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

Phase I Final Report

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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 details the progress at the end of Phase 1 on the program entitled "Smaller Footprint Drilling System for Deep and Hard Rock Environments: Feasibility of Ultra-High-Speed Diamond Drilling" for the period starting 1 March 2006 and concluding 30 June 2006. (Note: Results from 1 September 2005 through 28 February 2006 were included in the previous report (see Judzis, Black, and Robertson). Summarizing the accomplished during Phase 1:

- 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). Some difficulties continued in obtaining ultra-high speed motors. 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 Task 3 "Small-scale cutting performance tests."
    - Significant testing was performed on nine different rocks.
    - Five rocks were used for the final testing. The final tests were based on statistical design of experiments.
    - Two full-faced bits, a small diameter and a large diameter, were run in Berea sandstone.
- Analysis of data was completed and indicates that there is decreased specific energy as the rotational speed increases (Task 4). Data analysis from early trials was used to direct the efforts of the final testing for Phase I (Task 5).
- Technology transfer (Task 6) was accomplished with technical presentations to the industry (see Judzis, Boucher, McCammon, and Black).

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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 have been conducted to explore trends in penetration rates and specific energy at various rotational speeds and bit loads and investigate any evidence of changes in rock removal mechanisms at varying speeds and loads.

Accomplishments

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

- TerraTek reviewed applicable literature and documentation and convened a project kick-off meeting with Industry Advisors in attendance.
- TerraTek has designed and planned Phase I bench scale experiments. Some difficulties in obtaining ultra-high speed motors for this feasibility work were encountered.
- Some improvements over early NASA experiments were identified.
- Six preliminary drilling tests were run in Berea sandstone at various rotational speeds using nitrogen as a drilling fluid.
- Tests were conducted in Berea and Colton sandstones at various rotational speeds to determining the best drilling fluid (nitrogen or water) and flow rate. Water was selected for the drilling fluid and the optimum flow rate of 0.55 gal/min determined.
- Design improvements were made in the loading mechanism and the sensor for monitoring rotational speed.
- 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.
- Once all operational and sensor issues were resolved, testing continued with more than 80 tests using Berea sandstone, Colton sandstone, Nugget sandstone, Sulurian dolomite, and Winfield anhydrite. These tests were run with a core type bit at various rotational speeds and bit loads using water as a drilling fluid.
- 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 date on the Ultra-High Speed Diamond Drilling project.
- More than 20 tests were run with full-faced drilling bits using various loads and rotational speeds.

- Statistical analysis of the data revealed a general trend to more efficient drilling as rotational speeds increased above approximately 30,000 rpm.
- Preliminary engineering and assessment of high speed motors was begun. Contact was made with four parties regarding high speed motors for Phase 2 testing.

INTRODUCTION

Objective

The objective of the first phase of this test program was to explore trends in specific energy and penetration rates with high rotation speed.

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 (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 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 ROP rock cutting with substantially lower energy and load.

This document details the progress during the last stages of Phase 1 and analytical results of Phase 1 of the UHSDD program.

Plan

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 work will provide a "scale up" to ultra high speed drilling in mining-sized drill bits.

Industry Partners

Contributions in technical expertise and research have come from ReedHycalog, Shell International, and ConocoPhillips. Additionally, Impact Technologies, Technology International, and Smith International plan on supporting Phase 2 testing.

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 the previous report. However, some improvements have been 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. The data has been summarized and is presented in table form in Appendix A.

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 has been conducted. Four companies have been contacted regarding high speed motors.

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 date on the Ultra-High Speed Diamond Drilling project. Arnis 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 A met on 19 June 2006 for a Phase 1 lessons learned presentation and discussion of test findings.

All Phase 1 tasks have been completed. Accomplishments since the March 2006 report include:

1. Statistical design of experiment was completed for the final trials.
2. The motor support housing was modified to improve cooling and motor support.
3. New test bits were obtained.
4. Full-face drill bits were acquired.
5. Bit wear was evaluated.
6. A thorough statistical analysis of all data was completed and findings determined.
7. The preliminary engineering was completed for equipment scale up.
8. A "lesson's learned" meeting was held.

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

Specific Energy 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 component and axial components (Equation 1). The rotational specific energy was calculated using the voltage across the motor, the current used by the motor, the ROP, and the area of rock removed (Equation 2). The axial component was determined using the weight on bit and the area of the rock removed (Equation 3). Reported units for specific energy are ft-lb/in^3.

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

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

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

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

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

Test Apparatus

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" x 5" x 1.5" 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 in 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 fittings attached with adhesive.

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. 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

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

Rock Type	Compressive Strength, Unconfined (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

technique. The early bits used in these tests typically had about 60 diamonds on the cutting kerf. Of these 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 more controlled to improve drilling performance. The bits were dynamically balanced at about 6,000 rpm.

The Hall Effect drive motor is no load rated for 51,000 rpm. The drill bit is 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, passed over a pulley, and then attached to a hanging rod of known mass. The rod was restricted only 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 stationary 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 by recording the number of times a black strip on a white background painted on the bit passed the sensor. The setup included the sample, fluid lines, and instruments. Measurements of the current and voltage supplied to the motor were taken.

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

- Rotational speeds (at the start of each test) were 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 was 1500, 2500, and 3500 grams for the final statistically designed trials.

Statistical Design of Experiments

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 3. 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

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.

Data Reduction and Statistics

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 A-1 in Appendix A.

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.

RESULTS AND DISCUSSION

A summary of all data obtained since the last report are presented in Tables A-1 through A-3 of Appendix A. 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 their 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 weight on bit 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 4 and 6. Similar plots for other rock types are found in Appendix B.

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 5 and 7 and the surface plots for the other rock types are in Appendix B.

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 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 4 through 7 provide examples of the specific energy and rate of penetration as the weight on bit and rotational speeds 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 4 and 5. Figures 6 and 7 provide the same graphics for rate of penetration in Berea sandstone. This 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 Appendix B.

Results of the Full-faced Bit Trials

Two sizes of full-faced bits (Figure 8) 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 full-faced trials and the calculated values for specific energy and rate of penetration are included in Table A-2 of Appendix A. The diameter of the bore through the rock is listed on the table (refer to Rock Samples section in Test Apparatus). The “Rock Bore Diameter” 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 9 through 16. There was a general increase in rate of penetration with the larger bit to approximately 25,000 rpm and then a decrease (see Figures 9 and 10). 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 11 and 12 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 13 and 14. 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 15 and 16).

CONCLUSIONS AND RECOMMENDATION

The results of test analysis for Phase 1 of UHSDD program for the coring bits indicate 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 is recommended that testing continue with the Phase 2 scale up to mining sized bits. This will provide additional data to confirm the study findings to date and will provide, with proper design for cuttings collection, an opportunity to evaluate rock failure mechanisms at high rotational speeds.

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.

FIGURES

Figure 1. Core drilling bits used for the high speed drilling tests. The one on the left was used earlier in the program and the one on the right was designed for consistency of diamond placement. Two of these bits were used in the final statistically designed and analyzed trials.

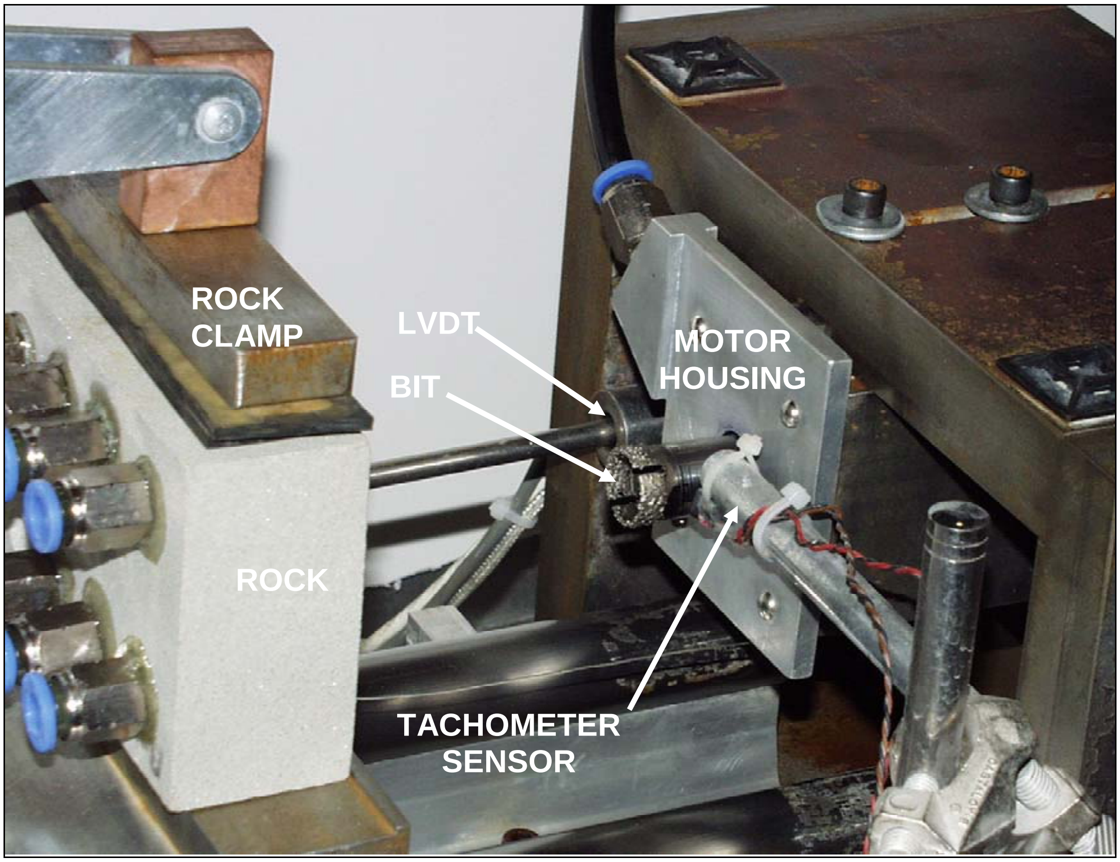

Figure 2. Photograph of the high speed drilling test setup.

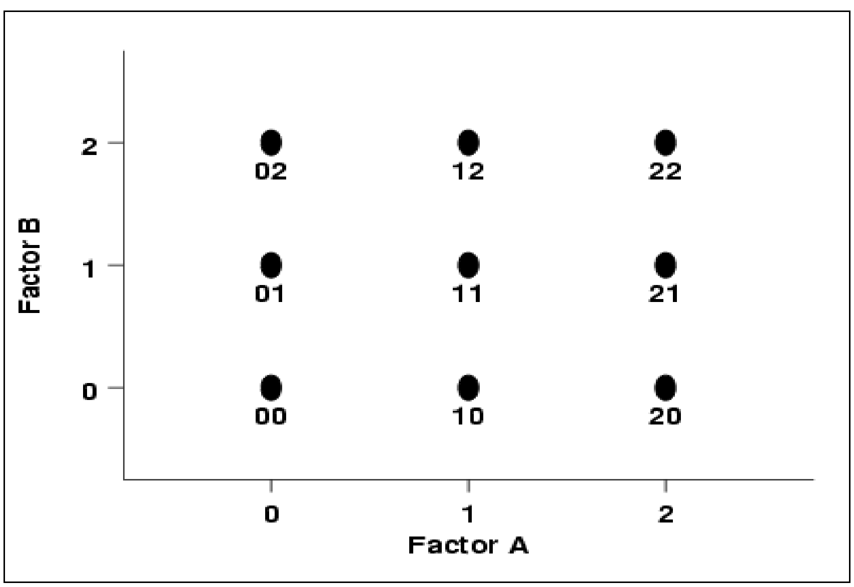

Figure 3. Two factor central composite design used in designing tests. Factor A was typically rotational speed and Factor B the weight on bit.

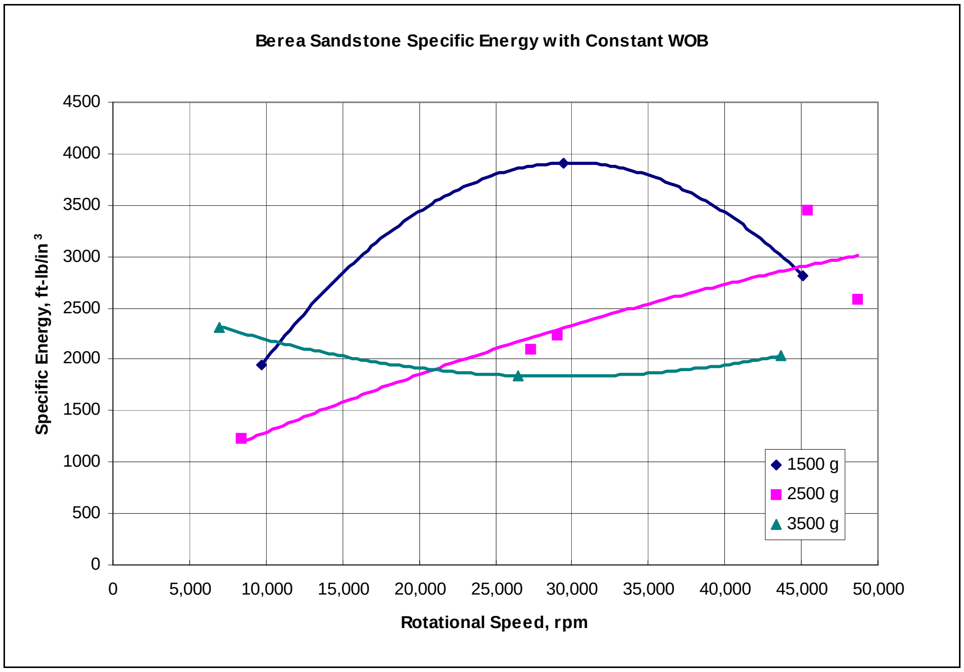

Figure 4. Specific Energy data plot for Berea Sandstone. Each line of the plot represents a specific weight on bit.

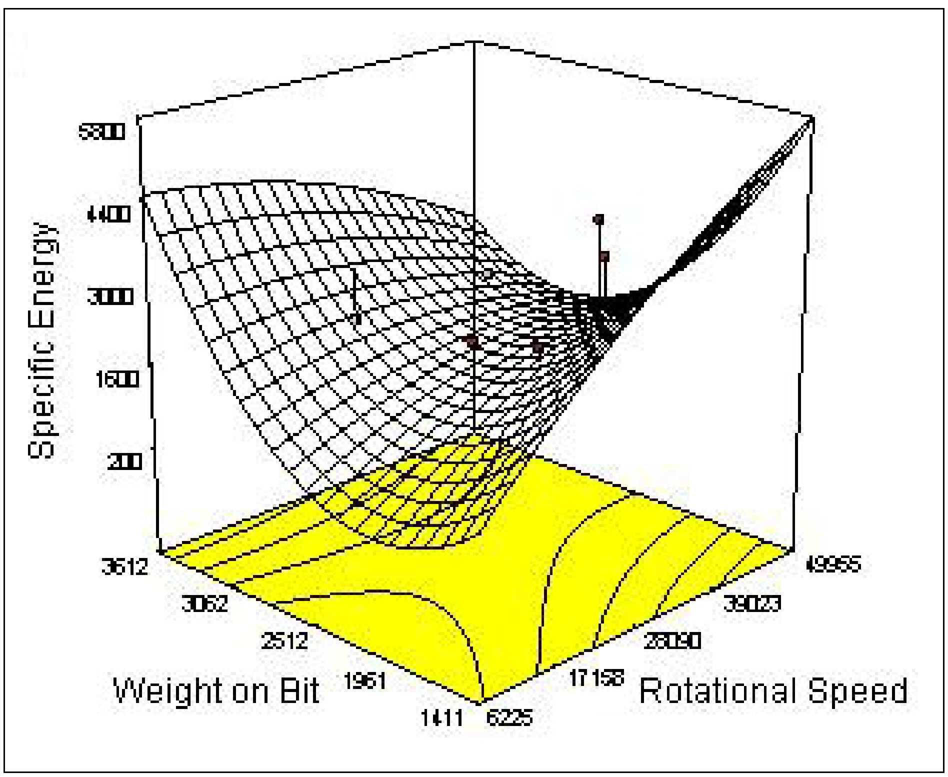

Figure 5. Specific Energy results in a response surface plot for Berea sandstone trials.

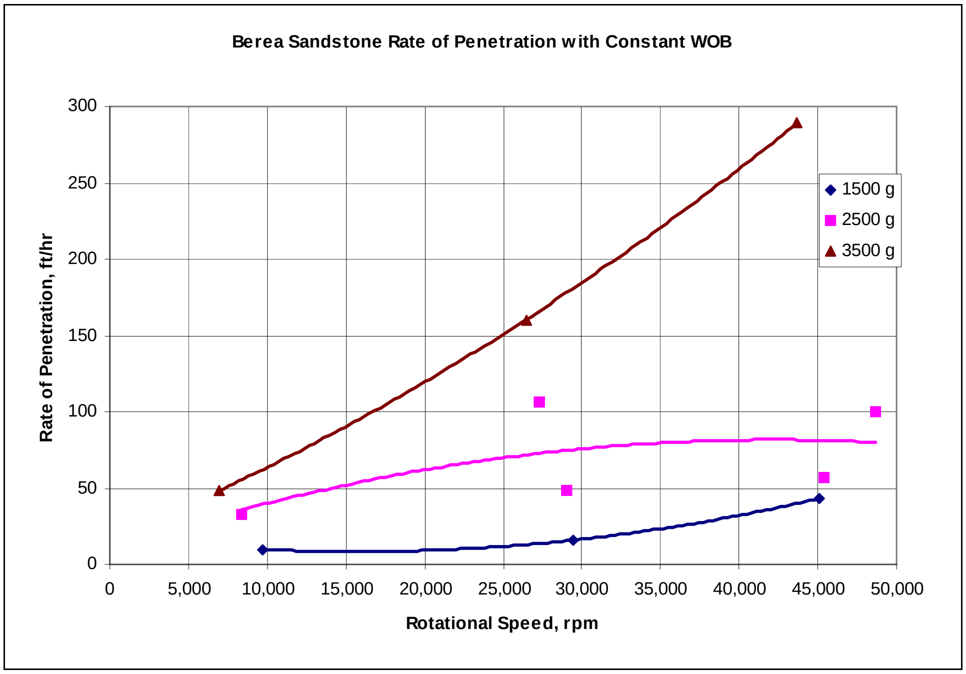

Figure 6. Rate of penetration results are graphed for Berea Sandstone trials. Each line of the plot is for a specific weight on bit.

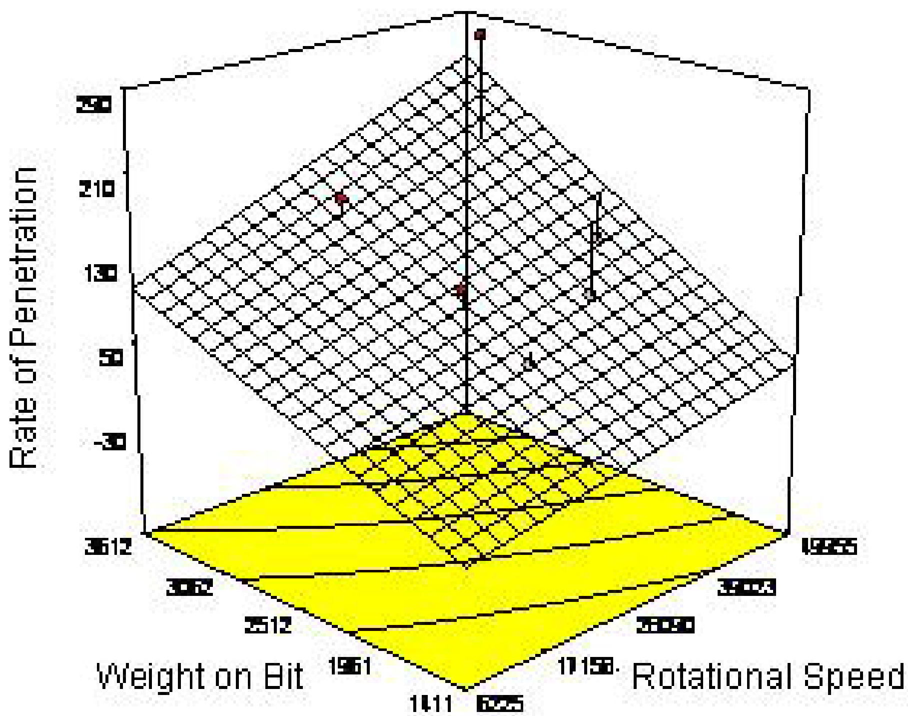

Figure 7. Rate of penetration results are shown using a response surface plot for Berea Sandstone.

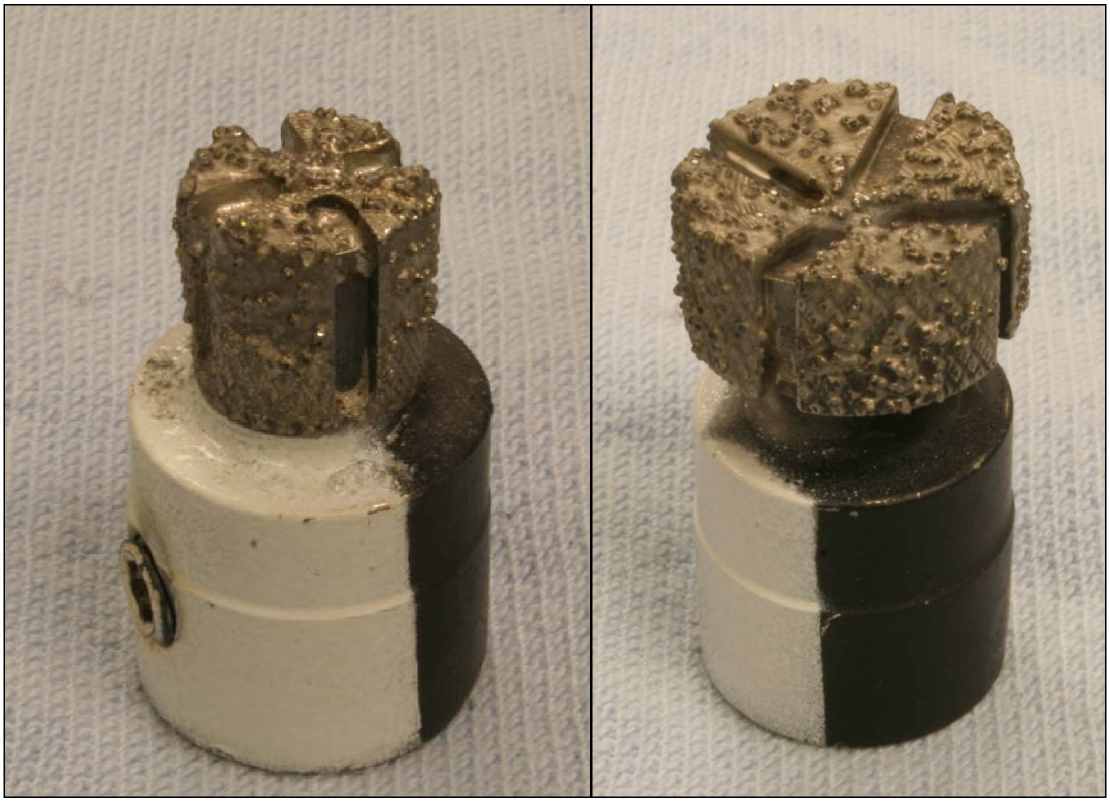

Figure 8. Small and large full-faced drill bits used in the UHSDD.

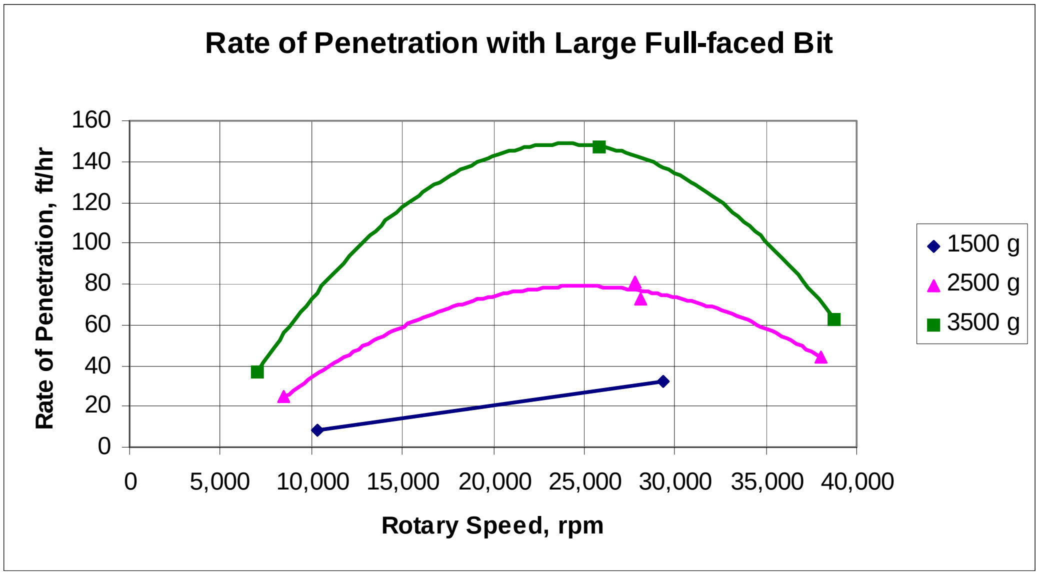

Figure 9. Rate of Penetration data plot for the large full-faced drill bit.

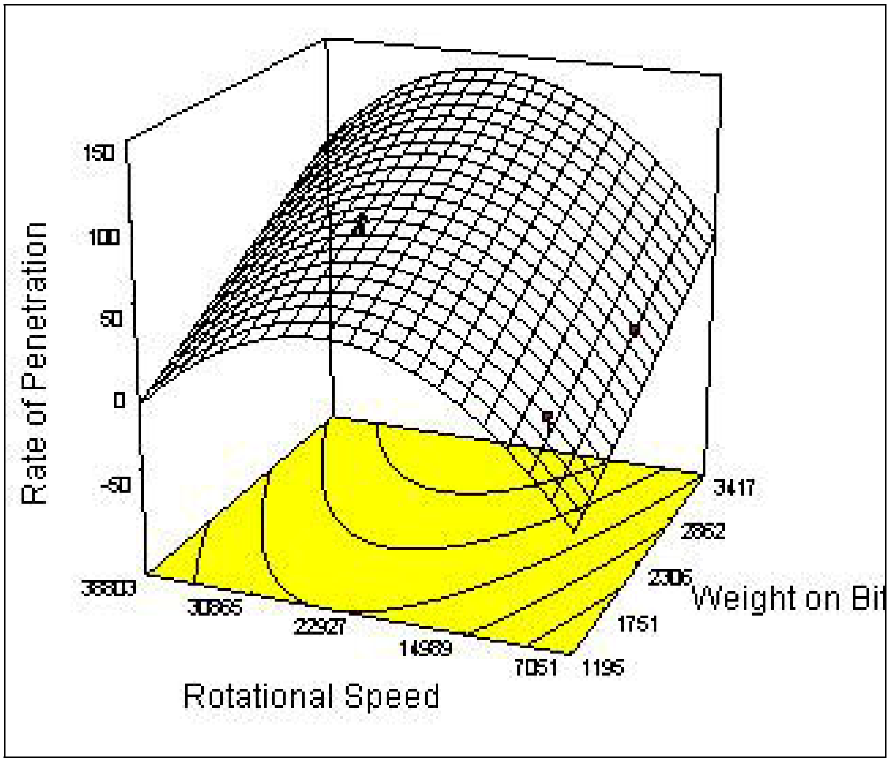

Figure 10. Response surface plot of the rate of penetration data when using the large full-faced drill bit.

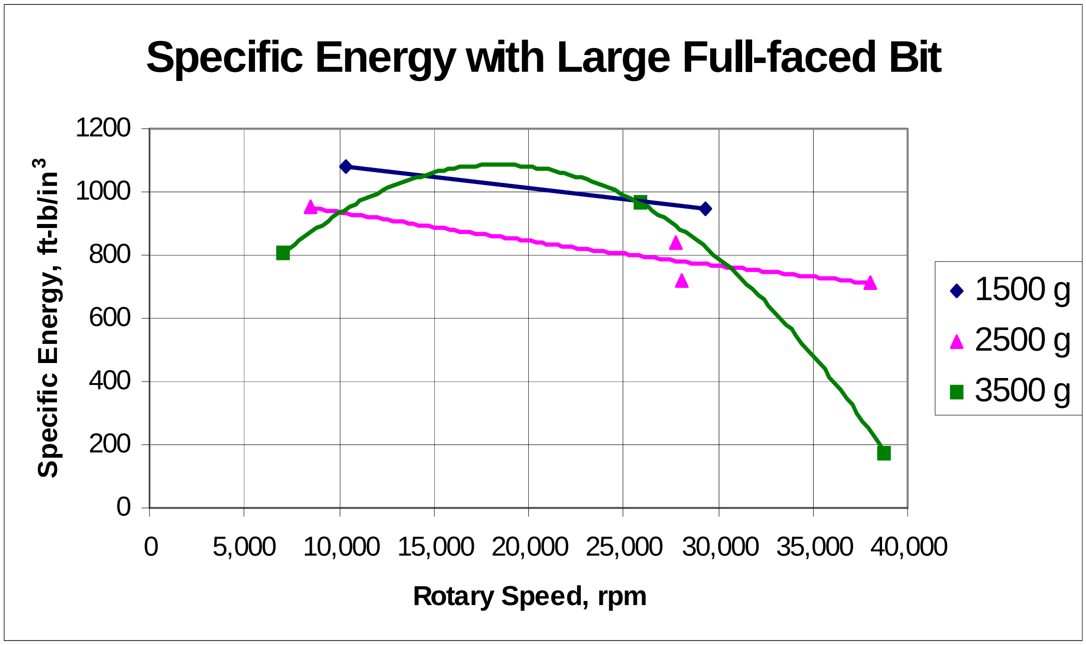

Figure 11. Large full-faced bit specific energy plots with the weight on bit held constant.

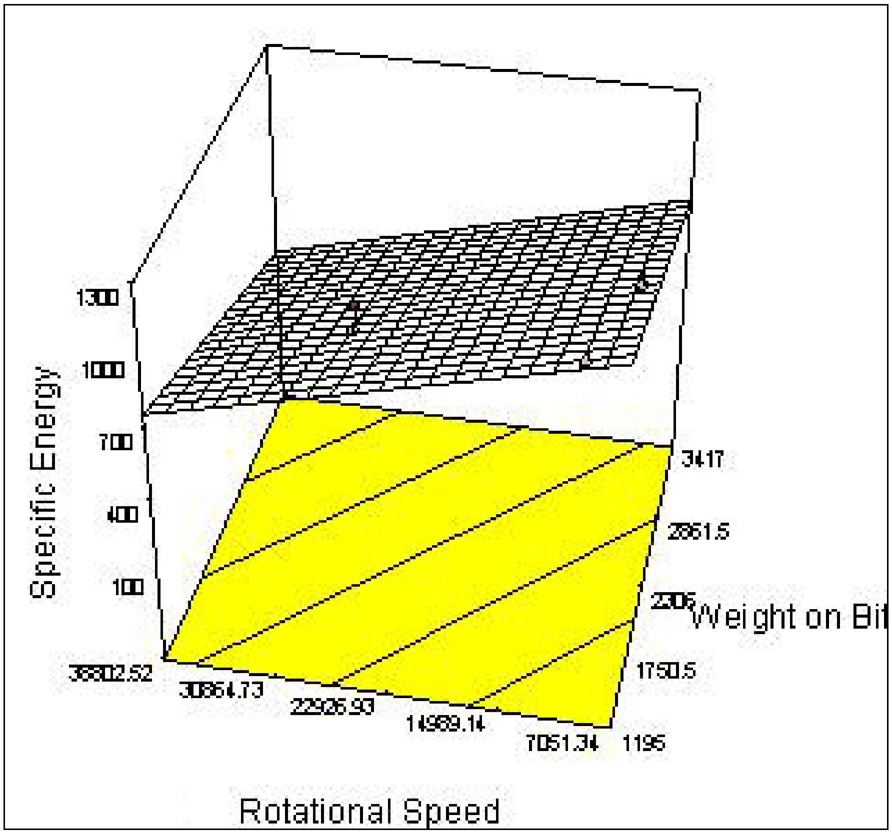

Figure 12. Specific energy response surface plot of data from the large full-faced bit.

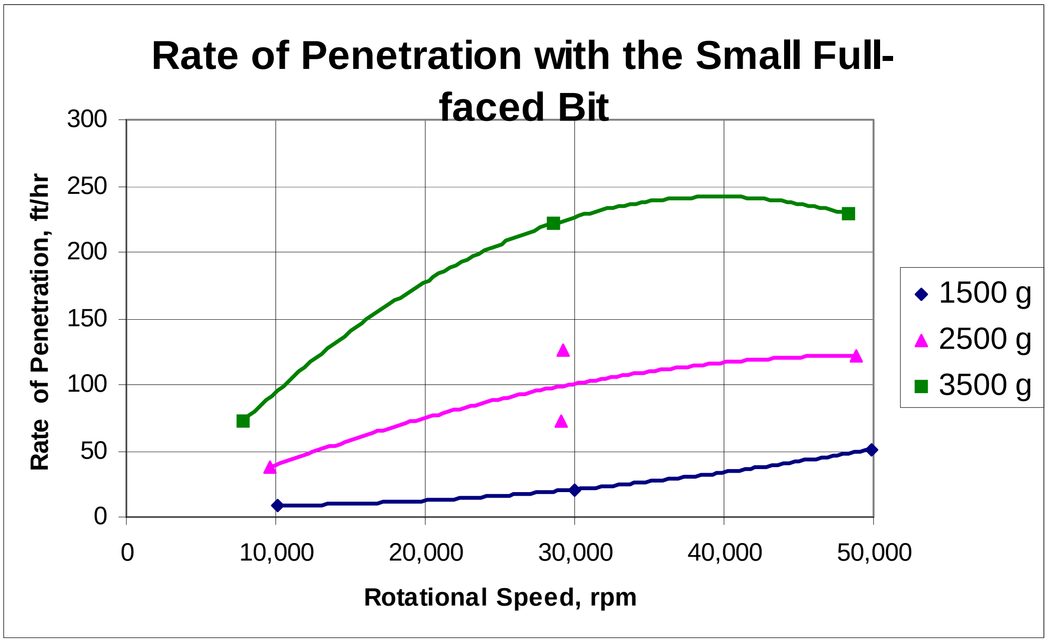

Figure 13. Small full-faced bit rate of penetration results are shown with the weight on bit held constant.

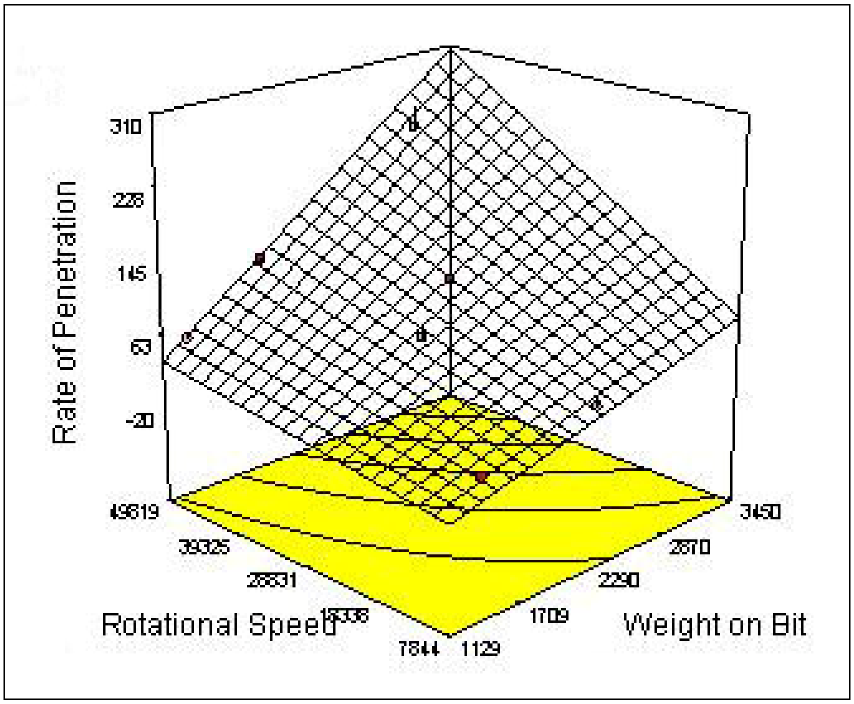

Figure 14. Response surface plot of the rate of penetration data from the small full-faced drill bit.

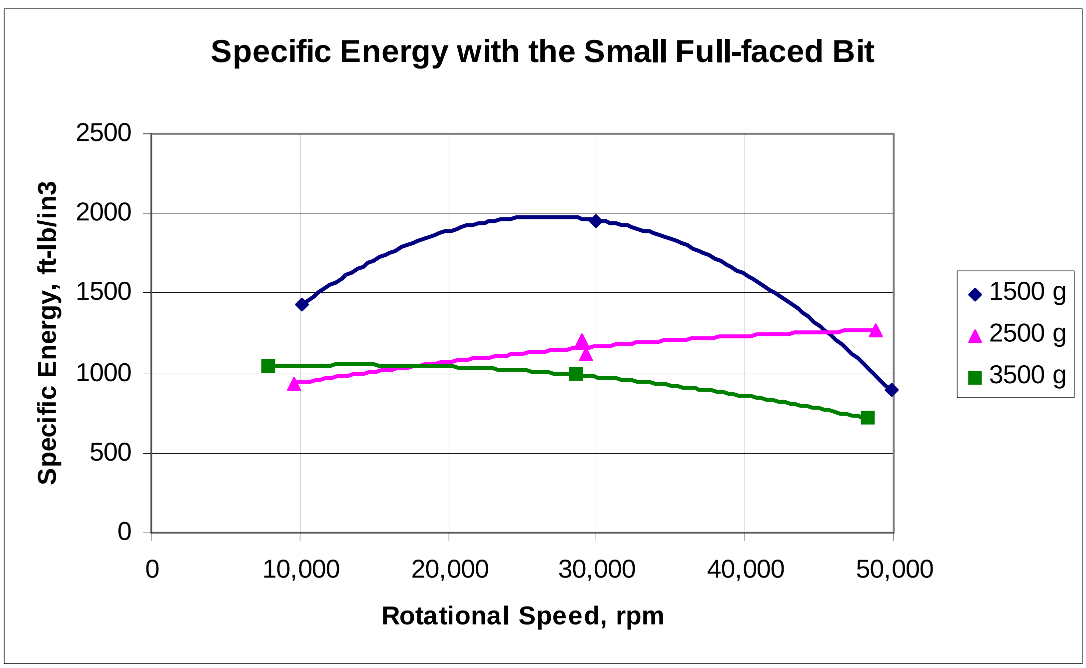

Figure 15. Specific energy plot of data from the small full-faced drill bit.

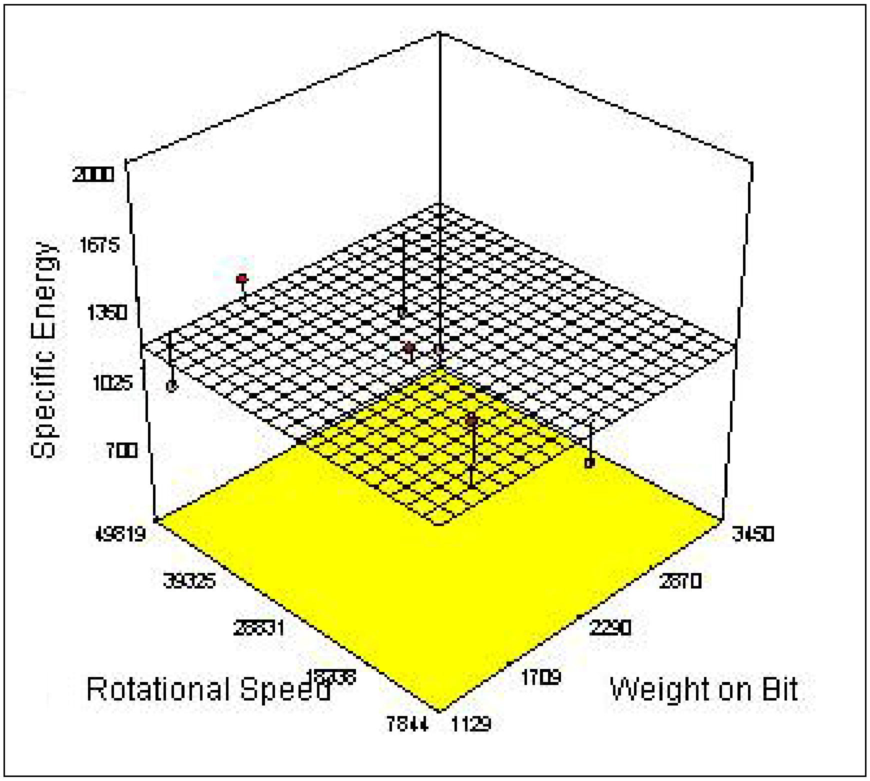

Figure 16. Response surface plot of the specific energy from the small full-faced drill bit data.

APPENDIX A
Tables of Drilling Parameters and Results

List of Tables

Table A-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 A-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 A-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/in3)	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 A-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 A-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

APPENDIX B
Graphs of Core Bit Results

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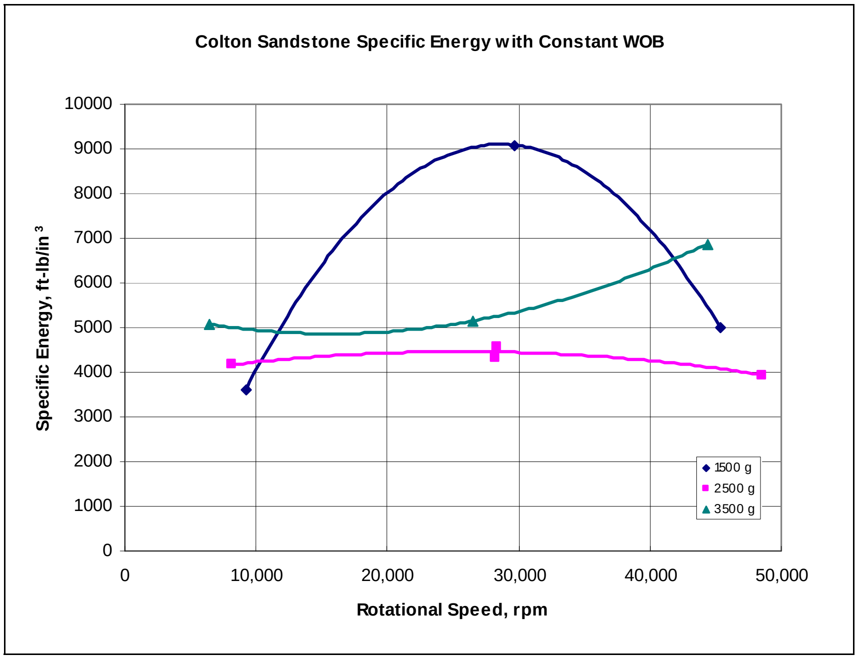


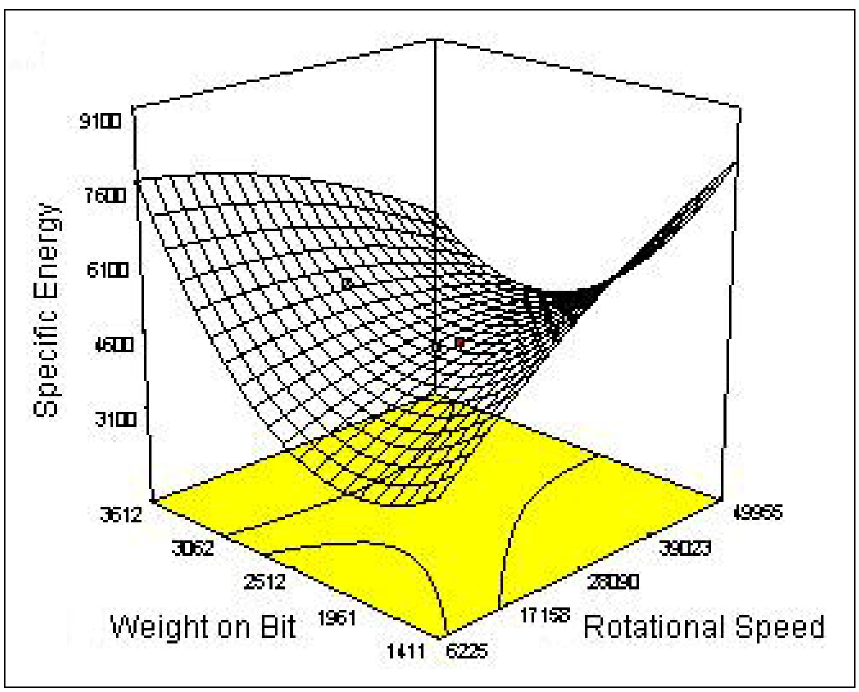


Figure B-1. Specific energy graph and response surface plot for Colton sandstone at various rotational speeds and weights on bit.

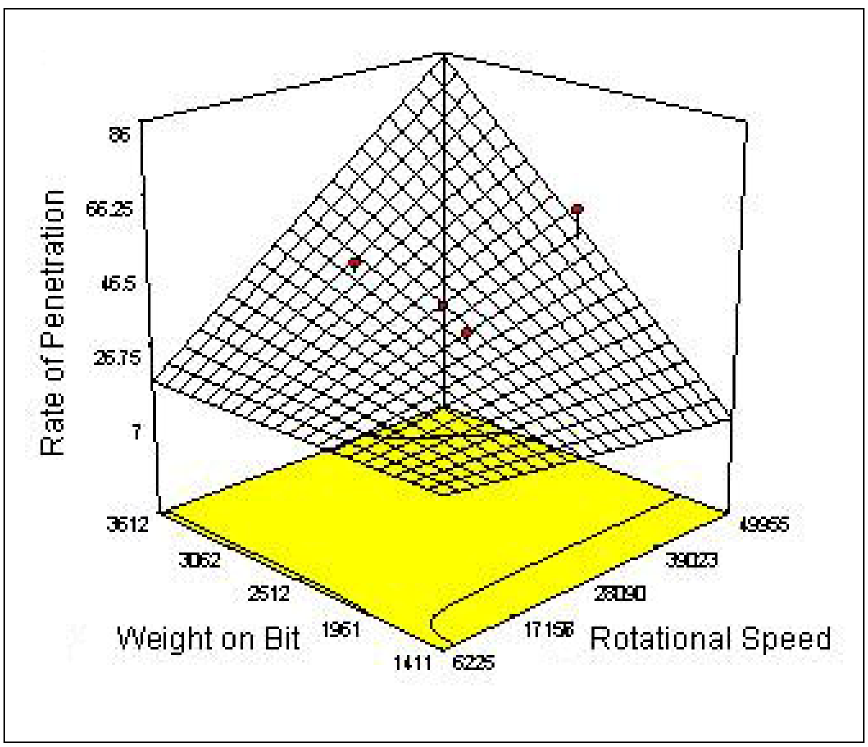
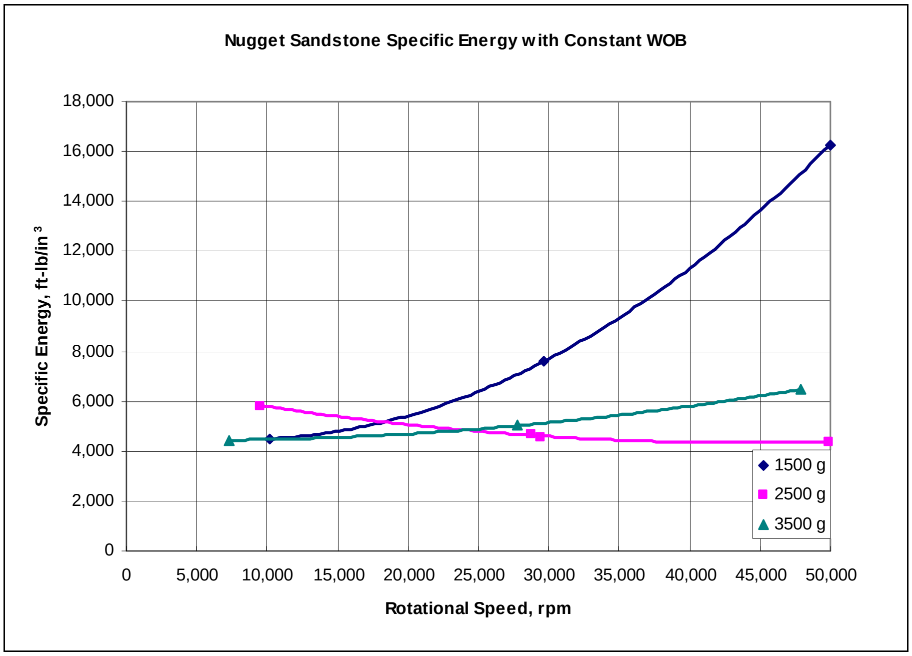


Figure B-2. Rate of penetration graph and response surface plot for Colton sandstone at various rotational speeds and weights on bit.



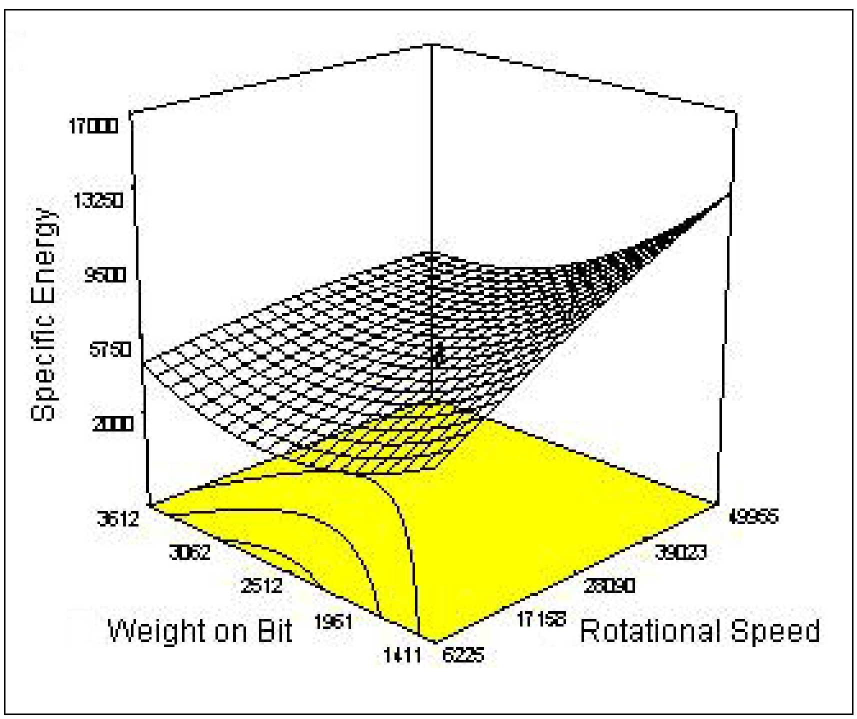
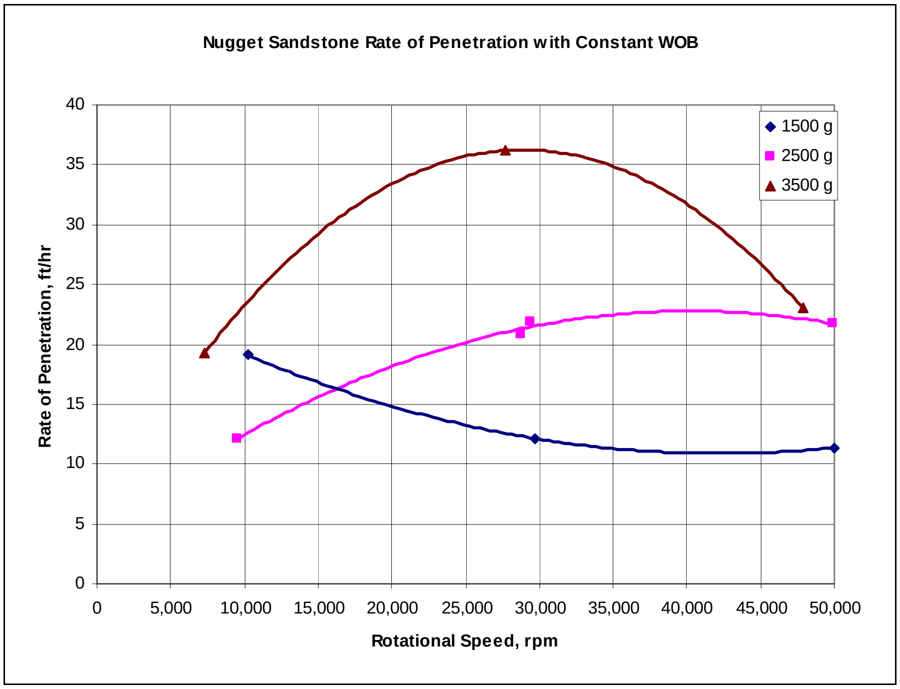


Figure B-3. Specific energy graph and response surface plot for Nugget sandstone at various rotational speeds and weights on bit.



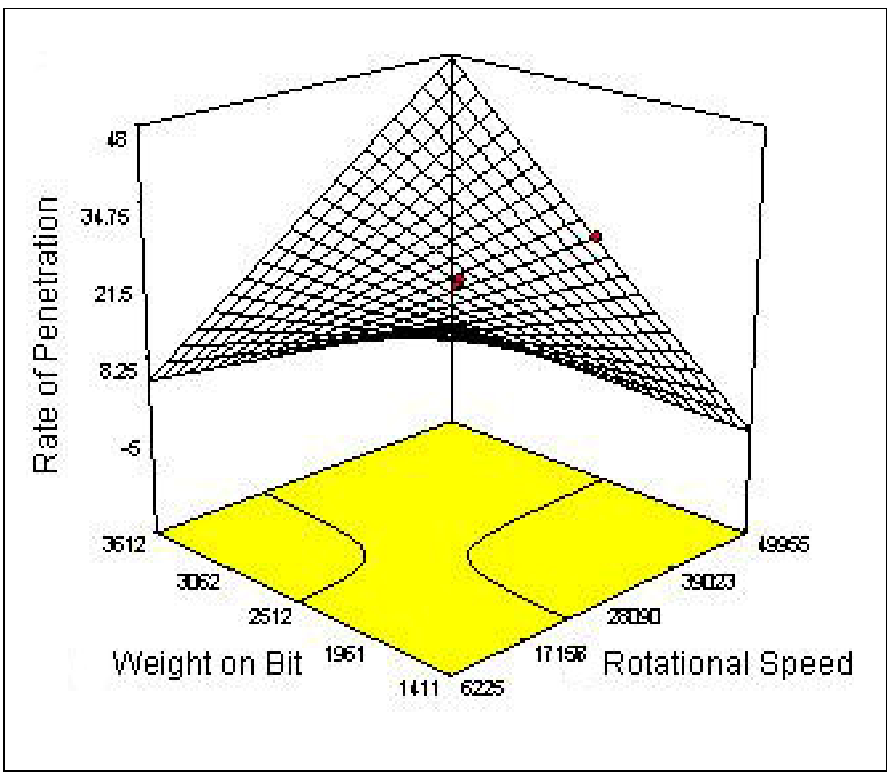
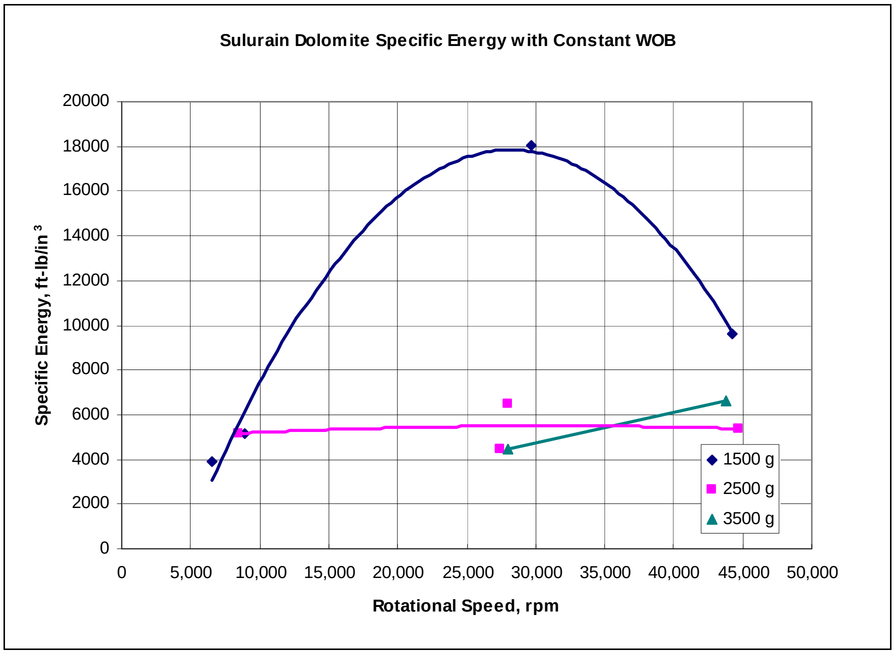


Figure B-4. Rate of penetration graph and response surface plot for Nugget sandstone at various rotational speeds and weights on bit.



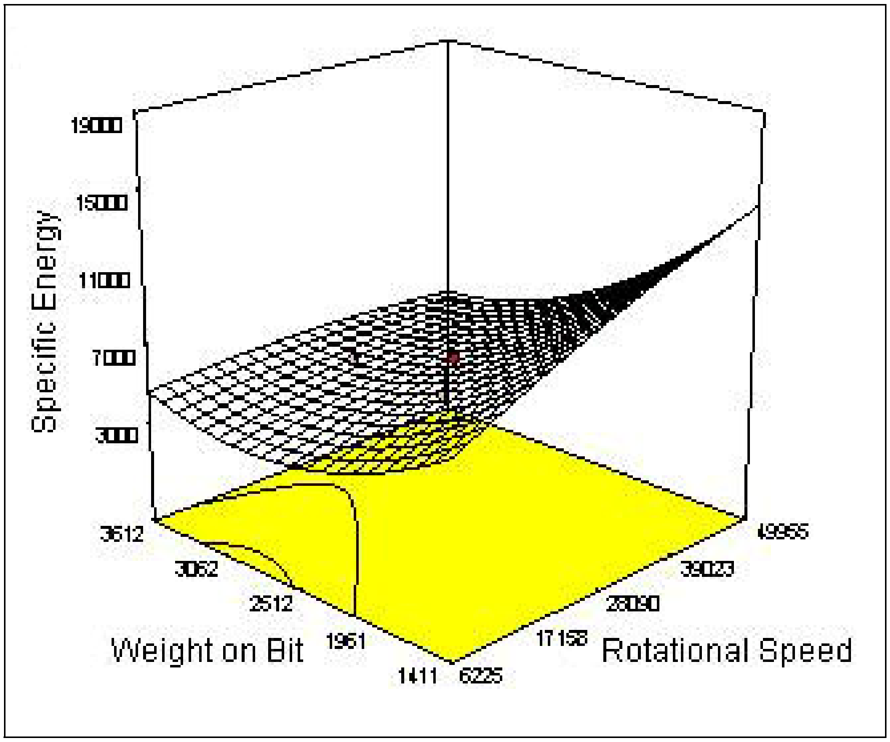
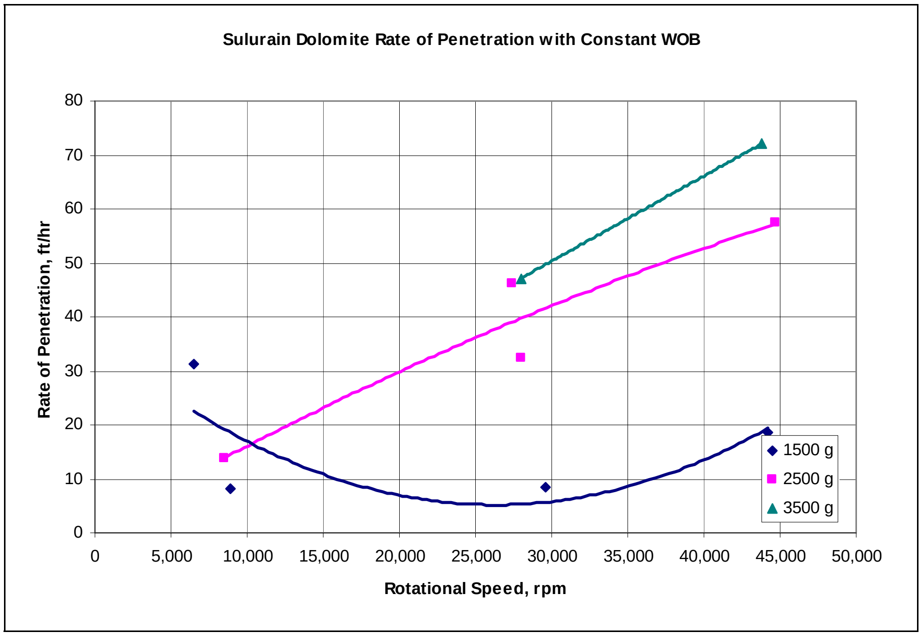


Figure B-5. Specific energy graph and response surface plot for Sulurain dolomite at various rotational speeds and weights on bit.



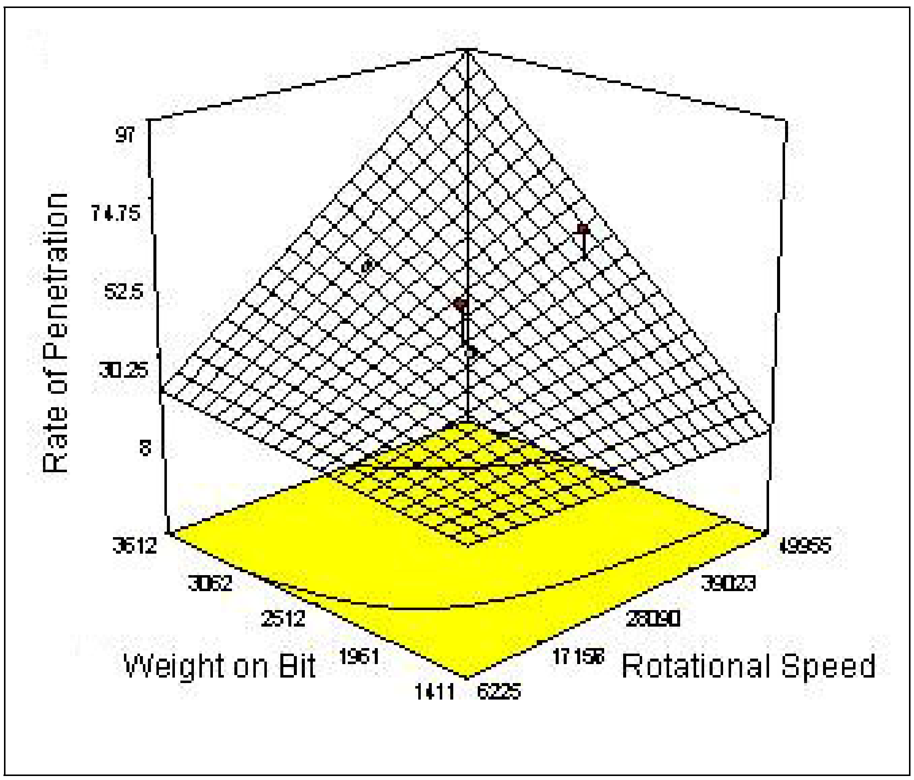
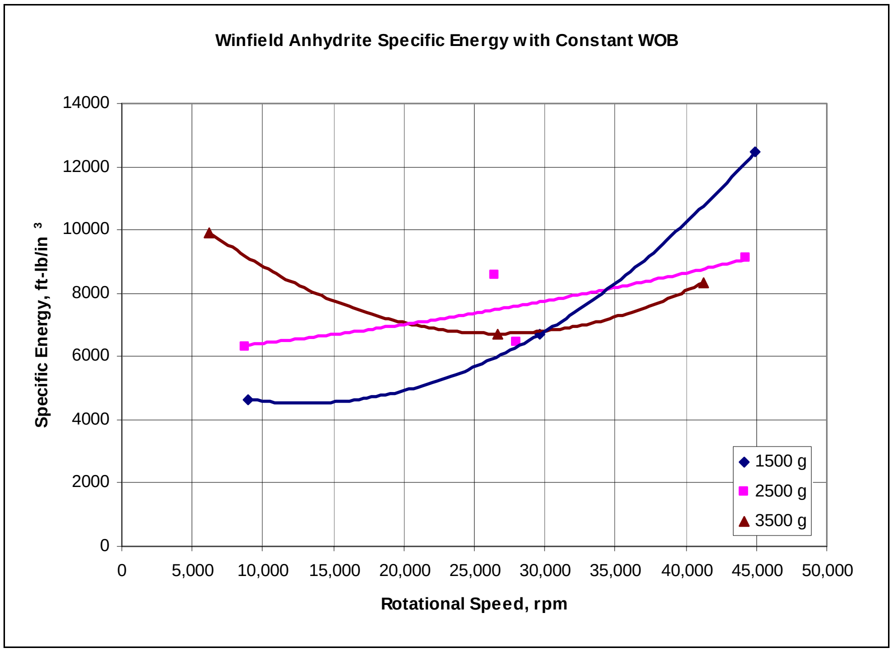


Figure B-6. Rate of penetration graph and response surface plot for Sulurain dolomite at various rotational speeds and weights on bit.



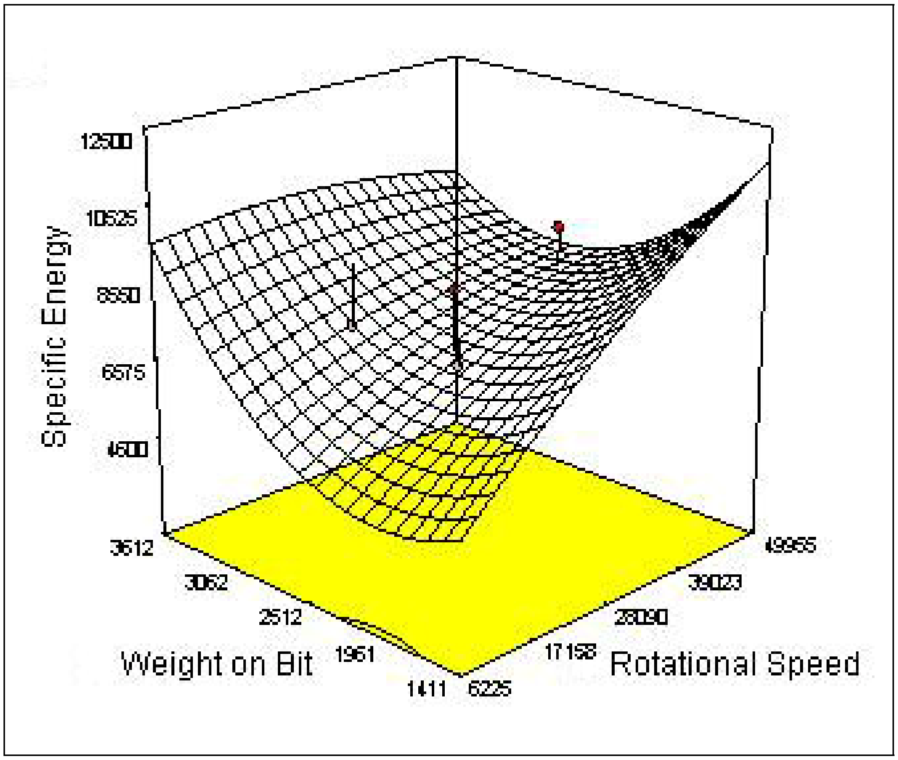
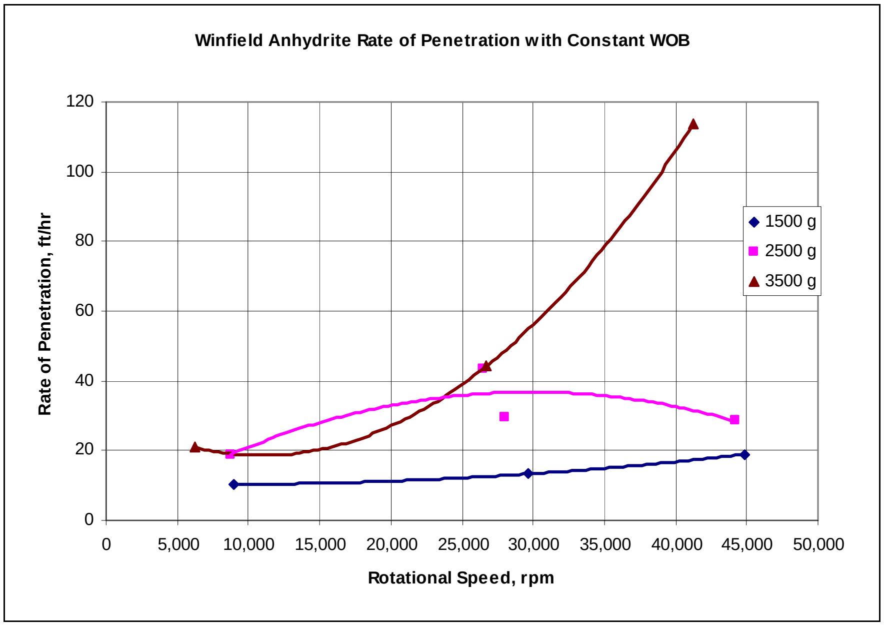


Figure B-7. Specific energy graph and response surface plot for Winfield anhydrite at various rotational speeds and weights on bit.



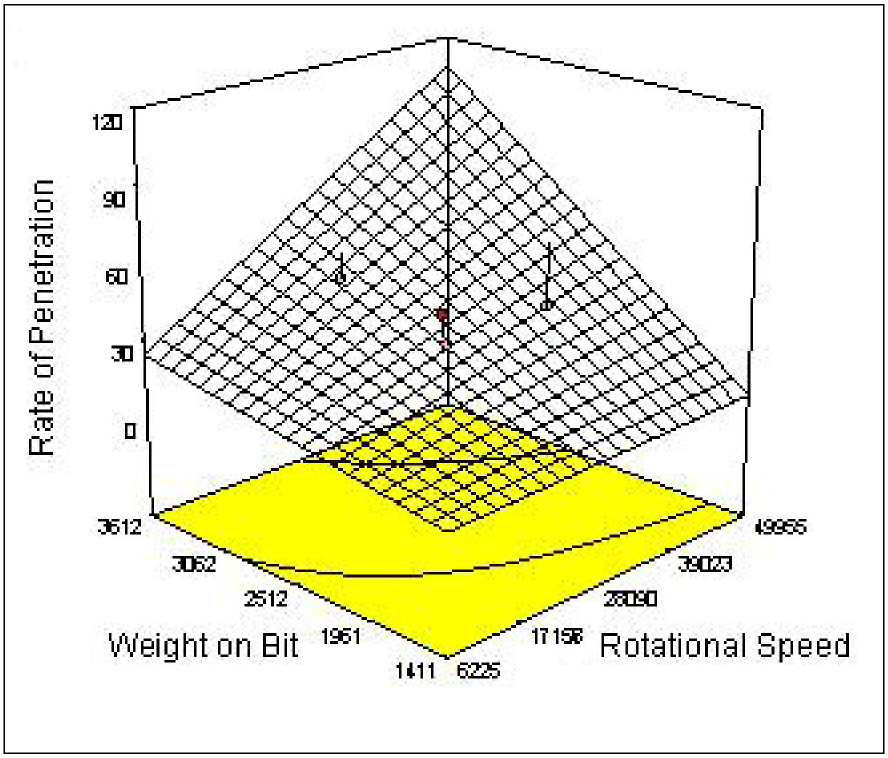


Figure B-8. Rate of penetration graph and response surface plot for Winfield anhydrite at various rotational speeds and weights on bit.