was used, a safety problem would not exist. For example, if we use a 1/4-in.-I.D. high-pressure line surrounded by a 5-in.-O.D. drill pipe, even a catastrophic failure of the inner tube would result in a pressure pulse at the outer wall of only 3,000 psi. This pressure rise would not burst the drill pipe, and thus, no damage would be incurred on the rig.

A third consideration for high-pressure drilling is the amount of energy required to pump the drilling fluid to high pressures. If we pump all the fluid at high pressures, as would be the case of a single-pipe system, a large amount of power would be required. As an example, if 300 gpm of liquid is pumped at 60,000 psi, the power required is approximately 11,000 horsepower. This number does not account for losses in the pumping system, so the actual horsepower needed would be even higher. If a dual pipe was utilized, approximately 500 horsepower or less would be required to produce the high-pressure fluid. The latter is a much more reasonable power requirement and would be more economical.

A final consideration is the sealing of the high-pressure tubing. Methods presently exist for sealing high-pressures, and new methods will undoubtedly be developed; however, all these methods have one fact

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in common -- the larger the seal area the more difficult it is to seal. Consequently, sealing a small-diameter tube for high-pressures is easier and more feasible than sealing a larger tube. A large-diameter tube would be required in a single-pipe system. Since sealing could prove to be one of the largest problems in high-pressure coring, we would most easily solve it by using a dual-pipe system.

From the above arguments, it is felt that a dual-pipe system will meet the system criteria better than a single-pipe system. There will, however, still be problems associated with dual pipes, particularly in connection with sealing and ease of operation. Sealing of small-diameter high-pressure tubing can be accomplished by standard means, but the available method is slow and time-consuming. To better use a dual-pipe system, we need to develop new sealing techniques.

The ease of operation of a dual-pipe system will be highly dependent on the method of sealing. At the present time, it appears that a dual-pipe system will be far more difficult to assemble and disassemble than a standard drill string. This difficulty will present two major problems: the increase in the time required to pull a drill string, and the retraining of drill personnel to handle the dual pipes. Still, these problems can be handled more easily than the technical problems that exist for a single, high capacity, high-pressure drill string.

5.1.2 High-Pressure Waterjet Coring Schemes

Two coring schemes were devised for the feasibility study. Both use a dual-pipe system, and the schemes are basically similar. The principal difference is in the manner of achieving core barrel rotation. In one scheme, a conventional rotary table is employed; in the second, a down-hole turbine or mud motor is used to achieve rotation. Both schemes require a two-passage swivel. The rig equipment was changed as little as possible, so most of the equipment used in these schemes are standard, off-the-shelf items. Below, the two schemes are described in detail.

5.1.2.1 Coring System I

Coring system I is shown schematically in Figure 20. In this system, rotation is achieved with a standard rotary table. The two-passage swivel is located where a conventional swivel would be located

on the drill string. This location is indicated in Detail I of the figure. Not shown in this figure is the location of the high-pressure pumps; they can be located on the rig floor or directly above the swivel and will be connected to the swivel by high-pressure tubing. A description of the operation of this system is presented below.

The high-pressure fluid and the standard drilling fluid are delivered to the two-passage swivel by their respective pumping systems. The exit of the swivel leads to coaxial tubing, consisting of small-diameter high-pressure tube inside a standard kelly section. Rotation of the drill string and vertical motion are achieved by a conventional rotary table and a traveling block, respectively. The coaxial tubing extends to the coring section, which is located at the bottom of the borehole. In the coring section, the high-pressure tubing is split into two to four small tubes and is guided into the annulus of the core barrel above the down hole coring swivel for the inner barrel. The tubing then extends down to the cutting head, where it is manifolded to give an even pressure distribution for the coring jets. The cutting jets are located at the bottom of the manifold. A schematic of the core barrel is shown in Figure 21(a). The operation of this system is identical to a standard coring system except the coaxial tubing requires special connecting procedures. These procedures will depend on the final design of the coaxial high-pressure tubing.

The system as described above is a direct adaptation of a conventional coring system to a high-pressure waterjet coring system. The components that have to be modified for use under high pressures are the swivel, the tubing, and the core barrel. These modifications will be described in Section 5.2.

5.1.2.2 Coring System II

The second coring scheme is shown schematically in Figure 22. In this system, rotation is achieved by a downhole turbine or mud motor. A two-passage swivel and the core barrel will be located below the turbine.

The high-pressure fluid and the standard pressure drilling fluid are delivered to the two-passage swivel, which is suspended from the traveling block, by their respective pumping systems. The traveling block gives vertical motion to the drill string. The exit of the two-passage swivel

goes through a coaxial section into a kelly section. The kelly section is needed for proper positioning of the drill string. From the kelly section, the high-pressure tubing extends down to the turbine and goes through the turbine shaft. The mud passes through the annulus to drive the turbine. At the exit of the turbine, the high-pressure water and mud go through a second downhole swivel. The swivel is shown in Figure 21(b). From this point, the fluids pass through the core barrel in manner similar to that described in Section 5.1.2.2.

The system as described above is a modification of standard coring device, but it uses conventional equipment to obtain rotation. The high rotation speeds of the turbine could be necessary to obtain the optimum traverse speed of the jets for cutting. Lower speeds can be obtained with a mud motor if they are required. A system such as this would also be more amenable to using a downhole high-pressure pump if such a pumping system should prove feasible. The components that must be modified or constructed specially for this system are the surface and downhole swivels, the drill string, the transition sections, and the core barrel. These modifications will be described in Section 5.2.

5.2 High-Pressure Waterjet Coring Component Feasibility

Once the coring schemes were determined, we were able to determine the system components and what components were currently available to the drilling industry. After examining available components and comparing their specifications against our requirements, those components that needed modifications were determined. Preliminary design of the modified components was done using existing high-pressure technology and standard high-pressure components when available. The results are presented in this section.

Examination of currently available drilling equipment indicated that standard components are not suitable for high-pressure waterjet coring. No standard component was capable of going to pressures higher than 15,000 psi. Even at these pressures, the equipment is marginal, and safety and reliability would be a problem. Consequently, modified equipment will be necessary for high-pressure waterjet coring or drilling. High-pressure technology, however, does exist, and, by adapting existing high-pressure equipment to standard rig components, a rig that is compatible with high-pressure drilling

systems can be developed. The feasibility study concentrated on adapting standard rig equipment for use with high fluid pressures.

Because of the reasons presented in Section 5.1.1, we have adopted a dual-pipe system for high-pressure drilling. Based on an equipment point of view, a dual-pipe system is the more advantageous for equipment modification. It allows for the containment of the high-pressure fluid in small tubing, and also, in the dual-pipe system, there is a low mass flow rate of the high-pressure fluid. Thus, we can use existing low-flow-rate equipment and tubing for the high-pressure fluid, and the system will keep the high-pressure fluid separated from the standard equipment. Standard high-pressure equipment is used for the modified swivels, drill string and coring head. These modifications are described in detail.

5.2.1 Swivels

5.2.1.1 Above-Ground Swivel

A graphical representation of a modified two-passage swivel is shown in Figure 20, Detail I. This is a modified conventional swivel. To convert a conventional swivel to a two-passage swivel, we replaced the standard goose neck by a special block. In this block, we placed a high-pressure swivel. This swivel could be a conventional high-pressure swivel, which is capable of holding the pressure, or it could be another design, such as a leaking swivel or a swivel with metal to metal seals. Surrounding the outside of the swivel case will be a static seal, capable of containing the 3,000-psi mud. The high-pressure tubing, from the high-pressure swivel, extends through the throat of the conventional swivel. Drilling fluid enters the second passage and is ducted through the conventional swivel as it normally would be. Figure 23 is a schematic of the design.

The above-ground swivel is only slightly modified from a conventional oil-well-type swivel. It uses all components of conventional swivels and simply uses a commercially available swivel for the high pressure. In this swivel, as with all other components of this system, proven equipment is being used. In this way, there are no technical barriers to overcome, and the system should have relatively high reliability.

5.2.1.2 Downhole Swivel

Scheme II uses a downhole turbine, and the rotation of the drill string requires a swivel located downhole and one similar to that described in 5.2.1.1. If a downhole swivel is needed, it will have to be built specially for this coring device. A schematic of such a component is shown in Figure 21(b). The swivel will be located between the turbine and core barrel, and it would allow for rotation of the high-pressure tubing. There are two sets of seals for this swivel. The first seals the high-pressure water; the second seal keeps the mud out of the swivel. Work has been done on swivels of this type and has found that they can be manufactured to use either tight seals or leaking seals. Based on current knowledge of high-pressure swivels, a downhole swivel using state-of-the-art technology can be fabricated.

The use of a downhole swivel is not a new idea. For example, a swivel is located in the core barrel to keep the inner barrel from rotating. Servicing, however, is obviously difficult; therefore, it may prove more advantageous to use an above-ground swivel.

5.2.2 Core Barrel

The core barrel for high-pressure waterjet coring has been modified as little as possible from the standard design. The main change in design is that the outer casing is larger in both O.D. and I.D. than that of a standard barrel so that high-pressure tubing can be strung through the annulus. Consequently, a 2-1/8-in.-O.D. internal core barrel with a 5-3/4-in.-O.D. outer barrel to create a larger annulus is considered in this study. The standard dimension for the outer barrel is a 4-1/8-in.-O.D. As a result, the core barrel for high-pressure waterjet coring is larger than a conventional barrel, but this larger diameter will not result in the need for larger holes since the diameter of the coring head determines the ultimate hole diameter. In general, however, smaller stabilizers will be required.

A schematic of high-pressure waterjet core barrel is shown in Figure 21(a). As seen in the figure, the high-pressure tubing enters the core barrel, is split into smaller tubes, and then is channeled into the core

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barrel annulus. This action occurs above the core barrel swivel so that no rotation is imparted to the core catcher. The high-pressure tubing then extends to the coring head, where it feeds the nozzles. The nozzle array will be determined during the experimental portion of this program. The drilling fluid in the core barrel is ducted to the annulus in the standard manner. It exits the annulus above the cutting head, where it is mixed with the jet fluid and the cuttings and then transports the cuttings to the surface.

5.2.3 Drill String

The drill string for high-pressure waterjet coring will consist of a drilling fluid pipe and a high-pressure fluid pipe. In the dual-pipe scheme, the elongation and thermal expansion of the two pipes must be matched to avoid buckling of the drill string. The two items that have to be determined are the manner of sealing the high-pressure tubing and the procedure for assembling the dual pipes. At the present time, sealing is the most crucial component of the coring systems since it is the most different from a conventional drilling operation.

The high-pressure tubing can be sealed using commercially available ferule type fittings. These are not quick-disconnect fittings, but they are rugged and seal well at high pressures. If fittings such as these were used, a procedure must be developed for rapid and safe assembly, however, the procedure would never become as fast as conventional drill-pipe assemblies. This method of sealing is not the most advantageous because of assembly time, but it will work for the purpose of field testing. It does make it possible to conduct high-pressure waterjet coring field tests without major seal development.

Other types of seals for use with high pressures do exist. Some examples are packed seals and tapered metal-to-metal seals. For oil-well operation, each has a disadvantage. Packed seals will not be reusable, and the sealing of tapered metal-to-metal seals depends on the cleanliness of the surfaces. Although these seals do not seem suitable at the present time, by using existing knowledge of seals, it may be possible to develop quick-disconnect high-pressure seals within a short period of time. This type of seal will make high-pressure waterjet coring more practical, but with ferule-type fittings, high-pressure coring is currently feasible.

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The exact assembly procedure for dual-pipe systems will depend on the scheme used and the seals available. Once this has been determined, we will have to develop a compatible assembly procedure and demonstrate it to rig personnel.

5.2.4 High-Pressure Pump

Because of the dual-pipe concept, the pumping requirements for the high-pressure fluid are considerably easier than those of a single-pipe system. For the dual-pipe system, 250 to 500 hydraulic horsepower will be required. This horsepower can be supplied for example, by one or two commercially available intensifier pumps. These pumps are proven products, and can pump either water or polymer to pressures of up to 60,000 psi. Mud would be difficult to pump, but, based on our findings discussed in Section 5.3, this presents no limitation. These pumping units are reliable and will be suitable for use in oil fields.

5.3 Feasibility of Waterjet Coring Using Water, Polymer, and Drilling Mud

In the drilling of deep wells, a special drilling fluid is generally required, depending on the depth of the well and the geological formation being drilled. These are a variety of reasons for choosing a given drilling fluid; some determined scientifically, others by experience.

Briefly stated, the reasons for using a drilling fluid are:

- (a) To remove the cuttings from the bottom of the hole and carry them to the surface,
- (b) To cool and lubricate the bit and drill string,
- (c) To wall the hole with an impermeable cake,
- (d) To control subsurface pressures,
- (e) To hold cuttings and weight material in suspension when circulation is interrupted,
- (f) To release sand and cuttings at the surface,
- (g) To support part of the weight of the drill pipe and casing,
- (h) To reduce to a minimum any adverse effects upon the formation adjacent to the hole,
- (i) To ensure maximum information about the formations penetrated, and
- (j) To transmit hydraulic horsepower to the bit.

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For all of the above reasons, the choice of drilling fluid is very important for well control. It is not the objective of this program to develop drilling fluids that are compatible with waterjets, but rather to develop the waterjet system so that it is compatible with the drilling fluids generally in use today.

There are two methods of approaching this problem. The first approach is to pump the drilling fluid through the nozzles at high pressure. The second approach is to use a waterjet for cutting and a standard drilling fluid for well control. Both methods have benefits and disadvantages which will be discussed in detail. At the present time, based on our analysis, the second approach appears to be the most advantageous from a hardware and economy point of view.

5.3.1 Use of Drilling Fluid As Jet Fluid

A drilling fluid that is directly compatible with the high-pressure intensifier and nozzles would be the simplest setup for high-pressure fluid jet coring. Currently, we believe that this may not be possible unless the drilling fluid is water (which could certainly be pumped) or possibly, polymer drilling fluid.

Experiments have been conducted on a polymer-water solution. The results of the experiments indicate that the high-pressure intensifier pump can adequately pump polymer and that no excessive wear of the high-pressure seals takes place. There could be a problem, however, with pumping polymer from a fluid property point of view. In the intensifier, high shear loads are exerted on the fluid; in addition, the fluid experiences a high shear as it exits the nozzles. In many cases, high shear will break the long-chain polymer molecules and cause the fluid to change its properties and, therefore, change its ability to function as an adequate drilling fluid, particularly when it is recycled. Whether or not this happens depends strongly on the polymer used. Consequently, we must determine if the phenomena of polymer chain breakup in high-shear flows will be a problem for polymer drilling fluids. It is will, we must develop an alternative scheme, as discussed in Section 5.3.2.

When mud is the drilling fluid, there is much greater problem in using it as the fluid for the high-pressure coring device. Some of the problems that will be encountered are:

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- (a) The wear of the high-pressure seals in the intensifier will be increased over the wear caused by a pure, filtered fluid because of the abrasives in the drilling mud,
- (b) The abrasives in the fluid will result in higher nozzle wear, which limits bit life and can cause the jet to lose much of its cutting effectiveness because of increased jet instability,
- (c) A danger of scratching and/or gouging the high-pressure components of the system exists. Any scratches will be sites for stress concentrations which could result in equipment failure,
- (d) Drilling abrasives cannot be filtered well enough to allow the use of small-diameter nozzles. Exxon found that nozzles smaller than 1/8 in. would have plugging problems. For a nozzle of this diameter and a jet with a stagnation pressure of 60,000 psi, 4,000 hydraulic horsepower are required to power the jet.

For these reasons, mud would be very difficult to pump to high pressures in an intensifier. To pump mud, we would have to undertake an extensive pump program.

5.3.2 Water-Drilling Fluid System

As an alternative to pumping drilling fluid at high pressures, we propose a scheme for using a two-fluid system. In this scheme, water would be the jet fluid, and, consequently, it would be pumped through the nozzles at high pressure. Water would be the cutting media in this method. The drilling fluid necessary for cutting removal, well control, etc., would be pumped at a lower pressure to the well bottom and then mixed with the water. This alternative would eliminate the problems associated with both polymer and mud drilling fluids that were mentioned in Section 5.3.1. Also, this system would maximize equipment reliability because of increased seal and nozzle life, and would minimize the energy requirements for drilling. If water was the jet fluid, five nozzles either of 0.014 in. or 0.02 in. diameters could be used. Operation of these nozzles would require 250 hp or 500 hp respectively, and a flow rate of only 7 to 15 gpm of water. This power level is far more reasonable than the 4,000 hp required for a 1/8-in. nozzle.

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The amount of water used in the two-fluid scheme represents approximately 5 percent of the total fluid flow, and consequently, we do not anticipate that any special mud-handling equipment will be required for the system. In our examination of drilling fluids and high-pressure coring, we have found that the two-fluid system (water-drilling fluid) has many advantages over a single-fluid system. The two-fluid system is easier from a mechanical point of view, and its use would result in more efficient and durable equipment. Also, the two-fluid system will more effectively conserve energy. The experience of Exxon with high-pressure mud drilling supports these arguments.

5.4 Alternative Coring Schemes

The coring systems presented in Section 5.1 were based on the philosophy of adapting available high-pressure components to existing drilling apparatus. These systems could be used for field testing in a relatively short time and would require no major development program to get them out in the field. There are, however, alternative systems that are not yet ready for use but, with some development effort, could be available for testing in several years. One of these systems could possibly be the most advantageous for high-pressure coring and drilling, and, should be examined. Systems that are often mentioned for high-pressure fluid jet applications use downhole intensifiers as opposed to above-ground systems. With a downhole intensifier, high-pressure fluid would not have to be pumped downhole since all high pressures would be generated by the downhole intensifier. This type of system could have distinct advantages over "conventional" type systems, and a development effort could be justified for long-term technology utilization.

Various types of high-pressure downhole intensifiers have been proposed. Of the various proposed types, three will be discussed here. They are:

- (1) Clear-fluid-powered/clear-drilling fluid system,
- (2) Clear-fluid-powered/mud-drilling fluid system,
- (3) Mud-powered/mud-drilling fluid system.

These systems will be discussed with regard to their application, the development work needed, the time required to get them into the field, and their chances of success.

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5.4.1 Clear-Fluid-Powered/Clear-Drilling Fluid System

Of the three downhole intensifier schemes previously mentioned, the clear-fluid-powered/clear-drilling fluid system is the most advantageous from a design standpoint. The advantages of this type of downhole intensifier scheme are:

- (a) The intensifier would be in a relatively clean environment,
- (b) The particles in the fluid could be removed by filtration,
- (c) The system uses one fluid, so there is no need for coaxial tubing,
- (d) Seals capable of operating in a clear-fluid environment already exist, and
- (e) The operation of the drilling system would not differ from that of a conventional drilling system.

There are, however, problems in designing this type of intensifier, in particular, and any downhole intensifier, in general. Some of the problems are listed below. The first is specific to the clear-fluid/clear-fluid intensifier, while the next three are problems that will be encountered with any downhole intensifier. The problems are:

- (1) The areas of application will be limited because of the need for other types of drilling fluids in many situations,
- (2) The intensifier will have to be large if it is to deliver significant amounts of horsepower. If it is designed to fit into a small drill pipe, its length may prove to be excessive,
- (3) The fluid has to be filtered in order to remove all cuttings, and
- (4) Servicing of downhole intensifiers may be a limiting factor in determining the actual advantage of such a system.

Even with the problems that will be encountered in the design of a water-water intensifier, this system should prove to be the most technically feasible of the possible downhole intensifiers. The state-of-the-art in intensifier design is such that a clear-fluid-powered intensifier can be fabricated and designed to fit in a relatively small (on the order of 4 in. diameter) drill pipe. Additional work would be

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necessary to make these intensifiers as efficient as possible in energy output and space required. With present technology, however, an operating downhole intensifier could be designed and fabricated in a reasonable period of time using existing technology.

5.4.2 Clear-Fluid-Powered/Mud-Drilling Fluid System

In order to make a downhole intensifier a more general drilling device, it would be desirable to have the intensifier be part of a conventional drilling fluid system. From a technical viewpoint, the easiest way to accomplish this is to have a coaxial drill pipe scheme, where clear-fluid is supplied to the intensifier by one pipe, and conventional drilling mud is pumped through the other pipe. In this scheme, all the fluid pumped through the coaxial drill pipe is at a relatively low pressure. Thus, the sealing requirements that are imposed in the other coring schemes described in Sections 5.1 and 5.2 are eliminated. Many of the advantages listed for the clear-fluid/clear-fluid system hold true for the clear-fluid/mud system; however, several problems arise with the clear-fluid/mud system which are not problems of the clear-fluid/clear-fluid system. The problems that will be encountered are:

- (1)through(3) Problems 2 through 4 listed in Section 5.4.1,
- (4) Ensuring complete isolation of the mud from the intensifier,
- (5) Possible excessive dillution of the drilling mud; a 250 hp intensifier has to be driven by 140 gallons of clear-fluid per minute for a 20:1 area ratio. This fluid would have to be dumped into the borehole and mixed with the mud.
- (6) A possible unfavorable differential pressure for the dumping of the driving fluid,
- (7) Coaxial tubing requiring new rig techniques, and
- (8) A need for an extensive above-ground mud-separation facility.

The above problems make the clear-fluid/mud system a more difficult system to develop than the clear-fluid/clear-fluid system. There is a greater need in the clear-fluid/mud system for basic work in intensifier design and drill string design. New and innovative ideas will be required to make the clear-fluid/mud system a viable downhole system. Because of these requirements, the development of this system will take more time

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than the clear-fluid/clear-fluid system. It appears, however, that if the clear-fluid/ mud system is determined to be an advantageous system, it could be developed.

5.4.3 Mud-Powered/Mud Drilling Fluid System

The most versatile type of downhole intensifier that could be built would be a mud/mud type system. With this type of intensifier, no new procedures or equipment would be needed on the rig. There would be no need for a coaxial drill string, and standard drill pipe assembly procedures could be used. In addition, this sytem would be versatile enough to drill in any type of geological formation and would require no above-ground mud-handling system other than what is normally used. The mud/mud system also represents the most difficult system technically. The problems with this type of system are similar to those of the other downhole intensifiers, plus several additional problems. Also, all the problems of pumping mud that were mentioned in Section 4 for the "standard" coring schemes would apply to the downhole intensifier as well. Some of the problems that would be encountered are:

- (1)through(6) Same as section 5.4.2,
- (7) Poorer system reliability because of increased wear of the intensifier and possible plugging,
- (8) Increased wear of the high-pressure seals in the intensifier over wear caused by abrasives in the drilling mud,
- (9) Higher nozzle wear, due to abrasives in the fluid, which limits bit life and can cause the jet to lose much of its cutting effectiveness because of increased jet instability,
- (10) Danger of scratching and/or gouging the high-pressure components of the system; any scratches will be sites for stress concentration, which could result in equipment failure, and
- (11) Difficulty with drilling abrasives filtering well enough to allow the use of small-diameter nozzles. Exxon found that nozzles smaller than 1/8 in. would have plugging problems. For a nozzle of this diameter and a jet with a stagnation pressure of 60,000 psi, 4,000 hydraulic horsepower are required to power the jet.

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Many of the problems of intensifier mud pumps are common to all mud pumps. For many of the above reasons, current mud pumps go up to pressures of 20,000 psi. Generally, they run at pressures of less than 5,000 psi. Consequently, high-pressure (up to 60,000 psi) mud pumps would represent a totally new generation of pumps. This development would be a very large effort and would, in all probability, take many years. The mud/mud drilling system is a long way from being technically feasible, but it should not be forgotten. If high-pressure drilling proves to be advantageous, then the mud/mud system will be required because it can be used in the widest variety of drilling applications.

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6. Conclusions

Based on both the linear cutting tests and the coring tests, it can be concluded that the use of waterjets to core hard rocks under geothermal well conditions is feasible. Based on linear cutting data, the study concluded:

1. Under nominal back-pressure conditions, waterjets can effectively cut granite and basalt,
2. Of the environmental parameters studied, back-pressure had the greatest effect on waterjet cutting due to rapid pressure decay,
3. Temperature and confining pressure have a minimal effect on jet cutting effectiveness of hard rocks, and
4. Under simulated conditions, waterjets do not effectively cut basalt due to its high threshold pressure.

Based on the results of the coring tests, the advantages of waterjet coring over conventional coring methods are:

1. The coring rate is enhanced over a conventional coring device,
2. The recovery of core should approach 100% since no mechanical force is put on the cored rock,
3. Waterjets can core through soft and hard layered material since very little thrust is required on the bit, and
4. Deep well conditions (elevated pressures and temperatures) do not have a significant effect on waterjet coring.

The limitations of waterjets for coring based on this study are:

1. Systems required for waterjet coring are complex, particularly with regard to pumping high-pressure fluids through coaxial drill string,
2. Sealing of high-pressure tubing under work environments will be a crucial problem,
3. Waterjet coring will be of most benefit for difficult to core formations where rubbelized or very hard rock is encountered, and

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4. Under deepwell conditions pressures on the order of 60,000 psi will be required to effectively cut very hard rocks.

High-pressure waterjet coring however, appears to be an overall technically feasible method of coring in geothermal formations. Based on our feasibility study, high-pressure waterjet coring is a realistic process. There will be equipment reliability problems, which can best be solved by experience and by an effort from the major oil-well supply companies.

More work needs to be conducted before waterjets can be used in actual field work. Future work should be aimed at equipment development since this is the pacing area for field applications. Some areas for additional work are:

1. Developing an easy to assemble dual drill string capable of withstanding high pressures if a surface pump is used,
2. Developing reliable high-pressure seals and swivels, and
3. Developing a downhole intensifier, designed and tested for deep drilling.

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Table 1. St. Cloud Gray Granodiorite Test Results.

Property ¹	Composite	
	Mean	CV ²
Porosity.....pct..	0.08	61.2
Permeability..... $\mu\text{m}/\text{sec}..$	(³)	-
Density..... $\text{g}/\text{cm}^3..$	2.72	0.1
Shore hardness.....	99.8	3.5
Compressive strength..... $\text{MN}/\text{m}^2..$	282	2.2
Do..... $10^3 \text{ psi}..$	40.9	2.2
Compressive Young's modulus		
..... $\text{GN}/\text{m}^2..$	70.8	9.1
Do..... $10^6 \text{ psi}..$	10.3	9.1
Tensile strength..... $\text{MN}/\text{m}^2..$	6.97	13.8
Do..... $10^3 \text{ psi}..$	1.01	13.8
Tensile Young's modulus.... $\text{GN}/\text{m}^2..$	30.0	24.1
Do..... $10^6 \text{ psi}..$	4.35	24.1
Pulse velocity..... $\text{km}/\text{sec}..$	4.60	4.5
Bar velocity..... $\text{km}/\text{sec}..$	4.21	5.1
Torsional velocity..... $\text{km}/\text{sec}..$	2.96	2.3
Dynamic Young's modulus ⁴ $\text{GN}/\text{m}^2..$	48.4	10.2
Dynamic shear modulus ⁴ $\text{GN}/\text{m}^2..$	23.9	4.5
Poisson's ratio ⁴	0.245	4.0

¹Specimen prepared with the long axis perpendicular to the top face (along Z-axis).

²Coefficient of variation, percent.

³Less than $1 \times 10^{-4} \mu\text{m}/\text{sec}.$

⁴Calculation is based on the assumption of isotropy.

Table 2. Dresser Basalt Test Results.

Property ¹	Composite	
	Mean	CV ²
Porosity.....pct..	0.19	57.3
Permeability..... $\mu\text{m}/\text{sec}..$	(³)	-
Density..... $\text{g}/\text{cm}^3..$	3.01	0.5
Shore hardness.....	94.1	2.6
Compressive strength..... $\text{MN}/\text{m}^2..$	440	11.0
Do..... $10^3 \text{ psi}..$	63.9	11.0
Compressive Young's modulus		
$\text{GN}/\text{m}^2..$	86.1	4.1
Do..... $10^6 \text{ psi}..$	12.5	4.1
Tensile strength..... $\text{MN}/\text{m}^2..$	22.1	39.7
Do..... $10^3 \text{ psi}..$	3.20	39.7
Tensile Youngs' modulus.... $\text{GN}/\text{m}^2..$	119	20.2
Do..... $10^6 \text{ psi}..$	17.3	20.2
Pulse velocity..... $\text{km}/\text{sec}..$	6.72	0.7
Bar velocity..... $\text{km}/\text{sec}..$	6.05	1.0
Torsional velocity..... $\text{km}/\text{sec}..$	3.80	1.2
Dynamic Young's modulus ⁴ ... $\text{GN}/\text{m}^2..$	110	2.5
Dynamic shear modulus ⁴ $\text{GN}/\text{m}^2..$	43.6	2.6
Poisson's ratio ⁴	0.264	1.6

¹Specimen prepared with the long axis perpendicular to the top face (along Z-axis).

²Coefficient of variation, percent.

³Less than $1 \times 10^{-4} \mu\text{m}/\text{sec}.$

⁴Calculation is based on the assumption of isotropy.

Table 3. Coring Results.

Feed Rate, fph	RPM	Result
37	50	Cut hole; no core recovered
37	75	Cut core; complete recovery
60	75	Feed rate too fast

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Figure 1. Cutting Booth.

Figure 2. Confining Pressure Chamber Schematic.

Figure 3. Temperature Chamber Schematic.

Figure 4. Intensifier Schematic.

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$T = T$
 $l = 0.25$ in.
 $D = 0.010$ in.
 $P_{\text{borehole}} = P_{\text{atm}}$
 $\sigma = \sigma_{\text{atm}}$

Δ Charcoal Granite
 $\circ$ Dresser Basalt

Figure 5. Effect of Jet Pressure on Cutting.

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Figure 6. Effect of Traverse Velocity on Jet Cutting.

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SUBMERGED JET

$P_o = 50,000$

$D = 0.01$ in.

$l = 0.25$ in.

○ Charcoal Granite
△ Dresser Basalt

Figure 7. Area Removal Rate versus Traverse Velocity.

Figure 8. Effect of Back Pressure on Jet Cutting.

Figure 9. Centerline Pressure Decay for Submerged Waterjet.

Figure 10. Effect of Confining Pressure on Jet Cutting.

$P_o = 50,000$ psi

$V_t = 4$ ips

$l = .44$ in.

$\sigma = 5,000$ psi

$d_o = .014$ in.

$P_o = 50,000$ psi

$V_t = 4$ ips

$l = .44$ in.

$\sigma = 10,000$ psi

$d_o = .014$ in.

Figure 11. Rock Samples on Several Confining Pressures.

Figure 12. Effect of Temperature on Jet Cutting.

Figure 13. Effect of Traverse Velocity on Slot Spacing for Two Rock Types.

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Figure 14. Linear Kerfing Nozzle.

Figure 15. High Pressure Swivel

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Figure 16. Core Barrel Schematic.

Figure 17. Core Barrel.

Figure 18. Cored Hole Cross Section.

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Figure 19. Recovered Core.

Figure 21. Component Schematics.

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Figure 23. Swivel Schematic.