Advanced Mud Hammer Systems

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Abstract

Novatek and the U.S. Department of Energy's Federal Energy Technology Center have engaged in a cooperative effort to develop an integrated, steerable drilling system, which includes a mud-actuated hammer as a key element. The overall goal of this system is to provide significant cost reduction and technical advantage over current drilling practice, particularly in deep, medium-to-hard rock formations. Following preliminary evaluation of several advanced drilling concepts, a system concept has been developed which offers potential improvements in drilling rate, directional control, formation evaluation, and wellbore stability. This paper describes several key subsystems of the integrated drilling system concept in some detail, including an advanced telemetry system, a steerable drilling head that offers advanced sensing capabilities, and a means of lining the wellbore while drilling. Progress on prototype development is reported, and key technological developments and hurdles are described.

Introduction

In a study completed in 1994, a committee appointed to review the future needs of drilling technology concluded that "the principal thrust of an R&D program should be on the development of the smart drilling system." A "smart" drilling system is defined as a system that is able to sense conditions at and ahead of the drill bit and adapt to these varying conditions while drilling. This drilling system was identified to include, among other things: a) sensors to measure conditions at and ahead of the drill bit; b) improved methods to steer the drill bit; c) improved telemetry methods to transmit real time data to the surface; and d) continuous and instantaneous support of the borehole.[1]

Identifying that several of these functions could be supplied by a down-hole mud actuated hammer, Novatek began a joint development effort in 1997 with the US Department of Energy's Federal Energy Technology Center to develop key elements of this "smart drilling system." This effort was first to evaluate several competing methods of accomplishing the above-mentioned functions, and then proceed with development of the most promising technologies. The competitive evaluation just mentioned was accomplished during the first phase of work ending in fall of 1998. A discussion of the concepts evaluated and the conclusions of the initial evaluation have been submitted previously in reports to the U.S. Department of Energy.[2,3]

Since that time, Novatek has refined the designs of the key components of the smart system and has begun prototype manufacture to enable verification and further refinement of the various subsystems. The purpose of this writing is to report on these activities which have taken place since the phase I reports.

Objectives

The overall objectives of the present research effort are to decrease the cost of drilling wells and extend the capabilities of current drilling technology to more effectively tap energy reserves. More specifically, the program objectives are to:

1) Develop key elements of a smart drilling system including an improved steerable drilling head, advanced formation sensing means, high data rate communication between top and bottom of well, and an *in-situ* wellbore lining means, and
2) Provide means for integrating these individual elements into a complete system

The first objective mentioned above focuses on improvements to present drilling technology and is expected to yield tools and subsystems capable of stand-alone use*; the second focuses on compatibility of the subsystems and thereby assures that a complete system may be developed.

Approach

To accomplish the above objectives, the study has sought first to develop and exploit various features of Novatek's mud hammer drilling head. The features most readily exploited are the hammer's ability to improve penetration rate, its interaction with the formation, and the linear oscillation of the hammer piston. The first of these features offers the ability of the system to drill more rapidly, thereby helping to decrease well costs. The second feature offers novel means of diagnosing the formation characteristics at and ahead of the drill bit, thereby allowing adjustment of drilling parameters to meet changing drilling conditions, and facilitating direction of the drill into the desired formations. The third feature enables down-hole generation of high-pressure hydraulic power, which is important in further penetration rate increase and improved steering.

Although it is technically possible to use the oscillation of the hammer piston to also drive rotation of the drill bit, generate electrical power, and even send mud pulse or acoustic signals for communication with the surface, the present study has chosen not to pursue these functions because better approaches are possible. Since the hammer alone cannot accomplish the objectives outlined above, novel downhole mechanisms have been designed to complete the remaining objectives. These mechanisms include a very high data rate communications system and a means of lining the borehole while drilling.

As mentioned previously, the first phase of activity in this project has been a conceptual distillation process, wherein several competing concepts were evaluated, and the most promising were selected for further study. The current phase of work includes:

1. Generating detailed designs of the selected subsystems

* Varying development times and market pull for various of the concepts discussed herein will necessitate introduction of some of the technologies as stand-alone tools, or as enhancements which build upon existing systems. The first of these stand-alone tools will most probably be a down-hole hammer drill.

2. Building prototype models of these designs
3. Testing prototype models under laboratory conditions (and field sites where possible), and
4. Evaluating test results to determine the technical fitness and probable economic impact of the tested mechanisms.

A third phase of work will take promising technologies to field sites for testing and demonstration, and will lead to commercialization of these technologies.

Description of Technology

Overall System

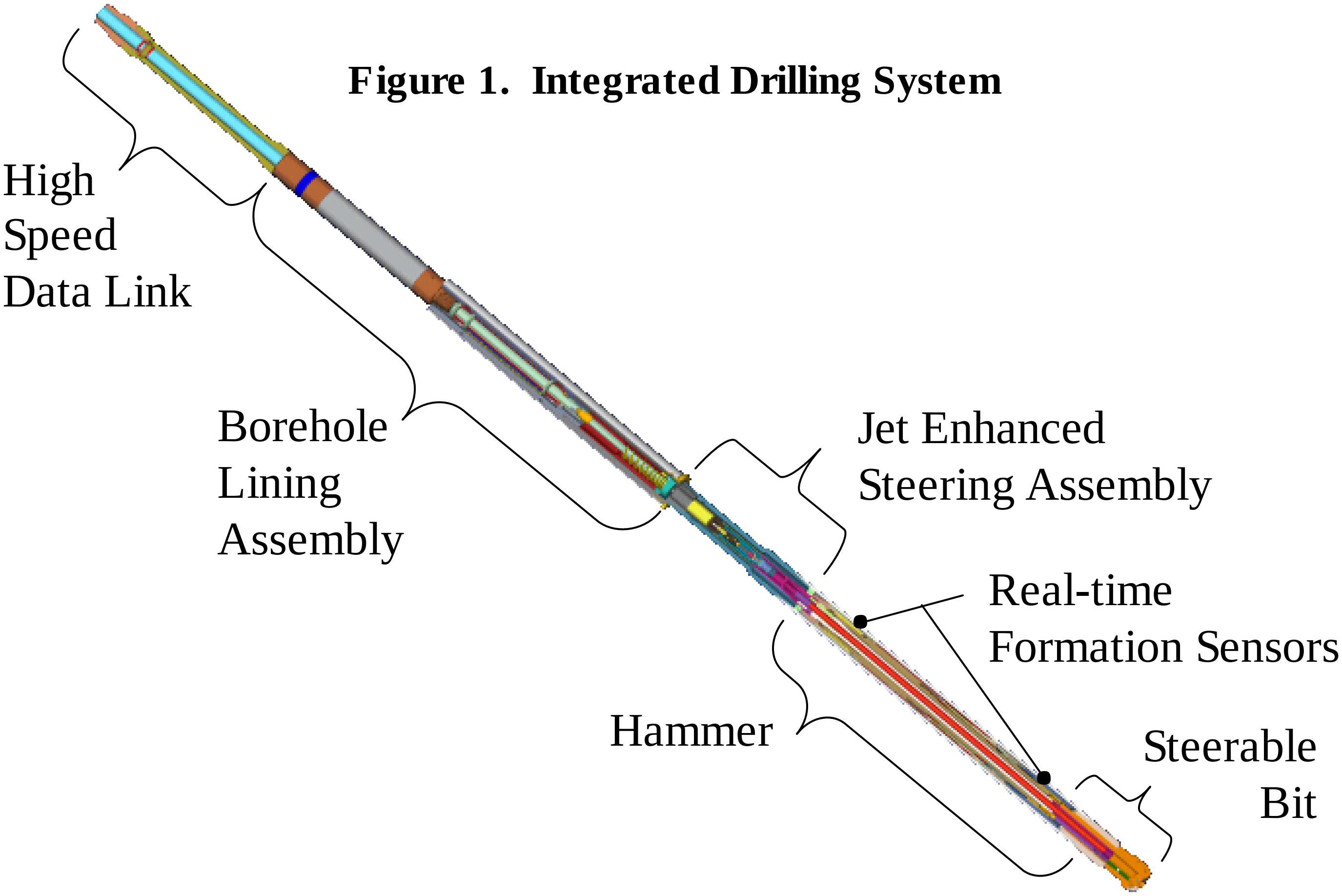
Figure 1 illustrates the basic components of the overall system, which have been selected for consideration in this study. As shown, the system includes a mud-actuated hammer drilling head, real time formation sensors, a high-pressure jet enhanced steering assembly, a borehole lining assembly, and a high-speed data link. It is anticipated that, along with the formation sensors described herein, other current art and novel sensors will be added as needed to provide more complete downhole diagnostic information. Also not specifically shown is a central processing unit and associated hardware that enables adaptation of the hammer and steering assembly to the diagnostic information provided by the sensors and the operator. This unit will likely reside in the steering assembly shown in the figure. A discussion of each of the main subsystems follows.

Mud Hammer Drilling Head/Formation Sensors

As mentioned, a key component of the overall drilling system is a down-hole mud hammer. The primary motivation for employing the hammer in the system is of course its potential to bring improved rate of penetration (ROP). The hammer does this by creating an instantaneously high axial force, which in brittle formations causes high fracturing, and in more ductile formations causes greater indentation of the cutters in the bit. In previous field trials, hammers have also been noted to help remove unwanted deviation, and improve bit footage.[4,5]

Aside from these benefits, the motion and vibrational output of the hammer may also potentially be used as a type of formation sensor, and also provide a seismic signal while drilling. The ability of the hammer to act as a formation sensor derives from the fact that it is influenced somewhat by the formation it is drilling: formations of differing mechanical properties will cause different rebound in the hammer as it strikes the formation. If the linear motion of the hammer can be evaluated near impact, this information can be used to determine at least a composite index that identifies overall rock characteristics. This information may be used alone or to supplement formation data obtained from other current art sensors and give a more detailed picture of the formation. By so combining data from multiple sources, fewer assumptions than presently required may need to be made, resulting in more accurate data interpretation. Furthermore, the motion of the hammer can be used as an important feedback quantity to verify and quantify the output of the hammer drill as the hole progresses in time and depth.

Figure 1. Integrated Drilling System



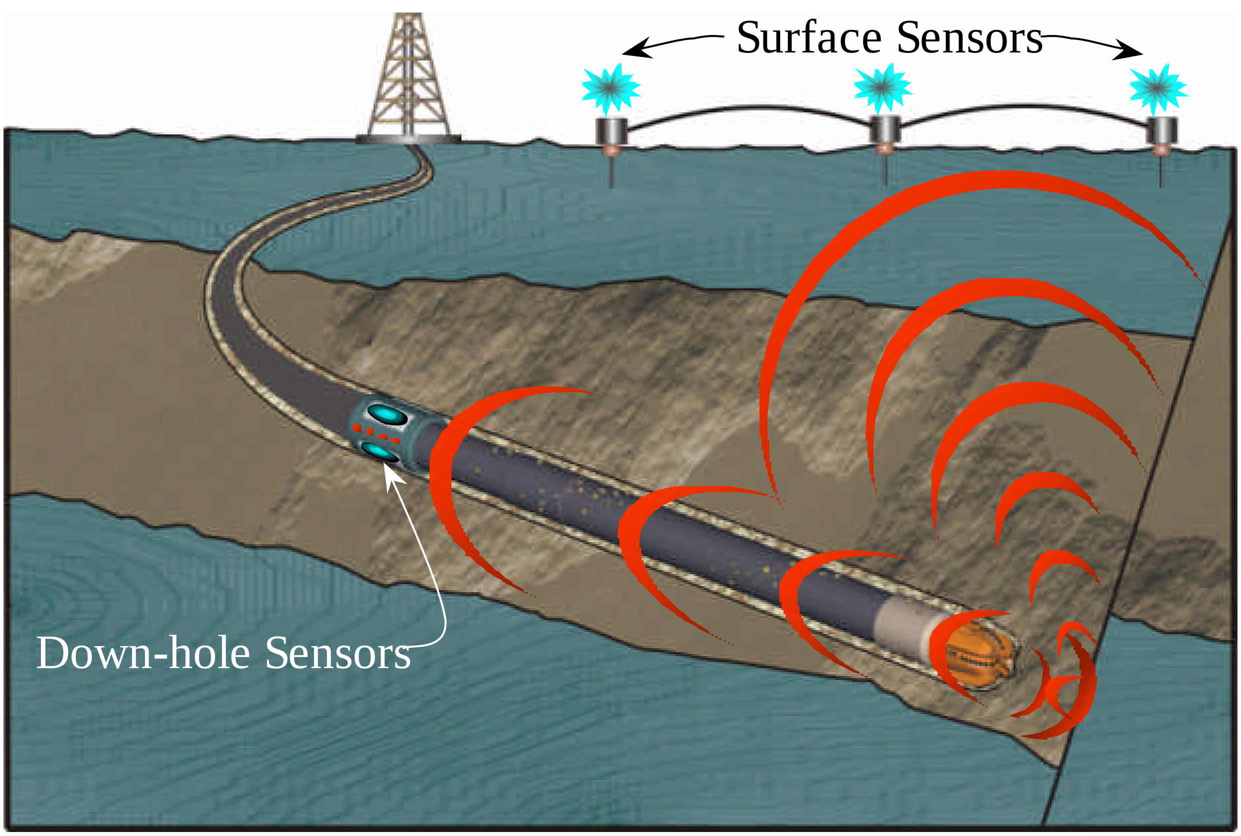


Figure 2. Percussion Bit Seismic

The impact of the hammer upon the formation being drilled also provides a steady seismic signal at the hole bottom, which may be used for reverse vertical seismic profiling and look ahead measurements. This concept is similar to the concept of drill bit seismic, which is already in practice.[6] This system would ideally require seismic sensors near bit and at the surface, as shown in Figure 2.

High Pressure Jet-enhanced Steering System

The reciprocating motion of the mud hammer may further be used to drive a hydraulic piston and generate high hydraulic pressure down hole. This high-pressure fluid may be used to enhance bottom hole cleaning and rock fragmentation, resulting in faster penetration of the bit.

If this high-pressure fluid is applied only to a certain region of the hole, the drill bit will preferentially drill in that region, resulting in deviation of the bit. In this manner, the bit may be steered to a desired location. This concept is shown in Figure 3. As shown, drilling fluid enters passages in the drill bit and is intensified in pressure by the hammer piston striking intensifier pistons in the bit face. This intensified fluid then exits the bit through nozzles distributed about its face and impinges just adjacent to the region of the rock being drilled by the cutters. Figure 4 depicts the hardware necessary to control application of the high-pressure fluid to one region of the borehole. Key elements of this control system are: a rotary valve, which is capable of segmenting flow for directional drilling, while still allowing flow to all regions of the borehole for straight-ahead drilling; a sensory module comprised of an accelerometer /magnetometer package, which determines rotational position of the drill head; a rotary actuator, which turns the valve relative to the rotational position of the drill; and a computer driver which converts uphole commands and data from the sensory module into a control signal which selects the appropriate positioning of the valve.

Borehole Lining while Drilling System

Beyond the hammer-related drilling and sensing systems, a means of supporting and stabilizing the drilled borehole is required by the overall system. Supporting the rock while drilling prevents a variety of borehole stability problems and enables drilling horizontally in poorly consolidated or fractured formations and shales. Currently, mud cake or other sealing agents are used to stabilize the borehole while drilling. The technology investigated in this study involves casting a more permanent and structurally competent liner into the borehole while drilling. Whereas current (temporary) stabilization means must be followed by cementing steel casing at several points along the length of the well, the liner under investigation would permit the use of a single continuous steel casing string, or none at all in some cases.

Key to the success of such a system are the means of conveying material continuously to the bottom of the borehole, and the means of applying the material to the rock. Figure 5 shows the concept under investigation. As shown, the lining material is fed to the bottom of the well by injection into the drilling fluid. The material is then strained out of the fluid, ground up downhole, and deposited against the borehole wall. The material is shaped and cured inside a form that is friction heated to allow control of cure time. Figure 6 shows other components required for the system. As can be seen, a bit with an offset reamer is used to drill and ream the hole oversize, so that the bit assembly may be retrieved back through the

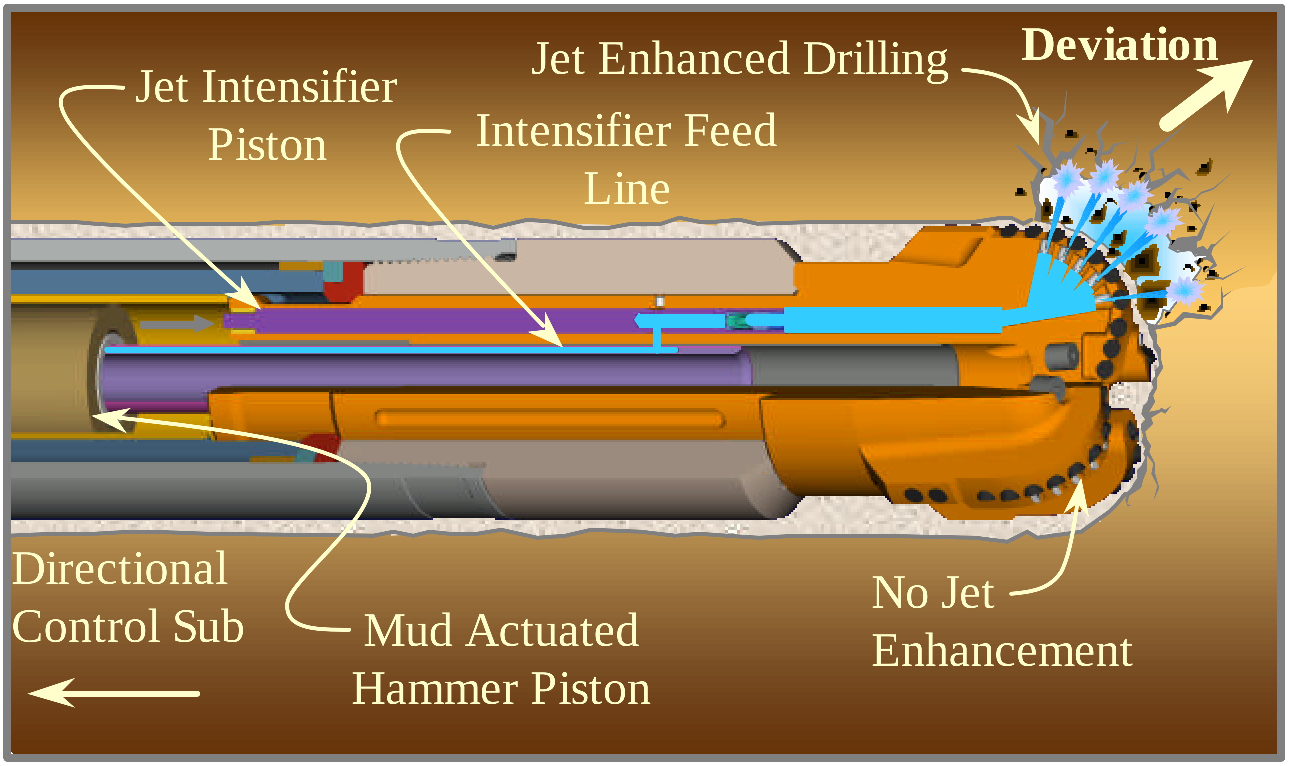


Figure 3. Jet Enhanced Steering Concept

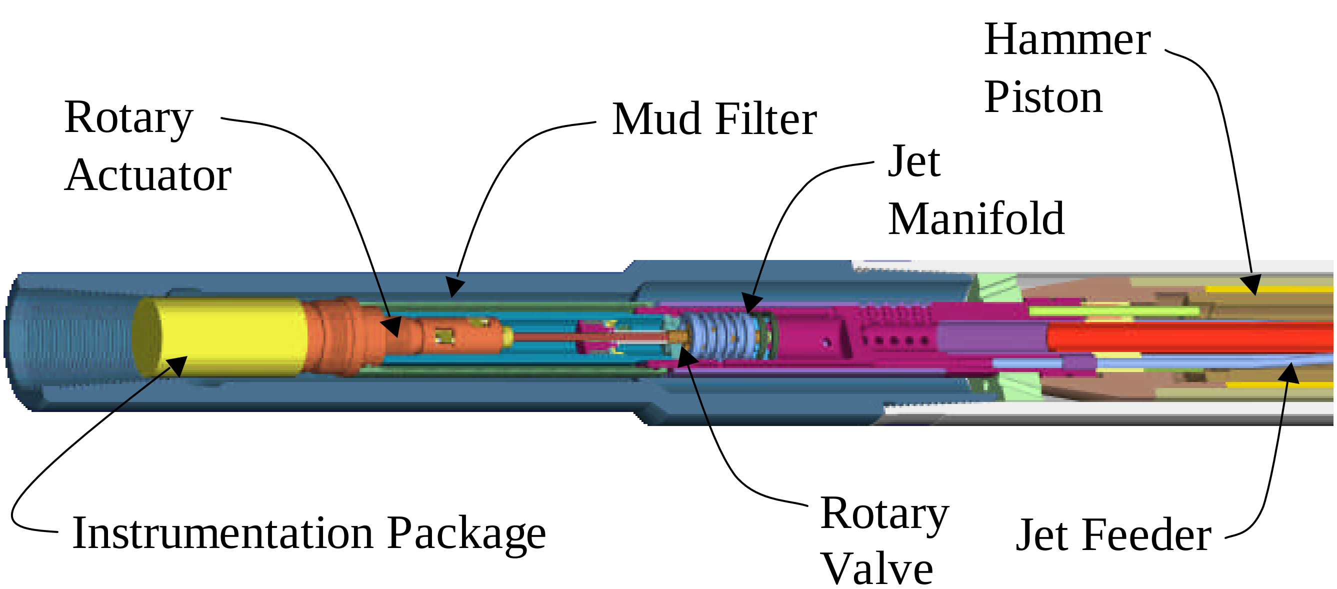


Figure 4. Steering Control Components

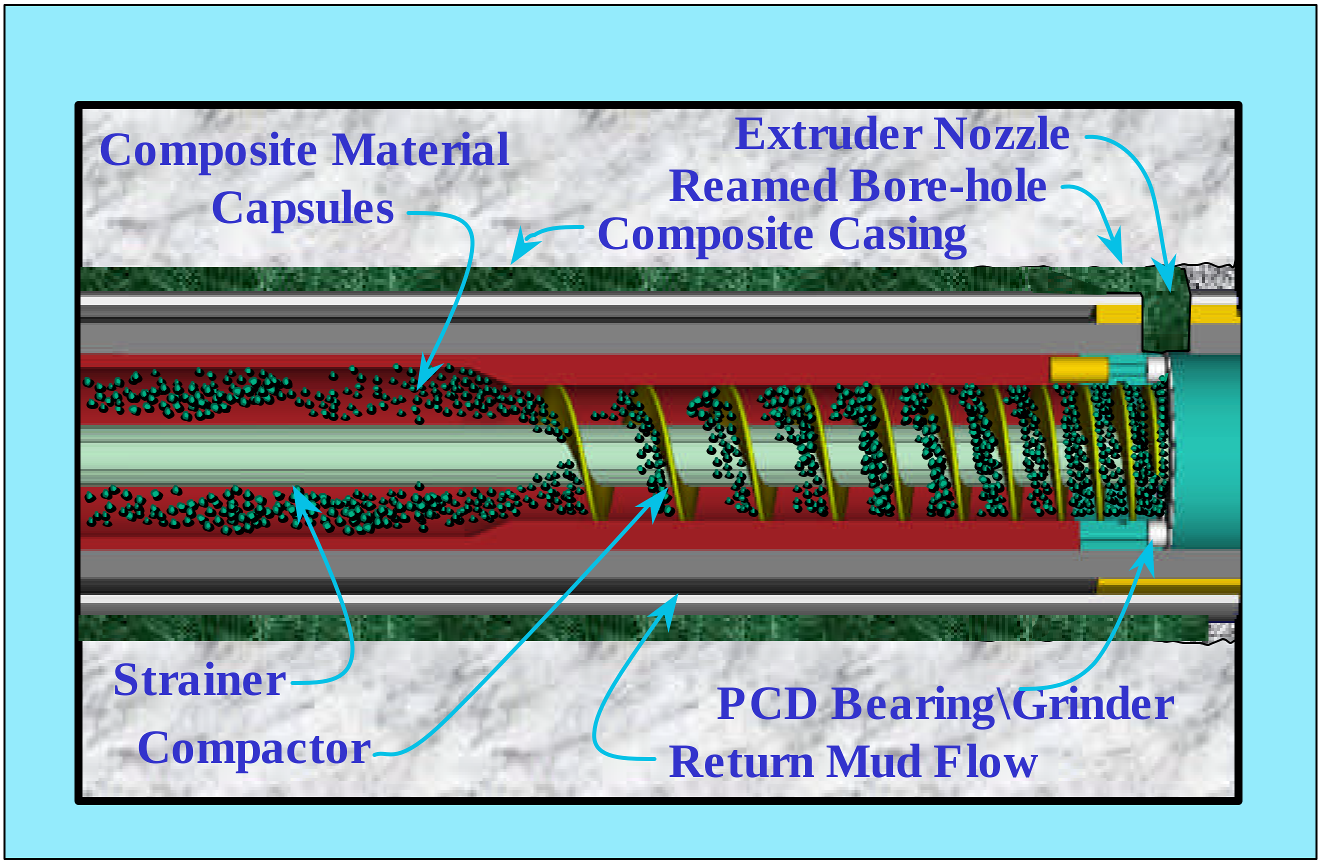


Figure 5. Lining While Drilling Concept

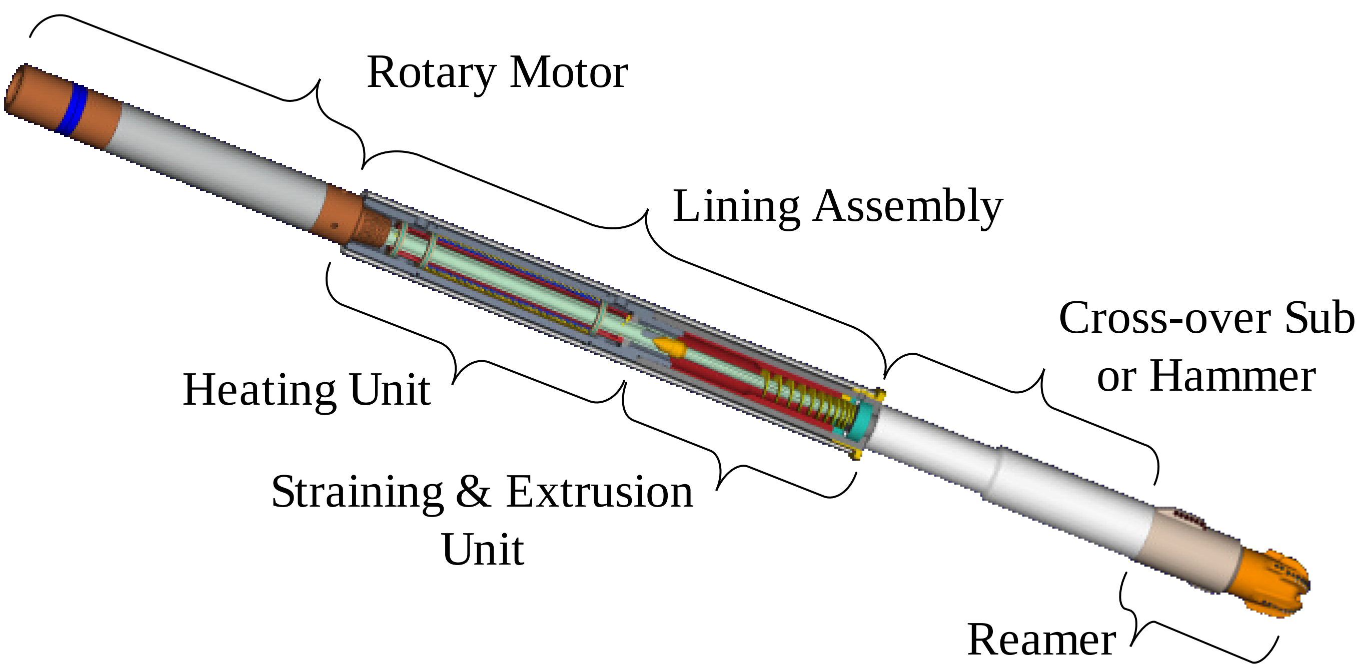


Figure 6. Lining While Drilling System

completed liner. A small high-speed down-hole motor is also required to drive the grinding mechanism and friction heater in the form. Care is taken to route annular return flow around the liner form so that the liner is not damaged during cure.

High Data Rate Communication System

Completing the basic drilling system is a high data rate communication system. Such a system allows for more detailed communications between operator and drilling assembly, and enables greater understanding of the conditions at the drill bit, while minimizing the burden of downhole data processing and storage. Current systems used by the industry communicate between top and bottom of the wellbore by sending low frequency signals the entire distance. While other transmission media have been investigated, e.g., the drill pipe and the earth, the drilling fluid is the present medium of choice. These systems are presently limited to a few bits per second data rate – tens of bits per second, if data compression techniques are used.

The current system under investigation takes a different approach: that of sending very high frequency signals a very short distance, and repeating the signal several times to traverse the length of the drill string. This system fundamentally offers a very high data rate. Several systems are possible using this approach and these are described below.

Accomplishments and Future Activities

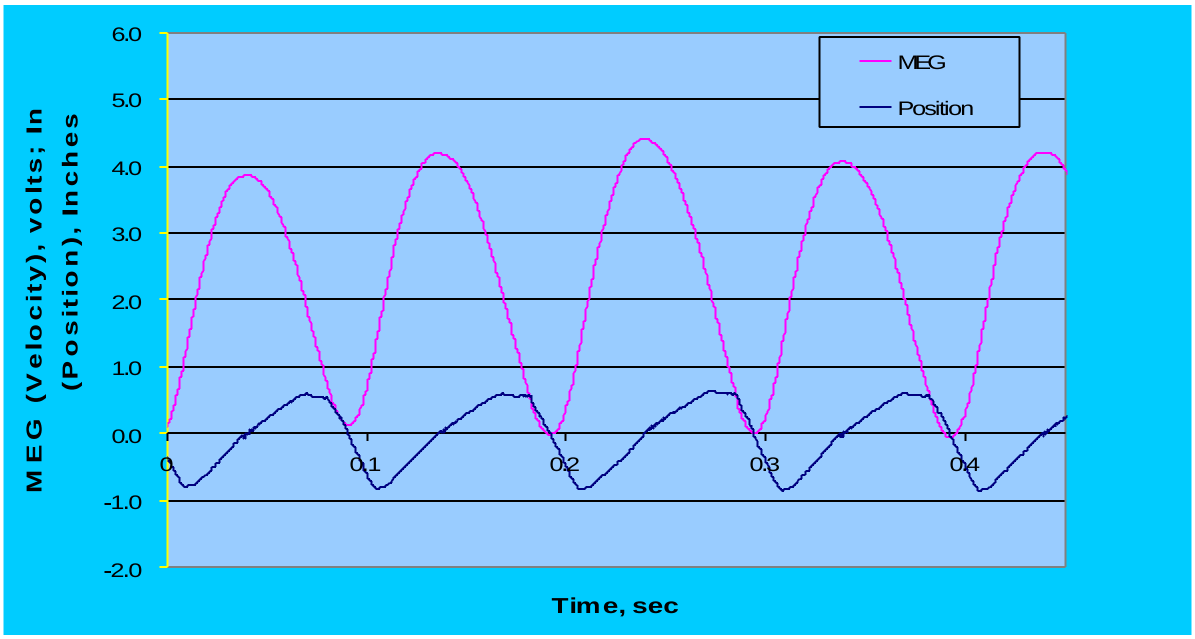
Mud Hammer Drilling Head/Formation Sensors

Performance of Drilling Head. The operation and effectiveness of the Novatek mud hammer has been published previously.[7] In short, this tool has been shown to operate on a variety of drilling fluids, from water to a 10 lb bentonite/barite mud, and has improved drilling rate in Carthage marble by between 15% and 300%, depending on drilling conditions. Recent development efforts have focused on improving hammer performance, particularly in medium to deep well conditions, where benefits were shown to be the least. Optimization of valve timing and reduction of cycle inefficiencies in recent months has resulted in an estimated doubling the output impact energy of the tool. Optimization efforts are expected to continue into early fall, where further quantitative drilling tests will be carried out to verify improvements.

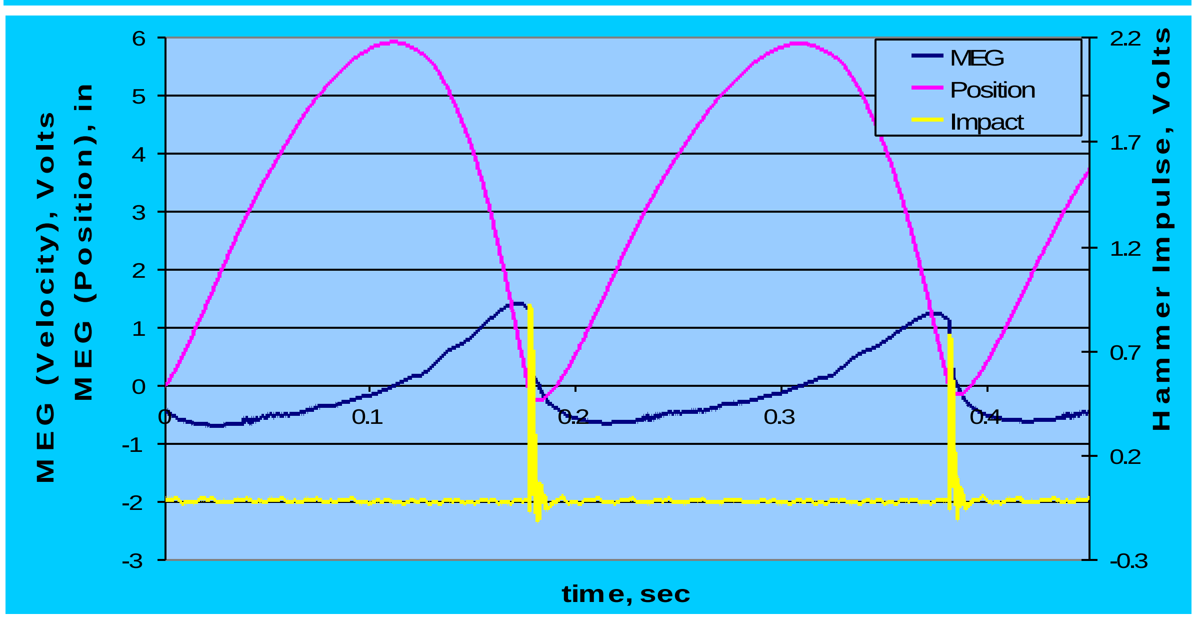
Hammer rebound sensor. A simple prototype transducer has been built using a magnet and coil arrangement that fits inside the hammer piston. This transducer, shown in Figure 7, was designed to not only measure hammer motion near impact, but to measure hammer motion at all points in the hammer cycle. This increased measurement range is important in using the transducer as a diagnostic tool that monitors hammer performance continually.

Testing of the rebound sensor has shown that such a device can determine differences in operation of the hammer. An example of such operational information is shown in Figure 8. As can be seen in Figure 8a, the hammer cycle is very symmetrical on the leading and falling edges, suggesting equivalent biasing of upstroke and drive stroke portions of hammer movement. Note also that the hammer does not appear to impact at the bottom of its stroke. These indications are quantitative evidence of short-stroking of the hammer. Figure 8b shows improved timing of the upstroke and drive stroke motions, showing a clear bias

Figure 7: Prototype Rebound Transducer (MEG)



8a)



8b)

Figure 8: Sample Output from Rebound Transducer

towards the drive stroke. Impact is also evident, as the velocity signal drops quickly to zero; in fact, a quantification of impact velocity is possible. Hence, it may be concluded that the present configuration may provide important system diagnostics.

Further work is needed to verify that the hammer rebound sensor is useful in discriminating rock properties. Fundamental studies have concluded that the percussive rebound may be related to rock type through a drillability constant K, and the governing theoretical model for this relationship has been proposed. However, values of K for different lithologies have yet to be determined. Furthermore, it is suggested that correlation with a second measured quantity, such as sonic velocity, may enhance the usefulness of the rebound measurement. Future work will therefore focus on two areas: gathering and correlation of empirical data relating sensor output to useful rock characteristics and ensuring that the transducer used within the hammer is sensitive enough to measure rebound of the hammer with the required accuracy. Gathering of data will need to be done with full-scale prototype hammers to minimize geometrical concerns. Of particular interest is the influence of drill bit geometry or complexity on the constants obtained.

Hammer seismic qualities. Instrumentation of the hammer drill has yielded a better understanding of the useful vibrational frequencies generated by the hammer. The hammer induces vibrations into the rock formation by means of mechanical impact waves transmitted to the rock through the drill bit, and also by means of hydraulic pressure fluctuations in the borehole. Both of these sources have been instrumented and analyzed, and samples of these signals are shown in Figure 9. As can be seen from the frequency domain plots of Figures 9b and 9c, a wide spectrum is offered by the various physical outputs of the hammer. Particular vibrational energy can be seen in the 10-20 kHz range, which range has been found useful for acoustic wireline and logging while drilling tools. Such tools have been used to estimate porosity, compute elastic moduli of the rock, and create synthetic seismograms for comparison with surface seismic data.[8]

Fundamentally, these higher frequency components must be measured in close proximity to the bit; hence downhole sensors will be key for collecting information from this signal. Lower frequency components may be used to measure grosser formation qualities that are measurable at the surface. Usefulness of the generated frequencies will best be determined by instrumenting field tests of the hammer. Future work in this area will focus first on signals that are measurable using existing surface geophone arrays, and later on the signals to be measured down-hole.

High Pressure Jet-enhanced Steering System

Preliminary studies have shown an average of 34% increase in depth of penetration of a *percussive* cutter in Missouri Red Granite when a 6000-psi fluid jet is added.[9] This implies that significant bit deviation can be accomplished if that increase is focused towards a particular region of the borehole. What remains to be determined is the actual response of a multi-cutter bit to these differential drilling forces. To this end, focus has been placed on development of a full-scale prototype bit with an in-bit mud jet intensifier[*] and a deviation control system. Developments regarding the full-scale bit have been reported previously.[10]

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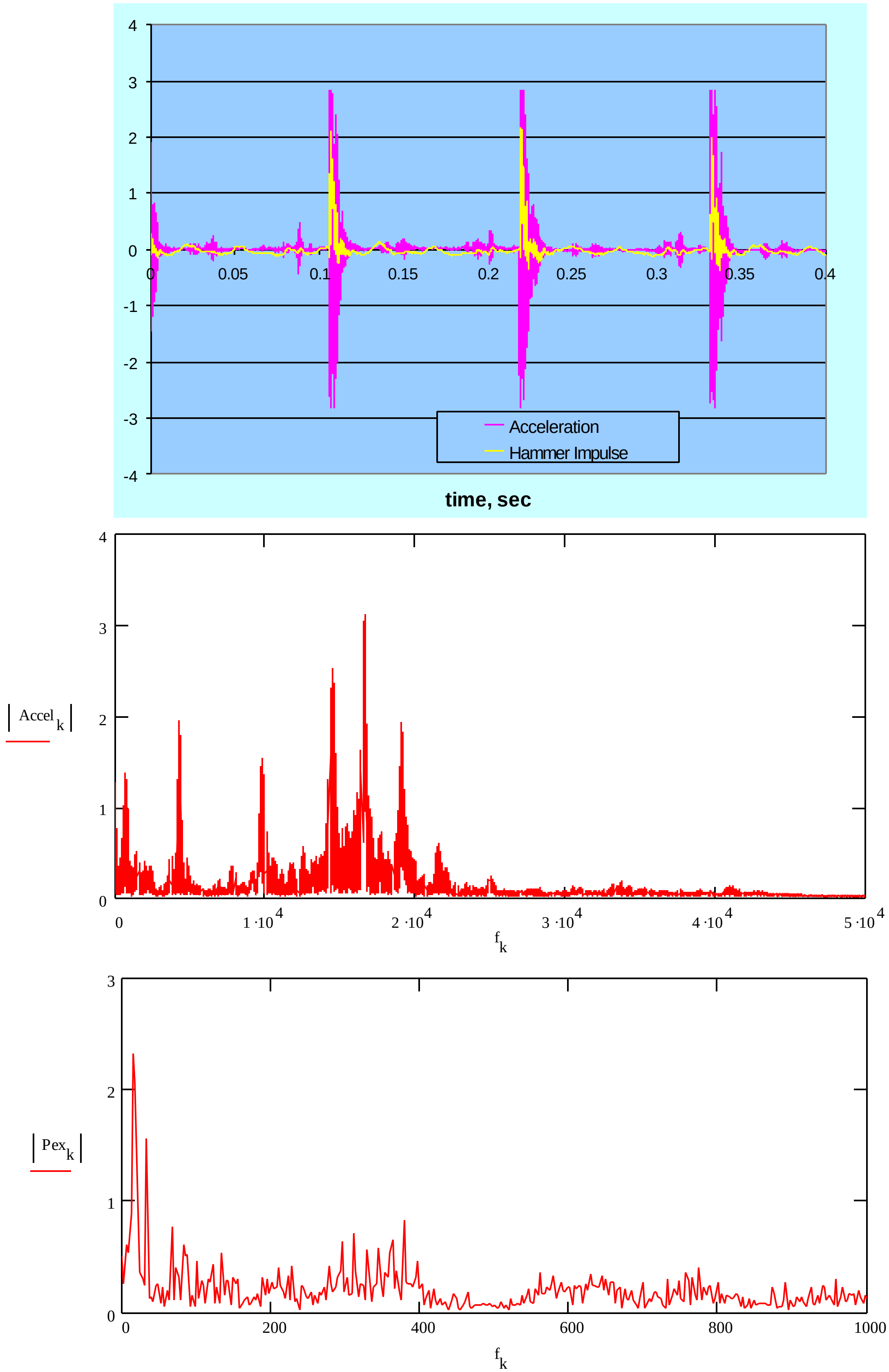
[*] Bit development under contract DE-FG03-96ER82242, scheduled for completion fall 1999.



9a)

9b)

9c)

Figure 9: Vibrations at Hammer Bit: a) Time domain b) and c) Frequency Domain

Efforts to direct a bit by biasing *conventional* bit hydraulics (as opposed to the high-pressure jets of the present system) have been exerted previously.[11] The resultant system, which seems to have most likely application in softer formations where conventional bit hydraulics are more effective, suffered from valve wear problems. To minimize this concern in the present system, the control system design includes a fully pressure-balanced valve, thereby minimizing torque and thrust on the valve. The valve has also been designed to minimize the potential for erosion and clogging from drilling mud, resulting in high life and reliability, as well as minimal power requirements. Figure 10 shows the prototype valve assembly to be used in fundamental and full-scale operational verification tests. Bench testing of these mechanisms is expected to begin in fall of 1999. Once proper operation is demonstrated, further work will focus on implementing downhole-compatible rotary actuators and, finally, position measurement sensors.

Borehole Lining while Drilling System

Initial studies of the borehole lining system have focused on the type of material to be employed in the lining and the means of applying it to a submerged borehole. Several different materials have been investigated for the lining material, including metals and metal reinforced polymers, aggregate reinforced materials, and fiber reinforced polymers. Difficulties encountered with several of these materials included problems with underwater adhesion, density (which manifests itself in slumping or sloughing of the material), and poor strength. This investigation found fiber-reinforced polymer systems to provide the best combination of cost, strength, and workability.

A key issue when dealing with polymer systems is curing method. Cure time is particularly an issue with a down-hole system, since too slow a cure time impedes drilling progress and too fast a cure time compromises material strength and poses potential problems with clogging mixing and application mechanisms. Furthermore, variable down-hole temperatures may adversely influence cure time. To obtain better control over cure time, polymerization processes other than simple chemical initiation have been considered, including UV, gamma ray, and thermal initiators. While the former two were unacceptable for depth of cure and cost considerations respectively, the study has concluded that a thermal initiation process, where polymerization is initiated at a temperature above down-hole ambient, may give the most repeatable casing quality. Accordingly, a system utilizing a fluid-driven friction heater has been designed (see Figure 6). Further work with the materials system will include verification of cure time and strength and final composition. Some work has previously been done to characterize the improvement to borehole stability offered by another polymer lining system[12]; further such work will be necessary in order to determine suitable applications for the current system.

Studies into the means of application of the material to the borehole have included simple mockup tests, where a bead of material was applied to the bore of a concrete pipe in a coiled rope fashion, then smoothed and trowelled in place. A sample result from these mockup tests is shown in Figure 11. From these tests, it was determined that good adhesion could be achieved with a submerged surface, but that mechanical working of the materials into the rock was important to exclude wellbore fluids and promote this adhesion. Due to difficulties working the material into the rock in an unconfined space, as required by the coiled rope approach, it has been determined that this method is less desirable. An

Figure 10: Prototype Directional Valve

Figure 11: Mock-up Test Of Lining While Drilling

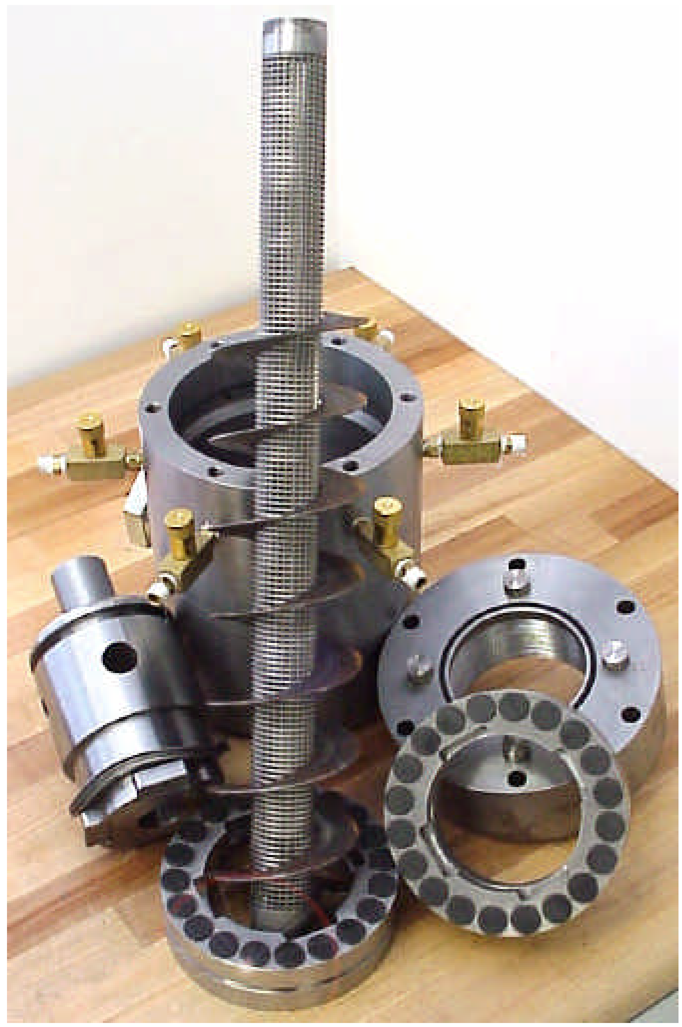


Figure 12: Fixture Parts for Testing Liner Material Feed System

alternative method, where the lining material is extruded into a trapped volume, has been chosen instead. This method is depicted in Figure 5.

Current focus has been placed on verifying the fundamental concept of feeding the lining material to the bottom of the borehole through the drilling mud. A test fixture has been built, shown in Figure 12, and the key functions of straining, compacting, and grinding the lining material will be demonstrated in a flow loop.

High Data Rate Communication System

One approach to achieving a high data rate communication system is to use high frequency acoustic signals to traverse one or more sections of drill pipe, and to repeat the transmission at each pipe joint. Fundamental studies have shown that a 4.6 MHz acoustic pulse from a point source travels up to 72 ft in a small diameter steel rod. However, poor propagation occurs in 4-1/2 drill pipe. This difference is assumed to be due to geometrical concerns. More work is needed to quantify gains offered by better matching of source and conductor geometries. Lower frequency acoustic signals (100 kHz range) have been used in some commercial systems to communicate through piping.[13] These transducers are physically larger than the MHz range transducers and therefore pose some design constraints for use in down-hole systems. However, such transducers may provide for less attenuation of the signal in the given geometry. Further work is needed here as well to determine the range of propagation of these lower frequency signals in drill pipe.

An alternative approach to transmission of acoustic signals over one or more lengths of pipe is to transmit the signal a very short distance (e.g., across the drill joint) and use electrical wire embedded in the drill pipe to carry the signal the rest of the way. At present, acoustic and other means of coupling a signal across drill joints are being investigated. This type of system could offer very good data rates at reasonable power levels. For example, with an acoustic coupling system operating at 4.36 MHz, with a 5 V peak-to-peak drive, 10% duty cycle, and requiring 5 pulses per bit for adequate resolution, a time averaged data rate of 87 kbaud may be obtained. If the drive circuit were 50% efficient it would require 16 milliwatts. An AA alkaline cell driving such a circuit would last about 200 hours.

Application/Benefits

It is believed that significant benefits will derive from the overall system outlined, as well as from the individual subsystems. On a broad scale, the anticipated benefits of the overall system include *faster* drilling and *more effective* drilling. The first of these benefits arises directly from the faster jet-assisted hammer drilling action of the drilling head, and from the ability of the complete system to optimize drilling performance by sensing conditions at and ahead of the drill bit and adapting to those conditions while drilling. Further drilling rate improvements would be seen from reduced borehole problems due to the continuous lining process. Such borehole problems would include most notably caving shale and lost circulation problems.

The second mentioned benefit would be expected from the improved sensing, steering, and communication systems under consideration. The effect of a high data rate communications system alone on the industry's ability to drill more effectively will be great. Not only will it make it possible for more information to be sent between surface and hole bottom, but it will also enable implementation and development of more sophisticated sensing means. A near-term benefit of such a system would also be a minimization of the dependence on downhole electronics for data processing and storage.

Further benefits are expected because of the potential of the present system to provide a smoother and less tortuous well bore. Since the system does not rely on conventional technology for directional control, a consistent diameter and more continuously directed borehole may be expected. Continuous lining of the borehole further improves the borehole quality. Hence, borehole cleaning is improved, and friction, which limits the reach of wells, is reduced.

Key advantages of the current system over other systems that offer a subset of these functions include:

1) Faster steerable drilling, particularly in hard formations. Other rotary steerable systems are available which offer steering without requiring downhole motors and their attendant "sliding mode" problems.[14] These offer significant improvements over current art directional systems but utilize current art drilling methods, which are slower than the proposed methods.
2) Lack of special conduits to feed downhole devices. All devices in the system are intended to be fed through existing conduits and means, namely, the drillstring and the drilling fluid. Hence, the high-pressure fluid utilized by the jet-enhanced bit is created downhole, using existing flow. Similarly, the casing material is continuously fed to the bottom of the hole in the drilling mud, eliminating the need for special tubing to provide the material from the surface. This design goal ensures that rig floor operations are kept as simple as possible and that auxiliary surface equipment needs are minimized.
3) New sensing capabilities. Current drill bit seismic systems can help locate the drill bit, generate look-ahead images, predict pore pressure at and ahead of the bit, and predict depth to drilling hazards. However, current systems are limited to use with rollercone bits, therefore limiting bit selection and drilling speed in some formations. The proposed system extends the art of drill bit seismic to faster drilling rotary percussion bits. In addition, the hammer rebound sensor mentioned above offers completely new system and formation diagnostic capabilities.
4) Extremely high data rate. The proposed system has the potential to provide at least one or two orders of magnitude higher data rate than currently conceived EMMWD, acoustic, or improved mud pulse systems.

Along with the specific fossil fuels application discussed herein, the described technology is expected to have similar application in geothermal drilling, and in a large variety of construction-oriented drilling applications: placing utility conduits under roads, buildings, remote or protected areas, etc.

Acknowledgement

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