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Final Report

Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High-Speed Diamond Drilling

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ABSTRACT

The two phase program addresses long-term developments in deep well and hard rock drilling. TerraTek believes that significant improvements in drilling deep hard rock will be obtained by applying ultra-high rotational speeds (greater than 10,000 rpm). The work includes a feasibility of concept research effort aimed at development that will ultimately result in the ability to reliably drill "faster and deeper" possibly with smaller, more mobile rigs. The principle focus is on demonstration testing of diamond bits rotating at speeds in excess of 10,000 rpm to achieve high rate of penetration (ROP) rock cutting with substantially lower inputs of energy and loads.

The significance of the "ultra-high rotary speed drilling system" is the ability to drill into rock at very low weights on bit and possibly lower energy levels. The drilling and coring industry today does not practice this technology. The highest rotary speed systems in oil field and mining drilling and coring today run less than 10,000 rpm—usually well below 5,000 rpm.

This document provides the progress through two phases of the program entitled "Smaller Footprint Drilling System for Deep and Hard Rock Environments: Feasibility of Ultra-High-Speed Diamond Drilling" for the period starting 30 June 2003 and concluding 31 March 2009. The accomplishments of Phases 1 and 2 are summarized as follows:

- TerraTek reviewed applicable literature and documentation and convened a project kick-off meeting with Industry Advisors in attendance (see Black and Judzis).
- TerraTek designed and planned Phase I bench scale experiments (See Black and Judzis). Improvements were made to the loading mechanism and the rotational speed monitoring instrumentation. New drill bit designs were developed to provided a more consistent product with consistent performance. A test matrix for the final core bit testing program was completed.
- TerraTek concluded small-scale cutting performance tests.
- Analysis of Phase 1 data indicated that there is decreased specific energy as the rotational speed increases.
- Technology transfer, as part of Phase 1, was accomplished with technical presentations to the industry (see Judzis, Boucher, McCammon, and Black).
- TerraTek prepared a design concept for the high speed drilling test stand, which was planned around the proposed high speed mud motor concept. Alternative drives for the test stand were explored; a high speed hydraulic motor concept was finally used.
- The high speed system was modified to accommodate larger drill bits than originally planned.
- Prototype mud turbine motors and the high speed test stand were used to drive the drill bits at high speed.
- Three different rock types were used during the testing: Sierra White granite, Crab Orchard sandstone, and Colton sandstone. The drill bits used included diamond impregnated bits, a polycrystalline diamond compact (PDC) bit, a thermally stable PDC (TSP) bit, and a hybrid TSP and natural diamond bit.

- The drill bits were run at rotary speeds up to 5500 rpm and weight on bit (WOB) to 8000 lbf.

During Phase 2, the ROP as measured in depth of cut per bit revolution generally increased with increased WOB. The performance was mixed with increased rotary speed, with the depth cut with the impregnated drill bit generally increasing and the TSP and hybrid TSP drill bits generally decreasing.

The ROP in ft/hr generally increased with all bits with increased WOB and rotary speed.

The mechanical specific energy generally improved (decreased) with increased WOB and was mixed with increased rotary speed.

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EXECUTIVE SUMMARY

Background

The "Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High-Speed Diamond Drilling" (UHSDD) Phase 1 tests were conducted to explore trends in penetration rates and specific energy at various rotational speeds and bit loads and to investigate any evidence of changes in rock removal mechanisms at varying speeds and loads. This was accomplished in Phase 1 and lead to the continuation of the project into an additional phase. Phase 2 tasks included scaling up the experiments to small-sized oilfield drill bits to prove the concept.

Accomplishments

Significant accomplishments during Phases 1 and 2 of the UHSDD are listed below. Details of earlier accomplishments were reported during the regular reporting periods (Black and Judzis; Judzis, Black, and Robertson; and Judzis, Robertson, and Black).

- TerraTek reviewed applicable literature and documentation and convened a project kick-off meeting with Industry Advisors in attendance.
- TerraTek designed and planned Phase I bench scale experiments.
- Preliminary bench-scale tests were conducted to optimize fluids, flow rates, and improve core bit design.
- Methods of statistical design of experiments were introduced to provide direction in determine the sequence for bit loading, rotational speed and rock tested for the final series of tests.
- More than 100 tests using various rock types and bit types were conducted in Phase 1.
- A paper titled "Investigation of Smaller Footprint Drilling System; Ultra-High Rotary Speed Diamond Drilling Has Potential for Reduced Energy Requirements," authored by Arnis Judzis, et al. (see Judzis, Boucher, McCammon, and Black), was prepared and presented at the IADC/SPE Drilling Conference in February 2006. This paper outlined accomplishments to that time on the Ultra-High Speed Diamond Drilling project.
- Statistical analysis of the bench-scale data revealed a general trend to more efficient drilling as rotational speeds increased above approximately 30,000 rpm.
- TerraTek met with industry advisors for a Phase 2 kickoff meeting to determine the direction of Phase 2 systems and tests.
- Two test concepts were used for Phase 2 testing. The first utilized prototype turbine mud motors and the second high speed hydraulic motors to drive the drill bits. TerraTek's full-scale drill rig was utilized for the turbine motor tests and a high-speed drilling test stand was engineered and constructed for additional tests.
- Various drill bit manufacturers supplied drill bits for high rotational speed drilling. Manufacturers supporting the test program included ReedHycalog and Hughes

Christensen. Drill bits were also supplied by Technology International, Inc. for the mud turbine drilling tests.

- Tests conducted provided benchmark performance of drill bits at rotary speeds to about 5500 rpm.

It is recommended that additional tests be conducted at higher rotary speeds and with additional rock types to determine the effects of higher rotary speeds on drilling performance and energy requirements.

A better torque sensing method is requisite to provide the quality of data required.

INTRODUCTION

Objective

The primary objective of the first phase of this test program was to explore trends in specific energy and penetration rates with high rotational speeds. The second phase of the program demonstrated the concept of high speed drilling with larger, commercial-sized drill bits.

Scope

The two-phase program addresses long-term developments in deep well and hard rock drilling. TerraTek believes that significant improvements in drilling deep hard rock will be obtained by applying ultra-high rotational speeds. The research included a feasibility of concept effort aimed at development that will ultimately result in the ability to drill 'faster and deeper' with smaller, more mobile rigs. The principle focus is on demonstration testing of diamond bits rotating at speeds in excess of 10,000 rpm to achieve high rate of penetration (ROP) rock cutting with substantially lower energy and load.

This document details the progress during Phases 1 and 2 including trends in specific energy during high speed drilling and the test concept development, testing, and analysis.

Plans

The plan of Phase 1 of the program was to develop equipment necessary (on a small scale) to test the high rotational speed drilling concept to determine if less specific energy is required to drill at higher rotational speeds. The test apparatus and instrumentation were developed, testing was conducted, and analysis of results concluded. With the concept proven, Phase 2 was initiated.

The plan for Phase 2 was to determine if less specific energy is required to drill at higher rotational speeds using commercial-scale drill bits. The two parts of this program phase included tests which (1) used prototype downhole turbine motors and drill bits and (2) test three types of diamond drill bits at high rotational speeds using a specially designed high speed drill stand.

Change in Scope of Phase 2

The Phase 2 plan originally called for mining-sized drill bits. To optimize the bit size and motor size, it was necessary and desirable to use small-sized oilfield drill bits for the testing.

The original plan for the drilling machine included using a new mud motor concept under being developed by Impact Industries. Because the motor development was delayed, it was necessary to design a hydraulic rotary drive for the drilling machine. Additionally, Smith Neyrfor and Technology International, Inc., under U.S. Department of Energy project DE-FC26-05NT15486 were able to use TerraTek's test facility to test prototype mud turbines and drill bits at high rotational speeds. The resources required to develop equipment and test at a commercial scale were substantially higher than originally planned and it was therefore necessary to scale back the amount of testing. Tests were conducted at a maximum rotational speed of 5500 rpm.

Industry Partners

Contributions in technical expertise and research have come from ReedHycalog, Shell International, ConocoPhillips, Hughes Christensen, Smith Neyrfor, and Technology International, Inc.

TASK ACCOMPLISHMENTS

The following is a summary of the accomplishments for each of the Phase I tasks.

Task 1.0 – Assessment of deep and hard rock drilling environments requiring novel technologies and tools. This work was completed and reported previously (see Black and Judzis and Judzis, Black, and Robertson).

Task 2.0 – Design, engineer, and plan ultra-high speed drilling program concepts. This task was addressed in a previous report. However, some improvements were made to improve the test operation data collection and quality. Drill bits were redesigned and methods of manufacture developed to produce a consistent core bit configuration during this reporting period.

Task 3.0 – Small-scale cutting performance tests. Extensive tests were run with various rock, bits, fluids, and loads. Testing was extended to full-faced drill bits that were run in Berea sandstone.

Task 4.0 – Analysis of data and concept evaluation. Data analysis was performed after each series of tests to evaluate the trends in rate of penetration and specific energy for each rock. Design and analysis were improved by using statistical design and analytical techniques.

Task 5.0 – Engineering design. Preliminary engineering for the demonstration of the ultra-high speed drilling concept at mining bit size was conducted in Phase 1 and then significantly revised in Phase 2. The concept changed from the mining-sized bit to small, standard-sized drill bits.

Task 6.0 – Transfer of technology. A paper titled "Investigation of Smaller Footprint Drilling System; Ultra-High Rotary Speed Diamond Drilling Has Potential for Reduced Energy Requirements," (see Judzis) authored by Arnis Judzis, et al., was prepared and presented at the IADC/SPE Drilling Conference held in Miami, Florida on 23 February 2006. This paper outlined accomplishments to that date on the Ultra-High Speed Diamond Drilling project. Judzis gave a presentation on test findings and potential for ultra high speed drilling at the Petroleum Technology Transfer Council's (PTTC) Microhole Integration Meeting in Houston, TX on 22 March 2006. The DOE/NETL and industry partners met on 19 June 2006 for a Phase 1 lessons learned presentation and discussion of test findings. Phase 1 Tasks 1 through 6 were reported in the Phase 1 report titled, "Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High-Speed Diamond Drilling" (Judzis, Robertson, and Black).

Task 7 – Job pre-planning and characterization of applications. This task was completed with consultation with industry advisors from TerraTek, ReedHycalog, and Impact Industries in June 2007. The initial pre-planning was supplemented with discussions with Smith International, Hughes Christensen, Technology International, Inc., Scorpion Engineering, New Tech, American Diamond Tools, and Atlas Copco. Once the scale of drill bits was increased, bit manufacturers were revisited to obtain additional direction and support.

Task 8 – Prototype bit design and equipment construction. Because of rotary speed constraints, it was necessary to increase the size of drill bits to small, commercial sized bits. Once this decision was made, drill bit manufacturers were able to supply standard and prototype drill bits for the testing. Diamond drill bits supplied were 4 1/8 inch diameter. The drill system design was changed to accommodate the increased bit size.

Task 9 – Demonstration of ultra-high speed bit technology. A number of diamond drill bit technologies were candidates for testing. Those considered and used included two diamond impregnated bits, a polycrystalline diamond compact (PDC) bit, a thermally stable PDC (TSP) bit, and a hybrid TSP and natural diamond bit. The number and distribution of cutters, the size of cutters, matrix material, and the manufacturing methods were determined by drill bit manufacturers.

Task 10 – Benchmarking of ultra-high speed drilling performance. Statistical test design was not practical for Phase 2 because of the high penetration rates and limited sample length. Because of resource limitations, accomplishments were limited to benchmark testing. Before future testing, industry advisors should be consulted about potential changes to increase drilling performance.

Task 11 – Review of technology progress against plan and technology transfer. It is recommended that once industry advisors and government investigators have reviewed the report and data, that a meeting be held to discuss accomplishments and future action.

Task 12 – The data analysis and test report have been completed for the testing performed.

All Phase 1 and Phase 2 tasks were completed; however, the benchmark testing (Task 10) was limited to 5500 rpm.

An additional task was defined during the test program: to determine the mechanism of rock failure when drilling at ultra high speeds. Cuttings analysis was deemed to be an important tool in this investigation. However, the equipment configuration did not allow collection of representative cuttings samples and analysis could not be conducted.

METHODS, ASSUMPTIONS, and PROCEDURES

Theory

The cost of drilling a well is dominated by the length of time required to drill a well. In evaluating the data, it is helpful to look at the amount of rock removed per revolution of the bit.

Mechanical specific energy (MSE) refers to the amount of energy required to remove a volume of rock while drilling. The total specific energy for rotary drilling is the sum of the rotational and axial components (Equation 1). For Phase 1 the specific energy was determined by measuring voltage and current, weight on bit, and rock removed (Equations 2 and 3). In Phase 2, rotational specific energy was calculated using the torque, rotational speed, ROP, and area of rock removed (Equation 4). The axial component was determined using weight on bit (WOB) and area of the rock removed (Equation 5). Reported units for specific energy are lbf/in^2 (psi).

$$SE_{Tot} = SE_{Rot} + SE_{Ax} \qquad (1)$$

$$SE_{Rot} = \frac{1.726(VI)}{ROP(D_o^2 - D_i^2)} \qquad (2)$$

$$SE_{Ax} = \frac{0.00043WOB}{D_o^2 - D_i^2} \qquad (3)$$

Where:

D_i = inside diameter, inches
D_0 = outside diameter, inches
I = current, amperes
SE_{Tot} = total specific energy, ft-lbs/in^3
SE_{Rot} = rotational specific energy, ft-lbs/in^3
SE_{Ax} = axial specific energy, ft-lbs/in^3
ROP = rate of penetration, inches/sec
V = voltage, volts
WOB = weight on bit, g

$$SE_{Rot} = \frac{480 \times T \times (RPM)}{ROP \times D^2} \qquad (4)$$

$$SE_{Ax} = \frac{4 \times WOB}{\pi \times D^2} \qquad (5)$$

Where:

SE_{Tot} = total specific energy, psi
SE_{Rot} = rotational specific energy, psi
SE_{Ax} = axial specific energy, psi
ROP = rate of penetration, ft/hr
RPM = rotary speed, rev/min
D = outside diameter, inches
T = torque, ft-lbf
WOB = weight on bit, lbf

For applications of high rotary speeds and low WOB, the rotational component is significantly greater than the axial component.

Test Apparatus—Phase 1

Rock Samples. Initially, samples of nine different lithologies were tested. Five of the rock types were used for the final testing and analysis. They included: Berea sandstone, Colton sandstone, Nugget sandstone, Sulurain dolomite, and Winfield anhydrite. Berea sandstone was used as a baseline rock and repeat tests in Berea sandstone were run to detect any performance changes due to bit wear. The rock types used in this study and their properties are listed in Table 1. Rock samples 3 in x 5 in x 1.5 in were prepared by first cutting the rocks such that the bedding planes ran parallel to the largest face, the face where the rocks were to be drilled. Ten holes, 3/16 inch diameter, were drilled through each rock (two rows of five holes) for the introduction of fluid to assist in cooling and cleaning the bits. The back of the samples were counter bored and fluid fittings were attached with adhesive.

Table 1. Properties of the rock used for Ultra-High Speed Diamond Drilling tests.

Rock Type	Unconfined Compressive Strength (psi)	Porosity (%)	Bulk Density (g/cm^3)
Berea Sandstone	8,600	20.0	2.230
Castlegate Sandstone	1,500	25.0	1.970
Colton Sandstone	7,600	10.9	2.380
Nugget Sandstone	18,500	9.7	2.393
Austin Chalk	2,000	29.0	1.960
Leuders Limestone	7,000	18.9	2.190
Sulurain Dolomite	8,150	20.9	2.864
Winfield Anhydrite	6,200	1.1	2.925
Burlington Limestone	16,000	1.4	2.650

The rocks used for the final, statistically designed trials, included Berea sandstone, Colton sandstone, Nugget sandstone, Sulurain dolomite, and Winfield anhydrite.

Coring Bits and Drive Motor. Natural diamond coring bits (Figure 1), nominally 0.82" outside diameter x 0.51" inside diameter x 0.5" drilling length with a kerf area of about 0.324 in^2, were sized to allow drilling with a commercially available "Hall Effect" ultra-high speed motor. Natural diamonds (20/25 mesh) were applied to the core bit head using an electrolysis coating technique. The early bits used in these tests typically had about 60 diamonds on the cutting edge. Of the 60 diamonds, only a small number were in contact with the formation due to variability in diamond height. Bit designs used for the final series of core tests had about 25 diamonds on the cutting surface. The diamond spacing was controlled to improve drilling performance. The bits were dynamically balanced at about 6,000 rpm. The final series of tests were conducted using full-faced drill bits as seen in Figure 1.

The Hall Effect drive motor was no-load rated at 51,000 rpm. The drill bit was mounted directly to the motor shaft.

Drilling Apparatus and Instrumentation Setup. The rock samples were clamped to a low friction table. A steel cable was attached to the front of the table. It was passed over a pulley, and then attached to a hanging rod of known mass. The rod was restricted to axial translation by Thompson bearings. The motor and bit were rigidly mounted such that the weight pulled the table and rock sample into the bit during drilling. Pins were set up as stops to control the travel of the table and sample to 0.375" distance. Figure 2 is a photograph of the test apparatus setup.

Displacement was measured by means of a linear variable displacement transducer (LVDT) mounted to the table and the frame of the apparatus. An optical tachometer measured revolutions of the bit. Measurements were also taken of the current and voltage supplied to the motor.

Test Apparatus—Phase 2

Rock Samples. The rock originally selected for drilling tests during Phase 2 included five rock types: Berea sandstone, Colton sandstone, Nugget sandstone, Sulurain dolomite, and Winfield anhydrite. These were the primary rocks tested in Phase 1. Smith Neyrfor and Technology International, Inc. requested using Crab Orchard sandstone and Sierra White granite for their test program. This request was granted. Budget constraints made it necessary to limit the testing in the test stand to Colton sandstone. The properties of the rock used in this test program are listed in Table 2. Rock cylinders 15 ½ inch diameter by 36 inches long of the Crab Orchard sandstone and Sierra White granite were prepared. Figure 3 is a photograph of a cylindrical rock sample installed in the drilling cellar. Rock samples for the test frame were cut approximately 9 inches by 9 inches by 24 inches with the bedding planes parallel to the cutting face of the rock.

Drill Bits. Hybrid TSP and natural diamond, PDC, TSP, and impregnated drill bits were used in Phase 2 tests. Bits were dynamically balanced at about 6,000 rpm prior to testing. Figure 4 is photographs of the two drill bits used with the turbine motors and Figure 5 is a photograph of the three drill bits used in the test stand.

Motor. The first series of tests were conducted with three Smith Neyrfor turbine motors: BAND, High Energy Advanced Turbodrill, and Standard. These were prototype motors developed for coiled tubing drilling. A high speed hydraulic motor was used for testing in the high speed test stand. This motor provided good torque at speeds above 4000 rpm. A second, higher speed hydraulic motor, which would run near 10,000 rpm was planned; however, budget limitations ended the testing before it could be used.

Drilling Apparatus. The Smith Neyrfor turbine motors were run in TerraTek's drilling test facility. The motor was attached below the test rig and atmospheric drilling was run in the drilling cellar. Support bushings were provided to stabilize the drill string. An engineering layout of the test setup is in Figure 6 and a photograph of the motor installation is shown in Figure 7.

The high speed drilling test stand used during the second part of Phase 2 testing is shown in Figure 8. This drilling machine is capable of operation at drilling speeds up to 10,000 rpm with 45 ft-lbf torque or 4500 rpm with 350 ft-lbf torque. The drilling fluid is introduced into the drill string and the bit in the conventional manner. The rock is supported at the base of the drilling stand and drilling fluids with cuttings return to the mud pit. The rock is at atmospheric condition during drilling.

Instrumentation, Controls, and Data Acquisition. Instrumentation used during the testing includes: load cell (weight on bit), torque cell, bit displacement, rotational speed, and flow rate. Budget constraints limited the system to manual control. Data was collected at about 8 Hz over entire test sequences.

Table 2. Properties of the rock used for Ultra-High Speed Diamond Drilling tests.

Property	Crab Orchard Sandstone	Sierra White Granite	Colton Sandstone
Unconfined Compressive Strength (psi)	20,000 – 30,000	28,000	7,600
Porosity (%)	7	< 1	11
Poisson's Ratio	0.2	---	---
Permeability (md)	0.1	Negligible	1-4
Bulk Density (g/cc)	2.47	2.65	2.65
Grain Density, (g/cc)	2.64	---	2.38

Test Parameters—Phase 1

Test Parameters. The test parameters used in the final round of testing (DOEH103 through DOEH217 included:

- Rotational speeds (at the start of each test): 10,000 rpm, 30,000 rpm, and 50,000 rpm (40,000 rpm maximum for the larger full-faced drill bit).
- The weight on bit: 1500, 2500, and 3500 grams for the final statistically designed trials.

Test Parameters—Phase 2

The test parameters used during the testing are provided in Table 3 and Table 4.

Statistical Design of Experiments—Phase 1

Beginning with test DOEH103, a two factor central composite statistical design was used to select the parameters to be used in each test as illustrated in Figure 9. Typically, ten trials were run on each rock type with all combinations of weight on bit and rotational speed factors tested and a replicate run at the mid setting of each factor. The sequence of factor combinations was selected randomly.

Test Procedure—Phase 1

The procedure used for Phase 1 tests is provided in Appendix A

Table 3. Test parameters used with the turbine motors.

Independent Factors (Factors to be Varied)	Test Points
Flow rate (gpm) Weight on bit (lbf) Bit type	80, 90, 100, 110, 120 550, 1100, 1650 TSP and impregnated
Dependent Factors (Measured Response)	
Torque on bit (ft-lbf) Penetration over time (ft/min)	

Table 4. Test parameters used during Phase 2 testing when using the high speed test stand.

Independent Factors (Factors to be Varied)	Test Points
Rotational speed (rpm) Weight on bit (lbf) Fluid flow rate (gpm) Bit type	1000, 2500, 4000 300, 500, 750, 1000 30 Hybrid TSP and natural diamond, PDC, and impregnated
Dependent Factors (Measured Response)	
Torque on bit (ft-lbf) Penetration over time (ft/min)	

Test Procedure—Phase 2

The test procedures used for the turbine drilling tests and drilling tests using the high speed drilling test stand are provided in Appendix A.

Test Matrix—Phase 1

The test matrix for Phase 1 tests DOEH103 through DEH193 is not presented; however, it is the same matrix as shown in Appendix B, Table B-1, which lists the rock type and drilling parameters used in the testing. Likewise, Tables B-2 and B-3 show the matrix used with the full-faced drill bits.

Test Matrix—Phase 2

The test matrix used for the turbine drilling tests is shown in Table 5 and the matrix for the high speed drilling test stand is in Table 6.

Data Reduction and Statistics—Phase 1

After each test the data were plotted and analyzed. Key plots were used to analyze each test, including: penetration and rotational speed versus time and current and voltage versus time. The slope of the penetration curve was examined and areas of steady penetration rate identified. The slope of this line over the steady interval was used to calculate the penetration rate and also average values of rotational speed, current and voltage over the same interval were used in the specific energy calculations. Intervals of steady penetration rates are indicated on the penetration plot. For each test, the dimensions of the annulus cut in the rock were also measured and used in the calculation of specific energy. A summary of performance for tests DOEH103 through DOEH193 is on Table B-1 in Appendix B.

Statistical analysis was conducted on each individual rock type beginning with test DOEH143. Three-dimensional response surface plots were generated for the rate of penetration and specific energy for each type of rock as a function of weight on bit and rotational speed.

Table 5. Test matrix showing the turbine, bit, rock, flow and WOB used for each test.

Test	Turbine	Bit	Rock	Mud Flow	WOB
1	BAND	Impregnated	Sierra White granite	80, 90, 100, 110, 120	550, 1100, 1650
2	BAND	Impregnated	Crab Orchard sandstone	80, 90, 100, 110, 120	550, 1100, 1650
3	BAND	TSP[1]	Crab Orchard sandstone	80, 90, 100, 110, 120	550, 1100, 1650
4	BAND	TSP	Sierra White granite	80, 90, 100, 110, 120	550, 1100, 1650
5	HEAT[2]	Impregnated	Crab Orchard sandstone	80, 90, 100, 110, 120	550, 1100, 1650
6	HEAT	Impregnated	Sierra White granite	80, 90, 100, 110, 120	550, 1100, 1650
7	Standard	TSP	Crab Orchard sandstone	80, 90, 100, 110, 120	550, 1100, 1650
8	Standard	TSP	Sierra White granite	80, 90, 100, 110, 120	550, 1100, 1650

[1]TSP—Thermally stable polycrystalline diamond compact (PDC)
[2]HEAT—High Energy Advanced Turbodrill
NOTE: Tests using the High Energy Advanced Turbodrill turbine and TSP bits were canceled due to engine failure. Tests of the Standard turbine with the impregnated bit were canceled because of bit wear and time constraints.

Table 6. Test matrix for tests run on the high speed drilling test stand.

Test	Bit	Rock	WOB[1]	Rotary Speed
1	Hybrid TSP[2] and natural diamond	Colton Sandstone	NA	NA
2	Hybrid TSP and natural diamond	Colton Sandstone	NA	NA
3	Hybrid TSP and natural diamond	Colton Sandstone	100, 400	1000, 1000
4	Hybrid TSP and natural diamond	Colton Sandstone	300, 300, 500	600, 1000, 1000
5	Hybrid TSP and natural diamond	Colton Sandstone	200, 200, 750	750, 1000, 1000
6	Hybrid TSP and natural diamond	Colton Sandstone	300, 300, 500	600, 2500, 2500
7	Hybrid TSP and natural diamond	Colton Sandstone	200, 750	750, 2500
8	Hybrid TSP and natural diamond	Colton Sandstone	200, 300, 300, 400	750, 750, 4000, 4000
9	Hybrid TSP and natural diamond	Colton Sandstone	200, 500, 500	750, 4000, 4000
10	Hybrid TSP and natural diamond	Colton Sandstone	300, ,200, 200, 500, 750	750, 5500, 4500, 4000, 4000
11	Hybrid TSP and natural diamond	Colton Sandstone	200, 1000	750, 1000
12	Hybrid TSP and natural diamond	Colton Sandstone	200, 200, 1000	750, 5000, 2500
13	Hybrid TSP and natural diamond	Colton Sandstone	200, 200, 1000	750, 1500, 4000
14	Impregnated	Colton Sandstone	200, 300, 300, 300, 300, 500, 750, 1000, 1000, 300, 300, 300, 500, 500, 500, 750, 750, 750, 750, 750, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 400, 750, 750, 750	750, 750, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1100, 1000, 2500, 1100, 2500, 4000, 1000, 2500, 4000, 2100, 1100, 1100, 2500, 4000, 1000, 1000, 2500, 4000, 1000, 1000, 2500, 4000
15	Impregnated	Colton Sandstone	300, 500, 500, 750, 1000, 300, 500, 750, 1000, 300, 500, 750, 1000	1100, 1100, 1250, 1250, 1250, 2500, 2500, 2500, 2500, 4000, 4000, 4000, 4000
16	PDC	Colton Sandstone	100, 200, 200, 500	600, 600, 1000, 1000

[1]WOB—weight on bit
[2]TSP—Thermally stable PDC
[3]PDC—Polycrystalline diamond compact

Data Reduction—Phase 2

The data was plotted and data intervals of relative stability were selected for further processing. The data over these intervals was averaged, and values of bit hydraulic horsepower per square inch of the bit (HSI), ROP, and MSE were calculated. These data were used for further analysis. Tables B-3 and B-4 in Appendix B provide listings of this reduced data.

RESULTS AND DISCUSSION—PHASE 1

A summary of all Phase 1 data are presented in Tables B-1 through B-3 of Appendix B. This includes trials DOEH103 through DOEH217. Graphical presentation of the results of the core bit tests from DOEH143 to DOEH193 and full face bit tests from DOEH194 to DOEH217 are presented. Analysis of core bit trials was limited to DOEH143 through DOEH193 because the test matrix for these trials was statistically designed to enhance the analysis. The full-faced bit trials were also statistically designed, but the complexity was reduced because they were run using only one rock type.

The rock selected for the core bit trials was based upon preliminary work done with the full suite of rock. It was determined to use rock that represented a reasonable range of properties while generally excluding those with issues, such as bit balling, which created significant outliers in the results. Discussion will consider the core bit trails and the full-faced bit trials separately.

As noted previously, the trials used in the final analysis were statistically designed to sequence the tests in a random fashion with weight on bit, rotational speed, rock type, and bit number being model input factors. The responses were rate of penetration and specific energy. An exception to the evaluation of all rock types was made for the Nugget sandstone because of the excessive bit wear observed in previous trials. The Nugget trials were designed and executed in the same statistically relevant manner, but were run after all the other trails were concluded.

Trials with the full-faced bits were conducted with Berea sandstone only. The two sizes of bits were run independently.

To determine the effects of bit wear on the results, control trials were run in a single block of Berea sandstone. These trials were run at 1500 g WOB and 10,000 rpm rotational speed. Plots were made of the specific energy and rate of penetration as a function of trial number to develop equations to eliminate the effects of bit wear on the results.

The rate of penetration and specific energy results of the trials with each rock type were graphed with the WOB held constant. These graphs provided general trends of the effect of rotational speed. Examples of these trends in Berea sandstone using core bits are provided in Figures 10 and 12. Similar plots for other rock types are found in the Phase 1 report (Judzis, Robertson, and Black).

Statistical design and analysis was accomplished using software for that purpose. The results of this analysis are provided in response surface plots for each rock type. The Berea sandstone plots are provided in Figures 11 and 13 and the surface plots for the other rock types are in the Phase 1 report (Judzis, Robertson, and Black).

Results of the Core Bit Trials

Though the general trends in specific energy and ROP were consistent with the expectations, both of these values are somewhat unstable from test to test. Inconsistencies in strength and composition within a single rock sample account for some of the ROP variation observed. Also, the placement of diamonds on each bit and the number of diamonds on each bit varies from bit to bit. Additionally, bit wear is a factor in the performance. Special drill bits were designed for the final trails which had a more uniform configuration and distribution of diamond cutters (see Figure 1). The final tests were designed to monitor the reduction in performance due to wear and where appropriate, adjustments were made to account for the observed wear.

Figures 10 through 13 provide examples of the specific energy and rate of penetration as the weight on bit and rotational speeds were varied. It will be noted that the performance at low weight on bit was very erratic for most of the rocks. A line graph and surface plot of the specific energy with varying rotational speed and weight on bit for Berea sandstone are given in Figures 10 and 11. Figures 12 and 13 provide the same graphics for rate of penetration in Berea sandstone. The analysis considered all five rock types together. As expected, ROP generally increased with higher rotational speed. As a general trend, specific energy decreased with increasing rotational speed once higher rotational speeds were reached. The ROP trend is consistent with existing theory and the trend in specific energy, while a departure from existing theory, is consistent with the expectations of this testing program. Plots of the results of the trials of the other four rock types are in the Phase 1 report (Judzis, Robertson, and Black).

Results of the Full-faced Bit Trials

Two sizes of full-faced bits (Figure 1) were run to determine the trends in specific energy and rate of penetration. The smaller full-faced bit, configured to have the same contact area as the core bits, was run with the same set of parameters as the core bits. The larger full-faced bit had a diameter similar to the core bits. Because of the mass of the larger full-faced bit, the motor was run at a maximum rotational speed of 40,000 rpm. Vibrations prevented the large full-faced bit from being run at 1500 g weight on bit and 40,000 rpm. A summary of the small and large full-faced trials and the calculated values for specific energy and rate of penetration are included in Tables B-2 and B-3 of Appendix B. The diameters of the bores through the rock are listed in Tables B-2 and B-3. The “Rock Bore Diameter” (the bore through whick drilling fluid was introduced) measurement was used in calculating the rock removed during drilling.

The results of the analysis of the full-faced bits are presented in graphical format in Figures 14 through 21. There was a general increase in rate of penetration with the larger bit to approximately 25,000 rpm and then a decrease (see Figures 14 and 15). This is contrary to what was experienced with the core bits, where there was a general trend toward higher rate of penetration with increasing weight on bit and rotational speed. Figures 16 and 17 show a decrease in specific energy with increased rotational speed at the low to middle weights on bit. At higher weights on bit, the trend was similar to the core bits; however, the curve of the specific energy was more favorable with the full-faced bit. At 3500 g weight on bit, the specific energy began to decline at around 20,000 rpm.

The rate of penetration trend for the small full-faced core bit was generally increasing with rotational speed. This is illustrated in Figures 18 and 19. The specific energy was somewhat steady at 2500 g weight on bit and declined at 25,000 rpm with 3500 g weight on bit (see Figures 20 and 21).

TEST RESULTS and DISCUSSION—PHASE 2

The results of the two series of tests are discussed below. There were issues with the torque and load measurement systems that are discussed in the following section of this report. These issues were identified during testing and impacted the quality of the data obtained.

The effects of drill bit wear are not considered in the results.

Issues with Torque and Load Measurements

The torque cell used for the tests was very sensitive to offset loading in the axial direction. Improper alignment of the rock sample relative to the sensor in the turbine tests caused significant offsets in the recorded values. Figures 3 and 6 show the location of the torque transducer in the test assembly.

In tests conducted in the high speed drilling test stand, the torque changed as a function of drilled depth. The cause was identified as bending moment on the transducer caused by the hydraulic hoses attached to the high speed motor. Changes to the configuration of the hoses were made to minimize the bending as much as possible. The effects were documented and corrected for during the data reduction. The data presented are the best available, with the understanding that corrections were made.

The load (WOB) transducer in the high speed drilling test stand was sensitive to temperature. During tests of long duration, the heat generated by the high speed hydraulic motor was transferred to the transducer. This made it necessary to correct the load data based on the measured temperature of the load cell. In some tests, there seemed to be a small offset in the load as a function of depth drilled. When necessary, this effect was corrected in a similar manner used to correct for the torque measurements above.

Results of the Smith Neyrfor Turbine Drilling Tests

The results of the high speed drilling tests using Smith Neyrfor prototype mud turbines are summarized in Appendix B, Table B-4. This table provides averaged data from the raw data files. The data provided include: WOB, rotary speed, ROP, and MSE, along with other data.

Plots of the reduced data are provided for each rock and bit type showing the ROP as a function of WOB and rotary speed. Representative graphs are shown in Figures 22 through 24. Plots of the MSE as a function of WOB and rotary speed are provided in Figures 25 and 26. There is an anomaly in the results when drilling the Sierra White granite with an impregnated drill bit. The ROP in feet per hour declines with increased WOB as shown in Figure 27.

Tests conducted in the Crab Orchard sandstone with the impregnated drill bit showed a significant increase in ROP as the WOB and rotary speed increased. The MSE decreased with increased WOB and rotary speed. These results, along with those of other bits and rock are summarized in Table 7.

The results of the TSP drill bit in Crab Orchard sandstone showed increased ROP with WOB and mixed results with increased rotary speed. The MSE was decreased with increased WOB and increased with increased rotary speed.

The ROP declined with increased WOB the impregnated drill bit in Sierra White granite, which was counter to the trends observed in the other tests. The ROP increased with increase rotary speed. The MSE increased with increased WOB and was mixed with increased rotary speed.

Table 7. Summary of the drilling performance when using mud turbine motors. Trends in rate of penetration (ROP) and mechanical specific energy (MSE) with different rocks and bits, as influenced by the weight on bit (WOB) and rotary speed, are provided.

Rock	**Bit**	**Rate of Penetration (in/rev)**	**Rate of Penetration (ft/hr)**	**Mechanical Specific Energy (psi)**
Crab Orchard sandstone	Impregnated	Increased with increased WOB and rotary speed	Increased with increased WOB and rotary speed	Decreased with increased WOB and rotary speed
Crab Orchard sandstone	TSP[1]	Increased with increased WOB and decreased with increased rotary speed	Increased with increased WOB and mixed with increased rotary speed	Decreased with increased WOB and increased with increased rotary speed
Sierra White granite	Impregnated	Decreased with increased WOB and usually increased with increased rotary speed	Decreased with increased WOB and increased with increased rotary speed	Increased with increased WOB and mixed with increased rotary speed
Sierra White granite	TSP	Mixed at lower rotary speeds with increased WOB and increased with increased rotary speed	Mixed at lower rotary speeds with increased WOB and increased with increased rotary speed	Mixed with increased WOB and decreased with increased rotary speed

[1]TSP—thermally stable polycrystalline diamond compact (PDC)

The tests in the Sierra White granite with the TSP drill bit showed that the ROP was mixed with increased WOB and increased with increased rotary speed. The MSE was mixed with increased WOB and decreased with increased rotary speed.

The impregnated bit used with the turbines had exceptional penetration in the Crab Orchard sandstone (see Figure 22). At low rotary speed, the ROP was very low; however, increasing the rotary speed significantly improves the ROP. Exceptional penetration rates were observed in the Sierra White granite when the WOB was low as seen in Figure 23.

Results of the High Speed Drilling Test Stand Tests

The results of the high speed drilling tests conducted with the test stand are summarized on Table B-5 in Appendix B. This provides the averaged raw data and calculated values of HSI, ROP, and MSE. The ROP is provided in feet per hour, the traditional oilfield units, and inch per revolution.

Representative results are plotted in Figures 28 through 34, which show the ROP as a function of WOB and rotary speed and the MSE as a function of rotary speed.

The tests conducted in Colton sandstone with an impregnated drill bit showed increased ROP with increased WOB and rotary speed. The MSE results were mixed with the increased WOB but there was a decrease in MSE with increased rotary speed.

There was not sufficient data to draw conclusions for tests run with the PDC drill bit.

Tests run with the hybrid drill bit in Colton sandstone provided results that were contrary to MSE trends experienced with the other tests. The ROP increased with increased WOB, and there was less material removed per revolution as the rotary speed increased (similar to the TSP drill bit above), but there was a decline in the MSE as the WOB increased but the MSE increased with increased rotary speed. The drilling performance using the high speed test stand is summarized in Table 8.

Discussion

The results of this test program provide insight into the effects of increased rotary speed on the ROP and the MSE. As generally expected, increased WOB will increase the ROP. Increased rotary speed translates into faster drilling with less energy. Some anomalies were observed that should be further investigated. Budget and time constraints limited the testing to rotary speeds below 6000 rpm. This test program was intended to be preliminary, to establish baselines for future tests. Limitations on the rotary speed with smaller drill bits, forced the investigators to use larger drill bits—a good thing. However, it was not the intent of this second phase of the program to drill under conditions other than atmospheric.

Future testing should address the issues of measuring torque and load at the drill bit. Additional testing over a wider range of parameters should be considered; then testing should be conducted at pressures and stresses simulating field conditions.

Table 8. Summary of drilling performance during testing on the high speed drilling test stand. Rate of penetration (ROP) and mechanical specific energy trends with different drill bits are presented. These tendencies are provided as influenced by weight on bit and rotary speed.

Rock	**Bit**	**Rate of Penetration (in/rev)**	**Rate of Penetration (ft/hr)**	**Mechanical Specific Energy (psi)**
Colton sandstone	Impregnated	Increased with increased WOB and rotary speed	Increased with increased WOB and rotary speed	Mixed with increased WOB and decreased with increased rotary speed
Colton sandstone	PDC	Limited data, not conclusive	Limited data, not conclusive	Limited data, not conclusive
Colton sandstone	Hybrid TSP and natural diamond	Increased with increased WOB and decreased with increased rotary speed	Increased with increased WOB and increased rotary speed	Decreased with increased WOB and increased with increased rotary speed

[1]WOB—weight on bit
[2]PDC—Polycrystalline diamond compact
[3]TSP—Thermally Stable PDC

CONCLUSIONS AND RECOMMENDATION—PHASE 1

The results of test analysis for Phase 1 of UHSDD program for the coring bits indicated that after reaching a certain rotational speed level, the specific energy decreases with increased rotational speed. The rate of penetration increases with increased rotational speed and weight on bit. When drilling with full-faced bits, the data indicate that there may be some speed/weight combination that is optimum. The rate of penetration declined at higher weights while the specific energy showed significant decline with the larger bit and was flat with the smaller.

It was recommended that testing continue with the Phase 2 scale-up to field-sized drill bits.

CONCLUSIONS AND RECOMMENDATIONS—PHASE 2

There are a number of conclusions drawn from the high speed tests conducted:

1. Generally, the ROP increased with increased WOB and rotary speed.
2. The MSE generally decreased with increased WOB and the results were mixed with increased rotary speed.
3. The impregnated drill bit used with the turbine motors drilled exceptionally well in both the sandstone and granite with ROP up to 40 ft/hr. Drill bits with TSP cutters performed well with ROP beyond 100 ft/hr.
4. Higher rotary speeds usually created an overall increase in ROP, though the amount of rock removed per revolution may have reduced. The ROP per revolution declined during testing when using a hybrid drill bit in Colton sandstone as shown in Figure 30.
5. Regarding the MSE, Figure 25 does not provide a clear picture of the effects of increased rotary speed when using an impregnated drill bit; however, the plots in Figure 26 give a strong indication of declining energy required with increased rotary speed when drilling granite with a TSP drill bit. Figure 33 shows a general decline in MSE with increased rotary speed using an impregnated bit and Figure 34 indicates that more energy may be required to drill with increased rotary speeds when using a hybrid TSP bit. It may require additional testing at higher rotary speeds to see if the trends continue, or if the energy requirement will decrease at higher rotary speeds.
6. Though there were quality issues with the torque data, there is still sufficient data to see trends from the mud turbine testing that indicate little to no change or decease in required energy to increase the ROP at higher rotational speeds. Given additional data, this trend may be further supported and validated.

Recommendations for practices and future testing include:

1. Although drill bit wear was not considered in this study indications are that wear may be accelerated at these high rotational speeds. Wear measurements and high speed wear testing of cutting elements should be included in future testing.
2. Additional data, at higher rotary speeds, should be generated before definitive conclusions can be drawn to support the theory of faster drilling with less energy.
3. A wider range of rock types should be included in future studies.

4. Additional tests should be conducted using the hybrid TSP and natural diamond drill bit to determine why the MSE declined with increased WOB and increased with rotary speed. This was contrary to all other tests.

5. A better method of measuring the torque and weight on bit must be found in order to obtain quality data from the high speed drilling stand.

6. Testing at downhole conditions should be considered. The atmospheric testing provides an indication of what will happen in the real world, but it is important to know how downhole stresses and pressures affect rock cutting efficiency at high speed drilling conditions.

REFERENCES

Judzis, Arnis, Black, Alan, Robertson, Homer, “Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High Speed Diamond Drilling,” March 2006, Technical Progress Report for the Department of Energy, DOE Award Number: DE-FC26-03NT15401.

Black, Alan, Judzis, Arnis, “Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High Speed Diamond Drilling,” October 2004, Technical Progress Report for the Department of Energy, DOE Award Number: DE-FC26-03NT15401.

Judzis, Arnis, Boucher, Marcel, McCammon, Jason, Black, Alan, 2006, “Investigation of Smaller Footprint Drilling System; Ultra-High Rotary Speed Diamond Drilling has Potential for Reduced Energy Requirements,” IADC/SPE 99020, presented at the IADC/SPE Drilling Conference, Miami, Florida, U.S.A., 21-23 February 2006.

Judzis, Arnis, Robertson, Homer, Black, Alan, “Smaller Footprint Drilling System for Deep and Hard Rock Environments; Feasibility of Ultra-High-Speed Diamond Drilling” Phase 1 Final Report, DOE Award Number: DE-FC26-03NT15401, January 2007.

FIGURES

Figure 1. Core and full-faced drilling bits used for the high speed drilling tests. The core bit on the top left was used earlier in the program and the one on the top right was designed for consistency of diamond placement. Similar bits to the one on the top right were used in the final statistically designed and analyzed trials. Photographs of the small and large full-faced bits used are shown at the bottom of the figure.

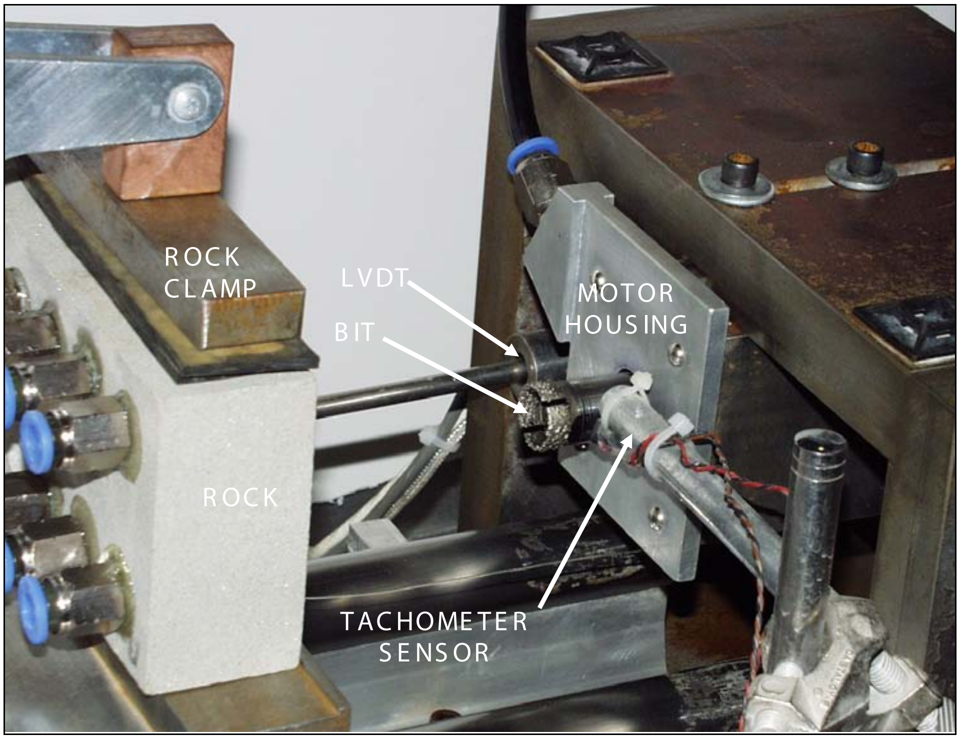

Figure 2. Photograph of the high speed drilling test setup.

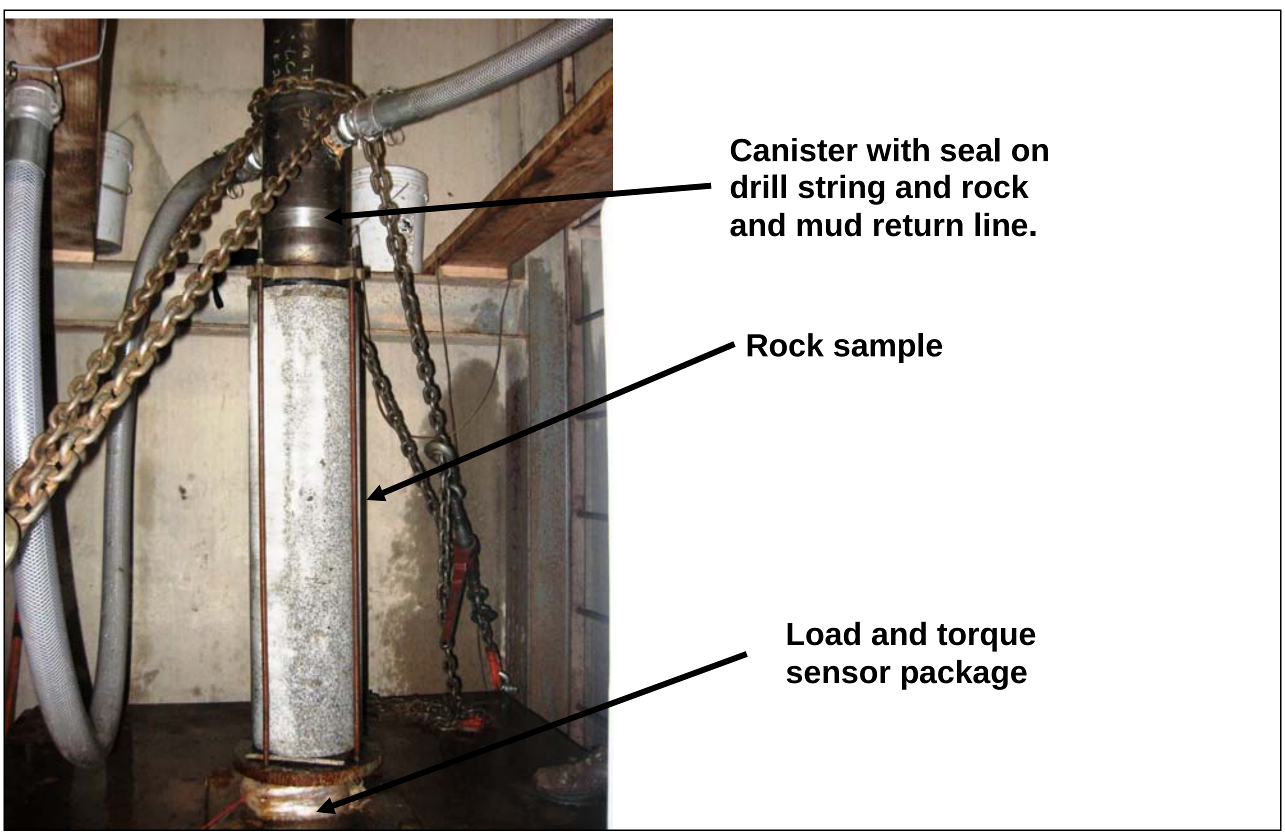

Figure 3. Rock sample installed in the drill cellar.

Figure 4. The impregnated and TSP drill bits used with the turbine mud motors.

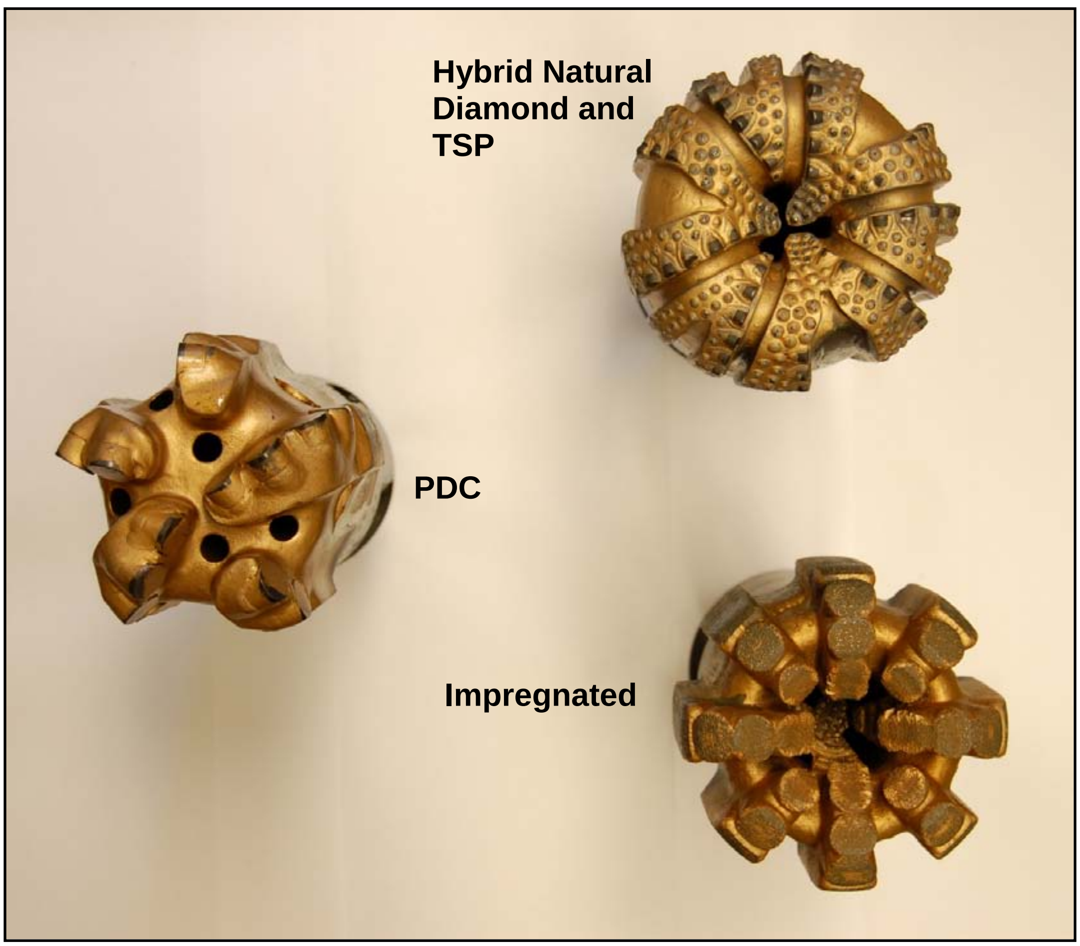

Figure 5. Drill bits used in testing in the high speed drilling test stand. These bits were all 4 1/8 inch diameter.

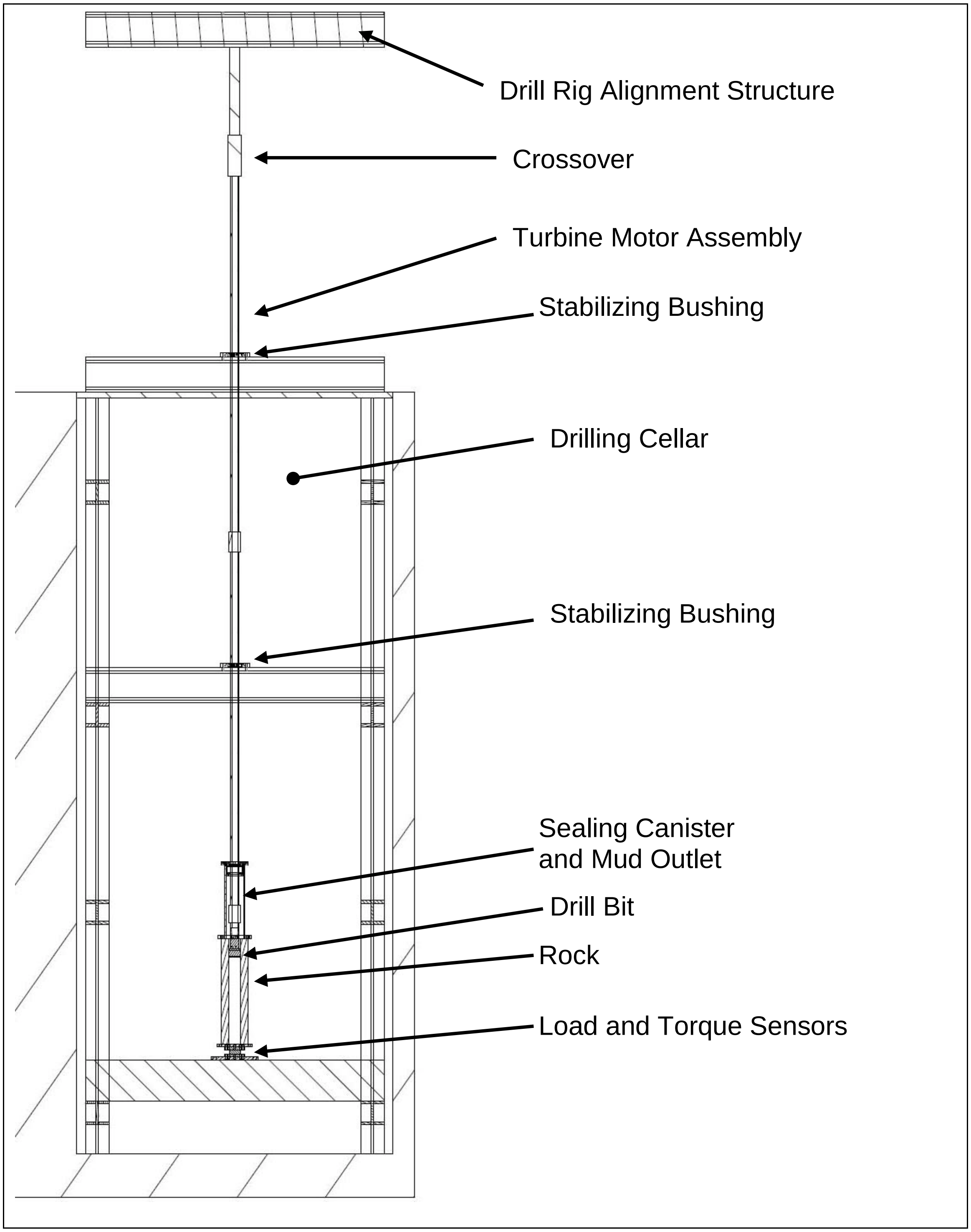

Figure 6. Engineering layout of the test cellar with the turbine motor.

Figure 7. Photograph of a mud turbine installation.

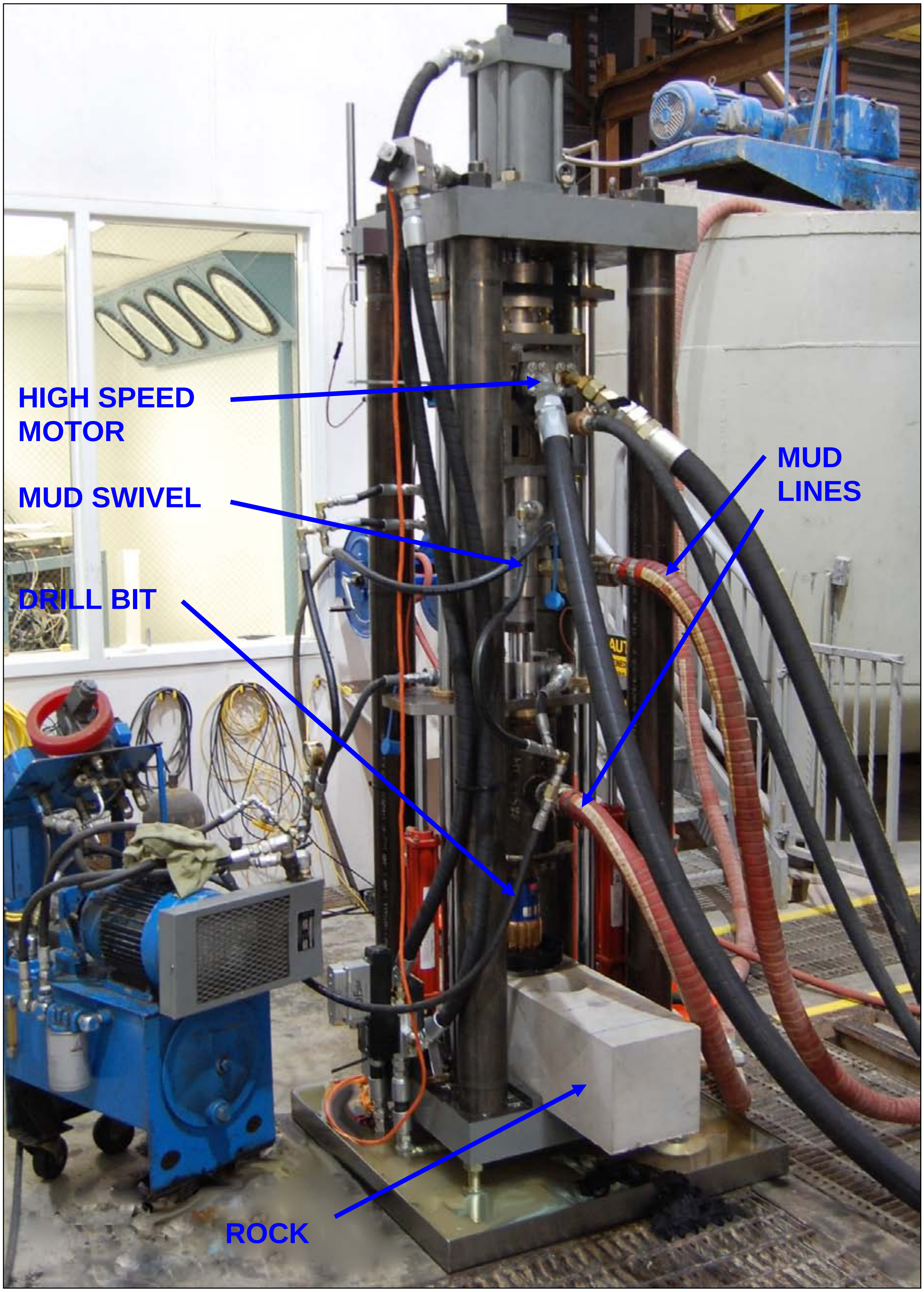

Figure 8. High speed drilling test stand.

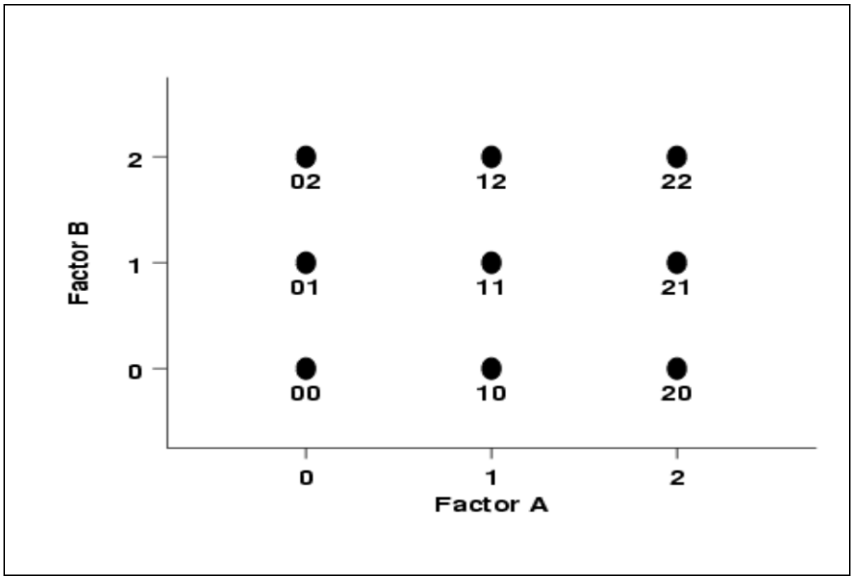

Figure 9. Two factor central composite design used in designing tests. Factor A was typically rotational speed and Factor B the weight on bit.

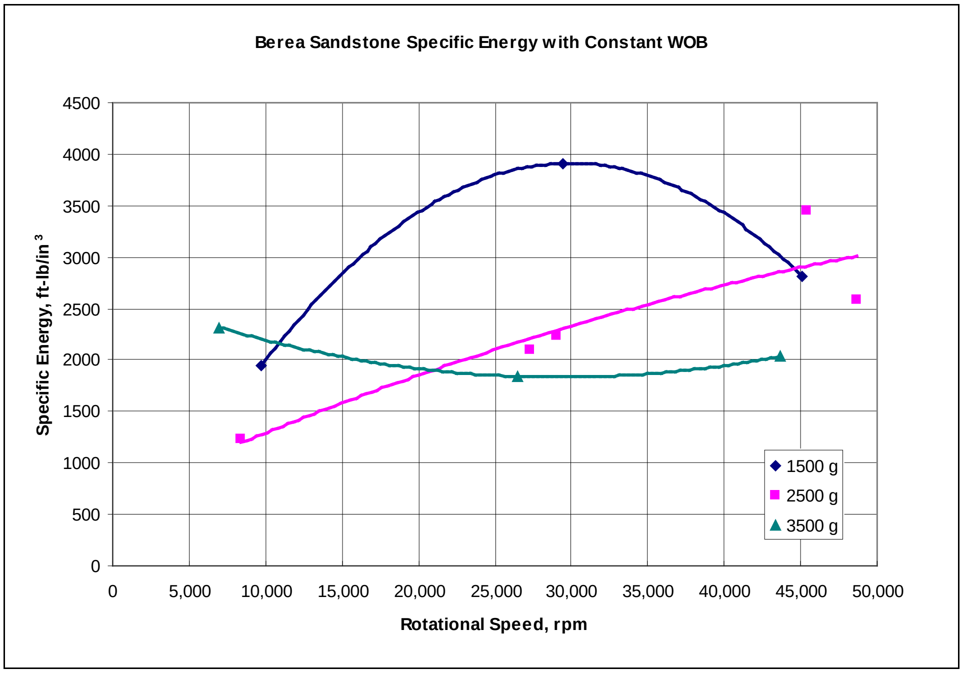

Figure 10. Specific Energy data plot for Berea Sandstone as a function of rotary speed. Each line of the plot represents a specific weight on bit.

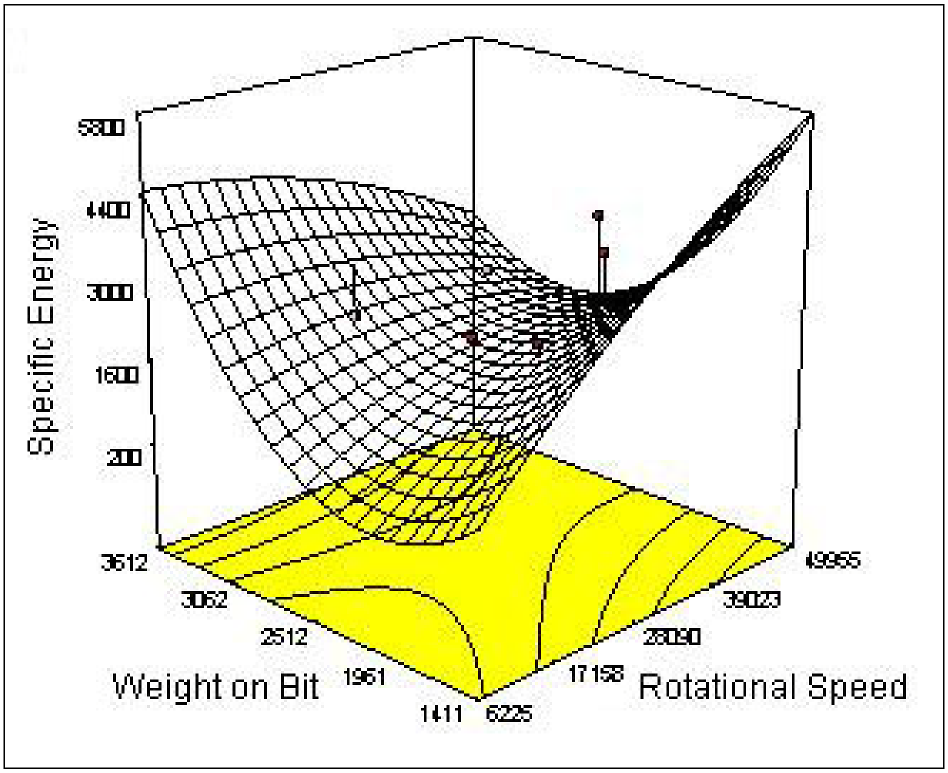

Figure 11. Specific Energy results in a response surface plot for Berea sandstone trials.

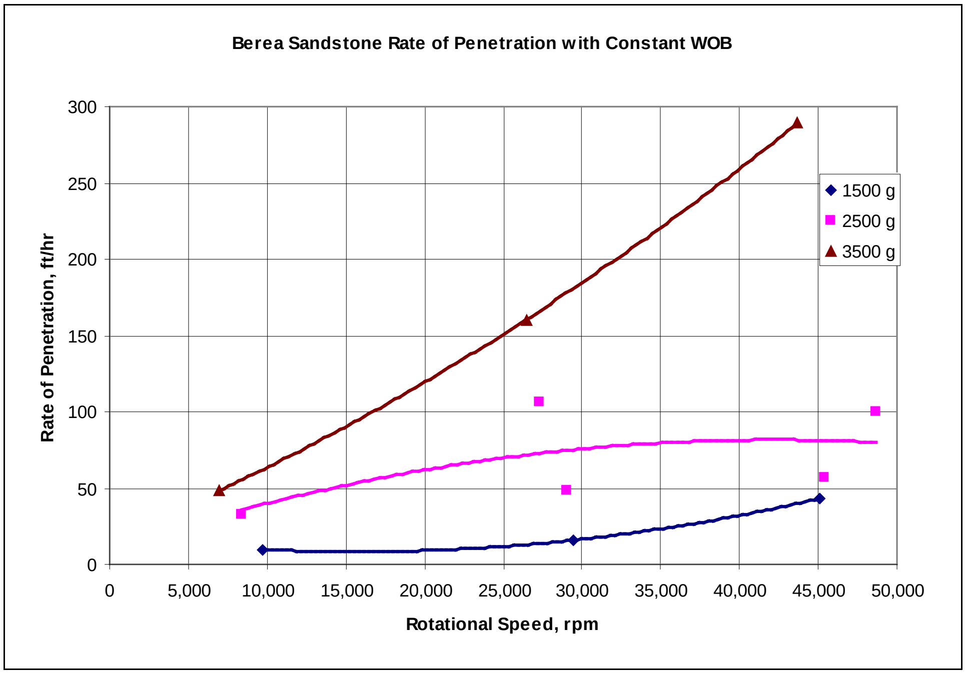

Figure 12. Rate of penetration results are graphed for Berea Sandstone trials. Each line of the plot is for a specific weight on bit.

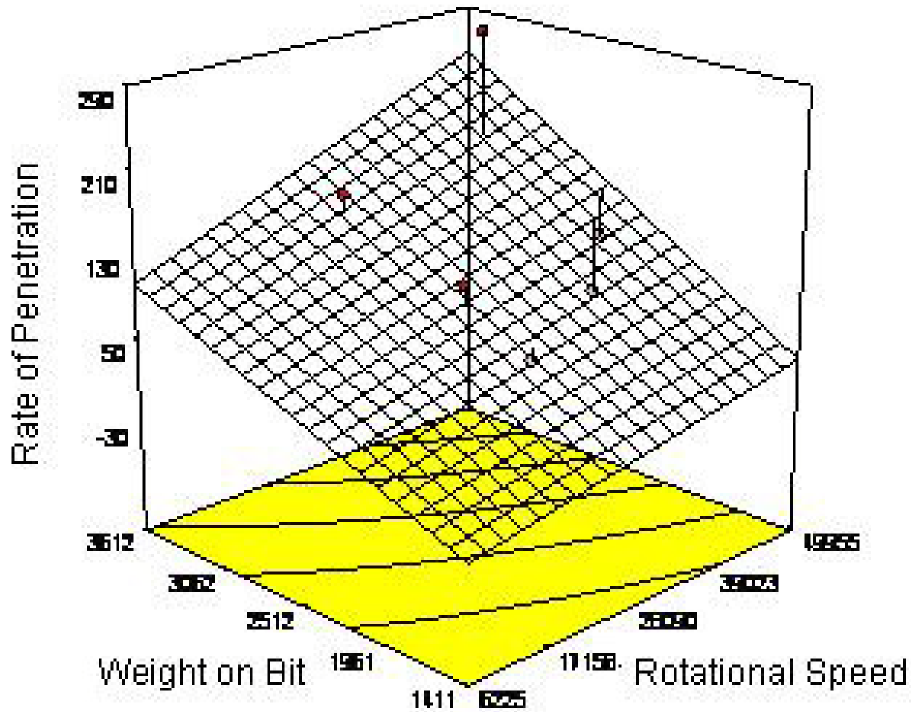

Figure 13. Rate of penetration results on a response surface plot for Berea sandstone.

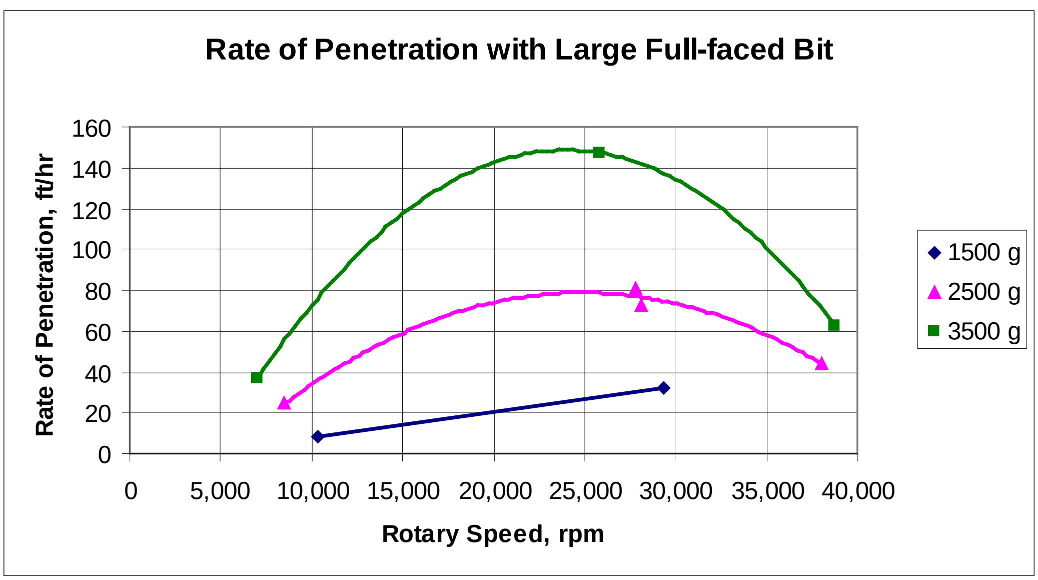

Figure 14. Rate of Penetration data plot for the large full-faced drill bit.

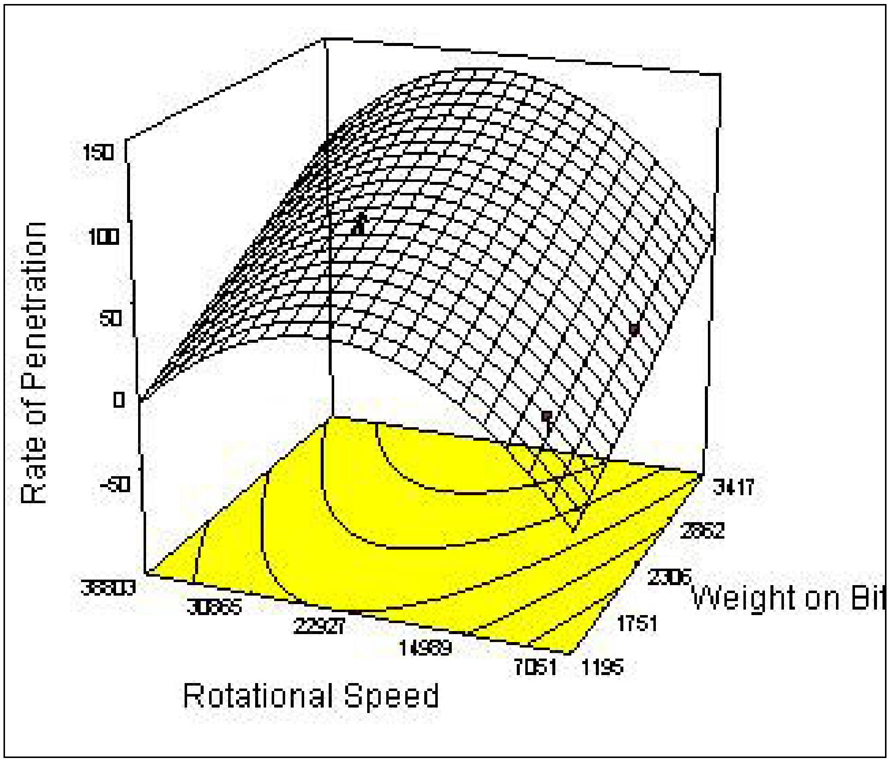

Figure 15. Response surface plot of the rate of penetration data with a large full-faced drill bit.

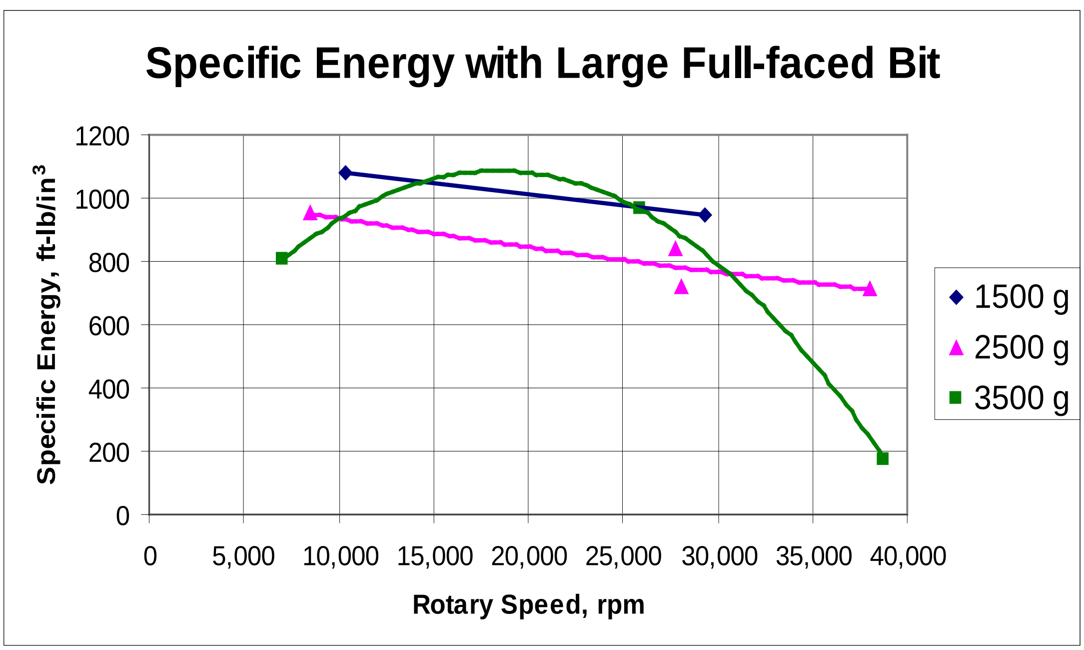

Figure 16. Large full-faced bit specific energy plots with the weight on bit held constant.

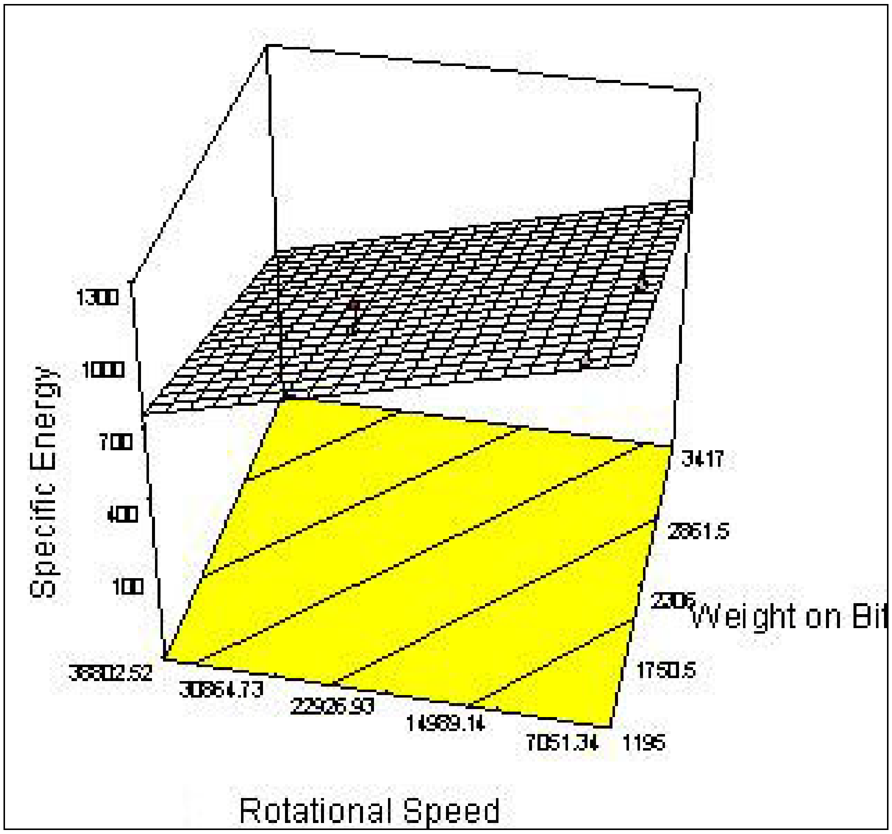

Figure 17. Specific energy response surface plot of data from the large full-faced bit.

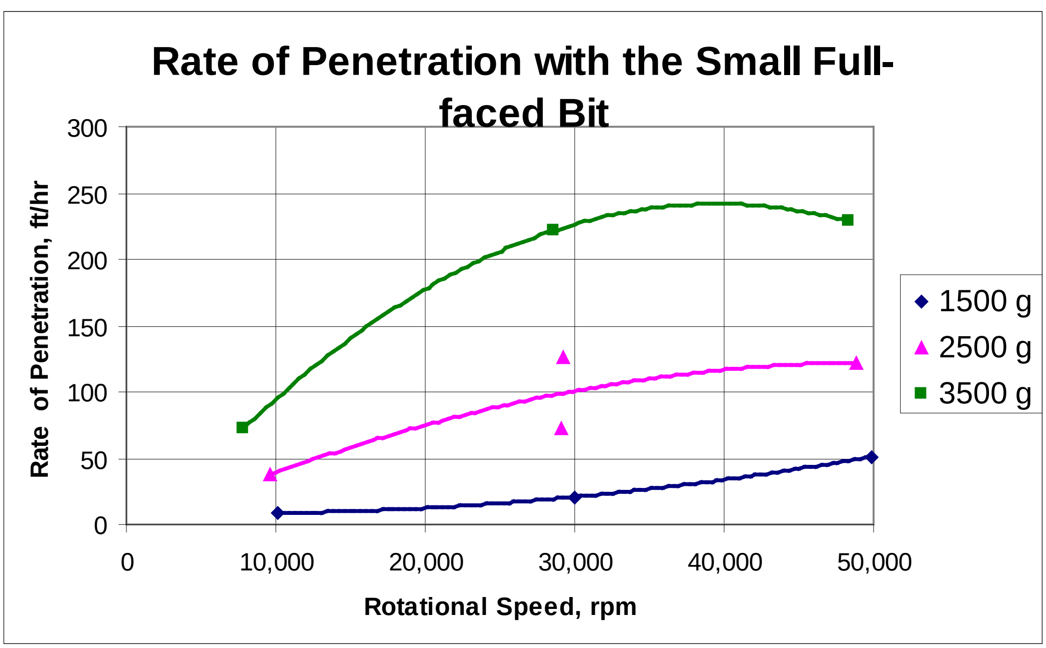

Figure 18. Small full-faced bit rate of penetration results with the weight on bit held constant.

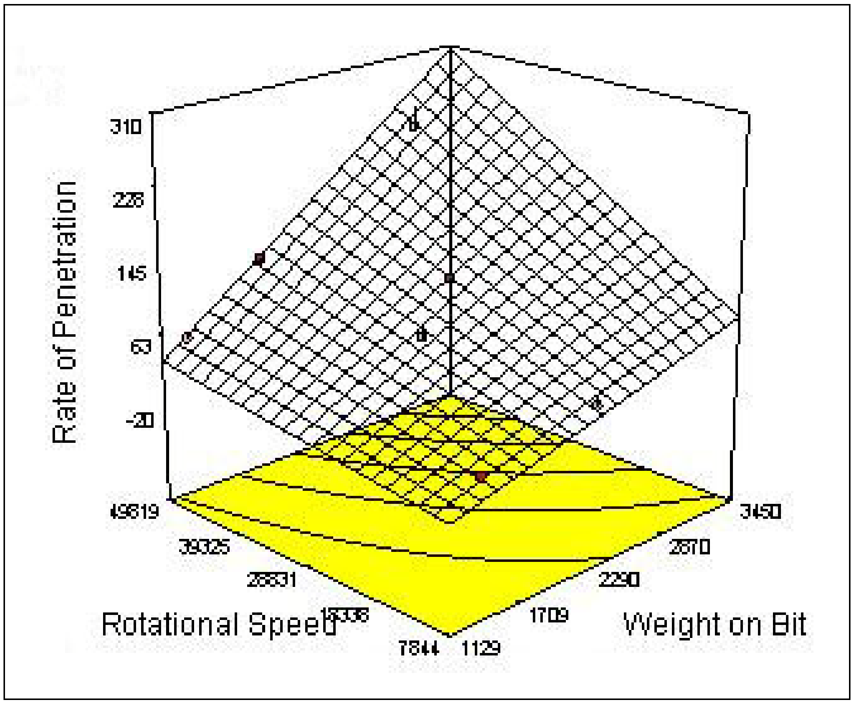

Figure 19. Response surface plot of the rate of penetration data with a small full-faced drill bit.

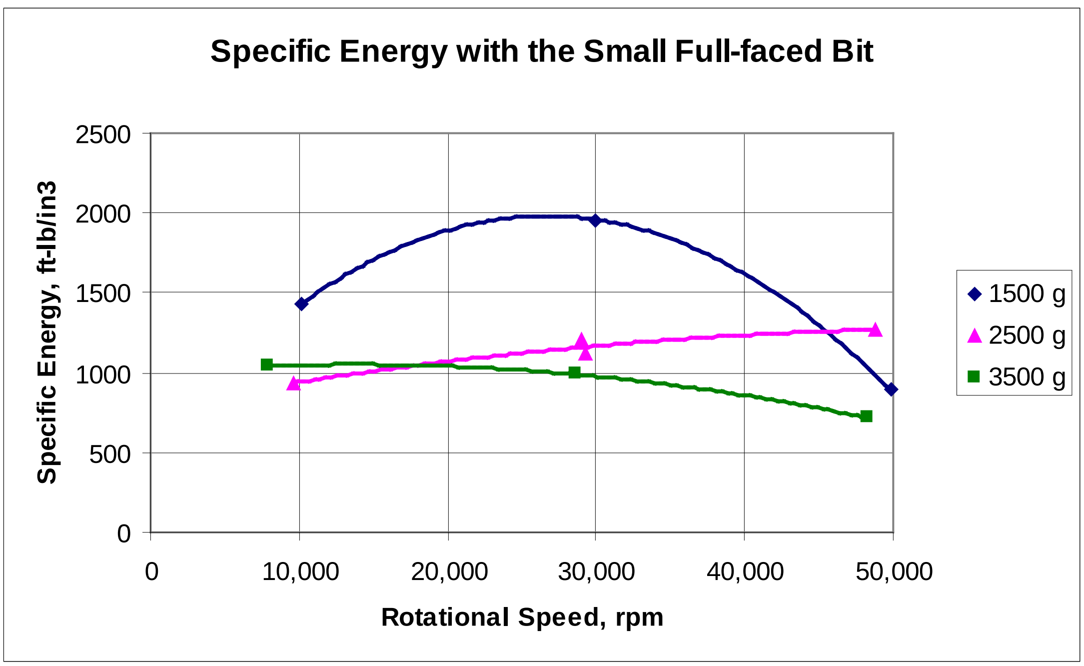

Figure 20. Specific energy plot of data from the small full-faced drill bit.

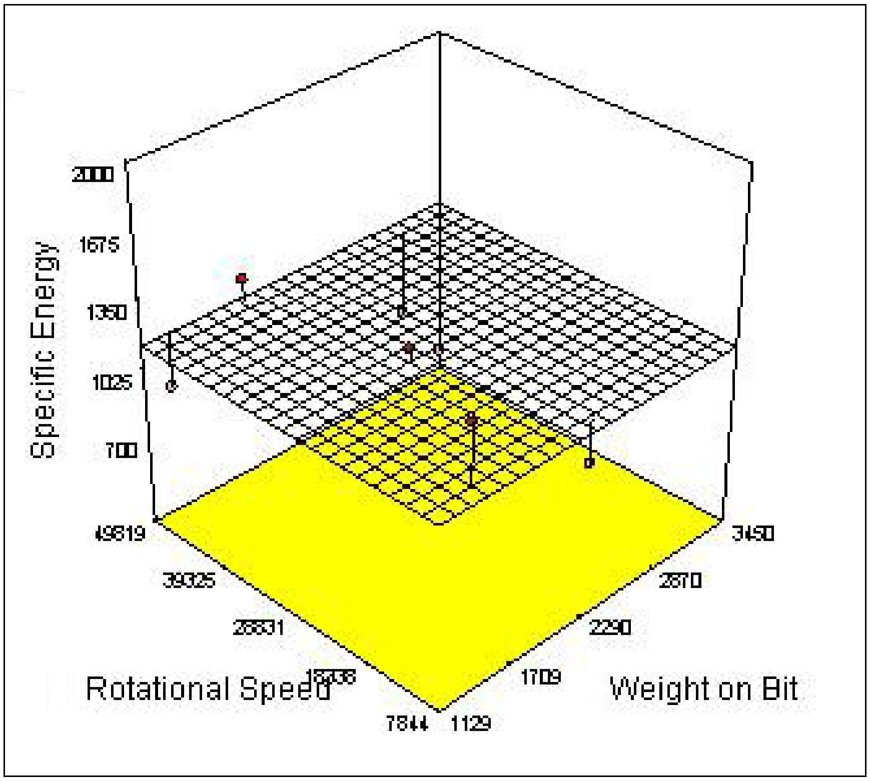

Figure 21. Response surface plot of the specific energy with a small full-faced drill bit.

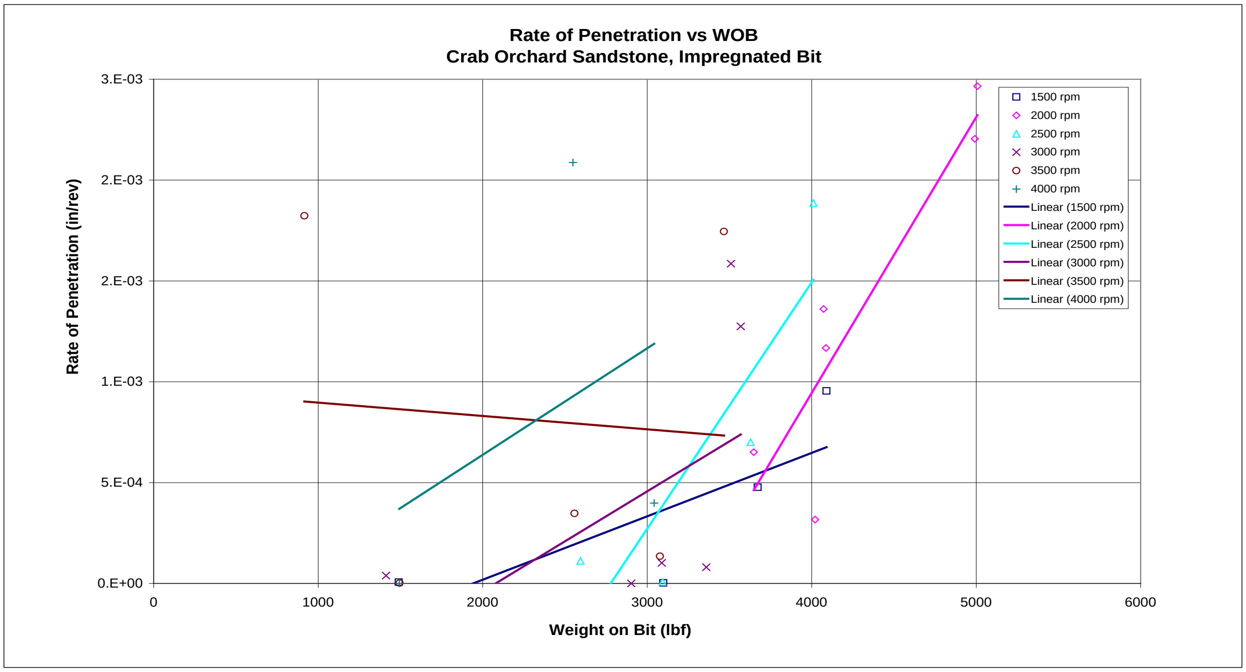

Figure 22. Rate of penetration is plotted as a function of weight on bit in Crab Orchard sandstone with an impregnated drill bit. The trend lines plot data with similar rotary speeds.

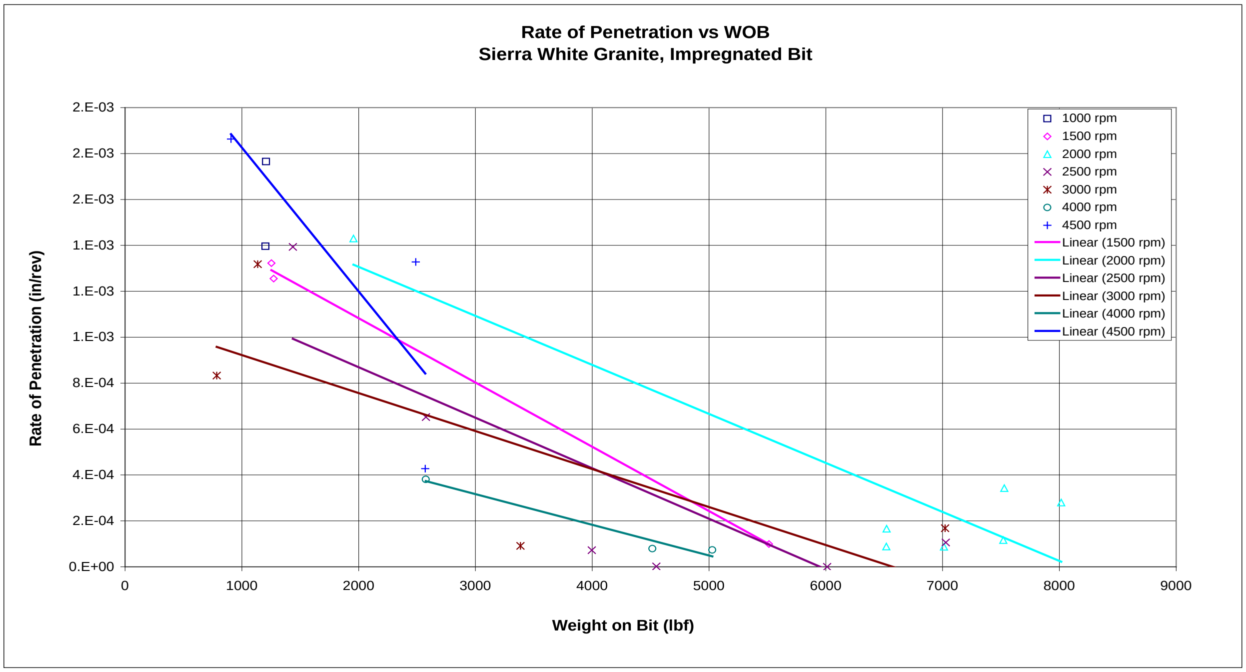

Figure 23. Rate of penetration is plotted as a function of weight on bit in Sierra White Granite with an impregnated drill bit. The trend lines plot data with similar rotary speeds.

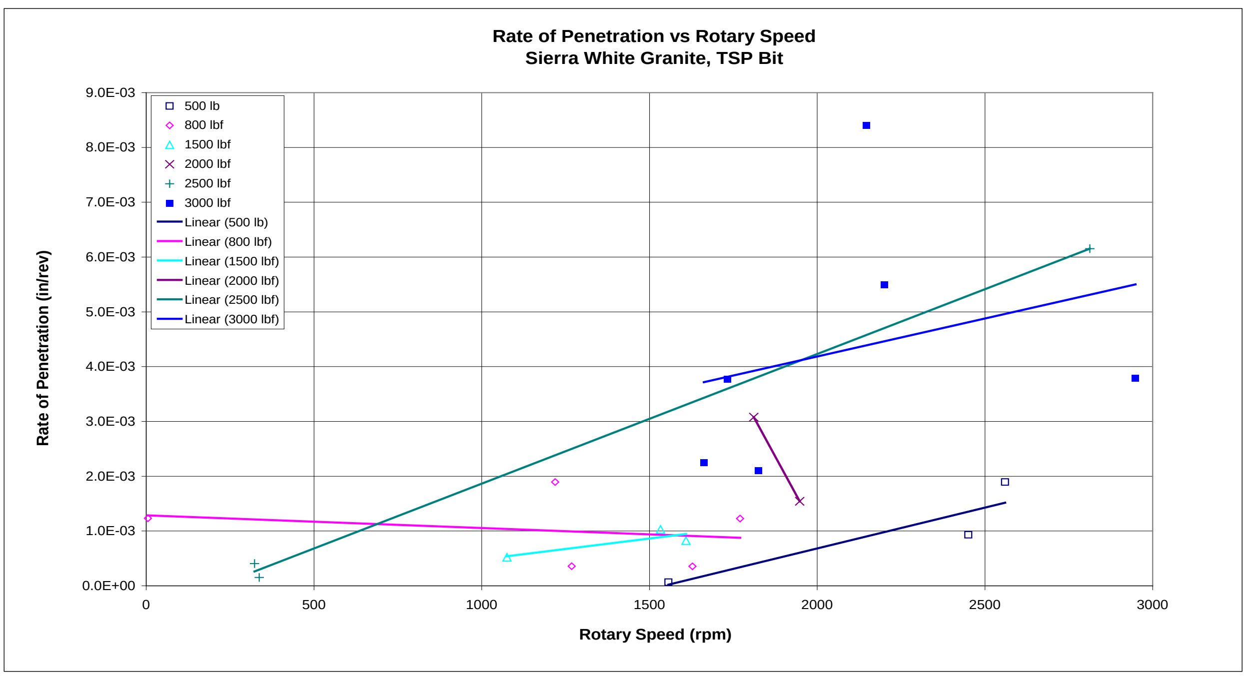

Figure 24. Rate of penetration is plotted as a function of rotary speed in Sierra White Granite with a TSP drill bit. The trend lines represent a particular weight on bit.

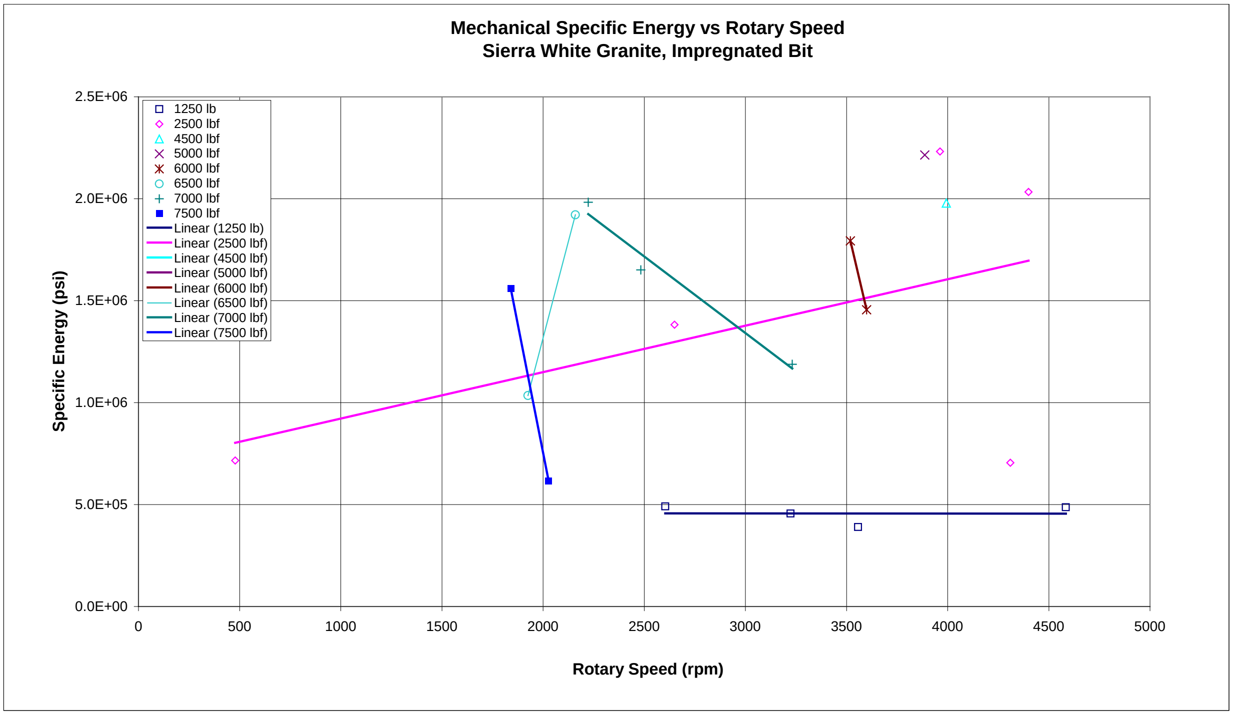

Figure 25. The mechanical specific energy is plotted as a function of rotary speed in Sierra White Granite using an impregnated drill bit. The trend lines represent a particular weight on bit.

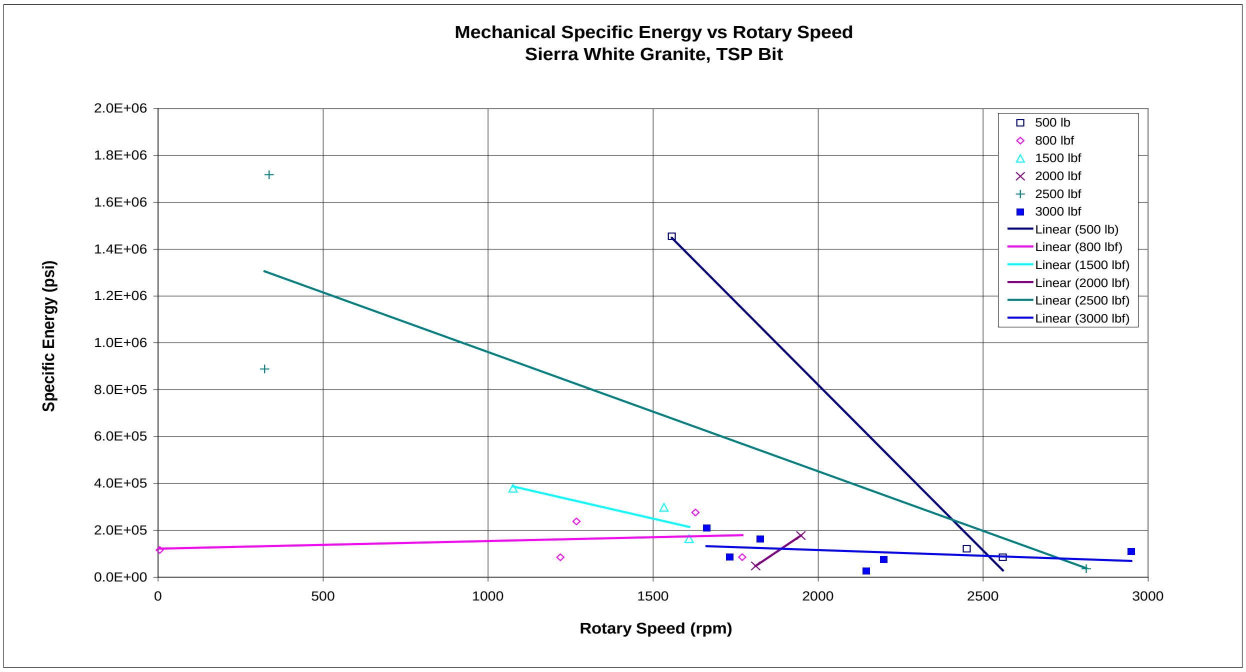

Figure 26. Mechanical specific energy is plotted as a function of rotary speed with a TSP drill bit in Sierra White Granite.

Figure 27. Rate of penetration is plotted as a function of weight on bit in Sierra White granite with an impregnated drill bit.

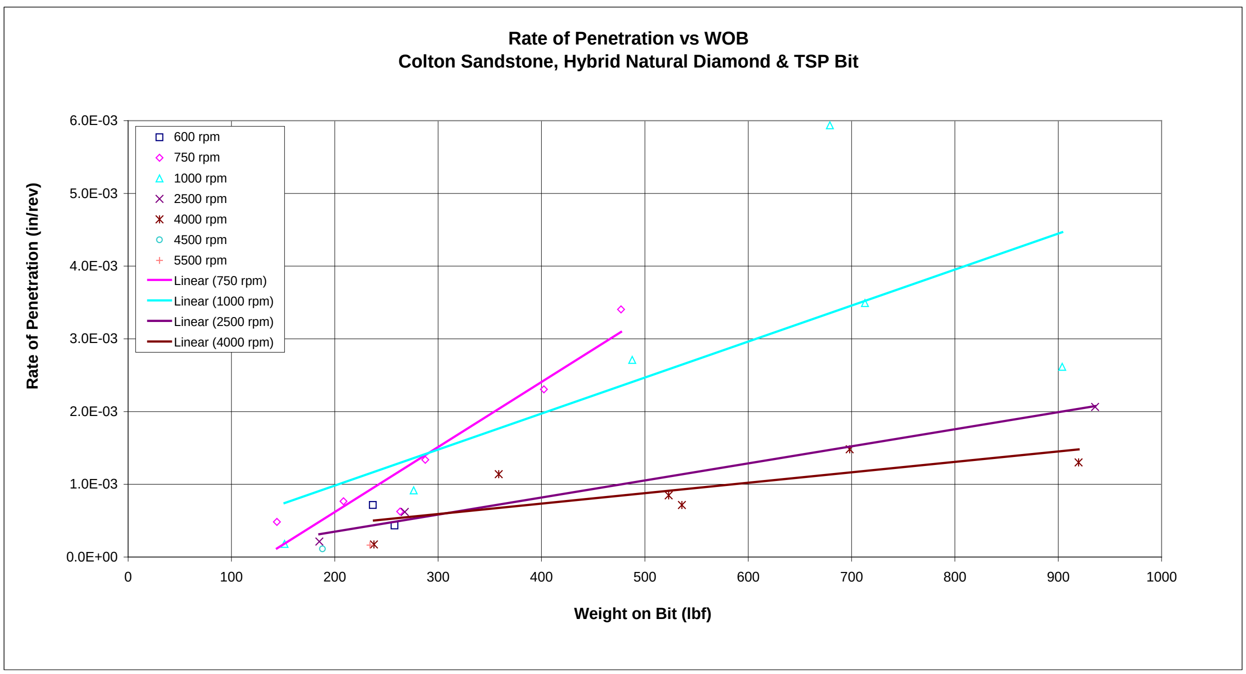

Figure 28. Rate of penetration is plotted as a function of weight on bit in Colton Sandstone with a hybrid natural diamond and TSP drill bit.

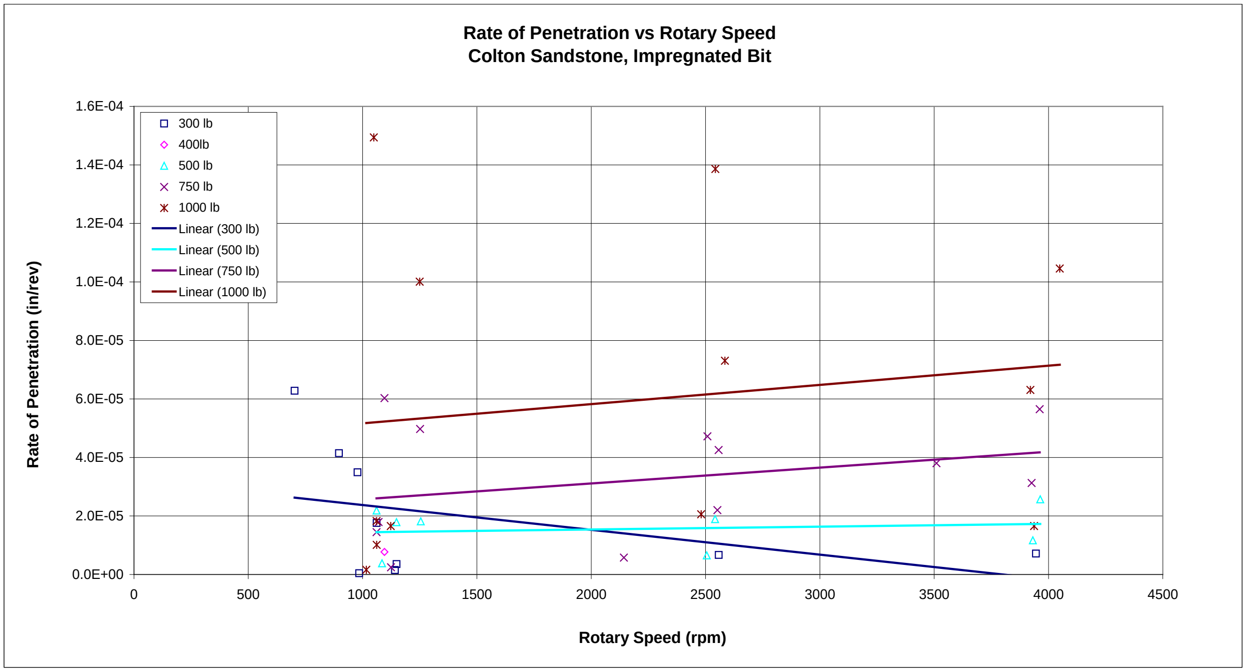

Figure 29. Rate of penetration is plotted as a function of rotary speed in Colton Sandstone with an impregnated drill bit.

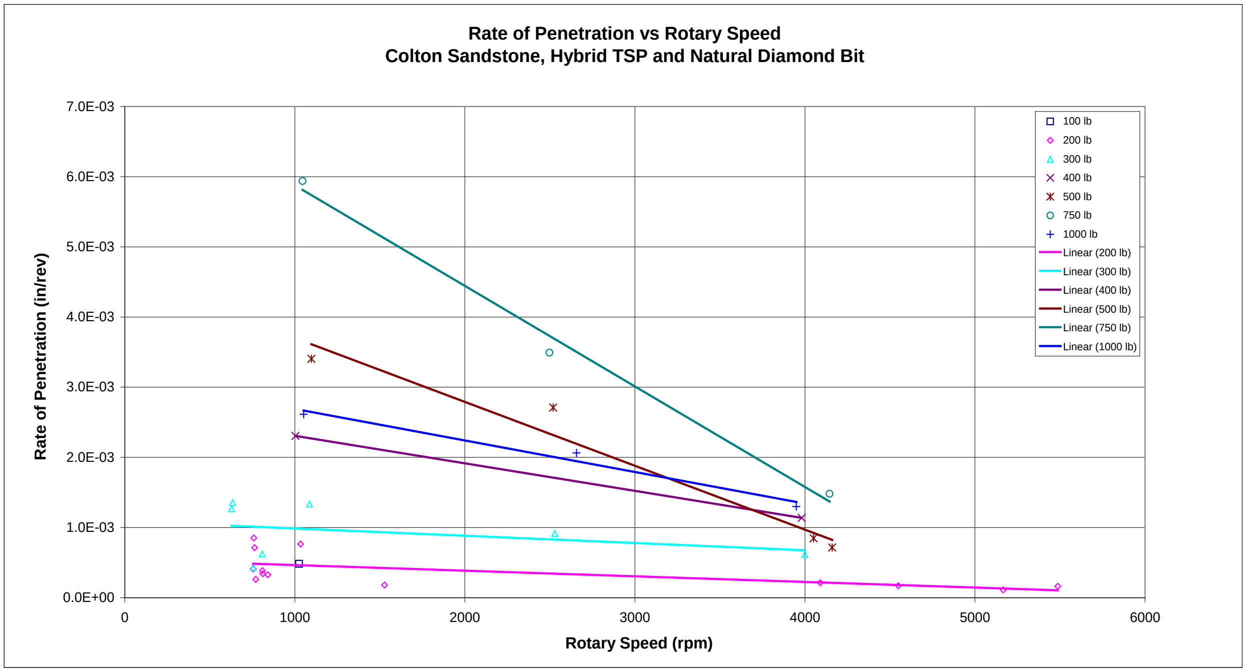

Figure 30. Rate of penetration is plotted as a function of rotary speed in Colton Sandstone with a hybrid natural diamond and TSP drill bit.

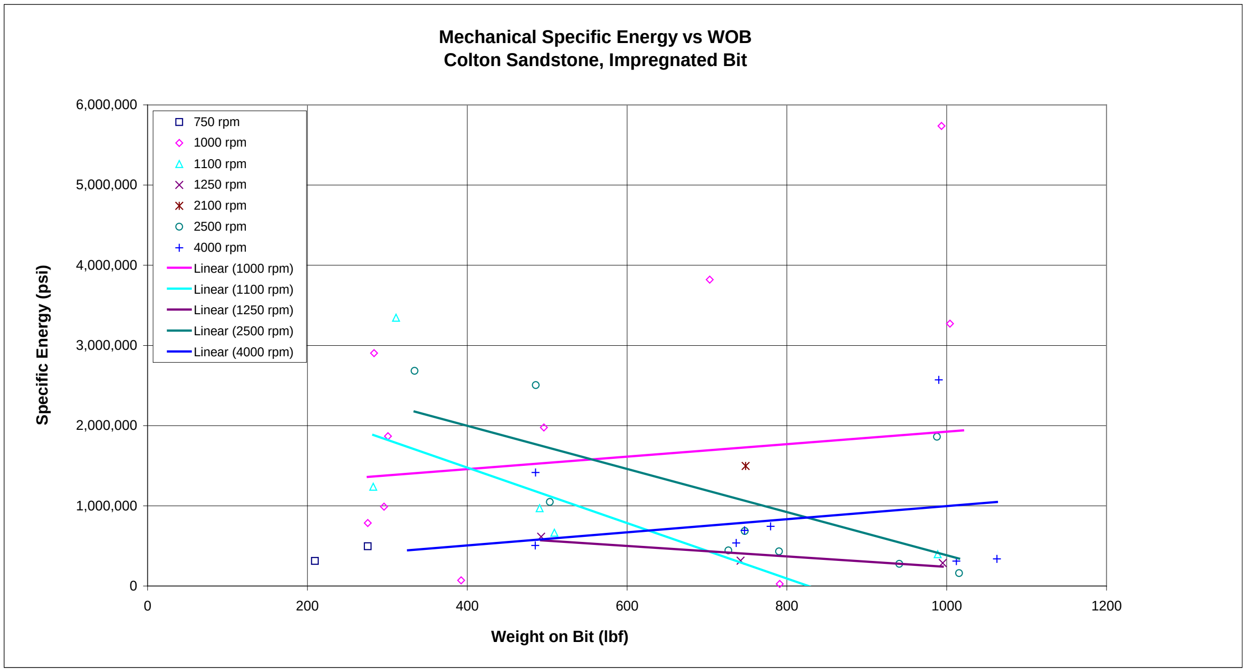

Figure 31. . Mechanical specific energy is plotted as a function of weight on bit in Colton Sandstone with an impregnated drill bit.

Figure 32. Mechanical specific energy is plotted as a function of weight on bit in Colton Sandstone with a hybrid natural diamond and TSP drill bit.

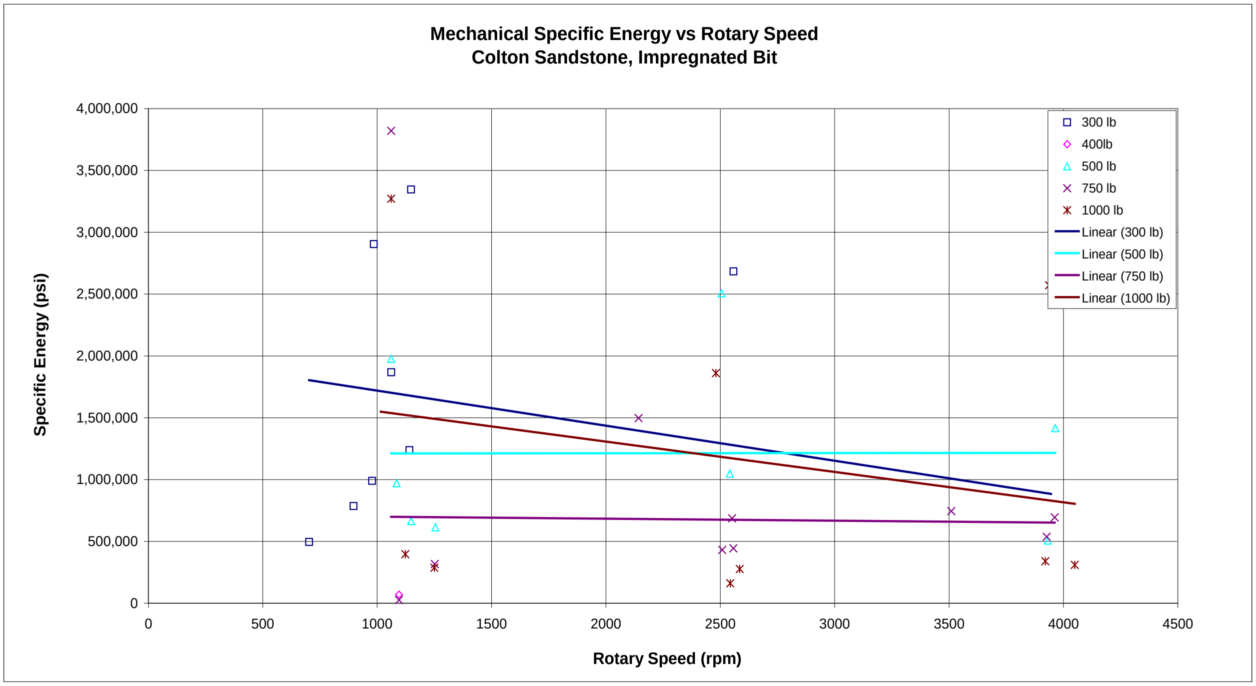

Figure 33. Mechanical specific energy is plotted as a function of rotary speed in Colton Sandstone with an impregnated drill bit.

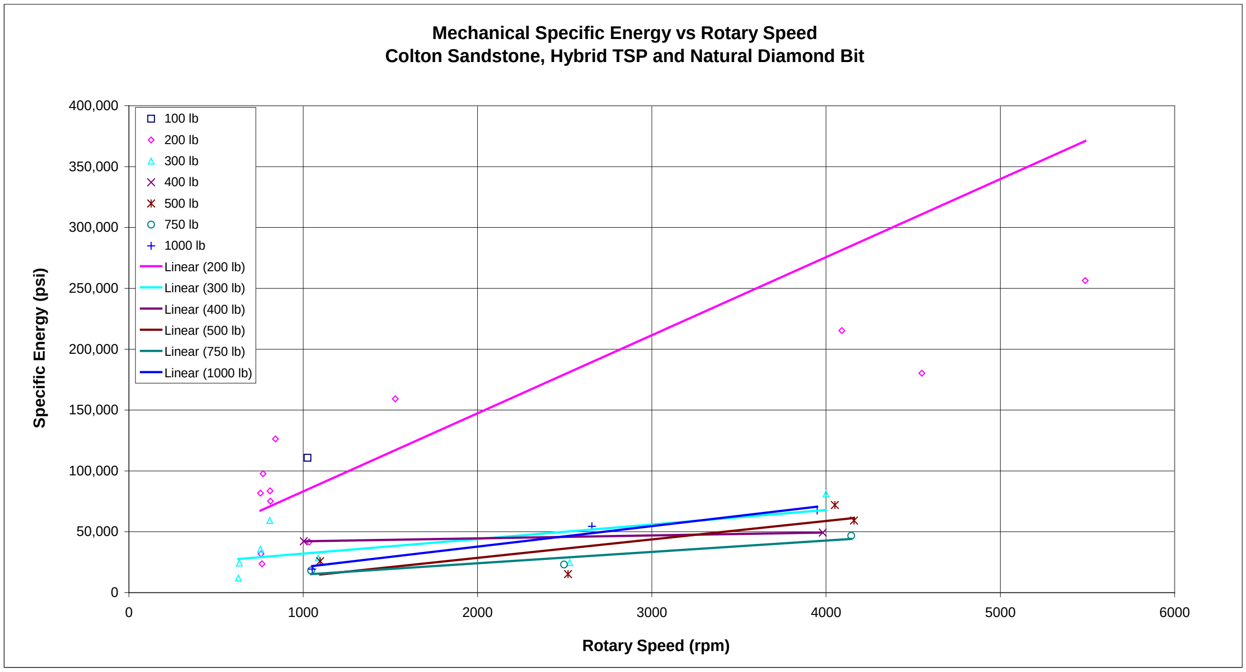

Figure 34. Mechanical specific energy is plotted as a function of rotary speed in Colton Sandstone with a hybrid natural diamond and TSP drill bit.

APPENDIX A. Test Plans

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Test Plan—Ultra High Speed Drilling Feasibility with Miniature Natural Diamond Core Bits

The motor was initially brought up to the nominal rotary speed with the rock sample very near but not in contact with the bit. The low friction table was then released allowing the sample to be forced into the bit at a constant weight on bit by means of gravitational forces on the attached mass. Samples of the cuttings were collected during each test for later analysis.

The detailed procedure included the following steps:

1. Measure no load amps to detect pending motor failure.
2. Install bit on motor shaft.
3. Clamp rock sample to table, aligning hole to the bit.
4. Set start pin to space the bit off the rock 0.002 inch.
5. Move bit forward to engage start pin.
6. Attach water line to back of sample making sure that the ball valve is closed and the needle valve is set.
7. Check the optical tachometer alignment.
8. Place an aluminum tray, to catch cuttings, on the table under the bit.
9. Zero Instruments.
10. Setup x-y-y' recorder.
11. Open ball valve to start water flow at 0.55 gpm.
12. Rotate drill bit to specified rotational speed.
13. Start the high rate data acquisition.
14. Pull start pin.
15. When stop pin is reached, or if ROP is less than slope line on x-y-y' (20 ft/hr), or if motor stalls, lift weight to stop drilling.
16. Bring rotational speed to zero.
17. Stop water flow.
18. Remove cuttings in aluminum tray, label and dry.
19. Label hole drilled and measure inside diameter and outside diameter of the hole.
20. Photograph bit.
21. Examine cuttings under microscope and photograph.
22. Calculate ROP (in/rev), average voltage, average amperage change (subtract initial amps), rotational speed, pressure, and perform specific energy calculations.
23. Generate plots and add test data and calculated specific energy to a table.

Test Plan—Ultra High Speed Drilling with Impregnated and TSP Drill Bits using Smith Neyrfor Turbines

Objective: Determine the rate of penetration, specific energy, efficiency and aggressiveness of impregnated and thermally stable PDC bits when drilling at ultra high speeds in hard rock at atmospheric conditions.

TEST MATERIALS AND EQUIPMENT

Test Articles

Drill bits:

- Thermally Stable PDC bit
- Impregnated drill bit

Rock:

Property	Crab Orchard Sandstone	Sierra White Granite
Unconfined Compressive Strength, (psi)	20,000 – 30,000	28,000
Porosity, (%)	7	< 1
Poisson's Ratio	0.2	---
Permeability, (md)	0.1	Negligible
Bulk Density, (g/cc)	2.47	2.65
Grain Density, (g/cc)	2.64	---

Test Equipment

Smith Neyrfor Turbines:
BAND Turbine
High Energy Advanced Turbodrill
Standard Turbine

Test Rig:
The test rig will be run with the low pressure setting on the hydraulic supply.

Mud Pump and Fluid System:

TerraTek's 1600 HP mud pump will be used to power the turbines and to clear cuttings from the sample. Water will be pumped through the center of the turbine and down into the sealing can. The sealing can is equipped with two exhaust ports, through which the water will exit. The water will then be pumped into a hatch basket, where it will be filtered for reuse.

Special Fixturing:

Turbine support:

A turbine support structure was constructed out of brass bushings split in half and bolted to steel plates. This setup was placed on each end of the turbine and acted as a tool guide and restraint. The lower turbine support structure was bolted to I-beams, which were bolted to the existing structure within the pit. The upper support structure was bolted directly to the grating, which was bolted to the drill rig rails.

Sample support:

From the bottom up: A bottom plate was bolted to the reaction floor. The load/torque cell was bolted to this plate. The rock sample was mounted onto a pivot above the load cell. Tie rods made from Allthread secured the rock sample to the base plate. The sealing canister, which housed the bit, was placed above the rock sample. Lead rope and bronze semi-circular plates sealed the top and bottom of the canister, preventing water leakage. The canister was secured by wrapping chains around the canister above the exhaust ports (added after the 2^{nd} or 3^{rd} test) to minimize vibrations. The turbine extended up through the canister. Near the top of the turbine (drill shaft?), a proximity switch was added to monitor the rotary speed.

Load cell:

Instrumentation:
Proximity switch to measure rotary speed located on top of drill shaft: digital meter readout
Mud flow rate
Drill depth
Weight on bit
Torque

TEST MATRIX

Factors and responses include:

- Categorical factors: Turbine, Bit, and Rock.
- Numeric factors: Mud flow rate and weight on bit (WOB).
- Responses: Torque, rotary speed, and rate of penetration.

Order of testing showing the turbine, bit, and rock used for each test.

Test	Turbine	Bit	Rock
1	BAND	Impregnated	Sierra White granite
2	BAND	Impregnated	Crab Orchard sandstone
3	BAND	TSP[1]	Crab Orchard sandstone
4	BAND	TSP	Sierra White granite
5	HEAT[2]	Impregnated	Crab Orchard sandstone
6	HEAT	Impregnated	Sierra White granite
~~7~~	~~HEAT~~	~~TSP~~	~~Crab Orchard sandstone~~
~~8~~	~~HEAT~~	~~TSP~~	~~Sierra White granite~~
~~9~~	~~Standard~~	~~Impregnated~~	~~Crab Orchard sandstone~~
~~10~~	~~Standard~~	~~Impregnated~~	~~Sierra White granite~~
11	Standard	TSP	Crab Orchard sandstone
12	Standard	TSP	Sierra White granite

[1]TSP—Thermally Stable Polycrystalline diamond compact (PDC)
[2]HEAT—High Energy Advanced Turbodrill
NOTE: Tests using the High Energy Advanced Turbodrill turbine and PDC bits were canceled due to turbine failure. Tests of the Standard turbine with the impregnated bit were canceled because of bit wear and time constraints.

Test Matrix for the individual tests with flow and weight on bit.

Flow Rate, (gal/min)	Weight on Bit, (lbf)		
80	1650	1100	550
90	1650	1100	550
100	1650	1100	550
110	1650	1100	550
120	1650	1100	550

TEST PREPARATION

Sample Preparation

1. The rock samples were cored from large blocks and trimmed to length using a large diamond saw.
2. Bit cutters were measured.

TEST SETUP

1. The drilling test equipment was set up and tested.
2. Rock support equipment and sensors were placed in the drilling cellar.
3. Special structures and bushings were installed to support the mud motors.

PRELIMINARY OPERATIONS CHECKS

Flow through turbine and check rotational sensor

Check on sensitivity of applying WOB

1. Zero all instruments using the signal conditioners.
2. Assemble the rock on load cell.
3. Configure rock hold-down and fluid return system with packing and bushing and tie down the system.
4. Advance the drill string until the bit is making contact with the rock.
5. Lift the string ½ in. and clamp the hydraulic system.
6. Unclamp the hydraulic system and, using the load control setting, bring the bit in contact with the rock and determine how fine a load can be applied.
7. Retract the bit and reapply load several times until we are comfortable that the load can be controlled when the bit first contacts the rock.

TEST PROCEDURES

Checkout

1. Fluid system checked for valve positioning and proper installation of fluid hardware.
2. Go through the operation of cuttings sample collection.
3. Check the rig.
4. Check instrumentation and confirm zeros.
5. Check the data acquisition systems.
6. Check the turbine installation and alignment.
7. Check the rock support canister.

Spud

1. Establish the distance between the bit and the rock.
2. Remove nonessential personnel from the Drill Laboratory.
3. Position cutting collection personnel and establish that the 2-way radios are functional.
4. Start the mud pump at 40 gpm flow rate and check for returns in the mud pit.
5. Bring the mud pump up to 80 gpm flow rate.
6. Bring the bit in contact with the rock under minimum load and drill 1 in. into the rock. Increase the WOB in 500 lbf increments until the bit stalls.
7. Back off the WOB to 0 lbf.
8. Lower the bit into the wellbore and continue spudding until the bit is 5 in. into the rock.

Test

1. Set the pump to the desired flow rate and establish the desired weight on bit (WOB).
2. Radio those collecting cutting to begin.
3. Drill to the desired depth.
4. Radio to stop cuttings collection.
5. Continue using Steps 1 through 4 using the settings on the test matrix.
6. After completing the test matrix, lift the bit off the bottom hole.
7. Reduce the mud flow rate to zero and stop the mud pump.

8. Remove the bushing and packing from the canister assembly.
9. Remove the bit/string from the canister.
10. Remove the canister assembly from the rock.
11. Remove the rock cylinder from the pit.

POST TEST PROCEDURES

1. Save all rock cylinders for later profiling.
2. Visually inspect the drill bit and photograph.
3. Gauge the cutters for wear and record.

Test Plan—Ultra-High-Speed Drilling with Hybrid TSP and Natural Diamond Drill Bits, Impregnated Drill Bits, and PDC Drill Bits

Test Objective: Determine the rate of penetration, specific energy, efficiency and aggressiveness of impregnated and thermally stable PDC bits when drilling at ultra high speeds in hard rock at atmospheric conditions.

TEST MATERIALS AND EQUIPMENT

Test Articles

Drill bits:

- ReedHycalog 4 1/8 inch hybrid TSP and natural diamond drill bit
- Hughes Christensen 4 1/8 inch impregnated drill bit
- Hughes Christensen 4 1/8 inch PDC drill bit

Rock:

The original plan called for five different rock types; however resource limitations limited the tests to Colton sandstone. The properties of Colton sandstone are:

Property	Colton Sandstone
Unconfined Compressive Strength, (psi)	7,600
Porosity, (%)	11
Poisson's Ratio	NA
Permeability, (md)	1 to 4 mD
Bulk Density, (g/cc)	2.38
Grain Density, (g/cc)	2.65

Test Equipment

Test Rig:

The specially designed high speed test rig will be run using a 300 HP hydraulic supply for rotation and a 40 HP hydraulic supply for axial motion.

Mud Pump and Fluid System:

TerraTek's mud pump will be used to pump drilling fluid (water).

Special Fixturing:

Load/torque cell

Instrumentation:

- Reflective laser tachometer will be used to measure rotary speed. It will be located on top of drill shaft. Readout will be provided for the data acquisition system.

- Mud flow rate will be monitored using the mud pump sensor.
- Drill depth will be measured using an LVDT.
- Weight on bit will be measured from a load/torque cell.
- Torque will be measured using the load/torque cell.

TEST MATRIX

A sequence of tests is provided in Table 1. Table 2 shows the weight on bit (WOB) and rotary speeds used. Factors and responses include:

- Categorical factors: Bit
- Numeric factors: Rotary speed and WOB.
- Responses: Torque and rate of penetration.

Table 1. Order of testing showing the turbine, bit, and rock used for each test.

Test	Bit	Rock
1	Hybrid TSP and natural diamond	Colton Sandstone
2	Hybrid TSP and natural diamond	Colton Sandstone
3	Hybrid TSP and natural diamond	Colton Sandstone
4	Hybrid TSP and natural diamond	Colton Sandstone
5	Hybrid TSP and natural diamond	Colton Sandstone
6	Hybrid TSP and natural diamond	Colton Sandstone
7	Hybrid TSP and natural diamond	Colton Sandstone
8	Hybrid TSP and natural diamond	Colton Sandstone
9	Hybrid TSP and natural diamond	Colton Sandstone
10	Hybrid TSP and natural diamond	Colton Sandstone
11	Hybrid TSP and natural diamond	Colton Sandstone
12	Hybrid TSP and natural diamond	Colton Sandstone
13	Hybrid TSP and natural diamond	Colton Sandstone
14	Impregnated	Colton Sandstone
15	Impregnated	Colton Sandstone
16	PDC	Colton Sandstone

*Five rock types were originally selected for testing. However, resource constraints limited the testing to Colton sandstone.

Table 2. Test Matrix for the individual tests with weight on bit and rotational speed.

Weight on Bit (lbf)	Rotational Speed (rpm)*		
200-300	700-800		
300	1000	2500	4000
500	1000	2500	4000
750	1000	2500	4000
1000	1000	2500	4000

*Original plans included rotational speeds to 10,000 rpm; however, resource limitations did not allow testing with the higher speed motor.

TEST PREPARATION

Sample Preparation

Rock slabs sized for drilling five holes were prepared from Colton sandstone.

PRELIMINARY OPERATIONS CHECKS

Rotate the drill string and check the rotational sensor.

Check on sensitivity of applying WOB

1. Zero all instruments using the signal conditioners.
2. Assemble the rock on test rig platform.
3. Clamp the rock to the platform and prepare the fluid return.
4. Advance the drill string until the bit is making contact with the rock.
5. Lift the string ½ in. and clamp the hydraulic system.
6. Unclamp the hydraulic system and, using the load control setting, bring the bit in contact with the rock and determine how fine a load can be applied.
7. Retract the bit and reapply load several times until comfortable that the load can be controlled when the bit first contacts the rock.

TEST PROCEDURES

Checkout

8. Bring up the mud charge system: check for valve positioning and return flow.
9. Check the rig.
10. Check instrumentation and confirm zeros.
11. Check the data acquisition systems.
12. Check the rock to bit distance.

Spud

9. Remove nonessential personnel from the Drill Laboratory.
10. Start the mud pump and bring the flow to 30 gpm.
11. Start the drill string rotation and bring the rotary speed to approximately 700 rpm.
12. Bring the bit in contact with the rock under minimum load and spud 2 1/2 in. into the rock. The rotary speed should be approximately 700 rpm and the WOB at about 200 lbf.

Test

12. Set the data acquisition system to 8 Hz.
13. Set the rotary speed to the desired rate and establish the desired WOB.
14. Drill at the designated parameters until the readings are stable.
15. Continue using Steps 2 through 3 using the settings on the test matrix.
16. After completing the test matrix or when the string is out of stroke, lift the bit off the bottom hole.
17. Stroke the drill string out, back into, and out of the wellbore to monitor the offset in load and torque readings with depth.
18. Reduce the rotary speed to zero and stop the mud pump.
19. Raise the bit/string and mud canister from the rock.
20. Reposition the rock for the next drilling sequence.
21. Remove the rock from the platform when spent.

POST TEST PROCEDURES

1. Visually inspect the drill bit and photograph.
2. Photograph the wellbores.

APPENDIX B. Test Result Data Tables

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Table B-2. Drilling parameters and results for small full face bit testing for Trials DOEH194 through DOEH205 in Berea sandstone. 54

Table B-3. Drilling parameters and results for large full face bit testing for trials DOEH206 through DOEH217 in Berea sandstone. 54

Table B-4. Summary test data for all tests using mud turbine motors. 55

Table B-5. Summary test data for all tests using the high speed drilling test stand. 59

Table B-1. Drilling parameters and results for core bit trials DOEH103 through DOEH193.

Trial	Test Date	Bit	Rock	Block	Target Weight on Bit (g)	Target Rotary Speed (rpm)	Actual Weight on Bit (g)	Actual Rotary Speed (rpm)	Hole Outside Diameter (in)	Hole Inside Diameter (in)	Total Specific Energy (ft-lbs/in^3)	Rate of Penetration (ft/hr)
DOEH103	2/28/06	20	Berea	9	3000	40,000	3083	32949	0.844	0.565	4623	90.540
DOEH104	2/28/06	20	Berea	9	3000	20,000	2913	15976	0.834	0.570	5405	47.220
DOEH105	2/28/06	20	Berea	11	3000	25,000	2997	22136	0.839	0.570	2707	41.940
DOEH106	2/28/06	20	Berea	11	3000	30,000	2990	26583	0.847	0.565	2618	50.490
DOEH107b	2/28/06	20	Berea	11	3000	40,000	3000	36152	0.843	0.566	3841	84.720
DOEH107c	2/28/06	20	Berea	27	3000	40,000	2999	33161	0.844	0.565	5596	70.920
DOEH108	3/30/06	29	Berea	24	1500	10,000	1443	9661	0.783	0.618	3031	8.760
DOEH109	3/30/06	29	Berea	24	1500	10,000	1442	9324	0.784	0.617	2961	6.630
DOEH110	3/31/06	29	Winfield	22	1500	30,000	1528	29198	0.786	0.610	10970	9.790
DOEH111	3/31/06	29	Winfield	22	1500	30,000	1477	28640	0.783	0.616	13636	8.520
DOEH112	3/31/06	29	Winfield	22	1500	10,000	1476	7469	0.777	0.622	5518	5.567
DOEH113	3/31/06	29	Winfield	22	1500	10,000	1458	9689	0.778	0.624	16219	3.525
DOEH114	3/31/06	29	Winfield	22	1500	50,000	1516	43794	0.813	0.584	7159	8.850
DOEH115	3/31/06	29	Berea	24	1500	10,000	1474	10198	0.782	0.622	3089	4.620
DOEH116	4/3/06	30	Berea	24	1500	10,000	1458	9259	0.781	0.622	3423	6.254
DOEH117	4/3/06	30	Berea	24	1500	10,000	1477	9462	0.782	0.624	3372	5.655
DOEH118	4/3/06	30	Berea	23	1500	50,000	1548	44351	0.787	0.615	6849	14.850
DOEH119	4/3/06	30	Berea	23	1500	30,000	1572	30465	0.783	0.622	4346	18.510
DOEH120	4/3/06	30	Berea	23	1500	10,000	1490	9816	0.775	0.627	330	3.900
DOEH121	4/3/06	30	Berea	23	1500	50,000	1559	44345	0.779	0.618	2482	21.750
DOEH122	4/3/06	30	Berea	23	1500	30,000	1554	29978	0.777	0.625	5959	10.860
DOEH123	4/3/06	30	Berea	23	1500	10,000	1487	9947	0.781	0.625	2023	6.600
DOEH124	4/3/06	30	Berea	23	1500	10,000	1478	9376	0.778	0.626	2107	5.370
DOEH125	4/3/06	30	Berea	4	1500	10,000	1476	9354	0.774	0.625	2732	4.620
DOEH126	4/6/06	30	Berea	23	1500	50,000	1555	45207	0.781	0.617	6285	20.730
DOEH127	4/6/06	30	Winfield	22	1500	50,000	1538	44549	0.780	0.618	9388	11.610
DOEH128	4/6/06	30	Winfield	22	1500	20,000	1513	19947	0.779	0.621	10680	5.640
DOEH129	4/6/06	30	Berea	23	1500	20,000	1502	20556	0.782	0.623	6329	6.000
DOEH130	4/6/06	30	Berea	23	1500	40,000	1494	40260	0.779	0.621	6989	15.690
DOEH131	4/6/06	30	Berea	24	1500	10,000	1508	10510	0.772	0.631	3864	2.280
DOEH132	4/7/06	30	Winfield	22	1500	50,000	1511	45162	0.782	0.617	8528	11.304

Table B-1. Drilling parameters and results for core bit trials DOEH103 through DOEH193 (continued).

Trial	Test Date	Bit	Rock	Block	Target Weight on Bit (g)	Target Rotary Speed (rpm)	Actual Weight on Bit (g)	Actual Rotary Speed (rpm)	Hole Outside Diameter (in)	Hole Inside Diameter (in)	Total Specific Energy (ft-lbs/in^3)	Rate of Penetration (ft/hr)
DOEH134	4/11/06	31	Berea	21	1500	10,000	1453	8822	0.804	0.589	2089	12.990
DOEH137	4/12/06	31	Berea	21	3500	50,000	3489	45273	0.820	0.579	2637	275.131
DOEH138	4/13/06	31	Berea	21	1500	10,000	1501	9153	0.783	0.618	2714	8.173
DOEH139	4/13/06	31	Winfield	22	1500	50,000	1484	44870	0.784	0.617	12450	18.210
DOEH140	4/13/06	31	Winfield	22	3500	50,000	3532	41261	0.786	0.610	8331	112.800
DOEH141	4/13/06	31	Sulurain	25	1500	10,000	1464	8949	0.786	0.610	5168	7.080
DOEH142	4/13/06	31	Winfield	22	2500	30,000	2459	26488	0.783	0.616	8577	42.480
DOEH143	4/13/06	31	Berea	29	1500	50,000	1508	45049	0.826	0.588	2816	41.885
DOEH144	4/13/06	31	Winfield	22	3500	10,000	3456	6225	0.777	0.622	9919	19.560
DOEH145	4/13/06	31	Berea	29	3500	50,000	3186	43699	0.818	0.583	2036	287.580
DOEH146	4/13/06	31	Sulurain	25	1500	10,000	3388	6517	0.815	0.584	3906	29.610
DOEH147	4/13/06	31	Sulurain	25	1500	50,000	1516	44241	0.821	0.589	9627	16.680
DOEH148	4/13/06	31	Colton	26	1500	10,000	1454	9191	0.770	0.611	3602	8.447
DOEH149	4/13/06	31	Berea	21	1500	10,000	1487	9092	0.788	0.603	2381	8.264
DOEH150	4/17/06	31	Winfield	22	1500	10,000	1485	8926	0.801	0.592	4651	8.096
DOEH151	4/17/06	31	Colton	26	3500	10,000	3368	6423	0.823	0.579	5073	25.250
DOEH152	4/17/06	31	Colton	26	1500	50,000	1504	45317	0.825	0.586	5012	15.176
DOEH153	4/17/06	31	Berea	29	2500	30,000	2490	27275	0.821	0.582	2098	103.912
DOEH154	4/17/06	31	Berea	29	3500	10,000	3347	6910	0.816	0.582	2318	45.307
DOEH155	4/17/06	31	Colton	26	3500	50,000	3537	44354	0.816	0.582	6871	54.240
DOEH156	4/17/06	31	Colton	26	2500	30,000	2514	28214	0.820	0.583	4325	34.661
DOEH157	4/17/06	31	Sulurain	25	3500	50,000	3612	43766	0.817	0.581	6593	68.831
DOEH158	4/17/06	31	Berea	29	1500	10,000	1489	9738	0.789	0.590	1950	6.474
DOEH159	4/17/06	31	Sulurain	25	2500	30,000	2519	27433	0.810	0.582	4486	42.783
DOEH160	4/17/06	31	Berea	21	1500	10,000	1446	9428	0.785	0.600	1832	7.676
DOEH161	4/18/06	31	Berea	29	1500	30,000	1411	29426	0.802	0.595	3911	12.049
DOEH162	4/18/06	31	Winfield	22	3500	30,000	3232	26703	0.813	0.581	6724	40.308
DOEH163	4/18/06	31	Winfield	22	2500	50,000	2561	44225	0.819	0.583	9114	24.731
DOEH164	4/18/06	31	Winfield	22	1500	30,000	1499	29601	0.795	0.593	6690	9.080
DOEH165	4/18/06	31	Colton	26	3500	30,000	3112	26580	0.822	0.581	5154	39.020
DOEH166	4/18/06	31	Colton	26	1500	30,000	1513	29742	0.790	0.601	9081	4.943

Table B-1. Drilling parameters and results for core bit trials DOEH103 through DOEH193 (continued).

Trial	Test Date	Bit	Rock	Block	Target Weight on Bit (g)	Target Rotary Speed (rpm)	Actual Weight on Bit (g)	Actual Rotary Speed (rpm)	Hole Outside Diameter (in)	Hole Inside Diameter (in)	Total Specific Energy (ft-lbs/in^3)	Rate of Penetration (ft/hr)
DOEH167	4/18/06	31	Colton	26	2500	30,000	2346	28388	0.817	0.583	4589	27.772
DOEH168	4/18/06	31	Sulurain	25	1500	30,000	1515	29635	0.780	0.620	18036	3.578
DOEH169	4/18/06	31	Sulurain	25	2500	10,000	2362	8521	0.796	0.593	5182	8.888
DOEH170	4/18/06	31	Berea	29	2500	50,000	2507	45353	0.822	0.586	3457	51.430
DOEH170r1	6/14/06	31	Berea	29	2500	50,000	2618	48690	0.821	0.583	2589	91.632
DOEH135	4/11/06	32	Berea	21	1500	10,000	1496	9060	0.839	0.565	1653	9.922
DOEH136	4/11/06	33	Berea	21	1500	10,000	1495	8940	0.812	0.588	1965	12.618
DOEH171	4/18/06	33	Berea	21	1500	10,000	1329	9855	0.783	0.620	2639	4.335
DOEH171B	4/19/06	33	Berea	21	1500	10,000	1378	9447	0.811	0.591	1837	7.899
DOEH172	4/18/06	33	Berea	29	2500	30,000	2139	28992	0.820	0.583	2335	43.176
DOEH173	4/18/06	33	Sulurain	25	3500	30,000	3232	27994	0.819	0.581	4628	41.699
DOEH174	4/18/06	33	Sulurain	25	2500	50,000	2487	44722	0.810	0.585	5570	51.746
DOEH175	4/18/06	33	Winfield	22	2500	10,000	2352	8721	0.805	0.589	6580	12.922
DOEH176	5/4/06	33	Colton	26	2500	50,000	2482	48553	0.810	0.577	4314	46.740
DOEH177	5/4/06	33	Colton	26	2500	10,000	2452	8176	0.812	0.585	4595	11.015
DOEH178	5/4/06	33	Sulurain	25	2500	30,000	2469	28003	0.809	0.589	6980	26.196
DOEH179	5/4/06	33	Berea	29	3500	30,000	3267	26450	0.811	0.588	2371	153.960
DOEH180	5/4/06	33	Winfield	22	2500	30,000	2505	27987	0.812	0.589	7058	22.802
DOEH181	5/4/06	33	Berea	29	2500	10,000	2380	8414	0.810	0.588	1873	25.897
DOEH182	5/4/06	33	Berea	21	1500	10,000	1454	9929	0.781	0.599	3393	4.148
DOEH183	5/4/06	33	Nugget	28	1500	10,000	1516	10206	0.761	0.612	866	1.744
DOEH184	5/15/06	33	Nugget	28	3500	10,000	3413	7282	0.812	0.587	5241	12.089
DOEH185	5/15/06	33	Nugget	28	3500	50,000	3480	47856	0.823	0.574	7327	15.768
DOEH186	5/15/06	33	Nugget	28	3500	30,000	3506	27731	0.811	0.589	5917	28.793
DOEH187	5/15/06	33	Nugget	28	1500	50,000	1505	49955	0.815	0.577	17222	3.798
DOEH188	5/15/06	33	Nugget	28	2500	30,000	2497	28770	0.812	0.583	5704	13.206
DOEH189	5/15/06	33	Nugget	28	2500	30,000	2509	29432	0.815	0.582	5603	14.027
DOEH190	5/15/06	33	Nugget	28	2500	50,000	2496	49881	0.818	0.574	5484	13.747
DOEH191	5/15/06	33	Nugget	28	1500	30,000	1511	29689	0.816	0.585	8771	4.021
DOEH192	5/15/06	33	Nugget	28	2500	10,000	2416	9534	0.801	0.586	7043	3.902
DOEH193	5/15/06	33	Berea	21	1500	10,000	1516	10296	0.809	0.595	3371	2.796

Table B-2. Drilling parameters and results for small full face bit testing for Trials DOEH194 through DOEH205 in Berea sandstone.

Trial	Test Date	Bit	Block	Target Weight on Bit (g)	Target Rotary Speed (rpm)	Actual Weight on Bit (g)	Actual Rotary Speed (rpm)	Drilled Hole Diameter (in)	Rock Bore Diameter (in)	Total Specific Energy (ft-lbs/in^3)	Rate of Penetration (ft/hr)
DOEH194	5/16/06	34	30	1500	10,000	1400	9,940	0.516	0.196	1,338	12.174
DOEH195	5/16/06	34	31	3500	10,000	3450	7,844	0.535	0.196	1,075	71.539
DOEH196	5/16/06	34	31	2500	30,000	2320	29,237	0.533	0.196	1,182	124.183
DOEH197	5/16/06	34	31	2500	10,000	2361	9,582	0.535	0.196	1,034	35.163
DOEH198	5/16/06	34	31	2500	50,000	1830	48,820	0.545	0.196	1,402	119.155
DOEH199	5/16/06	34	31	3500	30,000	3338	28,573	0.538	0.196	1,154	217.796
DOEH200	5/16/06	34	31	1500	50,000	1321	49,819	0.555	0.196	1,087	46.699
DOEH201	5/16/06	34	31	1500	10,000	1493	10,175	0.502	0.196	1,663	3.547
DOEH202	5/16/06	34	31	1500	30,000	1129	29,972	0.524	0.196	2,222	14.808
DOEH203	5/16/06	34	31	2500	30,000	2086	29,075	0.534	0.196	1,503	65.523
DOEH204	5/16/06	34	31	3500	50,000	3063	48,287	0.547	0.196	1,046	221.373
DOEH205	5/16/06	34	30	1500	10,000	1430	10,217	0.501	0.196	1,701	3.987

Table B-3. Drilling parameters and results for large full face bit testing for trials DOEH206 through DOEH217 in Berea sandstone.

Trial	Test Date	Bit	Block	Target Weight on Bit (g)	Target Rotary Speed (rpm)	Actual Weight on Bit (g)	Actual Rotary Speed (rpm)	Drilled Hole Diameter (in)	Rock Bore Diameter (in)	Total Specific Energy (ft-lbs/in^3)	Rate of Penetration (ft/hr)
DOEH206	5/16/06	35	30	1500	10,000	1444	9,857	0.800	0.196	1,294	8.843
DOEH207	5/16/06	35	32	3500	30,000	3130	25,871	0.820	0.196	1,014	146.490
DOEH208	5/16/06	35	32	2500	40,000	1989	38,066	0.834	0.196	814	42.495
DOEH209	5/16/06	35	32	1500	30,000	1195	29,334	0.812	0.196	1,100	30.248
DOEH210	5/16/06	35	32	2500	10,000	2373	8,484	0.800	0.196	1,154	21.640
DOEH211	5/16/06	35	32	2500	30,000	2139	27,763	0.811	0.196	1,093	77.798
DOEH212	5/16/06	35	32	3500	10,000	3417	7,051	0.806	0.196	1,109	33.000
DOEH213	5/16/06	35	32	3500	40,000	3114	38,803	0.836	0.196	530	57.557
DOEH214	5/16/06	35	32	2500	30,000	2159	28,079	0.815	0.196	1,129	67.242
DOEH215	5/16/06	35	32	1500	10,000	1467	10,311	0.786	0.196	1,540	2.402
DOEH216	5/16/06	35	32	1500	50,000	0	0	0.000	0.000	0	0.000
DOEH217	5/16/06	35	30	1500	10,000	1469	10,284	0.801	0.196	1,801	596.842

Table B-4. Summary test data for all tests using mud turbine motors. All tests were performed with water as a drilling fluid. (Abbreviations used in the table are listed in expanded form at the bottom of the table.)

Test Number	Trial Number	Rock	Bit	Turbine	Target WOB lb	Target Rotary Speed rpm	Depth Interval in	Weight on Bit lb	Rotary Speed rpm	Bit Torque ft-lb	Flow Rate gpm	Total Δ Press psi	Penetration Rate ft/hr	Penetration Rate in/rev	Mechanical Specific Energy psi
1	1	Sierra White	Imp	BAND	800	3000	0.36828	785	2826	10	80	894	11.77	8.332E-04	2,683
1	2	Sierra White	Imp	BAND	1500	2500	0.52159	1437	2287	21	80	907	15.93	1.393E-03	10,426
1	3	Sierra White	Imp	BAND	2000	2000	0.29268	1956	2004	33	80	919	14.33	1.430E-03	22,481
1	4	Sierra White	Imp	BAND	1100	3000	0.10131	1135	3004	25	88	1099	19.80	1.318E-03	9,001
1	5	Sierra White	Imp	BAND	900	4500	0.67073	908	4447	40	124	1933	41.43	1.863E-03	8,339
1b	1	Sierra White	Imp	BAND	1250	1500	1.60851	1272	2604	109	89	1156	16.34	1.255E-03	43,886
1b	2	Sierra White	Imp	BAND	1250	1500	1.17595	1253	3223	107	103	1388	21.32	1.323E-03	36,526
1b	3	Sierra White	Imp	BAND	1250	1000	0.71962	1207	3557	122	115	1655	31.39	1.765E-03	36,196
1b	4	Sierra White	Imp	BAND	1250	1000	0.5219	1202	4584	121	124	1908	32.01	1.396E-03	32,905
1b	5	Sierra White	Imp	BAND	2500	500	0.05692	2595	478	184	81	890	3.47	1.449E-03	166,293
1b	6	Sierra White	Imp	BAND	2500	2500	0.14157	2577	2649	160	89	1160	8.64	6.522E-04	130,874
1b	7	Sierra White	Imp	BAND	2500	4000	0.12571	2575	3962	151	103	1340	7.54	3.807E-04	105,805
1b	8	Sierra White	Imp	BAND	2500	4500	0.15716	2570	4399	154	114	1597	9.41	4.277E-04	97,659
1b	9	Sierra White	Imp	BAND	2500	4500	0.52007	2489	4310	166	124	1906	28.61	1.328E-03	93,826
2	1	Crab Orchard	Imp	BAND	1500	3000	0.00798	1412	3062	47	82	875	0.60	3.889E-05	23,007
2	2	Crab Orchard	Imp	BAND	1500	3500	0.00041	1495	3602	47	90	1090	0.04	2.186E-06	22,181
2	3	Crab Orchard	Imp	BAND	1500	4000	4.1E-05	1494	4102	47	104	1330	0.00	1.653E-07	19,008
2	4	Crab Orchard	Imp	BAND	1500	1500	0.00206	1490	4512	48	114	1545	0.15	6.442E-06	17,565
2	5	Crab Orchard	Imp	BAND	1500	5000	0.08617	1454	5046	49	125	1869	4.28	1.695E-04	16,023
2	6	Crab Orchard	Imp	BAND	3000	3000	8E-05	2904	2799	15	82	896	0.00	3.063E-07	15,016
2	7	Crab Orchard	Imp	BAND	1000	3500	0.33083	916	3478	35	81	851	31.71	1.823E-03	11,134
2	8	Crab Orchard	Imp	BAND	3000	3000	-0.0001	2931	2892	-8	81	885	-0.01	-7.959E-07	-7,930
2	9	Crab Orchard	Imp	BAND	3500	3000	0.02001	3359	2757	-14	81	900	1.11	8.067E-05	-16,068
2b	1	Crab Orchard	Imp	BAND	2500	4000	0.65732	2549	3833	37	124	1977	40.01	2.087E-03	21,424
2b	2	Crab Orchard	Imp	BAND	2500	3500	0.11104	2558	3290	12	87	1130	5.71	3.470E-04	9,517
2b	3	Crab Orchard	Imp	BAND	2500	2500	0.02598	2594	2606	6	80	920	1.45	1.116E-04	5,751
2b	4	Crab Orchard	Imp	BAND	3500	3500	0.47835	3467	3351	43	123	1961	29.24	1.745E-03	34,415
2b	5	Crab Orchard	Imp	BAND	3500	3000	0.40587	3510	3168	35	114	1705	25.12	1.586E-03	30,130

Table B-4. Summary test data for all tests using mud turbine motors. All tests were performed with water as a drilling fluid (continued). (Abbreviations used in the table are listed in expanded form at the bottom of the table.)

Test Number	Trial Number	Rock	Bit	Turbine	Target WOB lb	Target Rotary Speed rpm	Depth Interval in	Weight on Bit lb	Rotary Speed rpm	Bit Torque ft-lb	Flow Rate gpm	Total Δ Press psi	Penetration Rate ft/hr	Penetration Rate in/rev	Mechanical Specific Energy psi
2b	6	Crab Orchard	Imp	BAND	3500	3000	0.31084	3569	2933	27	102	1455	18.70	1.275E-03	26,373
2b	7	Crab Orchard	Imp	BAND	3500	2500	0.11137	3628	2411	16	88	1180	8.44	7.004E-04	18,293
2b	8	Crab Orchard	Imp	BAND	3500	2000	0.11822	3648	2144	8	80	1075	6.98	6.509E-04	10,275
2b	9	Crab Orchard	Imp	BAND	3500	1500	0.05146	3672	1285	13	80	898	3.07	4.770E-04	16,507
3	1	Crab Orchard	TSP	BAND	1500	2000	0.48883	1570	1978	33	84	1130	46.13	4.665E-03	17,477
3	2	Crab Orchard	TSP	BAND	2000	3000	1.56367	1944	3015	52	121	1893	127.58	8.463E-03	23,477
3	3	Crab Orchard	TSP	BAND	2000	3500	1.04893	1745	3469	46	121	1932	98.49	5.679E-03	18,736
3	4	Crab Orchard	TSP	BAND	2000	3500	1.04393	1817	3258	52	122	1958	97.38	5.977E-03	22,014
3	5	Crab Orchard	TSP	BAND	2000	3000	1.31041	2154	2906	58	121	1989	122.58	8.438E-03	29,163
3	6	Crab Orchard	TSP	BAND	2500	2000	0.57339	2637	1871	60	95	1389	54.26	5.802E-03	47,367
3	7	Crab Orchard	TSP	BAND	2500	1000	0.24107	2836	779	62	76	1004	21.99	5.642E-03	65,129
4	1	Sierra White	TSP	BAND	2000	2000	0.28783	2021	1811	26	93	1114	27.87	3.078E-03	15,935
4	2	Sierra White	TSP	BAND	2500	3000	0.88701	2607	2812	40	125	1849	86.54	6.154E-03	23,344
4	3	Sierra White	TSP	BAND	3000	2000	0.92252	2876	2146	39	125	1899	90.18	8.404E-03	25,574
4	4	Sierra White	TSP	BAND	3000	1500	0.33452	3055	1733	58	104	1390	32.70	3.775E-03	47,749
4	5	Sierra White	TSP	BAND	4000	2000	0.74864	4057	2019	61	125	1925	72.05	7.136E-03	56,335
4	6	Sierra White	TSP	BAND	3000	2000	0.31297	3041	1825	61	104	1379	19.19	2.103E-03	49,974
4	7	Sierra White	TSP	BAND	500	2500	0.36036	491	2560	28	93	1141	24.24	1.894E-03	4,224
4	8	Sierra White	TSP	BAND	2000	2000	0.22271	2033	1948	48	93	1146	15.02	1.542E-03	29,783
4	9	Sierra White	TSP	BAND	500	2500	0.11982	394	2450	20	83	913	11.40	9.305E-04	2,678
4	10	Sierra White	TSP	BAND	3000	3000	0.59036	2915	2949	74	125	1853	55.91	3.792E-03	48,775
4	11	Sierra White	TSP	BAND	3000	2000	0.64212	3059	2199	73	115	1822	60.44	5.496E-03	55,182
4	12	Sierra White	TSP	BAND	3000	1500	0.31071	3016	1662	83	104	1373	18.68	2.247E-03	68,094
5	1	Crab Orchard	Imp	HEAT	4000	2000	0.03393	4021	2037	37	92	1323	3.23	3.169E-04	45,596
5	2	Crab Orchard	Imp	HEAT	3000	4000	0.11751	3043	3850	34	125	2234	7.67	3.983E-04	23,512
5	3	Crab Orchard	Imp	HEAT	3000	3500	0.04287	3078	3469	31	114	1881	2.35	1.353E-04	23,685
5	4	Crab Orchard	Imp	HEAT	3000	3000	0.02662	3089	3059	31	104	1593	1.56	1.020E-04	26,036
5	5	Crab Orchard	Imp	HEAT	3000	2500	0.00117	3094	2508	29	91	1330	0.09	7.257E-06	28,004
5	6	Crab Orchard	Imp	HEAT	3000	1500	0.00035	3098	1666	28	82	1049	0.02	2.668E-06	29,680
5	7	Crab Orchard	Imp	HEAT	4000	2500	0.46399	4011	2448	64	125	2167	23.08	1.886E-03	58,080

Table B-4. Summary test data for all tests using mud turbine motors. All tests were performed with water as a drilling fluid (continued). (Abbreviations used in the table are listed in expanded form at the bottom of the table.)

Test Number	Trial Number	Rock	Bit	Turbine	Target WOB lb	Target Rotary Speed rpm	Depth Interval in	Weight on Bit lb	Rotary Speed rpm	Bit Torque ft-lb	Flow Rate gpm	Total Δ Press psi	Penetration Rate ft/hr	Penetration Rate in/rev	Mechanical Specific Energy psi
5	8	Crab Orchard	Imp	HEAT	4000	2000	0.20399	4072	2094	51	104	1686	14.25	1.361E-03	56,030
5	9	Crab Orchard	Imp	HEAT	4000	2000	0.19085	4087	1900	51	104	1602	11.09	1.167E-03	56,100
5	10	Crab Orchard	Imp	HEAT	4000	1500	0.10306	4090	1365	50	92	1316	6.52	9.549E-04	63,156
5	11	Crab Orchard	Imp	HEAT	5000	2000	0.33001	4992	2084	75	125	2210	22.97	2.204E-03	84,658
5	12	Crab Orchard	Imp	HEAT	5000	2000	0.33838	5007	1904	66	114	1900	23.48	2.466E-03	80,864
5	13	Crab Orchard	Imp	HEAT	5000	700	0.11689	5078	696	66	104	1528	8.15	2.341E-03	91,065
6	1	Sierra White	Imp	HEAT	4500	4000	0.03349	4515	3993	28	124	2104	1.58	7.900E-05	28,386
6	2	Sierra White	Imp	HEAT	5000	4000	0.03041	5028	3887	29	124	2137	1.43	7.347E-05	32,896
6	3	Sierra White	Imp	HEAT	5000	3500	-5E-05	5509	3570	30	124	2093	0.00	-1.157E-07	37,190
6	4	Sierra White	Imp	HEAT	6000	3500	0.03548	6017	3519	30	124	2166	1.67	9.502E-05	41,229
6	5	Sierra White	Imp	HEAT	6000	3500	0.06075	6503	3599	31	124	2250	2.13	1.184E-04	45,063
6	6	Sierra White	Imp	HEAT	7000	3000	0.07724	7021	3232	35	124	2335	2.72	1.682E-04	56,382
6	7	Sierra White	Imp	HEAT	7500	2000	0.07294	7528	2027	37	124	2353	3.48	3.428E-04	63,772
6	8	Sierra White	Imp	HEAT	8000	2000	0.06791	8015	2175	36	124	2337	3.05	2.800E-04	64,707
6	9	Sierra White	Imp	HEAT	6000	3000	-0.0021	6006	3017	30	114	1947	-0.10	-6.596E-06	44,853
6	10	Sierra White	Imp	HEAT	6500	2000	0.03344	6521	1925	30	114	2004	1.60	1.658E-04	49,032
6	11	Sierra White	Imp	HEAT	7000	2500	0.02796	7027	2483	31	114	1986	1.32	1.060E-04	53,892
6	12	Sierra White	Imp	HEAT	7500	2000	0.02296	7519	1840	32	114	1937	1.07	1.165E-04	59,883
6	13	Sierra White	Imp	HEAT	6000	2500	4E-06	6011	2519	31	114	1867	0.00	1.043E-08	45,530
6	14	Sierra White	Imp	HEAT	7000	2000	0.03982	7012	2223	31	114	1998	0.97	8.732E-05	53,221
6	15	Sierra White	Imp	HEAT	6500	2000	0.0339	6519	2159	30	114	2000	0.95	8.823E-05	48,457
6	16	Sierra White	Imp	HEAT	3500	3000	0.03233	3385	3150	24	114	1420	1.43	9.106E-05	19,929
6	17	Sierra White	Imp	HEAT	4000	2500	0.02399	3996	2744	25	114	1387	0.99	7.236E-05	24,937
6	18	Sierra White	Imp	HEAT	4500	2500	0.00058	4549	2402	27	114	1343	0.02	1.895E-06	30,395
6	19	Sierra White	Imp	HEAT	5500	1500	0.02302	5512	1470	29	114	1284	0.73	9.942E-05	39,415
7	1	Crab Orchard	TSP	Standard	500	1500	0.00727	495	1578	52	113	624	0.64	8.171E-05	6,486
7	2	Crab Orchard	TSP	Standard	900	2500	0.20578	881	2727	61	120	1080	17.93	1.315E-03	12,689
7	3	Crab Orchard	TSP	Standard	600	2000	0.19014	663	2232	59	106	882	12.87	1.154E-03	10,478
7	4	Crab Orchard	TSP	Standard	800	2000	0.08667	822	1783	54	92	655	7.58	8.497E-04	13,475
7	5	Crab Orchard	TSP	Standard	1500	2000	0.16305	1495	2114	62	120	859	12.62	1.194E-03	21,711

Table B-4. Summary test data for all tests using mud turbine motors. All tests were performed with water as a drilling fluid (continued). (Abbreviations used in the table are listed in expanded form at the bottom of the table.)

Test Number	Trial Number	Rock	Bit	Turbine	Target WOB lb	Target Rotary Speed rpm	Depth Interval in	Weight on Bit lb	Rotary Speed rpm	Bit Torque ft-lb	Flow Rate gpm	Total Δ Press psi	Penetration Rate ft/hr	Penetration Rate in/rev	Mechanical Specific Energy psi
7	6	Crab Orchard	TSP	Standard	1500	2500	0.26025	1461	2423	45	120	944	13.77	1.137E-03	15,333
7	7	Crab Orchard	TSP	Standard	1500	2000	0.16256	1487	1983	33	111	825	14.05	1.416E-03	12,375
7	8	Crab Orchard	TSP	Standard	1500	1500	0.08133	1540	1586	33	92	583	7.06	8.900E-04	15,304
7	9	Crab Orchard	TSP	Standard	2500	2000	0.26383	2321	1911	44	119	892	12.77	1.336E-03	24,351
8	1	Sierra White	TSP	Standard	500	1500	0.00549	517	1557	17	121	629	0.52	6.687E-05	2,085
8	2	Sierra White	TSP	Standard	800	2000	0.11478	795	1770	25	122	826	10.91	1.233E-03	4,643
8	3	Sierra White	TSP	Standard	800	1500	0.13965	810	1628	19	114	724	10.00	1.228E-03	3,731
8	4	Sierra White	TSP	Standard	800	1500	0.03489	861	1268	17	97	587	2.25	3.555E-04	4,339
8	5	Sierra White	TSP	Standard	800	1000	0.02424	856	1219	15	99	576	2.19	3.586E-04	3,676
8	6	Sierra White	TSP	Standard	1500	1500	0.09527	1512	1609	24	122	827	6.63	8.239E-04	8,364
8	7	Sierra White	TSP	Standard	1500	1500	0.03612	1550	1075	35	114	708	2.80	5.199E-04	13,414
8	8	Sierra White	TSP	Standard	2500	2500	0.01052	2340	323	64	123	766	0.66	4.063E-04	34,441
8	9	Sierra White	TSP	Standard	1500	1500	0.09021	1506	1533	54	122	812	7.89	1.029E-03	18,840
8	10	Sierra White	TSP	Standard	2500	2500	0.00296	2319	337	47	122	773	0.26	1.528E-04	24,845

WOB-weight on bit, Press-pressure, HP-horsepower, HSI-horsepower across the bit per square inch of bit face, Pen-penetration, Sierra White granite, Crab Orchard sandstone, TSP-thermally stabilized polycrystalline diamond compact bit (PDC), Imp-impregnated bit, HEAT-High Energy Advanced Turbodrill.

Table B-5. Summary test data for all tests using the high speed drilling test stand. All tests were performed in Colton sandstone with water as a drilling fluid. (Abbreviations used in the table are listed in expanded form at the bottom of the table.)

Test	Trial	Bit	Target WOB lb	Target Rotary Speed rpm	Depth Interval in	Weight on Bit lb	Rotary Speed rpm	Torque ft-lb	Flow Rate gpm	Bit Δ Press psi	Bit HP Hp	HSI Hp/in^2	Rate of Penetration ft/hr	Rate of Penetration in/rev	Specific Energy psi
3	1	Hyb	100	1000	1.2846	144	1025	9.49	25.9	24.1	0.36	0.027	2.478	4.834E-04	110,771
3	2	Hyb	400	1000	1.2978	402	1003	17.25	25.8	23.9	0.36	0.027	11.565	2.306E-03	42,231
4	1	Hyb	300	600	1.0186	307	634	5.86	26.1	17.3	0.26	0.020	4.301	1.357E-03	24,375
4	2	Hyb	300	1000	0.9347	288	1086	6.74	26.2	17.4	0.27	0.020	7.261	1.337E-03	28,454
4	3	Hyb	500	1000	1.6157	477	1097	15.53	26.4	24.1	0.37	0.028	18.681	3.405E-03	25,767
5	1	Hyb	200	750	0.3362	202	758	4.80	26.5	23.5	0.36	0.027	3.234	8.531E-04	31,791
5	2	Hyb	200	1000	0.0787	208	1034	5.65	26.2	23.6	0.36	0.027	3.962	7.661E-04	41,647
5	3	Hyb	750	1000	3.6292	679	1045	19.09	26.4	23.8	0.37	0.027	31.034	5.938E-03	18,191
6	1	Hyb	300	600	0.2851	307	628	2.69	26.0	20.0	0.30	0.023	3.980	1.268E-03	11,975
6	2	Hyb	300	2500	0.9772	276	2529	4.02	25.8	21.1	0.32	0.024	11.602	9.175E-04	24,728
6	3	Hyb	500	2500	2.0109	488	2519	7.28	25.8	20.5	0.31	0.023	34.137	2.710E-03	15,199
7	1	Hyb	200	750	0.2473	237	764	2.99	26.2	30.0	0.46	0.034	2.729	7.146E-04	23,600
7	2	Hyb	750	2500	3.0308	713	2497	14.27	26.2	30.8	0.47	0.035	43.613	3.493E-03	23,099
8	1	Hyb	200	750	0.2629	189	810	5.74	25.6	22.2	0.33	0.025	1.568	3.873E-04	83,628
8	2	Hyb	300	750	0.0806	263	808	6.56	25.6	22.0	0.33	0.025	2.526	6.250E-04	59,238
8	3	Hyb	300	4000	1.2962	268	3999	8.92	25.7	23.6	0.35	0.026	12.401	6.201E-04	81,137
8	4	Hyb	400	4000	1.8459	359	3981	9.96	25.4	23.3	0.34	0.026	22.669	1.139E-03	49,377
9	1	Hyb	200	750	0.2578	193	812	4.58	26.4	24.2	0.37	0.028	1.397	3.441E-04	75,146
9	2	Hyb	200	4000	0.0503	185	4090	8.14	25.9	25.6	0.39	0.029	4.362	2.133E-04	215,254
9	3	Hyb	500	4000	0.5516	523	4051	10.81	26.1	25.8	0.39	0.029	17.178	8.481E-04	71,973
10	1	Hyb	300	750	0.2865	258	755	2.74	26.1	12.7	0.19	0.014	1.636	4.334E-04	35,725
10	2	Hyb	200	5500	0.0188	234	5487	7.46	25.6	15.5	0.23	0.017	4.505	1.642E-04	256,395
10	3	Hyb	200	4500	0.0815	238	4550	5.51	26.6	14.9	0.23	0.017	3.925	1.726E-04	180,216
10	4	Hyb	500	4000	1.2512	536	4160	7.52	26.2	14.5	0.22	0.017	14.899	7.162E-04	59,249
10	5	Hyb	750	4000	1.3802	698	4145	12.28	26.1	14.1	0.21	0.016	30.720	1.482E-03	46,782
11	1	Hyb	200	750	0.2636	194	755	5.97	7.7	25.4	0.11	0.009	1.555	4.119E-04	81,767

Table B-5. Summary test data for all tests using the high speed drilling test stand. All tests were performed in Colton sandstone with water as a drilling fluid (continued). (Abbreviations used in the table are listed in expanded form at the bottom of the table.)

Test	Trial	Bit	Target WOB lb	Target Rotary Speed rpm	Depth Interval in	Weight on Bit lb	Rotary Speed rpm	Torque ft-lb	Flow Rate gpm	Bit Δ Press psi	Bit HP Hp	HSI Hp/in^2	Rate of Penetration ft/hr	Rate of Penetration in/rev	Specific Energy psi
11	2	Hyb	1000	1000	2.6626	904	1052	8.91	7.6	25.6	0.11	0.009	13.755	2.615E-03	19,301
12	1	Hyb	200	750	0.2545	219	841	7.32	7.6	23.7	0.10	0.008	1.377	3.273E-04	126,257
12	2	Hyb	200	5000	0.0590	188	5166	12.57	7.6	28.3	0.12	0.009	2.908	1.126E-04	629,782
12	3	Hyb	1000	2500	2.7625	936	2657	19.90	7.6	24.8	0.11	0.008	27.410	2.064E-03	54,470
13	1	Hyb	200	750	0.1812	166	770	4.56	7.8	24.8	0.11	0.008	1.013	2.632E-04	97,741
13	2	Hyb	200	1500	0.0288	151	1528	5.10	7.8	25.3	0.12	0.009	1.380	1.806E-04	159,257
13	3	Hyb	1000	4000	3.1376	920	3949	15.56	7.8	27.3	0.12	0.009	25.684	1.301E-03	67,542
14	1	Imp	200	750	0.1796	209	702	5.20	25.8	26.3	0.40	0.030	0.330	9.395E-05	312,258
14	2	Imp	300	750	0.1304	276	703	5.52	25.8	26.0	0.39	0.029	0.221	6.282E-05	495,447
14	3	Imp	300	1000	0.1178	276	897	5.78	25.7	26.2	0.39	0.029	0.186	4.146E-05	786,103
14	4	Imp	300	1000	0.0082	296	978	6.12	25.8	26.3	0.40	0.030	0.171	3.491E-05	989,510
14	5	Imp	300	1000	0.2136	301	1062	5.83	25.8	26.9	0.40	0.030	0.093	1.760E-05	1,868,309
14	6	Imp	500	1000	0.2370	496	1061	7.66	25.8	28.0	0.42	0.032	0.116	2.184E-05	1,977,115
14	7	Imp	750	1000	0.3419	703	1061	9.83	25.8	28.9	0.43	0.033	0.077	1.449E-05	3,820,850
14	8	Imp	1000	1000	0.0749	1004	1061	10.60	25.8	29.5	0.44	0.033	0.097	1.824E-05	3,271,436
14	9	Imp	1000	1000	0.0148	994	1061	10.27	25.9	29.9	0.45	0.034	0.054	1.011E-05	5,738,030
14	10	Imp	300	1100	0.0047	282	1141	0.33	25.9	30.0	0.45	0.034	0.009	1.511E-06	1,238,039
14	11	Imp	300	1000	0.0004	283	985	0.20	26.1	30.1	0.46	0.034	0.002	4.139E-07	2,903,818
14	12	Imp	300	2500	0.0034	281	2461	3.78	25.7	31.2	0.47	0.035	0.014	1.172E-06	18,199,252
14	13	Imp	500	1100	0.0073	491	1085	0.66	25.9	31.2	0.47	0.035	0.021	3.823E-06	969,815
14	14	Imp	500	2500	0.0047	486	2505	2.89	26.1	31.5	0.48	0.036	0.082	6.507E-06	2,505,886
14	15	Imp	500	4000	0.0908	485	3964	6.46	25.8	33.6	0.51	0.038	0.510	2.569E-05	1,416,565
14	16	Imp	750	1000	0.0170	748	1070	-0.21	25.7	32.3	0.48	0.036	0.096	1.796E-05	-65,088
14	17	Imp	750	2500	0.0551	747	2552	2.68	25.9	32.6	0.49	0.037	0.281	2.201E-05	686,116
14	18	Imp	750	4000	0.1914	747	3962	6.96	25.8	34.2	0.52	0.039	1.119	5.653E-05	694,673
14	19	Imp	750	2100	0.0005	748	2143	1.54	25.7	32.5	0.49	0.036	0.062	5.784E-06	1,496,820
14	20	Imp	750	1100	0.0076	751	1124	-0.42	25.9	32.2	0.49	0.036	0.014	2.440E-06	-976,056
14	21	Imp	1000	1100	0.0185	989	1123	1.16	25.9	32.3	0.49	0.036	0.093	1.655E-05	396,760
14	22	Imp	1000	2500	0.2905	988	2481	6.80	26.0	32.7	0.49	0.037	0.256	2.060E-05	1,860,706
14	23	Imp	1000	4000	0.0660	990	3937	7.55	26.0	35.0	0.53	0.040	0.326	1.656E-05	2,571,542

Table B-5. Summary test data for all tests using the high speed drilling test stand. All tests were performed in Colton sandstone with water as a drilling fluid (continued). (Abbreviations used in the table are listed in expanded form at the bottom of the table.)

Test	**Trial**	**Bit**	**Target WOB lb**	**Target Rotary Speed rpm**	**Depth Interval in**	**Weight on Bit lb**	**Rotary Speed rpm**	**Torque ft-lb**	**Flow Rate gpm**	**Bit Δ Press psi**	**Bit HP Hp**	**HSI Hp/in^2**	**Rate of Penetration ft/hr**	**Rate of Penetration in/rev**	**Specific Energy psi**
14	24	Imp	1000	1000	0.0071	992	1016	-0.01	26.0	33.4	0.51	0.038	0.008	1.631E-06	-27,668
14	25	Imp	1000	1000	0.1205	1021	1049	-0.16	26.1	33.5	0.51	0.038	0.783	1.494E-04	-5,999
14	26	Imp	1000	2500	0.1290	1016	2543	3.95	25.9	34.4	0.52	0.039	1.762	1.386E-04	160,896
14	27	Imp	1000	4000	0.6300	1012	4049	5.75	26.1	36.3	0.55	0.041	2.118	1.046E-04	310,145
14	28	Imp	400	1000	0.0083	392	1095	0.10	26.0	33.8	0.51	0.038	0.042	7.725E-06	70,295
14	29	Imp	750	1000	0.0420	791	1095	0.28	26.1	33.9	0.52	0.039	0.330	6.028E-05	26,129
14	30	Imp	750	2500	0.2081	790	2509	3.61	26.1	34.9	0.53	0.040	0.592	4.721E-05	431,456
14	31	Imp	750	4000	0.3687	780	3510	4.85	26.1	36.1	0.55	0.041	0.644	3.803E-05	744,558
15	1	Imp	300	1100	0.0083	311	1149	2.12	25.9	29.7	0.45	0.034	0.020	3.569E-06	3,345,428
15	2	Imp	500	1100	0.0213	509	1148	2.11	25.8	29.8	0.45	0.034	0.103	1.791E-05	664,175
15	3	Imp	500	1250	0.0124	492	1255	1.98	25.8	29.8	0.45	0.034	0.114	1.819E-05	614,639
15	4	Imp	750	1250	0.1126	742	1252	2.79	25.9	29.8	0.45	0.034	0.311	4.974E-05	316,414
15	5	Imp	1000	1250	0.1619	995	1250	5.08	25.9	29.9	0.45	0.034	0.625	1.001E-04	286,577
15	6	Imp	300	2500	0.0331	334	2558	3.19	25.8	30.9	0.46	0.035	0.086	6.696E-06	2,683,979
15	7	Imp	500	2500	0.0868	503	2542	3.52	25.8	31.1	0.47	0.035	0.241	1.894E-05	1,048,326
15	8	Imp	750	2500	0.1728	727	2557	3.35	25.9	31.6	0.48	0.036	0.544	4.255E-05	444,048
15	9	Imp	1000	2500	0.2944	941	2585	3.58	25.8	31.8	0.48	0.036	0.945	7.308E-05	276,318
15	10	Imp	300	4000	0.0525	326	3945	-0.11	25.8	33.6	0.51	0.038	0.141	7.139E-06	-90,772
15	11	Imp	500	4000	0.0726	485	3932	1.05	25.7	33.8	0.51	0.038	0.230	1.168E-05	506,575
15	12	Imp	750	4000	0.2344	737	3926	2.98	25.8	34.0	0.51	0.038	0.614	3.128E-05	537,383
15	13	Imp	1000	4000	0.4416	1063	3921	3.79	25.8	34.3	0.52	0.039	1.237	6.310E-05	339,243
16	1	PDC	100	600	0.2165	117	588	0.70	25.6	21.8	0.33	0.024	4.717	1.609E-03	2,488
16	2	PDC	200	600	1.1225	219	601	2.74	25.7	21.6	0.32	0.024	4.773	1.607E-03	9,756
16	3	PDC	200	1000	1.2264	232	993	4.54	25.6	22.5	0.34	0.025	7.528	1.518E-03	16,912
16	4	PDC	500	1000	1.4205	454	1016	10.98	25.7	22.6	0.34	0.025	23.720	4.754E-03	13,302

WOB-weight on bit, Press-pressure, HP-horsepower, HSI-horsepower across the bit per square inch of bit face, Pen-penetration, Hyb-hybrid natural diamond and thermally stabilized polycrystalline diamond compact bit, Imp-impregnated bit, PDC-polycrystalline diamond compact bit.

ABBREVIATIONS

HSI –. bit hydraulic horsepower per square inch

LVDT – linear variable displacement transducer

MSE – mechanical specific energy

PDC –polycrystalline diamond compact

ROP – rate of penetration

TSP – thermally stable PDC

UHSDD – Ultra-High-Speed Diamond Drilling

WOB – weight on bit

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