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Innovative Design Processes and Technologies Improve PDC Bit Performance in Harsh Drilling Environments

G. Mensa-Wilmot and B. Mikhail, Varel Intl.; and M. Al-Saeedi, M. Sounderrajan, D. Al-Enezi, and M. Al-Khaldi, Kuwait Oil Co.

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Abstract

PDC bits are still confronted with performance challenges, especially in hard and/or abrasive formations. In most instances, the bit development or selection process compromises ROP for durability or vice versa. These solutions do not create the types of conditions needed to ensure the expected *measurable* gains in performance. As such effective product development, which targets the ROP/durability relationship, based on the performance optimization requirements of different applications, must be sought.

This paper will discuss field proven design processes and technologies, which have successfully been used to improve PDC bit performance in harsh drilling environments. The importance and contributions of bit stabilization in this effort, as well as its effects on ROP and durability, will be discussed.

As part of the product development processes that will be presented in this paper, drilling efficiency (DE) will also be discussed. In addition, the effect and influences of bit durability on drilling efficiency will be presented. Field data showing the positive impact of the new process on PDC bit performance, especially in hard and/or abrasive formations, will also be presented.

Background

As performance qualifiers (*PQ*), ROP and bit durability (BD) have the biggest effects on drilling efficiency and operational costs. In this regard, both ROP and BD must be improved, in order to achieve substantial and measurable improvements in drilling performance. This requirement, which is more critical in hard and/or abrasive formations, is hardly achieved.

This situation is primarily due to the types of solutions used¹, as well as the types of compromises they present. Bit features, believed to have influences on ROP² and durability, include the following - cutter size, back rake, cutter count, and blade count. When all other design features are kept constant, these features cause strong inverse relationships between ROP and durability (**Figure 1a–d**). In addition some of the features, such as cutter size and cutter count are dependent on each other, and exhibit an inverse relationship (**Figure 2**). As mentioned in this section, these solutions do not yield the types of improvements needed due to the relationships and types of effects they have on ROP and BD.

Bit stabilization^{3,4}, achieved through the effective management, control and prediction of bit behavior, establishes the *appropriate* medium needed for ROP and BD improvement. Stabilization minimizes pre-mature PDC cutter failure (**Figure 3**), due to reduced impact loads, thereby enhancing BD. In addition, stabilization ensures efficient use of available operational parameters (RPM and WOB) for ROP maximization. Consequently, stabilization establishes the necessary and sufficient conditions needed to improve both ROP and BD.

The recognition of stabilization's effects on ROP, DB and overall bit performance, has not translated into an acceptance of its achievement methodology. ROP and/or BD (needed to improve bit performance) cannot be compromised to achieve bit stabilization. Certain bit features and/or technologies, that are intended to improve bit stabilization, have negative effects on ROP and BD, and end up not having the expected effects, especially in hard and/or abrasive formations.

The low depth of cut (LDOC) or managed depth of cut (MDOC) concept (**Figure 4**), which aims to enhance stabilization, by making bits passive, compromises both ROP and BD. In such deployments, the blade tops of PDC bits are raised to heights that are very close to the cutter tip. ROP potential is severely compromised, because the cutters can only engage the formation to a depth that is equivalent to the exposure differential between the cutter tip and the blade top (**Figure 5**). In addition, this type of deployment also comprises BD. Cutter exposure, usually dependent on cutter size (**Figure 6**), dictates the amount of diamond that can be used before blade tops come into contact with the formation being drilled.

Due to the reduced cutter exposures of MDOC bits, such bits are only able to use a limited portion of the available diamond. In abrasive and/or hard formations, as well as high RPM applications, minimal cutter wear brings the blade top into contact with the formation. In these instances, the reduced cutter exposure (useable diamond) of MDOC type bits compromises BD.

A second deployment, which is usually used to improve BD, is the back-up blade feature (**Figure 7**). In this instance, BD is assumed to be dependent on cutter count, and so the intent is diamond content maximization. Such an approach assumes that BD is a physical property that can be judged from the appearance of a bit. However, BD is a functional property which depends on ROP and stabilization. The only certainty, resulting from an increased cutter count, is reduced ROP. With the increased cutter count, bits with back-up blades experience rapid ROP decays with minimal cutter wear⁵. The total wear flat area (**Figure 8**), due to the increased cutter count, is very high even with minimal wear. In addition, nozzle layout aimed at ensuring efficient cuttings evacuation tends to be compromised (**Figure 9**). These situations compromise ROP in hard and/or abrasive formations (wear flats), and also in soft formations (nozzle layout and cleaning).

As a result of the above discussions, processes and/or technologies aimed at improving PDC bit performance must focus on effective design analysis and behavior predictions. As explained, MDOC and back-up blades compromise the ROP/BD relationship, the very condition that their use was intended to improve.

An innovative design process, which achieves the conditions identified for ROP and BD improvement, will be discussed in this paper. Coupled with new developments in PDC cutter technology, the positive effects of the processes on PDC bit performance will be presented. Field performances will also be discussed and supported with appropriate data.

Drilling Efficiency: ROP and BD Discussion

Drilling efficiency (DE) has primarily been used to categorize bits, from an ROP perspective^{6,7}. DE is usually defined as the energy required by a bit to fail or dislocate a unit volume of rock. From this standpoint, bits are classified as being efficient when their energy requirements are low. However, it must be noted, that this discussion makes no mention of BD.

From a field operations perspective, ROP can be classified into two categories – *instantaneous (IR)* and *average (AR)*. IR is measured at discrete times or depths, and represents a bit's advancement per unit time in that instance. On the other hand, AR denotes bit advancement in unit time, and is measured over the total interval drilled or total time spent in the hole.

IR values are comparatively high in soft formations, or at the commencement of a run, when the bit is usually in good condition.

AR has a strong dependence on *IR, formation hardness, bit behavior, interval length and time spent in hole*. The

relationship between IR and AR can be summarized as follows:

- High IR values can result in high AR values, when the high IR values are sustained over long periods of time or over long intervals.
- Decaying IR values (which are initially high) will result in low AR values.

AR is influenced by BD, due to the interval and/or time effect. Bits must have good BD characteristics, in order to achieve and sustain high IR values over long periods of time or distance. PDC cutter deterioration, as a result of impact damage and/or wear, must be minimized in order to maintain high IR values – *which will then yield high AR values*.

Since bits are required to drill specific intervals, usually “shoe to shoe”, and knowing the effect of BD on AR, a new definition is thus needed for DE. As such, a bit is said to exhibit effective DE characteristics when it achieves high IR values, and establishes the conditions needed for AR maximization over a specified drilling interval.

The processes and technologies to be described in this paper stem from this new DE definition.

Application Description and Project Challenges

A deep drilling project, operated by a major operator in Kuwait, requires the drilling of a challenging 16” hole. The interval, which consists of limestone, sandstone, siltstone, dolomite and anhydrite, starts from the top of the Ratawi limestone formation and ends in the Hith anhydrite formation. Unconfined compressive strength averages 25kpsi, with peak values reaching 35kpsi. The section's high level of heterogeneity, coupled with the application's large hole diameter, has presented performance challenges, even for roller cone bits – *short and slow runs*. In addition, there are gross formation drillability differences across the different fields, which further complicates the poor performance issues. As such, bit performances had been poor and inconsistent. On average, 6 roller cone (RC) bits were typically used to drill this section, at an average ROP of 3.9fph (**Table 1**). A representative lithological description of the mentioned 16” application is shown in (**Figure 10**).

After several meetings and discussions with the operator, a drilling performance improvement task force (PTF) was created and challenged with the following issues/questions:

1. Can a PDC bit be successfully developed for the 16” application
2. Can the section be drilled with a single PDC bit, thereby eliminating the numerous roller cone bit trips
3. Can PDC bits establish performance consistency across the different fields
4. Considering the RC bit performances, what are the likely ROP expectations for the PDC bits

Notable Performance – First Successful PDC Bit

It must be mentioned, that a 16” PDC bit run in Northern Kuwait had achieved good results. This specific PDC bit had

12 blades and was designed with 16mm and 13mm cutters (**Figure 11**). Two of the mentioned PDC bits drilled the intended section. Although the two PDC bit runs were deemed successful (**Table 2**), the issue of performance consistency, resulting from the formation drillability differences across the various fields, still posed a serious challenge. In addition, the PTF had also concluded that the 16" section could be drilled with a single PDC bit, and at a much higher ROP. It is worth noting, that other PDC bits developed by other manufacturers have also gained limited success in this application (as per the PTF recommendations). However, and as will be discussed, the operator's commitment to the PTF's recommendations necessitated the development of application specific and effectively engineered products.

New Product Development

The product development procedure went through two distinct phases. The first part focused on the design methodology and evaluation processes. This was intended to characterize the bit's behavior, so as to predict overall performance in the formations to be drilled (using appropriate field mechanical and geologic data). In addition, sensitivity analyses that detailed the bit's response to different operational conditions (WOB and RPM) were performed. These evaluations were done using bottom hole assemblies (BHAs) that are commonly used in the different fields.

The design and product analysis processes described above were intended to improve DE. In addition, the evaluations sought to minimize bit vibrations, so as to reduce their negative effects on ROP and BD, without resorting to compromising solutions such as LDOC and back-up blades.

The second part of the process focused on the development of application specific PDC cutters. Based on the intended performance expectations, specifically the durability requirements, it was evident that specialized PDC cutters were needed for the application. The cutters had to be developed to minimize wear initiation, without compromising impact damage. Considering the project's ROP expectations, and the resulting loading conditions, these cutters had to exhibit reduced chippage, spalling and delamination tendencies. In addition, and based on the interval length and effects of hole size on wear initiation, the PDC cutters had to exhibit superior abrasion and thermal resistance characteristics.

This effort was aimed at minimizing PDC cutter deterioration, resulting from either impact damage or wear, so as to improve bit durability. In such a scenario, the PDC cutters will stay sharper for longer periods, thereby improving BD, AR and overall bit performance.

Design Process

PDC bit design has historically been done through an iterative process. In some instances, the bits are tested in the laboratory, under controlled operational conditions and in specific rock samples, after which design modifications are subsequently made. Obviously, laboratory testing serves as the most effective approach to bit design verification and performance monitoring. However, laboratory testing of all

design modifications, various bit sizes, different bit types, rock samples and operational environments will be highly time consuming and exorbitantly expensive.

In most situations, assumptions are made in the design phase that point to how a specific bit design will perform or behave in field operations. The bit is then field tested to verify the assumptions made, based on a defined set of performance expectations. From the evaluations of the field data, design modifications are then made to the bit to further improve its performance.

This iterative process (**Figure 12**) continues, until the product under development is deemed optimized for the application. In addition to the process's exorbitant cost, the associated time "from initiation to completion" is also very long. In some instances, drilling projects come to their finality before the developmental process produces the "supposed" optimized bit. From an operator's perspective, this situation is unacceptable, as the expected benefits, from the invested resources and time, may NOT be gained.

Based on the above realizations, the PTF used a "middle ground" approach for the project. The intent was to shorten the bit development cycle, without compromising the positive effects of laboratory and field tests in bit development. In this regard, an elaborate laboratory testing program, which had been on-going, was expanded and made more comprehensive. This enabled the development of processes that were subsequently used to model bit behavior and performance. Specific analytical algorithms were also developed and used, as part of the evaluation process.

Input Data and Conditions

For the process to be effective, the following inputs - drilling environment, rock type, rock properties and operational parameters - must be accurately described. In particular, the use of *cohesion* and *internal friction angle* values has shown to be more accurate, in the characterization of rock mechanical properties and behavior. In this regard, lithology type and UCS are used as inputs to determine cohesion and internal friction angle. In addition, friction values at the cutter rock interface, drilling fluid density, and the well bore pressure environment are also used as inputs in the evaluation process.

Material properties of PDC cutters, (tungsten carbide and diamond) as well as the thermal properties of the rocks to be drilled are also used as inputs in the analysis.

Performance sensitivity analysis, using different ranges of operational parameters (consistent with offset bit runs and BHA design) were also performed. The inputs used to analyze and predict bit performance is shown in (**Figure 13**).

Bit Development and Analysis: PDC- A

As a start to the project, and considering the performances and dull grades of the offset bits in the different fields, a new bit was developed. This bit had a medium parabolic profile, with 8 blades, 12 nozzles, and 16mm cutters (**Figure 14**). Using the bit's design file (profile, cutter sizes, cutter counts, back

rake, side rake and cutter layout), and the input data files described earlier, the bit's behavior was modeled to evaluate its stabilization characteristics. The loads, work, and wear rates were also analyzed to determine the bit's durability and ROP characteristics.

Loads: The normal or penetrating loads on the PDC cutters, at one of the evaluation conditions described earlier, is shown in (Figure 15). The highest loads, which were observed in the center of the bit, were compared to loads on similar size bits that had been evaluated under comparable conditions. The intent was to verify if PDC-A's loads posed any challenges to cutter durability, from an impact resistance standpoint. Based on findings from the comparisons, the cutter layout and some design parameters were modified in certain regions of the bit.

Work Rate: As with the cutter loads, the work rate values of the cutters were also analyzed (Figure 16). The intent was to identify if there were any weak areas or regions along the bit's profile (similar criteria as that used for the load analysis). From a work rate analysis perspective, no weak areas/regions were identified on the bit.

Wear Rate: The wear rates on the cutters were also analyzed (Figure 17). Considering the material properties of the cutters, as well as that of the rock to be drilled, the effects of the loads and work rates on PDC cutter wear (initiation and growth) was also analyzed. This evaluation also considered the effects of downhole conditions on drilling performance. As in the previous evaluations, the results were compared to similar size bits that had been evaluated under comparable conditions and in similar applications. The intent was to ensure the absence of weak areas/regions, which could either initiate and/or accelerate wear. Based on the results of the evaluations, modifications were made to improve the bit's durability.

Performance Analysis: PDC-A

Following its elaborate development process, PDC-A was used in the Rawdhatain field of Northern Kuwait. In this field, the benchmark PDC bit had drilled the 16" section (2148ft) at an average ROP of 9fph. PDC-A drilled the same section (2150ft) at an average ROP of 11.9fph. PDC-A's performance represented a 32% increase in ROP, over that of the benchmark bit. The comparison data (Table 3), as well as the dull condition of PDC-A is shown in (Figure 18).

PDC-A established a substantial performance improvement on its first run. However, considering its dull condition, and based on the need for constant performance improvement, the project team decided to develop a more aggressive bit. This new bit was expected to achieve a higher ROP than that achieved by PDC-A, without compromises to the established durability and stability characteristics.

To achieve these objectives, certain developmental and performance conditions (to be discussed later) had to be achieved. In addition, PDC cutter development and

performance also had to be re-evaluated and improved.

PDC Cutter Development

Abrasion and impact resistance properties dictate PDC cutter performance. Traditionally, these characteristics have exhibited an inverse⁸ relationship (Figure 19). Recent technological advancements have broken the dependence of impact and abrasion resistance on diamond grain size. In addition, the inverse relationship between impact and abrasion resistance has also been nullified. The PDC cutter development process was intended to minimize cutter deterioration, from a wear and/or impact perspective. Abrasion resistance had to be maximized, without compromising impact characteristics. To achieve these objectives, the developmental process had to go through the following stages:

Carbide Interface Geometry (CIG) Optimization: PDC cutters with high residual stresses, in the diamond table and at the tungsten carbide/diamond table interface, are susceptible to impact damage. To minimize this form of damage, residual stresses (axial, radial and hoop) in the PDC cutter had to be minimized. In addition the stress gradients, which depict how transitions from tensile to compressional loads occur or vice versa, also had to be minimized. Finite element analysis (FEA) was used to evaluate and reduce the residual stresses at the carbide interface (Figure 20). The evaluations also served to re-locate the damaging residual stresses away from the periphery of the PDC cutter. Through this process, the PDC cutter's susceptibility to impact damage is drastically minimized.

Materials – Diamond Feed and Tungsten Carbide: In the general sense, the diamond feed used for a cutter determines its impact and/or abrasion characteristics. While coarse grain feeds have been noted to improve impact resistance, finer grain feeds enhance abrasion resistance (Figure 21). Since the PDC cutter was expected to exhibit superior properties in both abrasion and impact resistance, it meant that the diamond feed could not be evaluated as "fine or coarse". In this regard, an improved grain size analysis and selection process was developed. The process enabled the grading and selection of multiple grain sizes, in different percentages. As a result, a wide range of grain sizes, which presents the combined advantages of "fine and coarse" diamond feeds, was selected and analyzed.

This process also ensures high density diamond packing, as the smaller grain sizes are able to fill the voids created around the larger grain sizes. This new diamond feed technology promotes optimization of impact and abrasion resistance properties. Material properties of the tungsten carbide substrate were also optimized to enhance impact and erosion resistance.

Sintering Process: Unique pressure and temperature profiles were also developed for the sintering process. This was done to complement CIG and the diamond feed stock, so

as to achieve the intended impact and abrasion properties of the PDC cutters.

Additional processes were developed to improve the thermal stability of the PDC cutters. In this regard, diamond material loss and/or graphitization, as a result of the elevated heat levels experienced in abrasive and/or hard formations was minimized. PDC cutter deterioration, caused by differential thermal expansion at high heat levels, accelerates wear initiation and growth. Such a situation compromises cutter durability and overall performance. Enhanced thermal stability substantially improves abrasion resistance, thereby minimizing PDC cutter wear.

Bit Development and Analysis: PDC-B

As discussed earlier, the initial run of PDC-A achieved the performance objectives laid out by the PTF. The bit's behavior, response to different operational parameters, and overall performance (ROP, footage and stability) were extremely close to what had been predicted in the design phase.

The biggest disparity occurred between the predicted and actual dull conditions of the bit. As discussed previously, the dull condition of a bit is influenced by several factors including abrasion and impact resistance. These characteristics are also dependent on several other factors. As an example, abrasion resistance depends on diamond material, CIG, sintering protocol, formation hardness and/or abrasiveness, thermal stability, drilling fluid type and cutter cooling rate. Whereas laboratory tests give an indication of cutter behavior, the results are more reliable when used for *relative cutter wear* comparisons. High performance cutters usually show better dull characteristics, than that predicted by bit design models, especially when used in stable bit designs.

Considering the dull condition of PDC-A, and the improvements that had been made in cutter development, new performance objectives were defined by the PTF.

Could a new bit be developed, to exhibit comparable stabilization and durability characteristics as PDC-A, but with a higher ROP potential? As was established at the beginning of the project, the new bit, if developed, had to drill the entire interval and also establish performance consistency across the different fields. The follow-up project was intended to improve ROP over that achieved by PDC-A.

An ROP increase of 20% (over that of PDC-A) was established as the target for the new bit. The new bit (PDC-B) went through the same developmental processes as that used for PDC-A. In this instance, and based on the previously determined load, work, and wear rate analysis of PDC-A, threshold values were developed for the PDC-B.

The establishment of the threshold values was based on the following factors:

- ROP comparisons for PDC-A

- Modeled loading, work and wear rate values of PDC-A
- ROP expectations for PDC-B
 - % increased, compared to PDC-A (20%)
- Anticipated loading, work and wear rate values for PDC-B
 - Based on ROP expectations
- Impact and abrasion resistance comparisons between old and new PDC cutters
 - % gains in impact and abrasion resistance

PDC-B had 7 blades and 10 nozzles. It had a medium parabolic profile and was fitted with 16mm cutters (**Figure 22**). For the same rock types, rock properties, BHA and operating parameters, the load, wear and work rate conditions needed for PDC-B to achieve a 20% over PDC-A were determined. The maximum values of the mentioned parameters were determined and compared to those of PDC-A.

$$\begin{aligned} A_{\max} & (\text{load}_{m-a}, \text{wear}_{m-a} \text{ and } \text{work rate}_{m-a}) \\ B_{\max} & (\text{load}_{m-b}, \text{wear}_{m-b} \text{ and } \text{work rate}_{m-b}) \end{aligned}$$

Where A_{\max} and B_{\max} denote the groups of maximum *load*, *wear* and *work rate* values for PDC-A and PDC-B respectively. Ratios were calculated for the maximum *load*, *wear* and *work rate* values of the two bits as follows:

$$\begin{aligned} K_{\text{load}} &= \text{load}_{m-b} / \text{load}_{m-a} & (1) \\ K_{\text{wear rate}} &= \text{wear}_{m-b} / \text{wear}_{m-a} & (2) \\ K_{\text{work rate}} &= \text{work rate}_{m-b} / \text{work rate}_{m-a} & (3) \end{aligned}$$

The scaling factor used to determine the threshold values was finally determined as follows

$$K_s = \max (K_{\text{load}}, K_{\text{wear rate}}, K_{\text{work rate}}) \quad (4)$$

Considering the requirement to achieve a 20% increase in ROP, K_s has to meet the following condition:

$$K_s \leq 1.2 \quad (5)$$

If the above stipulation (equation 5) was not met, then the design parameters (i.e. profile, back rake, cutting structure etc) had to be modified, and the evaluation processes repeated. PDC-B met all the conditions discussed in this section.

Performance Analysis: PDC-B

PDC-B was used in the Minagish field of West Kuwait. In this field, the benchmark bit had drilled the 16" interval (2491ft) at 8.4fph. PDC-B drilled the required interval (2196 ft) at 18.93 ft per hr. The performance comparison of PDC-B, to that of the benchmark bit, is presented in (**Table 4**). The dull condition of PDC-B, after the record setting run is also shown in (**Figure 23**).

It must be mentioned, that in addition to the elaborate developmental processes used for the PDC-B project, the

improvements in PDC cutters also played an important role. As stated at the beginning of the projects discussed in this paper, bit design technologies must be complemented by effective PDC cutter development.

Conclusions

- To reduce operational costs, measurable performance gains must be achieved, especially in harsh environments.
- Bit stabilization influences ROP and BD
- Certain design features - cutter size, cutter count, blade count and back rake - cause inverse relationships between ROP and durability
- Drilling Efficiency, though measured in terms of ROP, is influenced by bit durability
- Cutter count and cutter size exhibit an inverse relationship
- Design methods, based on low depth of cut (LDOC) and back up cutters, compromise the ROP vs. BD relationship.
- Quantifiable engineering processes, as well as behavior and performance prediction tools, are critical for effective bit development.
- PDC cutter development is critical, and must be used to complement bit design technologies.
- Team oriented projects, which define common goals, will improve PDC bit performance in harsh drilling environments.

Nomenclature

PDC	- Polycrystalline Diamond Compact
ROP	- Rate of Penetration
PQ	- Performance Qualifier
BD	- Bit Durability
RPM	- Revolutions Per Minute
WOB	- Weight on Bit
DE	- Drilling Efficiency
IR	- Instantaneous Rate of Penetration
AR	- Average Rate of Penetration
RC	- Roller cone bit
PTF	- Project Task Force
BHA	- Bottom Hole Assembly
CIG	- Carbide Interface Geometry
PDC-A	- First Generation New PDC bit
PDC-B	- Second Generation New PDC Bit
Load _{m-a}	- Maximum cutter load for PDC-A
Wear rate _{m-a}	- Maximum cutter wear rate of PDC-A
Work rate _{m-a}	- Maximum cutter work rate for PDC-A
Load _{m-b}	- Maximum PDC cutter load for PDC-B
Wear rate _{m-b}	- Maximum cutter wear for PDC-B
Work rate _{m-a}	- Maximum cutter work rate for PDC-B
K _{load}	- Ratio between maximum load values
K _{wear rate}	- Ratio between maximum wear values
K _{work rate}	- Ratio between maximum work rate values
K _s	- Scaling factor used to develop PDC-B
Min	- Minimum value
Max	- Maximum value

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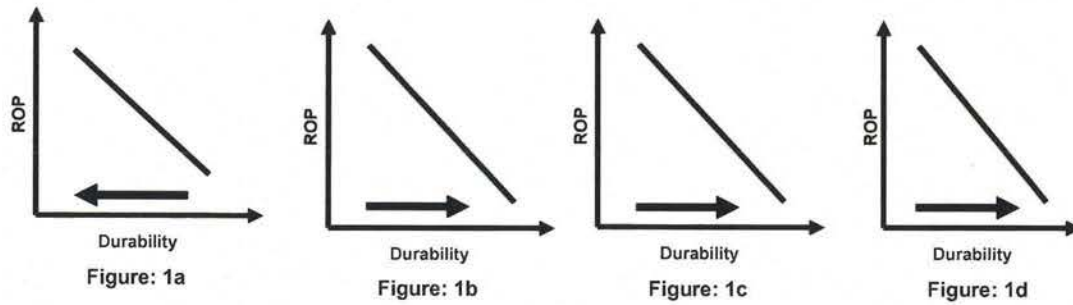


Figure 1: Effects of reduced cutter size (1a), increased back rake (1b), increased blade count (1c) and increased cutter count on the ROP vs. Durability relationship of PDC bits, when all other design features are kept constant in each instance.

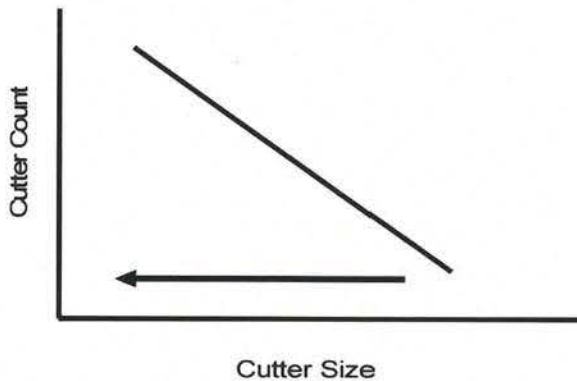


Figure 2: Effect of reduced cutter size on cutter count when design features such as blade count and bit profile are kept constant.



Figure 3: Impact damage to PDC cutters, as a result of severe bit vibrations.



Figure 4: Section of PDC bit designed with low depth of cut (LDOC) feature.



Figure 5: Low depth of cut (LDOC) implementation (left) showing PDC cutter with reduced exposure (X). Dull LDOC bit, which has drilled with blade top (compromising ROP) due to reduced cutter exposure is also shown (right)

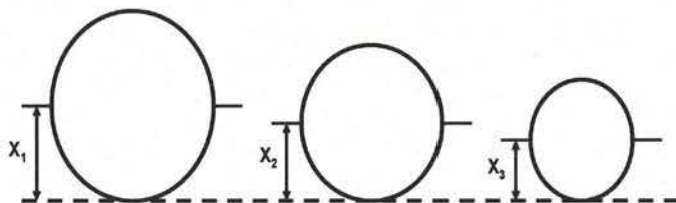


Figure 6: Normal exposures on different size PDC cutters (X_1 , X_2 , X_3). Exposure, represented by half the cutter diameter, establishes the amount of usable diamond and is higher for larger diameter cutters. LDOC designs nullify the higher exposure advantage of large diameter cutters



Figure 7: PDC bit developed with double row cutters



Figure 8: Dull condition of double row PDC bit. The increased blade deployment and resulting higher total cutter count drastically increases total wear flat area, even at low wear conditions. This condition has a huge negative effect on ROP, especially in hard and/or abrasive formations.



Figure 9: Packed cuttings (formation) between cutters on double row (back-up blade) bit. Inability to clean cutters on second row, due to inefficient nozzle layout, compromises bit performance, especially in soft (fast drilling) formations.

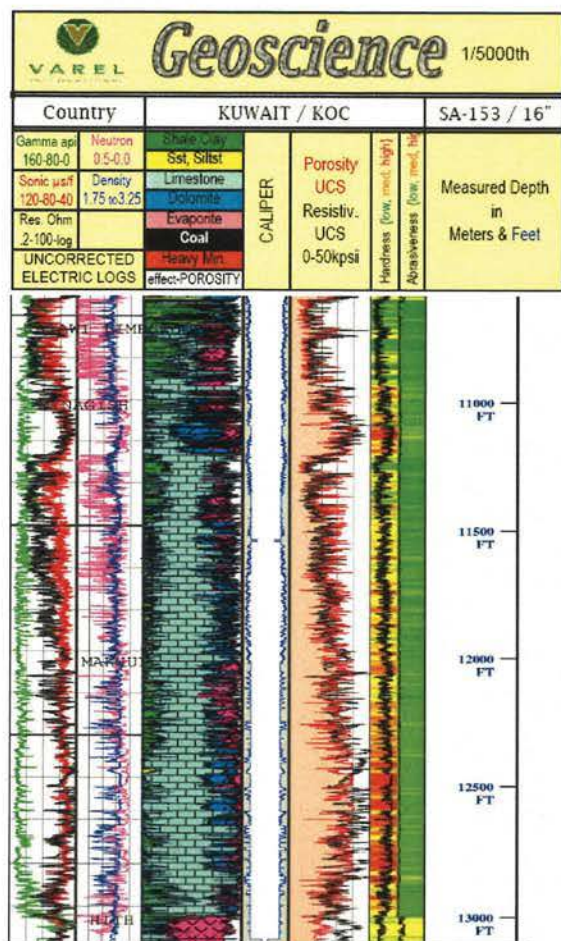


Figure 10: Lithological section of challenging 16" application



Figure 11: 12 bladed 16" PDC bit

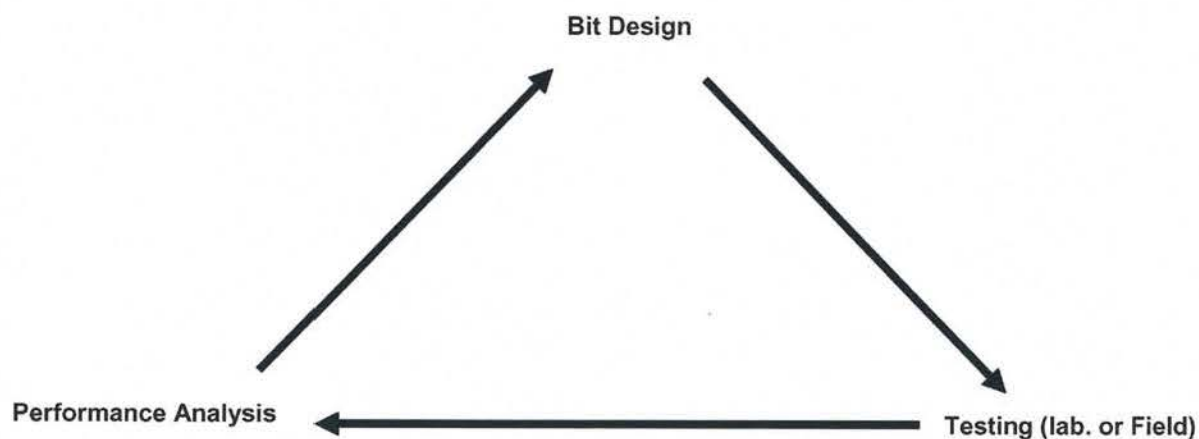


Figure 12: Diagram of Iterative processes used in conventional bit design

Dog Leg (°/30m)		ROP		ROP (m/h)		20.00	
Cutter/Rock Frict. Angle		RPM		150.00			
10.00		ROP min (m/h)		10.00			
Num. Of Iterations (Sections)		ROP max (m/h)		100.00			
10000		# of increment ROP		1			
Mud Pressure (MPa)		Depth		Pressure (MPa)			
1.50		1500.00		= 22.07			
Rock Characteristic		File name					
UCS 30.0000							
IFA 30.00		Cancel					
Cohesion 40.0000		Apply		Apply & Close			

Operating Parameters		
Depth in (m):	1000	Depth out (m): 2000
		Increment: 100
Diamond properties		Carbide properties
Diamond table thickness (mm): 2.00		Down hole conditions
Thermal conductivity (W/mK): 543.00	Thermal conductivity (W/mK): 100.00	Hole temperature (K): 200.00
Specific heat (J/Kg.K): 790.00	Specific heat (J/Kg.K): 230.00	Rock Density (ton/m3): 5.00
Density (ton/m3): 3.50	Density (ton/m3): 15.70	Rock thermal conductivity (W/mK): 3.60
Thermal weakness (MPa/k): 81.43	Thermal weakness (MPa/k): 19.07	Rock specific heat (J/Kg.K): 850.00
Hardness (MPa): 65000.00	Hardness (MPa): 15000.00	Grinding factor: 10.00

Figure 13: Input data files used in bit design analysis, behavior and performance prediction.



Figure 14: Face view of first generation 16" bit (PDC-A) developed with new processes

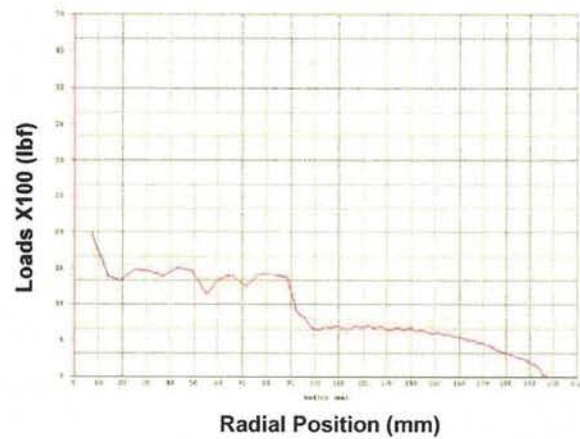


Figure 15: Load analysis by radial position for new generation bit (PDC-A) during design phase.

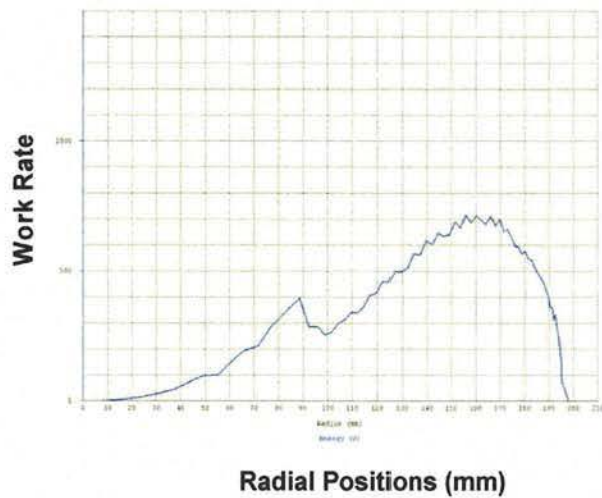


Figure 16: Work rate analysis by radial position for new generation bit (PDC-A) during design phase.

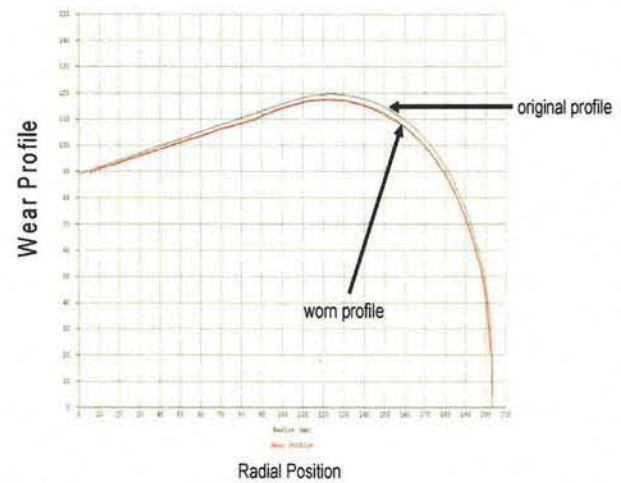


Figure 17: Wear profile analysis (comparison to original cutter tip profile) by radial position for new generation bit (PDC-A) during design phase.



Figure 18: Dull Condition of PDC-A, after record setting run in Rawdhatain field. PDC-A, as shown above and developed with the new processes, achieved all the performance objectives set forth by the PTF.

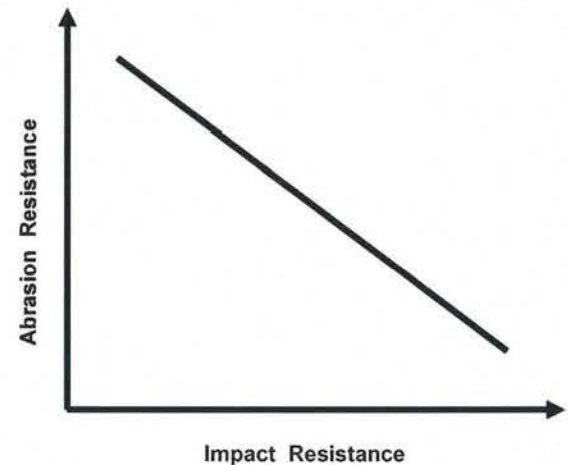


Figure 19: Inverse relationship between impact and abrasion resistance for conventional premium cutters



Figure 20: Carbide interface geometry (CIG) development through FEA analysis. The process is used to enhance impact resistance by reducing damaging residual stresses and their gradients.

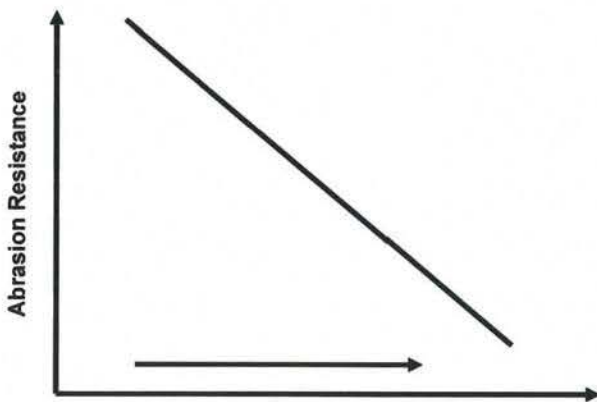


Figure 21: Effect of increasing grain size on the impact and abrasion resistance properties of PDC cutters.



Figure 22: Face view of PDC-B, developed to achieve 20% ROP improvement at comparable durability and stabilization characteristics. Bit behavior was completely analyzed, as per the project's objectives.



Figure 23: Dull condition of PDC-B, after run in West Kuwait (Minagish Field). The bit established a new field record, and performed as predicted, giving credibility to the engineering processes used in its development.

16" Section - North Kuwait					
Bit Type	Depth In (ft)	Interval (ft)	MW (ppg)	ROP (ft/hr)	Dul Grade
RC1	10647	248	13	4.4	N/A
RC2	10895	503	14	4.9	4: 7: BT: G: IN: HR
RC3	11459	300	14	4.7	3: 4: WT: A: IN: HR
RC4	11759	327	14	3.8	4: 5: WT: A: IN: PR
RC5	12086	348	14	3.3	N/A
RC6	12434	332	14.8	2.8	N/A

6 Roller Cone bits were used to drill from 10647ft to 12766ft (2119 ft) at an average ROP of 3.9fph

Table 1: Offset roller cone (RC) bit performances in Challenging 16" hard and abrasive application

16" Section - North Kuwait					
Bit Type	Depth In (ft)	Interval (ft)	MW (ppg)	ROP (ft/hr)	Dul Grade
PDC	10525	1947	12.3	8.5	2: 3: BT: A: IN: WT: BHA
PDC	12472	603	13.3	10.6	0: 1: NO: A: IN: NO: TD

2 PDC bits were used to drill from 10525ft to 13075ft (2550 ft) at an average ROP of 8.9fph

Table 2: Performance data of first successful PDC bits used in challenging 16" hard and abrasive application in Kuwait

North Kuwait - Rawdhatain Field

Bit Type	Depth In (ft)	Interval (ft)	ROP (ft/hr)	Dul Grade
PDC Bit*	11414	2148	9	Only reported as TD
PDC-A	11270	2150	11.9	1: 1: WT: S: X: IN: CT: TD

PDC* was benchmark bit in Rawdhatain field.

PDC* drilled from 11414ft to 13562ft (2148 ft) at an average ROP of 9fph

PDC-A was developed using the new processes and guidelines

PDC-A drilled from 11270ft to 13420ft (2150ft) at an average ROP of 11.9fph

Table 3: Performance comparison in Rawdhatain field. New Process bit (PDC-A) achieved a 32% ROP improvement over that of the benchmark bit (PDC*)

West Kuwait - Minagish Field

Bit Type	Depth In (ft)	Interval (ft)	ROP (ft/hr)	Dul Grade
PDC Bit**	9330	2491	8.37	Only reported as TD
PDC-B	9216	2196	18.93	1: 1: WT: S: X: IN: NO: TD

PDC was benchmark bit in Minagish field.**

PDC* drilled from 9330ft to 11821ft (2491 ft) at an average ROP of 8.9fph

PDC-B was developed using the new processes and guidelines (To Drill 20% faster than PDC-A)

PDC-B drilled from 9216ft to 11412ft (2150ft) at an average ROP of 18.9fph

Table 4: Performance comparison in Minagish field. Second generation newProcess bit (PDC-B) achieved a 126% ROP improvement over that of the benchmark bit (PDC**)