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New Laboratory Device Evaluates Bit Balling in Carbonates

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Abstract

An Accretion Drilling Simulator (ADS) laboratory device has been developed to study bit balling while drilling carbonate formations. Test results, generally in accord with well-known balling behavior, are supporting changes in operational practices that are improving penetration rates and reducing NPT in the field.

The ADS permits evaluation of the combined effects of cuttings characteristics, PDC bit design, drilling fluid chemistry and rheological properties, and drilling operations parameters. Resultant values include penetration rate, torque, and calculated mechanical specific energy.

Central to the ADS design is the synthetic formations created by moderately compressing blends of selected clays with carbonates with a wide choice of selected particle size and distribution. The 2.5-in. test bits are exact scaled-down replicas printed in hard plastic and coated with a polyurethane paint containing stainless-steel flakes. Experiments are quick, inexpensive, and repeatable. Although testing is conducted under ambient conditions, results are representative of field observations.

This paper presents results from parametric tests involving different bit designs, fluids, parameters, and customized formation blends. It also will discuss the test equipment and highlight opportunities for further experimentation.

Introduction

Fig. 1- PDC bit balling in carbonates

Bit balling is a well-known problem typically associated with rapid drilling of shales and other water-sensitive formations with water-based drilling fluids. PDC bits are particularly vulnerable. Visually, balling can be identified by significant accretion of a sticky cuttings/ mud mass on the cutting structure and/or junk slots as seen in Fig. 1. Operationally, bit balling is consistent with lower rates of penetration (ROP) and reduced torque, resulting in invisible lost time (iLT). A fully balled bit forcing a trip increases the non-productive time (NPT).

Interestingly, the bit in Fig. 1 was used to drill carbonate instead of shale formations. Fine-grained and/or mechanically weak carbonates can, in fact, create a plastic, low-permeability mass. Left undispersed, this mass can build up on cutters and in the junk slots in sufficient volume to keep the bit from drilling, or to at least significantly reduce drilling efficiency.

An excellent discussion of bit balling in argillaceous limestone has been presented for S-shaped directional wells drilled in the Arabian Gulf.[1] The paper also discusses an ROP management process implemented to address incipient bit balling due to insufficient bit structure cleaning (BSC) and other important drilling issues.

Regarding bit balling in general, a different paper[2] suggested that empirically predicting bit-balling potential based on junk-slot area, face volume and hydraulic horsepower per square inch (HSI) can yield inconsistent results. These authors present new bit design methods that use empirical design rules that govern pinch points and junk-slot profiles. The methods were validated by tests in a large-scale drilling simulator used previously to study balling in water-based drilling fluids.[3] Similar units have been developed by others to benchmark drilling performance that invariably is impacted by bit balling.[4]

In addition to empirical realism, large-scale drilling simulators have the distinct advantage of evaluating the combined effects of the critical parameters that control bit balling – formation lithology, bit design, drilling fluid chemistry, bit hydraulics, and drilling practices. Among the disadvantages are their massive size, cost, test time, and limited flexibility. Equipment designs based on micro-bits can address some, but not all, of these issues.

Without the availability of a suitable drilling simulator, studies to understand and mitigate bit balling fall independently to the drilling systems technology providers. For example, drilling fluid chemistry might be evaluated by cuttings accretion on steel bars hot-rolled in jars of the test fluid. Bit designs might be limited to computer studies and tests with water or very simple fluids.

This paper presents a novel option – a “bench-top” Accretion Drilling Simulator (ADS) that is proving to be useful as a rapid, inexpensive, repeatable test system to study bit balling. Description of the device, with focus on several key elements, is an important part of this paper. Also presented are results from parametric tests involving different bit designs, fluids, drilling practices, and custom-designed test formation.

Equipment Design Criteria

The primary design criterion of the ADS was to permit laboratory evaluation of the combined effects of cuttings characteristics, PDC bit design, drilling fluid properties, and drilling parameters (flow rate, rotary speed, and weight on bit). Secondary goals included the ability to easily and quickly vary each of the primary parameters independently, and the use of small-scale components and small fluid volumes for logistical and cost reasons. Good correlation with field observations and results was paramount.

An early, simple design was based on a milling machine concept whereby Pierre shale and limestone samples were milled in the presence of different fluids. Results on shale were encouraging, but the limestone powder would not ball appropriately. This experience identified the formation material as a key component that would drive the remaining specifications.

A novel idea was to work with synthetic formations that could be formulated on demand. Instead of synthesizing rock, formations could be created from expected cuttings characteristics with respect to lithology, bit design and operating practices. Instead of drilling the synthetic formations in normal fashion, properly sized cuttings could be released as the bit "drilled" through the moderately compressed material, whether uniform or layered. This also meant that different test bits could be manufactured to scale in a material other than metal.

The final design criterion was a data acquisition system to provide real-time ROP and torque from the manually run tests. These two resultants in combination with operating parameters could be used to calculate a synthetic mechanical specific energy (MSE) to monitor results and provide insight into the various tests.

Equipment Design

Centerpieces of the ADS shown in Fig. 2 are the formation sample and replica bit highlighted shown on the right-hand side of the figure. A 2.5-in. wellbore/bit diameter was selected for convenience. Not shown is the archival video camera that, during testing, is pointed directly at the bit through a clear acrylic wellbore. An air cylinder is used to push the formation upwards past the rotating but otherwise stationary bit, thereby optimizing video capture. The bit "drills" through the synthetic formation, providing a physical model of cuttings/fluid flow and balling.

A DC-motor top drive spins the drill pipe on which interchangeable replica PDC bits are mounted. Pipe rotational speed and weight on bit (WOB) are manually controlled during tests as short as 8 seconds and as long as several minutes. The 3.5-gal volume of drilling fluid is pumped by progressive cavity pumps through the scaled bit jets to model fluid hydraulics and chemical interactions. A computerized data acquisition system records WOB, fluid pressure and flow rate, rotary speed, penetration depth and reaction torque.

Fig. 2 – Accretion Drilling Simulator.

Formations

Simulated formations are custom-made from sized carbonate particles mixed with clay and then compressed into the acrylic wellbore tubes. The $CaCO_3$ particle-size distribution (PSD) was originally determined by drilling Carthage marble with a single cutter drilling machine. However, the PSD can easily be altered to mimic the cuttings distribution expected in the field. Other powdered materials important to the particular test can also be incorporated into the formation.

Formation blends are homogenized in a mixer for 15 minutes in batches large enough to make multiple, consistent formation samples (Fig. 3). The mixture is then compacted with a 3,000 lb_f into 2.5-in. diameter by 14-in. long clear acrylic tubes in six 220-g layers. This process improves consistency of the pack and also allows formations to be layered with different blends and materials.

Fig. 3 – Blending and compacting formation samples.

Fig. 4 compares an unused replica bit to an ADS-balled bit drilled with water and to the same bit type that balled in the field. The formation used with Bit B contained increasing concentrations with depth of Arne clay. OCMA clay was eventually selected over Arne clay and Rev-Dust as the "standard" clay to blend with the carbonates for most tests.

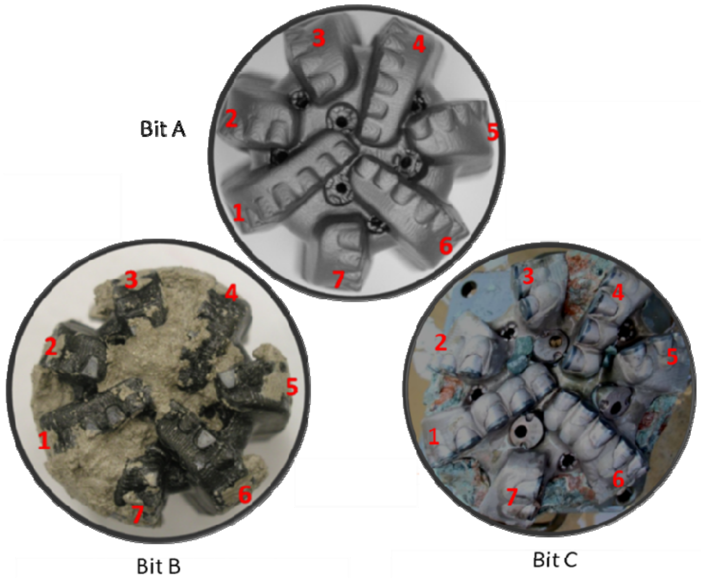

Fig. 4 – Comparison of 7-blade Bits (A) unused replica bit, (B) ADS-balled 2.5-in. replica bit, and (C) field-balled 8.5-in. bit.

Replica Bits

Exact-scale replica bits are printed in ABS plastic using a 3-D printer. The bits are painted with polyurethane paint containing stainless-steel flakes for protection and to improve surface realism. Stainless-steel, 3/16-in. "buttons" super-glued to the cutters prolong bit life and allow the bits to be reused. Fig. 5 is a picture of a sample bit that balled during ADS testing.

The replica bits are created from the very CAD drawings used to manufacture the real drill bits. This approach provides a means to quickly test new designs in the ADS. The drawings can even include specific scaled-nozzle configurations to alter bit hydraulics. The back-rake-angle resolution is less than ideal, but the impact of back rake angle can be simulated by changing the PSD of the carbonate particles.

Fig. 5 – Balled bit after completing ADS test.

Test Procedure

Central to the ADS test procedure is the preparation of the three key elements – formation, bit, and drilling fluid – for any given test. After the bit and formation module are mounted, the WOB air regulator pressure, pipe rotary speed, and drilling fluid flow rate are set and started. The video and computer data acquisition are engaged to start the test. After drilling to bottom, the wellbore is lowered to expose the replica bit and record any balling via video and digital photos (Fig. 6).

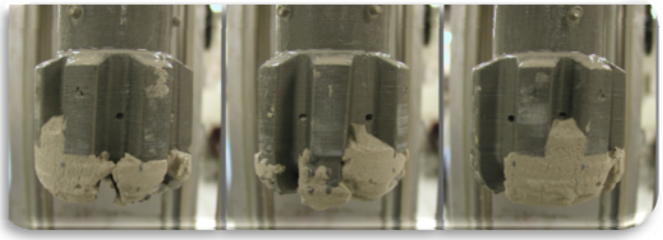

Fig. 6 – Pictures of different sides of a balled bit after testing.

Four types of data are obtained for each run to judge the relative degree of balling:

- Weight of balled material adhered to the bit is determined by comparing bit weights before and after the test run.
- Video is archived to permit analysis of unusual behavior such as drilling halts and breaks.
- Still images and retained ball mass are used to qualify the amount and type of balling.
- Computer records are used to calculate the ROP and a synthetic mechanical specific energy (MSE).

Test Series

Testing is continuing on the ADS to evaluate the combined effects and interactions among the important variables. Information on 12 of those tests is presented in this paper to support observations and demonstrate capabilities of the device. Table 1 is a summary of these tests that involved two PDC-bit designs, multiple carbonate/clay formation blends, and several water-based drilling fluids.

Test Nomenclature is shorthand code for the bit number, formation type, and drilling fluid. MSE calculations use the conventional equation[5]; however, results are purely relative since the ADS bit is not drilling rock. Test identification codes and details on the formation types given below are used in graphs and charts in the remainder of the paper:

O - 35% OCMA Clay, 32.5% C250, 32.5% C10
R - 35% Rev-Dust, 32.5% C250, 32.5% C10
O2 - 15% OCMA Clay, 42.5% C250, 42.5% C10 + O
O3 - 15% OCMA Clay, 42.5% C250, 42.5% C10 + O +
15% OCMA Clay, 42.5% C250, 42.5% C10

Fig. 7 includes drilling performance curves for the 12 tests. Higher ROPs are represented by steep curves, while rapid changes in slope are consistent with severe balling. As seen in Table 1, Test #9-B1-O-X2 involved a viscous xanthan gum polymer fluid that caused severe balling, limited the flow, and stopped the drilling process after only 3.39-in. penetration. Tests #11-B1-O3-X0.5 and #12-B1-O2-X0.5 were layered formation tests.

Table 1 – Summary of 12 ADS Tests.

Test Bit – Form-Fluid	Bit #	Form-ation*	Fluid	WOB (lb)	Rotary (rpm)	Flow (gpm)	Pressure (psi)	Avg ROP (ft/hr)	Avg MSE (psi)	TD (in)	Ball Wt (g)
#1-B1-O-W	1	O	Water	30	308	3.7	41	75.0	1,025	8.14	45.2
#2-B1-R-W	1	R	Water	30	311	3.9	41	129.0	630	8.62	9.8
#3-B2-O-W	2	O	Water	30	311	3.6	44	110.0	723	8.41	36.5
#4-B2-R-W	2	R	Water	29	311	4.2	45	272.0	193	8.52	6.2
#5-B2-O-X.5	2	O	0.5-ppb xanthan	30	311	3.7	52	59.0	1,094	8.19	93.0
#6-B2-O-X2	2	O	2-ppb xanthan	30	310	2.9	58	26.0	2,585	8.34	55.0
#7-B1-O-X.5	1	O	0.5-ppb xanthan	30	315	4.0	46	11.0	11,214	8.04	48.0
#8-B2-O-X1	2	O	1-ppb xanthan	30	310	2.7	47	38.0	1,407	8.29	47.0
#9-B1-O-X2	1	O	2-ppb xanthan	30	311	2.8	50	4.6	22,411	3.39	58.0
#10-B2-O-MMO	2	O	Field MMO mud	30	310	2.8	49	17.8	4,013	8.21	87.0
#11-B1-O3-X.5	1	O3	0.5-ppb xanthan	30	313	4.6	43	21.0	8,159	8.09	37.0
#12-B1-O2-X.5	1	O2	0.5-ppb xanthan	30-55	362	4.5	43	21.0	13,094	8.19	32.0

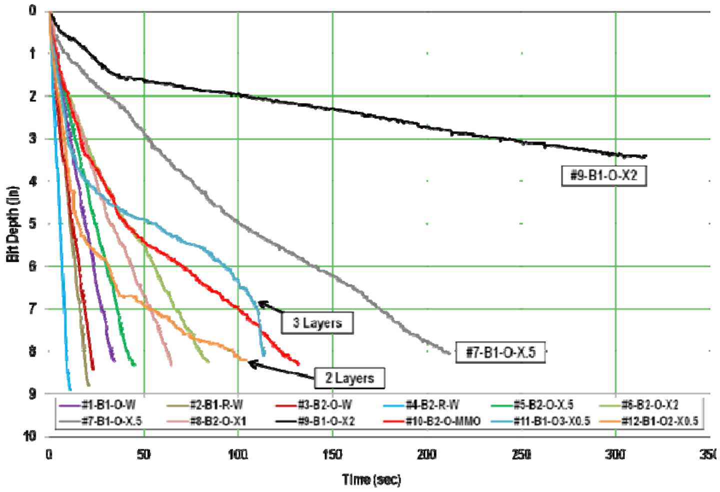

Fig. 7 – Drilling performance curves for 12 ADS tests.

Test Results

Some of the most encouraging test results have been the similarity between balling characteristics on the replica bits compared to those experienced in the field on actual bits. Additionally, the following topics have been selected to represent highlights of this test series:

a. Balling mitigation by improved bit design
b. Fluid chemical and rheological effects
c. Impact of multi-layered formations on balling and drilling performance

Bit Design

A distinct advantage of the ADS is its ability to test new bits that have been designed to mitigate bit balling. Three 2.5-in. bit designs were tested in this series. The first was a scaled replica of the 8.5-in. bit shown in Fig. 4, an example of those being used in the field at that time. In all fairness, the ADS design was fundamentally based on achieving significant balling with this particular bit design, labeled Bit #1 in this paper. Bit #2 was an engineered improvement of Bit #1. Bit #3 included nozzles in the gauge junk slots to the Bit #2 design (visible in Fig. 6), a change that was subsequently rejected.

Fig. 8 is a summary graph of Bit #1 while drilling an OCMA clay/carbonate formation with a 0.5-lb_m/bbl xanthan gum drilling fluid (Test #7-B1-O-X0.5). Average ROP was only 11 ft/hr and relative MSE was 11,214 psi. While the ball weight was unusually low at 48 g, not all of it was recovered before weighing. Similarly, torque was higher than expected, suggesting that other factors were in play. Visual inspection by bit experts pointed to opportunities for improvements with pinch points and flow in some of the junk slots.

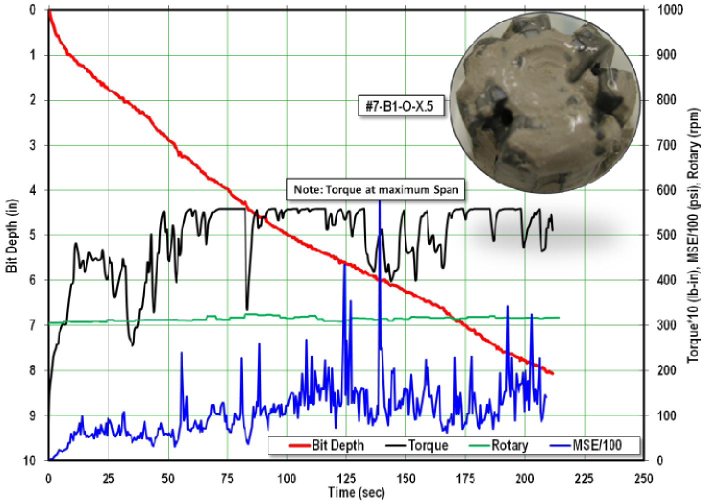

Fig. 8 – Bit #1 results in Test #7-B1-O-X-0.5 drilled with a polymer drilling fluid.

Sophisticated bit CFD software was used to optimize the bit design for field conditions and requirements. Strong upflow can be seen in Fig. 9 for Bits #1 and #2, except for two of the junk slots where some recirculation can be seen. Careful inspection of the bit faces clearly shows that critical pinch points were eliminated and nozzle placement was slightly altered in Bit #2. Further refinement of Bit #2 subsequently resulted in a record field bit run.

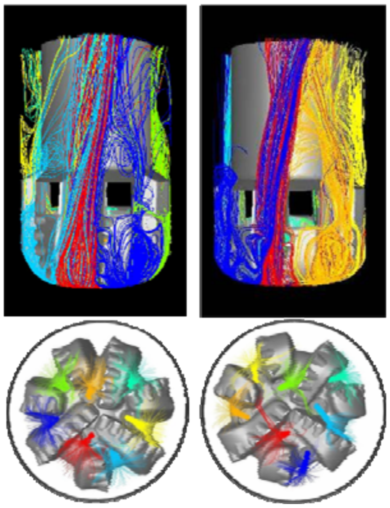

Fig. 9 – CFD results for Bit #1 on the left and Bit #2 on the right.

While the ADS testing did not contribute significantly to the redesign, it provided physical evidence that improved performance could be achieved. The ADS generated information not available from the software analysis, such as the impact of solids and complex fluid rheological properties.

Fig. 10 presents results for the optimized Bit #2 (Test #5-B2-O-X0.5) run under the same operating conditions used in Test #7-B1-O-X0.5 (Fig. 9). Average ROP increased by over five times to 59 ft/hr and relative MSE was reduced to 1,094 psi.

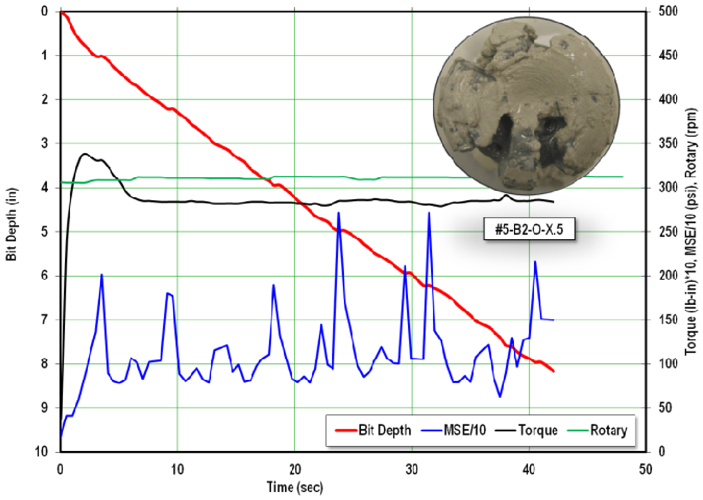

Fig. 10 – Bit #2 results in Test #5-B2-O-X0.5 drilled with a polymer drilling fluid.

Fluid Chemical and Rheological Effects

Balling tendency and ROP as a function of clear fluid properties have been well studied. Gross viscosity reduces the rate of fluid invasion and also slows dispersion of the incipient ball. As shown in Fig. 11, drilling with a standard formation blend in 9.8-lb$_m$/gal (23 wt%) NaCl brine resulted in a distinctly slower ROP than clear water, consistent with its roughly three- times-greater kinematic viscosity. Normalized ROPs as a percent of their initial ROP are plotted versus drill depth. Four other tests illustrate the effects of added ions in the freshwater environment. Only the $CaCl_2$ fluid shown as a vertical line in Fig. 11 maintained its initial ROP. Some of these tests are separate from those listed in Table 1.

Selective-ion adsorption can induce changes in particle net surface charge measured as zeta potential. By increasing or reducing inter-particle repulsive forces, the permeability of a packed bed of particles can be increased or reduced. This effect has been shown to directly impact ROP.[7] Adding soda ash (sodium carbonate) introduced excess carbonate ions into the fluid, shifting the zeta potential of the calcium carbonate particles to the negative. Calcium ions introduced into the system shift zeta potential to the positive. The ADS results clearly show a reduction in ROP with carbonate ions and an increase (over pure water) with calcium ions. TKPP (tetra-potassium pyrophosphate or $K_4P_20_7$) had an even larger effect on the calcite surface, forming even less soluble phosphates. These results are most easily explained by a positive zeta potential on the calcite that is enhanced with calcium ions and partially neutralized by carbonate and phosphate.

Fig 11 also shows that the 10-lb$_m$/bbl bentonite slurry behaved as predicted, drilling significantly slower than water. Clay suspensions can exhibit higher viscosity, but they also can reduce the rate of invasion into micron-sized pores and fissures as a function of time and depth of invasion.

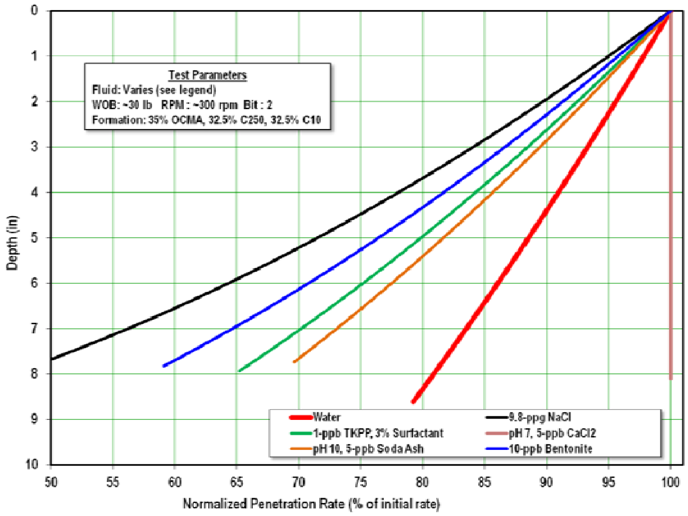

Fig. 11 – Normalized ROPs as functions of initial ROP for 6 different drilling fluids under similar operating conditions.

Multi-Layered Formations

Fig. 12 demonstrates the effects on ROP, torque and MSE when drilling into a formation layer with higher clay content. The upper and lower formations indicated on the graph contained lower concentrations of OCMA clay. The inset side view of Bit #1 shows how the junk slots on one side were completely packed with cuttings. The drilling fluid was a 0.5-lb$_m$/bbl xanthan polymer fluid.

Soon after penetrating the center layer, changes in ROP and MSE were as expected. WOB was not changed. Torque was not affected much, but became erratic as cuttings filled the junk slots. The drilling parameters returned to those in layer one within one inch of penetration into layer three. This suggests that the balling on the bit face dissipated gradually with the formation change.

Fig. 13 shows a two-layer-formation test, with the upper layer blended with a lower concentration of clay. This test also was run with Bit #1 and a 0.5-lb$_m$/bbl xanthan polymer fluid. ROP and MSE responded as expect during the first inch of penetration into the lower layer. In order to mimic a common response not recommended in the field, WOB was increased to compensate for the reduction in ROP. While the ROP increased for a short period, it soon dropped significantly due to the high level balling.

Other tests were run with different combinations of layered formations, drilling fluids, and drilling practices. While they are not discussed in this paper, they did show the wide utility of the ADS for studying these interactions.

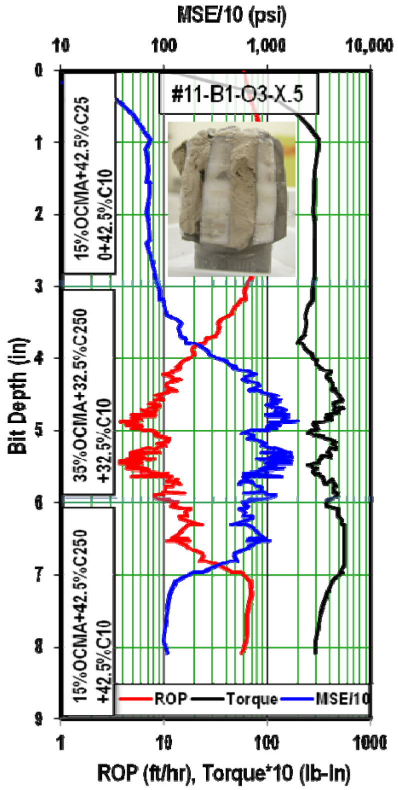

Fig. 12 – Drilling through a high-clay-content formation sandwiched between two lower-clay-content layers.

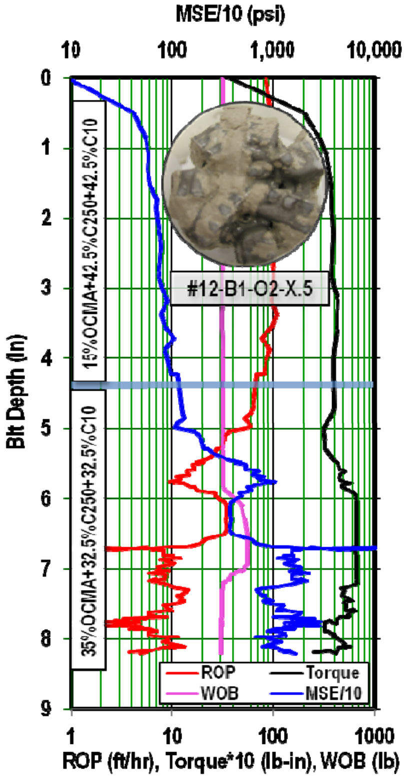

Fig. 13 – Drilling from a lower-clay-content formation into a higher-clay content layer followed by an increase in WOB.

Opportunities for Further Experimentation

The very design of the ADS provides multiple opportunities to evaluate the combined effects of key factors on PDC bit balling in argillaceous carbonates. As much as possible, the synthetic formation columns should represent those encountered in the field with respect to lithology and cuttings PSD generated by field bits. In addition to field experience, bit designs clearly should first be improved by CFD software, and drilling fluids should be optimized in the fluids laboratory.

Conclusions

1. A laboratory device has been developed to evaluate combined bit-balling effects of formation lithology, bit design, drilling fluid chemistry, bit hydraulics, and drilling practices in carbonate formations.
2. Key elements of the new test device include:
   a. Moderately compacted, customized formation columns consisting of carbonate particles blended with selected clays
   b. Exact-scale replica PDC bits constructed on a 3-D printer in ABS plastic and coated with polyurethane paint containing stainless-steel flakes for surface realism and protection
   c. A video system to archive tests and permit evaluation of unusual behavior.
3. Overall, test results are consistent with field operations, impacts of inappropriate drilling practices, and visual analyses of balled bits.

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Nomenclature

ADS = *Accretion Drilling Simulator*
BSC = *Bit Structure Cleaning*
C### = *$CaCO_3$ d_{50} ###*
CAD = *Computer-Aided Design*
HSI = *Hydraulic Horsepower per Square Inch*
iLT = *Invisible Lost Time*
MSE = *Mechanical Specific Energy*
NPT = *Non-Productive Time*
OCMA = *Oil Company Materials Association (defunct)*
PDC = *Polycrystalline Diamond Compact*
PSD = *Particle-Size Distribution*
ROP = *Rate of Penetration*

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