SPE 90752

Drilling Optimization Using Bit Selection Expert System and ROP Prediction Algorithm Improves Drilling Performance and Enhances Operational Decision Making by Reducing Performance Uncertainties

E. Bjornsson P.Eng SPE Baker Hughes OASIS, B. Hucik PET SPE CNRL, G. Szutiak SPE Baker Hughes OASIS, L.A. Brown, Jr. SPE Baker Hughes OASIS, H. Evans SPE Baker Hughes OASIS, D. Curry C.E. SPE Baker Hughes OASIS, P. Perry SPE Baker Hughes OASIS.

This paper was prepared for presentation at the SPE Annual Technical Conference and Exhibition held in Houston, Texas, U.S.A., 26–29 September 2004.

Abstract

A rule based drill bit selection expert software system and Rate of Penetration (ROP) prediction algorithm has been recently applied in the optimization process of a 4500 m vertical foothills well in Western Canada. Post well analysis shows that when the expert system recommendations were followed by the operator, increases in ROP and run length over the local pacesetter well were experienced in each hole section. ROP increases of 15% in the 311.1mm section, 52% in the 215.9mm section and 60% in the 142.9mm section were achieved, as well as bit life increases up to 33% with TCI bits. Although the operator did not follow all of the expert system recommendations through the entire well, these increases did contribute to savings in drilling time below AFE of 15 days over the entire well. Comparison with the actual drilling performance showed close agreement in trend to the predicted ROP through most lithological intervals, which helped to confirm the accuracy of the process of geological / pore pressure predictions and the ROP prediction algorithm.

The expert system is a rule based bit selection system that uses a detailed description of the drilling environment, including meter based lithology, synthetic wireline logs, predicted pore pressures and anticipated operating parameters of the well or hole interval being analyzed to produce a bit selection recommendation including IADC bit type and bit features. The ROP algorithm has been developed as a drilling optimization tool and attempts to model the technical limit ROP that can be expected through a given hole interval. The ROP algorithm uses as its inputs detailed lithological descriptions of the anticipated formations, hole size, mud weight, predicted pore pressure, bit type, and anticipated operating parameters to calculate an accurate meter based ROP prediction. The ROP algorithm has been applied in several drilling environments worldwide and comparisons with actual drilling performance have been used to modify the calculations and improve predictions.

The ROP algorithm improves drilling decisions, and provides performance analysis while guiding financial planning. The ROP algorithm can be applied in the planning phase of a project to develop time curves based on expected performance and to compare and contrast potential bit/BHA types based on performance predictions. Furthermore, the ROP algorithm can be used in post-well analysis to identify areas where potential drilling performance was not achieved, and help in identifying improvements for future projects.

Introduction

Expert System Development

An expert system for drill bit selection[1,2] has been in development for over ten years.

This development has utilized knowledge extraction and engineering techniques to encode bit design and application knowledge from experts in the developer's various research and application departments over a number of years. This process has resulted in a highly complex set of rules which model expert understanding governing the selection of drill-bit features according to the physical properties of the drilling environment under study.

Rule-bases have been developed which separately deal with Impregnated, PDC, Steel-Tooth and Tungsten Carbide Insert (TCI) bits. Each rule base represents generically the major component features of the drill bit (cutting structure, bearing type, seal type, gauge enhancements etc.) and our understanding of the effect a range of rock and environmental properties have over their selection. Such environmental factors represented include, but are by no means limited to unconfined compressive strength, interfacial severity[3], bit run length, BHA type etc… Statistical analyses of the rock properties within an application are included in the derivation of other attributes (e.g. abrasivity[4], hardness meterage etc.) which are accumulated over the entire bit run length. This analytical approach allows the system to make decisions on bit selection and drillability in both homogeneous and inhomogeneous drilling applications[5].

Supplementary rule bases exist which represent expert knowledge of drillability problems in rule format. In essence, once the system is loaded with the physical description of the drilling environment, it is able to generate a suite of bit and feature recommendations for each bit class, an identification of potential drillability problems and suggest recommended operating practices to mitigate these problems.

Each rulebase is continually updated with new research and validated against field applications. The benefits of utilizing an expert system approach like this to support engineering decision making processes are:

- The system always considers all known bit selection criteria in order to give a viable recommendation of bit choice for a given interval,
- The system provides an improved basis for developing "what-if" or contingency scenarios in the planning of a well or if drilling progress differs from what is planned.
- The system improves the consistency of the recommendations made through time, by different personnel and across geographic boundaries.
- The system serves as a decision support tool and training aid for less experienced staff.
- The system is used in the planning, drilling and post-well analysis phases of a drilling optimisation project to qualify bit selection and operating practice recommendation.

Use of Expert System in Drilling Optimisation

The expert system is used to provide decision support to engineers in all phases of the analytical process utilized in drilling performance optimization. In the planning phase, a depth matched offset well description is built in the system using a combination of manual inputs and imported offset well data. During the implementation phase a new well description can be compiled from a combination of the actual drilling data and the offset well description which can then be further iterated in the event of unplanned geological or bit run changes. In the post well analysis phase a complete description of the actual well can be imported and the review of recommendations based on this new description can be performed to iterate the bit selection for subsequent wells.

The well description in the expert system is comprised of discrete information for the well trajectory, fluid type, BHA type and formation tops. The depth matched meter-based data (from offsets) is imported in ASCII format into the system. This imported data set is comprised of:-

- Interpreted Lithology
- Compressional Sonic travel time
- Gamma Ray
- Proposed Bit RPM
- Proposed WOB
- Mud Weight
- Pore Pressure
- Bit Run Length

From this data set the expert system derives:-

- Unconfined Compressive Strength
- Bit Run Hardness
- Abrasivity
- Bit Run Abrasivity (Discrete)
- Estimated ROP
- Bit Run Average EROP

These main attribute derivations, meter-based data, together with other intermediate attributes and the discrete well description are then passed to the expert systems inference engine. The inference engine processes the attribute values into the rules defined in the system to generate the bit feature, problem identification and operating practice recommendations.

ROP Estimation

Many factors influence the instantaneous rate of penetration (ROP), including rock properties, borehole and pore pressures, mud properties, bit design and wear state, operating parameters, and bit hydraulics. Further, the rate of penetration can be reduced by the occurrence of many different drillability problems such as bit or drill string vibrations, bit balling, etc…

There has been much work in the past to build models capable of predicting rate of penetration. In general these have suffered from one of two limitations. Mechanistic models usually require access to input parameters that are not normally known or readily measurable. Conversely, empirical models require calibration against ROP measurements made in the environment in question. These cannot readily make allowance for drilling problems that occurred when those measurements were made, and so have limited ability to predict penetration rate if those problems were to be controlled.

An ROP model has been developed using the concept of mechanical specific energy (MSE)[6,7]. This is the energy required to excavate a unit volume of rock. The model involves three steps. First, the minimum specific energy that can reasonably be expected at the depth in question **MSEmin** is estimated from wireline log data, lithology, and downhole pressures, using an empirical relationship developed from laboratory drilling test data. Next the power **W** transmitted by the bit into rock destruction is calculated from the weight on bit, rotary speed, bit diameter and a friction factor that is itself dependent on bit type and rock properties[8]. Finally the instantaneous ROP is estimated from the minimum specific energy, the hole diameter **Dia** and the power input to rock destruction:

$$\mathbf{ROP = 2{,}538 * W / (MSEmin * Dia\hat{}2)}$$

where **ROP** is in ft/hr, **W** is in HP, **MSEmin** is in ksi, and **Dia** is in inches. The resultant estimated instantaneous rate of penetration can be thought of as that which would be seen if the most appropriate bit for that interval of rock had been selected and if no significant drillability problems were to occur.

This model has been validated using both laboratory and field data and has been shown to be capable of making reasonable ROP predictions in a wide variety of drilling environments. It can be used in several ways in drilling optimisation projects. While planning, it can help set drilling time targets and expectations. Additionally, comparison of the model's predictions with penetration rates seen in offset wells can reveal areas of sub-optimal performance with potential for improvement. And while drilling, comparison of current penetration rates with those predicted by the model can assist the detection of drillability problems.

Application of The Expert System for Drill Bit Selection and ROP Estimation Algorithm in Western Canada

Through the summer of 2003, a 4550m vertical gas well was drilled in the foothills of Western Canada. The objective of the well was to penetrate a narrowly defined (100 x 100 m) seismic target in the Wabamun (Upper Devonian) formation to tap into a high pressure (93,000 kPa) gas pocket. Wells in the area had typically been difficult to drill, with days to Total Depth (TD) ranging from 150 to 180 days, and requiring 30-55 bit runs. The most recent (sping - summer 2000) and closest offset required 37 bits to reach a TD of 4496m MD.

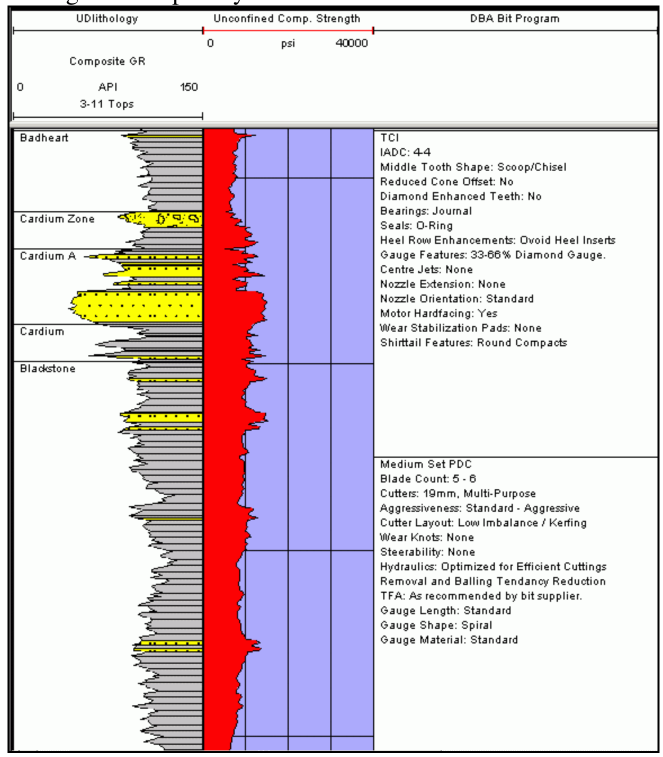
In the planning phase of the project, a detailed analysis of offset well data on 4 wells (wireline logs, strip logs, daily drilling and geology reports) identified highly variable lithology with Unconfined Compressive Strength (UCS) values ranging from ~5,000 psi to 35,000 psi throughout the well. Breaking down the UCS for the entire well is as follows:

- 5,000 - 15,000 psi in the upper to middle cretaceous formations
- 5000 - 25,000 psi in the lower cretaceous (with values as high as 40,000 psi in chert lenses in the Cadomin formation)
- 5,000 - 20,000 psi in the Jurassic formations
- 10,000 - 40,000 psi from the Triassic to Upper Devonian formations.

On past wells, bit selection had typically been based on past experience of local personal through trial and error and personal preferences, without attempting to optimize bit selection by hole interval or rock properties. In order to optimize bit selection and improve drilling performance on the target well, a detailed analysis was carried out to define the rock properties of the expected lithology, which included an estimation of rock type from depth matched offset wireline logs corrected against offset strip logs and checked against seismic profiles. UCS and friction angles were then calculated based on this predicted lithology as well as a pore pressure analysis of the entire interval from surface to TD. This information along with offset performance records, planned BHA's (Bottom Hole Assemblies), and operating parameters was studied to estimate projected bit run intervals and PDC (Poly-Crystalline Diamond) drillable lithology. Significant time was spent qualifying the accuracy of the data in order to develop the best expert system recommendations and ROP prediction possible. These data sets were then used as inputs to the expert system to develop a recommended bit program for each hole interval that identified the IADC bit type, and bit features specific to tri-cone and PDC bits; insert type, seals and bearings, heal row enhancements and gauge features, nozzle options and shirttail features for tri-cone bits, and cutter size, type, and placement, blade count, hydraulics optimization, and gauge length and style for PDC bits.

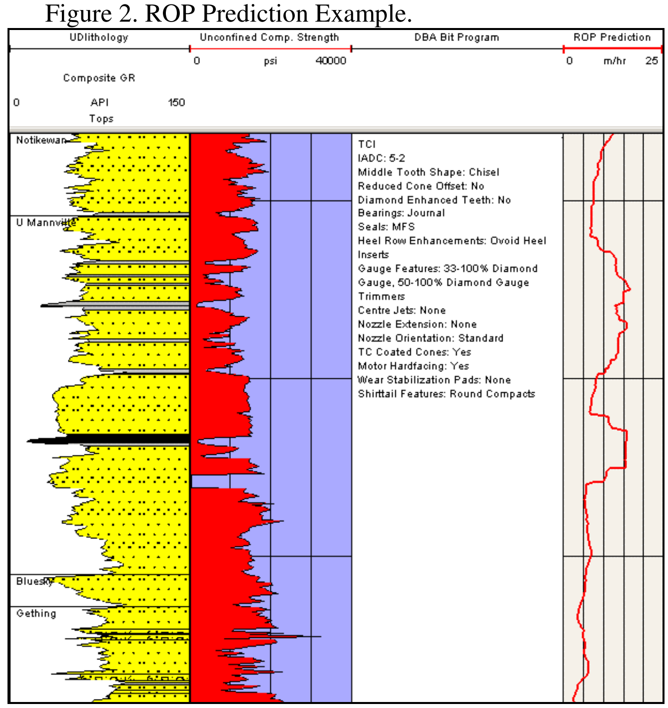
Figure 1 shows an example of the bit recommendations for an interval of interbedded sandstone, shale and conglomerate in the middle Cretaceous.

Figure 1. Expert System Bit Recommendations.



Once the bit recommendations for the target well had been developed through the expert system, this information was then added to the collective data sets and used in the ROP algorithm to calculate the technical limit ROP for the entire well. Figure 2 shows an example of the technical limit ROP in conjunction with lithology and bit selection through an interval in the lower Cretaceous to Jurassic formations.

Figure 2. ROP Prediction Example.



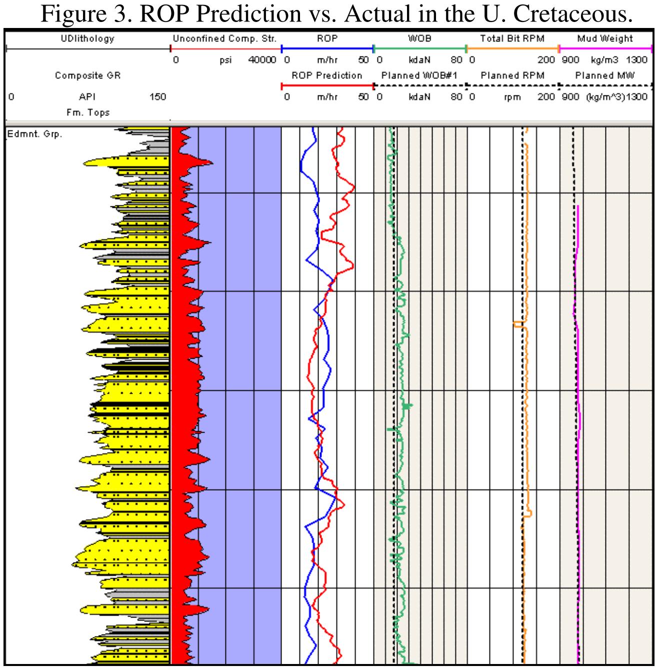
As this was the first time that the ROP algorithm was applied to a well in Western Canada, it was not proposed as an ROP target, but rather as a test case to compare the predicted versus actual ROP and evaluate the validity of the prediction. Through the drilling phase of the project, the meter based drilling data was captured and updated against the prediction, as well as all applicable drilling parameters (Weight on Bit, Rotary speed, Mud weight, Flow rate etc…) and bit selection, to compare the predicted ROP performance on an ongoing basis and collect the data for post well analysis of the effectiveness of the prediction.

Application Results

ROP Algorithm

As described above, the results of the ROP prediction were included in the pre-well planning documentation and provided at the rig site for comparison to actual results. The drilling parameters and ROP results were updated while drilling and evaluated at the end of each hole section. Figure 3 shows a comparison of the ROP algorithm prediction to actual results.

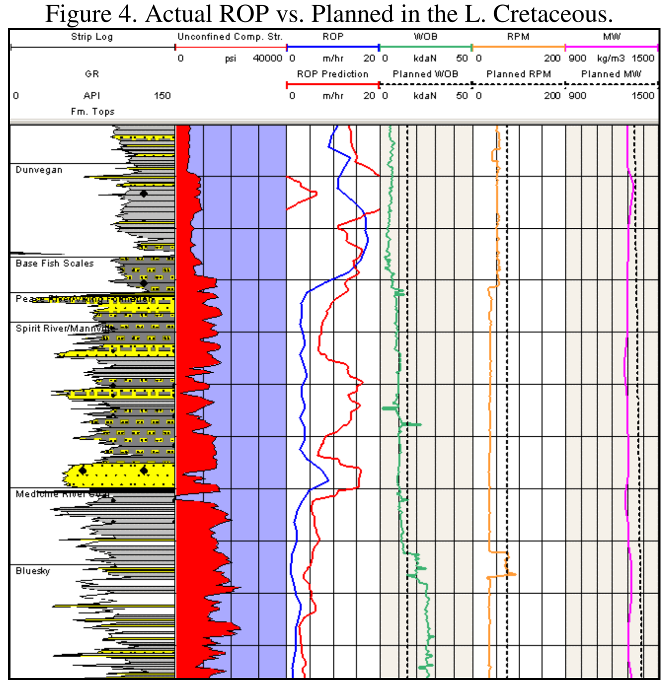
Figure 3. ROP Prediction vs. Actual in the U. Cretaceous.



In the above figure, the predicted ROP (red) has been plotted over the actual ROP (blue) along with the actual drilling parameters versus planned (dashed lines). It can be seen in this interval through the interbedded sandstones, shales, and coals in the upper Cretaceous formations that the actual ROP followed the same general trend as the predicted ROP, and there was strong correlation where the actual drilling parameters were similar to the planned drilling parameters.

Figure 4 is a plot of drilling performance through an interval in the lower Cretaceous formations that shows the differences in the actual to predicted ROP when the actual drilling parameters differed substantially from the planned values. Once again there was a good correlation in the general trend of the two curves.

Figure 4. Actual ROP vs. Planned in the L. Cretaceous.



As stated above, the application of the ROP algorithm to this well was intended to evaluate the validity and potential for use on future wells. Comparison of the predicted to actual ROP shows that where the predicted drilling parameters matched the actual drilling parameters, there was generally close agreement, and throughout the well the general trend of the actual ROP performance matched predicted. It was also found that there was generally better agreement through shale and siltstone formations than in sandstone formations, indicating there may have been some error in the pore pressure analysis. It was also observed in the planning phase that a highly detailed good quality lithology estimation was required to obtain a realistic ROP prediction.

Expert System

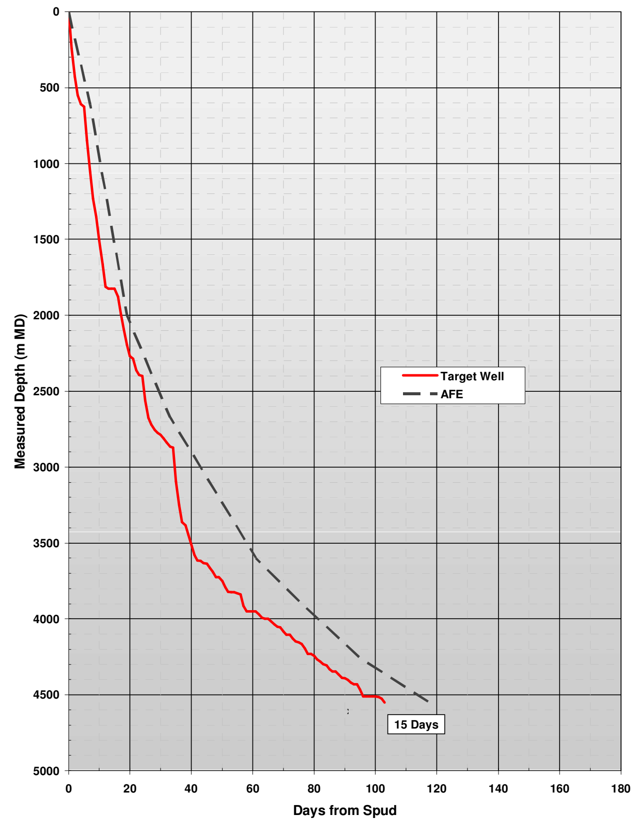
Once the expert system drill bit recommendations were finalized, they were then used as a guideline to evaluate various bit proposals to determine the best and most cost effective bit program for the well, given the availability of bits in the region. The expert system recommendations were more aggressive than the drill bit vendors recommended programs through several intervals, due to the use of application specific bit features rather than being based solely on past bit programs. The final bit program was then included in the pre-well documentation, and communicated to the field personal. The recommended drill bit selection was significantly different than past drill bit programs in the area and although significant time was spent to establish buy-in with the field personal, throughout the entire well, the recommendations were always followed due to external influences. However, when these recommendations were followed, significant increases in both run length and ROP over offset wells was experienced. The closest offset well required 37 bits to reach a

TD of 4496m MD. The target well was drilled to a TD of 4552m MD using 26 bits. The following table illustrates the bit usage by hole interval, and the ROP increases over recent offset wells (drilled since 2000). It should be noted that due to the lack of wireline or any offset log data an estimation of lithology was not possible for the 444.5mm surface hole, and so the expert system was not applied to this hole section.

Hole Section	Bits & IADC Type	Interval Length m	% ROP Increase Over Offset
Surface 444.5mm	2 1-1-5 to 4-2-7	626	0
Intermediate 311.2mm Upper Cretaceous	5 4-3-7 to 5-1-7, & 1 PDC	2052	15
Intermediate 215.9mm Upper Cretaceous - Upper Devonian	14 4-1-7 to 6-1-7 & 2 PDC	1587	52
Production 142.9mm Upper Devonian	5 5-1-7 to 5-3-7 & 1 PDC	287	60

In addition to the ROP increases identified above, bit life increases of up 33% with TCI bits were experienced. It should also be noted that while the use of the expert system was an important tool in the overall optimization of the drilling process on this well, a component of the improved performance increase must also be associated with improved BHA design, operating procedures and drilling practices. Any attempt to separate these would be subjective at best. The following plot (Figure 5) illustrates the time savings realized on this well, as compared to the AFE curve that was based on offset performance. The curve has been normalized to remove flat time events such a casing running, cementing, and surface equipment work to give a true comparison of drilling performance.

Figure 5. Normalized Time Curve versus AFE.



The normalized time curve shows that the optimization process including the use of the expert system saved approximately 15 drilling days from the planned time curve. At an average spread cost of $50,000.00 per day this translates into a cost savings of $750,000.

Conclusions

In a time when the oil industry is trying to cut costs and improve drilling performance more and more oil companies strive to better understand their exposed project risks and rewards based on their capital investment. To ensure that the balance of risk and reward is maintained it is essential to understand where improvements can be made and to what extent they may impact the overall drilling operation. Drilling optimization practices that utilize the techniques and Expert Systems presented here can not only reduce risks but better assess the amount and impact of investment required for a given drilling project. The Expert System takes into account the effects of many different variables and assesses not only their interaction but provides an estimate of drilling performance. Often engineers will optimize one component of an operation without considering how this component will be affected by the 100's of other components required to drill a best-in class or pacesetter well. The case history presented shows how drilling optimization can be achieved and how many diverse and complex variables can be better understood when assessing drilling performance at the planning, drilling, and post well review stage.

The Expert System and ROP Algorithm validated performance expectations and provided a means to improve performance on future wells in the area. Critical achievements noted were:

- 15% ROP improvement in the 311.2mm hole section.
- 52% ROP improvement in the 215.9mm hole section.
- 60% ROP improvement in the 142.9mm hole section.
- Up to 33% increase in TCI bit life.
- Overall time reduction of 15 days verses the planned AFE.

The Expert System and ROP Algorithm will be utilized on future optimization projects and the refinement of modeling process is underway to resolve misleading or screening bad log data with respect to lithology determination and comparisons with striplog data. The process described has provided encouraging results to date and the value will be further quantified on future projects.

Acknowledgments

The authors would like to thank Canadian Natural Resources Limited and Baker Hughes for their support of this project, and for their permission to publish this report.

References

1. M.J. Fear, N.C. Meany and J. M. Evans. “An Expert System for Drill Bit Selection” SPE/IADC paper no 27470, SPE/IADC Drilling Conf., Society of Petroleum Engineers, Dallas 1994.
2. J. M. Evans, M. J. Fear, N. C. Meany. “A New Graphical Representation for Rule Definition and Explanation in an Expert System”. Proceedings of Expert Systems ’95, 15th Annual Tech. Conf. of the British Computer Society Specialist Group on Expert Systems, Cambridge 1995.
3. N.C Meany, L. Ledgerwood, D.A. Curry and C. H. Cooley, US patent no 6,353,799, Method and apparatus for determining potential interfacial severity for a formation.
4. C. H. Cooley, D. A. Curry and L. Ledgerwood, US patent no 6,386,297, Method and apparatus for determining potential abrasivity in a wellbore.
5. D.A.Curry, P.B. Perry and J.M. Evans. “New Method Of Representing Rock Properties Over Entire Bit Run Improves Computer Generated Bit Recommendations” SPE/IADC paper no 87100, SPE/IADC Drilling Conf. Society of Petroleum Engineers, Dallas 2004.
6. R Simon, “Energy balance in rock drilling”, SPEJ (Dec 1963) 298-306.
7. R Teale, “The concept of specific energy in rock drilling”, Int J Rock Mech and Mining Sci, 2 (1965) 57-73.
8. R Pessier and M Fear, “Quantifying common drilling problems with mechanical specific energy and a bit-specific coefficient of sliding friction”, SPE paper no. 24584, presented at 67th SPE Annual Technical Conference and Exhibition, Washington, DC (Oct 1992).