



Unique ROP Predictor Using Bit-specific Coefficient of Sliding Friction and Mechanical Efficiency as a Function of Confined Compressive Strength Impacts Drilling Performance

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Abstract

Predicting the potential rate of penetration (ROP) for all bit types, fixed and roller cone, has been accomplished by applying specific energy theory and mechanical efficiency as a function of rock strength. After the apparent rock strength is accurately determined from either open-hole log analysis or core measurements, the ROP based on work and power input into the bit efficiency can be calculated. The influence of bit type and torque is represented by the parameters of coefficient of sliding friction and mechanical efficiency. Specific energy theory is not new and has been used for bit performance assessment for years. The technical paper will describe a unique and revolutionary approach to establish relationships for the sliding coefficient of friction, mechanical efficiency, weight on bit, and rpm as a function of rock strength, and then to use these relationships to predict a reasonable and achievable ROP with the associated bit torque for all bit types.

Because the development of the model requires extremely accurate and controlled drilling data, we performed full scale simulator tests, using several rock types with confined compressive strength (CCS) between 5,000 psi to 70,000 psi. The CCS approach better represents the apparent rock strength to the bit. The use of CCS has enabled us to identify key relationships and to develop globally applicable algorithms for bit performance prediction that require minimal or no calibration.

The ROP model has been field tested and validated on wells drilled and the predicted ROP value closely correlates with the actual ROP value for all bit types. The paper will illustrate how drilling performance can be enhanced by selecting the optimum drilling bits for any well or hole section during the planning phase or operation phase for optimization, thereby eliminating the learning curve and reducing both drilling time and cost.

Introduction

During the late 1990s, Chevron Exploration and Production Technology Company (EPTC) initiated work on a project to improve drilling performance and pre-drill drilling performance prediction based on a mechanical earth model (MEM). Required components of this project

were pre-drill bit selection, rate of penetration (ROP) prediction, and bit life prediction. Another objective of the project was the integration of this capability into tools/processes for rapid well design, planning, and cost estimating. People who understand what is necessary to build a MEM know that it requires an investment. A MEM is not always available or warranted, but its use is gaining popularity and proving to add value, especially with some of the major capital projects in more challenging and high-cost drilling environments.

As is typical of such endeavors, the existing literature was reviewed, various experts were consulted, and processes used by suppliers were reviewed. EPTC, as well as other operators and bit suppliers, had some capability in this regard but EPTC believed there were still considerable inaccuracies, subjectivity, or extensive local calibration required in the existing processes. EPTC concluded that the industry lacked relatively accurate yet simple and intuitive methods based on first principles for calculating the apparent rock strength to the bit and achievable ROP for predominant bit types. These were fundamental requirements needed to meet the EPTC project objectives. The EPTC Rock Mechanics team, consisting of rock mechanics, drilling engineers, and earth scientists, worked together to develop simple, robust, and globally applicable solutions for apparent rock strength (to the bit) and bit performance prediction methods.

The Current (and Problematic) State

Bit Performance Prediction.

One element of optimizing drilling performance is the optimization of bit selection and operating parameters. This optimization process is often accomplished by the process of trial and error. Not only can this present considerable unnecessary expense, it is a process that can proceed or conclude with considerable uncertainty and lack of optimization.

Bit performance optimization processes typically require rock strength and other rock properties (a MEM) and some form of bit performance prediction. One needs to know the character of what is being drilled to predict performance, and one needs to establish some criteria

of good or bad performance to optimize. Besides optimization, there is sometimes a critical need to reduce the uncertainty of drilling performance prediction. This may be for more confidence in AFE appropriation, time estimate for rig sharing agreements, time estimate to work within "weather windows," and so forth.

Pre-drill bit selection, performance prediction, and optimization based on MEM are predominantly limited to specialists within the bit supplier companies and some operators. To a large degree, a high level of expertise and/or reasonably robust and accurate methods is limited. To the extent that accurate bit performance predictions are developed, they are often complex, proprietary, or based on local empirical correlations. In addition, they may not be globally applicable from surface to great depths, across typical range of hole sizes, and for all predominant bit types. Bit performance prediction methods may not be linked or sensitive to rig capability (available power and drillstring specifications), though this could be a useful capability for optimizing equipment selection and field development planning.

Specific Energy Theory

Specific energy (E_s) principles provide a means of predicting or analyzing bit performance. E_s is based on fundamental principles related to the amount of energy required to destroy a unit volume of rock and the efficiency of bits to destroy the rock.

The E_s parameter is a useful measure for predicting the power requirements (bit torque and rpm) for a particular bit type to drill at a given ROP in a given rock type, and the ROP that a particular bit might be expected to achieve in a given rock type.

E_s theory is not new; it has been used for quick bit performance assessment for years. Equation 1 shows Teale's specific energy equation derived for rotary drilling at atmospheric conditions⁽¹⁾.

$$E_s = \frac{WOB}{A_B} + \frac{120 * \pi * N * T}{A_B * ROP} \quad (1)$$

Where: E_s = Specific energy (psi)
 WOB = Weight on bit (pounds)
 A_B = Borehole area (sq-in)
 N = rpm
 T = Torque (ft-lbf)
 ROP = Rate of penetration (ft/hr)

Pessier⁽²⁾ validated Equation 1 for drilling under hydrostatic pressure.

Because the majority of field data is in the form of surface measurements of weight on bit (WOB), rpm (N), and rate of penetration (ROP), a bit-specific coefficient of sliding friction (μ) was introduced to express torque (T) as a function of WOB ⁽¹⁾. This coefficient will

subsequently be used to compute specific input energy (E_s) values in the absence of reliable torque measurements, as follows:

$$\mu = 36 \frac{T}{D_B * WOB} \quad (2)$$

Where: T = Bit torque (ft-lbf)
 D_B = Bit size (inches)
 μ = Bit-specific coefficient of sliding friction (dimensionless)

Teale also introduced the concept of minimum specific energy and maximum mechanical efficiency⁽¹⁾. The minimum specific energy is reached when the specific energy approaches or is roughly equal to the compressive strength of the rock being drilled. The mechanical efficiency (EFF_M) for any bit type is then calculated as follows:

$$EFF_M = \frac{E_{s \min}}{E_s} * 100 \quad (3)$$

Where: $E_{s \min}$ = Rock strength (CCS)

The associated bit torque for a particular bit type to drill at a given ROP in a given rock type (CCS) is computed by using Equation 4, which is derived from Equation 1 and Equation 3, as follows:

$$T = \left(\frac{CCS}{EFF_M} - \frac{4 * WOB}{\pi * D_B^2} \right) * \left(\frac{D_B^2 * ROP}{480 * N} \right) \quad (4)$$

Substituting E_s in terms of mechanical efficiency and torque as a function of WOB and solving Equation 1 for ROP , the rate of penetration can be calculated with Equation 5, as follows:

$$ROP = \frac{13.33 * \mu * N}{D_B \left(\frac{CCS}{EFF_M * WOB} - \frac{1}{A_B} \right)} \quad (5)$$

Upon review of the specific energy theory and the work by Pessier, EPTC concluded that the coefficient of sliding friction, efficiency, WOB , and rpm could reasonably be defined for each bit type as a function of apparent rock strength to the bit. Lab work was initiated to confirm and quantify these relationships. Research on a reasonably accurate confined compressive strength solution for apparent rock strength to the bit was also initiated.

Specific Energy ROP Model (SEROP)

EPTC developed a method of predicting the coefficients required in Equation 5 as a function of rock strength. This was done for all predominant bit types, including:

- Steel tooth bits
- Insert tooth bits for soft formations
- Insert tooth bits for medium formations
- Insert tooth bits for hard formations
- PDC bits with three to four blades
- PDC bits with five to seven blades
- PDC bits with more than seven blades
- TSP bits
- Impregnated bits and
- Natural diamond bits

By using this new capability and our globally applicable rock property determination techniques, we can quickly calculate the ROP for all of the bit types with reasonable accuracy, without any calibration. The approach can also be easily updated as technology advances because it is based on fundamental rock destruction principles and on conservation of energy and efficiency principles that will not change. Additionally, the developed methodology and work process is relatively simple in comparison to other ROP predictive processes used in the industry. A skilled drilling engineer could use the methodology: it does not require a specialist.

After the relationships for bit-specific coefficient of sliding friction (μ) and mechanical efficiency (EFF_M) as a function of rock strength (CCS) have accurately been determined, the ROP for a sharp bit, based on work and power input into the bit (WOB and N), can be predicted. The specific energy ROP model uses Equation 5, derived from Equation 1 and Equation 4, to calculate the ROP for all bit types. Additionally, the SEROP model computes three ROP values for each bit type: a minimum ROP, a maximum ROP, and an average or nominal ROP. These computations are possible because three mechanical efficiencies (minimum efficiency, maximum efficiency, and nominal efficiency) are determined from the full-scale simulator tests for each bit type.

Full-Scale Simulator Tests.

The development of the SEROP model required accurate, controlled drilling data. We worked with Hughes Christensen to perform full scale testing with their pressurized test rig at their facility located in The Woodlands, Texas. We thoroughly evaluated all of the test data provided by Hughes Christensen to establish, confirm, and refine the coefficient of sliding friction and efficiency vs. rock strength for each bit type. The testing used several rock samples with CCS ranging from 5,000 psi to 70,000 psi.

Figure 1 shows data from one of the tests conducted to determine bit coefficient of sliding friction, mechanical efficiency, and specific energy as a function of rock strength. Each test provides a single point in the correlations. The test data shown in Figure 1 provided values for torque at several WOB/ROP pairs for a given CCS, whereby Es , μ , and EFF_M could be calculated.

Bit-Specific Coefficient of Sliding Friction (μ).

An example of how the bit-specific coefficient of sliding friction for PDC bits with more than seven blades was determined is illustrated in Figure 2. Rock samples from Crab Orchard Sandstone, Catoosa shale, and Carthage Marble were used for multiple tests with a PDC bit with more than seven blades. All tests used a mud weight of 9.5 ppg. The corresponding CCS values at 6,000 psi bottom hole pressure were 18,500 psi for Catoosa shale, 36,226 psi for Carthage Marble, and 66,000 psi for Crab Orchard.

The correlation developed to compute μ for a PDC bit with more than seven blades, derived from Figure 2, is shown in Equation 6.

$$\mu = 0.9402 * EXP(-8E - 06 * CCS) \quad (6)$$

The same procedure and full-scale simulator tests were performed to determine the relationships of μ as a function of the confined compressive strength for all bit types. Correlations for all bit types are not shown in this document.

Mechanical Efficiency (EFF_M).

As shown in Figure 1, Es changes as drilling parameters change. Consequently, Es cannot be represented by a single accurate number. Minimum and maximum values of Es were computed from each full-scale simulator test, and these values were used to compute minimum and maximum mechanical efficiencies for each test. For example, the test data from Figure 1 indicates a mechanical efficiency in the range of approximately 19% to 44% for this test.

Figure 3 illustrates the relationships of minimum and maximum efficiencies for PDC bits with more than seven blades. The minimum efficiency (Min EFF_M) and maximum efficiency (Max EFF_M) for PDC bits with more than seven blades, indicated in Figure 3, are computed using Equations 7 and 8.

$$\text{Min } EFF_M = 0.0008 * CCS + 8.834 \quad (7 \text{ and } 8)$$

$$\text{Max } EFF_M = 0.0011 * CCS + 13.804$$

A nominal mechanical efficiency (Nom EFF_M) is the

average efficiency derived from the minimum and maximum efficiencies. Equation 9 indicates the Nom EFF_M for PDC bits with more than seven blades.

$$\text{Nom } EFF_M = 0.00095 * CCS + 11.319 \quad (9)$$

Similar procedures and testing methods were applied to determine the mechanical efficiencies for all bit types. These correlations are not shown in this document.

Weight On Bit (WOB) and Bit RPM (N).

Drilling parameters WOB and N are variables that are selected based on field experience, bit type, and/or BHA configuration. However, the SEROP model has the capability of predicting the appropriate WOB and N based on CCS.

Adjustments to μ and EFF_M due to Drilling Environment.

Those who understand bit performance know that the efficiency of drill bits is affected by mud weight. The magnitude of efficiency loss arising from changes in mud weight has been determined by performing additional tests that use different mud weight systems. Because full-scale simulator tests for all bit types were performed using a 9.5-ppg mud weight, we evaluated the potential effect of mud weight on μ and EFF_M by using a heavier mud weight. Consequently, full-scale tests were performed for all bit types using a 16.5-ppg mud weight.

We determined that the value of μ for PDC bits is reduced by approximately 49% when increasing mud weight from 9.5 ppg to 16.5 ppg. As a result, the value of μ must be corrected if the mud weight is different from 9.5 ppg. From Figure 4, the following correction factor for μ for PDC bits with more than seven blades was established.

$$-0.8876 * \ln(\text{mud weight}) + 2.998 \quad (10)$$

Equation 11 is the revised formula for computing the value of μ for any mud weight.

$$\mu = [(0.9402 * \text{EXP}(-8E - 06 * CCS)] * [-0.8876 * \ln(\text{MudWeight}) + 2.998] \quad (11)$$

We determined that mechanical efficiency for PDC bits was reduced by approximately 56% when increasing the mud weight from 9.5 ppg to 16.5 ppg. **Figure 5** establishes the following correction factor to EFF_M for PDC bits with more than seven blades.

$$-1.0144 * \ln(\text{Mud Weight}) + 3.2836 \quad (12)$$

Equations 13 and 14 show the revised correlations for Min and Max mechanical efficiencies for PDC bits with more than seven blades for any mud weight.

$$\begin{aligned} \text{Min } EFF_M &= [0.0008 * CCS + 8.834] * \\ &[-1.0144 * \ln(\text{Mud Weight}) + 3.2836] \end{aligned} \quad (13 \text{ and } 14)$$

$$\begin{aligned} \text{Max } EFF_M &= [0.0011 * CCS + 13.804] * \\ &[-1.0144 * \ln(\text{Mud Weight}) + 3.2836] \end{aligned}$$

The same testing procedure was conducted to establish the correction factors for μ and EFF_M for all bit types.

Correction Factor for PDC Bits due to Cutter Size.

To account the effect of cutter size in the ROP model, full-scale simulator tests were performed using various cutter sizes with PDC bits. Figure 6 illustrates the effect of cutter size with PDC bits. Because full-scale simulator tests for PDC bits were performed using drill bits with 19-mm cutters, additional tests were performed with cutter sizes greater than or less than 19 mm. The test results indicated that the bit coefficient of sliding friction (μ) is decreased or increased by 1.77% when the cutter size is decreased or increased for each millimeter above or below 19 mm, as shown in Figure 6.

Therefore, the correction factor to adjust μ due to cutter size is as follows:

$$0.0177 * \text{Cutter Size} + 0.6637 \quad (15)$$

Where: Cutter size is in millimeters

Combining all of the correction factors, the final correlation for μ for PDC bits with more than seven blades is shown in Equation 16.

$$\begin{aligned} \mu &= [(0.9402 * \text{EXP}(-8E - 06 * CCS)] * \\ &[-0.8876 * \ln(\text{MudWeight}) + 2.998] * \\ &[0.0177 * \text{Cutter Size} + 0.6637] \end{aligned} \quad (16)$$

Final correlations for μ for all bit types are not shown in this paper.

Limitations of ROP Model

The ROP model does not take into account bit design features, such as cone offset angle, cone diameter, and

journal angle of roller cone bits, and does not take into account design features, such as back rack angle and bit profile of PDC bits. The selection of the proper bit design features for each application could impact the ROP. Although the impact of all design features on ROP was not quantitatively measured in the lab, field examples using the SEROP model indicate that the impact on ROP could be between 10% and 20%. The variation of ROP as a result of bit design features is assumed to be captured by the SEROP model because it computes a maximum and a minimum ROP as a function of maximum and minimum efficiency. In fact, in most of the field examples, the nominal ROP closely correlates with actual ROP, but there are a few cases in which either the minimum or the maximum ROP correlates with the actual ROP.

Mud systems, such as WBM or OBM/SBM, are not differentiated in the SEROP model. However, field examples show that the main factor affecting bit performance and ROP is bit balling with WBM. If bit balling is eliminated with optimum hydraulics and the control of mud properties, it is assumed the predicted ROP will be approximately the same for both mud systems.

The SEROP model does not consider or optimize hydraulics. Full scale simulator tests used to develop the ROP model were performed with optimum hydraulics. Again, because the SEROP model predicts minimum and maximum ROP values, the actual ROP value typically falls within the minimum and maximum ROP parameters for any bit type, provided that the actual hydraulics are adequate.

The current SEROP model is for sharp bits only. It does not take into account bit wear. The ROP model will be further adjusted as the bit wear and bit life models are developed and implemented.

Predicted ROP for PDC bits is for groups of bits based on blade count. We have established three groups: PDC bits with three to four blades, PDC bits with five to seven blades, and PDC bits with more than seven blades. Field experience indicates that minimum ROP generally correlates with PDC bits with the highest number of blades within the group and maximum ROP correlates with the lowest blade count in the group.

Predicted ROP for roller cone bits is for groups of bits based on rock strength. We have established four groups: steel tooth bits, insert tooth bits for soft formations, insert tooth bits for medium formations, and insert tooth bits for hard formations.

With the exception of very high strength rock, the ROP model will predict highest ROP value for a PDC bit with three to four blades, the next highest ROP value for a PDC bit with five to seven blades, and so forth, through the range of different bit types according to aggressiveness. Without an integrated wear model, which is one of the next objectives, the current model

can be misleading (that is, always suggesting that a three to four blade PDC bit achieves the greatest ROP, even for rock strength exceeding the capability of the bit). To prevent misapplication and to optimize overall drilling performance, expert judgment and/or a bit selector tool should be used.

Bit Selection and Optimization

The most common approach for evaluating drilling performance and bit selection in the oil field is based on past observed performance from offset wells. This methodology tends to apply the same drilling performance and rock strength to the current application without evaluating changes in rock strength, lithology, drilling environment, and potential ROP if other bit types are used. The SEROP model uses rock properties (CCS) and drilling environments to accurately predict the potential ROP for all bit types. Therefore, our approach is global; it is not restricted to a particular area or region nor does it necessarily require calibration to local conditions.

In a realtime bit optimization scenario, predicted ROP and Es energy values can be used to assess bit performance. This can be accomplished if the rock properties are known, either by correlation or directly measured and calculated from LWD data. Bit performance and condition can be evaluated by comparing the actual Es value to the predicted Es value, as well as by comparing the actual ROP value to the predicted ROP value. Bit performance analysis using realtime predicted Es and actual Es values can be also used to detect and correct drilling problems, such as bit vibration and bit balling, failure analysis, and dull bits.

Field Discussion

The field examples presented illustrate how the CCS approach and the SEROP model improved drilling performance by reducing both drilling time and drilling costs. This performance was achieved by selecting the optimum drill bits and drilling parameters for each application.

Well 1.

Figure 7 shows the drilling performance for a specific interval composed mainly of dolomite in which the ROP has been very low (approximately 1 meter/hour) with roller cone bits (TCI), heavy set PDC bits, and impregnated bits (IMPREG). The EPTC rock mechanics algorithm (RMA) analysis indicates that CCS ranged from about 20,000 psi to 35,000 psi.

Track 5 provides an example of the correlation between the values of the predicted ROP and the actual ROP for all bit types used to drill the interval. Predicted ROP is calculated using actual drilling parameters (WOB, rpm) from actual bit runs shown in Track 4. Track 3 shows the actual bits used and their dull grades. Track 6 illustrates the potential ROP for Insert bits (TCI

medium formations), PDC bits with five to seven blades and 19-mm cutters (PDC 5-7B), PDC bits with more than seven blades (PDC>7B), Natural Diamond (ND) bits, Thermally Stable Polycrystalline (TSP) bits, and Impregnated (IMPREG) bits. The predicted ROP for ND, TSP, and IMPREG bits is calculated using 700 rpm and 8.5-Klbs WOB.

The analysis suggested that neither roller cone bits nor Impreg bits and heavy set PDC bits are suitable for this application because of low ROP. It indicated that PDC bits with five to seven blades and 19-mm cutters could deliver a ROP between 6- and 8-meters per hour (WOB between 10- and 20-Klbs and N between 120- and 160-rpm). Although, a PDC bit with three to four blades will deliver a higher ROP (not shown here), this bit was not considered because the high rock strength exceeds the bit's rock strength capability. As a result, the recommended approach was to use a six-bladed PDC bit with 19-mm abrasive resistance cutters and thinner diamond tables (less than 0.120 inches thickness). Wells are now being drilled at an average ROP of 6- to 8-meters per hour.

Well 2.

Figure 8 provides another example of the use of the CCS and SEROP models to select the optimum bit for an exploratory well. Log data and drilling data from offset wells were used to create a composite for the proposed well, and then RMA and SEROP analyses were performed.

The evaluation showed that the interval is relatively soft, with CCS ranging between 3,000 psi and 5,000 psi, and that the interval could be drilled with an aggressive PDC bit. The recommended approach was to use a five-bladed PDC bit with 19-mm abrasive resistance cutters. The well was drilled at ROP rate of 160- to 180-ft/hr. Although, the lithology in the well drilled was not exactly the same as that of the offset wells, the predicted ROP (solid line, Track 4) closely correlated with actual ROP achieved in the well drilled.

Well 3.

Figure 9 shows the drilling performance for an 8-½-in. hole drilled using PDC bits with seven and nine blades. The well was drilled at a ROP of 20- to 40-ft/hr.

Figure 9 also illustrates the bit optimization performed for a sidetrack out of the same wellbore. The RMA analysis indicates that the CCS for the interval (CCS, Track 2) is between 8,000 psi to 10,000 psi and that the well could be drilled with a more aggressive PDC bits than the bits used to drill the original wellbore. The analysis suggested that the sidetrack be drilled with a six-bladed PDC bit with 19-mm cutters to achieve better penetration rates. See the actual ROP for original wellbore in Track 4 and predicted ROPs for the sidetrack in Track 5.

The sidetrack was drilled with one PDC bit at a ROP of 60- to 80-ft/hr. The sidetrack was drilled in four days, rather than the eight days required to drill the original wellbore. This well was located offshore in 7,000 ft water. The use of the CCS and SEROP models to identify a more aggressive PDC bit resulted in a savings of approximately 1.6 million dollars.

Well 4.

Figure 10 shows how the CCS and SEROP models can be used to assess bit performance real-time, and thereby optimize drilling performance. Predicted Es and ROP values can be used to determine whether or not the bit is performing efficiently or whether or not bit efficiency is affected by bit vibration, bit balling, and/or dull bits.

Figure 10 illustrates that the first bit drilled the top section of interval efficiently as the predicted ROP closely correlates with actual ROP (Track 5). In addition, actual Es also correlates with predicted Es except for shale intervals in which Es is several times higher than predicted Es (Track 6).

The second bit drilled the lower part of the section inefficiently. Neither the predicted ROP nor Es correlated with the actual ROP and Es values. The actual Es was higher than the predicted Es by more than eight times, indicating that bit efficiency is extremely low as a result of bit vibration and/or bit balling. The bit record showed that bit was balled up.

Conclusions

1. A methodology has been developed for the quantitative prediction of all the input variables to the specific energy ROP model, based on the apparent rock strength to the bit. This allows rapid prediction of the expected range of ROP and drilling parameters (WOB, rpm, torque) for all bit types, according to rock properties and the drilling environment.
2. The SEROP model has been implemented by ChevronTexaco.
3. The model is accurate, simple, robust, globally applicable, based on fundamental and first principles, require little or no calibration, and any calibration required is simple and intuitive.
4. The new model has proved valuable, improving drilling performance and reducing well cost by improving bit performance prediction, bit selection, and determination of optimum drilling parameters.
5. The method can be applied real time to identify drilling problems (bit balling, bit vibration, and dull bits) and to optimize drilling parameters (WOB, rpm).
6. The SEROP model can be used to back calculate CCS and rock properties in the absence of log or other data. The rock properties can then be used for

real-time or post-well wellbore stability and sanding analysis.

Acknowledgements

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Nomenclature

- A_B = Borehole area (sq-in)
- CCS = Confined Compressive Strength, psi
- D_B = Bit size (inches)
- DP = (ECD pressure – PP), psi
- EFF_M = Mechanical efficiency
- Es = Specific energy (psi)
- Es_{min} = Minimum Specific energy (psi)

- N = Rpm
- ppg = Pounds per gallon
- ROP = Rate of Penetration (ft/hr)
- $SEROP$ = Specific Energy ROP
- T = Torque (ft-lbf)
- UCS = Rock Unconfined Compressive Strength, psi
- WOB = Weight On Bit (pounds)
- μ = Bit-specific coefficient of sliding friction (dimensionless)

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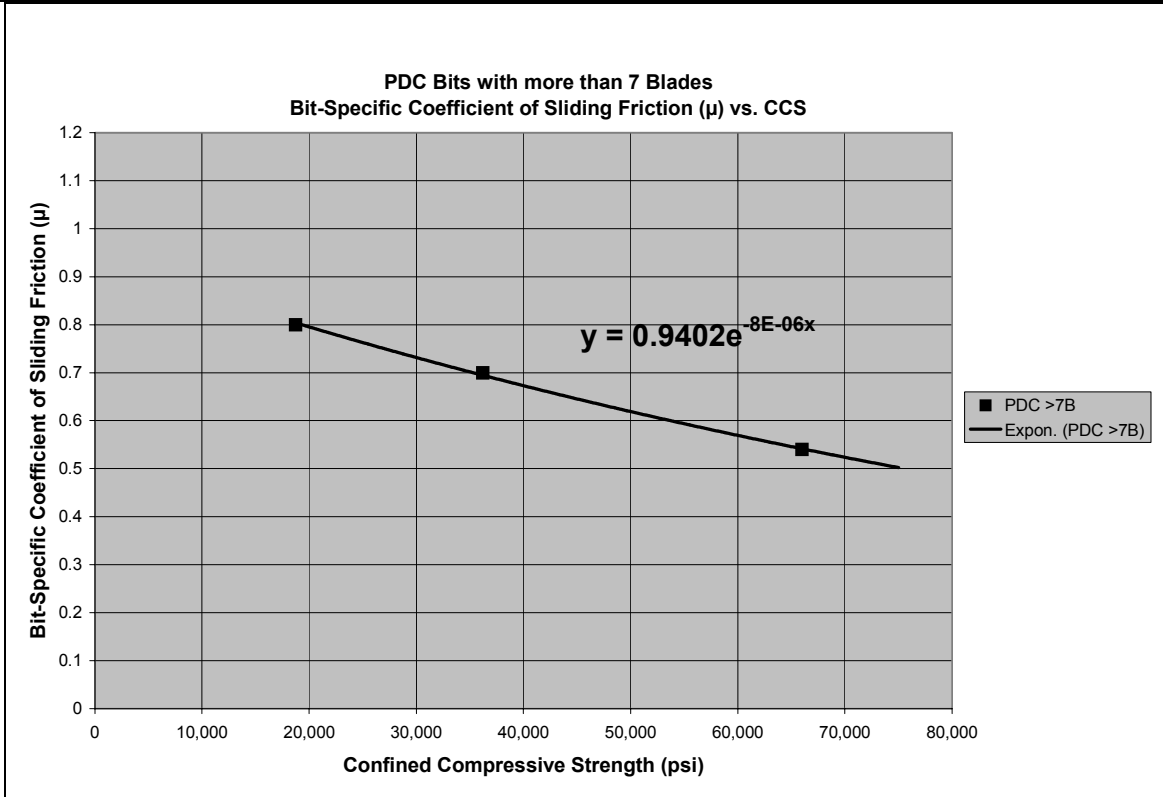


Figure 2. Bit-specific coefficient of sliding friction for PDC bits with more than seven blades

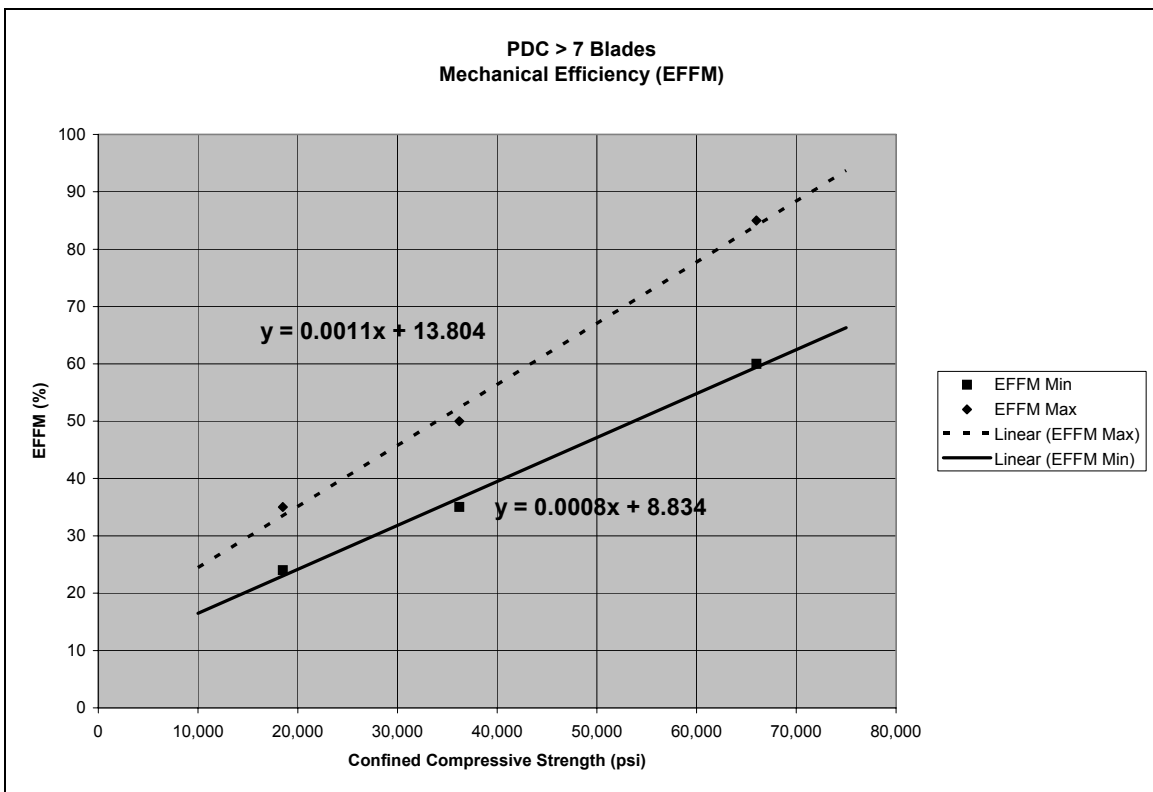


Figure 3. Minimum and maximum efficiencies for PDC bits with more than seven blades

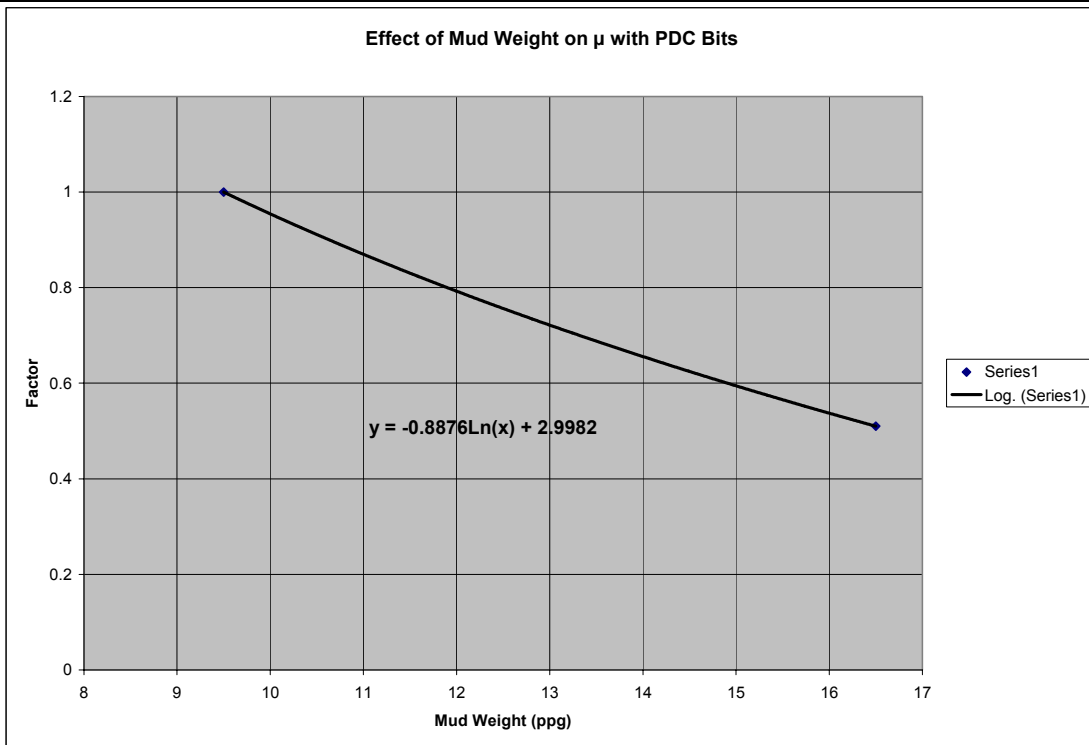


Figure 4. Correction factor for μ due to mud weight for PDC bits

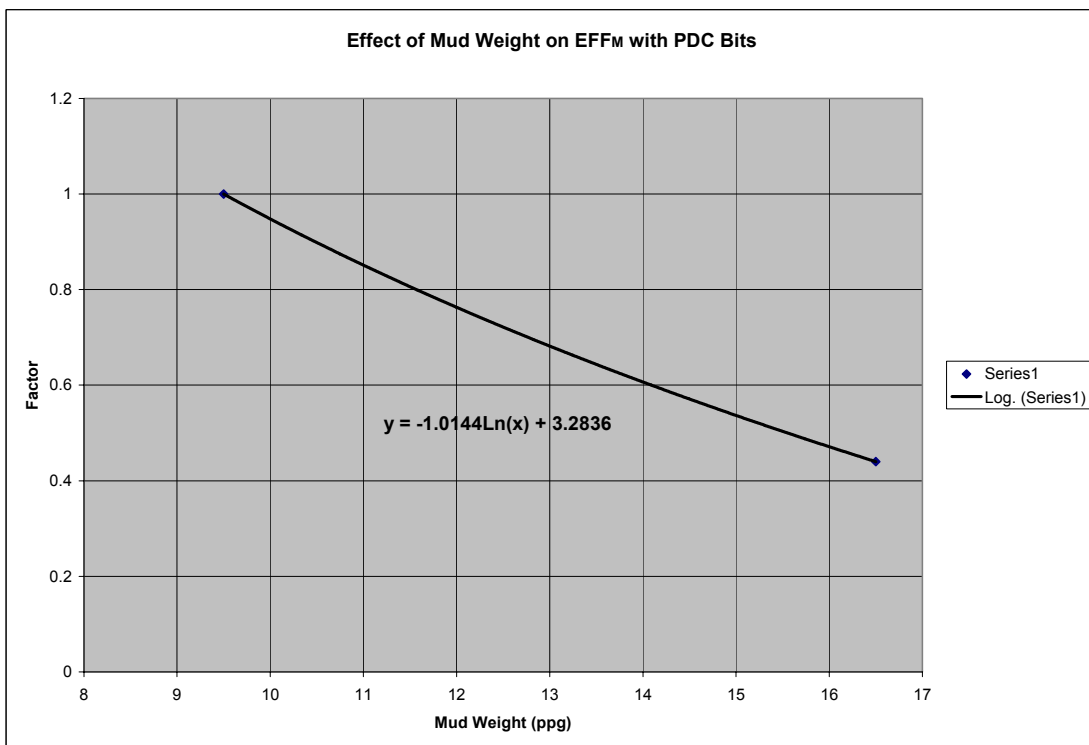


Figure 5. Correction factor for EFF^M due to mud weight for PDC bits

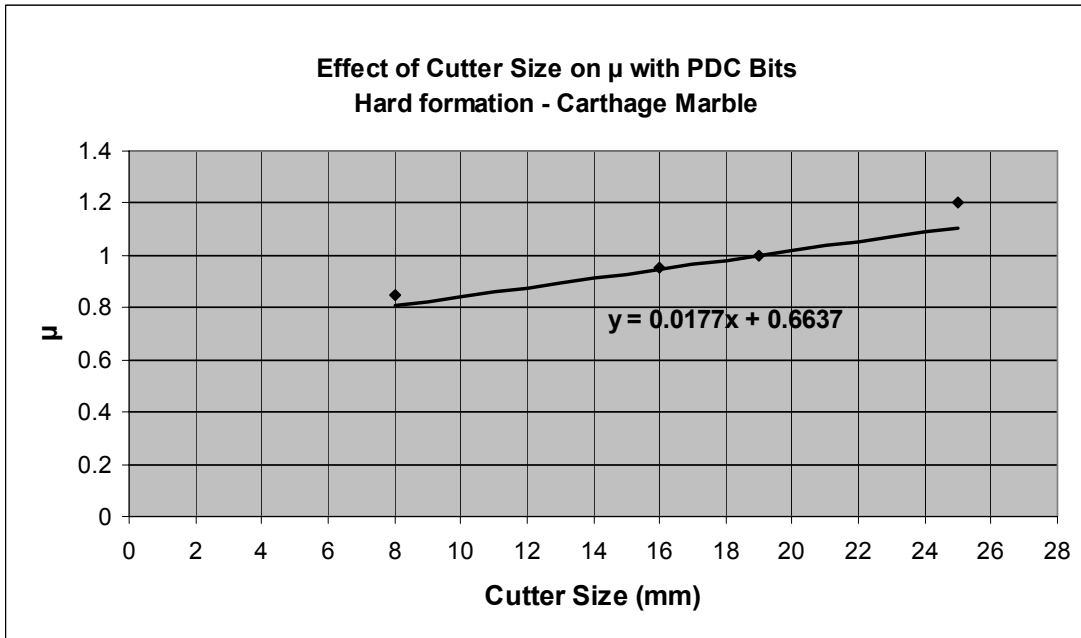


Figure 6. Correction factor by cutter size

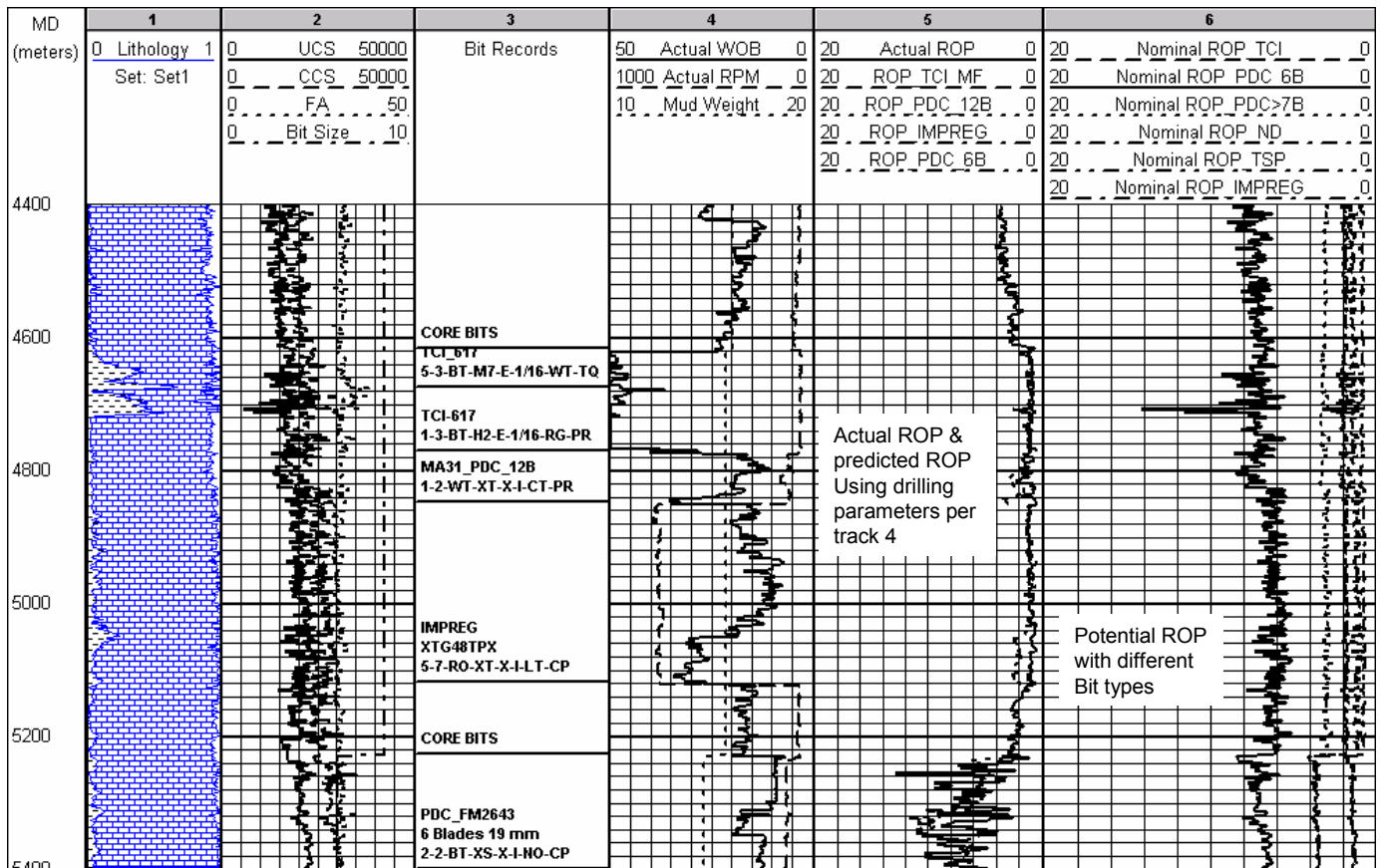


Figure 7. Well 1 - Bit optimization and selection

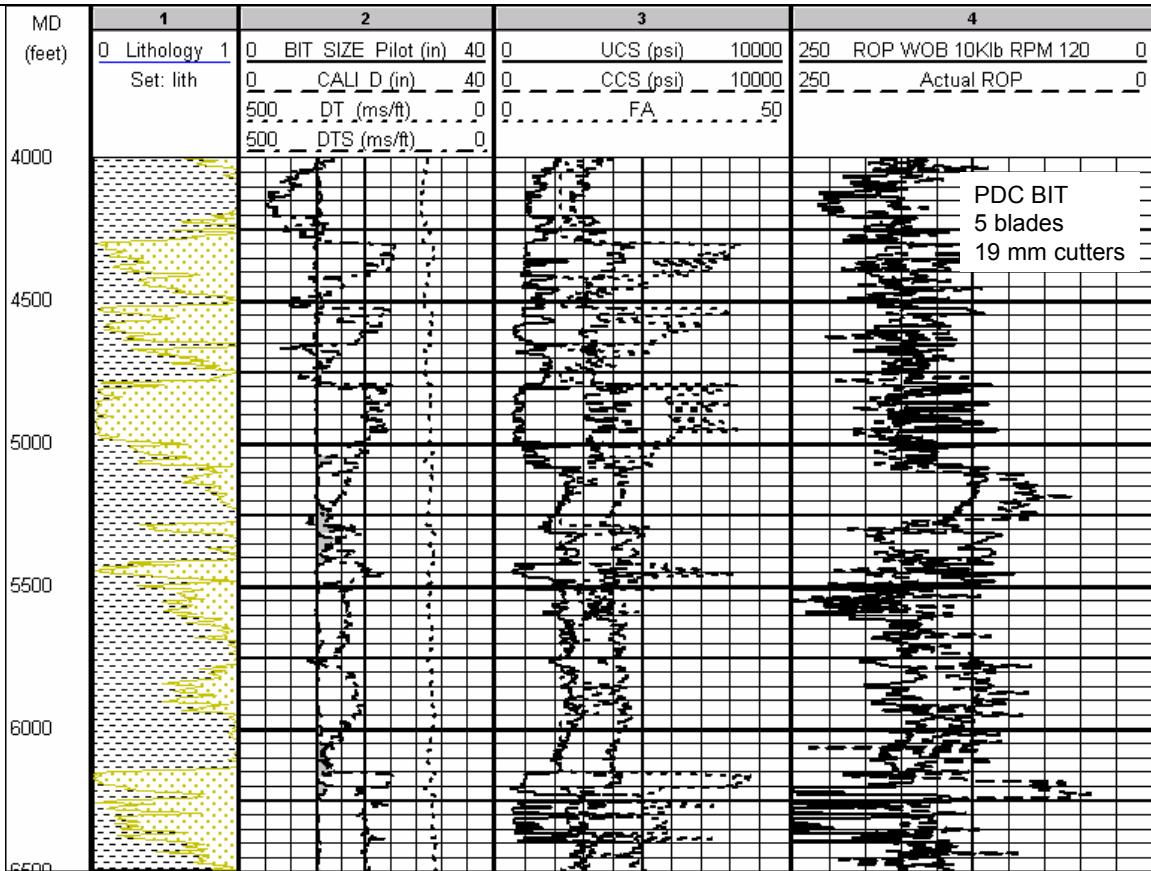


Figure 8. Bit optimization utilizing well offset data

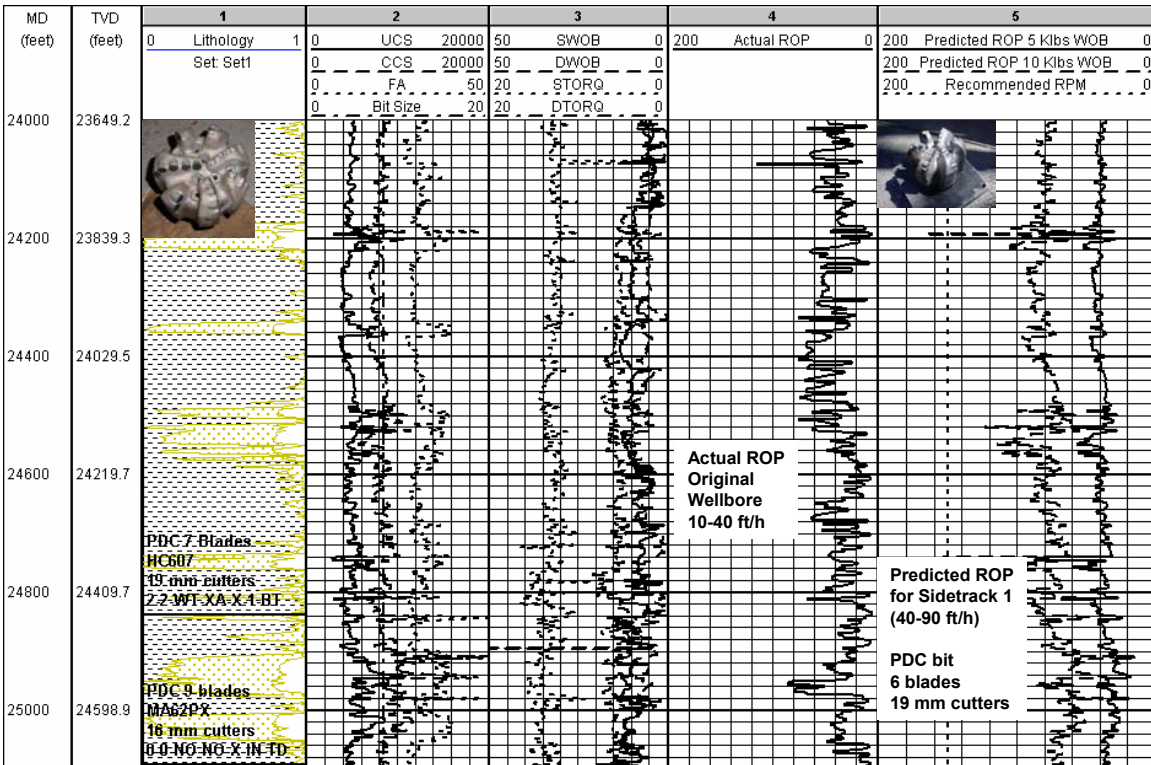


Figure 9. Well 4 - Bit optimization and selection

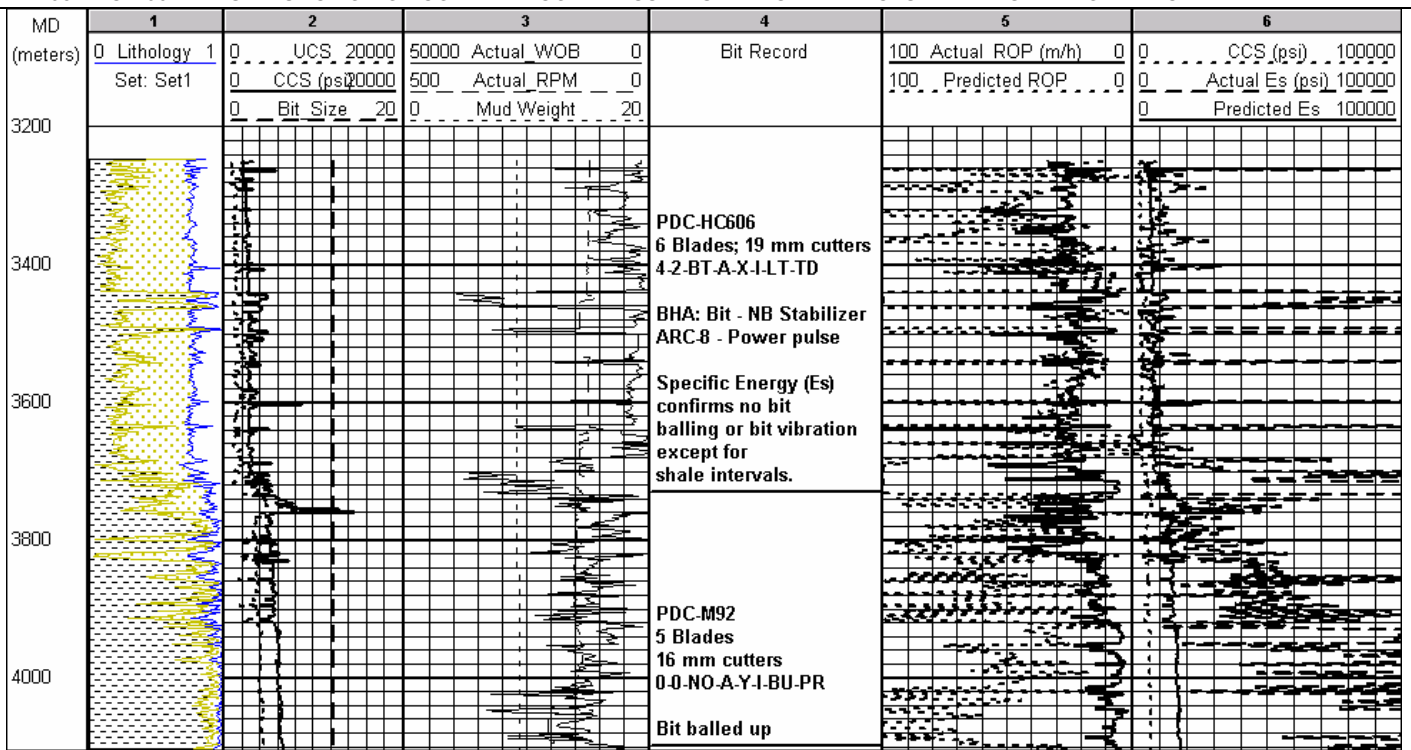


Figure 10. Well 5 - Bit performance using specific energy and predicted ROP values