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ROP Enhancement in Ultrahard Rock

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Abstract

Drilling the Middle and Upper Bunter formation (Triassic) in North-West Germany has been a challenge for nearly 40 years. The Bunter is a hard and very abrasive formation, typically in a depth range of 8000ft – 12500 ft. It consists of layers of quartzitic sandstone and silificated claystone. Low ROP and extremely high wear of tools is characteristic for drilling this formation. To improve the performance and decrease cost/ft, intensive research was done in the past.

This paper deals with the results of the analysis of historical data and the development of bits, motors and other BHA components to one system. This BHA system is to enhance ROP and reduce trips due to dull bits or BHA and drillstring failure. To date, 15 runs of these improved BHA systems have been performed. Performance data have been analyzed and will be presented to document improvements achieved. An outlook for future opportunities will be given.

Drilling the Bunter is still time consuming and expensive. In the past, typical ROPs in 12 1/4" sections were 3 – 6ft/hr. Back in the 1970's and 80's, 15 to 20 insert bits were required to drill the section and reaming was necessary due to under-gauge bits. Both, low ROP and short bit life contributed to significant total section times. The combination of new impregnated bits and new downhole motors together with improved hydraulics in larger ID drillpipe were the basis for improvement. Today, with an optimized system, ROPs of 8 – 19 ft/hr have been achieved. In addition, it is now possible to drill the bunter section in one trip. Two world records, for single footage and cumulative footage of an impregnated bit are held within EMPG (German ExxonMobil affiliate) in this section.

In recent and upcoming wells, new motor developments are tested to repeat latest successful results and to further improve ROP. In addition, a different bit design will be run for further potential ROP enhancement. Significant reduction of section time justifies the application of more sophisticated and more expensive tools on German land rigs to further reduce cost/ft.

Introduction

In the 1990s a research project was initiated and funded by the German drilling industry to improve ROP in ultrahard and abrasive formations. In the past, this section was characterized by lowest ROP, shortest bit life and highest cost per foot. As a potential for improvement, the increase of the depth of cut of impregnated bits in the Middle and Lower Bunter was identified. In the case of impregnated bits, depth of cut means the length which is drilled with one revolution of the bit. An increase in depth of cut can be achieved by a decrease of overbalance or an increase in the amount of power available for drilling the rock.

In order to analyze the key parameters, drill-off-tests or drilling tests at fixed drilling parameters have been conducted and plotted into Bingham-Diagrams[1].

Within the German drilling industry, two approaches to increase ROP have been chosen – use of down hole turbines and use of high-speed downhole motors in combination with improved hydraulics due to larger ID drillpipe.

This paper deals with results from downhole motor runs with impregnated bits. The characteristics of downhole motors allow more accurate estimates of bit-RPM and bit torque than those of turbine applications. Larger ID drillpipe gives the opportunity to determine the effect of the flowrate on ROP within a broader range. All results are based on 12 ¼" bit size because this is the most common bit size in the Bunter formation in Germany. The results, although derived from downhole motor runs, can be used for turbine drilling applications as well.

Change of drilling parameters within the last decade

The Bunter is a hard and very abrasive formation, typically in a depth range of 8000ft – 12500 ft. It consists of layers of quartzitic sandstone and silificated claystone with a compressive strength of 30 to 50 ksi. In the past, typical ROPs in 12 1/4" sections were 3 – 6ft/hr. In the 1970's and 80's, 15 to 20 insert bits were required to drill the section and reaming was necessary due to under-gauge bits.[3]

Continuous development and improvements in BHA components shift the limits of drilling parameters. The right balance between the system of bit, BHA, drilling parameters and formation is the main driver for ROP enhancement.

Weight on bit and revolutions per minute

Up to 1997, the standard for high-speed downhole motor was 400 rpm at 790 gpm (360 HP). In 1997, a 9 ½” downhole motor was tested in Germany. The limit for revolutions per minute was moved to 780 rpm at 840 gpm (515 HP).

In 2004, another new 9 ½” downhole motor was developed on demand of EMPG, delivering 975 rpm at 1055 gpm (1025 HP). This motor uses a precontoured stator covered with an elastomer of constant thickness.

The maximum permanent weight on bit of high-speed downhole motors in 2004 was limited to 21.4 t (48,100 lbs). The limit for the 975-rpm downhole motor was increased to 27 t (60,700 lbs) by improvements of bearings. A further increase in weight on bit capability can be achieved by again better bearing technology. Figure 1 displays, how the limits for weight on bit and revolutions per minute have changed over the last decade.

Flowrate

The standard casing scheme in North-West Germany accounts for salt sections at relatively deep TVD (up to 13,000 ft) in the open hole above the Bunter. The mudweight, required to handle the salt, varies between 13.3 ppg and 15 ppg, depending on TVD. Using 5” DP, common flowrates with this mudweight were limited to 600 gpm to 660 gpm. Due to this high mudweight and low flowrates, turbines could not be used effectively because of their high differential working pressure. Therefore the application of downhole motors was preferred. The flowrate with high-speed downhole motors was increased from 790 gpm before 1997 to 840 gpm in 1997 and 1055 gpm in 2004.

Today, the use of 6 5/8” DP allows to operate the 975-rpm downhole motor in a large range of parameters up to the operational limits of these motors. Even at mudweights of 13.3 ppg to 15 ppg, the common rig pumping pressure limit of 5000 psi is sufficient. The use of turbines in the Bunter formation is still not efficient at these parameters.

Influence of drilling parameters on depth of cut of 12 ¼” impregnated bits

The DOC of impregnated bit depends on bit-RPM, WOB and flowrate. ROP depends on RPM. RPM of a motor depends on flowrate. The flowrate again has a direct influence on bottom hole cleaning, and this – again – effects ROP. These two effects on ROP can almost be separated by introduction of depth of cut per revolution.

The influence of these parameters cannot be found by laboratory research due to large bit size, high RPM, high bottom hole pressure and availability of adequate formation material at surface. Therefore, influence and relation of the drilling parameters were derived from actual drilling data and drill-off tests.

Bit revolutions per minute

Data at different bit-RPM has been collected for rotary drilling (up to 220 rpm), 400-rpm motor applications (bit-RPM: 450 to 550 rpm), 780-rpm motor applications (bit-RPM: up to 830 rpm) and 975-rpm motor applications (bit-RPM: up to 1075 rpm). Plotting such data at a constant weight on bit shows a dropping tendency of the depth of cut curve corresponding to increased bit-RPM, as shown in figure 2.

Transferring this to ROP, the increase of ROP is not proportional to the increase of bit-RPM. Data from drill-off tests at different flowrates show a significant increase in depth of cut with higher flowrates (eg. figure 6).

Weight on bit

The depth of cut is directly linked to weight on bit and increases with higher weight on bit. The influence of weight on bit increases with higher flowrates (eg. figure 6).

Influence of overbalance on depth of cut

The influence of overbalance for drilling with rollercone bits and drag bits is well known in the drilling industry. For impregnated bits, however, this influence was masked by relatively low ROP. The decrease in ROP with increase of overbalance is qualitatively lower than with rollercone bits, but existing.[2]

Drill-off test data show, that the influence of flowrate is larger in very high overbalance situations. Wells that did not achieve noticeable depth of cut at flowrates below 660 gpm could be traced back to high differential pressures at bottom. This leads to the conclusion that a bottom hole balling effect occurs at high overbalance. A bed of fine cuttings and mud components hinders the diamonds-formation-contact at insufficient flowrates. An increase in flowrate leads to clean out of this bed, resulting in a higher depth of cut.

The higher bit-RPM, the shorter the contact time of mud and cutting bed. This could be an explanation for higher depth of cut of rotary BHA at lower bit-RPM than at high bit-RPM. Flowrate or bit hydraulics are essential for depth of cut and have to be in a proper relation to bit-RPM. At high bit-RPM, the flowrate must be sufficient to clean the cutting bed, before the subsequent segment of the impregnated bit re-drills the cuttings again.

New 975-rpm downhole motor

Results from drill-off tests show an almost linear relationship of depth of cut and flowrate. The former high-speed downhole motor was limited to 840 gpm.

A new downhole motor was developed and built in 2004 to examine the potential of further increase in depth of cut by increasing flowrates. A change in inclination of the 1/2-lobe contour resulted in a significant benefit in motor-RPM. Furthermore, the maximum flowrate was increased by more than 25% from 840 gpm to 1055 gpm. These improvements result in an almost 100% increase in nominal power output from 515 HP to 1025 HP.

At a flowrate of 1055 gpm, the nominal motor-RPM is 975 min^{-1}. This new downhole motor uses a new stator technology. Instead of a conventional stator, the stator is precontoured in the steel of the stator pipe. It is covered by a thin layer of polymer[4].

Due to improved bearings, higher weight on bit can be used and durability of the motor is enhanced. Typically, this type of motor is run with a long bearing housing stabilizer both in a rotary hold and build BHA for performance drilling.

New generation of impregnated bits and stabilizers

New materials and manufacturing processes made it possible to build 3rd generation impregnated bits in almost any design. A typical impregnated bit for drilling the Bunter formation in the late 1990s had a continuous cutting structure like the left bit in figure 3[4]. Typically, these bits were worn down after less than 500 ft in the Bunter section. The amount of diamonds has increased since then to make the bits more durable. The 3rd generation 12 ¼” impregnated bit has almost the fourfold amount of diamonds compared to an impregnated bit of the 1st generation (figure 4). Improved cooling of the impregnated bit segments of new generation bits was achieved by an interrupted cutting structure and optimized fluid courses like the right bit in figure 3[4]. For the application with high-speed motors, bits with a long gauge (initially 12”, now 13”) are used to prevent a spiral hole and to replace the near bit stabilizer. Near bit stabilizers used to wear down very quickly at high RPM, especially in deviated wells.

The wear of stabilizers is also an issue for the quality of the wellbore and the wellpath. Some of the conventional tungsten carbide protected stabilizers showed total wear after a 140 hrs run in the Bunter formation. A new stabilizer design with diamond protection was tested in four runs in three Bunter sections at a total length of 2960 ft and 240 hrs (figure 5). This development shows a significant reduction in wear and contributes to a better quality of the wellbore.

Field data

Within the last three years, data from six wells drilling the Bunter section with 780-rpm and 975-rpm downhole motors and impregnated bits were collected and analysed. The following sections deal with data from drilling the Middle and Lower Bunter formation with these BHA.

Well A (2003)

In 2003, the combination of a 12 ¼” impregnated bit with new design, a 9 ½” 780-rpm motor and 6 5/8” drillpipe was run for the first time. The total footage drilled was 2507 ft (764 m) and the inclination was increased from 36° to 48° according to plan. At the first roundtrip after drilling 1093 ft (333 m) of the Middle Bunter, the remaining height of the cutting structure was 0.4” (new: 1”). The remaining 1414 ft (431 m) of the section were drilled with a new bit. This bit had a remaining height of the cutting structure of 0.7” when pulled out of hole. In this well, the overbalance was 1650 psi.

Data from drill-off tests at different flowrates were used to calculate depth of cut. The resulting curve for the depth of cut over weight on bit is plotted in figure 6. The influence of flowrate and WOB on depth of cut and ROP is clearly demonstrated.

As mentioned above, the overbalance has a significant influence on drilling performance with impregnated bits. This indicates, that a higher flowrate is needed to prevent bottom hole balling when drilling with higher overbalance.

Well B (2004)

Well B was the fifth well in a field. The Bunter sections of this well and the preceeding well in this field were very similar. In this section, the same type of BHA was used as in well A – including the impregnated bit from the second run of well A. The mudweight was nearly at balance with the pore pressure in the Bunter. For the first time in this field, the 1920 ft Bunter section was drilled in one run with a 12 ¼” BHA. The average ROP was 14.7 ft/hr which is twice as much as the preceeding wells in this field (figure 7).

This bit drilled a total of 3333 ft in two runs and set a world record for 12 ¼” impregnated bits. After about 15 million revolutions at more than 750 rpm in deviated wells, the bit was still in gauge. In this well, the mudweight was close to pore pressure.

Figure 8 shows no major influence of the flowrate on depth of cut. This confirms the conclusion from well A, about the influence of the overbalance.

Well C (2004)

On Well C, two different high-speed downhole motors were used. The mudweight was nearly at balance with the pore pressure in the Bunter. ROP of previous wells in this field in the 1990s were around 3 ft/h in 8 ½” hole and less in 12 ¼” hole. The average ROP in this well was 8.8 ft/h, the maximum ROP was nearly 10 ft/h. The main differences between both motors were transmission (1/2 lobe and 2/3 lobe) and limitations in flowrate (850 gpm and 1060 gpm).

Data from drill-off tests of both motors at different flowrates are plotted in figure 9. On one hand, the curves indicate potential for depth of cut enhancement at lower revolutions per minute and at significantly lower flowrates. On the other hand, a minimum flowrate for sufficient bit cooling and hole cleaning has to be guaranteed.

This means, when drilling with impregnated bits, the influence of revolutions per minute on depth of cut is also significant and strongly associated with bottom hole cleaning. According to this, there are two strategies to increase ROP as a product of RPM and depth of cut. First, an increase of depth of cut at high RPM can be achieved by improved bottom hole cleaning in nearly balanced wells, too. The second way is to increase RPM and weight on bit. The method used to optimize ROP will depend on the specific application.

Well D (2004)

On well D, for the first time, a prototype of the 975-rpm downhole motor was used. At a maximum flowrate of 1055 gpm and string-RPM of 60 to 100, the bit was rotating at more than 1000 rpm.

A maximum ROP of 19 ft/hr was achieved at maximum flowrate and a weight on bit that was operationally limited to 50% of the nominal. This ROP is a 20% increase compared to well A at the same weight on bit and a lower (maximum) flowrate of 845 gpm. The average ROP was 12.9 ft/h.

In the Bingham-Diagram (figure 10) the influence of weight on bit and flowrate on depth of cut is as expected for a significantly overbalanced situation. For flowrates of 490 gpm and 635 gpm the depth of cut curves show the same behaviour like the curves for 530 gpm and 690 gpm in well C. At higher flowrates of 950 gpm and 1030 gpm, the depth of cut curves show the same behaviour like the curves with high flowrate in well A, B and C.

On this well, both effects on bottom hole cleaning – overbalance and revolutions per minute – were recognized.

Well E (2005)

Well E was drilled in close vicinity to the field of well C. The average ROP in this well was 10.1 ft/h.

In this well, the new diamond protected stabilizer was run for the first time and it was the second application of the 975-rpm motor. At a high weight on bit, the wear of the bit in the upper part of the Middle Bunter formation was much higher than expected. It was found, that – in these extremely hard and abrasive formations – high temperatures were generated at the bit and even flowrates of 1000 gpm were not sufficient for bit cooling. The diamond protected stabilizer was still in a good shape to be run on well F after finishing the Bunter section on this well. Figure 11 gives a historical overview of the average ROP in this region and also the recent wells C and E.

Well F (2005)

Well F was drilled in the same region as well D. The average ROP on this well was 13.1 ft/h. Figure 12 shows a comparison of the recent wells D and F and a well from the end of the 1990s in the same region. This shows that results from well D are reproducible with the system consisting of a 975-rpm motor and a 3rd generation impregnated bit.

The BHA in this well was similar to the one used in well E with the 975-rpm motor and the diamond protected stabilizer. Only the impregnated bit on this well was delivered by a diffent manufacturer but had a similar amout of diamonds. Specifications for this bit and experiences from bit wear in well E were reasons for initial limitations in weight on bit. The whole section of 1517 ft (462.5 m) was drilled with one bit that showed 50% wear when pulled out of hole and which was still in gauge. The diamond protected stabilizer was good for another run in the next Bunter section.

Results

Drill-off tests and tests with constant drilling parameters show the relationship of depth of cut, flowrate and weight on bit for drilling with systems of impregnated bits and 780-rpm or 975-rpm motors (figures 6, 8, 9 and 10). The increase of ROP in different regions (figures 7, 11 and 12) demonstrates the success of continuous improvements of bits and downhole motors, resulting in optimized drilling parameters.

Flowrate and revolutions per minute as well as overbalance have been identified as parameters with significant influence on depth of cut when drilling with impregnated bits in hard and abrasive formations. An improvement in bottom hole cleaning is seen as the next step on the way of ROP enhancement.

Figure 13 shows a combined diagram of drill test and drilling data from wells D, E and F. It can be seen, that drilling data at different flowrates and weights on bit from recent wells confirm the results of drill test from previous wells. Target is, to keep the operating range above a weight on bit of 20 t to 25 t to achieve a depth of cut more than 0.12 mm per revolution at the highest possible revolutions per minute.

Drilling data from monitoring future wells will be used for further optimization of drilling parameters and tools in order to improve drilling performance.

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Figure 1: Weight on bit and revolution per minute increases since 1997

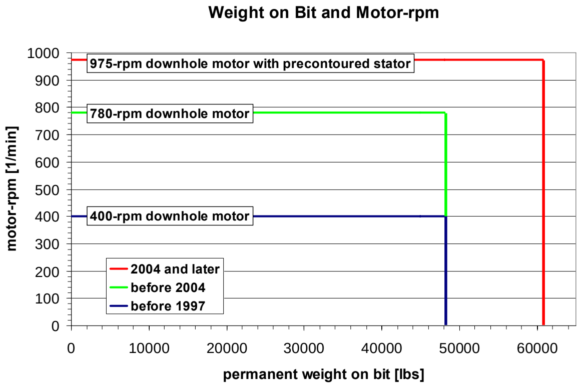

Figure 2: Depth of cut per revolution vs. revolution per minute in a 12 ¼" hole

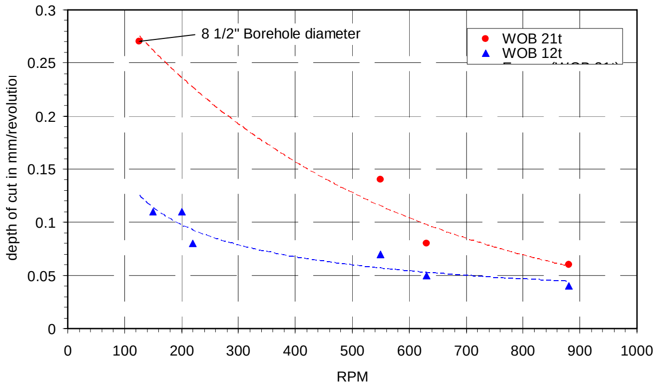

Figure 3: Impregnated bit with continuous (left) and interrupted (right) cutting structure[4]

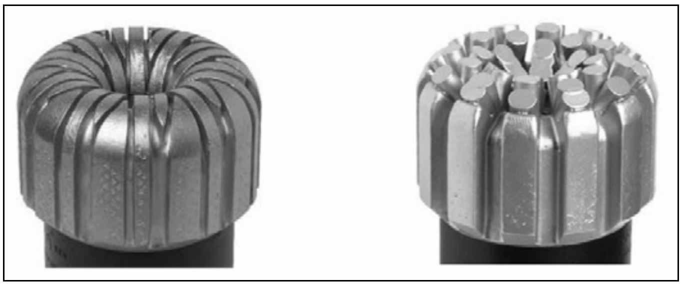

Figure 4: Increased amount of diamonds in new bits

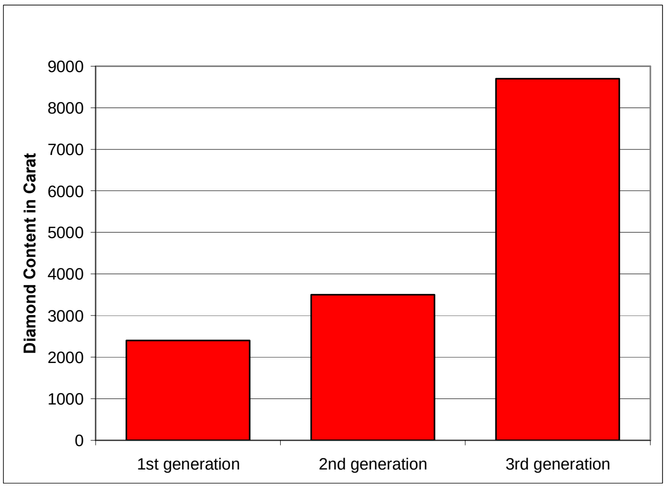

Figure 5: Conventional tungsten carbide protected stabilizer after 140 hrs in a hard and abrasive Bunter section (left) and diamond protected stabilizer after more than 240 hrs in different wells (right)

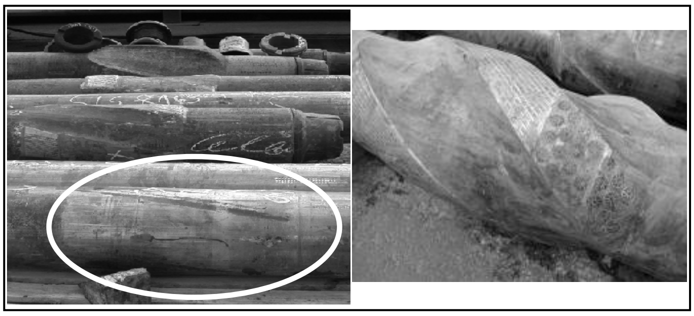

Figure 6: Well A – Depth of cut over weight on bit

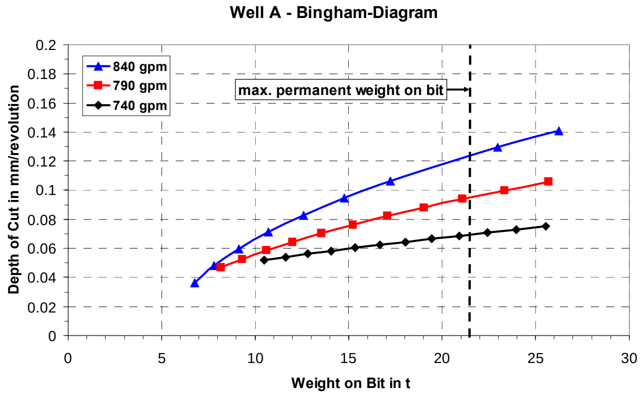

Figure 7: Well B – ROP enhancement with new technology

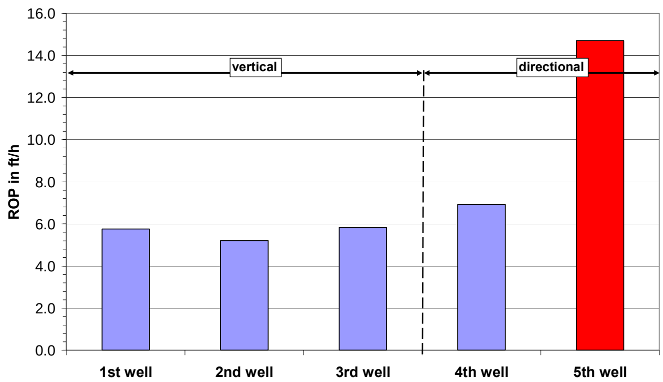

Figure 8: Well B – Depth of cut over weight on bit

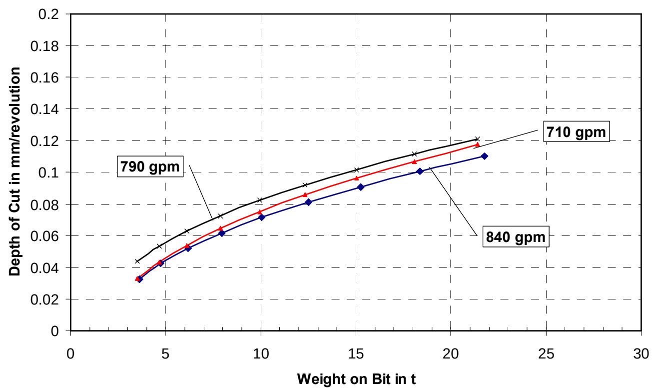

Figure 9: Well C – Depth of cut over weight on bit

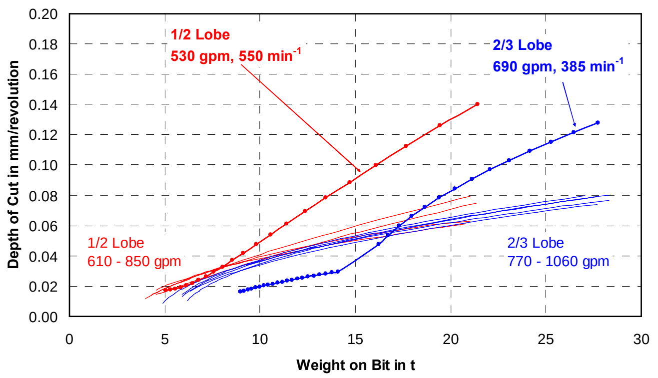

Figure 10: Well D – Depth of cut over weight on bit

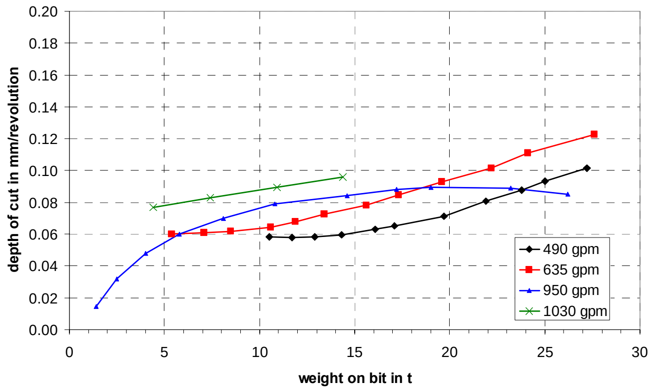

Figure 11: Overview of ROP enhancement in 8 ⅜" and 12 ¼" hole section

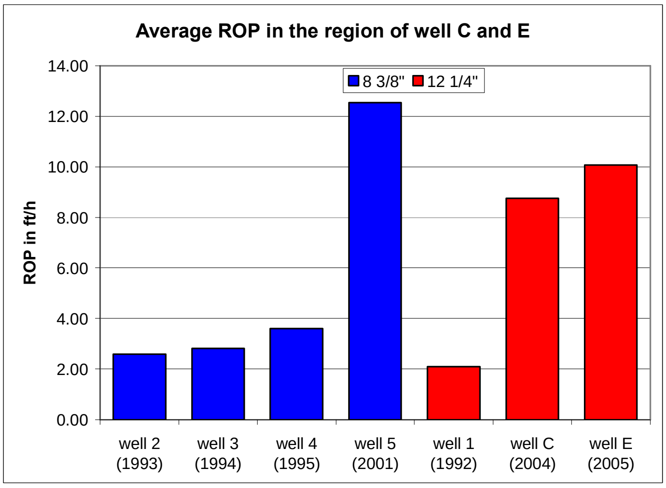

Figure 12: Comparison of ROP in 12 ¼" hole section

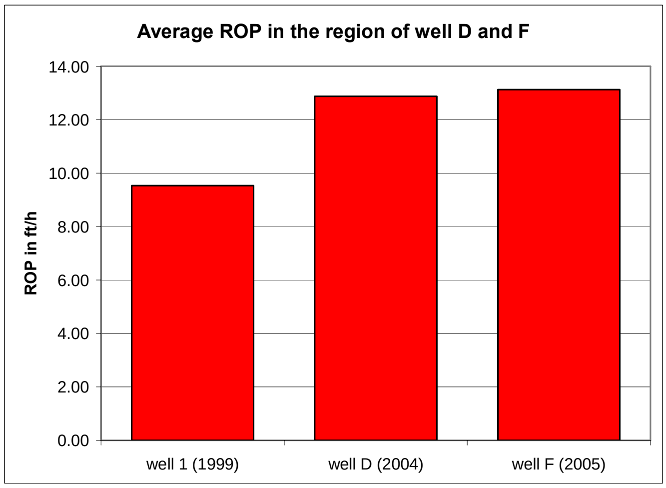

Figure 13: Drilling data and drill-off test frame