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# Coiled Tubing Drilling Advancement with Smallest Shaped Diamond Cutting Element

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## Abstract

This paper describes an innovative concept for the smallest polycrystalline diamond compact (PDC) cutter size with non-planar diamond table used on a fixed cutter drill bit. This unique PDC cutter significantly increases durability, enhancing the bit life to drill more footage in multi-lateral applications driven by motor or turbine in two different challenging formations. Collaboration between a national oil company and a drill bits provider resulted in achieving consistent records in footage while maintaining good rate of penetration (ROP).

This 8.2 mm diameter PDC cutter equipped with unique geometry was used on a 3.625 in. fixed cutter (PDC) drill bit design. Main objective of the unique geometry on this non-planar diamond table is to improve cooling efficiency compared to the standard diamond table of a PDC cutter. Traditionally, PDC cutter technology relies on the cutter's thermal stability and abrasion resistance. Often, those two properties may not provide sufficient durability in abrasive formations. Initially, this unique geometry was used on bigger PDC cutters including 13 mm and 16 mm where a performance improvement was achieved, leading to the decision to scale-down to the smallest PDC cutter size.

Two different 3.625 in. fixed-cutter drill bit designs were used with non-planar diamond table PDC cutters and successfully passed the client requirement and trial testing criteria. Based on the field deployment results, drilling performance in the field was monitored and compared to standard diamond table PDC drill bit designs also used in the past as the benchmark. Shaped non-planar diamond table bit designs surpassed the footage of standard diamond table PDC cutter bit designs by 12% and 36% respectively with two different bit designs. Other performance aspect including dull condition were also monitored and showed similar wear progression as seen with other bit designs used in the application.

This innovative concept demonstrates that the non-planar diamond table PDC cutter successfully delivers more footage per bit run. This led to increase overall performance with deployments on coiled tubing drilling rigs across this difficult drilling environment in the challenging wells drilled in the Middle East. The novel technology achieves all drilling objectives with fewer drill bits and fewer trips, delivering the target footage at improved ROP.

## Introduction

PDC bits were first introduced in the mid-1970s there have been many improvements in the materials, processes, and geometry of the PDC cutter, leading to substantial increases in performance that the industry achieves today (Scott 2006). These improvements range from innovations in management of the diamond particle size and density, diamond table thickness, non-planar interfaces for stress management, chamfers, surface finish, thermal stability, and high-pressure sintering.

Polycrystalline diamond cutter (PDC) technology is derived from a mixture of fine synthetic diamond grit that is formed into a solid composite with a metallic binder under extremely high pressure and temperature (HPHT) conditions. The HPHT conditions used in manufacturing are not unlike the environment that forms natural diamond deep in the earth. Diamond is the hardest bulk man-made material available in large quantities.

Although diamond possesses a wide range of high performance-enabling properties, in abrasive cutting tools it has one significant weakness: temperature. In an environment where oxygen is present, diamond oxidizes as temperatures approach 650°C. This oxidation process becomes much more rapid at 750°C. These temperatures are attainable under abrasive rock cutting conditions. So, it is essential to keep the temperature of the diamond in PDC cutters as low as possible to promote diamond stability, which retains the high strength and hardness of the material and translates to prolonged cutting efficiency and drilling progression.

Each formation has unique characteristic which has direct influence on PDC cutters. For example, in very hard sandstones with low depths of cut or interbedded sandstones and carbonates, bit performance can depend strongly on the thermal stability of PDC. PDC cutters exposed to very high heat levels experience abrasive wear faster, leading to lower rates of penetration (ROP) and higher mechanical specific energy (MSE) or wasted energy that is not directly transferred into removing rock.

A comprehensive testing and development program was carried out to understand the implications of the non-planar design features on the thermal efficiency and the cutting mechanics of multidimensional diamond tables in PDC cutters. Single-cutter designs were tested in atmospheric vertical turret lathe tests, pressurized single-cutter tests, full bit testing in a downhole simulator, and finally using finite-element modeling methods (DiGiovanni 2014). The most promising designs were then sent to the field for performance validation in challenging drilling applications across the United States.

## Multidimensional Non-Planar Cutter Design

Because of the performance limiting characteristics of hard abrasive sandstone and carbonates along with the interbedded nature of many challenging lithologies several studies of the effect of PDC cutting edge geometry in a variety of formations were conducted. In particular, the behavior of the rock, cuttings, and cutter interface was a focal area of development.

Previous studies on planar cutters with polished and non-polished surfaces have suggested the influence of frictional forces along the cutter surface as being significant for rock cuttings under pressure and contributing significantly to the mechanical specific energy of the cutting process. The use of polished cutter surfaces has demonstrated benefits for operators in several applications over the years (Al-Hinaai, 2013; Hakam & Felderhoff, 2013; Scott, 2012; Smith, 1995).

Studies that examine PDC thermal stability have demonstrated that cutter efficiency and life could be increased by reducing heat generation when drilling abrasive rocks, a main contributor to failure of PDC cutters (Teasdale 2013). While most of these findings highlight the underlying material properties for a standard planar cutter design, one recent article speaks to a highly non-planar shape with improved drilling efficiency (Azar 2013). While the latter article indicates performance gains in drilling, a cutter mechanism was not identified, and cutter performance appears tied to bit design.

A review of previous non-planar cutter designs led to the adoption of a non-planar diamond table as shown in Fig. 1. A portion of the diamond table has a recessed feature that is composed of a leading-edge geometry that subsequently transitions discontinuously into a second regional geometry. The leading edge geometrical features demonstrate a complex interplay of mechanical and thermal work when cutting rock that changes as wear progresses through the original structure.

Figure 1—Innovative non-planar cutter

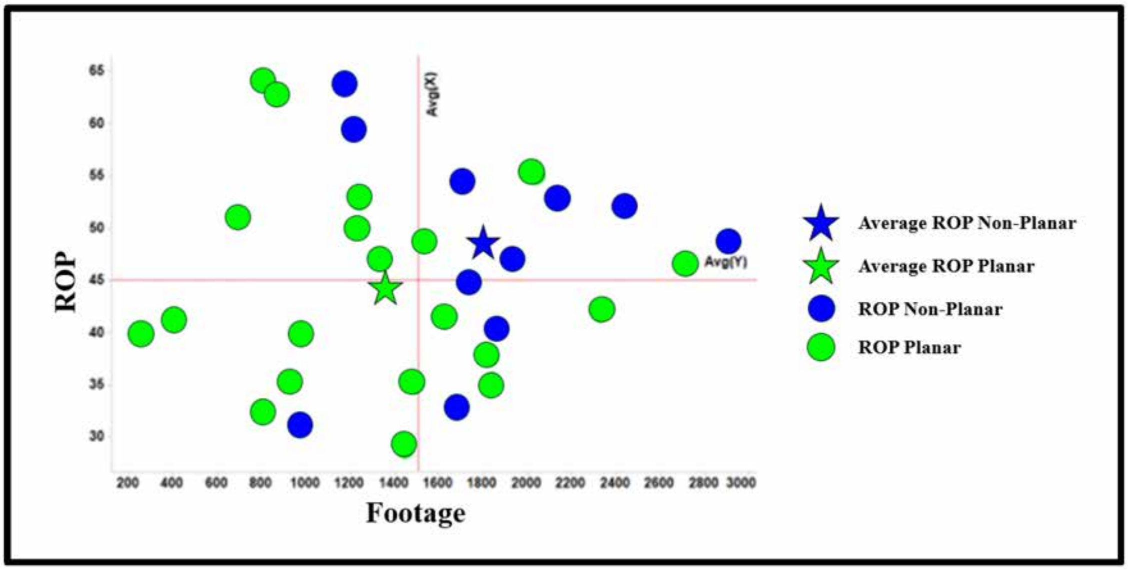
Understanding the various features and their wear state progression characteristics enables the designers to tailor specific non-planar cutting face technology to manage friction between the rock cuttings and the cutter. This design understanding has led to significant performance gains independent of the bit design or cutter size.

There are several advantages to this technology. First, the underlying material development can be advanced independently of the cutter design since this non-planar still using the standard cylindrical cutter dimension on both diamond table and substrate. Material development mainly focus on the improvement on the diamond table, as the thermal stability gains are additive. Secondly, the modifications to the manner including chamfer and size of planar PDC cutters enable a direct swap in any existing bit design to achieve the benefit.

The current multi-dimensional diamond table design was put through a rigorous series of laboratory tests before undergoing field trials then released for the global deployment into the applications that could benefited from this non-planar cutter design.

In one of the case studies which relevant to the targeted application in this paper, multi-dimentional non-planar PDC cutter successfully surpassed the performance of planar PDC cutter for the same given bit design (same frame) with the achievement summary as below and comparison result as shown in the Graph 1.

- 10% increases in rate of penetration (ROP)
- 35% increased in footage drilled
- Overall bit dull condition of non-planar benefited the lesser wear
- Less chippage at the leading (cutting) edge with reduction in spalling




Graph 1—Non-planar vs planar PDC cutter bits performance comparison result

Dull condition between non-planar and planar PDC cutter bits from this case study also were evaluated and compared as per Figure 2. Both non-planar and planar PDC cutter bits show similar dull trend and similar progression in term of wear grade. However, significant difference observed on wear characteristic where non-planar PDC cutter shows more sharp-edge wear with no spalling on the diamond table. Whilst planar PDC cutters experienced many spalling on the diamond table which could affect the durability of the cutting structure resulted with lower ROP or lesser footage, or in combination of both.

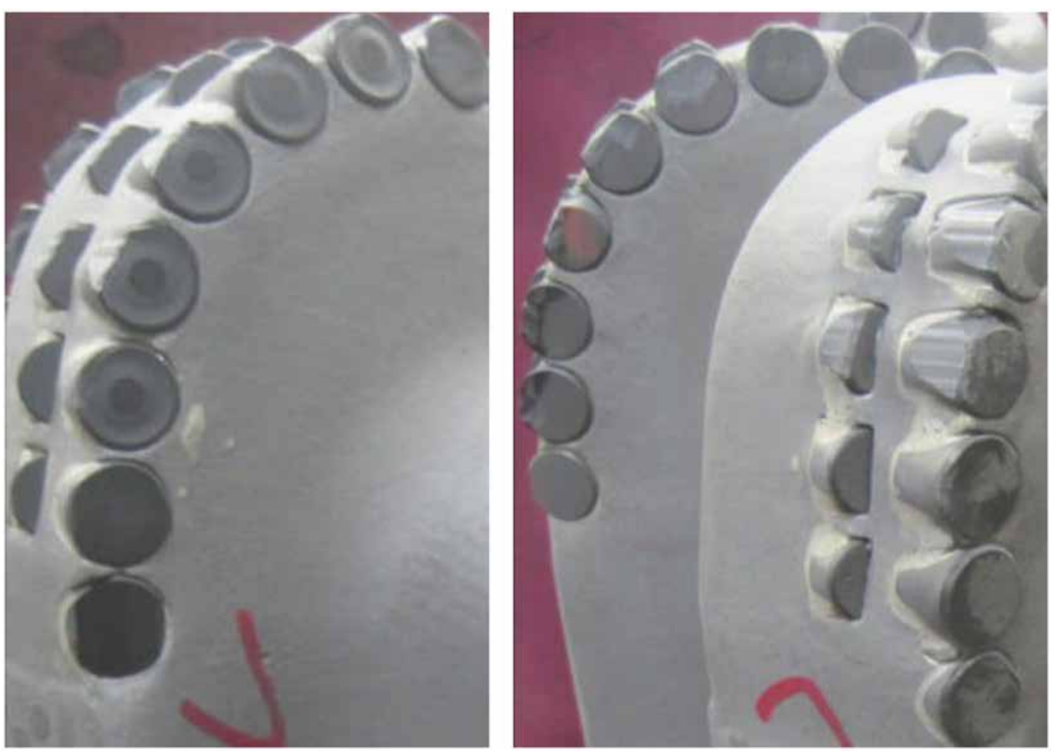


Figure 2—Non-planar (left) vs planar PDC (right) cutter dulls for the same bit frame

## Application Descriptions

This coil-tubing drilling application located in the onshore Middle East. It is targeting two different group of gas producer formations – named as A formation and the formation below it, B formation as illustrated in the Figure 3.

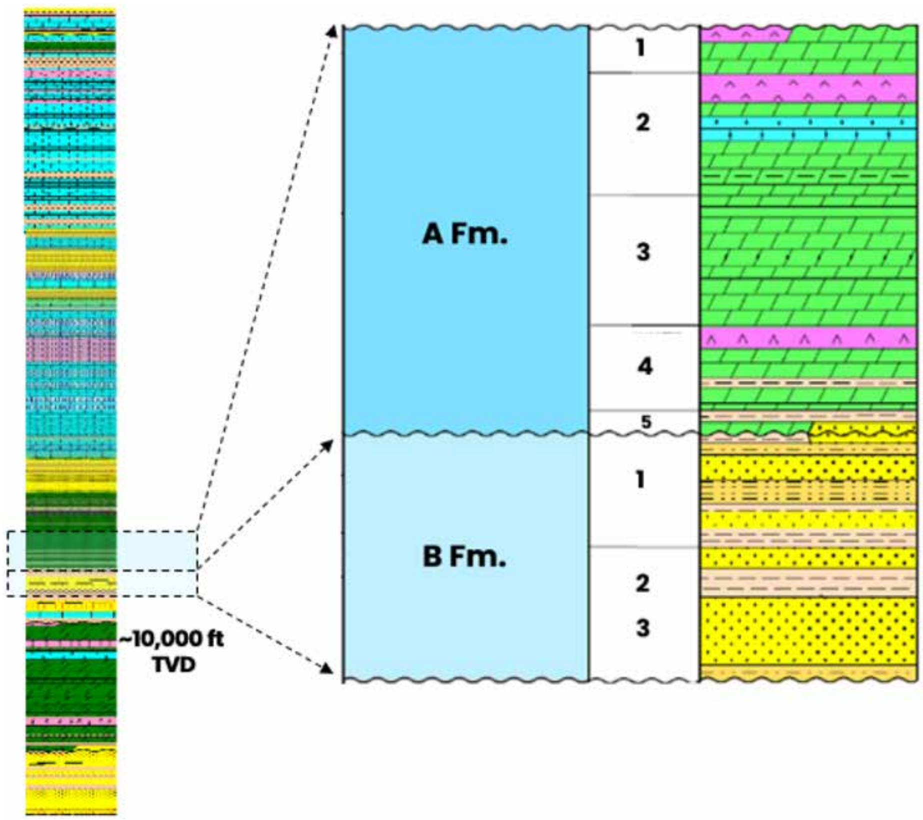



Figure 3—Main formations with common layers

Upper formation – "A" formation has five layers and usually drilling through sub layer no.2 and no.3. "A" formation is composed of carbonate lithology and its characteristic is hard and usually unstable, which could lead to inducing the vibration. However, drilling footage for this formation is long with relatively higher ROP, ranging from 15 to 20 ft/hr. Drilling this formation resulted with less bit wear and bit commonly in re-runable condition once Pulled out of Hole (POOH). This formation is also drilled in the 5.875in hole size (Mahmoud 2020).

The lower formation – "B" formation is mainly sandstone that has three layers which is hard with abrasive characteristic, hence drilling resulted with short footage and low average ROP. Bit typically came out on surface in severe wear condition and mostly in irreparable condition. From three layers, layer no.3 is the most common drilled in this application.

In terms of drilling process, this application requires coil tubing BHAs to drill multiple laterals in a single well with operation sequence as shown in the Figure 4.

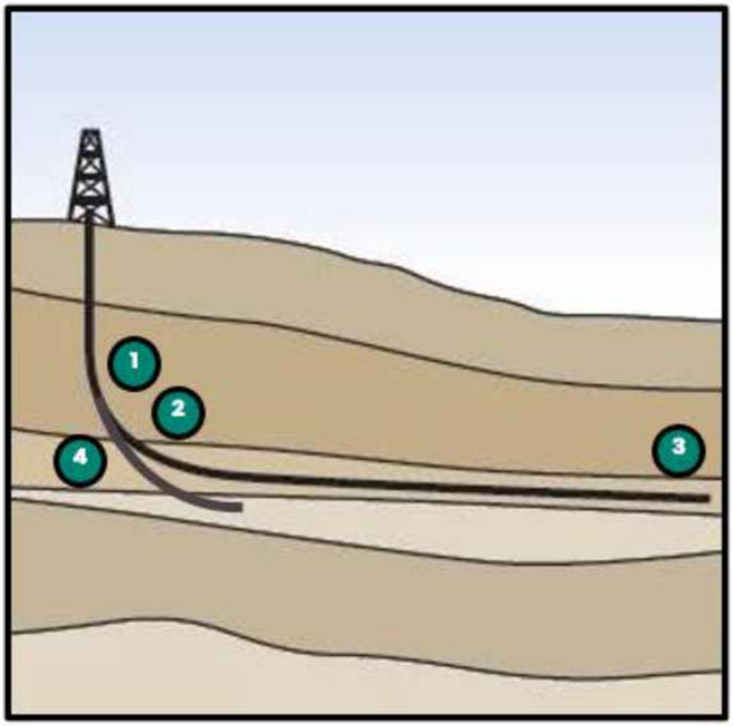



**Figure 4—Operation sequence on coil-tubing drilling**

Coil-tubing drilling starts with clean-out operation usually using motor BHA. Clean-out operation requires to drill-out cement, shoe (sometime reamer shoe) and rathole. Thus, bit life is usually short, with impact damage and abrasive wear is common (1).

Once the hole is free from debris or obstruction, build-up section BHAs using motors or turbines with high AKO are used for drilling directionally. Depending on the well plan, this section's footage is usually short, and the section is completed once inclination and azimuth are achieved (Figure 4).

At the build-up section is completed the BHA is POOH and a lateral section BHA with lower AKO is used to deliver the planned footage – this may require two or more runs with new bits for each run before reaching lateral TD. Drilling "B" formation historically requires extra runs compared to A formation due to hard and abrasive nature of the formation. Completing the last lateral is then also the well TD (Figure 4).

Depending on the well plan, after the lateral reaches TD, the same bit and lateral BHA will be used to initiate the side-track to drill next lateral. This might take longer time to try initiate side-track subject to bit dull condition and this unsuccessful it should require another trip to complete the side-track with a new bit and high AKO motor or turbine.

Since this application drilled in a very small hole size (3.625 in.), a unique BHA is required to be used on coil-tubing instead of typical drill pipe.

Figure 5 shows a generic BHA for coil tubing drilling operation. It has similar basic BHA components as a conventional drilling BHA, a drive system which either is a motor or a turbine, an orienter tool to establish the tool face, measurement-while drilling (MWD), circulating sub, vibration sensor, and other downhole sensors.

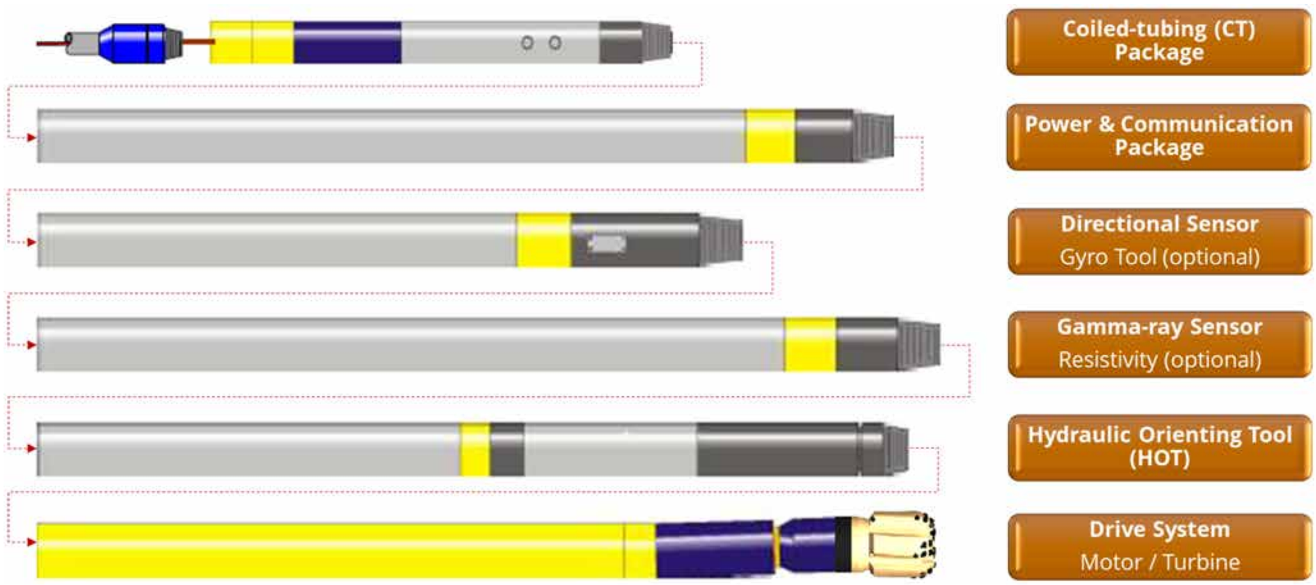



**Figure 5—Generic BHA components including options**

The directional gamma sub (DGS) provides both MWD capability and gamma-ray sensor. A resistivity sensor is optional and is provided as standalone component. The hydraulic power controller (HPC) includes the hydraulic orienting tool (HOT) which helps steer drive system together with the bit.

Two drive types are commonly used in this application: turbines and motors with various RPM ranges based on different configurations and revolution-per-gallon (RPG). Bit RPM can be as high as 2,500 RPM. Both drive systems are used in both formation "A" and "B" based on the contractual requirement. However, flow rate used in this application regardless of drive type is an average of 95 gallon per minute (GPM) with mud weight of 63 pounds cubic feet (PCF).

## Challenges and Technology Deployment

Durability of the PDC bit cutting structure is identified as limiting factor considering the small bit diameter used in this application. Thus, extending the PDC cutter life is one of the optionsto allow the bit to stay sharp longer and be able to drill more total footage per bit without the need to increase the PDC cutter count (which is difficult due to the small bit size). This approach also allows other bit design requirements, including hydraulic efficiency and directional steerability, to be met.

Based on the proven non-planar diamond table design used in the similar application, decision made to implement non-planar and evaluate with comparison to the planar design using similar bit design and diamond table material in the "A" formation application.

The non-planar diamond table design selected for this application helps to optimize the wear state up to T3 which represent 37.5% diamond table used on the average for the PDC cutters. Figure 6 shows how the contoured multi-dimensional cutter design interacting with formation in sequential of wear progression stage. The angle where the diamond table interacts with the rock gets more aggressive as the cutter wears down, allowing the non-planar cutter to maintain a more aggressive cutting edge.

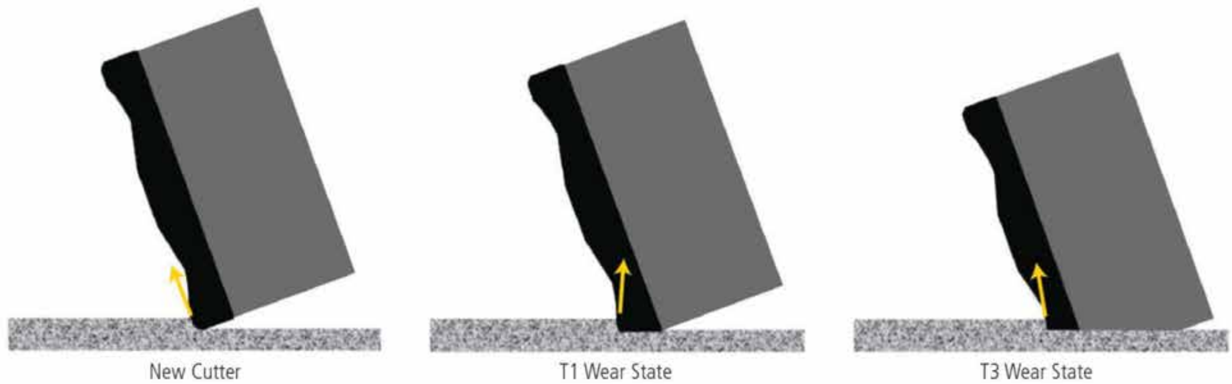



**Figure 6—Multi-dimensional non-planar wear progression**

As part of pre-deployment process, IADC bit dull grade was evaluated on the 5 blades and 8.2mm PDC cutter bit design used in this application as shown in the Figure 7.

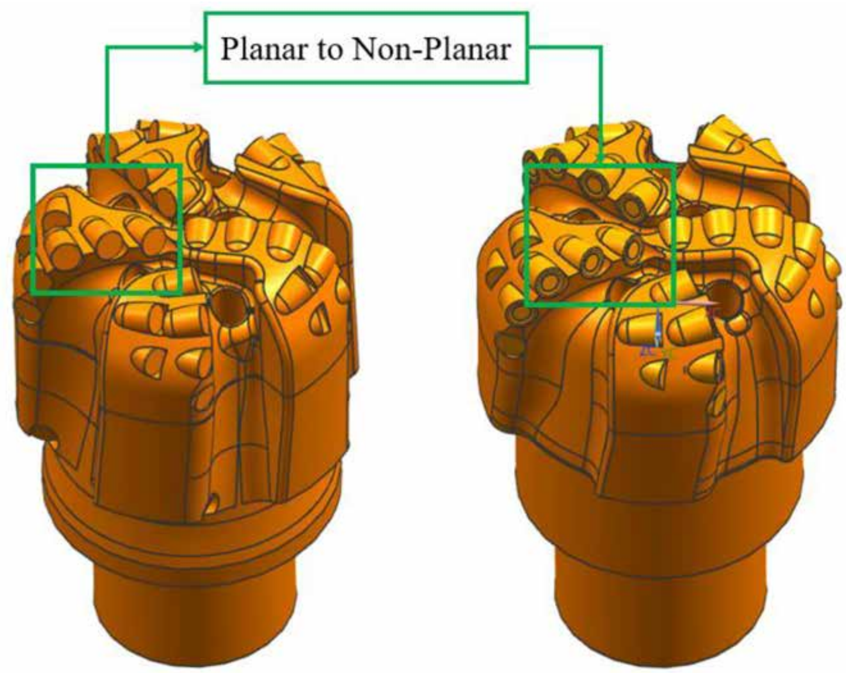
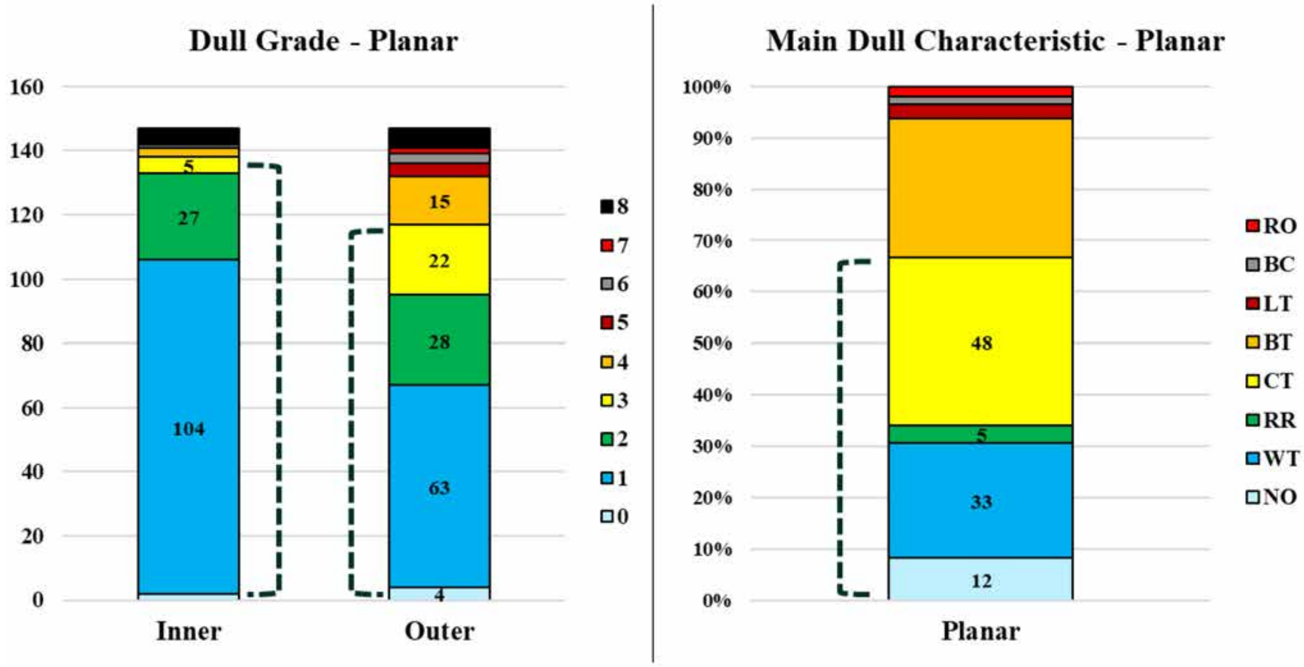



**Figure 7—3.625in. diameter PDC bit with 5-blades and 8.2mm cutter (planar and non-planar)**

This process is important to ensure the technology is implemented correctly and to ensurethe design objective is met. Critical aspects for the PDC bit cutting structure wear progression and its main dull characteristics were plotted and analyzed as shown on the Graph 2.




**Graph 2—Inner and outer rows wear with main IADC dull characteristic**

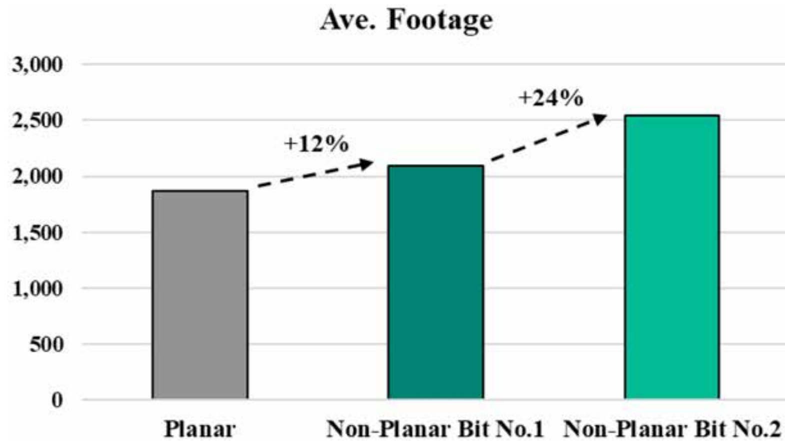
From inner and outer rows wear ratings as shown on the Graph 2, most of the wear ratings are up to T3 representing 94% and 80% dull grade in both cutter locations respectively. This strongly suggests the concept of the non-planar PDC cutter applicable to replace planar PDC cutter since non-planar wear progression matched with the wear seen in the field using planar diamond table design. Hence, the non-planar PDC cutter be able to drill more footage as compared to planar PDC cutters for the same wear condition.

The main dull characteristic of the cutting structure also suggests most of the wear condition is related to normal wear (NO, WT, RR) combined with the less to impact damage (chipped teeth, CT) which represented approximately 65% of the bit dull condition. The completed evaluation increases the confidence level that the non-planar PDC cutters will be able to improve overall the cutting structure life, hence drilling longer footage is expected.

## Result

After successful operational deployment of multi-dimensional diamond table PDC bit design in the "A" formation, result show consistent improvements achieved, and this technology delivered good performance result in terms of footage drilled as shown in the Graph 3 with summary as below:

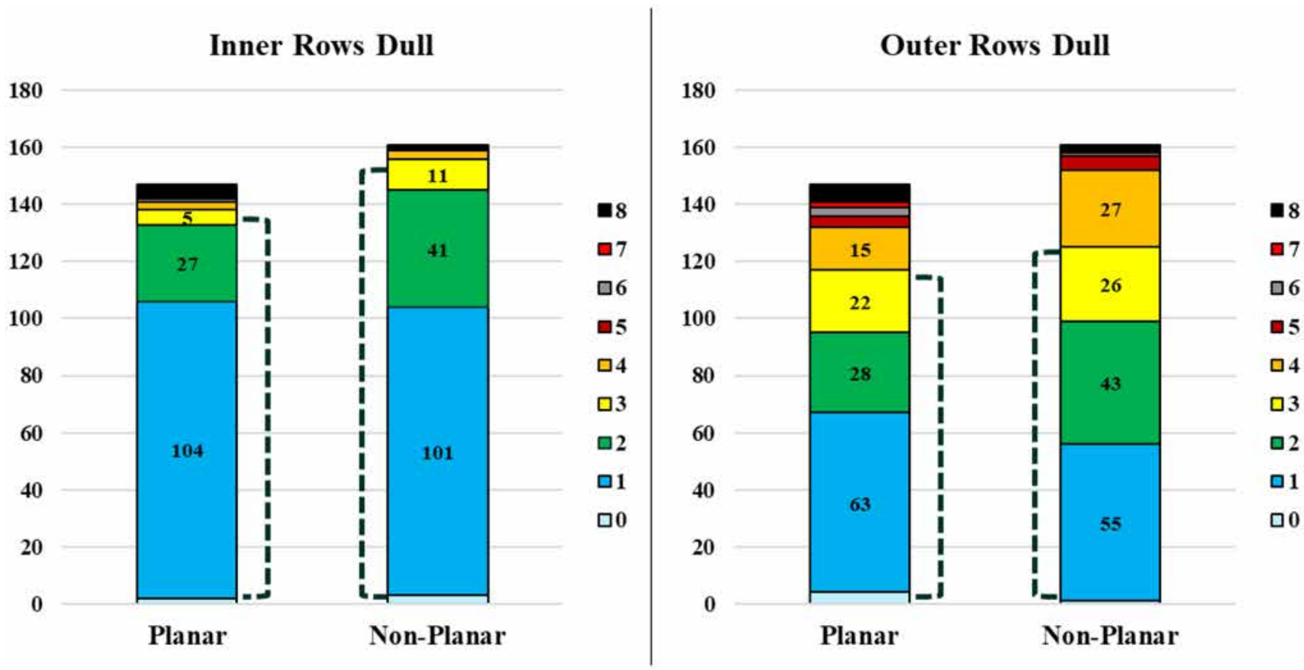
1. Overall, multi-dimensional diamond table (Bit No.1) drilled 12% more footage than planar diamond table.
2. Minor changes to bit cutting structure (same baseline; 5-blades and 8.2mm cutter) further improve footage drilled to the total of 36% as shown by Bit No.2.



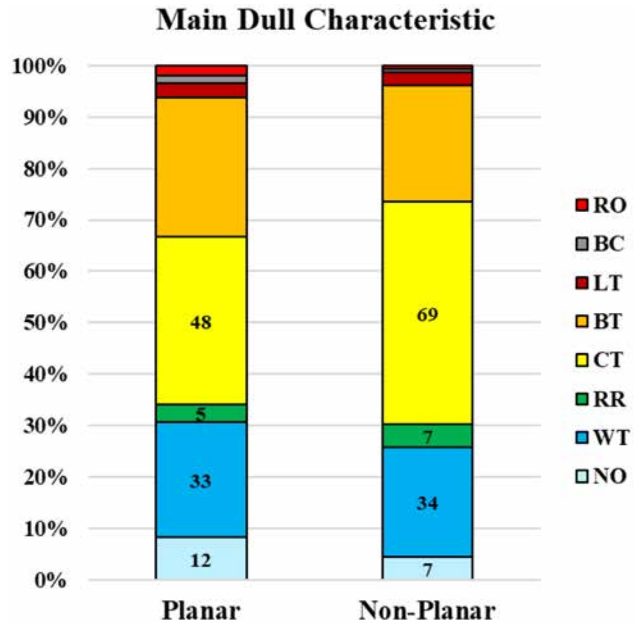

**Graph 3—Planar vs Non-Planar Cutter on Bit Types**

Bit dull grades were evaluated as part of the post deployment analysis to understand how this new technology performs with regards to wear progression. It is important to compare the wear when the bit cutting structure reached the end of life as indicated by the main dull characteristics, suggesting the bit not suitable to be re-run. In another scenario, a bit reached the end of life when the rate of penetration (ROP) became too low.

Graph 4 and Graph 5 populated for inner and outer rows wear together with the main dull characteristic for both planar and non-planar after the introduction of the new technology.




**Graph 4—Inner and outer rows wear for planar vs non-planar**




Graph 5—Main dull characteristic for planar vs non-planar

With benefit of non-planar PDC cutter design which can swap with planar PDC cutter on the same bit design, performance of the new bit using non-planar PDC can be compared directly provided the drilling parameters and bit wear are similar with the one using planar PDC cutter. In this test, non-planar PDC cutter shows similar wear progression when compared to planar PDC cutter performance where the same bit design equipped with non-planar achieved longer footage drilled.

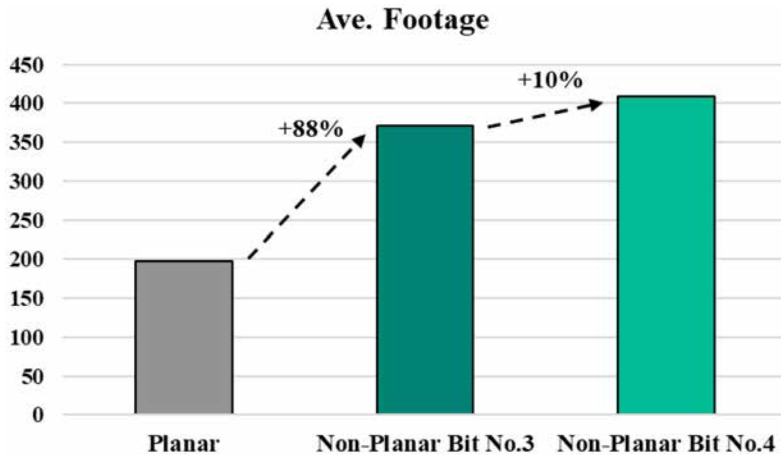
Overall, the result shows another good success since both types of diamond table wear trends are almost the same from the wear progression comparison with the summary as below:

1. Very similar population wear progression up to Tier 3 (T3) with non-planar (97% vs 94%) for inner rows.
2. Very similar population wear progression up to Tier 3 (T3) with non-planar (78% vs 80%) for outer rows.
3. Slight improvement seen with main dull characteristic – reduction in broken teeth, BT when using non-planar (thus, CT increases).

With the successful deployment of this technology for drilling in "A" formation, the same bit design was introduced to drill in "B" formation. Historically, there were fewer bit runs per section with planar diamond table used prior to the introduction of non-planar diamond table in this application. Also, the material used for diamond table is different whilst other bit design features remained the same with 5-blades and 8.2mm PDC cutter.

Non-planar diamond table PDC bit design once again showed improvement in terms of footage drilled as shown in the Graph 6 with summary as below:

1. Big improvement observed when diamond table material coupled with non-planar diamond table dimension (Bit No.3) changed from planar diamond table with up to 88% improvement in average footage drilled was achieved.
2. Minor changes to cutting structure (Bit No.4) helped improve overall multi-dimensional bit type average footage drilled by 10%.




**Graph 6—Non-Planar Bit Types Comparison**

Figure 8 shows a typical wear condition when the non-planar cutters reached the T3 wear state in this application. This dull is typical when the ROP drops and application of higher parameters, especially weight-on-bit (WOB) does not improve the drilling efficiency before a decision is made to POOH for bit change.

**Figure 8—Multi-dimensional non-planar post-run wear state T3**

## Conclusion

Non-planar diamond tables used in the smallest size PDC cutter have a significant effect towards extending the bit cutting structure life to drill more footage in these applications. The results clearly suggest that changing the diamond table geometry has more significant effects than changing the cutting structure layout. With the known constraints of the bit design due to small diameter size of 3.625in., continuous development of the multi-dimensional diamond table is required to further help pushing the achievable performance.

New cutting structures might be required to further explore the benefits of this non-planar diamond table to be able drill more footage per bit whilst reduce the number of drilling trips to complete each lateral while reducing the cost-per-foot (CPF) as much as possible.

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