AADE-07-NTCE-07

Geometry and Placement of Torque Control Components – How does this affect Torque Response with FC drill bits?

Steve Barton, Henry May, and Simon Johnson, ReedHycalog

Abstract

Torque control is a key issue with Fixed Cutter (FC) drill bits in many different applications. One of the most widely recognised is toolface control on Positive Displacement Motors (PDM).

Toolface offset is proportional to the torque generated by the bit. FC bits, by nature, generate high levels of torque. If an external force acting on the bit causes a FC bit to over-engage, a large change in downhole torque is typically produced, which causes rotation of the drill string, and loss of toolface orientation. It is therefore desirable for a FC bit to produce a torque response that does not vary greatly with changes in the external force applied.

This paper discloses a comprehensive laboratory test program used to evaluate the effectiveness of a number of varied, removable Torque Controlling Components (TCC) in producing a desirable torque response. Test results reveal the most effective component configurations that provide predictable torque response to applied weight on bit, allowing cutting structures to be optimized for overall higher penetration rates**.**

These configurations were engineered into drill bits for field application, with a variety of tip height offsets. The tip height offset is defined as the distance from the tip of the TCC to the tip of the cutter (Fig 1). Trials were established not only to evaluate response with directional motor assemblies, but also to review performance on both Rotary Steerable and Rotary drives. These were conducted in a variety of well trajectories, lithologies, and geographical locations.

Field performance studies clearly demonstrate that matching TCC configurations to directional motor assemblies delivers smooth torque response and improved toolface control. The results also depict reduced torsional vibration, particularly when used in Rotary Steerable and Rotary applications. Successful application has resulted in significant time and cost savings.

Introduction

Directional drilling using steerable systems has advanced considerably since the mid-twentieth century, where directional control was attained with rotary assemblies and deflection devices such as whipstocks. The development of the positive displacement motor (PDM) in the early 1980's provided the ability to make course corrections and counteract formation tendencies on a continuous basis. The operational concept of the PDM is well documented in several papers[1,2,3] but the key aspect relating to this paper is the difference in performance of the drill bit when sliding as compared to when rotating.

In rotating mode, the drill bit is being turned from both rotation of the drillstring and the downhole rotation generated by the mud motor. This resultant increased RPM is particularly beneficial for attaining high penetration rates with FC drill bits. Relatively aggressive designs can be used to optimize ROP because there are no toolface concerns in this mode. However, when sliding, the mud motor is rotating the bit downhole without any rotation of the drillstring from surface. This allows for the required toolface to be held stationary to attain deviation. In this mode, the reactive torque generated by an aggressive FC drill bit can cause the drillstring to twist unpredictably, resulting in the bit no longer being orientated in the desired direction. The amount of reactive torque required to cause this is dependant on several factors including the lobe and stage configuration of the specific motor employed, though the general relationship is that the more aggressive the drill bit, the more unpredictable the toolface offset will be. This relates to the fact that the curve of the gradient depicting the relationship between torque and Weight-on-Bit (WOB) steepens with increasing aggressivity (Fig 2).

The introduction of Rotary Steerable Systems (RSS) has contributed significantly to improved drilling performance and higher quality directional boreholes[4]. Most significant is the elimination of the slide mode; Directional drilling is attained with continuous drill string rotation. Reduction of the torque constraints associated with sliding paved the way for an increase in the use of aggressive FC drill bits for directional drilling with RSS. In many instances this has successfully provided substantial increases in ROP, but we should not overlook two key points:

1) Vibration Issues: More aggressive FC bits have a higher risk of inducing Stick-Slip, particularly with lower rotation speeds. This can lead to severe bit and BHA damage. Another resultant detriment is loss of steering potential due to overgauge hole.
2) Tool Diversity: As with downhole motors, the current

commercial RS tools have distinct variation in design and operation, thus requiring drill bit designs that have characteristics matched specifically to the system, trajectory, and lithology. As such, aggressive cutting structures are certainly not optimal for all applications.

The Compromise

There are four fundamental characteristics of drill bits; aggressivity, stability, durability, and steerability. The relationships they each have with the drive type, well lithology, and trajectory are key to improving performance[5]. FC drill bits designed for both directional motor assemblies and rotary steerable tools have specific profile, length, and gauge geometries to match the specific drive and trajectory. The cutting structure is also key, particularly in terms of lateral stability[6] and sidecutting capability[7]. However, cutting structure design is very dependent on lithology; Blade count, cutter size, and cutter backrakes are all optimized for the formations to be drilled so as to provide sufficient durability to drill the required section at the highest possible penetration rates.

How could we provide a design matched to the drive system and lithology that has a smooth torque response? The traditional approach would be to provide an unaggressive design by modification of the cutting structure. This though will affect all four fundamental characteristics, for example;

- An unaggressive FC design would improve toolface control when sliding on a steerable motor assembly but would have the downside of reducing penetration rates in rotating mode. This compromise is a concern given that the majority of intervals in directional runs are drilled in rotating mode.
- With RSS, an unaggressive design to reduce the risk of Stick-Slip would also result in lower potential ROP, but would also have a major impact on the bits sidecutting capability and therefore Steerability. Note that this could be positive or detrimental depending on the resultant Side Cutting Index (SCI) value, the operational mode of the RSS, and the directional objectives.

With the historical approach, reducing aggressivity via the cutting structure will result in compromising one or more of the four indices. It also results in a solution that is fixed and relatively slow to modify for subsequent changes in applications.

An alternative approach is to design the cutting structure of the bit to match the system, the trajectory and the lithology, whilst using secondary components such as inserts to control the reactive torque of the bit.

ReedHycalog introduced use of secondary ‘hybrid’ components on FC bits in the early eighties [8, 9]. Depending on their placement, these were used for several different functions including mitigation of lateral vibrations, controlling Depth-of-Cut for a smoother torque response, and for protection of the primary cutting structure in hard and interbedded formations. Use of secondary components on FC bits is now a widely adopted technology and over the years has seen many variation in terms of tip offset, location on the drill bit, geometry, material, and method of attachment (Fig. 3)

Throughout the existence of secondary components on FC bits, huge advances have been made in design methodology and modeling of FC designs to optimize cutting structures. This, coupled with step changes in PDC technology, justified further investigation into the design and placement of secondary components. A series of tests was devised to determine a variety of means of providing smooth and predictable torque response through the refined use of secondary components, while maintaining aggressive ROP through the cutting structure of the bit. A key objective was to define a solution that could be quickly and accurately modified, even after manufacture, for optimization to the specific application.

The following sections describe the test process and results that led to the development of specific insert configurations. Implementation of these has led to successful field performance across the range of directional drilling systems.

Laboratory Testing

The ideal bit for use on a motor will be very aggressive in rotating mode, and hence have a very steep gradient in its torque vs. WOB response, while being very unaggressive in sliding mode to give a very predictable torque response, and hence a very predictable toolface offset. This is shown in Figure 4.

One method of achieving this split response is to use an aggressive cutting structure with unaggressive secondary components that only engage at higher rates of penetration. The aggressive cutting structure delivers high ROP to the point that high WOB causes the secondary components to engage, leading to a shallower torque vs. WOB gradient and hence a more predictable toolface offset.

There are many ways in which the torque response of a FC drill bit can be modified through the use of secondary components. In order to establish which of these methods produces the most effective change in torque response, while delivering the least reduction in ROP, a series of laboratory tests were commissioned.

To achieve this goal, a special test bit was designed, shown in Figure 5. This test bit can be configured to control torque in 15 different ways. These include; rounded inserts positioned between cutters set off tip profile, flatted inserts positioned between cutters set off tip profile, high angle cutters leading conventional cutters, pre-flatted cutters set between cutters on the shoulder and many more. The test bit was designed so that many of these options could be configured such that the components were only present in a desired region of the bit, such as the cone, the nose or the shoulder.

The testing took place on a rotary test rig, under atmospheric conditions in Torrey Buff Sandstone (UCS 4,300 psi) and Carthage Marble (UCS 16,000 psi). The testing was carried out in both rocks to evaluate whether the torque control methods were effective in different formation types.

To give a baseline for the testing, all components were removed from the test bit except for the primary cutting structure. The bit was then tested at a range of WOB and RPM inputs to establish the torque behavior of the bit without any torque limiting components. For all tests a high frequency vibration-monitoring tool was used to record lateral, axial and torsional accelerations and the other drilling parameters, such as Torque, WOB and RPM. These were measured as described by Roberts *et al*[10]. The torque vs. WOB relationship for these tests for the baseline bit can be seen in Figure 6. It was observed that, as expected, when the bit was tested without any torque limiting components the torque vs. WOB was virtually linear.

Additional components were then assembled to the bit, typically by a brazing process. Each configuration of the bit was tested at the same range of WOB and RPM inputs as the baseline tests, and also in both rock types listed previously. In total, over 150 laboratory tests were carried out to establish the most effective method of limiting torque on a FC drill bit.

Test Results

Fifteen different configurations were tested in order to determine the most effective improvement in torque response. The relative success of different components was quantified by the difference in the slope of the Torque vs. WOB curve, with a reduction in slope corresponding to a decrease in reactive torque. The effect that the different features had on the ROP of the bit was also observed. Many of the tests did not yield a decrease in reactive torque, thus this paper will detail only the tests that yielded a significant improvement in reactive torque.

Configuration A

The first series of tests that yielded a positive result was configuration A (dome-topped inserts positioned between cutters across the bit face). The results showed that when the inserts engaged, there was a notable decrease in reactive torque. This is evident by the decrease in slope shown in Figure 6. This arrangement of TCC also recorded a decrease in the ROP vs. WOB graph as shown in Figure 7, however this decrease is not as pronounced as the decrease in reactive torque.

Configuration C

This configuration utilized a similar array of inserts as listed for configuration A (dome-topped inserts set between the cutters) with the exception that these were located in the cone only. As with configuration A, the results show that when the inserts engaged there was a notable decrease in reactive torque. This is indicated by the decrease in slope shown in Figure 8. There is also a corresponding change in the slope of the ROP vs. WOB curve (Figure 9) when the TCC engage formation. It is the decrease in the gradient of the torque curve that is most significant since any fluctuations in torque can lead to toolface control problems and risk of torsional vibration. The associated benefit of increasing the average ROP by virtue of reducing the 'flat time' from torque control far outweighs the minor reduction in the 'straight-line' ROP observed in the laboratory.

Insert Shape

Tests were conducted using the same configurations as described prior (A & C) but changing the dome-topped inserts to an insert with a flat-topped geometry. The tip height of these flat-topped inserts remained the same as that for the dome-topped components. The same reactive torque changes were recorded for these configurations, though it was noted that the flat-topped inserts had a greater initial effect on the slope of the Torque vs. WOB graph compared to that of the dome-topped inserts.

The effect that the flat-topped inserts had on ROP corresponded to the decrease in reactive torque as also seen with configurations A and C. The results for flat-topped and dome-topped inserts were very similar (Fig 10).

The prime difference between the characteristics of the dome-topped and flat-topped inserts used within the laboratory testing relates to the material that they were made of; the former utilized a PDC coating whereas the latter was made from tungsten carbide (TC). As such the PDC design has much higher abrasion resistance than that for the TC inserts, thus extending the effective life that they can provide engagement with the formation to control torque. This is a key factor for consideration in commercial applications, particularly when drilling hard and abrasive lithologies. Varied materials and geometries were evaluated for wear resistance within the field test phase.

Configurations with Less Positive Results

The test program explored the effect of 15 configurations and each demonstrated a variation in either the Torque vs. WOB curve or ROP relationship, or both. However the two configurations identified prior (A&C domed and flat-topped) were the most successful in reducing reactive torque without significant detriment to penetration rate. As such, those arrangements were taken forward into the field test phase, while the remaining configurations remain subject to further refinement and evaluation.

Test Result Summary

From the test results it can be concluded that the most effective way to improve torque control is by placement of secondary inserts between cutters and off tip profile in the cone of the drill bit. The area of the bit where the inserts are located is very important. The results indicated that placing inserts on the shoulder yields no significant improvement in torque control.

Placement of inserts between cutters on the nose of the bit appeared to have a negative effect on ROP while causing no significant improvement in torque control. However, the insert geometry around the nose appears to have significant effect on the ROP of the bit, as might be expected.

The geometry of the inserts used to control torque also appear to have an effect with a flatter insert showing a more pronounced decrease in reactive torque. This suggests that different geometries may be better suited to different formations, with a flatter insert having advantages in softer formations.

Field Configurations

From the testing in the lab, it was determined that the placing of inserts in the cone of the bit was the most effective way to reduce reactive torque. It was also clear that these components were the most effective when they were set behind and between the primary cutting structure. The durability, accuracy, and repairability were also considered in determining the best way to implement these components in a field capable bit.

Based on the test results, the decision was made to field test the effectiveness of using inserts to control torque. This allowed us to test different insert materials and geometries in the optimal configurations identified. Both flat-topped and dome-topped inserts were tested, using tungsten carbide, PDC coated, and diamond impregnated materials. The effect of adding additional rows of inserts for softer formations was also tested in the field. For all TCC arrangements, variation in the tip offset of the inserts was required in order to match the specific drive, parameters, and ROP objectives.

The first configuration tested employed round-topped PDC inserts positioned in-between cutters in the cone of the bit. The inserts were set at a constant offset from the primary cutters and were at different angles of rotation behind the primary cutters. In a dynamic drilling environment, these inserts are meant to sequentially engage, with the inserts that are furthest behind the primary cutting structure engaging first. PDC has the advantages of being very resistant to abrasion and has a low coefficient of friction.

Since PDC is a very hard material it can be susceptible to impact damage. For that reason tungsten carbide and diamond impregnated inserts were also evaluated, using similar configurations to those with the PDC inserts. The different materials were also tested in various combinations in order to minimize the effect of differences in the testing environment. Figure 11 illustrates the variance in durability witnessed within these tests.

For applications where greater contact between the TCC and formation was required, bits were built with multiple rows of inserts. Flatter inserts were also utilized to evaluate if they would absorb more weight at the same tip offset as a dome-topped insert, thus more suitable for softer formations.

Field Test Results

A significant number of commercial field runs have been conducted using TCC to provide smooth torque response. These were conducted in global applications across the range of drive types and large diversity of hole sizes. The following is a small selection showing the range of benefits provided by these designs.

Case Study: Rotary Steerable Application – Middle East

A new 6” Rotary Steerable design was developed to replace an existing product, which although successful in its time, was developed several years prior and had become outdated. The specific application utilized a push-the-bit rotary steerable system within a primarily horizontal section. Both Stick-Slip and lateral vibration issues had been identified as problematic with prior bit runs.

The bit designs can be viewed in Figure 12. Both designs are 6 bladed with a 13mm primary cutter size. However, the cutting structure of the replacement design was optimized to improve on the key indices of the bit, particularly the lateral stability and its sidecutting capability to match the requirement for this push-the-bit RS application.

Penetration rate was also important to the operator, thus an aggressive cutting structure was maintained. In order to reduce risk of stick-slip, the bit was equipped with a specific TCC configuration to provide torque control. The material, geometry, and offset of the configuration were adjusted specifically to the drive and lithology. In addition, the bit featured a taper on the gauge pad, known to reduce stick-slip events with this RS system[11].

On its trial run, the new design drilled 4,473ft in 71 hours for an average ROP of 63fph. This run was longer and significantly faster than the average offsets (average offset ROP was 47fph). The design performed as required in terms of steerability and directional behavior, with a maximum dogleg of over 6deg/100ft attained. In terms of vibration, no lateral shocks were observed and a 75% reduction in Stick-Slip was recorded.

This trial displays that with the use of an optimized TCC you can attain both aggressivity and smooth torque with FC drill bits on RSS without compromising features matched to the specific operation of the tool.

Case Study: Motor Steerable Application – Europe

The toolface control of the optimized TCC was put to the test on directional motor assemblies. One of the first designs to incorporate this feature provided significant success in an application within central Europe.

The directional objective was to kickoff from vertical and build out to 58 degrees inclination, then hold tangent to casing point. A build up rate of just under 3deg/30m was planned. An 8 ½”, 6 bladed FC drill bit was selected with a combination of 19 and 16mm primary cutters in order to optimize penetration rates. However, due to the interbedded sandstone, siltstone, and claystone, a specific TCC was employed to maintain constant toolface control. This bit design was run on a high torque motor with 1.15 degree bent housing. The run was a success and fulfilled all objectives;

Directional: Very steerable response, allowing slide intervals to be reduced by half. Toolface was smooth throughout the run, with the directional driller stating that you could ‘set and forget’.

Interval: The assembly drilled shoe to shoe. Compared to the average from 36 offset records, the bit drilled 51% further at an ROP 23% higher than average. It should also be noted that ROP was controlled due to logging requirements.

Durability: The bit reached the planned casing point and was pulled with very little wear (1-1-WT---TD) and no mechanical damage. The latter compliments the smooth toolface control observed and indicates no significant vibration issues.

This trial displays that with the use of an optimized TCC you can attain both aggressivity and smooth toolface control with FC drill bits on steerable motor assemblies.

Case Study: Vertical Application – U.S. Land

Controlling torque response is not just a requirement for FC drill bits in directional applications. High variance in reactive torque often results in stick-slip issues, detrimental to drilling performance in any application. The following example highlights successful application of TCC to improve penetration rates in vertical applications.

Prior vertical runs within this 7 7/8" application in Wyoming displayed high levels of stick-slip and resultant mechanical damage to the shoulder of FC bits used. Data from a proprietary downhole dynamics data recorder[12] indicate that the stick-slip occurs in a number of lithologies within the section typically drilled. As a result, average ROP was reduced and more drilling hours were required to complete the section. A relatively aggressive (5 bladed, 16mm PDC cutting structure) drill bit was selected that featured a specific TCC arrangement (Fig 13). The goal was to reduce incidents of stick-slip, improve dull condition, and thus increase penetration rate.

These objectives were exceeded: The use of the TCC inserts appeared to mitigate stick-slip and the dull condition reflects this (2-2-WT-N-X-I-CT-TD), with a normal wear pattern observed and only very minor evidence of mechanical damage. As a result, the run was superior, in terms of penetration rate, to all the runs to date in this field for the Operator. The average ROP was 13.8% higher than the best field offset run. This saved the operator over 30 hours for this section, thus considerably reducing operational cost.

Application Matched TCC

Torque control achieved by using the body of the bit is a frequently adopted method[13]. The concept is that at higher ROP's the blade acts as a bearing element and absorbs a proportion of the load. This thereby reduces the rate at which the torque increases. The main disadvantage is that the blades are set at a fixed offset during manufacture thus it is impossible to match the bit to the specific system in the field.

The following example demonstrates clearly how the use of a concept that allows rapid, post-manufacture modification does allow the drill bit to be matched specifically to the application.

Case Study: Vertical Application 2 – U.S. Land

This field test examines the effect of varying the tip offset height of the TCC's on penetration rate. The application is very similar to that of the vertical case study in U.S. land, described previously. The key objective was to reduce stick-slip and increase penetration rate.

In this example, a 7 7/8" 5 bladed FC design with 13mm primary cutting structure had been used on offset wells. This bit was equipped with a dome-topped TCC configuration with specific tip offset. Performance had already been increased by use of the TCC's with this bit, and average ROP attained was approximately 74ft/hr.

Inspired by the performance attained by using TCC within this field, it was decided to further optimize performance by increasing the tip offset of the secondary inserts. The exact design utilized was returned to the product center and the components replaced with inserts shortened by a specific length. This provided an additional 0.5mm tip offset below the primary cutting structure. Upon field test, this modified design achieved an average ROP of 100.6 ft/hr, an improvement of over 36% compared with the same design run prior.

This brief study clearly depicts the importance of being able to have a TCC configuration that can be modified post-manufacture, even post-run, to attain the optimal results demanded by application requirement.

Conclusions

A number of conclusions have been derived from both the laboratory and field testing. These include;

- Use of inserts between cutters, positioned off tip, within the cone is the most effective means of providing torque control with FC drill bits.
- TCC can be successfully applied on drill bits for RSS to reduce risk of Stick-Slip. This allows continued use of aggressive cutting structures for optimized penetration rates and sidecutting (as appropriate).
- Drill bits for directional motors can be optimized with use of TCC to provide 'set and forget' toolface control when sliding, while still maintaining aggressive cutting structures for high ROP in rotating mode.
- The use of TCC on bits used on Rotary assemblies can greatly assist superior penetration rates, reduced incidents of Stick-Slip and mechanical damage, delivering significant cost savings.
- The design and variation in offset, geometry and material of the TCC allows flexibility of the torque control feature to match to the specific drive, parameters, and lithologies.
- Use of replaceable TCC's allows great flexibility in modification of the design post manufacture, and even after the initial design has been run in the field. This allows continuous optimization of the bit to the specific application.

Acknowledgments

The authors would like to thank the management of ReedHycalog for granting permission to write this paper. A special thanks goes to Andy Murdock and John Clegg for editorial contributions.

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Figures

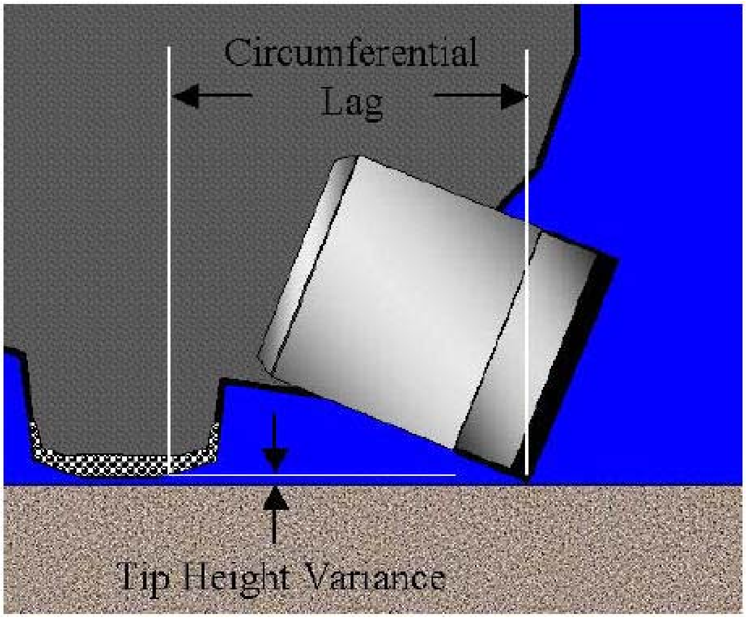

Figure 1: Secondary Component Tip Offset

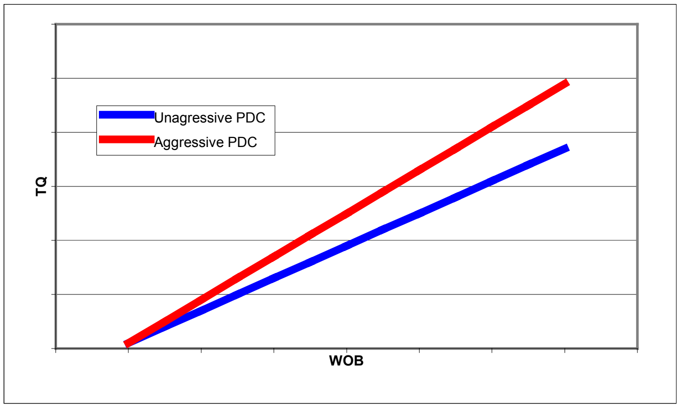

Figure 2: Torque relationship plot

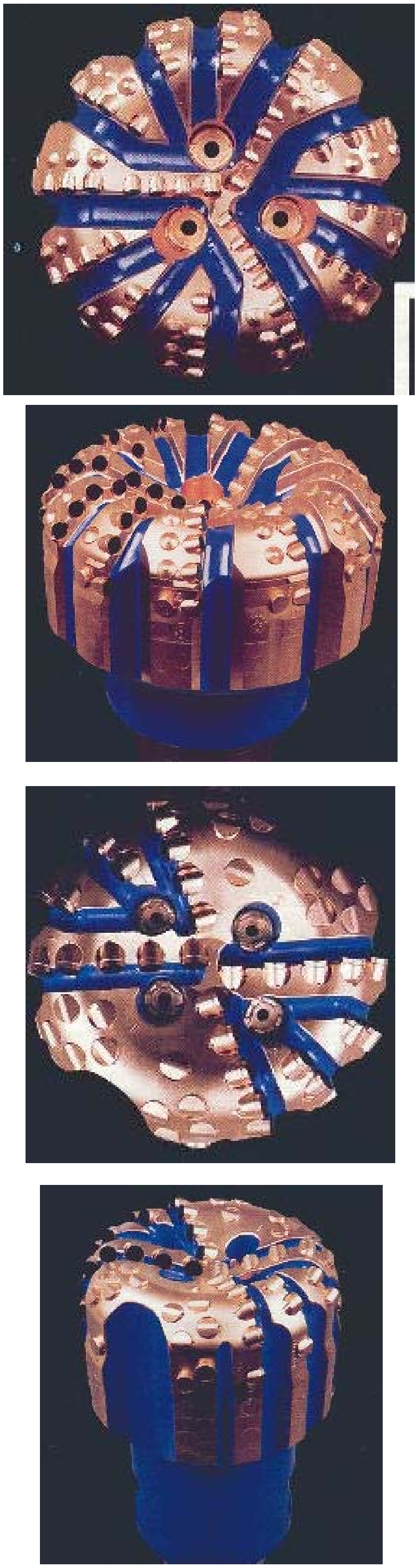

Figure 3: Early 'Hybrid' FC Designs

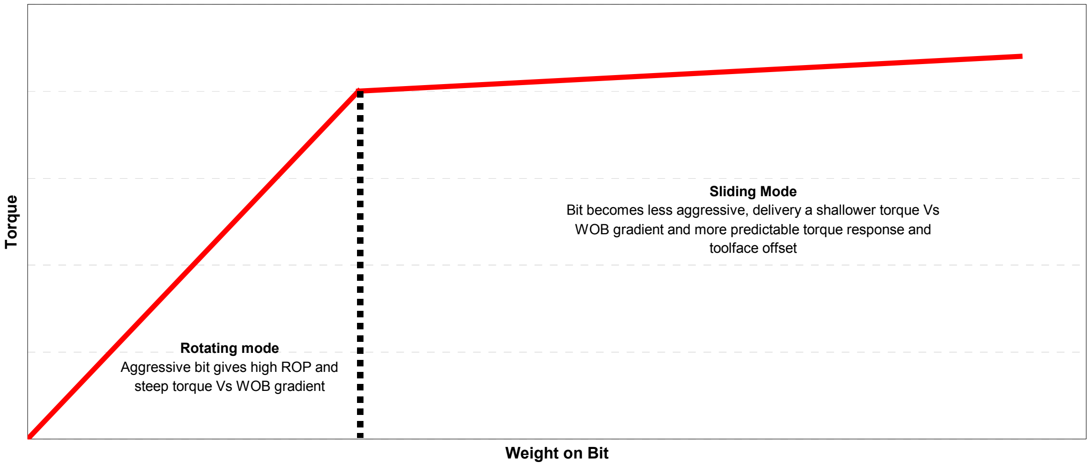

Figure 4: Torque vs. WOB relationship

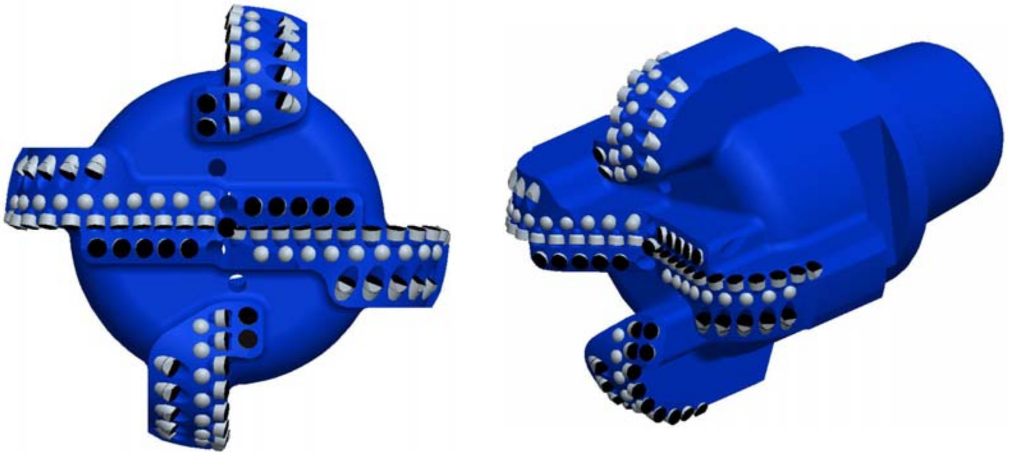

Figure 5: Test Designs

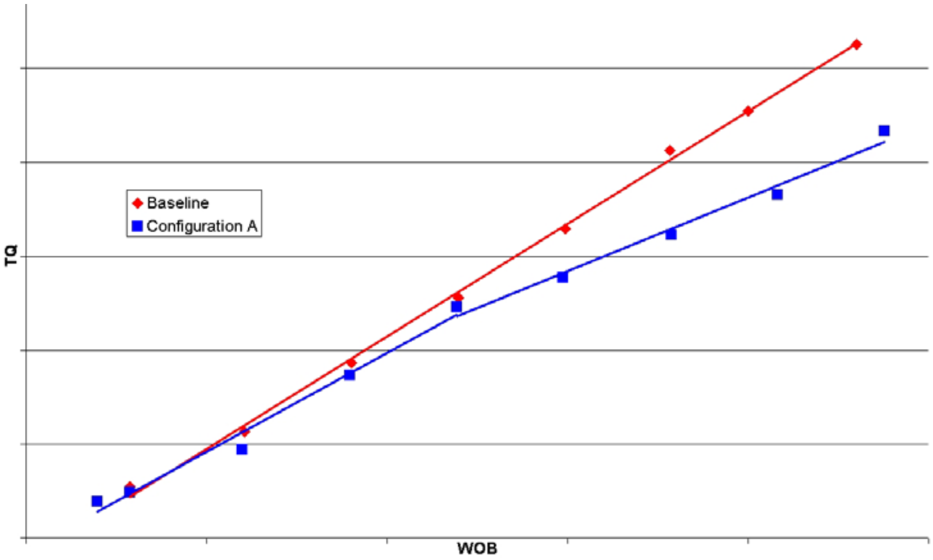

Figure 6: Configuration A – Torque vs. WOB

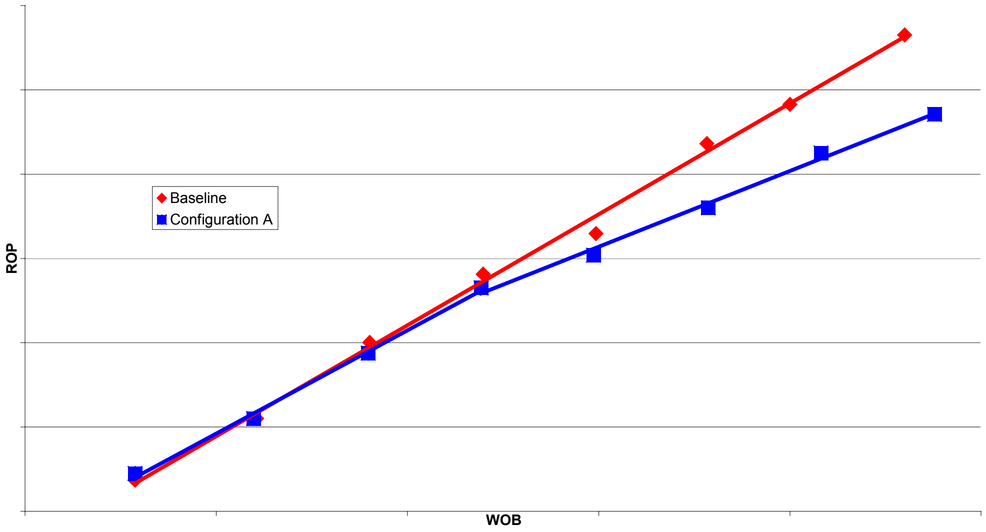

Figure 7: Configuration A – ROP vs. WOB

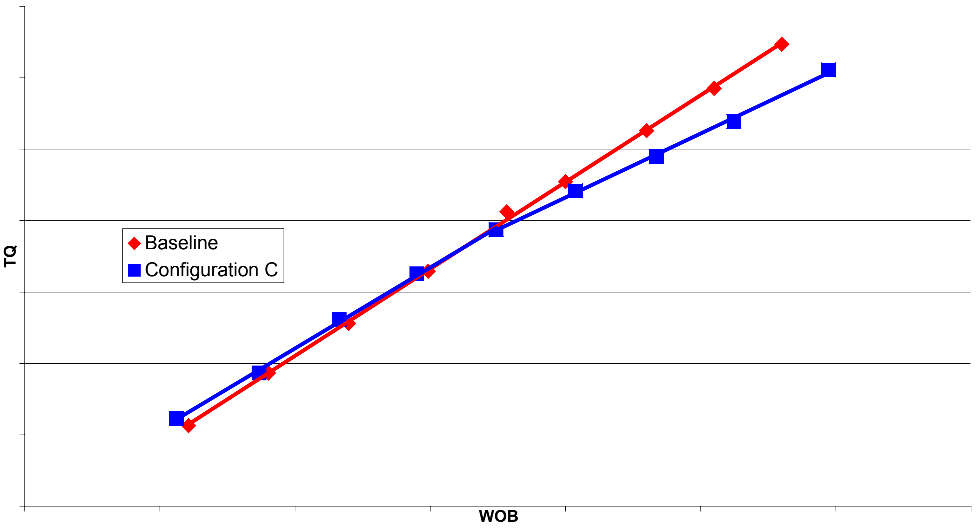

Figure 8: Configuration C – Torque vs. WOB

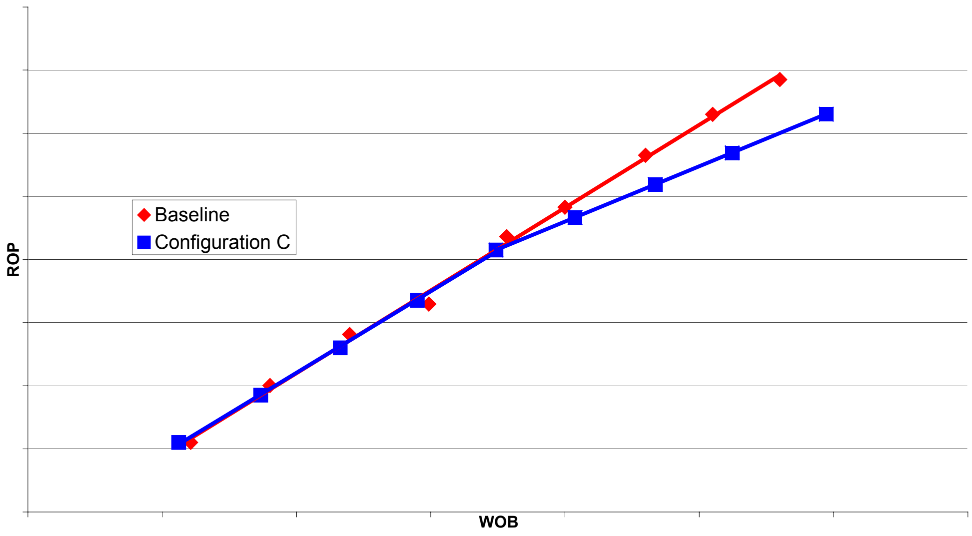

Figure 9: Configuration C – ROP vs. WOB

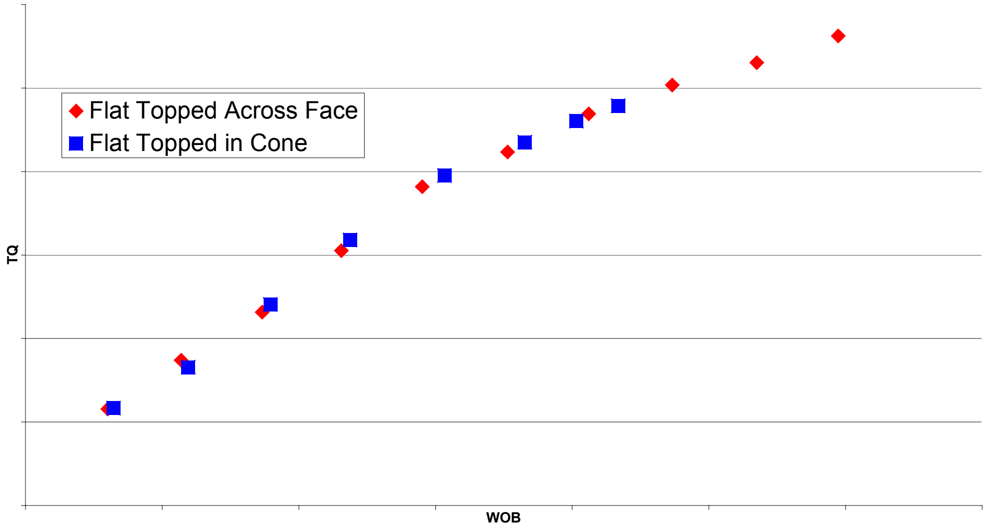

Figure 10: Torque vs. WOB for Flat Topped Inserts

Figure11: Test Bit with Different Material Inserts

Figure 13: PDC Design incorporating TCC used within Vertical application

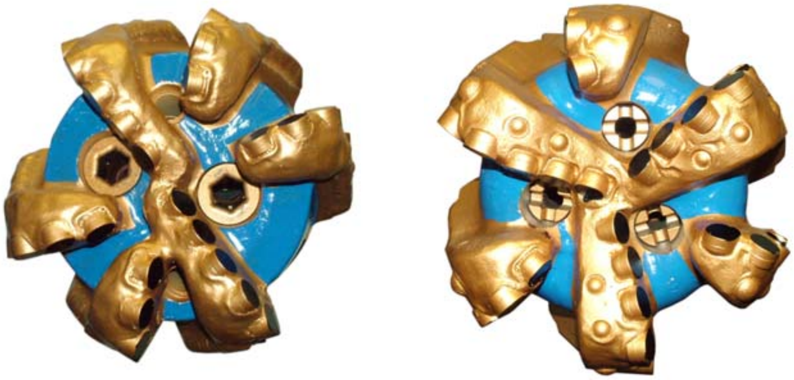

Figure 12: Offset (left) and Replacement (Right) FC bit