A New-Generation Mud-Hammer Drilling Tool
Annual Report

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Abstract

The economic and strategic significance of drilling technology has prompted the oil & gas industry to seek for new drilling tools and systems that increase both the rate and efficiency of drilling wells. Interest is focused on short-term improvements to drilling rate, particularly in hard rock formations, as well as on the longer-term development of and integrated "smart" drilling system. Over the past several years, a novel tool that addresses both of these issues has been developed. This tool, a mud actuated down-hole hammer drill, is designed to provide increased rate of penetration. In addition, this tool may be used as the central engine of an integrated drilling system, providing for electricity, data transmission, high-pressure mud jets, self-powered rotation, geophysical sensing, and steering.

At the commencement of the present contract, previous research had verified that the hammer tool could operate in deep, inclined gas wells, using a weighted drilling mud. However, improvements were shown to be needed in the life of the tool, the level of impact energy generated, and the effectiveness of transmitting this energy to the rock formation. Hence, the present investigation focuses on two primary objectives:

- Determining design and operating parameters of the hammer which will result in the greatest improvements in drilling rate, and
- Determining appropriate materials and design features which will optimize the operational life of the hammer.

To date, laboratory testing of a higher energy prototype hammer has shown that an increase in penetration rate can be obtained, even when using a standard roller-cone bit. However, the level of increase is dependent on drilling conditions, particularly, weight-on-bit and the depth of the borehole. The current prototype has produced rate of penetration increases in Carthage limestone of up to 75% in simulated shallow wells (600 ft), and 10% in deeper wells (6000 ft). Where weight on bit is constrained to under 10,000 lbf (for example, in extreme crooked hole territory), penetration rate increases over conventional drilling of 300% have been observed.

Further improvements in hammer effectiveness are currently being pursued in the following areas:

- **Cycle Efficiency.** The effectiveness of the current hammer is limited by inefficiencies in its cycle, which cause premature slowing of the hammer prior to impact. Efforts continue in characterization and optimization of the hammer cycle.
- **Efficiency of Energy Transfer.** A new, fixed cutter rotary-percussion bit, using advanced polycrystalline diamond inserts, is currently being developed in an effort to maximize transmission of the hammer impact energy to the rock. Unlike common flat-head button bits used in air hammer drilling, the new design will be able to drill interbedded hard and soft formations, and will be able to exploit rotational drilling energy as well as percussive energy.
- **Materials Improvements.** Advanced coating materials, including polycrystalline diamond, are being investigated in high wear regions of the hammer to give improved service life.
- **Integration of Advanced Drilling Mechanisms.** In cooperation with other research efforts, the benefits of integrating high-pressure mud jet technology with rotary-percussion drilling technology is being investigated. This integration is expected to have particular benefit in deep drilling applications, where hammer drilling effectiveness is lessened.

The ultimate goal of the mud driven hammer developments is to provide a down-hole power source for future “smart” drilling systems.

Introduction

The economic and strategic significance of drilling technology has prompted the oil and gas industry to seek for new drilling tools and systems that increase both the rate and efficiency of drilling wells. Interest is focused on short-term improvements to drilling rate, particularly in hard rock formations, as well as on the longer-term development of and integrated "smart" drilling system.[1] One advanced down-hole drilling system with the potential of addressing each of these areas is a down-hole hammer. This tool converts a portion of the power resident in the drilling fluid into mechanical impacts directly upon the drill bit, thus driving the drill bit into the formation. This percussive action has the effect of increasing the instantaneous weight on bit (WOB), even though the mean WOB may be kept at typical or below than typical levels for drilling. The end results of this action are that the penetration rate of the drill bit may be increased, drill bit life may be increased, and unplanned borehole deviation may be decreased. Each of these results offer economic benefits in terms of reducing drilling time by improving productivity during drilling and reducing costly down-time.

Several down-hole hammer tools are commercially available for boreholes where it is possible to use air as the drilling fluid. Such hammers have been able to improve upon drilling rate by a factor of two or three in certain rock formations. Over the past twenty years, several hammer drills have also been developed which utilize water or water and oil as the working fluid. Such hammers are typically used in mining applications, where use of clean water is acceptable. However, in wells where mud is the drilling fluid of choice, no economically viable down-hole hammer exists.

Mud actuated hammer developments. The large potential commercial benefit of a down-hole mud actuated hammer has motivated several development efforts over the last fifty years. Two basic design approaches have been taken: the design of a "native" mud system, and the conversion of a water-actuated system to mud. The former of these approaches begins the design process with a consideration of the peculiarities of drilling mud, while the latter attempts to build upon existing technologies in use in other applications. While the key in both of these approaches is to successfully utilize a non-ideal drilling fluid (one which is highly abrasive, contains particulates, and is designed to clog small fluid passages), the former allows such issues to be addressed from a very fundamental level – from the basic design of the cycle and valving scheme used by the tool.

An appreciation of the non-ideal nature of mud as an operating fluid has be gained over the past four decades of development efforts. Though previous efforts tallied substantial gains in drilling effectiveness, these efforts failed because of clogging of

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reciprocating members, valve and valve seat wear, deleterious effects of "water hammer"* on borehole stability and mechanical parts, and premature failure of dynamic mechanical elements such as springs and seals.[2],[3,4,5] Current international efforts to convert water-driven mining tools to the mud environment are likewise being hampered by high erosion of critical surfaces and clogging of the hammer mechanism.

To minimize these problems, a "native" mud-actuated hammer system has been designed and built.[6],[7] Figure 1 shows schematically this tool and its mode of operation. Basic operation of the tool begins with the tool positioned as shown in Figure 1a. In this condition, pressurized mud is allowed to flow along the outer path into the upper and lower chambers as shown. Mud pushing against the large surface in the lower chamber moves the hammer upward, overcoming the force of the mud pushing against the smaller surface in the upper chamber. Upward movement of the hammer causes the valve to move upward until it shuts off flow to the lower chamber as shown in Figure 1b. Mud is next allowed to exhaust from the lower chamber, causing a net force imbalance downward. This force acts to slow the upward movement of the hammer and return it towards its beginning point as shown in Figure 1c. Figure 1d shows the hammer at its impact point, where the momentum of the valve resets it to its beginning point.

The tool just described is fitted with a hydraulically assisted mechanical shuttle valve. As mentioned above, this valve is mechanically constrained to move in concert with the primary motion of the hammer. Therefore, the large forces that move the hammer also move the valve, thereby reducing the risk of fouling. In addition, the valve is also livened by hydraulic forces, which tend to prevent dwelling of the valve, even in a particulate environment. These features, along with the sliding/shearing motion of the valve shown in Figure 1, minimize the tendency of the valve to become fouled by the drilling mud.

Other design features of this tool have focused on other design weaknesses of previous attempts. In particular, the tool employs no dynamic springs or seals. Also, to minimize deleterious "water hammer" effects, the tool utilizes only a portion of the total flushing flow of mud to effect percussion. The remainder of the flow is allowed to pass directly to the drill bit, without dropping pressure across the tool, for bottom-hole cleaning. This is known as "in-parallel" hammer operation.

Objectives

At the commencement of the present work, previous research had verified that the new generation hammer tool mentioned above could operate in deep (>4000 m, >13,100 ft), inclined gas wells, using a weighted (1.7 kg/L, 14 lbm/gal) drilling mud. The robustness of the above mentioned cycle has also been shown in preliminary testing: the hammer was faithful in above-ground operation over a period of at least fifty hours in a weighted drilling mud with solids. However, this initial testing determined that improvements were necessary in the life of the tool, resetting the tool after stopping flow,

* "Water hammer" is a sudden increase in fluid pressure that results most typically from suddenly stopping the movement of a quantity of incompressible fluid. Such is typical with a liquid driven hammer, wherein the liquid driving the hammer undergoes sudden changes in direction as the hammer reciprocates.

the level of impact energy generated, and the effectiveness of transmitting this energy to the rock formation.[8] Hence, the present investigation focuses on two primary objectives:

- Determining design and operating parameters of the hammer which will result in the greatest improvements in drilling rate, and
- Determining appropriate materials and design features that will optimize the operational life of the hammer.

The goal of these two objectives is to improve the benefit/cost ratio of the tool so as to provide economic viability.

Approach

To accomplish these overall goals, a systematic study has begun with primary focus on characterizing and improving the effectiveness and life of the current mud-actuated hammer design. Three basic areas related to hammer effectiveness and life are being addressed in this study: system design, wear materials, and bit design.

System design. Hammer output parameters such as the energy, frequency, and peak force or velocity of hammer blows, as related to the characteristics of the rock formation being drilled are of particular interest in optimizing the effectiveness of the tool. Both physical and operational parameters combine to produce the output parameters above. The pressure of the working fluid and the access of flow to the workings of the tool are key operational parameters which may be altered during drilling to change energy and frequency of hammer blows. Physical parameters, such as the geometry and mass of the hammer, the geometry, stiffness and mass of the drill bit used, and the stroke of the hammer may likewise be optimized, although not real-time while drilling.

Of a necessity, the consideration of system design implies an ever-improving model of the hammer. This model includes fundamental mathematical models, as well as a database of experience with the tool. Of particular interest is the cataloging of drilling parameters vs. effectiveness in various formations.

Wear materials. As already described a key life and performance-limiting factor for a down-hole mud-actuated hammer is the effect of the abrasive mud on critical valve surfaces. Focus in this area is primarily upon hard-facing materials, which enhance the wear resistance of these surfaces. Of secondary interest are materials and treatments that help improve the life of impact surfaces. Since all surfaces of a down-hole hammer are typically bathed in the working fluid, impact surfaces are particularly susceptible to erosive damage from fluid quickly voiding across the surface just prior to impact. These areas of focus are critical to the overall economic success of the hammer design.

Bit design. In past development efforts, high-energy hammer drills have broken welded tri-cone bits. Even when such bits do not fail during hammer drilling, they do not transmit impact energy ideally. This fact is due to the complexity and the relatively high compliance of a tri-cone bit.* Historically, to compensate for this problem and provide a more effective application of the hammer impact to the rock being drilled, fixed-cutter, flat-faced, button bits were developed. However, this type of bit has the disadvantage that it cannot be used under heavy weight on bit, nor can it be used to ream a tapered hole. Under heavy axial load, the button cutters or the bit head on a flat faced bit will typically fail.

It is the authors' thesis that hammer drills will offer the best gains, particularly in deep or horizontal wells, if rotary drilling mechanisms as well as percussive drilling mechanisms are allowed to be operative. In this case, improved penetration due to hammer impact is followed directly by a shear removal of damaged rock. Hence, in deep wells where rock formations typically act more plastic due to a high pressure head, the bit is not relying solely on axial indentation for penetration. Also, in formations where soft rock is interbedded with hard, pure percussion drilling is not effective, so a rotary element is of great benefit. Such drilling is known as "rotary-percussion" drilling, as opposed to percussion or hammer drilling, wherein cutters are simply indexed between hammer blows, without providing significant rotary drilling action. The present tool's in-parallel mode of operation, in combination with rotary-percussion drilling carries with it an added benefit that the hammer may be modulated or turned on and off to give a particular drilling performance, tailored to rock formation. Also, with rotary-percussion drilling and in-parallel operation, drilling need not stop should the hammer fail to operate – it may continue using rotary mechanisms until a satisfactory time is reached to trip the drill string.

This overall area of focus is expected to significantly improve the efficiency of energy transfer between hammer and rock and improve particularly deep well drilling.

Each of the above areas of research is fed by continued desk studies, laboratory evaluations and field testing.

Project Description

Test bed. To accomplish the above research, a second generation prototype hammer tool (referred to as "N4") has been designed and built. This tool embodies two fundamental improvements over earlier prototypes: a capacity to generate higher impact energy levels, and a hammer which is more optimally matched in mass to the bit that it is driving. These features permit a greater range of test parameters, while fundamentally improving the efficiency of energy transfer to the drill bit.

Optimization of system design. Analysis of the operability and effectiveness of the prototype tools under different sets of operational and physical parameters is accomplished primarily through instrumented drilling tests. Initial emphasis of the current project has been placed on optimizing the new hammer's drilling effectiveness. The primary success criterion for this optimization process is a measure of hammer tool drilling rate as compared to a conventional drilling system operating at the same hydraulic horsepower. Economic advantage is expected to accrue once the hammer increases

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* In this work, the apparent compliance of an 8½-inch tri-cone rock bit was measured to be approximately 4 times that of the striking hammer.

drilling rate by a factor of 1.2 to 1.6, depending on the type of rock and cost of rig.[9] This factor is also sensitive to the usable life of the tool, as will be detailed later.

Of first interest is the effectiveness of the tool in rock formations that are typically difficult to drill using conventional procedures, but which are likely to be encountered in drilling for gas. Hence, laboratory tests have focused on rocks such as Carthage Marble, and Crab Orchard Sandstone.

Figure 2 depicts the equipment and setup used in a typical simulated borehole test at the Terratek Drilling Research Laboratory in Salt Lake City, Utah. This site has been used for initial quantification and optimization work because of its convenient location and its ability to provide identical drilling conditions repetitively. This work has been fed and supported by instrumented flow tests under atmospheric conditions. Such tests offer a lower cost means of verifying tool operation and putting operating hours on the tool; however, more importantly, such tests allow iterations which cannot be done while drilling. For example, during a recent flow test, a means of quickly modifying the stroke of the hammer, using servo positioning of the test rig, was employed to investigate the sensitivity of the hammer to variability in its impact point. Such simplified flow tests have also permitted the use of specialized position sensors that assist in gaining an understanding of the operation of the tool. Figure 3 shows the output of such a sensor, depicting the time record of a non-impacting cycle of the N4 hammer.

Other test objectives. The new N4 tool has been the primary vehicle for learning to date, and will continue to assist the optimization process during the course of the next year. However, other hammer prototypes will be built as more intensive field studies are implemented later in the program. Inasmuch as a primary goal for the remainder of the program is to obtain field experience and exposure of the new design, further use of previous prototypes is also expected for suitable less severe applications. Such usage will assist in gaining experience with the tool and in improving wear materials. Each field or laboratory test iteration offers an opportunity to improve and evaluate wear resistant materials. Indeed, one parameter that will be closely monitored in such tests will be wear or other damage to critical tool regions.

Results

Original prototype. Recent laboratory testing has yielded comparative data that has quantified the potential drilling benefits of the original prototypes. Figure 4 shows the rate of penetration of a conventional drilling system and the original new-generation prototype hammer drilling system as a function of WOB. This data is reported for drilling in Carthage Marble under shallow hole conditions (a simulated hole depth of 200 m, 600 ft) and at near maximum hammer impact levels. As shown, a nearly linear relationship exists between WOB and rate of penetration (ROP). Other more thorough studies of conventional drilling have been able to model this relationship reasonably well with a single line or a double-sloped line with a breakpoint near 65 kN (15,000 lbf) WOB.[10, 11] This linear behavior is to be expected, since applying WOB is the mechanism for applying drilling energy to the hole bottom. However, when the original prototype hammer is added into the drilling system, the slope of the ROP vs WOB curve does not fall off as rapidly as the conventional drilling curve. Hence, Figure 4 shows a cumulative effect of rotary and percussive drilling mechanisms. This supports the authors' thesis that a rotary percussion drilling system may have advantages over pure percussion drilling systems. At even lower WOB than that tested in this study,* it is expected that the slope of the ROP vs WOB curve will approach the horizontal, as the drilling energy supplied by rotary drilling mechanisms becomes insignificant and percussion energy dominates the process.

It should be noted that at high WOB, comparable to that most often used in drilling, the original prototype does not supply enough additional energy to significantly improve drilling rate. However, at low WOB, the original prototype improves drilling rate by as much as a factor of three. Physical circumstances which could lead to such WOB constraints include crooked hole territory, and shallow or horizontal wells. Hence, this data points out the ineffectiveness of the initial prototypes under common drilling conditions, but indicates possible application to special drilling applications.

Higher energy prototype. As mentioned, this apparent underpowering of the original hammer tools has led to the development of the N4 prototype. Successful operation of this significantly larger tool has been verified in both atmospheric and simulated borehole conditions (simulated depths of up to 6000 ft). This success has given a first indication that the current design may be scaled for different drilling applications (e.g., scaled up further for larger wellbores, scaled down for possible application to slimhole drilling).

Figure 5 shows the improvement in ROP offered by the N4 design, as compared to conventional drilling. The data reported is for drilling in Carthage Marble. In this figure, hammer energy level increases with the pressure drop at the bit (shown on the abscissa). Three different simulated down-hole conditions are also represented: 2070 kPa (300 psi), 6900 kPa (1000 psi), and 20700 kPa (3000 psi) borehole pressure. These pressures roughly correspond to 200 m (600 ft), 650 m (2000 ft), and 2000 m (6000 ft) drilling depths. As shown in this figure, the improvement in ROP offered by the hammer increases with hammer energy. Increases as high as 75% over conventional drilling can be seen for low borehole pressures. Though exhaustive data is not available at higher borehole pressures, there is also a distinct trend towards decreasing hammer effectiveness with increasing drilling depth. As shown, the hammer at 2000 m (6000 ft) simulated depth produces only a 12% increase in ROP under the same operating parameters which produce a 53% increase in ROP at 200 m (600 ft) simulated depth. The hammer does not appreciably change its operating characteristics at higher borehole pressures. Therefore, the change in hammer effectiveness may be attributed to effects of the higher borehole pressure on the rock. Such effects have been documented for conventional roller-cone drilling.[12]

One means of improving the above-mentioned performance of the N4 tool is to improve the efficiency of the tool. Inspection of the hammer's sliding surfaces after this testing suggested that the actual hammer stroke was not what was expected. Indications were present that suggested the hammer was short-cycling, i.e., the hammer was decelerating just prior to impact, reducing the velocity of impact, and therefore reducing

* This study was limited by the ability of the drill rig to maintain WOB at levels less than 10,000 lbf with the hammer operating.

the effectiveness of the tool. Further investigation wherein the time history of the hammer position was measured verified this notion. Referring to Figure 6, it can be noted that the peak velocity (the steepest slope of the position curve) occurs approximately 4.8 cm (1.9 in) above the normal impact point of the tool. As shown, the slowing of the hammer prior to impact in this particular case is approximately 55%. This represents a large source of inefficiency of the present tool.

Work subsequent to the testing just mentioned has focused on means of removing this inefficiency and thereby obtaining greater hammer performance. This work has determined that simple modifications to the hammer's valve may reclaim a significant portion of the lost energy. Preliminary flow testing has verified the feasibility of this approach. Quantitative drilling tests will follow.

One other significant observation of the current testing program is that the wear of the hammer valve must be improved to give economic life of the tool. Figure 7 shows typical wear of the valve. As can be seen, the areas most affected by the abrasive nature of the drilling fluid are the edges of the valve. As these areas wear, leakage through the valve increases which worsens the short-cycling problem mentioned above and leads to lower hammer effectiveness. Tool life may be extended by increasing the wear resistance of the valve and by decreasing the operating pressure of the hammer.

Benefits

Comparison of the effectiveness of the N4 prototype with earlier versions of the same overall design indicates that the impact energy levels and the improved energy transmission offered by the N4 design have certainly improved the drilling effectiveness of the tool. More improvement is necessary before the tool produces economic benefits for deep well drilling (high borehole pressure). Estimates of drilling performance of such a tool show a 20% to 60% increase in ROP, along with a useful hammer life of 720 hours (6 repair cycles anticipated) is needed for the tool to be cost effective.

While this goal is being pursued, current and previous prototypes have the potential to provide immediate economic benefits to drilling in special applications, such as shallow and WOB limited wells (crooked-hole, horizontal wells, etc.). Though these latter applications are not the ultimate target of the current research, such will undoubtedly assist the learning process by providing experience operating the tools, and opportunities to field test new materials, new design features, etc.

Beyond the present focus of improving drilling effectiveness, a hammer operating down-hole may also be used for a number of other functions, much like an automobile engine is used to drive auxiliary devices such as an air conditioning unit, a water pump, and an alternator. For example, one particular application that is being developed using an air hammer is a steerable drilling device that provides down-hole rotation by the reciprocation of the hammer.[13] Other possible applications of the reciprocating motion of the hammer include using impacts as an exciter for sonic look-ahead measurements, down-hole electricity generation, instantaneous geophysical measurements (using the rebound of the hammer as a transducer for such), and down-hole high-pressure jet intensification. Such collateral uses of the hammer further improve the benefit/cost ratio of the hammer.

Future Activities

Focus in this research remains on improving hammer effectiveness and life. Further improvements in hammer effectiveness are currently being pursued in the following areas:

- **Cycle Efficiency.** The test results discussed above show that the effectiveness of the current hammer is limited by inefficiencies in its cycle, which cause premature slowing of the hammer prior to impact. Further optimization of the hammer valve has begun to improve hammer efficiency. Efforts continue in the characterization and optimization of the hammer cycle.
- **Efficiency of Energy Transfer.** It should be noted that each of the drilling tests reported above have used a standard roller cone bit. As already described, such a bit is non-ideal for transferring impact energy to rock, although it preserves the ability to effectively use rotary drilling mechanisms to enhance percussion mechanisms. A fixed cutter bit, which allows significant rotary drilling, is seen as ideal for this application.

  A common PDC drag bit may lend itself well to this application, and will be evaluated for this purpose. However, an off-the-shelf bit may not be robust enough for percussive drilling. Also, a standard bit would need to be connected to the hammer tool via a rotary-shouldered connection, which attenuates the impact signal generated by the hammer. For these reasons, a new, fixed cutter rotary-percussion bit, using advanced polycrystalline diamond inserts, is currently being considered. New polycrystalline diamond inserts,[14] which give twice the impact resistance of a common PDC bit insert, have been developed for this bit. Figure 8 displays the basic design of this new insert.[*]

  Figure 9 is a rendering of a promising new bit design. This bit is currently being developed in a related research project[†] for use in a jet-assisted mechanical drilling application (see below), and lends itself well to the current effort. Unlike common flat-head button bits used in air hammer drilling, the goal of this new design is to be able to drill interbedded hard and soft formations, and will be able to exploit rotational drilling energy as well as percussive energy. Pending final analysis of the cutter pattern by Sandia National Laboratories, this new bit will be manufactured and tested in future hammer studies.
- **Integration of Advanced Drilling Mechanisms.** In cooperation with other research efforts, the benefits of integrating high-pressure mud jet technology with rotary-percussion drilling technology is being investigated. Figure 10 shows the basic components of such a system. As shown, this system exploits a synergistic action between rotary-percussion drilling and high-pressure jet scouring of the rock surface. In addition, the life of the diamond cutter is extended due to enhanced cooling of the cutter. Such a system has been shown

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[*] Patent pending.

[†] DOE Grant DE-FG03-96ER82242

in recent research to potentially double the ROP of a non-integrated drilling system.[15] These findings have also shown particular benefit to using jet-assisted drilling with percussive modes of drilling. Hence, this integration is expected to have particular benefit in deep drilling applications, where hammer drilling effectiveness is lessened.

Improvements in hammer life are primarily being sought in the following area:

- **Materials Improvements.** Currently, the valve is protected by a proprietary tungsten carbide coating. Advanced coating materials, including other tungsten carbide based coatings and polycrystalline diamond, are being investigated in high wear regions of the hammer to give improved service life. Super materials, such as polycrystalline diamond, are expected to be key to achieving the longevity required for optimal economic service. Figure 11 conceptually displays an enhanced hammer valve.

Once the above objectives are met, an effective drilling tool will be available to industry. On a grander scale, it is likely that the usefulness of the down-hole mud-actuated hammer will extend much farther than this - this tool may conceivably be used as the central engine of an integrated “smart” drilling system, providing for down-hole electricity, data transmission, high-pressure mud jets, self-powered rotation, geophysical sensing, and steering. The system envisioned is shown in Figure 12.

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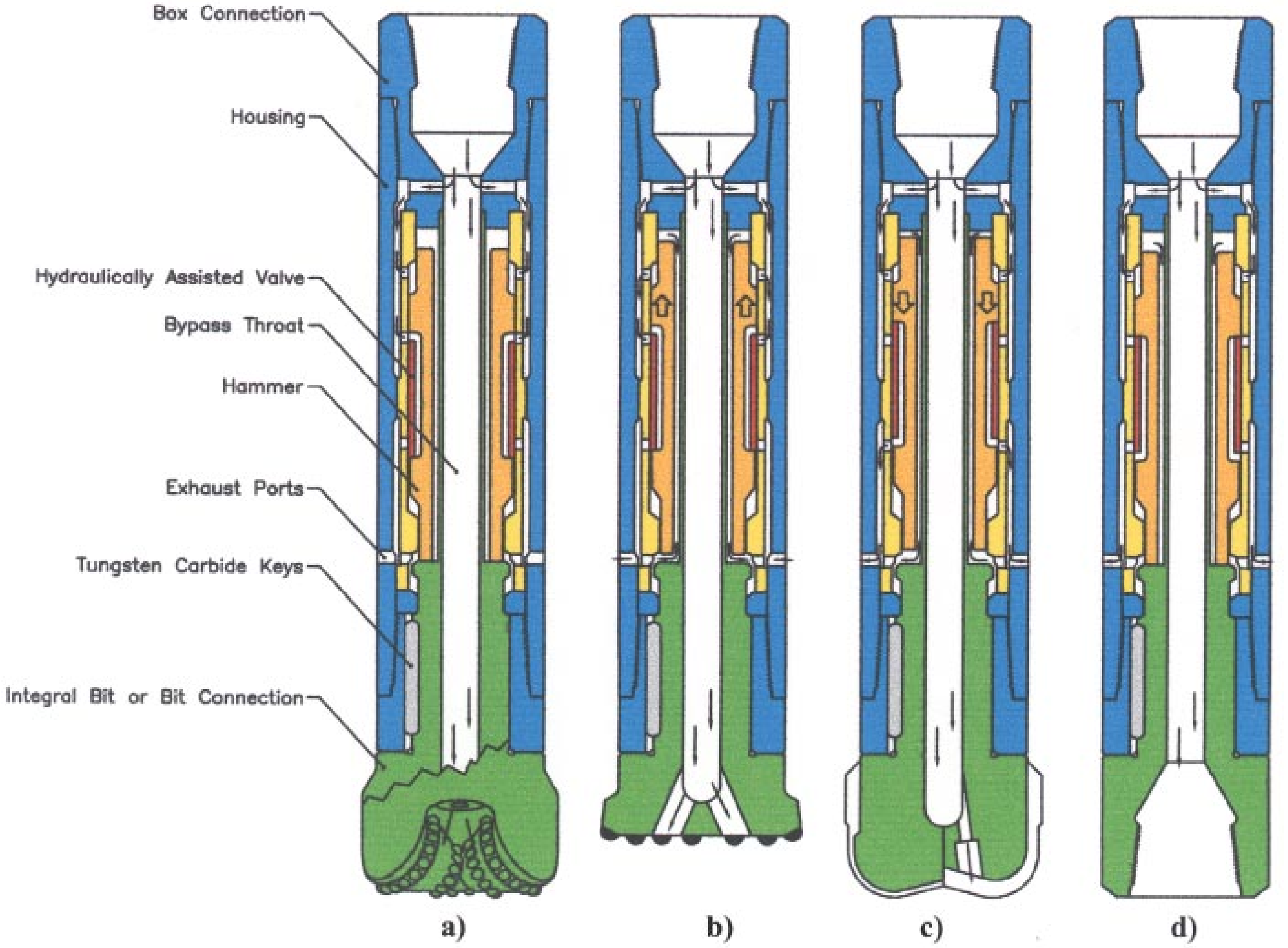

Figure 1: Operation of Novatek Hammer

Figure 2: Terratek Drilling Test Facility

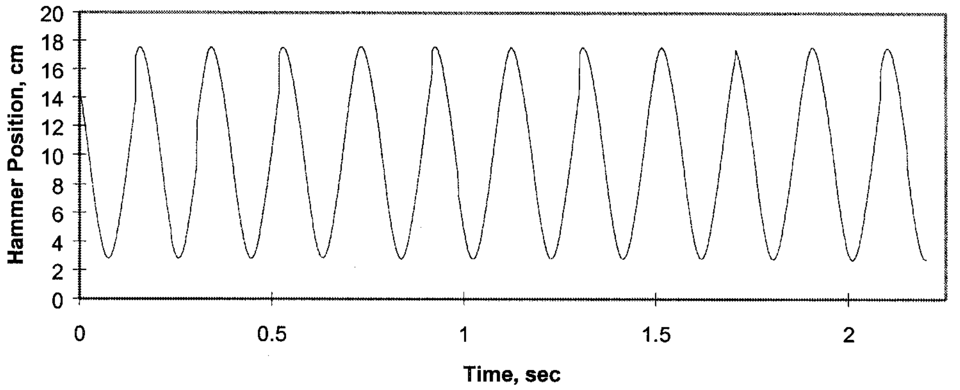

Figure 3: Time History of Hammer Motion from Position Sensor

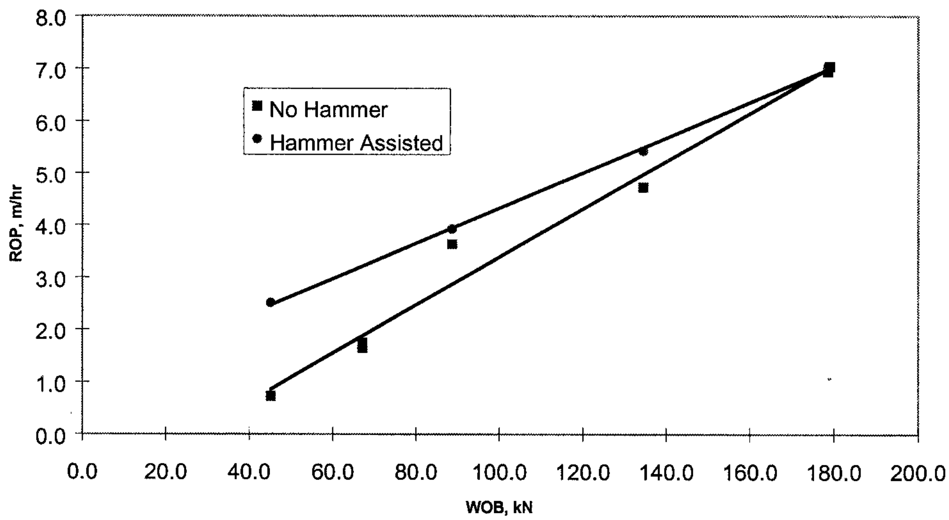

Figure 4: Original Prototype – ROP vs WOB in Carthage Marble

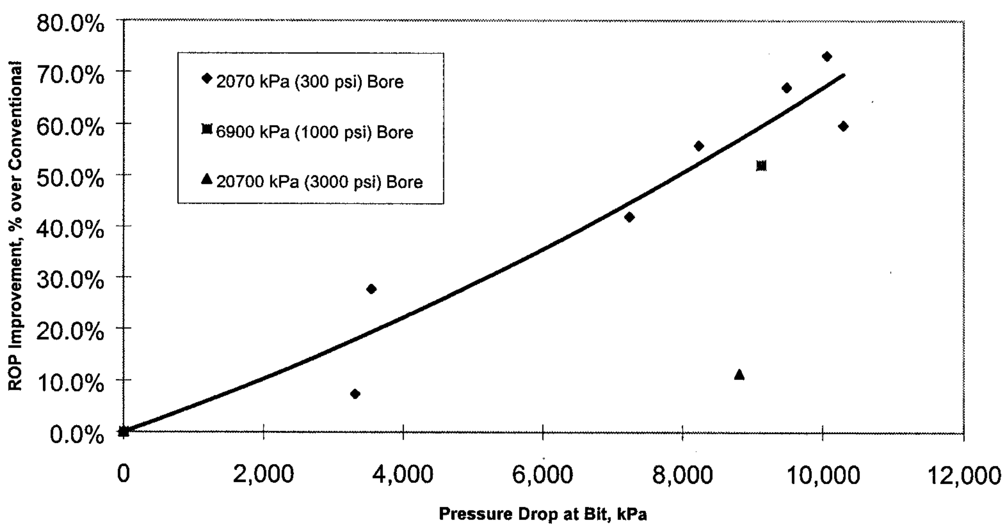

Figure 5: N4 Prototype – Effect of Hammer on ROP in Carthage Marble

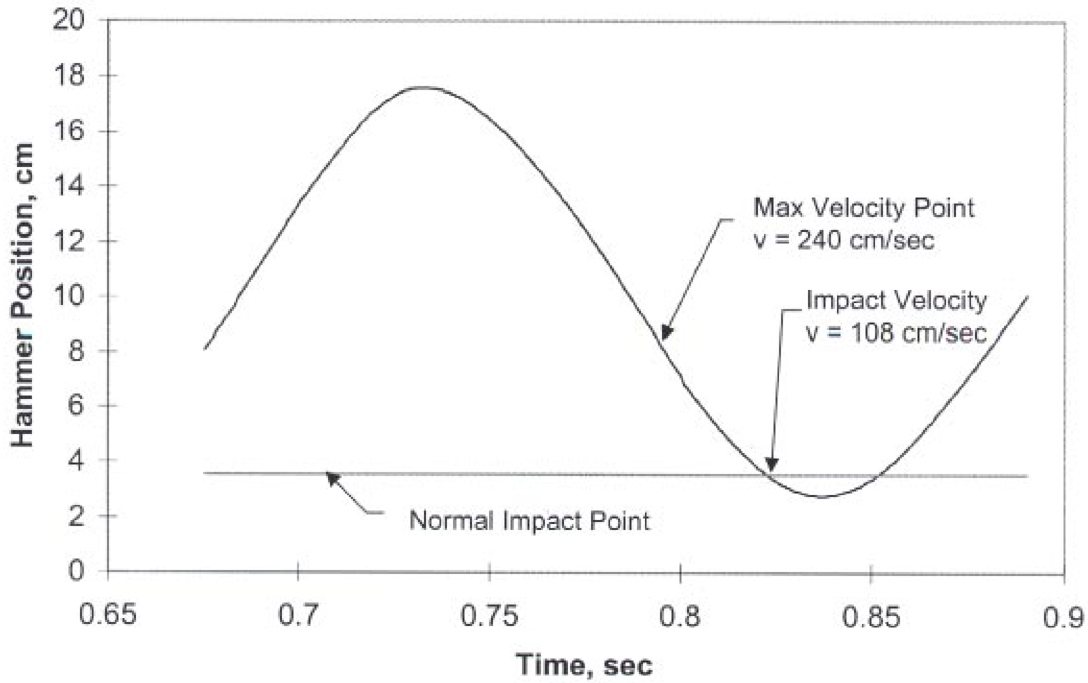

Figure 6: Short Cycling of N4 Tool

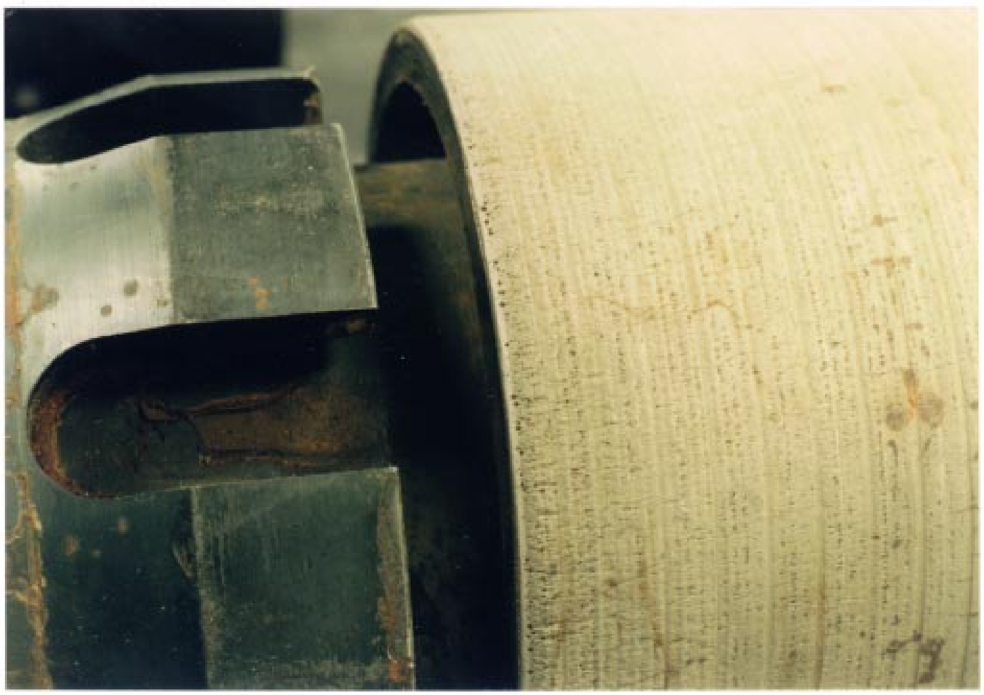

Figure 7: Wear of Valve Edges

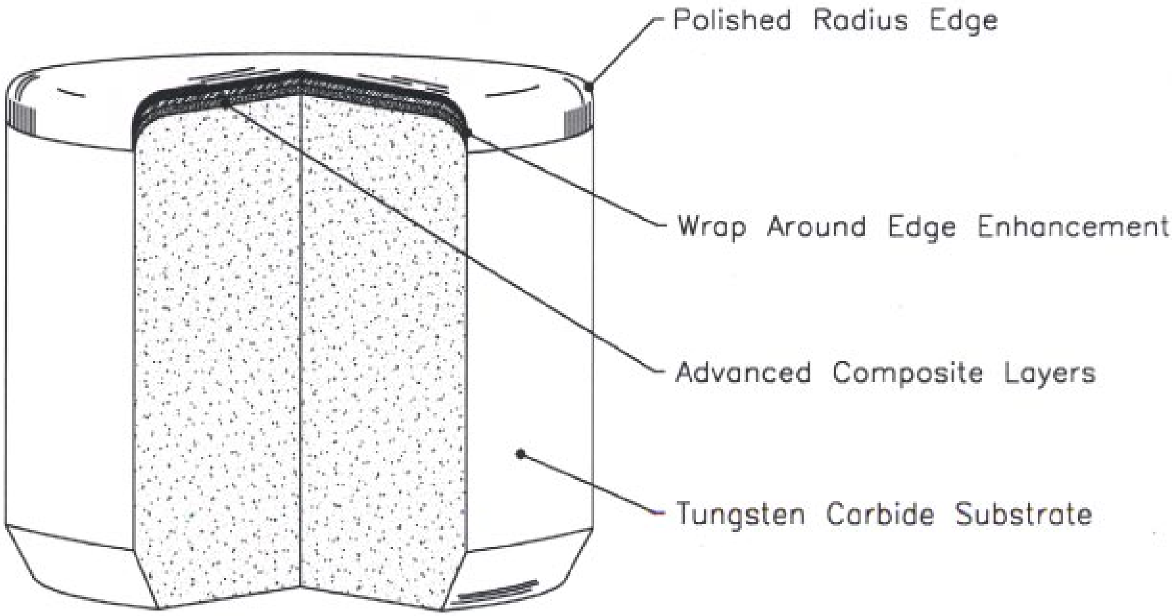

Figure 8: Advanced Polycrystalline Diamond Shear Cutter

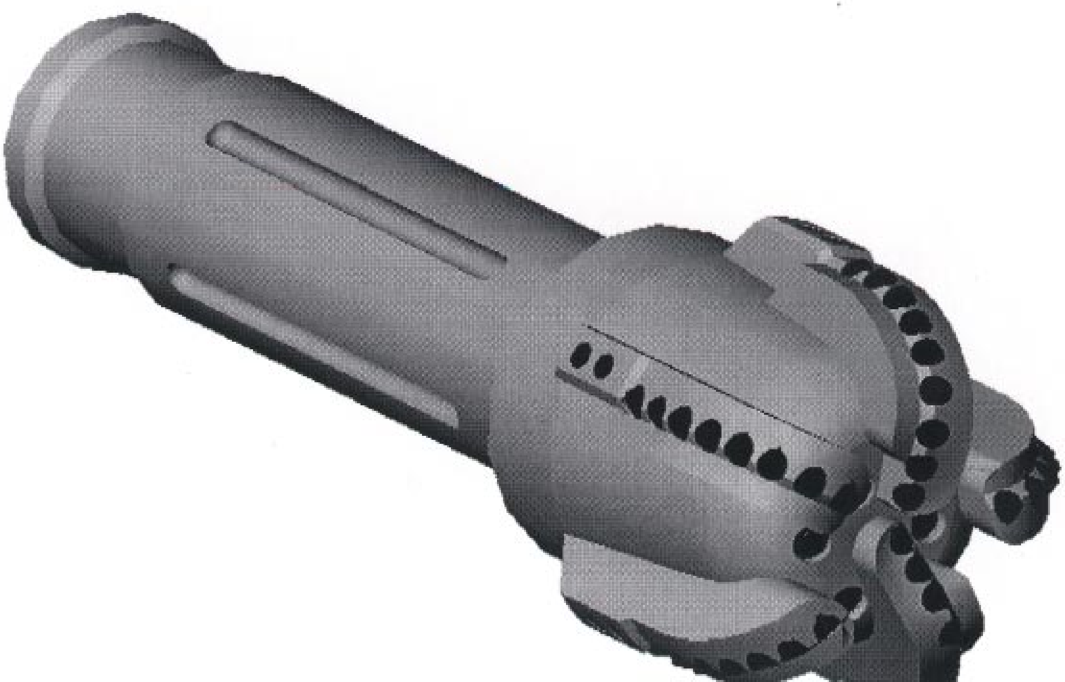

Figure 9: Novel Rotary-Percussion Bit

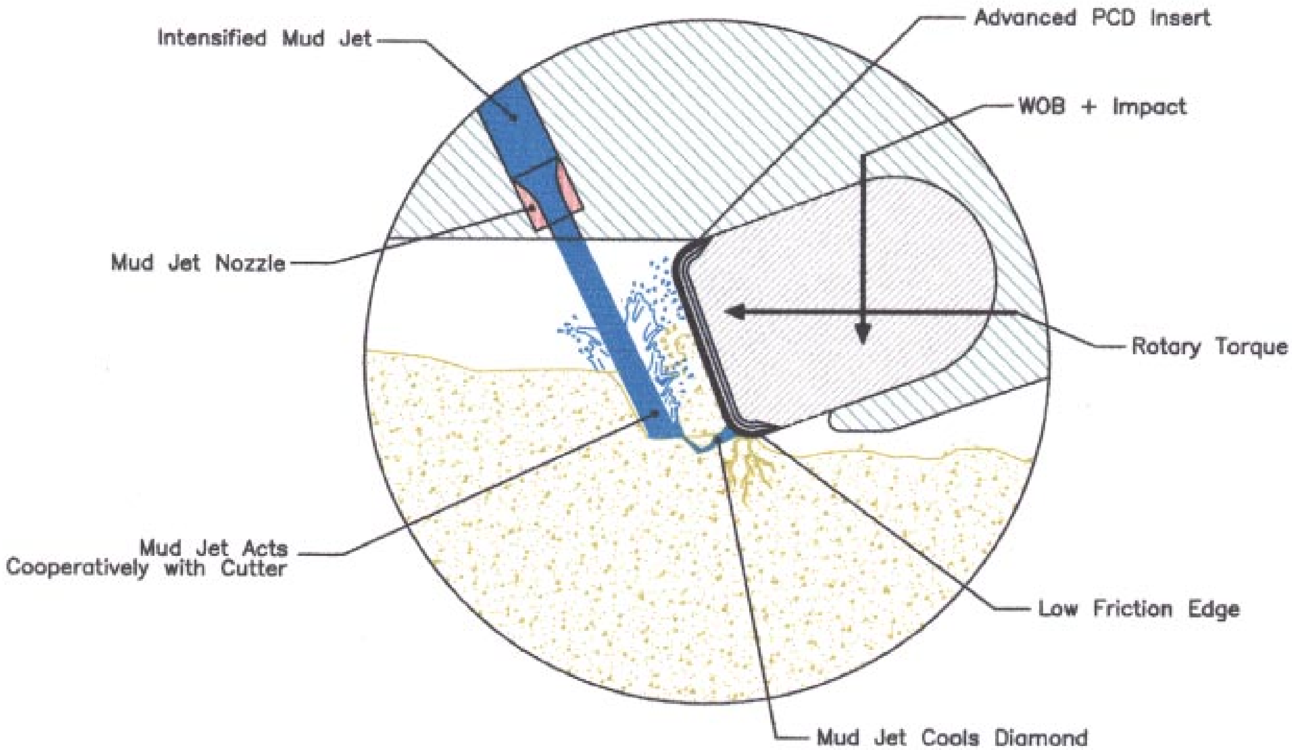

Figure 10: High Pressure Jet-Assisted Rotary-Percussion Drilling

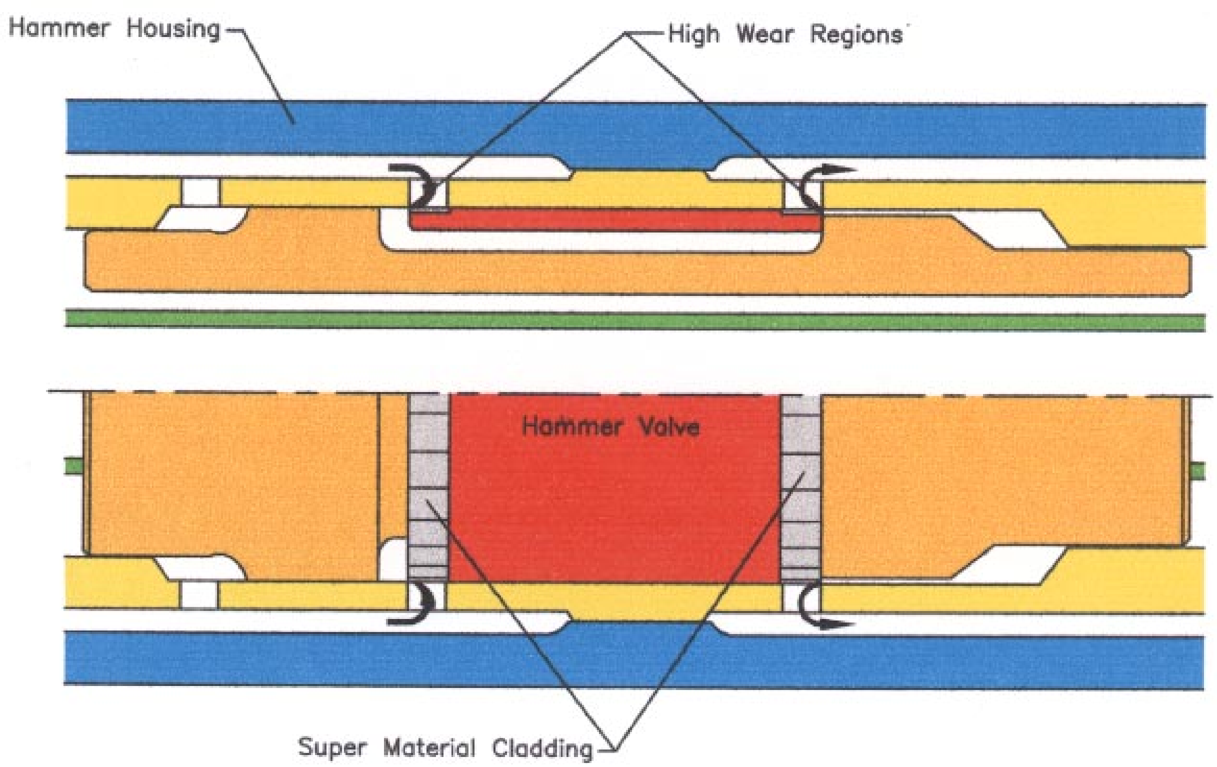

Figure 11: Hammer Valve Enhanced with Super Materials

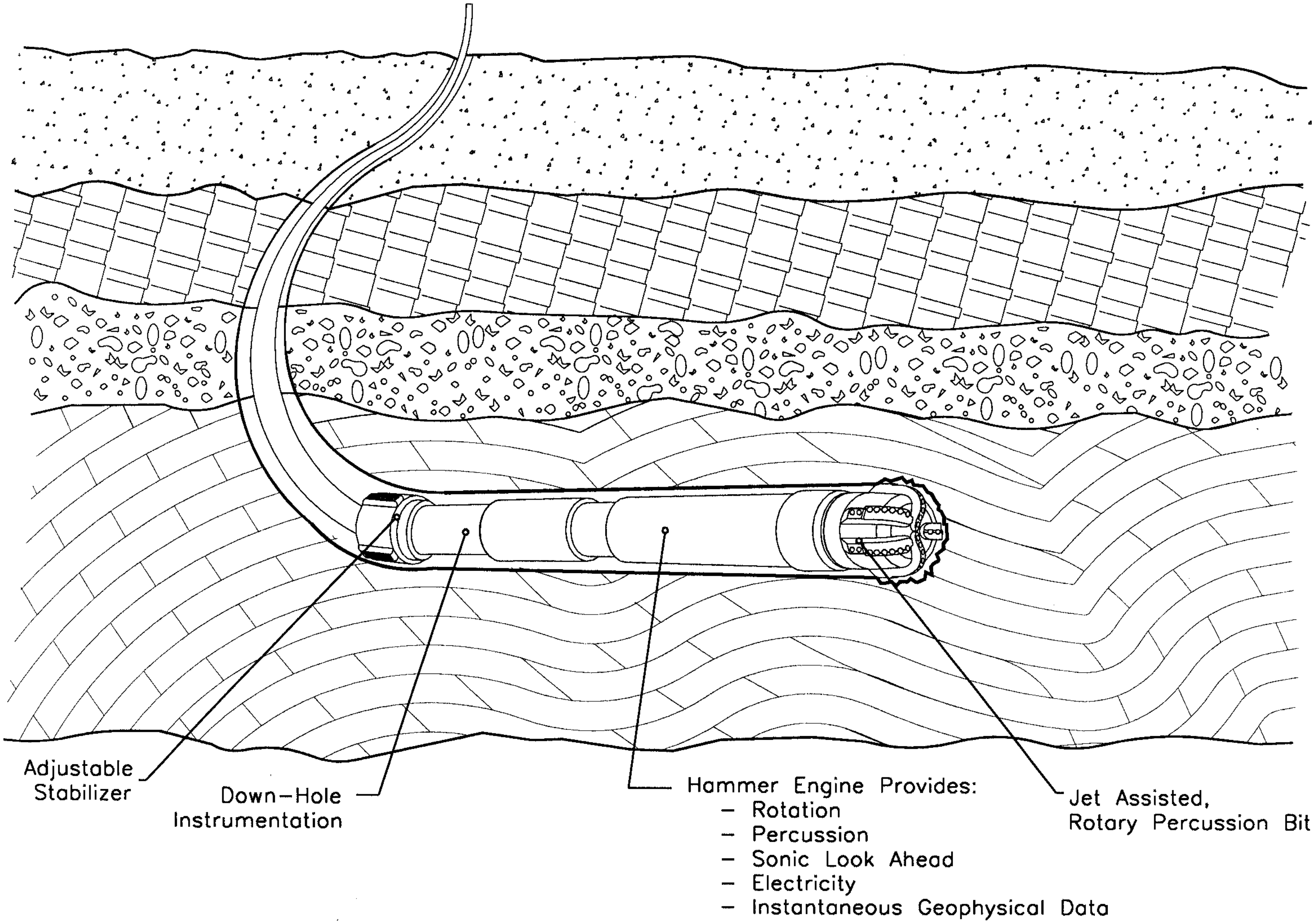

Figure 12: Advanced Drilling System