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Hydraulics Optimization Research in Large Diameter Bits Reduces Operator's Variable Costs

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Abstract

Operators demand continuous improvements in drilling efficiency to reduce their costs. Improvement in ROP is the most important factor in reducing variable costs and the drill bit is a critical element in this advancement.

Down-hole bit balling is a common problem that negatively affects penetration rates. This is especially true when drilling large diameter surface intervals. While these intervals are usually softer formations they are often sticky and yield slower ROP than expected. Down-hole balling is the most likely cause of these slower-than-expected penetration rates.

Improved research technology allows us to make improvements in hydraulic cleaning and now allows us to do much of the expected performance verification prior to actual field tests. This paper examines the R&D process undertaken to enhance hydraulic cleaning for reduced bit balling and improve ROP in roller cone bits larger than 12 ¼-in. diameter. It also reviews the associated ROP improvements and subsequent cost reductions.

Introduction

While there has been extensive research in hydraulics configurations for roller cone bits, the vast majority has involved smaller diameter bits. This research is still critical to studying hydraulic configurations, both for the small bits and bits in general, but we feel there is a definite need for increased research into hydraulics configurations specific to larger diameter bits.

It is important to understand the prior research that has brought us to this point. The first portion of this paper briefly details the background of some of the hydraulics research before going into the more recent large diameter bit research.

Background

Conventional hydraulics configurations for roller cone bits have basically been the same since the introduction of jet bits - three nozzle ports essentially directed fluid straight to the bottom of the hole. The flow was then forced back up the annulus without effectively cleaning the cones. In fact, it created stagnant zones, indicated by the yellow ovals in the graphics, which correspond to where inserts actually contact the bottom of the hole. **(Figure 1)**

While this was the accepted configuration in the industry, it did not effectively clean the cones or the bottom of the hole. A more effective cleaning pattern was needed.

This pattern was achieved with the development of the patented Mudpick (MP) hydraulics, which use slightly extended directional nozzles to precisely direct the fluid flow tangentially to the leading edge of the cutter trailing the nozzles. This action cleans the teeth or inserts prior to engagement of the cutting element with the formation, and then cleans the bottom of the hole. It also shifts the previously mentioned stagnant zones closer to the annulus area and more effectively cleans the inserts that are actually contacting the bottom of the hole, as indicated by the green dots in **Figure 2.**

The improved cleaning effect of this hydraulics configuration delivered ROP increases of up to 25% in laboratory tests. Field tests produced ROP increases of approximately 15% - 20%. These increases were particularly evident in low HSI applications such as with low flow rates or on motor applications. Details of the testing can be found in **Reference 1**.

Further testing developed other fluid-flow angles with continued improvements in cleaning the cones and the hole bottom. This led to the second generation of patented, directed-flow hydraulics commercially known as Mudpick II (MPII), which has a different flow angle and impingement point at the critical gauge area of the cones. **(Figure 3)** Laboratory tests of this angle delivered ROP increases of 70% and field tests provided ROP increases of 15% - 50%.

The precise nozzle direction required to achieve both patterns was arrived at through extensive testing in the ReedHycalog pressurized drilling laboratory (PDL), utilizing a pressure simulation vessel and visual flow chamber. The PDL **(Figure 4)** is essentially a small drilling rig in the laboratory, which provides the power for WOB and rpm, as well as flow rate and pump pressure, through two 500hp triplex pumps. Controls and all data gathering systems are computerized. Details of the testing can be found in **Reference 2**.

The pressure vessel is part of a closed mud system, which holds a core of specified rock formation that is subjected to different flow rates, mud weights and mud types to simulate down-hole drilling conditions. The visual flow chamber is a clear acrylic cylinder representing the borehole that allows visual inspection of actual fluid flow through the bit nozzles. **(Figure 5)** High-speed photography records the fluid flow patterns on the bit and the film is played back frame-by-frame to assist in evaluating the test.

Thousands of bits with an extended and precisely directed nozzle configuration have been used worldwide. This nozzle configuration is now the most accepted way to increase ROP. **(Reference 3)**

Big Bit Testing

The tests described in the previous paragraphs were performed with 7 7/8-in., 8 ½-in., 8 ¾-in. and 9 7/8-in. bits and could not take design differences of larger diameter bits into consideration. While our large diameter insert bits already utilize MPII hydraulics, (and we had seen significant ROP improvements as a result), previous field tests of large diameter tooth bits with that hydraulic configuration indicated some erosion on tooth hardmetal. Therefore, that particular angle was not used on commercial tooth bits and further testing had not been performed.

Previous laboratory testing was also limited to bit sizes 12 ¼-in. and smaller because of limitations imposed by test equipment. For more extensive testing on larger bits we designed and developed a visual flow chamber and pressure simulation vessel, which allows us to perform laboratory tests on bits up to 17 ½-in. in diameter. **(Figure 6)** Some design tools have also been improved.

Computational Fluid Dynamics (CFD) is now critical to hydraulics design. **(Reference 4)** CFD is the science of predicting fluid motion as well as heat and mass transfer by simulating computer models. CFD uses physical laws governing the motion of fluid that are determined numerically by solving incompressible Navier-Stokes equations for the conservation of mass, momentum and energy. The computer calculations are extensive and may be used for:

- velocity, pressure and temperature distributions
- bit and formation shear stresses
- flow turbulence information and flow path lines

While CFD has been in use for several years, the models created in the past were forced to undergo many simplifications due to the inability of computer hardware to provide a simulated result in a satisfactory period of time. As computer technology has advanced so has CFD and it is now possible to provide accurate bit design models to simulate and predict the complex turbulent fluid path around a drill bit. More importantly, many hydraulic modifications may be processed as part of the design/research process to allow us to more accurately view actual flow patterns on a bit design prior to manufacture. **(Figure 7)**

CFD Computation Results

Large diameter simulation vessels and CFD were not available at the time of MP II development so detailed tests had not been conducted to precisely determine the effects this hydraulics configuration has on cleaning. This was of particular interest because the distance from the nozzle to the cutter face and the bottom of the hole was substantially further from the exit point of the nozzle than with smaller diameter bits.

The primary objective of the tests was to find an angle that delivered performance equal to MPII hydraulics without creating erosion on the tooth hardmetal. CFD modeling was performed on a 16-in. 1-1-5 IADC code bit with MP hydraulics. This was designated the standard (std) bit in the tests. While the modeling on the std bit displayed some cleaning action from the fluid, much of the action remained in the area directly below the nozzle exit **(Figure 8)**. A change in the angle produced more sweeping action and moved the impact of the fluid closer to the cones prior to engaging the formation. **(Figure 9)** This angle was chosen for the laboratory test bit.

Figures 7 and 9 show the plan and isometric views of the optimized drill bit that display the fluid flow path colored by velocity magnitude. They clearly illustrate the improved sweeping fluid path as the jet impinges the borehole and sweeps over the cutting structure. This improved cleaning action has already been observed in our smaller bit range and enabled the rotating cutter teeth to be cleaned immediately before plunging deeper into the formation. Once the optimized jet impingement had been finalized it was decided to build a prototype bit so that laboratory tests could be performed.

Laboratory Test Results

A performance baseline was established using the std bit. The test bit used an identical cutting structure to help maintain controlled conditions. All laboratory tests used Mancos Shale in the pressure vessel since it has a tendency to ball-up at low HSI conditions (rock properties can be found in **Table 1**). All tests were conducted under similar conditions: 45,000 lb WOB, 100 rpm, 300 gpm and 700 psi borehole pressure. All bits used three 14/32-in. jets with no center jet. HSI for these tests was held at 0.32 to help induce balling.

There were 27 different PDL tests conducted on the std and test bits drilling through the 36-in. cores of Mancos Shale. Cores would be drilled at consistent parameters and the PDL would measure and record the

ROP. The bits were pulled out of the pressure vessel following each test and inspected for the amount of balling.

Although there were different degrees of balling on the std bit tests, the std bit consistently displayed heavy balling tendencies. **(Figure 10)** The test bit was consistently much cleaner when pulled from the PDL tests. **(Figure 11)** The test bit had varying degrees of ROP improvement but achieved a higher ROP than the std bit in all tests. Analysis of the data following the tests indicated that the nozzle angle in the test bit provided up to a 35% increase in ROP over the std bit. Based on the laboratory tests it was recommended that a series of field test bits be built.

Field Test Results

The test nozzle angle was used on both 1-1-5 and 1-3-5 bits. Several applications were identified that typically suffer from down-hole balling problems or were suspected to have down-hole balling because of slow ROP.

At the time of publishing this paper, field tests had been performed in three different applications – all offshore. Three 1-1-5 bits have been run on the Northwest Shelf in Australia, one 1-1-5 bit has been run off the east coast of Canada and two 1-3-5 bits have been run in the Mediterranean Sea off the coast of Egypt.

It is generally understood that it is extremely difficult to precisely duplicate field conditions from well to well to ensure accurate field test data. However, we were able to field test our bits directly against our std bits in two of the three cases. In all cases, we were diligent in comparing bits with like-run conditions as closely as possible.

AUSTRALIA

The std bits and test bits for this application, which carry an IADC code of 1-1-5, are the same as used in the laboratory tests. The formations drilled consisted of siltstone, claystone, marl, limestone and calcarenite. Because there were both vertical and directional applications in this test area, results are reported separately.

Vertical

One test bit was run against four of the std bits and four other runs we will refer to as X. The WOB, rpm and TFA were similar in all cases. Center jets were run in all bits. Note that the test bit had 10% less flow rate than the next closest flow rate and 32% less than the highest flow rate. Depth-in for all bits was similar and meters-drilled ranged from 456 to 996.

The test bit drilled at an average ROP of 48.5 m/hr, 42% faster than the average ROP of the std bits. The test bit also drilled 15% faster than the X bits. **(Table 2)** No increased erosion was observed on the test bits.

Directional

Two test bits were run against three std bits and four X bits. Once again, WOB, rpm and TFA were similar throughout the bits in the study. Depth-in for all bits was similar and meters-drilled ranged from 678 to 1187. Note that the two test bits drilled the longest and third longest intervals. Formations drilled were the same as in the vertical tests. All bits started drilling at 0^0 and built to an approximately 25^0 inclination. **(Table 3)**

In this case the test bits drilled at an average ROP of 58.4 m/hr, 30% faster than the average of the std bits. They also drilled 21% faster than the X bits in the study.

CANADA

There were no std bits run in this area for comparison of identical cutting structures. However, there were two X bits used with the same 1-1-5 IADC code as the test bit so the cutting structures were similar. The bits were all run in the Banquereau formation, which consists primarily of claystone, limestone and siltstone with traces of chert and quartz pebbles. All runs were directional with the final inclination ranging from 17.8^0 to 53^0. Depths-in were similar and meters-drilled ranged from 998 to 1418. The test bit had the highest build rate at 53^0 and the longest run at 1418 m. **(Table 4)**

The test bit drilled an average ROP of 107.8 m/hr while the X bits drilled an average ROP of 58.3 m/hr. This is a 45.7% increase over the X bits.

It is possible that the large difference in ROP between the test bit and the bit run on well A-1 is due to the improved cleaning on the gauge area of the test bit's cones, providing improved side-cutting action. No increase in erosion was reported.

EGYPT

The application for this test was harder than the previous tests and required harder formation bits. The bits used are designated as 1-3-5 IADC code and therefore have a higher tooth count and shorter tooth protrusion than the bits in the other field tests and in laboratory tests.

However, the nozzle angle for the std bits in this test was the same as for the other tests. Therefore, we will refer to them as std bits. The nozzle angle for the test bits in this test was the same as the test bits in the other tests and we will refer to them as test bits. The other bits in this test had similar 1-3-5 IADC cutting structures and they will be referred to as X.

This test was more difficult to evaluate and provided conflicting results. In an effort to normalize the data runs were separated into bits with a shallow entry point of 10 m **(Table 5)**, and a deeper entry point of, 348 - 800 m **(Table 6).** This also split the offset runs into deviated trajectories in the deeper entries and essentially vertical holes on the shallow entry runs.

One test bit was in the deeper entry point category and displayed significantly slower ROP. However, it was a side-track run so it is difficult to accurately compare and it was not considered in the test results.

The other test bit fell into the shallow entry category but drilled the longest interval of all the offset runs and included the highly deviated lower interval. When compared to the vertical wells it was 18% slower than the std run and 34% slower than the X run. However, it drilled 108% more interval than the std bit and 51% more interval than the X bit.

When compared to the deeper entry directional runs the test bit drilled 5% slower than the X average but 20% faster than the std average. It also drilled at least 25% more interval than either the std or X average. Other than the test bit, one std bit drilled a comparable interval (only one meter less) and had a 3% slower ROP. However, it drilled in the more difficult lower entry point category and had the highest build rate.

The variations in the data and the inconsistency of the results warrant further testing using this cutting structure. We will also construct CFD models with this cutting structure to determine if a different nozzle angle may be required.

These tests did allow us to evaluate the erosion potential of this nozzle angle on the cutting structure. Both bits were run for extended periods, 113 hours, with no increase in erosion noted.

Conclusions

While the number of field tests provided a smaller number of data points than preferred, it should be noted that the number of proper applications in large diameter bits is less than in small diameter bits. Therefore, extensive prior research was taken into consideration when making some recommendations.

Complex CFD modeling of the bit was used to study flow characteristics and determine the optimal impingement angle. The CFD models delivered a nozzle angle that provided more bottom hole sweeping action than MP hydraulics and placed the impact point of the fluid closer to the cone.

The performance viewed during the full-scale laboratory drilling tests indicated that the new nozzle angle would enhance cleaning properties and reduce the onset of bit balling, resulting in higher ROP. Field tests in different applications verified laboratory findings. Field tests also indicate that this particular nozzle angle does not increase erosion on the cutting structure. While this nozzle angle is not exactly the same as the MPII angle on insert bits, it provides an optimized nozzle for the 1-1-5 tooth bits. As noted, further tests will be performed on the 1-3-5 bits.

ROP is the most important variable when calculating drilling costs since it directly affects drilling time. With other costs being equal, a 35% increase in ROP translates into a 35% reduction in drilling time and subsequent costs. Research such as this leads to directly to cost savings for the operator.

Acknowledgements

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We would also like to thank all involved with the field tests of these bits.

Nomenclature

hp = *horsepower*
HSI = *horsepower per square inch*
psi = *pounds per square inch*
lpm = *liters per minute*
ROP = *drilling rate of penetration*
rpm = *revolutions per minute*
TFA = *total flow area*
m/hr = *meters per hour*
WOB = *weight on bit*

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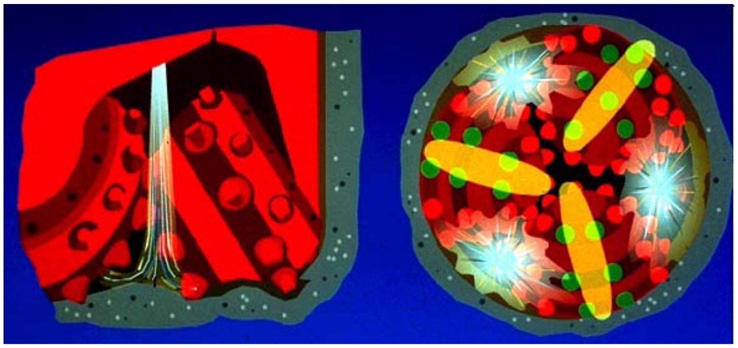


Fig. 1- Conventional Hydraulics.

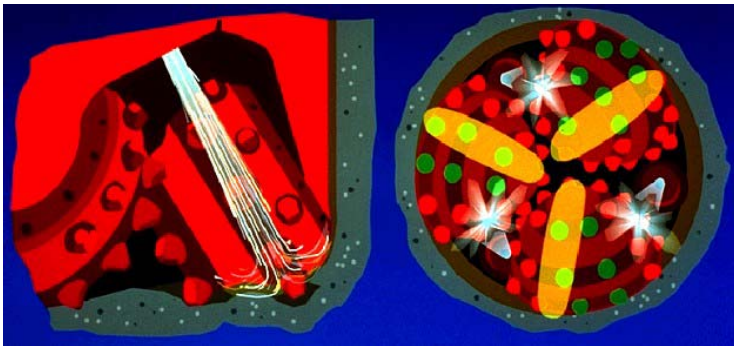


Fig. 2- Mudpick Hydraulics

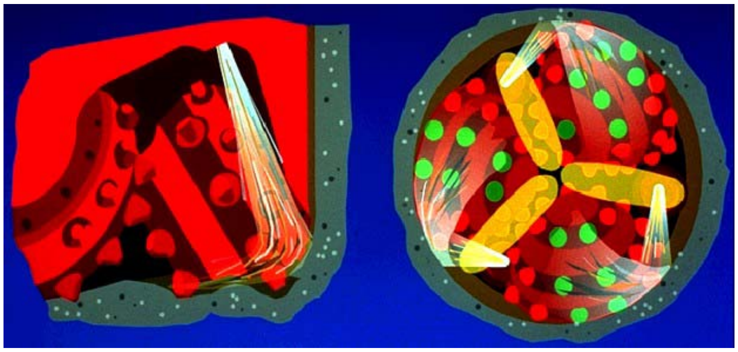


Fig. 3- Mudpick II Hydraulics

Fig. 4- Pressurized Drilling Laboratory

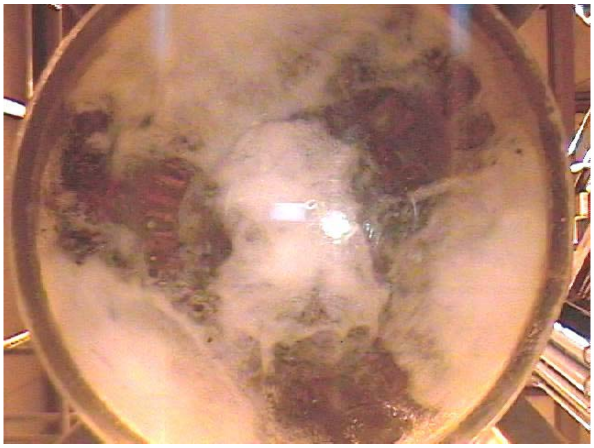
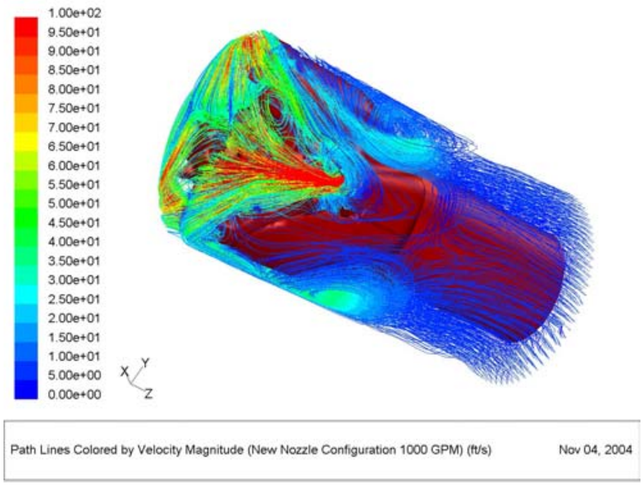


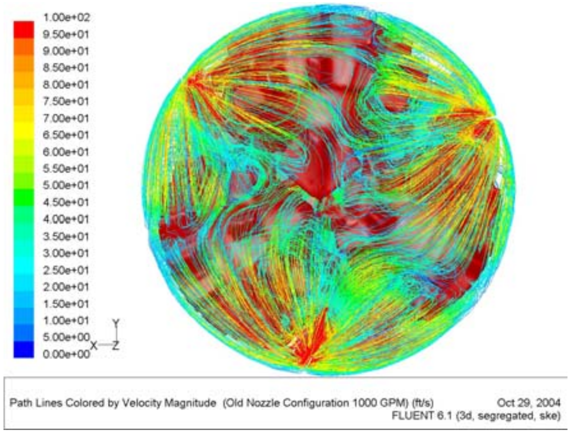
Fig. 5- Flow Chamber

Figure 6- Big Bit Simulation Vessel



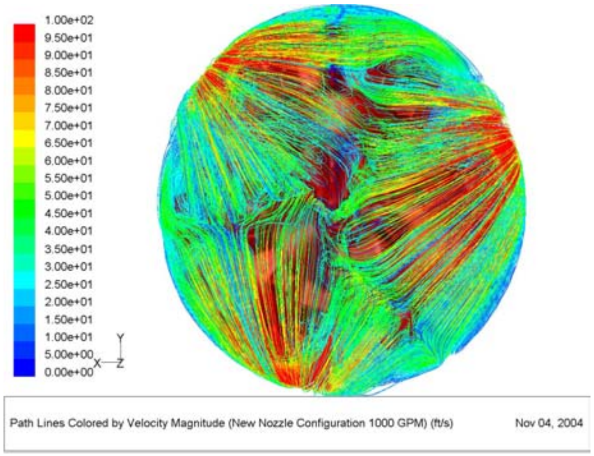
Path Lines Colored by Velocity Magnitude (New Nozzle Configuration 1000 GPM) (ft/s) Nov 04, 2004

Fig. 7- Computational Fluid Dynamics example



Path Lines Colored by Velocity Magnitude (Old Nozzle Configuration 1000 GPM) (ft/s) Oct 29, 2004
FLUENT 6.1 (3d, segregated, ske)

Fig. 8- CFD indicating flow patterns of std bit



Path Lines Colored by Velocity Magnitude (New Nozzle Configuration 1000 GPM) (ft/s) Nov 04, 2004

Fig. 9- CFD indicating flow patterns of test bit

Fig. 10- Lab Test on Standard Nozzle Angle

Fig. 11- Lab Test On New Nozzle Angle

Mancos Shale Properties	
BulkDensity (gm/cc)	2.54
Grain Density (gm/cc)	2.68
Porosity (%)	1.4
Permeability (darcys)	< E-06
Unconfined Compressive Strength (psi)	9,700
Confined Compressive Strength (Pc=4,000 psi)	21,000
Unconfined Young's Modulus (psi)	1.70E+06

Table 1- Test Rock Properties

Well Name	Type	Depth In	Depth Out	Meters	Hours	ROP	Dull Grade	WOB	RPM	LPM	TFA	Deviation
A-1	**Std**	82	538	456	10.5	43.4	1-1-WT-A-E-I-WT-TD	14	140	4270	1.31	Vertical
B-1	**Std**	69	730	661	21	31.5	1-1-WT-A-E-I-WT-TD	15	50	4200	1.31	Vertical
C-1	**Std**	46	655	609	12.5	48.7	3-3-WT-A-E-I-NO-TD	13	190	4515	1.60	Vertical
D-1	**Std**	97	1093	996	37.5	26.6	2-3-WT-A-E-I-SD-TD	19	130	4500	1.31	Vertical
Standard Bit Average				***680.5***	***20.4***	***33.4***						
E-1	**X**	47	756	709	20.2	35.1	1-1-WT-A-E-I-WT-TD	15	150	4200	1.50	Vertical
F-1	**X**	89	718	629	17.5	35.9	1-1-WT-A-E-I-WT-TD	18	110	5357	1.52	Vertical
G-1	**X**	0	669	669	17.2	38.9	2-1-ER-M-E-I-WT-TD	15	70	4040	1.45	Vertical
H-1	**X**	63	883	820	12.2	67.2	1-1-WT-A-E-I-WT-TD	15	170	4078	1.31	Vertical
X Bit Average				**706.8**	**16.8**	***42.1***						
I-1	**Test**	68	777	709	14.5	*48.5*	2-2-BU-A-E-I-NO-TD	14	105	3631	1.31	Vertical
Test Bit Average				***709***	***14.5***	***48.5***						

Table 2- Bit Runs in Vertical Wells – Australia

Well Name	Type	Depth In	Depth Out	Meters	Hours	ROP	Dull Grade	WOB	RPM	LPM	TFA	Deviation
J-1	**Std**	100	1201	1101	27	40.8	1-3-WT-A-E-I-NO-TD	18	250	4500	1.26	0 - 40 Degrees
K-1	**Std**	102	908	806	20	40.3	2-1-WT-A-E-I-SD-TD	17	200	4000	1.31	0 - 29 Degrees
L-1	**Std**	52	828	776	19	40.8	1-1-WT-A-E-I-WT-TD	22	N/A	N/A	1.06	0 - 31 Degrees
Standard Bit Average				***894***	***22***	**40.7**						
M-1	**X**	58	785	727	23.5	30.9	1-1-WT-A-E-I-WT-TD	35	140	4585	1.95	0 - 25 Degrees
N-1	**X**	58	780	722	18.2	39.7	1-1-WT-A-E-I-WT-TD	35	60	4585	1.95	0 - 23 Degrees
O-1	**X**	52	730	678	11.5	58.9	0-0-NO-A-E-I-NO-TD	14	100	4178	1.19	0 - 24 Degrees
P-1	**X**	50	730	680	7.49	90.8	1-1-BU-A-E-I-NO-TD	22	93	3991	1.06	0 - 23 Degrees
X Bit Average				**702**	**15**	**46.2**						
Q-1	**Test**	101	1288	1187	14.93	79.5	1-1-BU-A-E-I-PN-TD	22	142	4462	1.58	0 - 28 Degrees
R-1	**Test**	88	1058	970	22	44.1	1-1-NO-A-E-I-NO-TD	18	130	4800	1.7	0 - 25 Degrees
Test Bit Average				***2157***	***36.93***	**58.4**						

Table 3- Bit runs in Directional Wells – Australia

Well Name	Type	Depth In	Depth Out	Meters	Hours	ROP	Dull Grading	TFA	Deviation
A-1	**X**	232	1612	1380	28.6	48.3	2-1-WT-M-E-I-NO-TD	1.42	0 - 50 Degrees
A-2	**X**	224	1222	998	12.2	81.8	1-1-WT-A-E-I-NO-TD	1.42	0 - 18 Degrees
X Bit Average				**1189**	**20.4**	**58.3**			
A-3	**Test**	230	1648	1418	13.2	107.4	1-1-WT-A-E-I-NO-TD	1.25	0 - 53 Degrees
Test Bit Average				**1418**	**13.2**	**107.4**			

Table 4- Bit runs in Eastern Canada

Well Name	Bit Type	Depth In	Depth Out	Meters	Hours	ROP	Dull Grade	WOB (tons)	RPM	LPM	Jets	Deviation
A-7	**X**	10	800	790	49.5	16.0	1-2-WT-A-E-2-NO-BHA	4-8	140	2170	3x20 + 1x16	3.18
X Bit Average				***790.0***	***49.5***	***16.0***						
A-1	**Std**	10	582	572	44.5	12.9	2-2-WT-A-E-I-NO-DTF	10-15	70+M	2544	3x18 + 1x16	3.1
Std Bit Average				***572.0***	***44.5***	***12.9***						
A-8	**Test**	10	1203	1193	113	10.6	2-4-WT-A-E-2-BU-PR	5-15	50+M	2500	3X20 + 1X16	36
Test Bit Average				***1193.0***	***113.0***	***10.6***						

Table 5- Bit runs in shallow-entry / vertical wells in Egypt

Well Name	Bit Type	Depth In	Depth Out	Meters	Hours	ROP	Dull Grade	WOB (tons)	RPM	LPM	Jets	Deviation
A-5	X	350	1308	958	73	13.1	6-6-WT-A-E-1-PN-PR	5-12	80+M	2439	3X18 + 1X16	37.1
A-6	X	600	1325	725	80.5	9.0	3-4-WT-A-F-1-RO-PR	9-14	50+M	2545	3X18 + 1X16	39.5
A-9	X	450	1300	850	75.5	11.3	3-5-WT-A-E-1-NO-BHA	0-8	60+M	2250	3X18 + 1X16	43
X Bit Average				***844.3***	***76.3***	***11.1***						
A-7	Std	800	1497	697	106	6.6	1-2-WT-A-E-1-NO-HR	10-15	50+M	2315	3X18 + 1X16	46.73
A-4	Std	348	1540	1192	115.5	10.3	1-3-WT-A-E-2-NO-HR	15-20	60+M	2620	3X20 + 1X16	51.77
A-7BIS	Std	510	1476	966	103.5	9.3	3-3-WT-A-E-2-BU-HR	10-18	60+M	2439	3X20 + 1X16	40.6
Std Bit Average				***951.7***	***108.3***	***8.8***						
A-8	**Test**	10	1203	1193	113	10.6	2-4-WT-A-E-2-BU-PR	5-15	50+M	2500	3X20 + 1X16	36
Test Bit Average				***1193.0***	***113.0***	***10.6***	**Same bit as considered in shallow-entry comparison**					
A-8ST	Test	778	1595	817	113	7.2	1-2-WT-A-E-1-BU-TD	5-10	50+M	2160	3X20 + 1X16	39
Test Bit Average				***817.0***	***113.0***	***7.2***	**Side-track run - not considered in test results**					

Table 6- Bit runs in deep-entry / deviated wells in Egypt