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Balling in Water-Based Muds

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Abstract

Balling behavior of PDC bits in deep shale was evaluated using a full-scale high pressure drilling simulator. The importance of bit design, cutter design, mud type and use of a Drilling Enhancer/ROP enhancer was investigated. Balling and ROP correlate strongly with cutting size and cohesiveness/adhesiveness. Both are most effectively controlled with SBM. Addition of a Drilling Enhancer to WBM is another effective option. PDC cutter sharpness, size and surface finish favorably influence cutting size and cohesiveness/adhesiveness. Large open-face volume and junk slots tolerate larger and agglomerated cutting masses and help preserve ROP. Best performance is achieved when all factors including the hydraulic and mechanical operating parameters are optimized as a system.

Introduction

The difficulty of drilling pressured shales with water-based mud (WBM) and polycrystalline diamond compact (PDC) bits is well known and has been discussed in the literature[1,2,3]. Significant improvements have been made with bits and mud designs specifically tailored for these applications and in some cases the performance of oil-based mud (OBM) or synthetic-based mud (SBM) has been matched both in the laboratoy[4] and field[5]. This level of performance, however, is not being achieved consistently and the more reliable SBM/OBM systems are still preferred.

A series of full-scale drilling simulator tests was conducted to focus on the differences in balling characteristics in WBM versus SBM using different bit designs and operating parameters. The goal was to better characterize the range of conditions under which PDC bits can be successfully used with WBM without compromising performance and drilling efficiency and ultimately to extend those conditions.

Full Scale Drilling Simulator Testing

Full-scale drilling simulators are ideally suited for studying balling phenomena since they allow direct observation and good control of the test environment. The simulator used on this project has been described in detail in the literature[6].

Test Conditions.

The simulator tests were designed to replicate the formation behavior, mud system, and bottom hole conditions of deep Gulf of Mexico drilling. Tests were run in Catoosa shale at a bottom hole pressure of 6,000 psi, which is equivalent to drilling at approximately 9,600 ft depth with 12 lbm/gal mud. Hydraulic horsepower per square inch (HSI) was 1 and 3 HSI. Overburden pressure on the rock was maintained at 7,500 psi and confining pressure at 6,500 psi (1,500 and 500 psi above bore hole pressure, respectively). The compressive strength of Catoosa shale under 6,000 psi confinement is in the 4,000 to 8,000 psi range. The typical test was a rate of penetration (ROP) test at constant weight on bit (WOB). The WOB values were 5,10 and 15, 000 lbf for the 8 ½" and 7 7/8" bits and 5,8 and 10,000 lbf for the 6 ½" bit. Bit revolutions were a constant 120 rpm except for one bit balling test at constant ROP and variable rpm to simulate higher depth cuts (DOC) and produce thicker cuttings.

Bit Design

Three basic PDC bit types were used in this test series: an 8½" light set, three blade bit for soft formations, an 8½" heavy set, six blade bit for shale and hard stringers and a 6½" six blade, slim hole bit. A fourth bit tested was a field worn, six blade 7 7/8".

Mud Description

Initial discussions in the planning stage for this series of simulator tests established the importance of using "realistic" base mud systems consistent with systems currently in use in many areas of the Gulf of Mexico (GOM) for soft non-abrasive shales prone to bit balling. The WBM is a 12 lbm/gal fresh water chrome lignosulfonate (CLS)/lignite dispersed mud system augmented with PAC LV. This WBM mud system was used with and without a Drilling Enhancer (DE), sometimes referred to as an ROP enhancer or anti-balling additive, which has been described earlier[2,3,4,5].

The synthetic-based mud (SBM) system was an isomerized, olefin-based 12 lbm/gal field mud from a GOM liquid mud plant. The formulations and properties of the mud systems are listed in **Table 1**.

Discussion of Test Results

The numerical results are summarized in bar graphs that show average ROP as function of WOB. Close-up photographs show the condition of the bit and the type of cuttings collected after the test.

Three Blade PDC Bit

The 81/2", three blade PDC bit is shown in **Figure 1**. It is a popular GOM bit. The large junk slots and the unique nozzle arrangement, two per blade, are well suited for drilling soft, balling shale. It is dressed with sharp, polished ¾ " diameter cutters. In a previous paper[4] the authors reported on the performance of this bit with 3 HSI. In this test series we lowered the hydraulics to 1 HSI to increase the chances for balling. As the bar graph **Figure 2** shows, the bit drilled in WBM, WBM+DE and SBM up to 280 ft/hr. This is the ROP limit of the simulator and it was reached at 10,000 lbf WOB. The bit appeared to be slightly slower in the WBM and WBM+DE muds but it did not ball in any of the muds as shown in **Figures** 1,**3** and **4**. The effect of the mud type can best be seen in the pictures of the cuttings. **Figure 5** shows the typical WBM cuttings, they are large and stick together in a cohesive mass. The DE additive, **Figure 6**, appears to have little effect on the size of the cuttings but it makes them more distinct and keeps them from sticking to each other. The cuttings in SBM, **Figure 7** are much smaller, about half the size, and do not stick. Although the WBM cuttings did not ball this particular bit they might easily lead to problems in the borehole itself. Cleaning of directional wells is inherently more difficult and the complex configuration of some bottomhole assemblies (BHA) might constrain the flow of cuttings more than the wide open junk slots of a three blade bit.

Six Blade PDC Bit

While the light set, three blade bit is clearly the best choice from a balling standpoint, other factors such as bit wear and dynamics often dictate the application of heavier set, multi- blade bits. The six blade bit used in this test series is shown in **Figure 8**. It has ½" diameter, polished and chamfered cutters and the junk slots are about half the size of those on the three blade bit. The bit was run at 1 HSI in WBM+DE and SBM. As the bar graph in **Figure 9** shows, the bit drilled about the same in both muds but only at about half the ROP of the three blade bit. The difference in ROP is most likely due to the less aggressive, chamfered cutters since the bits did not ball. However, the photographs of the bit after the tests in WBM+DE and SBM, **Figures** 8 and **10** respectively, show the beginning of balling in one junk slot. In WBM+DE, **Figure 11**, the junk slot is completely packed and only the face volume is still open. In SBM, **Figure 12**, the accumulation of cuttings has just started. Balling is occurring although the cuttings are significantly smaller than those produced by the three blade bit (compare **Figure 13** and Figure 6). The smaller cutter size and greater redundancy are responsible for the narrower and thinner cuttings.

A constant ROP test, with incremental decreases in rpm, was run to confirm that cutting size is indeed an important factor in bit balling. The constant ROP was 120 ft/hr and the rpm was decreased from 120 to 90 and then to 60. The depth of cut for the bit is 0.20", 0.27 and 0.40 respectively. **Figure 14** shows that the bit required 10,000 lbf to drill at 120 ft/hr and 120 rpm, which is consistent with the test in Figure 9. When the rpm was dropped to 90 the weight went up proportionally as expected. At 60 rpm the WOB requirements shot up exponentially indicating that balling had occurred. The pictures of the bit and cuttings, **Figures 15** and **16**, tell the story. One junk slot is completely balled and the cuttings are thicker and larger than they were in the previous test (see Figure 13). The test confirms that cutting size, and not necessarily volume of cuttings, is an important factor. In the rpm test the volume generated is constant and the only variable is depth of cut or cutting size.

Polished versus standard Cutters

The effect of cutter surface finish on PDC bit performance in shale has been reported before[2,4,5]. In this test series we wanted to document that the non-polished PDC cutters do increase cutting size and thus lead to earlier balling. The bar graph in **Figure 17** shows that the non-polished cutters make the bit ball in WBM almost instantaneously at a WOB of less than 5,000 lbf. **Figure 18** shows the condition of the bit that never drilled faster than 10 ft/hr. The cuttings are large and have accumulated in a large mass in which individual cuttings are difficult to recognize. The effect of the addition of the DE to the WBM was striking. Although one of the junk slots balled up**,** **Figure 19**, the bit continued to drill up to a ROP of 140 ft/hr at 30,000 lbf WOB. **Figure 20**, showing the cuttings, illustrates that the DE does keep the cuttings discrete and slows agglomeration. The cutting size, however, is much larger than with the polished cutters (see Figure 13) and explains the dramatic difference in ROP.

Field Worn Six Blade Bit

After recognizing the importance of cutting size on the balling process another bit type was added to the test matrix. It was a 7 7/8" six blade bit with ¾ " diameter, polished and chamfered cutters (see **Figure 21**). The bit was returned from the field and had a small amount of cutter wear. The purpose of the additional tests was to determine the effect of the ¾" cutters on the balling characteristics of a six bladed bit and assess the role of cutter wear. The combined effect of cutter size and wear was instantaneous balling in WBM as illustrated in **Figure 22**. Even the DE addition to the WBM did not change the basic balling pattern. As shown in Figure 21 more than half of the bit was solidly balled and the cuttings, **Figure 23**, were larger and bulkier than those produced with the new ½" cutters (see Figure 13). The effect of the SBM was striking. The bit did not ball, as shown in **Figure 24**, and the cuttings were much smaller as shown in **Figure 25**. As a result, the penetration rate was five times higher at 15,000 lbf WOB. The advantage of SBM was clearly demonstrated in this test. With a heavier set bit and larger diameter, slightly worn cutters even polishing the cutter face and adding DE to the WBM are not sufficient to keep a bit from balling up. In this case only SBM can assure reliable PDC bit performance.

Slimhole PDC Bit

The last series of tests was conducted with a 6 ½", six blade, slimhole bit (see **Figure 26**). This particular bit was dressed with ½", polished and chamfered cutters. On a smaller bit the open face volume and junk slot area become even more constrained. The objective was to determine if the smaller dimensions adversely affect the balling characteristics. **Figure 27** shows that the bit drilled quite effectively up to a ROP of about 100 ft/hr. Then the bit started balling up first in WBM and then in WBM+DE. It did not ball in SBM. In WBM one junk slot balled completely (see **Figure 28**) and the cuttings were globular and formed a cohesive mass (see **Figure 29**). As in previous test the DE made the cuttings more discreete as shown in **Figure 30**, but they were stringier and one junk slot eventually balled up as shown in **Figure 31**. In SBM the bit was clean, as shown in **Figure 32**, and the cuttings were clearly smaller and discrete as shown in **Figure 33**. The small bit drilled quite efficiently at low WOB and ROP. However, in WBM and WBM+DE it appeared to have an ROP limit in the 100 to 140 ft/hr range, which is quite a bit lower than for the comparable 8 ½ bit (see Figure 9). The test suggests that the open face volume, junk slot area and the size, shape and composition of the cuttings, limits the ROP capability of a PDC bit.

Conclusions

The effectiveness of SBM in preventing balling of PDC bits in pressured shales was not fully matched with a conventional WBM or WBM + Drilling Enhancer. The cutting size in WBM was consistently larger than in SBM and the tendency to agglomerate was only partially overcome by addition of a Drilling Enhancer.

SBM or addition of Drilling Enhancers to WBM were equally effective in increasing ROP and preventing balling of an 8½ inch highly aggressive three blade PDC bit with ¾ inch sharp, polished cutters. The Drilling Enhancer appears to keep the cuttings discrete preventing them from sticking together in a cohesive mass but only the SBM appeared to reduce their size.

Use of SBM achieved slightly higher ROP than WBM + Drilling Enhancer with an 8½ inch six blade PDC bit having ½ inch polished and chamfered cutters. The improvement was only achieved at the highest WOB, at lower WOB the penetration rates were equivalent. The cuttings produced were smaller than those from the three blade PDC bit with ¾ inch cutters.

Increasing depth of cut, by lowering rotary speed, initiated balling with the 8½ inch six blade PDC bit with polished and chamfered cutters at 3 HSI. This confirms that cutting size and not only the volume of cuttings is an important factor in balling.

Addition of a Drilling Enhancer to WBM increased maximum ROP of the 8½ inch six blade PDC bit with non-polished cutters from 7 ft/hr to 40 ft/hr without balling. One junk slot balled at higher WOB but the Drilling Enhancer allowed the bit to continue to drill at up to 160 ft/hr. Cuttings were larger than with polished cutters.

Addition of a Drilling Enhancer to a WBM increased the penetration rate of a 7-7/8 inch six blade PDC bit with ¾ inch worn polished and chamfered cutters at low WOB. SBM, however, increased ROP by a factor of 3 or 4 confirming the advantages of SBM in more demanding applications with larger worn cutters.

Addition of a Drilling Enhancer to WBM increased ROP by 25% with a 6½ inch six blade PDC bit having ½ inch polished and chamfered cutters. Performance matched SBM at lower WOB. The bit balled at higher WOB with the WBM + Drilling Enhancer. The addition of the Drilling Enhancer appeared to keep the cuttings discrete and prevent formation of a cohesive mass as did the SBM, but only the SBM seemed to produce smaller cuttings.

Nomenclature

BHA= bottom-hole-assembly
BHP= bottom hole pressure
Caustic= sodium hydroxide (caustic soda)
DE= Drilling Enhancer
ECD = equivalent circulation density
EMW = equivalent mud weight
HSI= hydraulic horsepower/inch^2
MD= measured depth
MWD= measurement-while-drilling
OBM= oil-based mud
PAC LV= low viscosity polyanionic cellulose
PDC= polycrystalline-diamond compact
PV= plastic viscosity, cp
ROP= rate-of-penetration
rpm = revolutions per minute
SBM= synthetic-based mud
TFA= total flow area, in.^{2}

TD=total depth
YP= yield point, lbf/100 ft^2
WBM= water-based mud
WOB = weight on bit

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Metric Conversion Factors
bbl x 1.589873 E-01 = m^3
cp x 1.0 E-03 = Ps*s
in. x 2.54 E+01 = mm
(ºF-32)/1.98 E+00 = ºC
ft x 3.048 E-01 = m
lbf/100 ft^{2}x 4.788026 E-01 = Pa
lbm/bbl x 2.853010 E+00 = kg/m^3
lbm/U.S. gal x 1.198264 E+02 = kg/m^3

Table x: Drilling Simulator Mud Formulations & Properties

Formulation	**Dispersed**	**SBM**
Tap water, bbl	0.804	
Synthetic Base Fluid, bbl		0.591
Bentonite, lbm/bbl	23	
Organophilic clay, lbm/bbl		3
Chrome Lignosulfonate, lbm/bbl	4	
Lignite, lbm/bbl	5	
Primary Emulsifier, gal/bbl		1
Secondary Emulsifier, lbm/bbl		1
25% w/w $CaCl_2$ brine, bbl		0.209
PAC LV, lbm/bbl	0.5	
Modified Starch, lbm/bbl	0.5	
Barite, lbm/bbl	178	234
Rev Dust, lbm/bbl	45	
Caustic, lbm/bbl	As needed	
Drilling Enhancer, volume %	0 - 5	
Properties		
Density, lbm/U.S. gal	12.0 - 12.1	11.8 - 12.1
PV, cp	23 - 46	27 - 36
YP, lb/100 ft^2	8 - 15	9 - 26
Gel Strengths, lb/100 ft^2		
Initial	5 - 8	6 - 12
10 min.	6 - 10	10 - 17
pH	10.5 - 12.4	
API Filtrate Loss, cm^3	3.5 - 4	3.2-3.8
Retort		
Solids	19	17.5
Water	73 - 77	24
Drilling Enhancer	0 - 5	
Synthetic Base Fluid		58.5
SWR		71/29
Electrical Stability, volts		328 - 620

Figures

Figure 1. Three blade 8½ inch PDC bit with WBM.

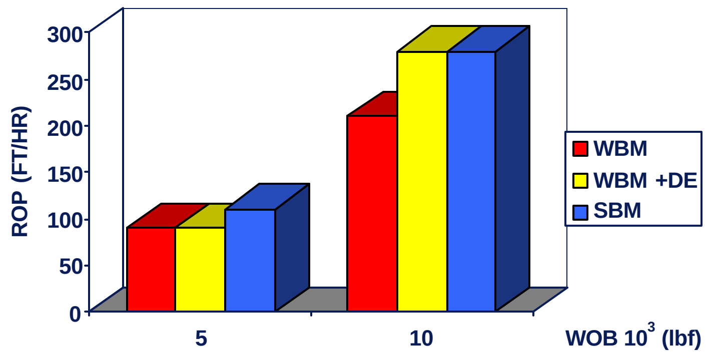

Figure 2: Three Blade PDC Bit

8.5 inch	120 RPM
1.2 HSI	6000 psi BHP

Figure 3. Three blade 8½ inch PDC bit with WBM + Drilling Enhancer.

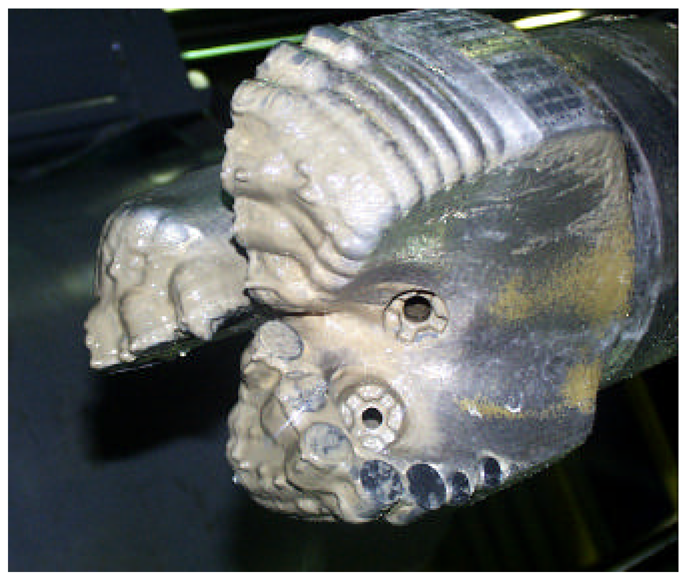

Figure 4. Three blade 8½ inch PDC bit with SBM.

Figure 5. Cuttings from three blade 8½ inch PDC bit with WBM.

Figure 6. Cuttings from three blade 8½ inch PDC bit with WBM + Drilling Enhancer.

Figure 7. Cuttings from three blade 8½ inch PDC bit with SBM.

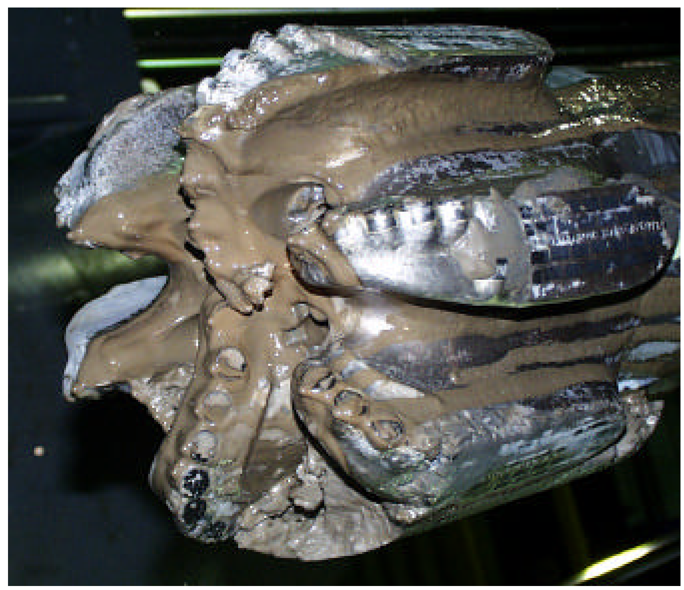

Figure 8. Six blade 8½ inch PDC bit with WBM + Drilling Enhancer.

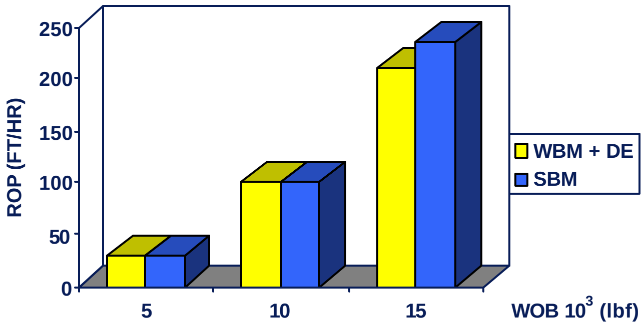

Figure 9: Six Blade PDC Bit

8.5 inch 120 RPM
1 HSI 6000 psi BHP

Figure 10. Six blade 8½ inch PDC bit with SBM.

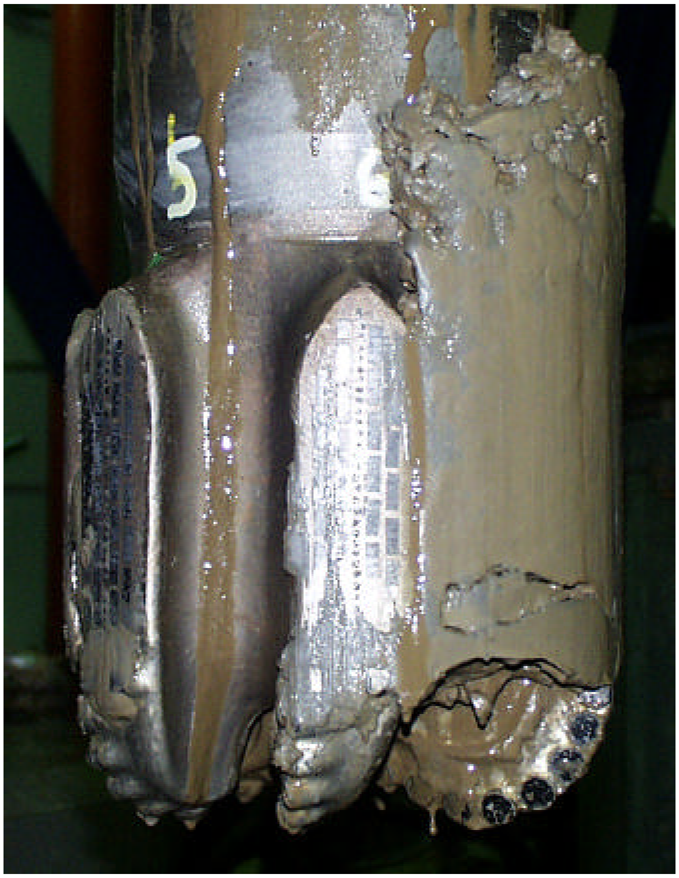

Figure 11. Six blade 8½ inch PDC with WBM + Drilling Enhancer.

Figure 12. Six blade 8½ inch PDC bit with SBM.

Figure 13. Cuttings from six blade 8½ inch PDC bit with WBM + Drilling Enhancer.

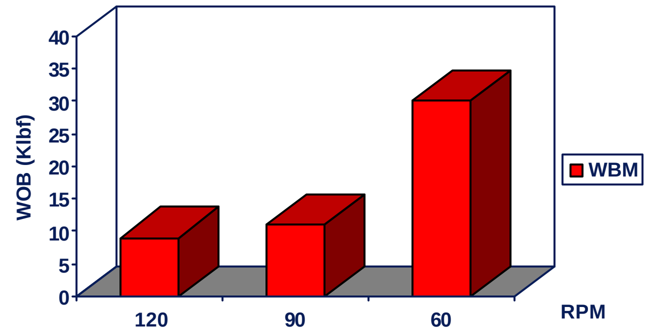

Figure 14: RPM Test - Six Blade PDC Bit
8.5 inch 120 RPM
3 HSI 6000 psi BHP

Figure 15. Six blade 8½ inch PDC bit rpm test with WBM.

Figure 16. Cuttings from six blade 8½ inch PDC bit rpm test with WBM.

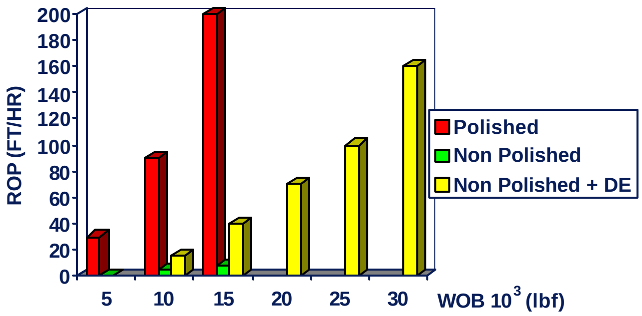

Figure 17: Six Blade PDC Bit - Non-Polished Cutters

8.5 inch 120 RPM
3 HSI 6000 psi BHP

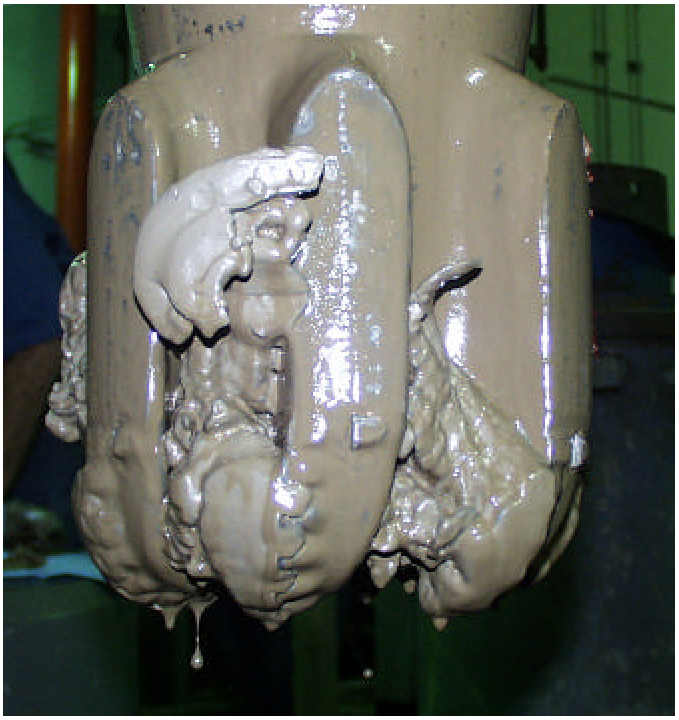

Figure 18. Six blade 8½ inch PDC bit with non-polished cutters and WBM.

Figure 19. Six blade 8½ inch PDC bit with non-polished cutters and WBM + Drilling Enhancer.

Figure 20. Cuttings from six blade 8½ inch PDC bit with non-polished cutters and WBM + Drilling Enhancer.

Figure 21. Six blade 7-7/8 inch PDC bit with worn cutters and WBM + Drilling Enhancer.

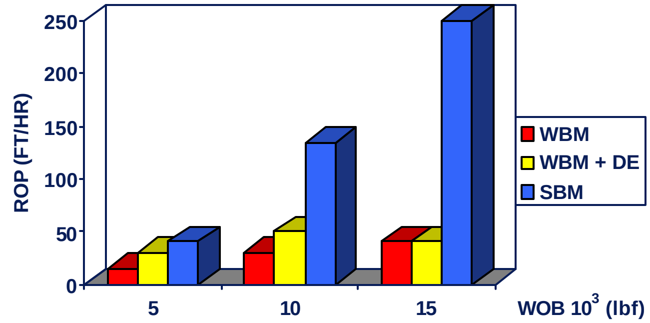

Figure 22: Six Blade PDC Bit - Worn Cutters

7-7/8 inch 120 RPM

3 HSI 6000 psi BHP

Figure 23. Cuttings from six blade 7-7/8 inch PDC bit with worn cutters and WBM + Drilling Enhancer.

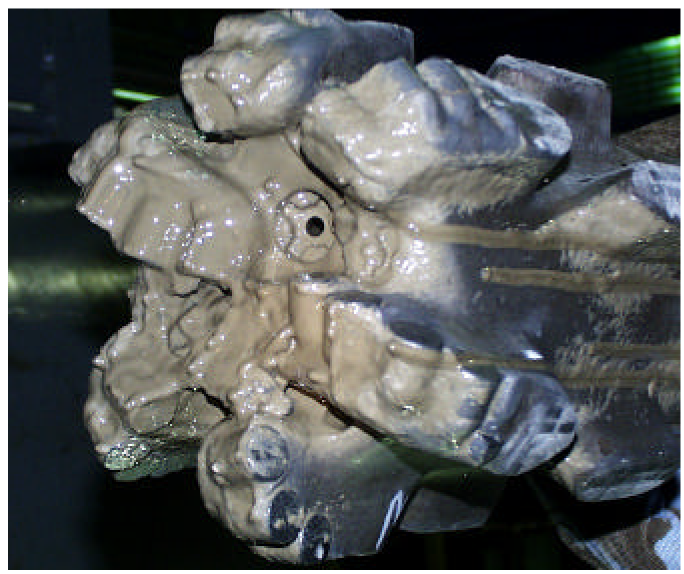

Figure 24. Six blade 7-7/8 inch PDC bit with worn cutters and SBM.

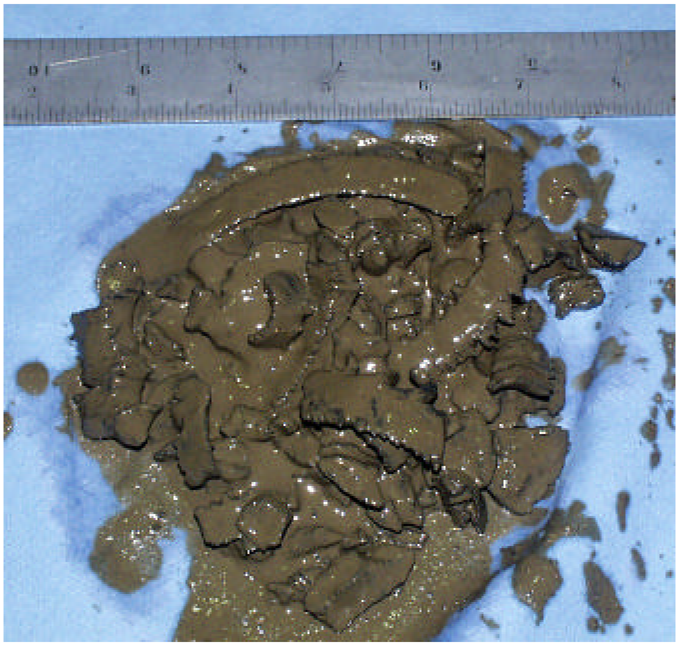

Figure 25. Cuttings from six blade 7-7/8 inch PDC bit with worn cutters and SBM.

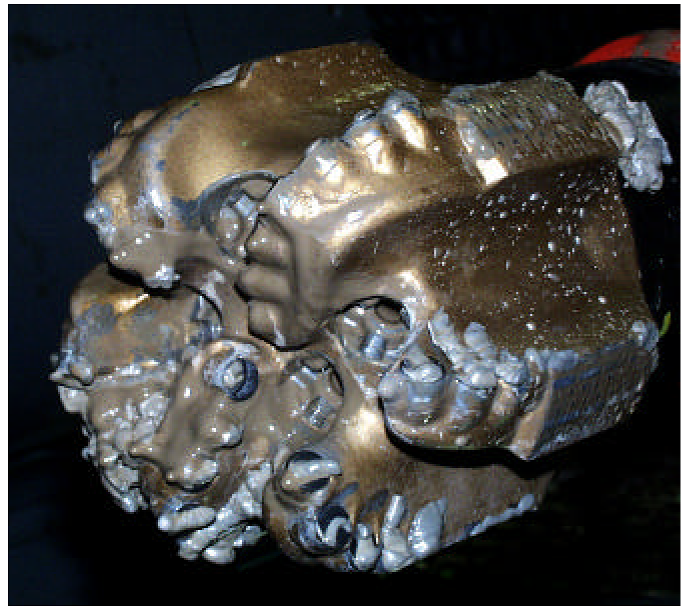

Figure 26. Six blade 6½ inch PDC bit with WBM.

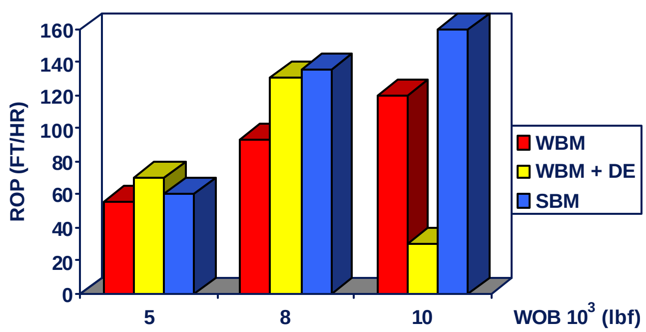

Figure 27: Six Blade Slimhole PDC Bit

6½ inch 120 RPM
1 HSI 6000 psi BHP

Figure 28. Six blade 6½ inch PDC bit with WBM.

Figure 29. Cuttings from six blade 6½ inch PDC bit with WBM.

Figure 30. Cuttings from six blade 6½ inch PDC bit with WBM + Drilling Enhancer.

Figure 31. Six blade 6½ inch PDC bit with WBM + Drilling Enhancer.

Figure 32. Six blade 6½ inch PDC bit with SBM.

Figure 33. Cuttings from six blade 6½ inch PDC bit with SBM.