**DEVELOPMENT AND TESTING OF A
JET ASSISTED
POLYCRYSTALLINE DIAMOND
DRILLING BIT**

PHASE II DEVELOPMENT EFFORTS

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BACKGROUND

Basic Concept

A variety of rock formations are typically encountered when drilling for subterranean resources. Of particular concern are hard, or hard and fractured formations, which are difficult to drill and often cause premature failure of drill bits. Further challenge is added to the drilling system when hard rock formations are interbedded with softer formations. In such a case, drill bits that are optimized for one type of formation are ineffective in the other, leading to slow drilling or downtime due to bit trips.

One possible means of accomplishing improved drilling effectiveness is to combine a few different drilling mechanisms in a synergistic manner. An example of such a combination is a roller cone drill bit, which combines a somewhat percussive drilling component with a drag component (this latter component is designed into the bit by cone offset). A further example is a system developed by FlowDrill, Inc., who have used high fluid jet pressures to cut a slot around the perimeter of the face into which a mechanical drill must advance, thereby reducing the work done by the mechanical cutters and increasing ROP to approximately double the unassisted rate.¹

A novel synergistic approach with potentially great benefit combines the effects of drag, percussive and high-pressure fluid jet drilling mechanisms. Figure 1 illustrates this combined drilling concept. As shown, the fundamental drilling action may be thought of as two separate actions, although much of the action happens concurrently. In the first (axial) component of the action, weight on bit (WOB) provides a somewhat steady force pressing the cutter against the formation, while impact from the hammer drives the cutter further into the rock formation at regular intervals. As the hammer impacts, a burst of high-pressure fluid is ejected directly towards the cutting zone of the cutter. This fluid burst acts to both remove crushed material from the cutting zone, and penetrate cracks created in the formation by the mechanical action of the cutter. Both of these activities aid in the removal of rock from the cutting zone and thus act in synergy with the mechanical cutter. The second (shear or drag) component of the action then follows, wherein the cutter (still under WOB) drags out of the crater it was driven into, shearing rock as it goes. A lower pressure jet is directed into the cutting region, again assisting removal of drill products from the face of the rock.

Project Background

In 1987, Novatek began development of a percussion tool for use in deep well drilling applications where drilling mud was the working fluid of choice.ⁱⁱ This tool adds percussive drilling action to the existing rotary action of a rotary drill, providing a "rotary-percussive" drilling mechanism. Refinement and testing of this device has continued over the past decade, resulting in a tool that has been able to produce modest increases in rate of penetration in medium to hard rocks.ⁱⁱⁱ Development of this tool continues with the goal of improving penetration rate further, particularly in deep formations where rock behavior is less brittle. During this development process, it became apparent that the addition of a high pressure fluid jet to this system could benefit the drilling process by more effectively removing crushed

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Initial studies done in 1996 at the University of Missouri-Rolla Rock Mechanics and Explosives Research Center (UMR-RMERC) have shown that indeed, the synergistic action of a high-pressure jet (5-6 ksi) with a mechanical cutter can improve the penetration of a cutter into Missouri Red Granite by approximately 100%. Both percussive and shearing cutting actions were independently seen to benefit from the addition of the jet.^{iv} Moreover, the incidence of damage to the cutter in these initial tests was zero when the jet was applied; without the jet the cutter chipped and broke on at least two occasions. This latter finding suggests that the jet acts to lessen the mechanical and/or thermal burden borne by the cutter. As a result of these encouraging findings, Phase II work commenced in the summer of 1997.

Phase II Objectives

The desired result of this project is to provide a means of improving drilling rate in hard rock under deep hole conditions. To accomplish this, the specific objectives of the current project have been:

- **to determine the design parameters for the jet assisted rotary-percussion bit which will provide the greatest benefit from use of the bit.**
- **to determine the operational parameters (energies, frequencies) which produce the greatest benefits of jet/rotary-percussion drilling in different formations .**
- **to optimize the life of the bit and bit components.**
- **to evaluate the potential effectiveness of the tool in providing directional control of the drill bit.**

The last of these objectives follows from the reasoning that if a high pressure jet can improve penetration of the bit on the whole, it may be possible to restrict the activity of the jet so that it will improve penetration of a portion of the bit, thereby causing an imbalance of drilling force, providing bit deviation. This latter objective, if demonstrated, offers much more utility to the drilling system than just improved penetration – it adds the ability to steer the bit in the desired direction with potentially high response.

Approach

The basic approach used in developing an effective jet-enhanced drilling system derives from two chief concepts. The first is the concept that a jet acting in concert with the mechanical cutter can be more efficient than the jet acting alone or acting sequentially with the cutter. While it has been demonstrated that a jet can cut rock by itself,^v such a process requires very high jet pressure, and is greatly influenced by the type of rock to be cut (not just its strength) and the depth of the formation. In contrast, the current approach allows for use of lower pressure jets and lower total jet horsepower. Lower pressure typically leads to a longer life of nozzles and other components. Lower overall horsepower offers the benefits of a smaller system and lower requirements from surface equipment (pumps, etc). In order to get the desired level of cooperative action between jet and cutter, the jet must be applied specifically when and where

needed. This concept implies the use of jets that are well distributed about the face of the bit and aimed at several key cutting zones.

The second chief concept is that the high-pressure fluid jet is best generated near the place of application of the jet, i.e., near or in the bit itself. This prevents the need for higher-pressure surface equipment and special conduits to conduct the flow to the bottom of the hole. The proposed system takes fluid at system pressure (already available down hole) and intensifies it by mechanical means to the needed pressure. As already mentioned, a down-hole hammer is a convenient and robust means of driving a down-hole jet intensifier, since its reciprocating action is compatible with the needs of a positive displacement pump/intensifier. The energy required by the intensifier is just a small percentage of the total energy developed by the hammer, and therefore is not expected to degrade hammer performance significantly. Furthermore, by using the hammer stroke to intensify the jet, the application of the high-pressure jet may be easily timed to the impacts imparted to the rock, thereby offering the assistance of the jet when it is needed the most, during the highest penetration. Yet further, the hammer is an excellent means of creating a pulsed jet, where the high-pressure portion of the jet is applied on an intermittent basis to the rock formation. This pulsed jet feature bears advantages over steady jet cutting of rock, including cyclical stress unloading and initial impact loading.^{vi} In addition, a pulsed jet system requires less overall horsepower, since the high-pressure portion of the jet is only momentary.

The major unknowns in this research effort include the operating parameters of the bit, and how they are affected by different rock types and drilling conditions (depth, etc). To obtain this information, both laboratory and field tests are required. Fundamental laboratory investigations were conducted at UMR-RMERC. Figure 2 shows a test apparatus that was built at UMR-RMERC for simulating the combined drilling action of rotary, percussive, and high-pressure jet cutting mechanisms. This machine and others were used to gain a better understanding of cutter-rock interactions when drilling with a combined action, and to gain understanding of cutter failure under loading by this type of drilling mechanism. Full-scale laboratory and field testing of the overall bit apparatus will be used to extend this fundamental knowledge to the real world: it will characterize the operation of the hammer-driven jet intensifier, measure the benefits of the overall integrated drill system, and gain experience with the system in a variety of rock formations.

RESEARCH RESULTS

Fundamental Jet-Assisted Rotary-percussion Studies

Initial tests of the fundamental jet-assisted rotary-percussion system have been conducted under atmospheric conditions, using the apparatus shown in Figure 2.^{vii} In these tests, a polycrystalline diamond (PCD) cutter was set in the apparatus, set to an initial penetration depth of approximately 0.06 inches, and dragged across a block of Missouri Red Granite. As the cutter traversed the block, impacts of 50 ft-lbf were imparted to the cutter over regular intervals (approximately 0.75 inches between centers). This test was repeated both without any jet assistance, and with a 6000 psi waterjet trained on the formation directly in front of the cutter. Figure 3 shows the results of this test. As is shown, the penetration depth of the cutter assisted by the jet increases an average of 34%, and in some configurations is approximately doubled.. It should be borne in mind that the baseline for comparison is a rotary-percussion drilling system, not a conventional rotary drilling system. Comparisons with conventional drilling will be made in full-scale bit tests.

A significant finding of this initial work is that the test insert that was operated without high-pressure jet assistance failed within two passes over the surface of the rock specimen. This result was obtained in two separate tests. When the high-pressure jet was added, the insert lasted 6 passes without failure. Thus, the rotary-percussion drilling action seems to be quite aggressive towards the cutter, but is tempered by the addition of the jet. The current thinking is that the cutter is overloaded when it is driven deep into the rock and then required to remove the increased bite by shearing it away. When the jet is added, it is likely that the jet pressurizes and lubricates impact fissures directly in front of the cutter improving material removal in front of the cutter, thereby relieving the forces on the cutter. This finding reconfirms that a high-pressure jet is likely to significantly improve aggressive drilling applications in hard rock.

Figure 4 shows the failure mode of a non-jet-assisted PCD insert. Note that the cutter is of simple cylindrical shape, which is common to PDC drag bits, but is oriented in its holder in this test at a 45-degree angle, rather than a more standard 20-degree angle common in shear cutters. This angle was chosen as a suitable starting point, among other reasons, due to the significant axial component of load imparted by the percussion component of the drilling action. This figure also shows that the jet nozzle (the hexagonal insert at the right hand end of the cutter) is directed nearly parallel, and in close proximity, to the face of the cutter. The failure mode exhibited here suggests the need for improvements in cutter design and perhaps also in its orientation.

Fundamental studies have focused on the optimal orientation of the cutter in the bit. Tests of cylindrical cutters operating in percussion mode only have shown that a 45 degree angle of attack poses the least resistance to axial penetration of all rock samples tested, including samples of Roubidoux sandstone, Holston limestone, Missouri red granite and black basalt. Moreover, an angle of 45 degrees or greater minimizes the incidence of damage to the cutter when drilling in these rock types in a percussion mode.^{viii} However, as shown in Figure 4, apparently a large shear component is present in the combined rotary-percussion drilling mode, which leads to cutter failure. Further investigation of the optimal angle of cutter orientation is required; it is clear that such investigation must be done considering the rotary and percussive drilling mechanisms as a system.

Cutter Studies

One of the supporting objectives of the current research is the development of an improved PCD cutter for rotary-percussion and other high impact drag applications. Much effort has been focused on improving the life of the cutter, despite the gains in cutter life achieved by enhancing the cutter with a jet. The primary reason for this effort is that for the cutter to work properly in a directional system (objective 5) it must be able to survive without localized jet impingement. There is also a great deal of industry interest in a high life cutter capable of surviving high impact and wear.

Current work is focused on improving the structural strength of the cutting table by increasing the bond strength of the diamond table at the impact region. This requires a cutter with higher contact area between the cutting table and the underlying tungsten carbide substrate. Since the cutter in the current configuration is tilted at 45° it is also imperative to coat diamond down the side of the cutter to protect the carbide from abrasion, which would weaken the support of the diamond cutting table. Traditionally, PCD cutters used in drag applications operate in a wearing mode – the supporting tungsten carbide is allowed to wear away behind the diamond table, leaving a sharp edge, but also leaving the diamond unsupported and prone to fracture. In percussion applications, PCD cutters operate in a non-wearing mode, where the entire exposed surface of the cutter is coated with diamond.

This diamond coating maintains cutter sharpness for the life of the cutter. Development of the enhanced rotary-percussion cutter is progressing in this latter direction.

Figure 5 shows the latest developments in high impact cutter technology. Novatek's nodular cutter technology shown in the figure is preferred as the nodules provide an interlocking, high surface area attachment for the diamond table, greatly improving bond strength. The nodules also supply cobalt to the diamond during the synthesis cycle improving diamond integrity and allowing for a thicker, longer lasting diamond table. This cutter design is currently being reduced to practice: a detailed cutter design using these principles has been completed, and carbide substrates for this cutter design are in the process of manufacture. It is Novatek's intention to use this design not only in the rotary percussion bit, but even more broadly as the next generation cutter for the larger drag bit market. If successfully implemented, this cutter could bring substantial gains to drag bit applications, since the cutter profile will stay sharper, and the cutter will be able to more effectively dissipate thermal and mechanical shock loads. For these reasons, development of this improved cutter has become a major focus of this research.

Jet Simulation Studies

Jet Intensity and Duration. In preparation for tests of the jet intensifier mechanism in a full-scale bit, a full-scale prototype of the jet intensifier portion of the bit has been built and tested at Novatek's facility. Figure 6 shows the testing apparatus developed. As shown, a cam (right hand end of table) is driven by a variable speed electrical motor and simulates the striking velocity and frequency of a hammer. This motion is transmitted to the jet intensifier (left hand end of table), causing fluid to be ejected from a nozzle in high-pressure pulses.

Figure 7 shows the results of a test sequence where the motor speed (simulated impact velocity of the hammer) was varied progressively and the dynamic waveform produced by the pulsed jet generator was recorded. In this test, water was used as the working fluid. As shown, the maximum magnitudes (and frequency) of the pressure pulses increase as the simulated hammer impact velocity increases. Pressure levels on the order of 5000 psi were recorded at the upper extents of the simulator's capabilities. These conditions have thus achieved the initial design requirements of the jet generator. Higher pressures will be obtained with higher density muds or higher impact velocities. The duration of the pressure pulse above 5000 psi, which is approximately 0.003 sec, appears to be sufficient to span the duration of the advance of a cutter during impact. However, the timing of the pulse may need fine-tuning, such that it arrives at the rock during cutter impact penetration. Both the timing and duration of the pulse may be altered by changing the point of contact of the "hammer" with the jet generator. Further fine-tuning of the pulse is possible using the current apparatus.

Check Valve Developments. Initial simulation tests utilized steel components, and an off-the-shelf stainless steel check valve. Testing in a weighted drilling mud has shown the tendency for the off-the-shelf check valve design to clog shortly after operation. For this reason, the check valve was redesigned to eliminate any close clearances within the wetted portion of the valve. At the same time wear resistant materials were incorporated into the design. Several different materials combinations were tested over an extended period in drilling mud, including tungsten carbide on tungsten carbide, a ceramic on tungsten carbide, and tungsten carbide on steel. Table 1 shows the results of these tests.

As shown, conventional materials are insufficient for long-term use in the check valve, even at reduced jet pressures.* Although the steel seat seemed to perform better in terms of maintaining pressure than did the tungsten carbide seat, its wear rate was unacceptable in weighted drilling mud. The tungsten carbide seat, on the other hand is less compliant and less prone to profiling by erosion or impact of the ball, and therefore is more sensitive to loss of roundness of the seat or the ball. It should be noted that one design goal of this effort is to avoid the use of elastomeric sealing devices, which would limit use of the tool in hot wells. Further work is required to attain a long-lasting material pair for the check valve. In particular, near term materials iterations will include polycrystalline diamond coated valve seats, and perhaps even diamond-coated balls. A polycrystalline diamond enhanced check valve assembly is seen as a separately marketable product with good market potential for oil and gas and other abrasive fluid applications.

Table 1. Results of materials tests for check valve (simulation pressure = 2 ksi)

Ball Material	Seat Material	Duration of Test	Observations
WC	WC	20 min.	Seat shattered and clogged nozzle
WC	Steel	15 hours	No degradation in pressure over time, extreme wear of seat (but conforms to ball profile), ball lost 0.0004 inches from diameter
Silicon Nitride	WC	15 hours	Steady degradation of pressure due to uneven wear of seat or ball, ball lost 0.0004 inches from diameter

Jet Nozzle Development

The configuration and placement of the jet nozzles in the jet-assisted bit are key practical design issues. The fluid exiting the nozzles must pass through a number of turns prior to exiting in a direction parallel with the faces of the cutters. To prevent the deleterious effects of rotational flow components, and improve the throw of the nozzles, smooth-radiused flow passages are employed just prior to entering the nozzles. A cross section of one of these flow passages is shown in Figure 8.

Another critical design issue is the size of the nozzle. To limit the hydraulic horsepower required by the nozzles and to accommodate available cross sectional areas inside the hammer bit, a small nozzle orifice is used. However, care must be taken to filter the fluid entering the nozzle chamber to avoid clogging the nozzle. Novatek is currently qualifying various filter designs for adequate rejection of clogging matter. An apparatus used in these tests is shown in Figure 9. As can be seen, a few of the nozzles in the nozzle bank are becoming clogged after a period of time flowing weighted drilling mud.

* The extended period simulations were done at reduced pressure because the tabletop tester was not sufficiently robust to survive the extreme impact of higher pressure levels for any extended time.

Bit Design and Development

The overall design of the in-bit jet generator is shown in Figure 10. Five intensifier pistons (one shown in section) slide parallel to axis of the bit and protrude just above the hammer impact surface. Mud is allowed into the intensifier piston through a mud inlet, and exits the piston into a chamber through a check valve. As the hammer strikes the impact surface, it also drives the pistons downward. As the pistons are driven downward, the check valve closes and the fluid in the chamber below the pistons gets compressed and exits through a set of pulsed jet nozzles.

It can be noted from the figure that the nozzles are distributed along each blade of the bit to impinge directly in front of the cutters in the bit. However, only the most critical cutters have been jet enhanced, so that the total flow through the intensifiers is kept low. The critical cutters were selected with the assistance of a bit analysis software package written by Sandia National Laboratories.

Tests using the jet simulator above have shown that the original design of jet pistons causes some yielding of the impactor (the analog of the hammer piston in the full-scale tool) surface due to high impact forces. To minimize this source of damage, the jet pistons have been redesigned to reduce their inertia and increase their impact area. These design features are also shown in Figure 10.

CONCLUSIONS

Based on the work described above, the following conclusions may be drawn:

1. On a fundamental level, adding a 5000-6000 psi jet to rotary, percussion, or combined rotary-percussion drilling improves penetration of the cutter into a variety of rock types
2. Aggressive rotary-percussive drilling action results in increased failure of drag-type polycrystalline diamond coated cutters
3. Addition of a 5000-6000 psi jet to a drag-type polycrystalline diamond coated cutter improves its ability to survive severe cutting conditions
4. Improvements are needed in polycrystalline diamond coated cutter design to enable cutters to withstand more aggressive drilling applications
5. Conventional valve materials are not sufficient for providing a long life check valve needed by this new bit design
6. A key component of the jet assisted bit is a suitable filtration system

FUTURE PLANS

Final bit assembly is pending development of the advanced cutter described above. As mentioned above, development of an advanced cutter is a key priority and is therefore the activity

receiving the most attention currently. However, initial qualification of the bit design is planned to proceed with or without the cutters, by the end of October. This testing will verify jet pressures and overall hammer-bit interaction. In parallel with this testing, bench tests will continue to improve check valve life and effectiveness and to select appropriate filtration means. Drilling tests will follow successful bench and qualification tests, and will be conducted initially at Novatek's test facility. Actual field application of the prototype is anticipated in the spring of 2000.

References

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- ⁱ Demonstrated at the 7th American Waterjet Conference, Seattle, Aug 1993.
 - ⁱⁱ Hall, D.R., D.S. Pixton, Yu Xiangguang. "Down-Hole Mud Actuated Hammer." U.S. Patent 5,396,965, Mar. 1995.
 - ⁱⁱⁱ Pixton, D.S., D.R. Hall, "A Rotary-Percussive Drilling Engine," in *Proceedings of the 1998 ASME Energy Sources Technology Conference*, February 2-4, 1998, Houston.
 - ^{iv} Pixton, D.S., D.R. Hall, D. Summers, R. Gertsch, "Development of a Jet-Assisted Polycrystalline Diamond Drill Bit," in *Proceedings, Geothermal Program Review XV*, March 24-26, 1997, San Francisco.
 - ^v Summers, D.A. and R.L. Henry, "A Comparison of Waterjet Cutting Efficiency, With and Without Mechanical Assistance," SPE 3533, Fall Meeting, 1971, New Orleans.
 - ^{vi} Nebeker, E.B. and S.E. Rodriguez, "Percussive Water Jets for Rock Cutting," in *Proceedings of the Third International Symposium on Jet Cutting Technology*, May 11-13, 1976, Chicago.
 - ^{vii} Santi, P., S. Bell, D.A. Summers, D. Pixton "Waterjet assisted polycrystalline diamond indentation drilling of rock," in *Proceedings, 14th International Conference of Jetting Technology*, Sept 21-23, 1998, Brugge, Belgium.
 - ^{viii} Li, X., "Investigation into the Penetration and Impact Resistance of PDC Cutters Inclined at Different Attack Angles," Internal Report, November 1998.

ILLUSTRATIONS

Figure 1. Fundamental Concept of Jet Assisted Rotary Percussive Drilling

Figure 2. Rotary Percussion Simulator at the University of Missouri-Rolla

Figure 3. Depth of penetration of cutter in rotary-percussion mode, with and without jet assistance. All measurements were made along a single 12 inch traverse in a sample of Missouri Red Granite.

Figure 4. Mode of failure of rotary percussion insert. This insert was operated without jet assistance.

Figure 5. New high impact cutter technology

Figure 6. Tabletop Pulsed Jet Simulator.

Figure 7. Characteristic waveform of jet pulse generated by simulator.

Figure 8. Nozzle and smoothed flow passageway.

Figure 9. Incipient clogging of high pressure jet nozzles.

Figure 10. Jet Assisted Bit Design with in-Bit Intensification