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## Advanced Cutting Structure Improves PDC Bit Performance in Hard and Abrasive Drilling Environments

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### Abstract

The performances of PDC bits in hard formations, especially when these formations are also abrasive, still lack effectiveness and consistency. In such applications, the industry has usually resorted to the use of “insert type” roller cone (RC) and impregnated diamond bits (ID) – *due primarily to their performance consistencies*.

Impregnated bits, usually, exhibit the durability characteristics needed to drill long footages in hard and abrasive formations. However, due to their grinding rock removal action, penetration rates (ROP) are typically low, commonly in the (3 – 9 fph) range. These low ROPs experience rapid deteriorations, once argillaceous and/or shale bearing formations are encountered. These conditions reduce the operational efficiency of impregnated bits, driving up drilling costs.

From an ROP perspective, roller cone bits perform better (6 – 12 fph) than impregnated bits in hard and abrasive formations. In addition, the ROPs of RC bits experience minimal decay in argillaceous and/or shale bearing formations. However RC bits are commonly tripped on hours and, do not exhibit the longevity needed for hard and abrasive environments. Considering the depths at which such hard and abrasive formations are usually encountered, trips increase operational hours, HSE risk and thus substantially add to drilling cost.

Due to their depositional depths, hard and abrasive formations are sometimes encountered in HP/HT environments. This condition often necessitates the use of high mud weights, or BHA's that incorporate high speed drive mechanisms - *PDMs or turbo-drills*. Such conditions, necessary to improve operational efficiency, further complicate the drilling environment - *affecting the ROP and/or durability of all drill bits*.

This paper discusses an innovative PDC bit, which has specifically been developed to improve operational efficiency in hard and abrasive formations. This new generation PDC bit effectively addresses the ROP limitations of impregnated bits, as well as the footage deficiencies of roller cone bits. In addition, these bits have been developed to be effective, even when hard abrasive formations are drilled with high mud weights and/or with high speed drive mechanisms.

### Background

The industry currently defaults to roller cone and impregnated bits, when it comes to hard and abrasive formation drilling. This situation has been predicated by past PDC bit experiences in these applications, which have consistently been poor. Heavy set PDC bits<sup>1</sup> (**Figure 1**) - *having high blade counts, small PDC cutting elements and high cutter counts* - have typically been used in these applications.

These bits have high total diamond volume, which was expected to improve durability, and thus longevity and run length. Such a gain, when combined with the known ROP potential of PDC bits, was expected to improve drilling performance in hard and abrasive formations. However, without a proper understanding and interpretation of the conditions needed for success in such applications, the performances of such “heavy set” bits always left much to be desired.

As has been shown by their ineffective performances, heavy set bits do not necessarily possess the attributes needed to be effective in hard and abrasive formations. Specific characteristics and functional behaviors have to be exhibited by PDC bits, to make them effective in these applications.

Research efforts, focusing on this specific application, have identified the requirements and conditions needed to improve PDC bit performance. The effects of operational parameters, specifically WOB and RPM, have been isolated and analyzed. The relationships between ROP, WOB and wear flat generation have also been quantified. In addition, the effects of RPM and time on *wear flat generation rate* have also been evaluated. The positives, as well as limitations of the resulting operational medium, from a vibration perspective, have also been analyzed.



PDC bits, intended for hard and abrasive formations, must have maximized axial ( $A_v$ ) and radial ( $R_v$ ) diamond volume distributions (**Figure 2**).  $A_v$  defines the amount of usable diamond on a bit – measured from the tips of the cutters to the bit body, and in a direction parallel to the bit axis.  $R_v$  defines the amount of useable diamond on a bit's *unit profile length* – measured from the center of the bit to its gage point. These bits must present high diamond volumes to the formations being drilled, as well as minimize wear flat sizes at *standard IADC dull grade values*. In addition, these bits must exhibit shearing rock removal characteristics, especially when argillaceous and/or shale bearing formations are encountered during drilling.

It has become apparent that the industry can not put PDC bits in these applications, *just because they are available*. Specialized bits, exhibiting the characteristics described above, are needed to extend PDC bit performance into hard and abrasive formations. In addition, unique PDC cutters with *very high abrasion resistance characteristics* are needed to complement these bits. This paper will describe the development, as well as functional characteristics, of a new generation PDC bit which has been specifically engineered for this challenging application.

#### Formation Drillability

Rock hardness has usually been used to define the application envelope of PDC bits. In general terms, *hard* rock was deemed non-drillable by PDC bits. Advancements in PDC bit technology<sup>2,3,4,5</sup> have exposed the deficiencies of this classification, specifically as it relates to the term “hard”. In developing an understanding, as to why some particular PDC bits perform poorly in certain applications, the word “hard” was identified and tagged as being very subjective<sup>6,7,8</sup>.

*Drillability*<sup>9</sup> should be defined in terms of *drilling difficulty*, and must not be equated with hardness. In this regard, formations of similar hardness but having different lithological make-ups will present different drilling challenges<sup>10</sup>. The effect of this realization, which introduces a new product development process, constitutes the basis of this paper.

#### Operational Concerns

RPM has a huge role in hard and abrasive formation drilling. These challenging applications are usually encountered at great depth, usually in smaller hole sizes (less than 9-7/8”) and, in HP/HT environments. Due to these issues, *turbo-drills* (**Figure 3**), with operational rotary speeds in excess of 800rpm have usually been used in these applications. In the environments described, turbo-drills have un-paralleled performance consistency and MTBF values when compared to PDMs. Considering the *high rotary speeds* needed to drill such applications, it is imperative for PDC bits, developed for these applications, to also function effectively at elevated RPM.

Presently, geared *turbo-drills* with reduced rotary speeds are in development (**Figure 4**). In addition to maintaining their current functional advantages, these new tools will also have higher torque outputs at much reduced pressure drops. This

advantage will further enhance drill bit performance especially that of PDC bits, in hard and abrasive formations.

#### PDC Bits – Type A

Certain PDC bits, to be referred to as *type A*, while not specifically developed for hard and abrasive formations, have found considerable success with high speed drive tools (turbo-drills) in same applications. In the *medium hard and abrasive* Rotliegendes formation (**Figure 5**) of the Southern North Sea, a 6” *type A* bit (PDC-A) (**Figure 6**) has achieved consistent performances when compared to impregnated and natural diamond bits. The runs under discussion (**Table 1**) have been with *turbo-drills*, in lateral legs of directional wells. As is typical with these runs, PDC-A is usually pulled in a heavily worn condition (**Figure 7**). On this particular run, *of which dull is shown*, PDC-A was still achieving instantaneous ROP in excess of 20fph just before it was pulled.

The successes of PDC-A in the Rotliegendes, helped identify the characteristics and conditions needed to make PDC bits consistently effective in *harder and more abrasive* applications. Major findings identified with the PDC-A runs can be summarized as follows:

- Although PDC cutter wear is more intense in abrasive formations, the penetration rates of PDC bits do not experience the types of decays usually seen in other formations.
- ROP exhibits positive correlations with RPM, even when large wear flats have been generated.
- With increasing hardness and/or abrasiveness, WOB has very little effect on ROP. This primarily is due to the large wear flats, which are generated in such instances.

#### New PDC Bit (NPDC) – Developmental Requirements

Different lithologies have dissimilar ROP responses to operational parameters such as WOB and RPM. Most formations tend to have different percentages of dissimilar lithologies – *signifying various degrees of heterogeneity*. Carbonates, due to their shearing and/or pre-fracturing requirements, exhibit strong ROP responses to increasing WOB. As wear flats are generated on PDC cutters, shales and carbonates tend to exhibit poor ROP responses..

PDC bits developed for hard and abrasive formations (NPDC) must be able to drill other formations and/or lithologies effectively. In this regard, it is important that these bits exhibit appropriate ROP responses to WOB and/or RPM, in the “*other*” formations that will be encountered.

To be successful, NPDC bits must drill shales at much higher ROPs. Consequently, junk slot area (JSA), void volume ratio ( $V_{vr}$ ) and face volume ( $F_v$ ), hydraulic parameters (**Figure 8**) with direct effects on cuttings evacuation, and thus ROP, must be maximized.

The influences of *bit profile* and *hole size*<sup>11</sup> on performance have to be analyzed and quantified. Durability<sup>12</sup>, defined here in terms of radial and axial diamond volumes must also be



maximized on NPDC bits. Specialized PDC cutters, with highly biased abrasion resistance characteristics have to be used in NPDC bits. In combination with NPDC's unique design attributes (to be discussed later), these specialized cutters must help reduce the rate of wear flat generation as well as wear flat size at all IADC dull grade conditions. These characteristics will maximize bit life and help sustain acceptable ROPs in the challenging applications described in this paper.

For NPDC bits, developed specifically for hard and abrasive formations, the conditions described ensure achievement of ROPs that are similar to that of roller cone bits, as well as footages comparable to that of impregnated bits.

### NPDC – Development Concept

This bit has a unique cutting structure (cutter layout). PDC cutters, having different back rakes, (Figure 9) are deployed along different blades. The back rakes alternate between low (*first group*) and high (*second group*) values on adjacent cutters on the same blade. When rotated onto a single radial plane, the first and second group of cutters overlap radially, establishing complete and independent bottom hole coverages. As such, if all the cutters in any *specific* group are intentionally removed from the bit, the remaining cutters belonging to the *other* group will still drill ahead effectively. In some instances, and based on the application intent and/or radial diamond volume requirements, the *second* group of cutters could be larger in diameter than the *first* (Figure 10).

Due to the unique cutter deployment, *neither* group of cutters are regionally localized along the profile, and/or placed specifically on individual blades, of the bit. Regardless of the scenario used in the development of these bits, the *second* group of cutters (high back rake) establishes the axial diamond volume of the bit.

The cutting structure is governed by the following equations:

$$\phi_{bh} \geq \phi_{bl} \quad \text{--- (1)}$$

$$\phi_{bh} \not\subset \phi_{bl} \quad \text{--- (2)}$$

$$\phi_{bh(i-1)} \cap \phi_{bh(i+1)} \neq 0 \quad \text{--- (3)}$$

$$\phi_{bl(i)} \cap \phi_{bl(i+2)} \neq 0 \quad \text{--- (4)}$$

Where  $\phi_{bh}$  and  $\phi_{bl}$  represent the diameters of the high and low back rake angle cutters respectively.

### NPDC – Functional Attributes

The functional and performance characteristics needed to make NPDC successful in hard and abrasive formations will now be discussed under the following headings – *ROP, Durability, Stabilization and PDC cutter development*.

**Rate of Penetration:** The *first* group of cutters, with low back rakes and establishing full bottom hole coverage, define the ROP potential of the bits. This ROP will be lower than that achievable with standard PDC bits of comparable blade

count and cutter size. However, because of the geometric conditions governing NPDC's cutting structure, this ROP will be higher than what PDC bits with blade counts, cutter sizes and back rakes similar to that of the *second* group of cutters can achieve (Table 2). This characteristic is very important, especially when NPDC traverses shale and/or carbonate bearing formations.

Due to the fact that NPDC is bladed, its hydraulic effectiveness is comparable to that of conventional PDC bits. Hydraulic parameters such as open face volume, junk slot area and void volume ratio are all maximized to enhance cleaning efficiency. The placement and orientation of nozzles are also optimized to eliminate re-circulation and/or stagnation zones. These attributes improve ROP, especially in shale bearing formations.

**Durability:** This characteristic is primarily established by the *second* group of cutters. Due to their relatively higher back rake angles, these cutters are able to take higher impact loads before the diamond table *chips and/or spalls*. An additional advantage of higher back rakes is the reduced wear flat sizes they generate at specific IADC dull grades (Figure 11). In this regard, heat retention as well as thermal degradation of the diamond table is minimized. This advantage also reduces the rate of wear flat generation. Consequently, additional WOB needed to sustain initial ROPs are lower.

$A_v$  is highest on the second group of cutters. Since this group of cutters establish full bottom hole coverage, they define the  $A_v$  of NPDC bits. The possible use of different cutter sizes, as previously described, increases  $R_v$  on NPDC bits. These properties further enhance durability, from a diamond volume (radial and axial) perspective.

**Stabilization:** For a PDC bit to be durable and/or fast, stabilization must be achieved first. The importance of this requirement grows exponentially, as rock hardness increases. PDC bits usually experience axial, torsional, lateral and whirl vibrations. The *high RPM* medium, in which NPDC bits are usually used, aid in the dampening of torsional and/or axial vibrations.

As such, lateral and whirl become the most dominant modes in *high RPM* environments. With NPDC bits, PDC cutters are laid out so as to create ridges in the formation being drilled. At the initiation of lateral offsets, the cutters bite into the side-walls of the formation being drilled. This condition results in the creation of stabilization forces, which are situated in a plane perpendicular to the bits axis. These stabilization forces act to re-establish the bit's true center rotation, thereby minimizing lateral and/or whirl vibration events. It must be mentioned, that the ridge geometries and sizes are controlled in the design process so as to not compromise ROP.

In instances where multiple cutter sizes are used in NPDC bits, the curvature differences between the different cutter sizes creates deeper ridges in the formation being drilled.



This condition enhances stabilization and durability (Rv) without compromising ROP.

**PDC Cutter Development:** Specialized PDC cutters have been developed, which complement the performance of NPDC bits. These cutters have highly biased abrasion characteristics. Maximization of abrasion and impact characteristics in a cutter, claims by certain pockets of the industry, which goes against the material properties and behavior of diamond was carefully re-evaluated. The particle size of diamond has a huge effect on the abrasion and impact resistance of a cutter, when everything else is the same. Fine particles improve abrasion resistance, whereas coarse particles enhance impact resistance (Figure 12).

This abrasion versus impact relationship has been re-defined by *multi-modal diamond table technology*. This concept uses different size particles, covering a wide distribution range and, having specific particle size percentages to achieve notable improvements in both impact and abrasion resistance. Basically, the gains are realized through a “right hand shift” in the abrasion-impact curve (Figure 13).

To gain the types of abrasion improvements needed for NPDC bits, cutter development has to evolve through the following stages:

1. Carbide interface development
2. Diamond/carbide material technology
3. Exact sintering Processes

*Carbide interface development* (Figure 14) is aimed at minimizing damaging residual stresses, especially tensile, in the diamond table and at the diamond-carbide interface. It is also intended to move these tensile stresses away from the periphery of the cutter, and also to reduce the stress gradients (Figure 15) in the diamond table and in the carbide substrate. These conditions will improve impact resistance by minimizing the cutters ability to chip and/or spall.

The next phase is the development of *appropriate diamond table technology*, based on the intended performance characteristics of the cutter. With regards to the specialized cutters, used in NPDC bits, this involved the development of a *highly abrasive multi-modal diamond table* (very fine diamond particles). Since every interface has a limiting diamond table thickness, beyond which the benefits gained with the first process (interface technology) are lost, determination of an appropriate diamond table thickness (Figure 16) is crucial at this stage. *The appropriate tungsten carbide grade must also be developed for the cutter at this stage.*

Every specific carbide interface (Figure 17), when coupled with the appropriate diamond table technology and thickness requires an *elaborate and exact sintering process*. The diamond table is attached to the carbide interface during the high temperature/high pressure sintering process. It must also be mentioned that the use of improved diamond material on sub-optimized interfaces yields minimal gains in performance improvement.

For any PDC cutter (type and size) the development stages and cycle described, each of which has a specific contribution to cutter performance (Figure 18), could take a couple of years to complete. This is due to the sophistication of the processes involved, as well as the amount of work associated with each of the phases.

In addition, a unique feature has been developed that helps reduce wear flat size. A relief, cut into the carbide substrate (Figure 19), reduces the total surface area embedded into the formation when cutters are new. As wear flats are generated during drilling, the relief reduces the total wear flat area (Figure 20) in contact with the formation being drilled, when compared to cutters without this feature (Figure 21). In addition to reducing WOB requirements, improving ROP and reducing torque, this feature minimizes heat checking, thus extending cutter life and bit durability.

#### Laboratory Testing of Specialized Cutters

The performance objectives of the specialized cutters developed for NPDC bits can be summarized as follows:

- Hard and abrasive drilling environments
- High RPM drilling environments

Based on the above objectives, specific and elaborate laboratory tests (Figure 22) were designed to verify the effectiveness of the developmental process as well as the abrasion characteristics of the NPDC cutter. The tests were used iteratively as part of the development cycle.

Samples of the developed cutters and impregnated segments (Figure 23) were tested in Berea Sandstone (BSS) and Sierra white granite (SWG). The test conditions (Table 3) were designed to mimic what the cutters will see in actual field conditions. This can be described as the drilling of hard and abrasive formations, at low depths of cut in high RPM environments. Test results, comparing the abrasion characteristics of the special PDC cutters to that of the impregnated segments, are shown in (Tables 4 and 5).

The effect of DOC, on the abrasion resistance of IS is shown in (Table 4a). At a low DOC (0.015”) wear resistance of IS is directly related to the differential abrasion characteristics of its constituent materials. In this regard, diamond particles are gradually exposed, thus slowing rate of wear and improving abrasion resistance. As DOC increases (0.030”), IS wear is characterized by diamond grain pull-out – *a mechanical condition that accelerates wear.*

The abrasion resistance of PDC-A, at similar operational conditions in Sierra white granite and Berea sandstone is shown in (Table 4b). Due to PDC-A’s highly specialized performance characteristics, rock properties had little effect on its abrasion resistance.

The wear characteristics, of IS and PDC-A are compared at identical test conditions in BSS and SWG. Higher abrasion resistance properties are exhibited by PDC-A in both rock types. Diamond particle distribution in IS is not as consistent



across defined planes in the element like it is with PDC-A. It is possible that the section tested had a diamond distribution that is below the element's average distribution. However, this does not detract from the test results, since PDC cutters have been known to have better abrasion resistance, due to diamond density, than impregnated segments.

The abrasion resistance of *PDC-A* and *IS* is measured in terms of their *G-ratio*. The *G-ratio* represents the volume of rock removed, per unit diamond consumed – the higher the value, the higher the abrasion resistance of the material. In field operations, impregnated bits have usually shown superior durability characteristics, due to the high total diamond volume in these bits. The SFPs used the tests, 2500 and 3000, correspond to RPMs of 1200 and 1500 respectively, due to the core diameters used.

It must be mentioned that several tests were performed during the development process, which led to modifications in the carbide interface technology and/or diamond table technology and/or sintering process. The results presented here are those of the very final product, after several iterative cycles.

#### Field Testing of NPDC

NPDC type bits, built with the specialized cutters described, have been tested in the field - *in hard and abrasive formations*. Although several successful runs have been recorded, three of such runs will be discussed in this paper.

#### Field Case #1 – Alaska

A 6" bit (NPDC<sub>1</sub>), incorporating the principles discussed was developed for the medium hard, highly abrasive and conglomerate infested Hemlock formation in Alaska. The bit was fitted with the specialized high abrasion cutters. *PDC bits with impregnated material back-ups (PDC-i)*, and expected to have superior durability<sup>13</sup>, had been developed by another bit manufacturer for this same application. NPDC<sub>1</sub> drilled faster and longer (Table 6) than all the previous offset *PDC-i* runs in the same application.

#### Field Case #2 – Alaska

A second NPDC<sub>1</sub> was run on a different well, also in the medium hard, highly abrasive and conglomerated infested Hemlock formation. This NPDC<sub>1</sub> (Figure 24) improved the best *PDC-i* footage in this application by 63%. Footage and ROP comparisons, to the offset *PDC-i* runs are presented in (Table 7).

The cases discussed above, are directional sidetrack wells. From an operational standpoint, the trips are very complicated, risky and time consuming. Drilling costs, which is heavily dependent on the high offshore rig rates, are very high. Being able to stay on bottom, with a durable bit, at a competitive ROP is critical to the success of the operation. NPDC bits continue to do very well in this challenging application.

#### Field Case #3 – Wyoming

An 8-1/2" bit (NPDC<sub>2</sub>) was developed for a challenging application in Wyoming. The target section consisted of the

hard and abrasive Woodside, Dinwoody and Phosphoria formations, with unconfined compressive strengths in excess of 25kpsi. This interval had been drilled with insert and impregnated diamond bits (Ti) on previous wells. NPDC<sub>2</sub> tripled the ROP of the offset impregnated bit, at a comparable footage (Table 8), and was still pulled in a much better dull condition (Figure 25).

#### Conclusions

- The performances of PDC bits, in hard and abrasive formations, have usually been poor and inconsistent.
- The industry usually defaults to impregnated and Roller Cone bits, which have ROP and longevity limitations respectively.
- A new generation PDC bit (NPDC), has been developed, which addresses the ROP and longevity issues of impregnated and roller cone bits.
- NPDC has a unique cutting structure and exhibits specific functional characteristics, especially in hard and abrasive formations.
- High performance PDC cutters must go through the following developmental stages – interface analysis, materials research, sintering technology.
- Specialized high abrasion PDC cutters have been developed to complement NPDC's performance in abrasive formations.
- NPDC bits, fitted with the high abrasion PDC cutters, are effective in abrasive formations, even under high RPM drilling conditions.
- NPDC bits are improving operational efficiency and reducing drilling costs in hard and abrasive formations.

#### Nomenclature

PDC	-	Polycrystalline Diamond Compact
RC	-	Roller Cone
ID	-	Impregnated Diamond
ROP	-	Rate of Penetration
fph	-	Feet per hour
BHA	-	Bottom Hole Assembly
PDM	-	Positive Displacement Motor
WOB	-	Weight On Bit
RPM	-	Revolutions Per Minute
Av	-	Axial Diamond Volume
Rv	-	Radial Diamond Volume
IADC	-	International Association of Drilling Contractors
HP/HT	-	High Pressure/High Pressure
PDC-A	-	PDC bit – Type A
NPDC	-	Hard and abrasive formation PDC bit
Vvr	-	Void volume ratio
Fv	-	Face volume
JSA	-	Junk slot area
Ø <sub>bh</sub>	-	Diameter of PDC cutters with high back rake
Ø <sub>bl</sub>	-	Diameter of PDC cutters with low back rake
NPDC <sub>1</sub>	-	6" Hard and Abrasive formation PDC bit
NPDC <sub>2</sub>	-	8-1/2" Hard and abrasive formation PDC bit
PDC-i	-	PDC with impregnated back-up material
Ti	-	Impregnated diamond bit
BSS	-	Berea Sandstone
SWG	-	Sierra white granite



### Acknowledgement

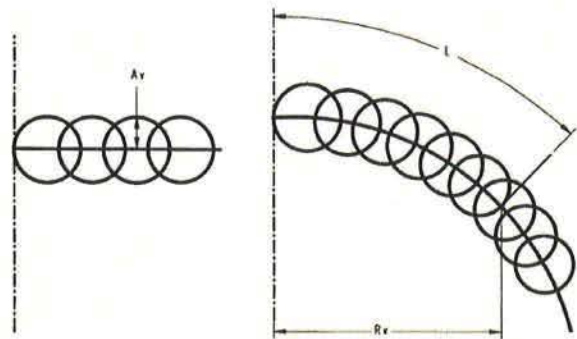
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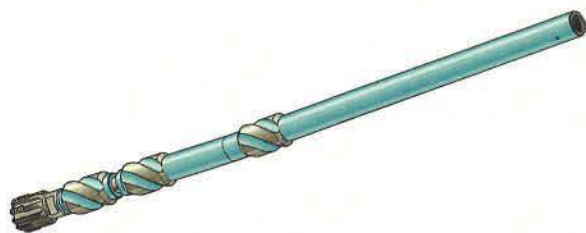
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**Figure 1** – Heavy set PDC bit with small cutters, high blade and cutter counts.



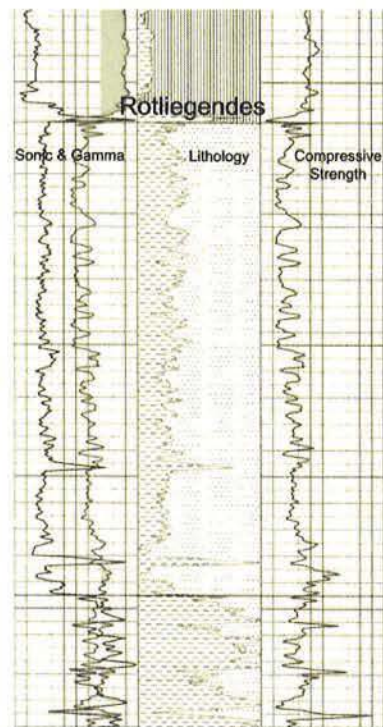
**Figure 2** – Depiction of Axial ( $A_v$ ) and Radial ( $R_v$ ) diamond distributions of a PDC bit. These durability characteristics must both be maximized to improve PDC bit performance in hard and abrasive formations.



**Figure 3** – Turbo-drill usually used with impregnated diamond bits in hard and abrasive bits. These tools, with operational rotary speeds in excess of 800 rpm, have much higher MTBF values, especially when used in HP/HT environments.



**Figure 4** – Geared turbo-drill, currently in development to offer reduced rotary speeds (less than 300rpm), lower operational pressure drops and higher torque values.



**Figure 5** – Geologic description of Rotliegendes formation, showing sandstone content and hardness.



**Figure 6** – 6" bit (PDC-A) used successfully with turbo-drills, in the medium hard and abrasive Rotliegendes formation, in Southern North Sea.





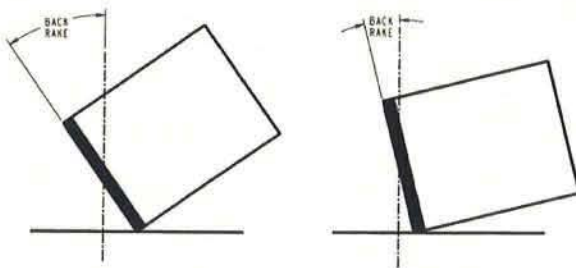
**Figure 7** – Dull Picture of PDC-A after a successful run in the Rotliegendes formation on a turbo-drill.



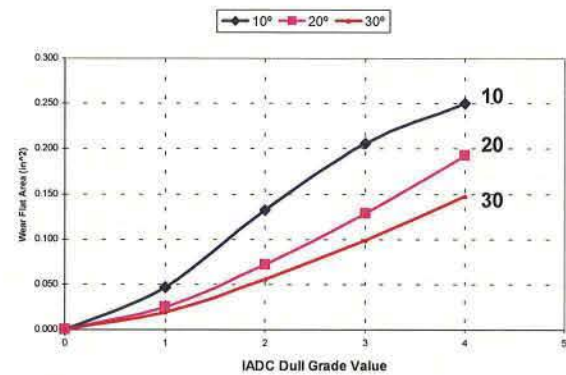
**Figure 10** – Side view of NPDC bit, showing alternate orientation of different size cutters with different back rakes along a blade.



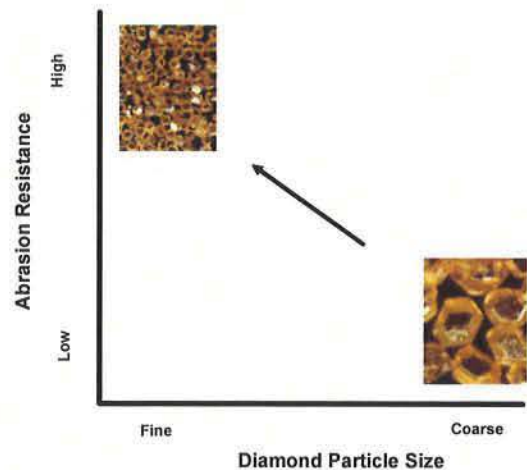
**Figure 8** – PDC bit with maximized hydraulics performance parameter- *open face volume, junk slot area and void volume ratio* - for efficient cleaning and high penetration rates.



**Figure 9** – PDC cutters orientated at different back rake angles.

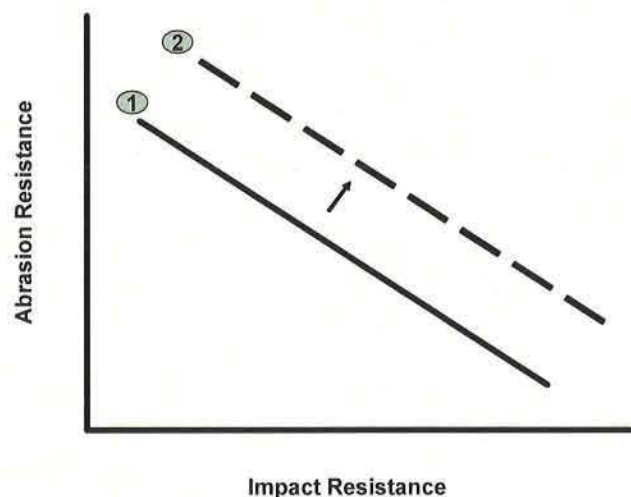


**Figure 11** – Graph showing wear flat size on a cutter as a function of its back rake angle. Wear flats are measure at standard IADC dull grade values.



**Figure 12** – Effect of diamond particle size on abrasion resistance, when all other factors are kept the same. Fine grains have higher abrasion resistance and lower impact resistance.

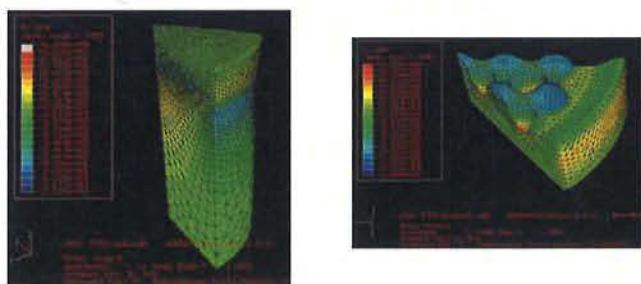




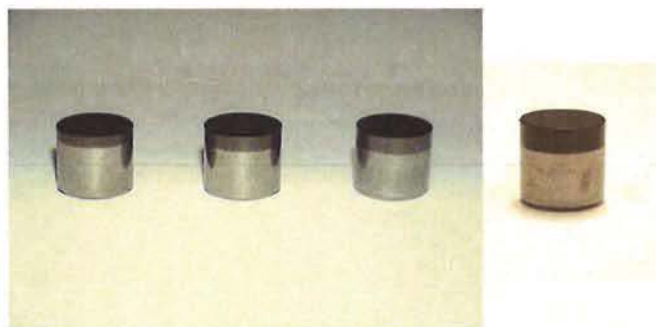
**Figure 13** – Effect of multi-modal diamond table technology on the impact and abrasion characteristics of PDC cutters.



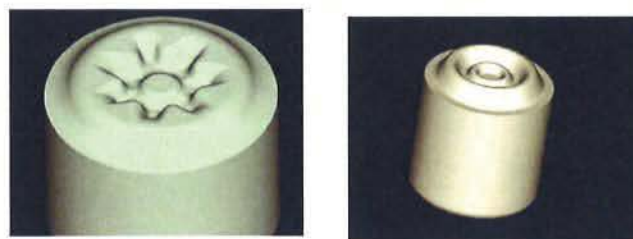
**Figure 14** – Evolution of tungsten carbide interface development. This iterative process helps reduce the stresses in a PDC cutter, thereby improving resistance to chipping and/or spalling.



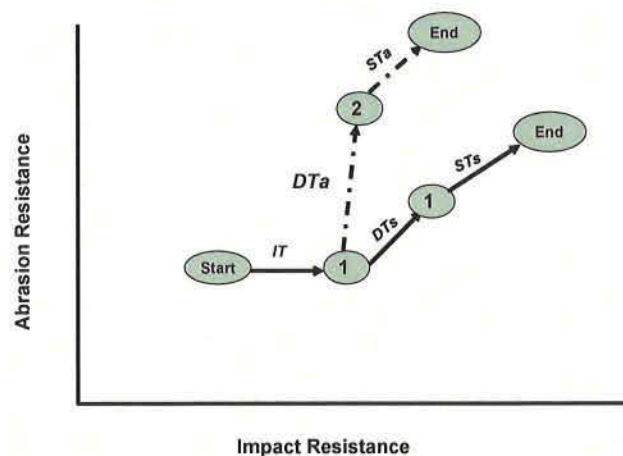
**Figure 15** – Finite element Analysis (FEA), of tungsten carbide interface and diamond table, aimed at reducing damaging stresses, especially tensile.



**Figure 16** – PDC Cutters with Different Diamond table thicknesses, due to variations in their tungsten carbide interface.



**Figure 17** – Different tungsten carbide interfaces, after elaborate FEA modeling.



**Figure 18** – Diagram showing effects of the different PDC development stages – interface (IT), Diamond (DT) and Sintering (ST) technologies - on impact and abrasion resistance. Two developmental paths – standard (s) and high abrasion (a) are shown.

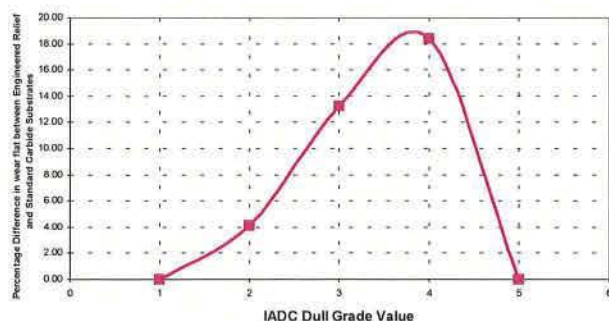




**Figure 19** – PDC cutter with engineered relief in tungsten carbide substrate.



**Figure 20** – PDC bit with relieved tungsten carbide substrate cutters after field run in abrasive formation. This specialized geometry reduces wear flat area, required WOB, and minimizes torque and heat checking.



**Figure 21** – Graph showing % difference in wear flat area comparison between PDC cutters with and without specialized relief in tungsten carbide. Relieved cutters have reduced wear flat areas at equal IADC dull grades.



**Figure 22** – Laboratory set-up used in testing specialized high abrasion cutters (PDC-A) and impregnated segments (IS). Samples were tested on Sierra white granite and Berrea Sandstone.



**Figure 23** – Representative wear flat sizes generated on impregnated segments (IS) and specialized PDC cutters (PDC-A) during abrasion tests at identical conditions.



**Figure 24** – Dull picture of 6" NPDC<sub>1</sub>, used in the hard, abrasive and conglomerate infested Hemlock formation in Alaska.





**Figure 25** – Dull Picture 8-1/2" NPDC<sub>2</sub>, used in the Wyoming application to drill the Woodside, Dinwoody and Phosphoria formations.

Bit Type	ROP (ft/hr)	Footage
<b>PDC-A</b>	<b>31.6</b>	<b>4487</b>
Impreg - Type A	42.3	2368
Impreg - Type B	40.8	3000
Impreg - Type C	42	1383
Natural Diamond - Type A	23.6	3289
Natural Diamond - Type B	29.7	616
Natural Diamond - Type C	36.7	1164

**Table 1** – Comparison of PDC-A performance to impregnated and natural diamond bits in the Rotliegendes formation in Southern North Sea. All runs were with *turbo-drills*, in lateral sections of directional wells.

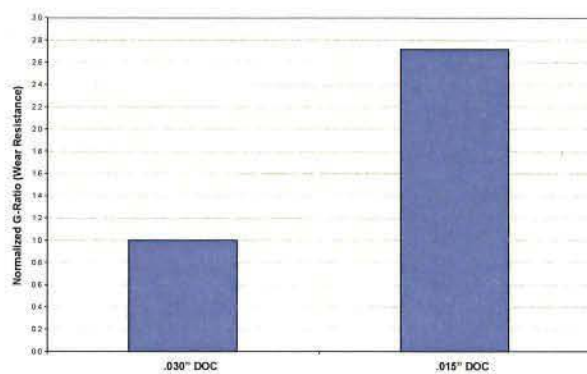
Evaluation Parameters			
	WOB	10klbs	
	RPM	120rpm	
	Formation	Carthage Limestone	
	Rock Hardness	18kpsi	
Bit Type	ROP (ft/hr)	%Change (ROP)	Torque (ft-lbs)
Standard	30	N/A	941
NPDC	19.7	-34	656
NPDC-h	17.2	-43	587

**Table 2** – Analytical comparison - ROP and Torque – at identical conditions between NPDC, standard bit (PDCs) and bit with back rakes (PDCh) equal to that of high back rakes on NPDC. Similar rock properties and operational conditions were used in the simulation.

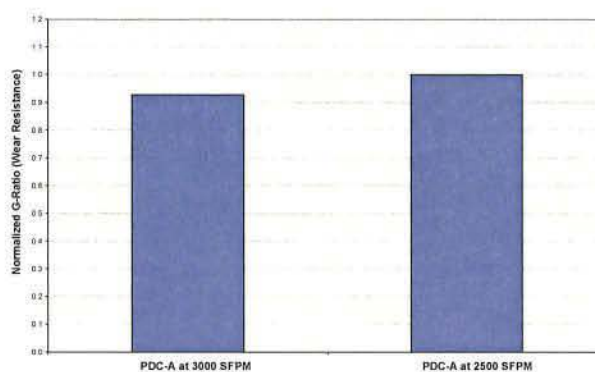
Laboratory Test Conditions	
Rock Types	Sierra White Granite & Barrea Sandstone
Surface Feet Per Minute (SFPm)	2500 and 3000
Depth of Cut (DOC)	0.015" and 0.030"
Feed Rate	0.0011 inches
Coolant Type	Bio 500
Test Pieces:	High Abrasion PDC Cutters
	Impregnated Diamond Segments

**Table 3** – Laboratory conditions and test conditions used in the analysis of high abrasion cutters (PDC-A) and impregnated segments (IS).



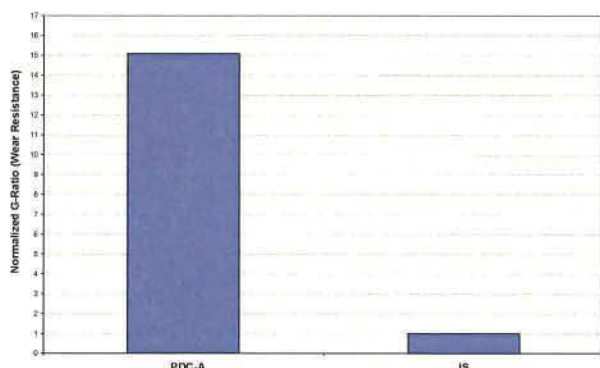


4 (a)

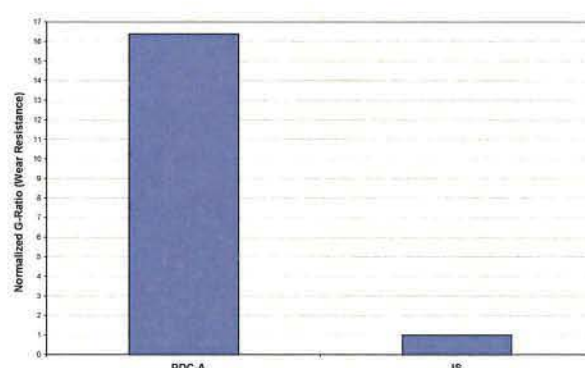


4 (b)

**Table 4** – Effect of DOC on abrasion resistance of IS in BSS at similar test conditions and 3000 sfpm (4a). Comparison of PDC-A abrasion performance in Sierra white Granite at different speeds, 2500 and 3000 sfpm is shown in also (4b).



5 (a)



5 (b)

**Table 5** – Comparison of abrasion resistance between high abrasion cutter (PDC-A) and impregnated segment (IS) in Sierra white granite at 2500 SFPM (1200 rpm) and 3000 SFPM (1500 rpm). High G-Ratio values denote higher abrasion resistance.

Well Name	Bit Type	Depth Out	ROP (ft/hr)	Footage
<b>1</b>	<b>NPDC1</b>	<b>13300</b>	11.5	<b>615</b>
2	PDC-i	11494	8.2	312
3	PDC-i	11840	9	346

**Table 6** – Comparison of *NPDC1* performance to *PDC-i* in hard, abrasive and conglomerate infested Hemlock formation in Alaska.

Well Name	Bit Type	Depth Out (ft)	ROP (ft/hr)	Footage
<b>A</b>	<b>NPDC2</b>	<b>11892</b>	<b>14.2</b>	<b>952</b>
B	PDC-i	11080	8.2	431
C	PDC-i	11290	18.7	585
D	PDC-i	11494	8.2	312
E	PDC-i	11840	9	346
F	PDC-i	12044	17	332
G	PDC-i	12168	7.8	310

**Table 7** – Comparison of *NPDC1* performance to *PDC-i* in hard abrasive and conglomerate infested Hemlock formation in Alaska (Second group of offsets).

Well Name	Bit Type	Depth In	Footage	ROP (ft/hr)
<b>X</b>	<b>NPDC2</b>	<b>15012</b>	<b>905</b>	<b>13.3</b>
Y	Impregnated Bit	15216	1078	4.8

**Table 8** – Comparison of *NPDC2* performance to *Ti* in hard and abrasive Dinwoody, Woodside and Phosphoria formations in Wyoming.