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FEASIBILITY OF WATER JET CORING

Task I Report

By
James M. Reichman
John B. Cheung

July 1976

Work Performed Under Contract No. EY-76-C-06-2325

Flow Research, Inc.
Kent, Washington

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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TASK I REPORT

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Feasibility of Water Jet Coring

Task I Report

by

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Abstract

A study was conducted to determine the feasibility of using high-pressure waterjets to core in geothermal formations. The study first examined systems for high-pressure waterjet coring and then considered component compatibility with high pressure. The results of the study indicate that a coaxial drill string is required as is a two-passage swivel. The systems are designed to separate the high-pressure fluid from the standard drilling fluids. The results also show that high-pressure waterjet coring is a feasible process, which could be demonstrated in the field in a relatively short time.

In addition, the feasibility of using various types of fluid as the jet fluid was investigated. The results indicate that water or any clear fluid is the most desirable jet fluid. When a clear fluid is used in conjunction with drilling mud, no appreciable dilution of the mud occurs because of the small volume flow rate of water. In addition, using a clear fluid minimizes the wear of the components of the pump.

A study was also made to examine the feasibility of using downhole intensifiers as a source of high-pressure fluid. Of the various schemes that were examined, it appears that a water-powered/water-drilling fluid intensifier is the most technically feasible.

1. Introduction

Under task I of the program, "Research and Development of a High-Pressure Waterjet Coring Device For Geothermal Exploration and Drilling," a system feasibility study was undertaken. The aim of this task was to study the coring system components with regard to their compatibility with high pressure. In addition, we investigated the feasibility of waterjet coring using water, polymer, and drilling mud. The results of this task are presented in this report.

Before a feasibility study could be initiated, it was necessary to develop several systems that could be used for geothermal coring. We examined various methods of waterjet coring and evaluated the systems that were most compatible with high pressure. This study resulted in two basic high-pressure coring systems; both use a dual-pipe concept. In section 2 we will describe these systems in detail.

Once the systems had been specified, the compatibility of each component with high-pressure fluids could be evaluated. We first determined whether or not each component was commercially available oil-well equipment and then, whether or not it would be suitable for use under high pressure. If the component was not, then we made a preliminary design modification to determine if the system could be made compatible with a high-pressure coring system. These design changes were based on available high-pressure equipment or proven high-pressure technology. After we had analyzed each component to determine its suitability, we examined the feasibility of the total system. This analysis included the method of operation, the adaptability to standard rig equipment, and safety. The results of this study are detailed in section 3.

In task I, we also examined the feasibility of using high-pressure water, polymer, and mud drilling fluids. We compared systems that pumped one fluid with systems that pumped two fluids. In the one-fluid system, the drilling fluid is pumped at high pressure and then mixed with low-pressure fluid of the same density in the borehole annulus. In the two-fluid system, water is always the jet fluid, and it is mixed after exiting from the nozzles, in the bottom of the hole, with the drilling fluid above the coring nozzles. This mixing produces the proper drilling-fluid concentration for the lifting of cuttings and other well-control functions. Based on our study, the two-fluid system is the most advantageous for high-pressure waterjet coring. The findings of this study are discussed in section 4.

In the final part of task I, we examined the feasibility of using downhole intensifiers for coring. Three types of intensifiers are discussed: a clear-fluid-powered/clear-drilling fluid system, a clear-fluid-powered/mud-drilling fluid system, and a mud-powered/mud-drilling fluid system. The advantages and problems of each system are presented. In addition, we discuss the relative time to get each type of intensifier on-line. Based on the study, the clear-fluid/clear-fluid system is the most feasible for the short term. The results of this portion of the study are discussed in section 5.

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.

2. High-Pressure Waterjet Coring Systems

In order to conduct a feasibility analysis of high-pressure waterjet coring system components, it was first necessary to narrowly define what overall systems would be suitable. We used the following criteria 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.
- (e) Methods of sealing the high-pressure fluid pipe must exist, and the seal life must be acceptable.
- (f) The overall system must be reliable.
- (g) The system must be easy to operate.

Once the systems that best meet these criteria were chosen, we could go through the systems, component by component, to determine their compatibility with the high pressures that would be required to adequately core geothermal formations.

We selected two systems 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.

2.1 Supplying High-Pressure Fluid to the Cutting Nozzles

Before we could determine the systems that we would consider for high-pressure waterjet coring, we first had to determine 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 will be used to carry the fluids. At the high pressures that we use (up to 60,000 psi), the thick wall tubing should have a O.D.-to-I.D. ratio of approximately 4:1 if a safety factor of four is to be maintained. Then, from a coring standpoint, we must drill larger holes 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 this amount of 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 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. The large-diameter tube would be required if we used 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, we feel 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-pressure drill string.

2.2 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 is used to achieve rotation. Both schemes require a two-passage swivel. We changed the rig equipment 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.

2.2.1 Coring System I

Coring system I is shown schematically in figure 1. In this system, rotation is achieved with a standard rotary table. The two-passage swivel is

FIGURE 1 CORING SYSTEM I

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 will be located on the rig floor 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 a 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 are 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 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 jets. The cutting jets are located at the bottom of the manifold. A schematic of the core barrel is shown in figure 2(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 3.

2.2.2 Coring System II

The second coring scheme is shown schematically in figure 3. In this system, rotation is achieved by a downhole turbine. A two-passage swivel and the core barrel will be located below the turbine. A description of the operation of this system is presented below.

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 goes through the shaft of the downhole turbine, and the mud passes

Core Head

(a)

A-A
New Seal

(b)

B-B
New Seal

(c)

FIGURE 2 COMPONENT SCHEMATICS

DATE	7/1/68	BY	J. L. H.	CHKD	J. L. H.
REV	1	DESCRIPTION	Core Head	DATE	7/1/68
REV	2	DESCRIPTION	Core Head	DATE	7/1/68
REV	3	DESCRIPTION	Core Head	DATE	7/1/68
REV	4	DESCRIPTION	Core Head	DATE	7/1/68
REV	5	DESCRIPTION	Core Head	DATE	7/1/68
REV	6	DESCRIPTION	Core Head	DATE	7/1/68
REV	7	DESCRIPTION	Core Head	DATE	7/1/68
REV	8	DESCRIPTION	Core Head	DATE	7/1/68
REV	9	DESCRIPTION	Core Head	DATE	7/1/68
REV	10	DESCRIPTION	Core Head	DATE	7/1/68

FIGURE 3 CORING SYSTEM II

through the annulus to drive the turbine. At the exit of the turbine, the high-pressure water and mud go through a downhole swivel. The swivel is shown in figure 2(b). From this point, the fluids pass through the core barrel in a manner similar to that described in section 2.2.1.

The system as described above is a modification of a 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. 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 3.

3. 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, we determined those components that needed modifications. Preliminary design of the modified components was done using existing high-pressure technology and standard high-pressure components when available. The results of the feasibility study 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, we can develop a rig that is compatible with high-pressure drilling systems. Our feasibility study concentrated on adapting standard rig equipment for use with high fluid pressures.

Because of the reasons presented in section 2.1, 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 will be described in detail.

3.1 Swivels

3.1.1 Above-Ground Swivel

A graphical representation of a modified two-passage swivel is shown in figure 1, 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 Harwood high-pressure swivel, which is capable of holding the pressure, or it could be another design, such as a leaking swivel.

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 Harwood 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 4 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 the system, we are using proven equipment. In this way, there are no technical barriers to overcome, and the system should have high reliability.

3.1.2 Downhole Swivel

Scheme II uses a downhole turbine, and the rotation of the drill string requires either a swivel located downhole or one similar to that described in 3.1.1. 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 2(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. Flow Research has worked with swivels of this type and has found that they can be manufactured to use either tight seals or leaking seals. Based on our experience with high-pressure swivels, we can construct this downhole swivel using state-of-the-art technology.

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. With existing technology, either type of swivel can be designed.

3.2 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, we will use 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. The standard dimension for the outer barrel is 4-1/8-in.-O.D. As a result, the core barrel for high-pressure

FIGURE 4 SCHEMATIC OF THE SWIVEL

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 hole diameter. In general, however, smaller stabilizers will be required.

A schematic of a high-pressure waterjet core barrel is shown in figure 2(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 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 task II 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.

3.3 Drill String

The drill string for high-pressure waterjet coring will consist of a drilling fluid pipe and a high-pressure fluid pipe; it is not important whether side-by-side or coaxial tubing is used. 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 swage-lock-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, we could develop a procedure for rapid and safe assembly, but 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 if we use special assembling procedures. It does make it possible to conduct high-pressure waterjet coring field tests without any further 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 reuseable, 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 swage-lock-type fittings high-pressure coring is currently feasible.

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.

3.4 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 by one or two Flow Research, Inc., intensifier pumps. These pumps are proven products, and they 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 4, this presents no limitation. These pumping units are reliable and will be suitable for use in oil fields.

4. The 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. There 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,
- (j) To transmit hydraulic horsepower to the bit.

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 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 economic point of view.

4.1 The 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. If it will, we must develop an alternative scheme, as discussed in section 4.2.

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:

- (a) Because of the abrasives in the drilling mud, the wear of the high-pressure seals in the intensifier will be increased over the wear caused by a pure, filtered fluid,
- (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) There is a danger of scratching and/or gouging the high-pressure components of the system. 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.

4.2 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 4.1. 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 .014 in. or .02 in. diameters could be used. Operation of these nozzles would require 250 hp or 500 hp respectively, and a flow rate of only 10 to 15 gpm of water. This power level is far more reasonable than the 4,000 hp required for a 1.8-in. nozzle.

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. Alternative Coring Schemes

The coring systems presented in section 2 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 assembly 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, therefore, we should examine all alternative systems in more detail. 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:

- (a) clear-fluid-powered/clear-drilling fluid system
- (b) clear-fluid-powered/mud-drilling fluid system
- (c) 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.

5.1 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,
- (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.
- (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 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.

5.2 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 on the other coring schemes described in sections 2 and 3 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)-(3) Problems 2 through 4 listed in section 5.1.
- (4) Ensuring complete isolation of the mud from the intensifier.
- (5) Possible excessive dilution of the drilling mud; a 250-hp intensifier has to be driven by 140 gallons of clear-fluid per minute. 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 requires new rig techniques.
- (8) There would be 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 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.

5.3 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 system 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)-(6) Same as section 5.2.
- (7) Poorer system reliability because of increased wear of the intensifier and possible plugging.
- (8) Because of the abrasives in the drilling mud, the wear of the high-pressure seals in the intensifier will be increased over

the wear caused by a pure, filtered fluid.

- (9) 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.
- (10) There is a 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.
- (11) 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.

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.

6. Conclusions

High-pressure waterjet coring appears to be a 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. With the equipment that can be constructed at the present time, however, we can fabricate and test a workable high-pressure coring system. No major development is required for any component of either system.

Based on our study, water and water-polymer solutions can be used as the jet fluid. Mud does not appear to be compatible with high-pressure systems. Based on the total flow of fluids through a drilling system, it appears that water will be the most economical jet fluid and will be the most compatible fluid for high-pressure equipment. Water-polymer solutions would be used only if a distinct increase in cutting performance is observed during experimental studies in which submerged jets exit into a fluid with high back pressure.

According to our study of downhole intensifiers, it appears that a clear-fluid/clear-fluid intensifier system is feasible and could be applicable within a short period. The other types of systems will take more time to develop. The clear-fluid/mud system can be developed just by making small advances in current high-pressure technology. The development of the mud/mud system will take the most time and will require major strides in high-pressure pump technology. If the economics favor its development, however, the mud/mud system could be made through an extensive development program.