

## Pointing Towards Improved PDC Bit Performance: Innovative Conical Shaped Polycrystalline Diamond Element Achieves Higher ROP and Total Footage

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### Abstract

Vibration induced impact damage/cutter chipping caused by inefficient shearing action at the center of a PDC bit can significantly reduce ROP and overall drilling efficiency in a wide range of formations. To solve the problem, a R&D initiative was launched to investigate new cutter designs and experiment with their count/placement to improve drilling efficiency and mitigate vibration. The research yielded an innovative conical shaped polycrystalline diamond element (CDE) with an ultra-thick synthetic diamond layer.

The conical element has undergone extensive laboratory testing to evaluate its potential to improve PDC bit performance. Using a single cutter test apparatus, engineers measured the element's ability to fracture rock at varying depths-of-cut. They determined the CDE exhibits up to a 70% increase in cutting efficiency compared to standard PDC cutters.

Next, an existing PDC bit was modified to include the new conical diamond element at bit center. The CDE was positioned at bit center with the conical tip pointing vertically down towards the rock. The location of the conical element combined with the optimized placement of the conventional PDC cutters allows an unconfined rock column to develop. The stress relieved column is then continuously crushed by the centrally positioned conical element. This solves the fundamental center cutting structure issues enabling the bit to deliver faster penetration rates and reduce the potential for vibration.

A base Mi616 type bit was fitted with a CDE and run in North Dakota and Utah through a highly mixed sequence of formations where the primary objective was to increase ROP and to reach kick-off point (KOP) in one run. The CDE equipped PDC bit improved ROP over a longer interval drilled compared to benchmark PDCs used in offsets. Subsequent field testing has substantiated the CDE's potential and how it can be used to deliver improved PDC bit performance.

### Introduction

In recent years, PDC bits have made significant progress encroaching on traditional rollercone applications because of their ability to drill longer intervals at higher penetration rates. The gains were initially driven by modeling of cutter loading and by analyzing drilling mechanics to quantify and mitigate downhole vibrations.<sup>1-2</sup>

As operators continued to explore the outer boundaries of the PDC application envelope, engineers began to describe the damaging effects that different types of vibrations have on PDC bits and cutters. R&D analysis successfully categorized the four main downhole vibration types (axial, lateral, torsional, whirl) and bit manufacturers began to produce specific technologies to stabilize the bit body and preserve the cutting structure in different formations.<sup>3-8</sup>

Additional research and manufacturing initiatives have produced superior cutter technology that can withstand harder and more abrasive formations.<sup>9-17</sup> In 2004, fixed cutter bits were crowned king with the total worldwide footage drilled by PDC (54%) surpassing that of rollercone (46%). However, efficiently drilling with PDC in very hard, interbedded and highly abrasive formations remains challenging.

### Conical Diamond Element

It is essential for the industry to create a differentiating drilling action to increase penetration rates and extend PDC bit life in abrasive and interbedded formations to further reduce drilling costs. To develop a combination shearing/crushing fixed cutter bit, a focused research initiative was launched to investigate new design elements and experiment with their count and placement to improve drilling performance. The project was successful and yielded an innovative new Stinger<sup>18</sup> conical shaped polycrystalline diamond element (CDE) with a thick synthetic diamond layer (**Figure 1**).

The element's innovative geometric design delivers high point loading for effective formation fracture. The conical element is constructed with advanced synthetic diamond manufacturing systems specifically designed to generate higher pressures and

temperatures during the sintering process while increasing micro-cell size for improved diamond quality.

### Advanced Materials Science

The CDE is fundamentally superior to traditional PDC cutters and diamond enhanced inserts (DEI) used in PDC and rollercone bits respectively. The element is manufactured using proprietary equipment and processes that are capable of producing extreme pressures and temperatures to form a substantial layer of polycrystalline diamond (PCD) on a conical geometry. The PCD layer on the CDE is approximately twice as thick as the diamond layer on a conventional PDC cutter. Compared to conventional PDC cutters the conical element exhibits 25% more wear resistance and almost double the impact strength (**Figure 2**). Combined with the unique conical geometry, the thick diamond structure creates an extremely robust and durable cutting element.

### Single Element Testing

The CDE has undergone extensive testing to evaluate its potential to improve penetration rates and increase total footage capabilities. In a single-cutter test apparatus, the CDE exhibited significant increases in resistance to impact damage and abrasive wear compared to conventional PDC cutters. Laboratory tests using CDEs on a vertical turret lathe (VTL) confirmed the following:

- At 0.02-in depth of cut with 1200lbs threshold, the CDE displayed a 70% increase in cutting efficiency compared to the baseline PDC cutter
- At 0.05-in depth of cut with 1200lbs threshold, the CDE cutter showed a 35% increase in cutting efficiency compared to the baseline PDC cutter
- The CDE has significantly improved abrasion resistance over extended wet testing on a VTL

### PDC Performance Limiter

With laboratory testing of single CDEs complete, the next challenge was to determine how to incorporate the element into a PDC cutting structure. The study focused on a conventional PDC bit's problematic center cutting structure, or cone area, which presents several distinct design challenges:

1. The physical space limitation creates an inherent problem because designers cannot simply position multiple cutters in this location.
2. The cutters at the bit center typically experience the lowest rotational velocity.
3. To produce an effective cutter layout that addresses the application requirements in terms of ROP, bit durability, stability and steerability the center most cutters are subjected to the highest axial load.

4. The cone area cutters are required to remove a relatively small volume of formation. This is an inefficient use of available energy to remove rock.

Combined, these fundamental issues create an inherently inefficient shearing mechanism at the center of all conventional PDC bits (**Figure 3**). This limitation is most evident when changing operating parameters (WOB/RPM) and drilling through transition zones with different lithologies and a high degree of UCS variance. As the center cutters engage formation their depth-of-cut can vary considerably impacting overall behavior of the entire cutting structure. The resulting torque fluctuations alter dynamic response exposing the bit to damaging lateral/torsional shock and vibration. The dysfunction reduces ROP and can cause cutting structure damage terminating the bit run resulting in multiple trips to complete the hole section. In harder formations, the intrinsic weakness of the center cutting structure design causes accelerated wear leading to a cored dull condition rendering the bit damaged beyond repair.

### Design Process

To fully exploit the CDE's innovative design advantages, engineers used an FEA-based drill bit design platform<sup>19</sup> to selectively abbreviate the blades that held the bit's low-velocity center cutters. The void space would allow a stress-relieved rock column to develop at the bit's center. Designers then strategically positioned the conical element in the newly created cavity to continuously crush and fracture the unconfined rock column (**Figure 4**). In addition, the abbreviated design contains fewer standard PDC cutters creating less division of weight-on-bit which increases cutter loading improving overall drilling efficiency.

Additional modeling tools were employed to further enhance performance of the new bit design. Using finite element analysis software, engineers then investigated the stress field at the precise point where the Stinger element indents the formation.

The study revealed high stress conditions at the contact point, which can increase fracture generation within the rock, can be achieved with significantly less applied force compared to standard PDC cutters. Bits equipped with a centrally located Stinger element have also displayed an increase in dynamic stability with less potential for vibration.

With the central placement of the CDE completed, the next step was to modify nozzle orientation to efficiently clean and cool the new style cutting structure. Using advanced computational fluid dynamics software, a hydraulic analysis was performed and nozzle positions were adjusted to enhance cuttings removal and cleaning of the conical element and adjacent borehole.

### Confirming Modifications

Using the dynamic modeling system created a time-based 3-D image that clearly illustrated the principle of rock column formation (**Figure 5**). As the rock column forms, it becomes less confined and fractures with significantly less energy than a typically confined formation. The study also enabled engineers to incorporate a high degree of stability into each design and to quantitatively analyze the results of iterative design changes.<sup>20-32</sup>

The result was optimized rock removal feature that produced a new-style PDC bit with a combination shearing/crushing rock failure mechanism. Virtual testing of the new PDC bit design swiftly advanced the engineering concept and confirmed the bit would improve ROP, eliminating costly and time-consuming field trials. As a result, the operator quickly benefits from improved bit performance while minimizing risk associated with an untested design. The next step was to test a full-scale CDE-equipped PDC bit in a pressurized drilling simulator to validate the results of the 4-D modeling study. The bit was manufactured in Houston and shipped to the company's test facility in Utah for further assessment. As expected, the previous conclusions were confirmed and the CDE-equipped PDC bit created a stress relieved rock column at the center of the hole which was crushed by the CDE (**Figure 6**).

Additional testing revealed a CDE equipped PDC bit also generates much larger drill cuttings than standard PDC bits thereby enabling rock characterization at the surface by geologists or mud logging personnel (**Figure 7**). This added benefit makes the CDE PDC bit ideal for high-profile exploratory wells through a reservoir section or when determining exact wellbore position in the stratigraphic column is critical.

### Hole Quality

Next, a next full-scale test bit was shipped to the service company's Cambridge research center to analyze the affect that a centrally placed CDE would have on bit behavior and hole quality. The test was run in hard-medium grained Lazonby sandstone with a UCS of 9,000psi. The experiment would determine how changes in WOB would influence borehole quality. Bit revolution would remain constant at 85RPM to control variance.

After the hole was drilled a laser scanning device was inserted into the hole to accurately measure variations in hole diameter. The results strongly indicate that standard PDC bits have a greater tendency to produce an out-of-gauge diameter than a bit equipped with the centrally placed CDE (**Figure 8**). The CDE-equipped bit displayed more consistent hole diameter/quality with less energy expended on unproductive movement.

### Novel PDC Design

The encouraging results of the modeling effort and laboratory testing convinced engineers that a single CDE positioned at bit center would improve ROP performance and enhance dynamic stability. An 8¾-in MDSi616 base design was selected for field testing and the conical element was positioned at the bit's central axis (**Figure 9**). The CDE's innovative material properties enable it to be run in a wide variety of formation types and BHA configurations.

### Field Test 1

An 8¾-in MDSi616 with a centrally placed CDE was field tested in the North Dakota portion of the Williston Basin. The bit was run on a steerable motor BHA in three similar vertical hole applications through a highly mixed and interbedded sequence of formations including sand/shale, salt and limestone/dolomite/anhydrite with UCS range between 2-25kpsi.

The main objectives were to improve ROP and reach kick-off point (KOP) in one run. The ROP on all three CDE runs was better than the best offset (131 ft/hr) and 56% better than the 11 well offset average (**Figure 10**). On the last run the CDE bit set a new field record delivering the fastest 8¾-in vertical drill-out to KOP in Divide County of 197.1 ft/hr. The record setting bit came out of the hole in good condition with no wear on the CDE and was dull graded 1-2-CT-S-X-IN-WT-KOP (**Figure 11**).

In another Williston Basin application a single 6-in MDSiZ613 with CDE drilled the entire lateral section of 9544 ft at 97 ft/hr in one run, a 49% improvement in ROP compared to three bit runs required on an offset well. The bit "locked in" and displayed excellent directional control staying within the narrow target reservoir window. The run set operator records for highest 24-hour footage (2903 ft/day) and fastest lateral TD to date (**Figure 12**).

### Field Test 2 (Duchesne County, Utah)

The next test was conducted in northern Utah with a 7 7/8-in Mi616 in a directional application on a steerable motor BHA with a 1.5° bend angle. The objective was to evaluate if the CDE equipped PDC bit could increase ROP, reduce vibration and reach section TD in one run.

The lithology of the application consists of difficult interbedded sand/shale/limestone with UCS varying between 2-30kpsi. Additional difficulty is encountered in the Wasatch formation (5900-10,500TVD) where 10-15kpsi sandstone is interbedded with soft shale (2-5kpsi) and hard sandstone stringers that peak at 25-30kpsi.

The steerable motor BHA went in at 277ft and drilled 6050ft of 7 7/8-in wellbore to TD the hole section at 6327ft in 43 IADC hours. The field test was successful and outperformed all four offset ROPs, drilling 4.4% faster than the best offset and reached section TD in one run (**Figure 13**). The bit came

out of the hole with a much better dull condition compared to the four offsets and was dull graded 1-2-BT-C-X-IN-WT-TD (**Figure 14**). The CDE was in excellent condition with no noticeable wear.

## Conclusions

Field tests in North Dakota and Utah USA strongly indicate that PDC bits equipped with CDE to form a centralized core then crush it are improving ROP in vertical, curve and lateral applications drilling through difficult interbedded formations with a high range of UCS values.

The thick synthetic diamond reduces wear especially in the cone area resulting in longer runs minimizing the cost of bit replacement trips. The conical element also forces the bit to rotate around its central axis enhancing dynamic stability while decreasing vibration.

The new style bit has the potential to increase performance in a wide range of formation types and applications in various worldwide applications. The conical element can be added to various designs with minor modifications then tailored for a specific application.

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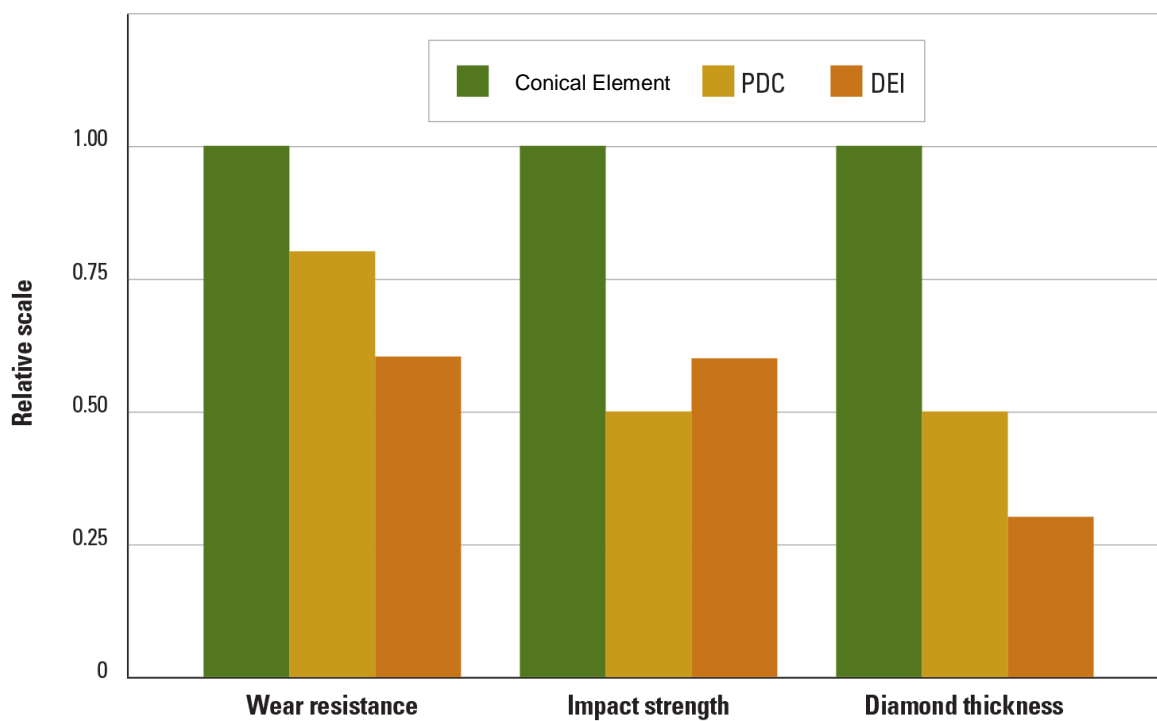
## References

1. Glowka, D.A.: "Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Development of a PDC Cutting Force Model" paper SPE 15619 presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 5-8 October 1986.
2. Warren, T.M., Sinor, L.A.: "Drag-Bit Performance Modeling" SPE paper 15618 presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 5-8 October 1986.
3. Behr, S.M., Warren, T.M., Sinor, L.A. Brett, J.F.: "3D PDC Bit Model Predicts Higher Cutter Loads" paper SPE 21928 presented at the SPE/IADC Drilling Conference, Amsterdam, 11-14 March 1991.
4. Brett, J.F., Warren, T.M., Behr, S.M.: "Bit Whirl - A New Theory of PDC Bit Failure" paper SPE 19571 presented at the SPE 64<sup>th</sup> Annual Technical Conference, San Antonio, Texas, 8-11 October 1989.
5. Warren, T.M., Brett, J.F., Sinor, L.A.: "Development of a Whirl-Resistant Bit" paper SPE 19572 presented at the SPE 64<sup>th</sup> Annual Technical Conference and Exhibition, San Antonio, Texas, 8-11 October 1989.
6. Sinor, L.A. Brett, J.F., Warren, T.M., Behr, S.M.: "Field Testing of Low-Friction-Gauge PDC Bits" SPE 20416 presented at SPE Annual Technical Conference, New Orleans, Louisiana, 23-26 September 1990.
7. Pastusek, P.E., Cooley, C.H., Sinor, L.A., Anderson, M.: "Directional and Stability Characteristics of Anti-Whirl Bits With Non-Axisymmetric Loading" paper SPE 24614 presented at the SPE 67<sup>th</sup> Annual Technical Conference, Washington DC, 4-7 October, 1992.
8. Warren, T.M., Sinor, L.A.: "PDC Bits: What's Needed To Meet Tomorrow's Challenge" SPE 27978 presented at the University of Tulsa Centennial Petroleum Engineering Symposium, Tulsa, Oklahoma, 29-31 August 1994.
9. Schell, E.J., Phillippi, D., Fabian, R.T., "New Stable PDC Technology Significantly Reduces Hard Rock Cost per Foot" paper SPE/IADC 79797 presented at the SPE/IADC Drilling Conference, Amsterdam, February 19-21 2003.
10. Clegg, J.: "Faster, Longer, and More-Reliable Bit Runs With New Generation PDC Cutter" paper SPE 102067 presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 24-27 September 2006.
11. Baker, R., Shen, Y., Zhang, J., Robertson, S.: "New Cutter Technology Redefining PDC Durability Standards for Directional Control: North Texas/Barnett Shale" paper IADC/SPE 128486 presented at the IADC/SPE Drilling Conference and Exhibition, New Orleans, Louisiana, 2-4 February 2010.
12. Plemons, B., Douglas, C., Shen, Y., Zhan, G., Zhang, Y.: "New Cutter Technology for Faster Drilling in Hard/Abrasive Formations" paper SPE 132143 presented at the CPS/SPE International Oil and Gas Conference and Exhibition in China, Beijing, China, 8-10 June 2010.
13. Murphy, D., Tetley, N., Partin U., Livingston, D.: "Deepwater Drilling in Both Hard and Abrasive Formations; The Challenges of Bit Optimisation" paper SPE 128295 presented at the North Africa Technical Conference and Exhibition, Cairo, Egypt, 14-17 February 2010.
14. Freeman, M., Shen, Y., Zhang, Y.: "Single PDC Cutter Studies of Fluid Heat Transfer and Cutter Thermal Mortality in Drilling Fluid" paper AADE-12-FTCE-38 presented at the AADE National Technical Conference and Exhibition, Houston, Texas, 10-11 April 2012.
15. Gonzales, A., Clark, T., Douglas, C., Mueller, L., Yu, J., Shi, J., Zhang, Y.: "Improvements in Cutter Technology Leads to Faster Drilling in Hard Abrasive Formations, East Texas Basin" paper SPE/IADC 156472 presented at the Middle East Drilling Technology Conference, Muscat, Oman, 24-26 October 2011.
16. Murphy, D., Mackay, D., Gilmour, J., Tetley, N., Centala, P., Iwere, E.: "Deepwater Drilling in Both Hard and Abrasive Formations: The Continuing Challenge of Bit Optimization" paper SPE 151787 presented at the North Africa Technical Conference and Exhibition, Cairo, Egypt, 20-22 February 2012.
17. Zhang, Y., Douglas, C., Mueller, L., Shen, Y., Likki, S.: "Refinements to Cutter Technology and PDC Bit Hydraulics Lead to Faster Drilling in Hard/Abrasive Formations, East Texas" paper IADC/SPE 156472 presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition Tianjin, China, 9-11 July 2012.
18. Durrand, C.J., Skeem, M.R., Hall, D.R.: "Thick PDC, Shaped Cutters for Geothermal Drilling: A Fixed Cutter Solution for a Roller Cone Environment" paper ARMA 10-524 presented at the 44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium, Salt

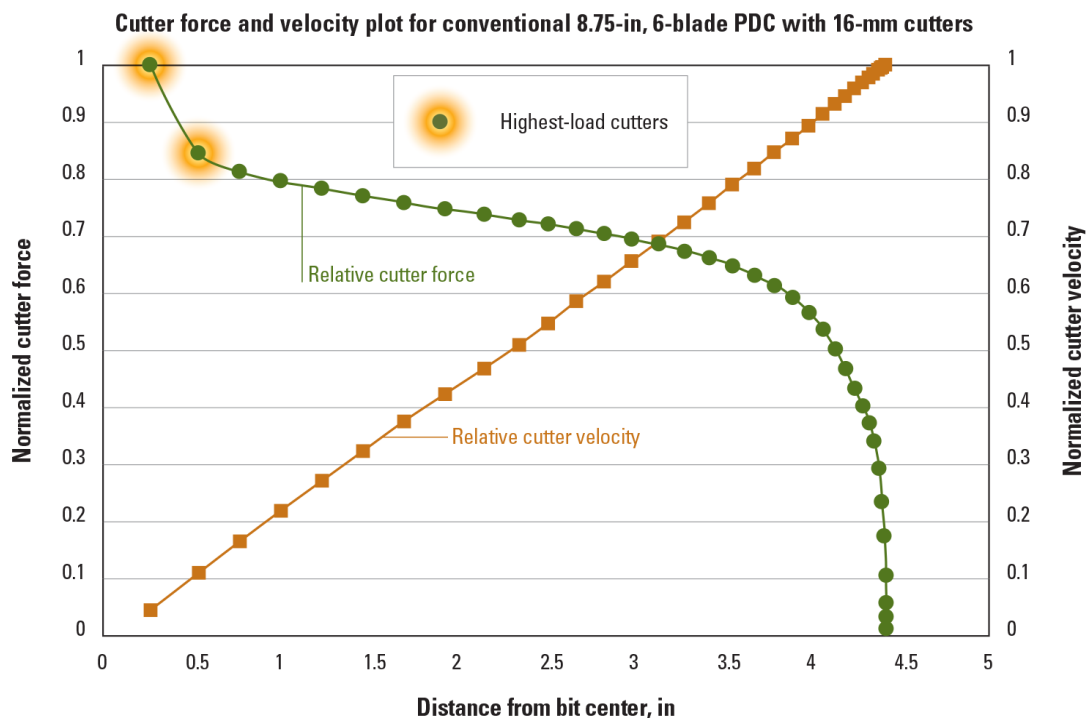
- Lake City, Utah June 27-30, 2010.
19. Gillick, S., Hamilton, A., Singh, A., van der Pouw K.: "Rock Mechanics Lab Testing and Computerized Simulation of Bit Dynamics Improves Drilling Performance in Horizontal Chalk Reservoirs" paper SPE 87101 presented at the IADC/SPE Drilling Conference, 2-4 March 2004, Dallas, Texas.
  20. Aslaksen, H., Annand, M., Duncan, R., Fjaere, A., Paez, L., Tran, U.: "Integrated FEA Modeling Offers System Approach to Drillstring Optimization", paper IADC/SPE 99018 presented at the IADC/SPE Drilling Conference, Miami, Florida, Feb 21-23, 2007.
  21. Frenzel, M.: "Dynamic Simulations Provide Development Drilling Improvements" paper OTC 19066 presented at the Offshore Technology Conference, Houston, Texas, April 30 - May 3, 2007.
  22. Frenzel, M., Kull, B.: "Dynamic Balancing of Bit/Reamer Cutters Improves Drilling Performance" *World Oil*, pp 67-72, March 2008.
  23. Algu, D.R., Denham, W., Nelson, G., Tang, W., Compton, M.T., Courville, D.F., Fitzmorris, D.L.: "Maximizing Hole Enlargement While Drilling (HEWD) Performance with State-of-the-art BHA Dynamic Analysis Program and Operation Road Map" paper SPE 115607 presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, September 21-24, 2008.
  24. Partin, U., Compton, M., Nelson, G., Livingston, D., Davis, P.: "Advanced Modeling Technology: Optimizing Bit-Reamer Interaction Leads to Performance Step-Change in Hole Enlargement While Drilling", paper IADC/SPE 128161 presented at the IADC/SPE Drilling Conference and Exhibition, New Orleans, Louisiana, 2-4 Feb, 2010.
  25. Wu, X., Paez, L., Partin, U., Agnihotri, M.: "Decoupling Stick-slip and Whirl to Achieve Breakthrough in Drilling Performance" paper IADC/SPE 128767 presented at the IADC/SPE Drilling Conference and Exhibition, New Orleans, Louisiana, 2-4 February, 2010.
  26. Barrett, M., Compton, M., Agnihotri, M., Verano, F., Mitchell, S., Fitzmorris, D.: "Dynamic BHA Modeling of Hole Enlargement While Drilling Lead to ROP Improvement in Gulf of Mexico" paper OTC 20370 presented at the Offshore Technology Conference, Houston, Texas, 3-6 May 2010.
  27. Compton, M., Verano, F., Nelson G., Wu, S.X.: "Managing Downhole Vibrations for Hole-Enlargement-While-Drilling in Deepwater Environment: A Proven Approach Utilizing Drillstring Dynamics Model" paper SPE 139234 presented at the Latin American & Caribbean Petroleum Engineering Conference, Lima, Peru, 1-3 Dec 2010.
  28. Wu, X., Karuppiiah, V., Nagaraj, M., Partin, U., Machado, M., Franco, M., Duvvuru, H.: "Identifying the Root Cause of Drilling Vibration and Stick-Slip Enables Fit-for-Purpose Solutions" paper IADC/SPE 151347 presented at the IADC/SPE Drilling Conference and Exhibition, San Diego, California, 6-8 March 2012.
  29. Snowie, M., Malcolm C., Alexander, G., Duncan, R., Alemi, H., Jolly I., Barlow, A.: "Solving Swelling Clay Issues: Modeling Effort/Concentric Reamer Saves Operator Over Seven Days Rig Time vs Plan, UK North Sea" paper SPE 158958 presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 8-10 October 2012.
  30. Tellez, C., Bedino, H., Casanova, O., Castelazo, P., Wu, S., Mayol, J., Paez, L., Verano F., Columba, J.: "Application of Advanced Dynamics Modeling Significantly Improves the Stability of Rotary Steerable Drilling with Roller Reamers, Mexico" presentation at the International Petroleum Technology Conference, Doha, Qatar, 7-9 December 2009.
  31. Rahman, N.A., Mohaideen, A., Bakar, F.H., Tang, K.H., Maury, R., Cox, P., Le, P., Donald, H., Brahmento, Subroto, E.B.: "Solving Stick-Slip Dilemma: Dynamic Modeling System Significantly Reduces Vibration, Increases ROP by 54%" paper 161155 presented at the Abu Dhabi International Petroleum Exhibition, Abu Dhabi, UAE 11-14 November 2012.
  32. Kieschnick, M., Jacob, T., James, B., Karuppiiah, V., Hamilton, R.: "Pre-Job Modeling/Resulting Integrated BHA System Solution Sets Multiple ROP Records, North Field Qatar" paper SPE/IADC 163464 presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands, 5-7 March 2013.



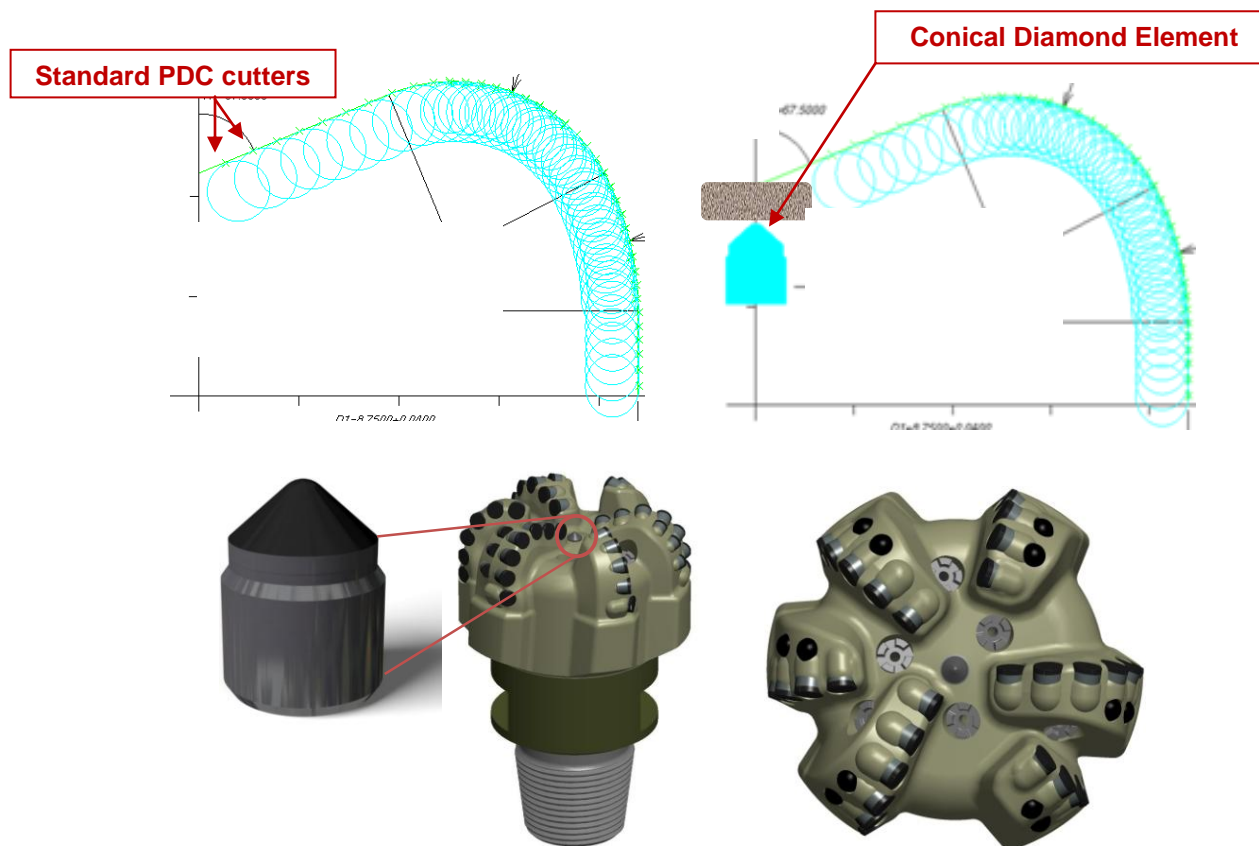
**Figure 1** – Unique conical geometry with thick layer of synthetic diamond enhances drilling efficiency and ROP



**Figure 2** – The conical element possesses superior wear/impact resistance compared to PDC cutters and DEI for rollercone

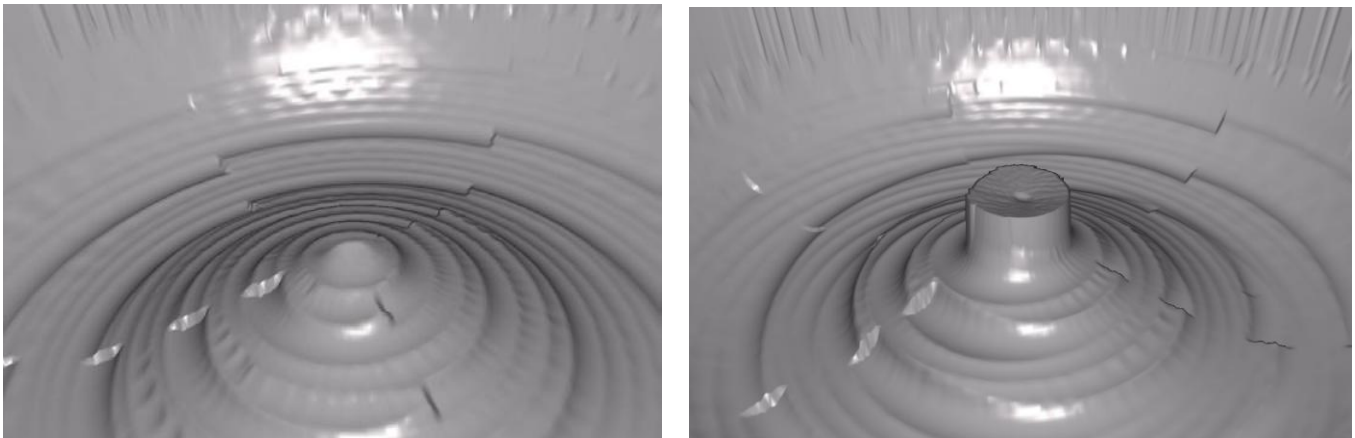


**Figure 3** – Conventional PDC bit design has difficulty with rock destruction at borehole center



**Figure 4** – Conical element's center position delivers unique crushing action delivering high point loading





**Figure 5** – Modeling system used to simulate dynamic bit behavior confirmed ROP improvement in different lithologies

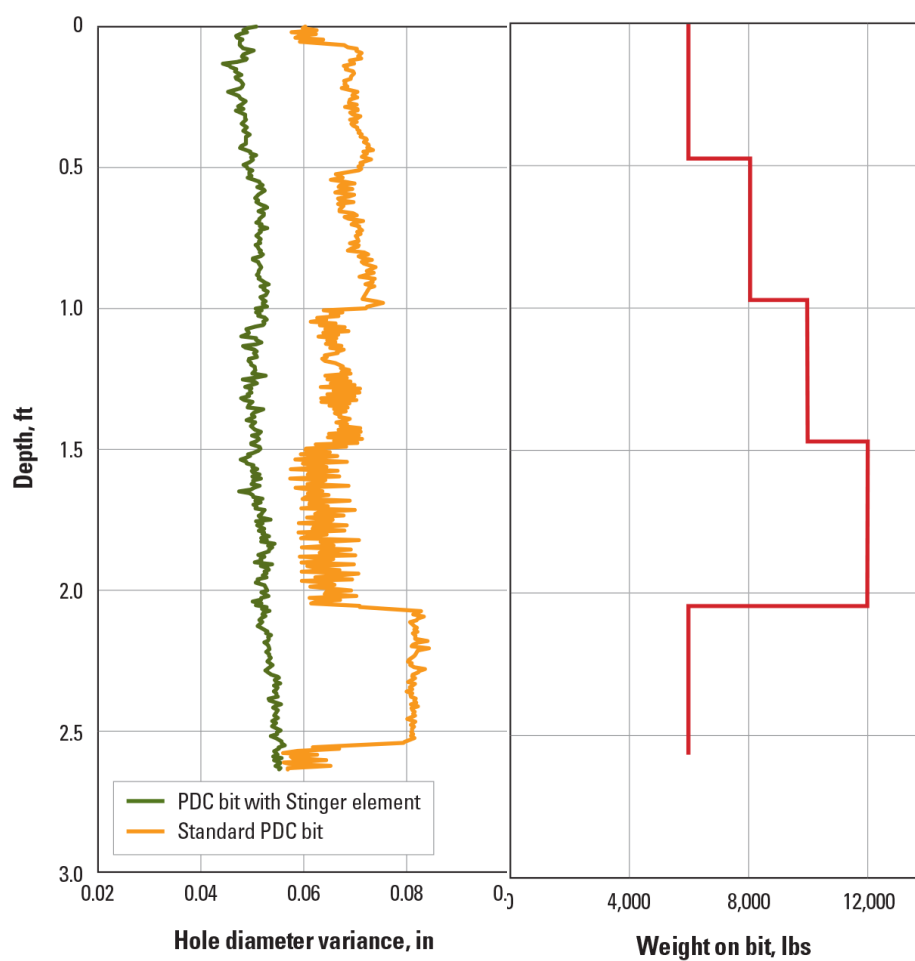


**Figure 6-** Full scale drilling simulator validated FEA-model with conventional PDC bit (l) and new CDE equipped bit (r)





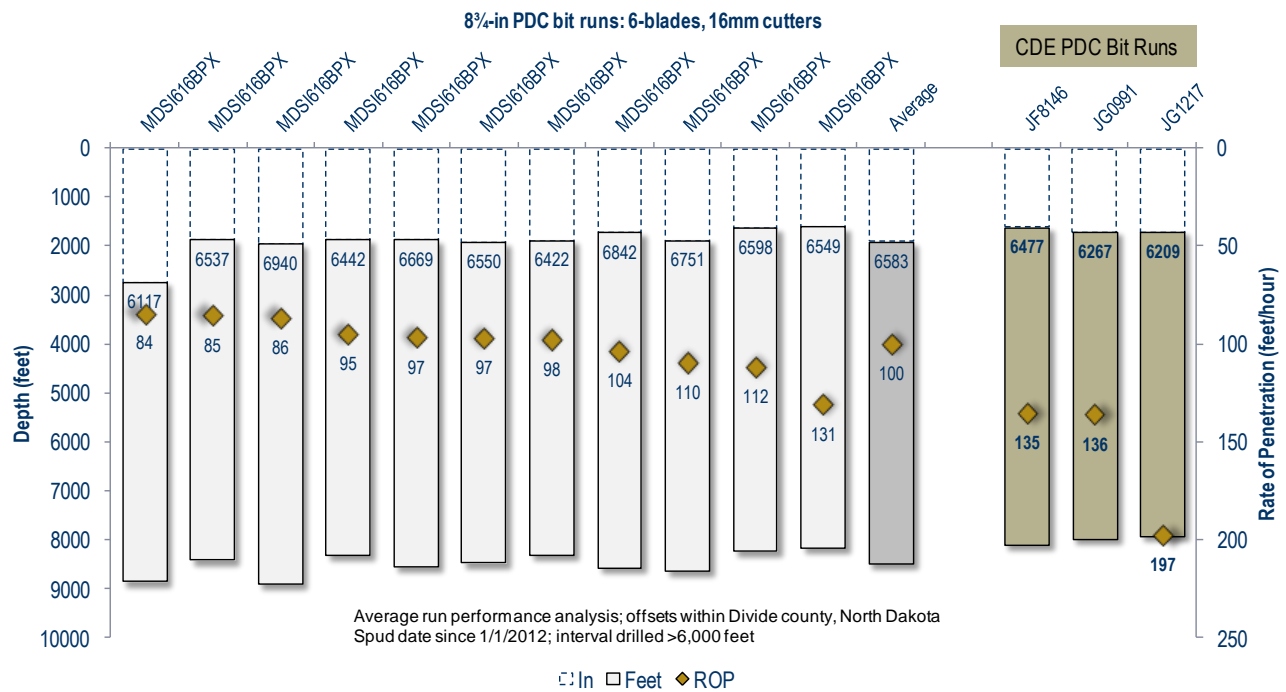
**Figure 7** - Large cuttings produce by CDE equipped PDC bit (right) greatly enhances geological/petrological evaluation



**Figure 8** – Laboratory testing confirmed bit with CDE demonstrates more stable drilling behavior for improved borehole quality



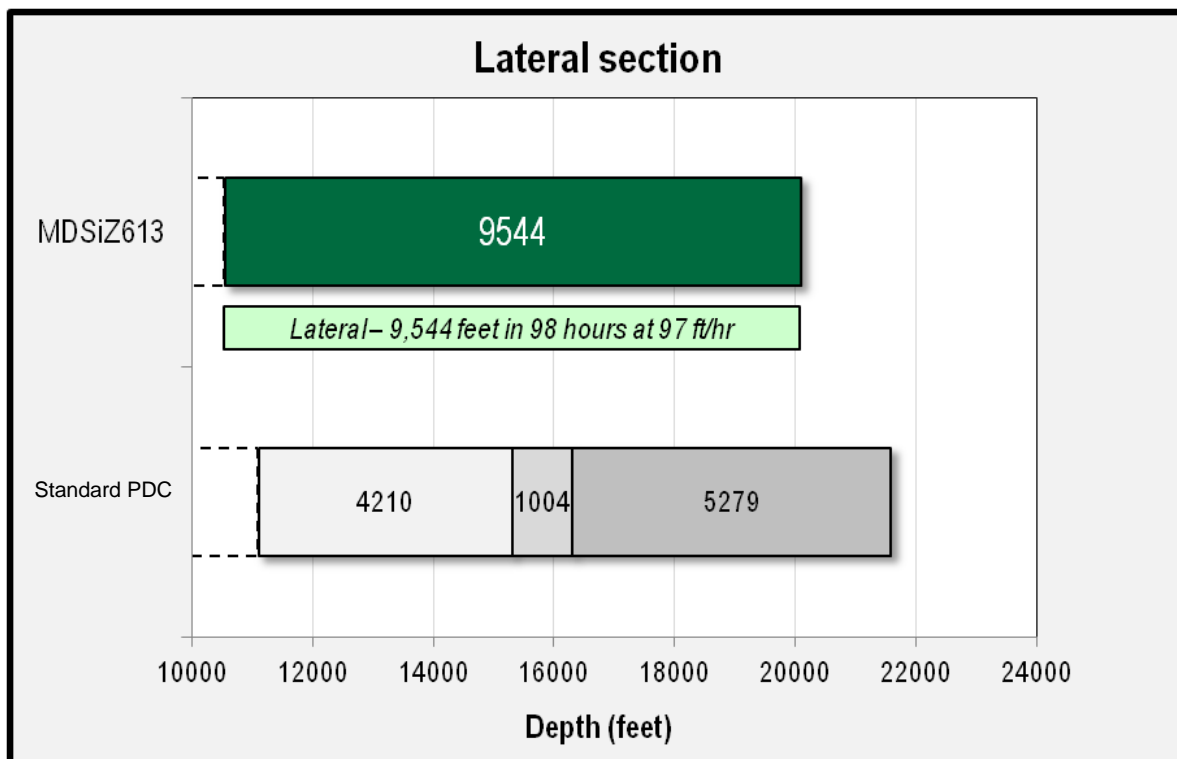
**Figure 9** - An 8 $\frac{3}{4}$ -in MDSi616 fitted with CDE technology to increase drilling efficiency/ROP



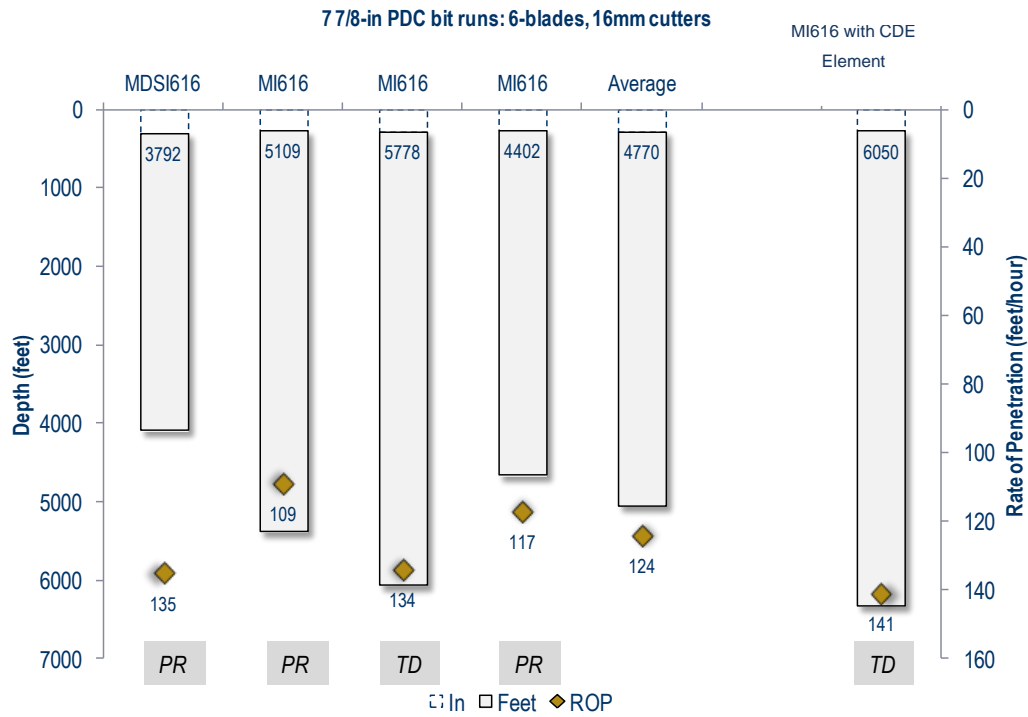
**Figure 10** – ROPs of three MDSi616 CDE runs is faster than the best offset drilled with conventional PDC bit



**Figure 11** – Record setting MDSi616 in excellent dull condition after drilling 6209ft of formation in 31.5 hrs



**Figure 12** – Record performance with CDE in Bakken lateral; Head-to-head comparison with same operator and rig.



Offsets within 10 miles of well location; Spud date since 1/1/2012; same operator/field

**Figure 13** – ROP of 7 7/8-in Mi616 test run with CDE drilled faster than best four offsets



**Figure 14** – New style 7 7/8-in Mi616 in good dull condition with the CDE's pointed tip fully intact