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Drill Bit Performance Improvements in Challenging North America Land Drilling Applications Through Optimization of PDC Cutter Technologies

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Abstract

The continuous push for faster and longer bit runs in heavily directional, motor-oriented drilling applications requires Polycrystalline Diamond Compacts (PDC) cutters to better resist impact damage and abrasive wear while providing improved drilling performance. Moreover, drilling longer sections with interbedded lithologies requires PDC cutters to possess both high abrasion resistance and durability to resist dulling from the varied lithologies and overcome drilling dysfunctions inherent to such sections. This work will present optimized PDC cutters that enabled improved drilling performance in a variety of challenging applications.

This work details the optimization of PDC cutter technology by balancing the Polycrystalline Diamond (PCD) properties, PDC composite design, and cutting geometry according to an application's demands. Three applications are identified to showcase PDC cutter improvements in abrasion, impact, and general-purpose performance categories. Each application's typical dull was forensically analyzed to assess the appropriate design direction for improved PDC performance. PDC cutters were lab screened with a standard test protocol for assessing abrasion resistance and impact resistance. Cutting geometries were modelled via Finite Element Analysis (FEA) and cutting performance was verified with a pressurized single cutter rock cutting test. Each PDC cutter type was tested in the field against suitable offsets to confirm improvements in drilling performance and dull characteristics.

The optimized PDC cutters showed significant performance gains in terms of footage, rate of penetration (ROP), and dull grade across the performance spectrum. In lateral sections of Canada's Falher abrasive lithology, an abrasion-oriented PDC cutter improved drilling footage by 48% and 30% while also increasing the average ROP by 4% compared to offset runs. The Southeast USA Haynesville intermediate is challenged by high interbedding of hard, abrasive lithologies and high lateral vibrations induced by drilling dysfunctions. Here, a general-purpose PDC cutter combining high abrasion resistance and durability, and a novel cutting geometry optimized for drilling efficiency and durability drilled 32% further with equivalent ROP and better dull condition. In West Texas USA, lateral sections in the Leonard B formation are

challenged with stringers that cause severe impact damage. An optimized impact cutter demonstrated 20% increased footage compared to offsets.

Optimization of the many facets of PDC cutter technologies proves effective in delivering drill bit performance in a variety of challenging applications. With the newly introduced cutters a higher footage per bit can be realized. Detailed analysis of the dysfunctions, lithologies, and operating conditions of a given application can further enable better PDC cutter designs and fruitful operating conditions.

Introduction

Since their inception in the 1970s, fixed-cutter drag bits, utilizing polycrystalline diamond compacts (PDCs), have far surpassed the performance of roller cone bits in terms of rate of penetration (ROP) and footage in most drilling applications and have grown to dominate the market with over 90% of all footage drilled today (Scott 2015). Service companies have been continually tasked with drilling further, faster, and with fewer bits per section across varied and challenging drilling environments in order to keep pace with the evolution in well construction designs and extraction technologies. To drive this progression in performance, service companies have researched numerous approaches to improve the fixed-cutter drag bit's longevity. Bit hydraulics, bit design, PDC cutter material properties, and PDC cutter geometry alterations are some of the most tangible methods to improving the life of fixed cutters drill bits (DiGiovanni 2014, Izbinski 2015).

One primary contributor to performance degradation in PDC bits is the progressive or sudden failure of PDC cutters. PDC cutters become damaged downhole due to combinations of thermal and mechanical loading and their failure can be attributed to abrasive wear, cracks forming due to tensile overload, thermal degradation, or any combination of these and other mechanisms (Glowka 1986, Appl 1993). One of the largest contributors to the failure of a PDC cutter is heat. The wear rate of a PDC cutter increases drastically once the temperature of the cutting edge of the diamond exceeds 932 °F (500 °C) and accelerates exponentially above 1380 °F (750 °C) (Glowka 1986, Appl 1993). Advancements in PDC cutter materials, such as higher pressure synthesis, thicker diamond tables [Bertagnolli and Vale 2000], and leaching [Scott 2015], have substantially improved the lifespan of PDC cutters. Additionally, non-planar cutting geometries have been developed to minimize cutting stress and cutting edge temperature to further improve cutting life and bit performance [DiGiovanni et al. 2014, Lyons et al. 2018, Russell et al. 2022].

Several North America Land (NAL) drilling applications, representing a broad spectrum of cutter performance categories, were selected to serve as case studies in the cutter development process. Each application was analyzed to assess lithologies and drilling challenges as well as typical dull characteristics.

Ongoing drilling located within the Kakwa field south of Grande Prairie, Alberta specifically in the gas producing Falher G sand formation required multiple lateral PDC's to complete the horizontal interval. The Falher G formation is a gas rich reservoir and has an excellent response to well stimulation. It is a mix of primarily quarzitic sand with a greater proportion of chert layers and widespread silica cements making it much more abrasive and slower to drill than the other Falher families. Bits are tripped frequently due to penetration rate after only few hundred meters drilled. The shoulder cutters exhibited smooth wear flats indicative of abrasive wear. The small wear flats increased difficulty penetrating the formation further which it was accompanied with shock and vibration. Weight transfer and cutter penetration during sliding was extremely inefficient and therefore required the use of a Rotary Steerable System.

Permian basin is widely characterized as a "multilayer" cake with different geologic zones comprising the layers in this analogy. From the drilling perspective is well known as an area where drilling conditions are demanding because of formations being interbedded causing impact damage to PDC cutters. Also, the energy input applied to bits has increased during the past years, testing the limits of PDC cutters to handle high loads. For example, more powerful motors, higher parameters applied to improve the rate of penetration, and all these variables could lead to overloading of PDC cutters.

Finally, the drilling of the Haynesville intermediate section has proven year after year to be the toughest and most challenging formation (Figure 1). The unique combination of balling and interbedded transition in the drill out section resulting in severe lateral drilling dysfunction and high cutter stresses condemned this section for cutters durability. The majority of the dulls in this section suffered chipped, sheared, and broken cutters (Figure 2). After that the drilling continues through hard interbedded section of the Travis Peak and into abrasive sands in the Cotton Valley that generates heavy thermal and abrasive damage to the cutters. Drilling this section requires a cutter with a balanced characteristics of thermal stability, abrasion resistance, and impact durability.

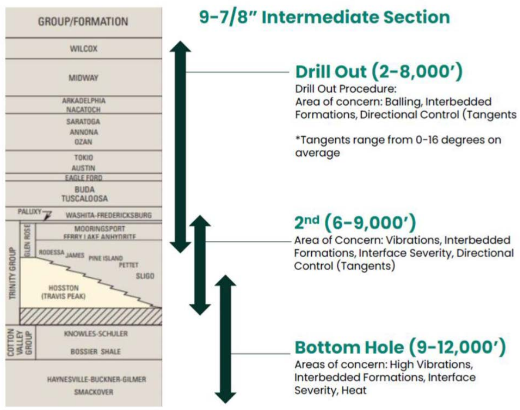

Figure 1—Summary of Haynesville intermediate lithologies and challenges.

Figure 2—Example dulls of Haynesville intermediate runs.

Across the different applications, it was concluded that a general purpose cutter was required.

In partnership with PDC cutter suppliers, a new generation of PDC cutters were then developed to target performance improvements in each of the applications. Each PDC cutter type was screened through lab testing of abrasion resistance and fracture toughness compared to each type's respective baseline prior to field testing. Field testing was performed through a protocol of mixed cutter tests, alternating prototype and baseline PDC cutters throughout the bit profile, followed by full bit tests to ensure a thorough understanding of the improvements in dull characteristics and bit performance with appropriate offsets.

Methodology

Application and Dull Review

The process of new cutter development heavily depends on the targeted applications and the failure modes observed on the baseline cutter. Challenges such as interbedded and hard abrasive formations require cutters to be impact resistant without sacrificing abrasion resistance. Moreover, the differences between drilling with conventional motors versus rotary steerable systems and the nature of drilling dysfunctions add further complexity to the cutter failure analysis process. These factors highlight the importance of detailed application studies coupled with drilling dysfunction diagnostics and cutter failure analysis to design a road map for what is needed from the next cutter. An overview of the selected applications and dull reviews is presented in the introduction.

Cutter Lab Testing and Development

Once an understanding of a particular drilling application is established, the PDC cutter property requirements can be defined relative to the selected baseline. These properties can be isolated to the PCD layer or carbide substrate or represent the composite PDC properties and include abrasion resistance, thermal stability, fracture strength, and fracture toughness to name a few. While the engineering value of a cutter is only realized in its field performance, with a dull representing the cutter's multi-component resistance to the combined conditions of a given drilling environment, the protracted timeframe for thorough field testing, often spanning many months, prohibits rapid development iteration when used as the only feedback loop. Consequently, initial lab testing, prior to field testing, is crucial to developing cutter solutions in a timely manner. It should be understood, however, that laboratory replication of any particular drilling environment's combined conditions, for the purposes of evaluating cutter breakdown, is exceptionally challenging. Instead, the approach is taken to measure PDC cutter properties individually and weigh the performance in each category according to the needs of the application. The scope of this discussion will be limited to the abrasion resistance and fracture toughness of PDC cutters. The details of abrasion resistance and fracture toughness testing of PDCs have been previously reported [Zhan et al. 2022] and are reiterated here for the reader's convenience.

Abrasion resistance is defined by a cutter's ability to resist progressive material loss under cutting conditions. This material loss is driven by cutting conditions such as rock hardness, quartz content, cutting energy, and cutting temperature and occur via several mechanisms ranging from microchipping of individual diamond grains to surface amorphization of carbon [Appl 1993, Glowka 1986, Lin et al. 1992]. The abrasion resistance of non-leached PDC cutters is evaluated by an atmospheric rock cutting test, as illustrated in Figure 3, whereby a granite rock is fixed to a vertical turret lathe (VTL) and rotated at constant RPM while a cutter held in a fixture traverses the rock radially at a constant depth of cut and water coolant is supplied to the cutter. Proprietary test parameters, such as rock type, cutter backrake angle, RPM, depth of cut, and infeed rate are constant across all tested cutters. After a prescribed number of passes, the test is stopped and the cutter removed for 3D scanning. Calculations of cutter wear scar volume, demonstrated in Figure 4, are performed by comparing 3D scans pre- and post-test. The abrasion resistance of a cutter is inversely proportional to the volume loss. Despite the test being performed on non-leached PDC cutters, the results have been observed to correlate well to field performance of leached PDC cutters.

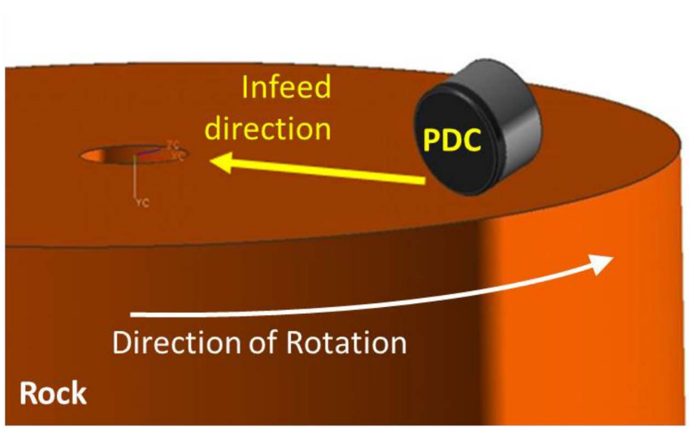

Figure 3—Schematic representation of VTL test to assess PDC cutter abrasion resistance.

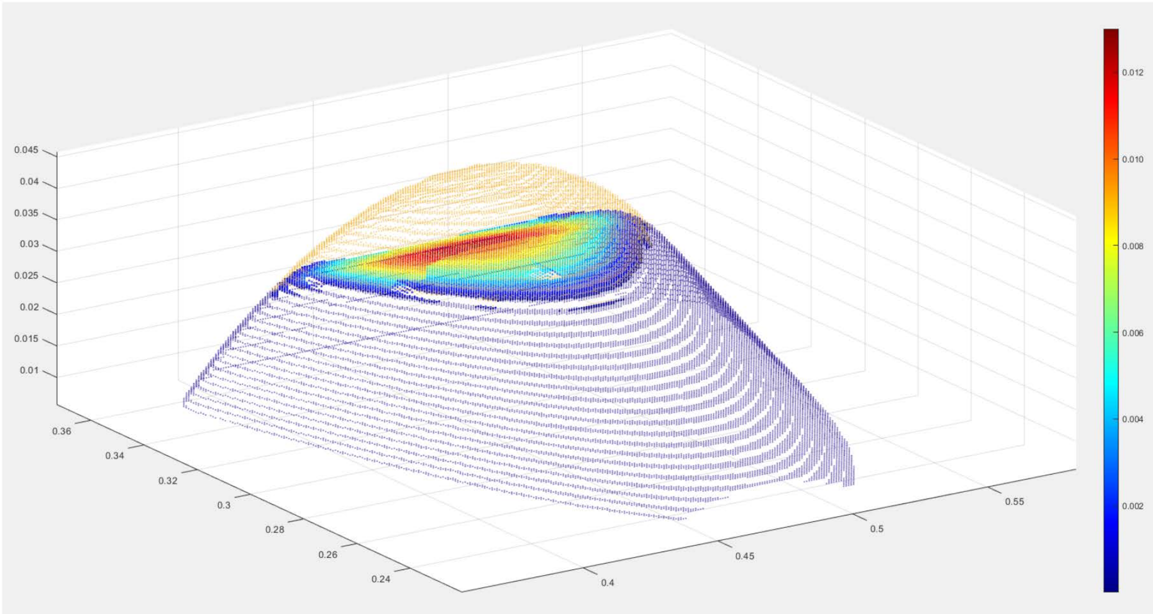

Figure 4—3D output of wear volume calculation showing original and worn scans with heat map of material loss.

Characterization of the durability of a cutter is multi-faceted and can be captured by a discussion on strength and fracture toughness. Strength is most often defined as a brittle material's ability to withstand fracture without the presence of a well-defined crack whereas fracture toughness is defined as a material's resistance to crack propagation. The strength of PDC cutters can be easily measured under a variety of loading conditions and applied to engineering computer models of drill bits to establish upper bounds of drilling operating parameters [Russell et al. 2022]. Fracture toughness, however, requires a more careful methodology for accurate measurement and a precise understanding of the geometry of cracks, which is nontrivial, to accurately predict cutter fracture behavior in engineering models of drill bits. Despite the practical challenges in implementing fracture toughness-based analyses to model cutter integrity during drilling, empirical observations suggest that cutters possessing a high fracture toughness, rather than high strength, are best correlated to high durability field performance. The plane strain fracture toughness of PDC cutters is evaluated by mechanical testing of notched cantilever beams according to fracture mechanics principles, as schematically represented in Figure 5. The cantilever beams are prepared by wire EDM or laser machining of the non-leached PCD material to nominal cantilever beam dimensions. A notch near the cantilever base and a fiducial loading mark near the cantilever free end are applied to each cantilever beam and the sample is fixtured to remain rigid during testing. A load is applied to the fiducial mark until fracture occurs, after which the fractured beam dimensions are measured with an optical microscope. Fracture toughness was calculated according to Equation 1:

$$K_{IC} = Y\left(\frac{a}{w}\right)\sigma\sqrt{\pi a} \quad (1)$$

Where Y is a geometric function dependent on the ratio of crack length, a, to the beam height, w, and σ is the bending stress in the absence of a crack at the critical load of fracture. The geometric function Y was calculated using contour integral evaluations in FEM simulations of equivalent cracked cantilever beam geometries. The FEM methodology was confirmed to be within 1.5% of the accepted solution for the standard single edge notched beam geometry (Srawley, 1976).

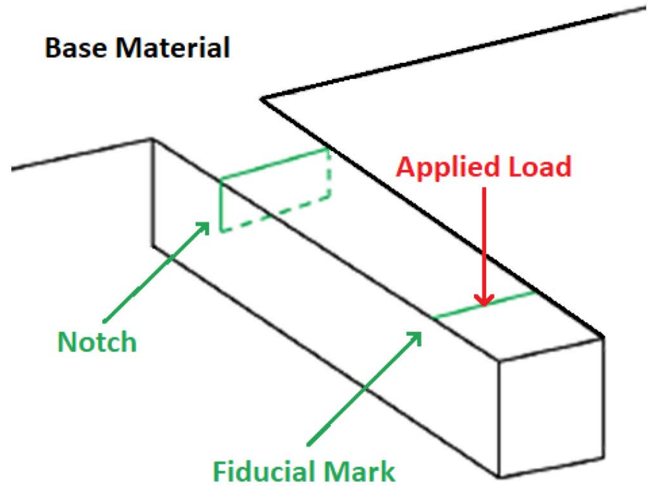

Figure 5—Schematic of fracture toughness test geometry.

The engineering design parameters of a PDC cutter are numerous and include diamond feed, substrate material, interface design, diamond table thickness, High Pressure High Temperature (HPHT) synthesis conditions, post-synthesis processing, leaching, and shaping, among others. All these parameters influence the final properties of a PDC cutter and are carefully selected and optimized for the intended applications. From a portfolio perspective, cutters can be bucketed into three broad performance categories: impact, general purpose, and abrasion with corresponding trade-offs in each property as depicted in Figure 6. Impact cutters tend to have coarser diamond grain structures and thicker diamond tables to maximize PCD fracture toughness [Lammer 1988] and composite durability [Bertagnolli and Vale 2000], while abrasion cutters tend to have finer diamond grain structures to maximize abrasion resistance[Sneddon and Hall 1988], and general purpose cutters fall in between to balance durability and abrasion resistance. Key advancements in cutter technology yield improvements in one or more properties without loss of performance in other properties.

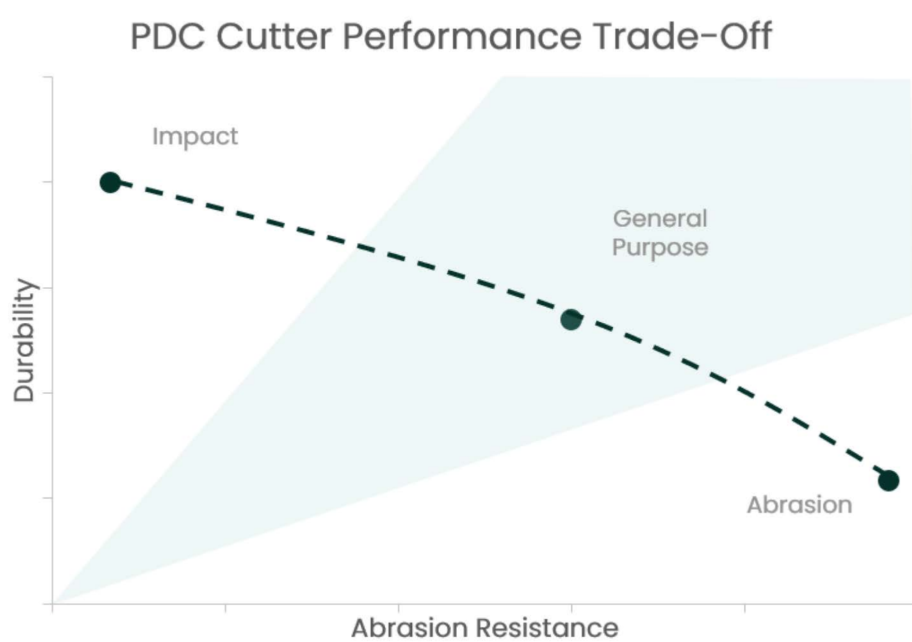

Figure 6—Schematic properties of cutter performance categories.

Single Point Cutter Testing

The development of new cutter shapes requires complete understanding of the endured tangential and axial forces during the cutting action. As the rock behave in more plastic fashion under confining pressure the energy required by the cutter is significantly higher at downhole drilling conditions compared to atmospheric conditions. Accordingly, the newly shaped cutters are tested in a single cutting point setup as shown in Figure 7, and it is all submerged in a pressurized vessel to ensure the application of the confining pressure to the rock. In this test the cutter is fixed on a load cell that can move vertically to establish a prescribed depth of cut. Meanwhile, the rock sample rotate anticlockwise at different RPMs. Steady state cutting is established after the first rotation at predefined RPM and DOC and the forces are measured.

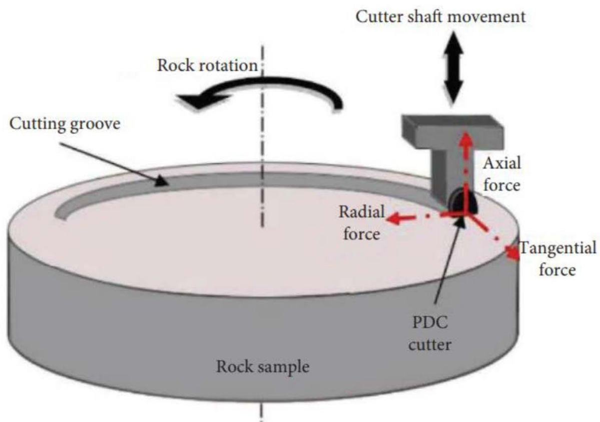

Figure 7—Schematic diagram of single cutter test.

Mixed Cutter Testing

The transition of the new cutter concepts from the lab to the field is a critical step in the cutter development lifecycle. Mixed cutter testing allows for testing a prototype cutter on a live field bit in as closely comparable drilling environment to a known baseline cutter with minimal risk to bit integrity in case of premature cutter failure. Cutter failures such as delamination of the diamond table, shearing, and/or premature abrasion can lead to severe drop in ROP and further on to complete failure of the drill bit. Accordingly, the prototype cutters are installed in the bits in a controlled fashion according to their risk factor. A higher risk cutter will first be tested using a handful of cutters in non-critical cutting locations. Upon validation of the cutter viability for field applications the number of test cutters on the bit are increased.

The design of the mixed cutter test depends on many factors, including the number of cutters and blades, cutter forces, cutter work rate, and dull analysis of previous runs. Also, the cutter testing location depend on the design philosophy and the lab results. As show in Figure 8, the presented mixed cutter 6-bladed bit test was designed with a radially alternating cutter layout with prototype cutters in between two of the incumbent cutters for maximizing head-to-head cutter comparisons and minimizing risk. In this case, the cutter is tested across the profile of the bit to ensure abrasion resistance and durability in all loading and cutting conditions on the profile.

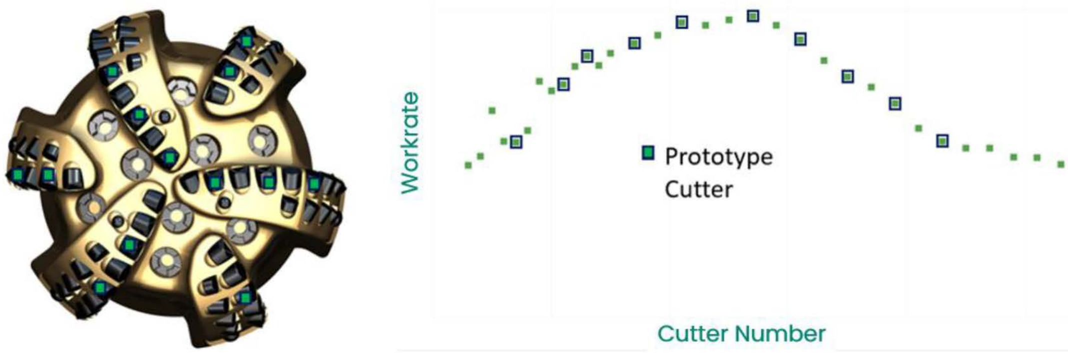

Figure 8—Example mixed cutter layout across bit profile.

Upon the completion of the mixed cutter test in the field, all cutters are visually inspected and imaged for head-to-head comparisons. As shown in Figure 9, the cutters are imaged to capture the damage on the barrel, chamfer, and face sections. Each cutter is graded relative to its comparable radial baseline neighbors as a win, loss, or tie. A cutter's relative performance in a given attribute, e.g. spall resistance, can be inferred from the win:loss:tie ratio for a set application and dull characteristic. The prototype cutter needs a statistically significant number of wins over the baseline, across multiple field test runs, to be considered for further testing and ensure that the stochastic differences among runs do not impact the conclusions of prototype performance.

Figure 9—Example mixed cutter test radial neighbor comparison. Light green represents prototype cutters and dark green represents baseline cutters.

Full Bit Testing

With a clear signal of prototype cutter performance improvement in mixed cutter testing against the baseline, it is important to validate these finding with full bit testing. Full bit testing ensures the elimination of the so-called knock-on effect whereby adjacent cutters of different dull states either suppress or exacerbate damage of one another depending on the perspective taken. Moreover, this type of testing shows the overall performance gains in the intended section. The full bit test targets the usage of the prototype cutter across the bit and target the bit to drill in a well benchmarked application with plenty of runs with the incumbent cutter. It is critical to highlight that such testing is ideally performed on the same bit design to avoid the impact of other bit design parameters.

After completion of field tests in the intended application, the runs are compared to the benchmark population in terms of dull, ROP, and footage. Multiple full bit tests are required to ensure statistical significance and elimination of challenges such as operating parameters and lithology differences.

Results

New Generation PDC Cutter Lab Performance

A new generation of PDC cutters in each performance category of impact, general purpose, and abrasion were developed by optimization of diamond feed, HPHT synthesis conditions, and composite design. The lab results comparing the standard baseline and new generation cutter in abrasion resistance and fracture toughness of each performance category are displayed in Figure 10, Figure 11, and Figure 12. For the impact category, a significant improvement of +14% in abrasion resistance with equivalent fracture toughness was achieved. For the general purpose category, a modest improvement of +5% in abrasion resistance with equivalent fracture toughness was achieved. Most notably, the new generation abrasion cutter boasts a +13% improvement in abrasion resistance and +11% improvement in fracture toughness.

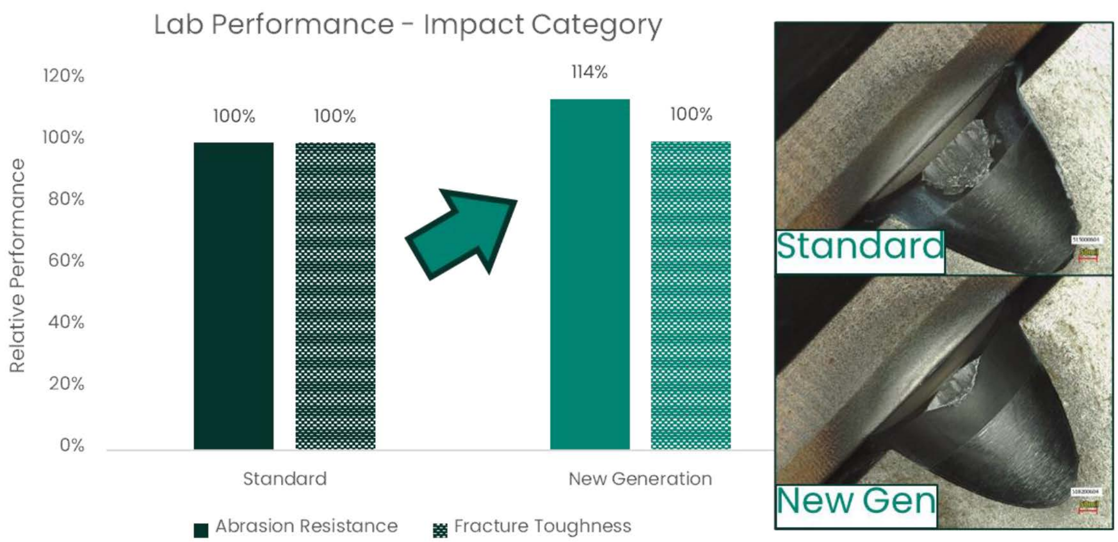

Figure 10—Lab performance of standard and new generation impact PDC cutters.

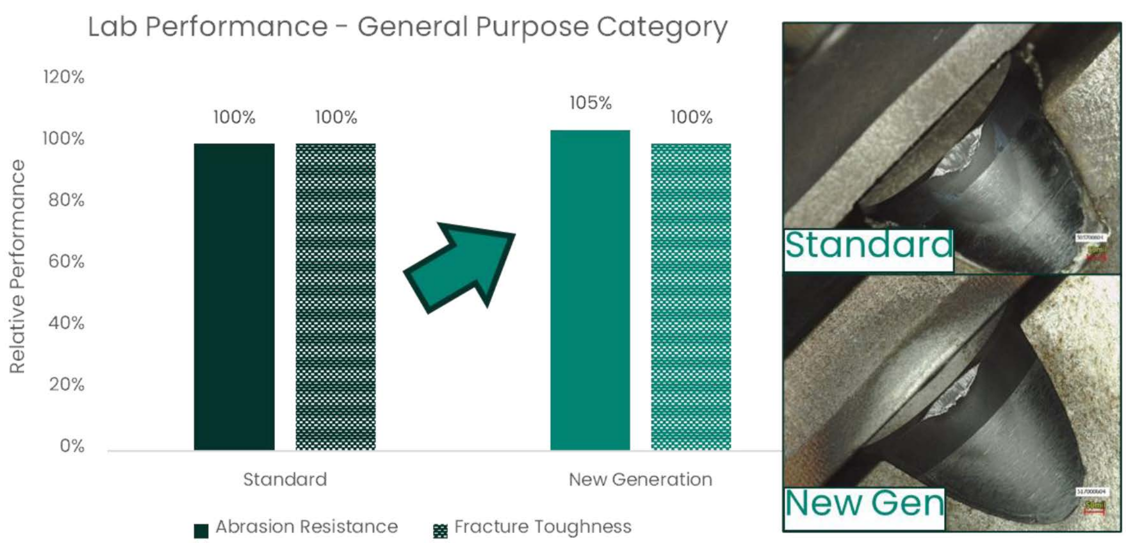

Figure 11—Lab performance of standard and new generation general purpose PDC cutters.

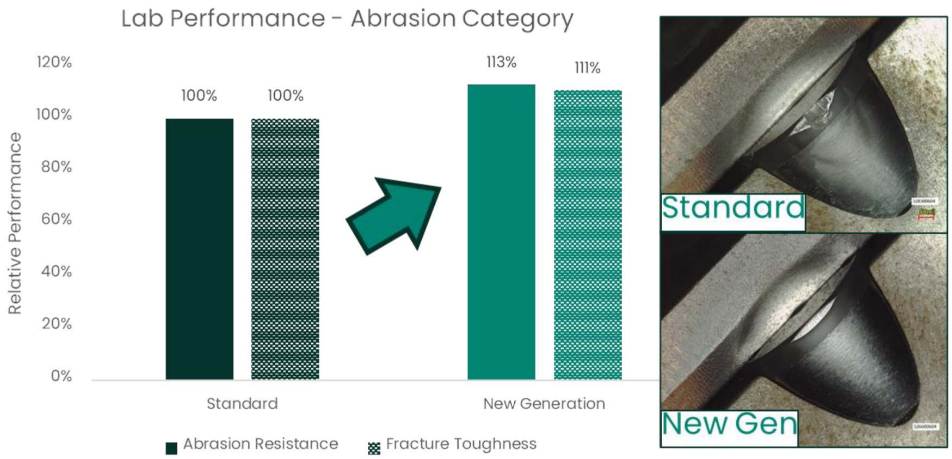

Figure 12—Lab performance of standard and new generation abrasion PDC cutters.

PDC Cutter Geometry Optimization

It has been well demonstrated that the utilization of shaped PDC cutter technology can influence various cutting mechanic efficiency gains in multiple drilling scenarios. One of particular interest is a multidimensional non-planar geometry that aids in maintaining low cutting temperatures in hard abrasive formations such as sandstones. Maintaining a temperature lower than the oxidization threshold of the PDC material aids in resisting the rapid propagation of abrasive wear during operation. It has also been well understood the relationship between shaping a PDC diamond table to a different cutting geometry and the stress state in the diamond table under normal cutting loads. This was less of a critical factor while operating in a lower depth of cut (DOC) hard sandstone environment, however with the ever-advancing drilling industry these requirements began to change.

As drilling operators increased the demands of the PDC bit, requiring one bit to drill multiple rock formations often drilling shoe-to-shoe sections at rig limits, thus the cutting force demands increased. Where previously the shaped PDC cutter could be targeted into one rock formation, now it must also meet the demands of the other formations in these shoe-to-shoe sections. This increase in demands on the cutter technology transitioning through multiple DOCs and formation interfaces can highlight a weakness in various PDC shapes thus requiring the shape be engineered in a way to maintain the cutting efficiency attribute while lowering the stress state within the diamond table.

This requirement is highlighted with the multidimensional non-planar shape which provides lower cutting temperatures in highly abrasive formations. Dull evaluations of this geometry show that when pushing into higher DOC and sometimes interbedded formations show a performance limiting weakness resulting in the potential to tangentially shear the cutter (Figure 13).

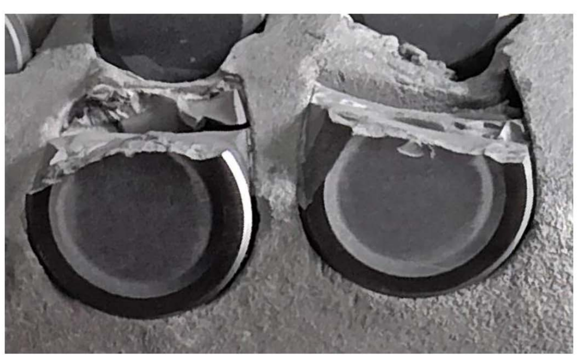

Figure 13—Multi-dimensional non-planar cutter with tangential shearing.

Upon evaluation of the geometry at the target DOC, it was determined that the stress state in the diamond table could be optimized to allow for an increased cutting force and prevent cutter damage during operation (Figure 14). This evaluation took place using Finite Element Analysis and drilling laboratory in a previously defined optimization process (2022 Russell et al). Multiple design concepts were evaluated using FEA to understand the design space (Figure 15).

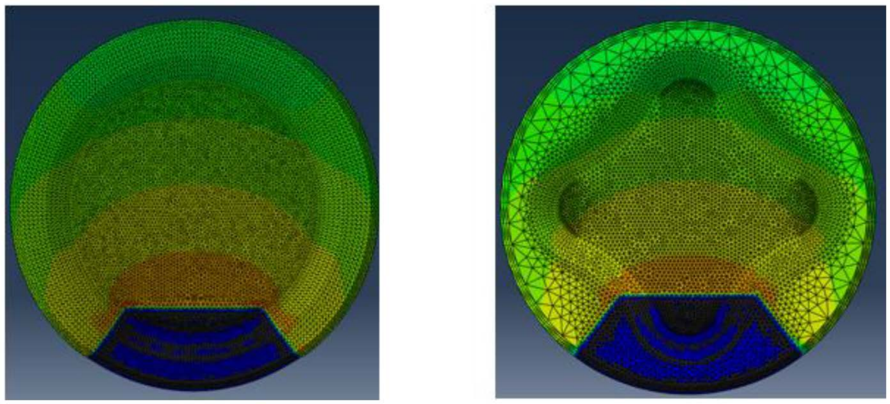

Figure 14—FEA Analysis of Multi-Dimensional Shaped cutters version 1 (left) and version 2 (right)

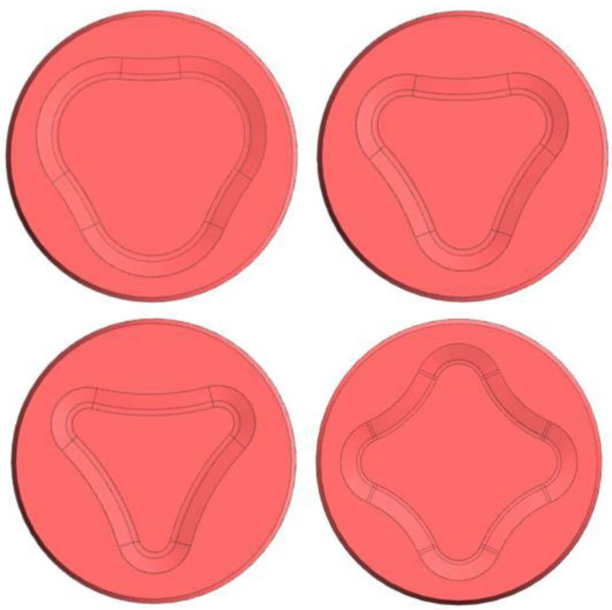

Figure 15—Example concept multi-dimensional non-planar geometries

By understanding the design space, it was possible to down select based on diamond table stress state to ensure the loading resistance capabilities were increased to the desired level. From there the improved geometries were taken to the drilling laboratory to be evaluated comparatively from a cutting force perspective in the target rock types. Cutting force and thus temperature generated by cutting was reduced similar to the initial non-planar multidimensional concept.

Upon review of the single point cutter test data, it is apparent that the same improvement in cutting force is demonstrated between the two non-planar multidimensional cutter geometries over the traditional planar (Figure 16). This is the initial indicator that multi-dimensional non-planar cutter was successfully optimized to improve the stress state within the diamond table without sacrificing the performance attributes achieved by the cutter geometry (Figure 17).

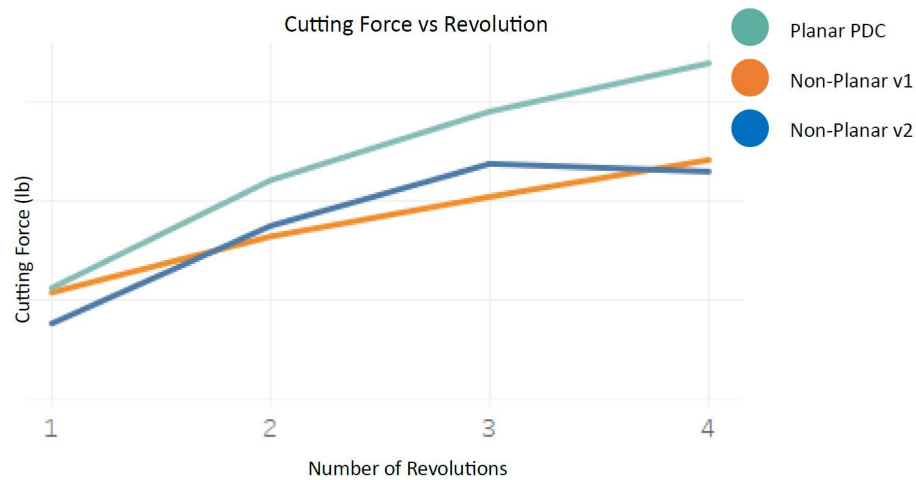

Figure 16—Single Point Cutter test data.

Figure 17—Comparative field test showing strength increase with new multi-dimensional non-planar cutter geometry.

Impact cutter for Challenging Permian Applications

A combination of mixed and full cutter tests were conducted in the Permian Basin to assess the improvement of impact resistance using the new cutter technology compared to the previous impact cutter generation. A total of 10 mixed cutter tests were conducted using previous and new cutter generation in the same bits. Statistics revealed the new cutter generation has better dull grading and less damage compared to the previous cutter generation. When looking at each dull grading picture (Figure 18) the new cutter generation showed a slight improvement in wear resistance and less impact damage compared to the previous.

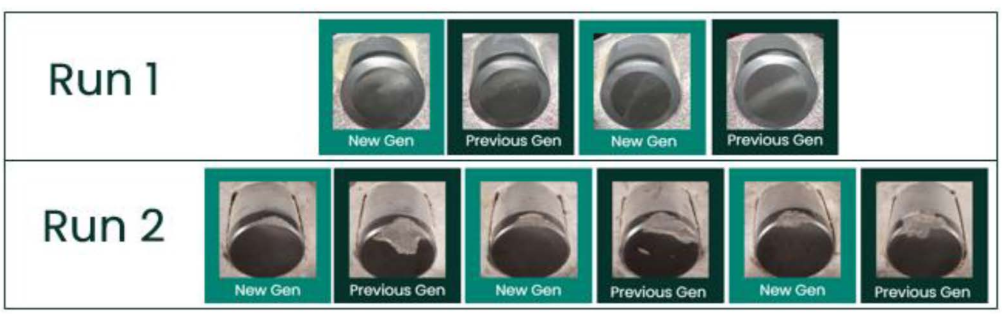

Figure 18—Permian mixed cutter test results of new generation impact cutter showing reduced wear and chipping compared to the previous generation cutter.

From the 10 mixed cutter tests, the dull grading winning rate of the new generation cutter was 23% versus 10% from the previous generation cutter (Figure 19).

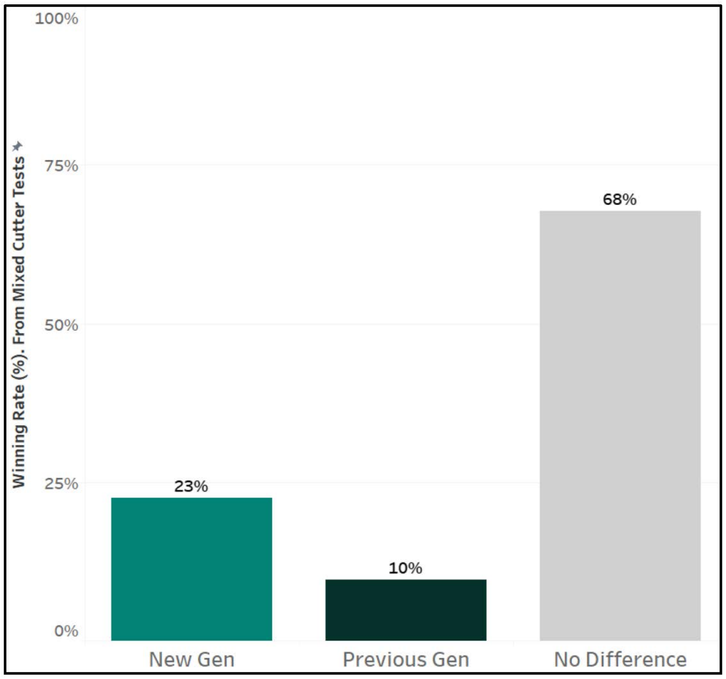

Figure 19—Impact Cutter Mixed Cutter Test Results

A total of 4 full bit tests were conducted to measure the performance improvement in distance drilled and ROP of the new cutter versus previous cutter generations in applications where impact damage is the main damage mechanism in PDC cutters. Table 1 shows the run details. All four runs were conducted while drilling lateral sections and all of them drilled in different formation targets. The green color means that while doing the benchmarking with offset wells the KPI's were above average with good customer feedback and performance. Yellow means that while doing the benchmarking with offset wells the KPI's were average.

Table 1—Permian full bit runs with new generation impact PDC cutter.

Size Size	Bit Details	Application	Formation	Distance	ROP	Dull
7 7/8"	6 blades with 13mm cutters	Lateral	2nd Bone Spring Sand	6531	83	1-2-FC-S
6.75	6 blades with 13mm cutters	Lateral	Jo Mill	6367	174	1-1-ER-N
7 7/8"	6 blades with 13mm cutters	Lateral	Leonard B	6704	84	2-3-BT-S
6.75	6 blades with 13mm cutters	Lateral	Wolfcamp M1	6939	85	1-2-WT-A

One of the full bit tests drilled in the Leonard B formation, which is known to be highly interbedded causing PDC cutters to suffer from impact damage. While drilling with bent motors in the lateral, the average footage drilled was 5600’ with an average ROP of 92 ft/hr. The damage beyond repair statistics in this application were more than 57% with bits pulled of the hole with severe damage. The test bit using the new cutter generation achieved 20% higher distance drilled compared to offset wells with similar ROP and came out the hole in a repairable condition (Figure 19a and Figure 20).

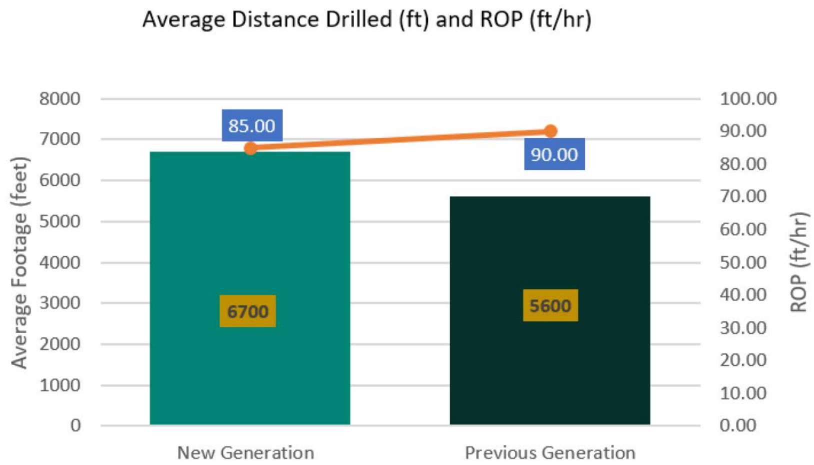

Figure 19a—Run performance in Permian lateral Leonard B formation with new generation impact PDC cutter vs. offset.

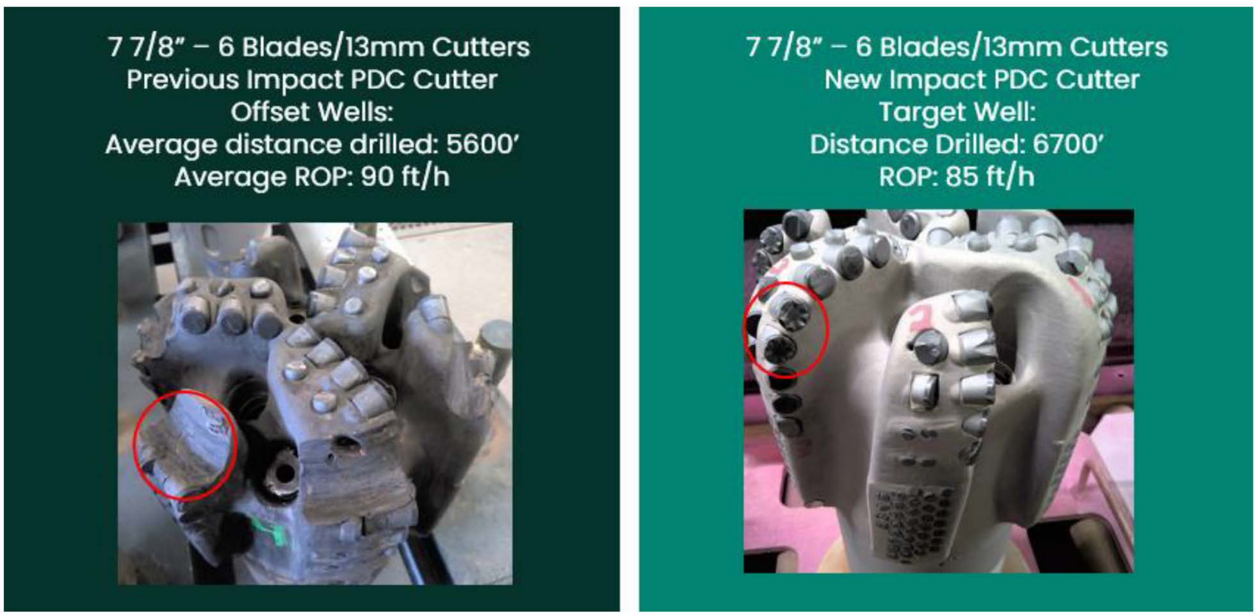

Figure 20—Dull comparison in Permian lateral Leonard B formation with new generation impact PDC cutter vs. offset.

Abrasion Cutter for Canada's Abrasive Applications

A mixed cutter test was conducted to compare the previous generation abrasion PDC cutter vs. the new generation abrasion PDC cutter. The first set of tests were performed using a 6 ¼" PDC bit with 6 blades using 13mm cutters in a mixed cutter configuration to benchmark both cutters prior to full bit testing. Observation of detailed dull pictures (Figure 21 and Figure 22), showed the new generation abrasion PDC cutter had better abrasion resistance and durability compared to the previous generation abrasion PDC cutter which led to push the new generation PDC cutter to full bit testing.

Figure 21—Mixed cutter results of new generation abrasion PDC cutter showing improved abrasion resistance.

Figure 22—Mixed cutter results of new generation abrasion PDC cutter showing improved durability.

The improved abrasion diamond grade and upgraded cutter shape helped to cool the cutter face on the shoulder of the bit to increase bit durability and maintain a sharp cutting edge for as long as possible. This trial was conducted in a 6.25" PDC bit with 6 blades using 11mm cutters (Figure 23). The sixteen cutters on the shoulder were replaced with new generation abrasion PDC cutters and modified face geometry as shown in Figure 24.

Figure 23—6.25" PDC bit with 6 blades using 11mm PDC cutters.

Figure 24—Left) Previous generation abrasion PDC cutter and multi-dimensional non-planar face geometry. Right) New generation abrasion PDC cutter and multi-dimensional non-planar face geometry.

Comparing the same PDC bit utilizing the new generation abrasion PDC cutters to offset wells utilizing the standard abrasion PDC cutters, there was significant improvement in meters drilled, ROP and dull condition as shown in Figure 25 and Figure 26.

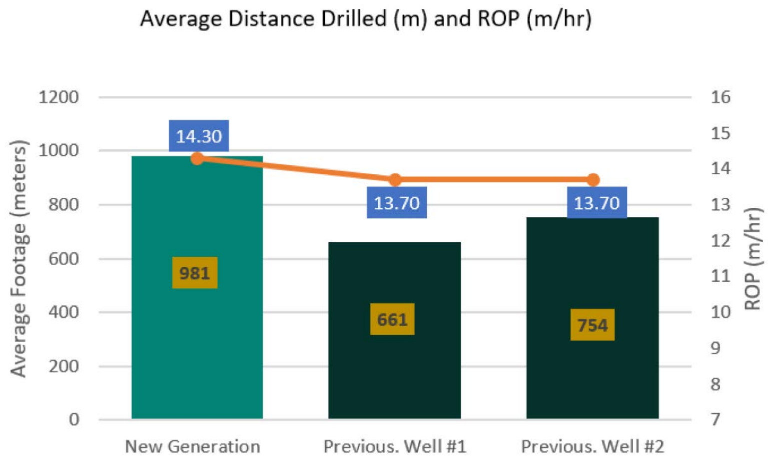

Figure 25—Run performance in Canada lateral Falher formation with new generation abrasion PDC cutter vs. offset wells.

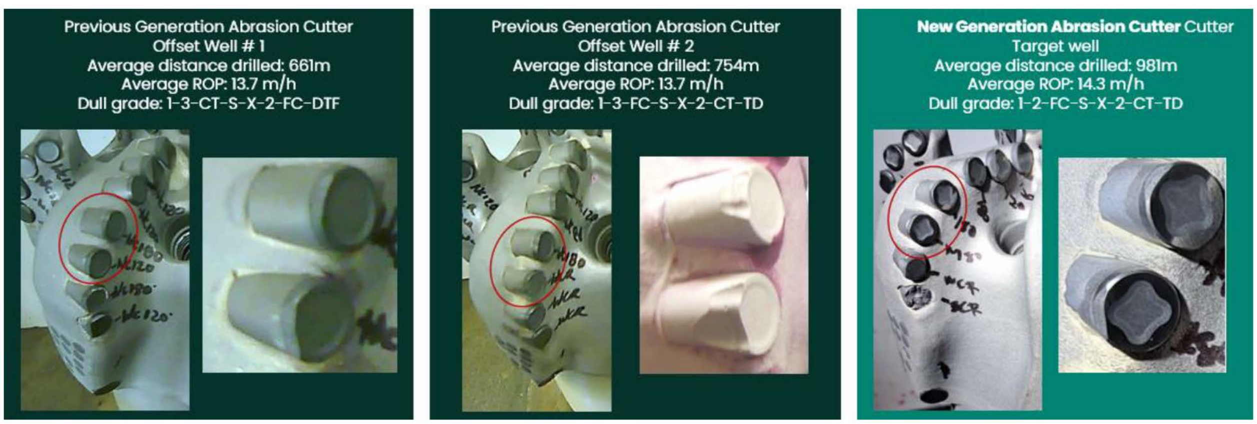

Figure 26—Dull comparison in Canada lateral Falher formation with new generation abrasion PDC cutter vs. offsets.

The standard abrasion PDC cutters exhibited large smooth wear flats along the shoulder and both runs were graded a 1-3, drilling 661m and 754m respectively. The new generation abrasion PDC cutters had smaller wear flat areas resulting in the bit drilling further and faster than the standard abrasion PDC cutter. The bit was graded a 1-2 and certainly could have drilled further if it was not pulled for TD. The new generation PDC cutters allowed the bit to drill 48% and 30% further while also increasing the average ROP by 4% compared to the offsets.

General Purpose Cutter for Haynesville Challenging Applications

The new generation general purpose PDC cutter was developed to target the Haynesville Intermediate section. This challenging section requires a PDC cutter proficient in both abrasion resistance and durability. Mixed cutter and full bit tests were conducted with the combination of new generation general purpose PDC cutter and new multi-dimensional non-planar geometry against the baseline general purpose cutter and multi-dimensional non-planar geometry. Eighteen of the previous generation cutter dulls were sampled, compared against seven mixed cutter tests, and thirteen full-bit tests. The addition of new generation general purpose and shaped cutters increased the performance and dull condition of 12.25" PDC bit with 7 blades and 16mm cutters.

Comparing mixed cutter tests, the new generation general purpose PDC cutter showed a modest reduction in material loss compared to the previous generation (Figure 27). After confirming the new generation PDC cutter's durability compared to the previous generation, full bit tests were performed.

Figure 27—Mixed cutter test results of the new generation general purpose PDC cutter showing reduced material loss.

Figure 28 summarizes the individual cutter dull grading of full bit runs, normalized to distance drilled, showing the previous generation PDC cutter damage per cutter in dark green, with new generation PDC cutter variant in light green. Use of the new generation PDC cutter reduced average shoulder damage from 2.2 to 1.5 (0-8, Dull Grade scale, Figure 29), a 32% decrease in average damage. Importantly, this trend is confirmed only with a sufficient number of runs to achieve statistical significance. From the distribution of dulls, if one selects only a few baselines and test runs, the probability of a false negative conclusion is significantly higher. Overall, introducing new generation PDC cutters, ROP increased by 12% and average distance drilled increased by 20% (Figure 30).

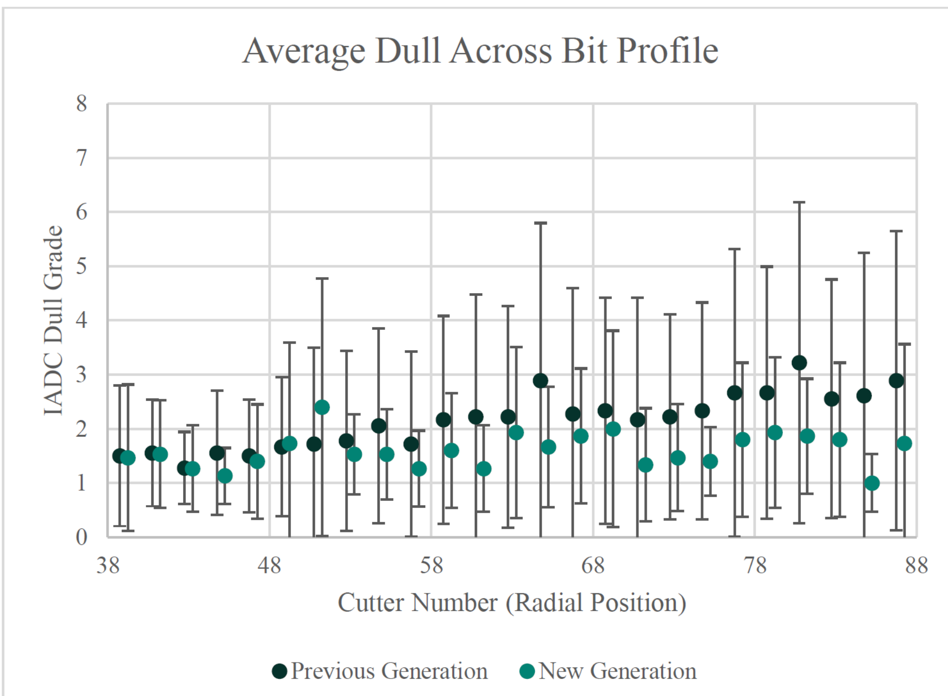

Figure 28—Average cutter dull grading across the bit profile of 12.25" Haynesville intermediate runs showing reduction in damage with new generation general purpose PDC cutters. Error bars represent the standard deviation of the sample set. Cutter number for each data set is slightly offset for visual clarity.

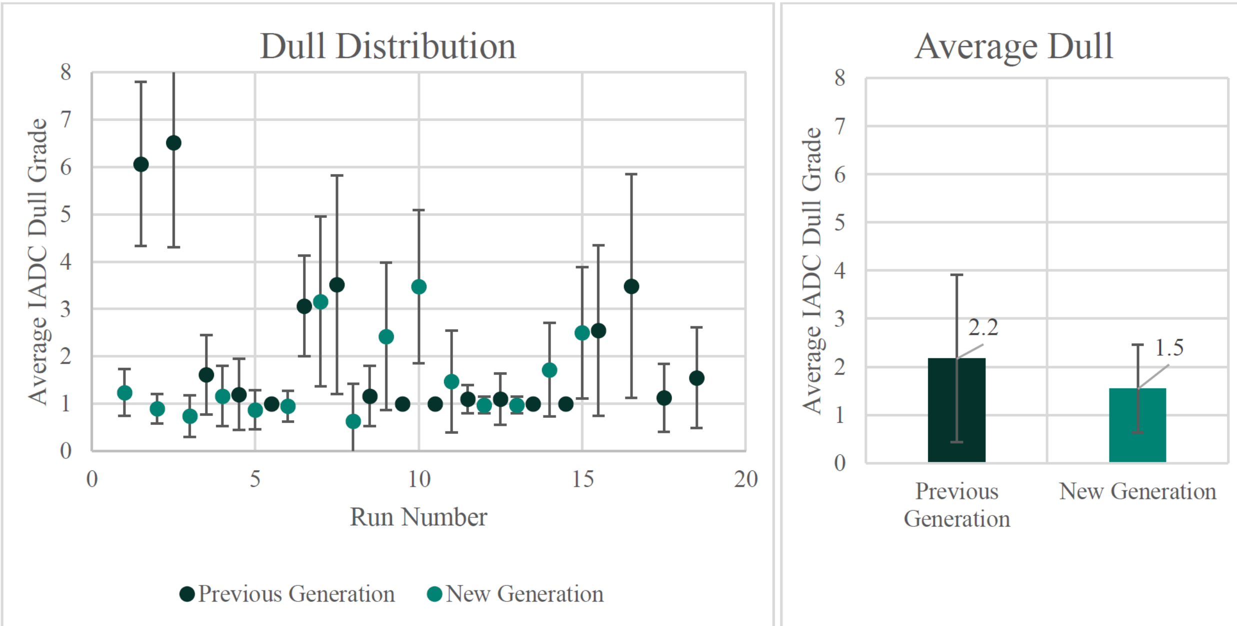

Figure 29—Left) Distribution of 12.25" Haynesville intermediate dulls across all runs. Error bars represent the standard deviation of the dull for a given run. Right) Average dull showing improvement with new generation general purpose cutter. Error bars represent the standard deviation of dulls across all runs.

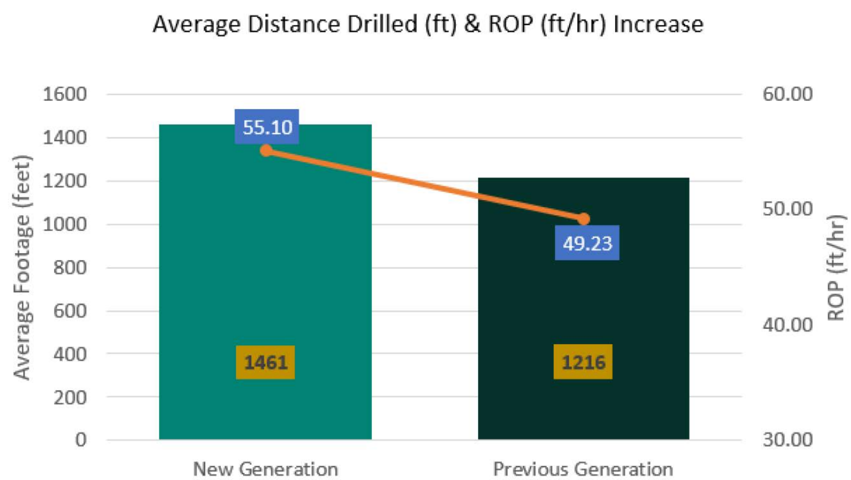

Figure 30—Run performance comparison in the 12.25" Haynesville intermediate showing improved footage and ROP with new generation general purpose PDC cutters.

Across full bit tests, an increase in performance (ROP) and dull condition was observed. Figure 31 details two representative runs, one with previous generation PDC cutter, and the other with the new generation PDC cutter. The bit with new generation PDC cutters drilled 32% further with equivalent ROP and better dull condition. Additionally, performance and dull conditions have continued to increase with run count and led to a 50% reduction in bits proclaimed "damaged beyond repair" since the introduction of the new generation PDC cutter.

Figure 31—Representative performance and dull photos of 12.25" Haynesville intermediate runs with new generation general purpose PDC cutters compared to offset.

Conclusions

Operators are drilling complex intervals with well plans that are aimed to improve drilling performance and ultimately, to maximize production in every well. The drill bit and the PDC cutters are expected to have exceptional consistent performance without compromise. In other words, cutters in abrasive applications need to not only perform in the wear environment, but also resist impact damage. The same applies for PDC cutters in impact applications, and more importantly, the applications that are in varied lithologies require more general or all-purpose cutters that withstand both thermomechanical wear and impact.

Application reviews prove critical to the development of successful cutters in the field. Understanding the drilling environment, drilling challenges, formation characteristics, and dull analysis are key components to identifying the PDC performance properties needed to enhance PDC cutter life and drill bit performance. Appropriate laboratory tests and engineering simulation capabilities that correlate with field performance also provide a faster iteration feedback loop for PDC cutter development. Mixed and full bit testing process and measurements, along with a statistically significant number of runs, were also critical to ensure the intended benefits.

The new generation of PDC cutters through field testing showed significant performance gains in terms of footage, ROP, and dull grade across the performance spectrum. In lateral sections of Canada's Falher abrasive lithology, a PDC cutter with improved abrasion resistance demonstrated to drill up to 48% further while also increasing the average ROP by 4%. The Southeast USA Haynesville intermediate is challenged by high interbedding of hard, abrasive lithologies and high lateral vibrations induced by drilling dysfunctions. Here, a general-purpose PDC cutter combining high abrasion resistance and durability, and a novel cutting geometry optimized for drilling efficiency and durability drilled 32% further with equivalent ROP and better dull condition. In West Texas USA, lateral sections in the Leonard B formation are challenged with stringers that cause severe impact damage. An optimized impact PDC cutter demonstrated 20% increased footage compared to offsets.

Following the process described on this paper was key for the team to target and execute a complete upgrade to the cutter portfolio for impact, abrasion and general purpose categories resulted in significantly improved drilling performance of over 20% longer staying on bottom, with higher ROP or equivalent, in wide range of formations and drilling applications.

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