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## Unique PDC Bit Technologies Combine to Consistently Reduce Drilling Time in Interbedded Formations

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### Abstract

Interbedded formations cause difficulty when selecting a drill bit for optimum section performance. Hard stringers require bit features that conflict with those required for softer homogeneous formations. Limited by conventional technology, this culminates in the selection of a bit too heavy set to maximise penetration rates through the soft formation or too light set to drill the hard stringers. This paper describes a unique combination of PDC bit technologies that provide a solution to consistently drill interbedded formations without compromising bit selection. The unconventional design consists of features to maintain high penetration rates in soft formations and the stability and life required to pierce through hard stringers.

The technologies are combined on a steel bit body. The nature of this material allows its fundamental engineering properties to be exploited to produce extreme features that can not be achieved using matrix powder technology. This material is the cornerstone that expands the design and manufacture windows for conventional PDC bit technologies.

Soft formations imply high penetration rates: the technologies developed are a novel hydraulic arrangement, bit face design, cutter size and usable diamond volume. Hard stringers require high stability in order to maintain bit life by preventing premature component failure. Technologies developed are conventional anti-whirl theory, localised cutter placement to extend bit life and an innovative low friction gauge pad that spans two blades and encloses a junkslot.

The case history demonstrates the significant performance improvement that can be achieved through interbedded formations by combining innovative PDC bit technologies. The study examines the development of the 12¼" section in the Tunu Field, Indonesia.

The continual development of the project is discussed including a lighter set variant to complete the same application and the successful translation of the design philosophy into a slimhole program.

### Introduction

Soft formations interbedded with hard stringers create a dilemma when selecting a PDC bit to economically complete a section. The primary objective, particularly for deep hole drilling, is to complete a section in one bit run to prevent loss of time tripping in and out of hole. The selection becomes increasingly difficult when the hard stringers are unpredictably scattered throughout the section.

Impacting a hard stringer with an unsuitable drill bit or drilling parameters can lead to catastrophic failure of components. This can ultimately result in the need to pull out of hole and change the bit or severely impair bit performance for the rest of the section. The worst case for this to occur is at the start of a run when only a short interval has been drilled.

Catastrophic failure through hard stringers may be caused by the initial collision of the cutters on entry or the increased vibration of the shoulder and gauge cutters when leaving the hard rock. A known cause of premature bit failure is bit whirl, the backwards whirling motion of PDC bits. This can be initiated by bit vibration or irregularities in the borehole wall which may cause a component on a bit to grab the formation. This can result in a PDC bit rotating about an axis which is not its design axis, producing bit whirl.

The cutting structure of conventional anti-whirl designs create an imbalance force that is directed onto a low friction area of a bit. The low friction area can not grab the formation so bit whirl can not be initiated. This drilling theory has been used in gun drilling for many years<sup>1</sup>.



The approach taken to provide a solution to drilling soft formations interbedded with hard stringers, is to combine PDC technologies suited for soft formation drilling with those for hard formation drilling.

### Trial Application

The Tunu Field, located in the Mahakam Delta near Balikpapan Indonesia, was identified as an appropriate application. The 12¼" section provided the troublesome interbedded formation.

At the top of the 12¼" section, the lithology consists of soft homogenous sand and claystones interbedded with lignite. Lower down, the formation firms up and consists of medium strength homogenous sandstones and shales. Throughout the section, limestone and dolomite stringers are unpredictably encountered. Their frequency per well can lie between 0 and 6. The limestone stringers are not abrasive, can be up to 2m thick and are much softer than the dolomite stringers. The dolomite stringers have an average thickness of 0.5m and can be described as 'massive'. This means that they have little porosity and are extremely hard.

Typical sonic values for the sandstones, claystones and shales are 100µs/ft decreasing to 80µs/ft; and in the harder stringers, 50-65µs/ft.

Development of the field commenced in 1973. By the mid 1970s, the 12¼" section was drilled with water based mud and roller cone bits. The section required eight to twelve bits which produced an average penetration rate of 9m/hr.

By the mid 1980s, PDC bits and oil based muds were introduced enhancing performance. The section then required three roller cone bits and three PDC bits, increasing the average penetration rate to 10m/hr. By the late 1980s, a total of three to four PDC bits completed the section replacing all roller cone bits.

The bit condition reports from these runs suggested that the dolomitic stringers were proving to be problematic, if not catastrophic, to PDC bits. Cutters were suffering high impact loads resulting in broken, chipped, foliated and lost cutters. On occasion, these failures resulted in bits being rung or cored out, see Figure 1.

To further improve performance more stable bits were required to reduce bit vibration and associated impact damage; the objective being to consistently complete the section in a single run. In the early 1990s two methods were proposed to reduce vibration. Firstly, bit force balancing, which attempts to minimise the lateral component of the resultant force created by the cutting structure. This reduces the force that pushes a section of the bit against a borehole wall. The lower the pushing force, the less likely the bit is to grip the formation, vibrate and initiate whirl. The second method was to develop conventional anti-whirl theory. Both options are still under evaluation, this paper addresses the results achieved by the second.

Many PDC bits have been run in the Tunu Field and it was observed that the steel bodied bits displayed significantly less impact damage than matrix bodied bits. This evidence initiated the development of a steel bodied bit for the application.

Analysis of the bit records indicates that bit balling has proved to be problematic while drilling the soft formations. The cleaning of cuttings from the bit face to the annulus was a required development to decrease the probability of future bit balling.

A typical well profile for the 12¼" hole is a tangent section and a drop into a target. Azimuth remains constant. The bottom hole assembly incorporates a variable gauge stabiliser to enable the selection of a holding or dropping assembly. A rotary drive is used on the majority of wells with an oil based mud system.

### Bit Specification

1. The primary objective when drilling interbedded formations is to consistently reach TD. To do this, the bit must have enough diamond volume to complete the section and not suffer catastrophic failure through the hard stringers. The bit must be able to drill into hard rock with the same parameters as for drilling soft rock with minimal component failure. Technologies to minimise component damage caused by entry into; departure from; or bit whirl through the hard rock must be developed.
2. Bit partial balling is the second most likely reason a section would not be consistently completed. Face cleaning technologies must be developed.
3. To increase the average performance over the entire section, features to improve the penetration rate through the soft formation must be developed.

### Bit Profile

The shape of PDC bit profile can be designed to minimise cutter damage when entering and leaving hard stringers. When entering hard rock, the face cutters are the first to collide and become overloaded as they resist the majority of weight on bit compared to those cutters still in soft formation. The overload condition can be minimised by designing a short profile.

On departure from a hard stringer it is the shoulder and gauge cutters that become overloaded. This overload condition is more damaging than when entering a hard rock, as the gauge cutters are at a higher radii than the face cutters increasing the inertia of the impacts. The effect can be minimised by attempting to prevent the gauge cutters becoming overloaded by designing the profile cone to be the same depth as the profile height, see Figure 2. This ensures that as a bit leaves a hard stringer the weight on bit is more evenly shared between the cone cutters and gauge cutters. The flat cone on the new bit exaggerates this feature.

Profile length greatly effects penetration rate. Longer profiles generally have more cutters reducing weight per cutter and its



respective aggressivity. A short profile has less cutters, increasing the potential for high penetration rates.

The forgiving nature of this profile allows the new bit to enter a hard formation with parameters suitable for soft formation drilling with minimal impact damage expected. It is also suitable for high penetration rates in soft formations.

### Cutter Size

The challenge when drilling any section is to remain on the well profile at the highest penetration rate possible without causing hole problems. Interbedded formations require an increase in the average penetration rate to reduce the total time for a section. The time to drill an interbedded section, like the Tunu Field, is more easily reduced by drilling faster through the soft formations than through the hard stringers, as illustrated in Figure 3.

This philosophy leads to a PDC bit design that can achieve high penetration rates through soft formations with only the stability to prevent component damage through hard stringers.

Large cutters have a proven field record for achieving high penetration rates through soft formations provided that cutter count, blade count, hydraulic arrangement and profile shape are suitable.

As for a conventional design, the bit must be durable enough to complete the section. Taking into account cutter exposure, larger cutters have more usable diamond volume than smaller cutters, see Figure 4. This increases bit durability. The bit durability required is estimated from previous offset and bit condition reports.

### Radial Imbalance Force

It is accepted that bits with larger cutters are more prone to impact damage than smaller cutters especially through harder stringers. A theoretical reason for this is that a lower number of large cutters can be fitted into a given bit than small cutters which increases the impact load per cutter. A cutter failure on a bit with larger cutters is more critical as there is less cutter redundancy.

The selection of larger cutters for interbedded formations demands a stable bit. Rotary drilling facilitates smooth transmission of weight to bit than that achievable in the sliding mode. This is beneficial for the larger cutter size as smooth weight transmission reduces impact loads.

To maintain a high penetration rate, especially towards the end of a run, it is essential to keep the cutters in good condition. Consequently bit stability through the hard stringers is of primary importance.

To reduce the risk of impact failure, vibration and bit whirl must be reduced to a minimum. It has been proven that anti-whirl theory is an effective method of reducing these

detrimental characteristics<sup>1</sup>. Anti-whirl theory consists of accurately positioning PDC cutters to produce an imbalance force<sup>2</sup>. The direction of this force is limited to a small arc on the bit's circumference and continually pushes this area of the bit against the formation, see Figure 5. The continuous contact against the formation reduces downhole vibrations and prevents the bit 'walking' around the hole, i.e. bit whirl.

The rotary mode is beneficial for generation of a consistent imbalance force<sup>1</sup> as a high weight on bit can be smoothly maintained with a limited rotary speed to ensure a large depth of cut. A large depth of cut ensures that an imbalance force with a consistent direction and magnitude is created, (magnitude can be considered to be a percentage of weight on bit).

### Steel Bit Body

Steel bits are inherently tougher than matrix bits and infrequently fail. The strength benefit makes it the immediate body material choice where high shock loads are expected.

Steel is elastic which makes it a suitable body material for the dynamic down hole environment. This property enables the energy from impacts to be transmitted through the cutters and absorbed into the 'elastic' blades. This reduces the impact energy absorbed by the PDC cutters, hence reducing cutter damage. Matrix bodied bits do not have this impact damping property.

Anti-whirl bits require accurate cutter placement to generate the predicted side force at the designed angle. The imbalance force is directly related to depth of cut or cusp size, (see Figure 6 for definition of 'cusp'). Larger cutters imply that larger cusps will generate the imbalance force. As a result, a large cusp is more influential on the resultant force than a small cusp. Therefore, larger cutters require more accurate cutter location than smaller cutters.

A benefit of a steel body is that it can be accurately machined to tight tolerance on CNC (Computer Numerical Control) machining centres. Matrix bits do not offer this accuracy as they go through various heat cycles resulting in high inaccuracies due to bit body shrinkage.

### Low Friction Pad

The radial imbalance force is designed to develop continuous contact between one angular section of the bit and the borehole wall. Intuitively, the section of the bit in constant contact with the borehole wall is more likely to 'grab' the formation than a section that is not. Standard practice with conventional anti-whirl PDC bits is to design the area in constant contact with low friction characteristics to prevent this section 'grabbing' the formation or 'tripping up' over any protrusions in the borehole wall and initiating bit whirl.

The dynamic nature of the down hole drilling environment causes even a smooth drilling bit to drill a slightly oversize



hole. As the cutters wear, the direction of the radial force changes. Furthermore, as a bit drills through the transition between soft formation and a hard stringer the relative cutter loads change. Consequently, the direction of the radial force fluctuates about a mean position. Therefore, the low friction pad must be of sufficient size to accommodate the range of angles expected.

Conventional PDC anti-whirl bits attempt to provide a low friction pad of sufficient size by designing the blade layout so that one of the gauge pads provides sufficient angular coverage. This has limited value as the range of angles required, depending on how oversize the hole is, is at least 90° which is much larger than can be realistically designed on a conventional bit.

To unconventionally increase the angular coverage, the low friction pad was designed to bridge two blades and enclose a junkslot. This considerably increases the angular contact area of the low friction pad<sup>3</sup>. The idea could be developed further by bridging the preceding or following sets of blades. The ultimate development for this idea is to bridge all the blades and provide full 360° contact. The full circumferential contact provides a low friction pad for an imbalance force in any direction which could be the full anti-whirl solution. This arrangement has been proved in the laboratory to reduce vibration and torque considerably compared to conventional gauge designs<sup>4</sup>. This arrangement is suitable for directional mud motor applications as the directing force, to maintain a constant toolface direction, 'travels' around the circumference of the bit. For interbedded formation rotary drilling the imbalance force rotates with the bit, so full 360° contact is not required.

Other conventional features included in the design to ensure that the angular section in contact with the borehole wall has no 'grabbing'/aggressive features are a large leading edge chamfer on the low friction pad. This allows the pad to ride over any protrusions in the borehole wall smoothly. The chamfer size is usually limited on conventional bits as the larger the chamfer, the smaller the pad. The large pad size on the unconventional design allows for a larger chamfer.

The type of gauge protection on the low friction pad is also critical to prevent the grabbing of the formation. The gauge protection must be able to withstand the increased tendency to wear due to the constant contact against the borehole wall. To this end the low friction pad is set with carbide blocks ground to create a smooth surface. Tiles can also be positioned very close together to provide the extra abrasion resistance required due to the constant contact of this area, see Figure 7.

The most common feature incorporated into conventional anti-whirl bits to create a low friction area is to leave the area cutter devoid. This is to prevent any cutter digging into or grabbing the formation and initiating bit whirl.

### Extended Bit Life

The conventional cutter devoid area of anti-whirl bits results in this section of the bit tip profile being lighter set than the rest of the bit which can potentially lead to ring outs.

This problem was overcome by positioning cutters off the bit tip profile in the cutter devoid area. They were positioned off the bit tip profile so that initially they do not contact the formation and so can not grab or dig into the formation and initiate whirl. Towards the end of a bit's life the standard cutters wear which exposes the cutters in the 'cutter devoid' area. This has no detrimental effect to the anti-whirl characteristics of the bit, since as a bit wears, it inherently becomes more stable. Therefore, in later bit life, the benefit of the anti-whirl imbalance force is replaced by the stability benefit of the worn cutters.

The extra cutters positioned off the bit tip profile increase the PDC diamond volume in the cutter devoid area reducing the tendency of the bit ringing out which increases bit life.

### Blade and Hydraulic Design

As the bit is designed to increase penetration rates through the softer formations, bit cleaning becomes more important. To provide adequate cleaning the blade and hydraulic design had to be more effective than conventional bits. To optimise hydraulic performance, the blades and position and orientation of the nozzles were developed in a hydraulic test rig<sup>5</sup>. This was a process of incremental improvement.

The average penetration rate can be improved by increasing the face volume of a PDC bit. One method for increasing the face volume is to increase the blade stand off utilising the strength of the steel body. To complement the high blade stand off a large junkslot area was designed to facilitate removal of cuttings from the bit face to the annulus. These features combined with a proven hydraulic design<sup>6</sup> whereby the blades that generate the most cuttings are cleaned by a cross flow arrangement from two nozzles rather than one, see Figure 8.

Since the large low friction pad bridges two blades the hydraulic design is complicated in this area. For optimum flow generation an enclosed junkslot was machined through the large low friction pad, see Figure 9. This provides access for mud to flow freely from the face of the bit to the annulus or vice-a-versa. For optimum performance, a nozzle was positioned in the enclosed junk slot and configured to direct the flow onto the face of the bit. The flow then combines with the face hydraulics to clean the second most major blade.

### Case History – Tunu J2, Tunu Field, Indonesia

The bit of choice for the section was originally a standard design and then a conventional anti-whirl design. For a direct comparison between the standard, conventional antiwhirl and new bit designs, see Figure 10.



The new bit design initially drilled the sandstones at 120m/hr and claystones at 80m/hr with an optimum rotary speed of 150rpm and 10tonnes weight on bit. As the formation firmed up towards the end of the section the sandstones were drilled at up to 40m/hr and the shales up to 30m/hr. The hard dolomitic stringers were drilled between 0.5 and 1m/hr at a lower rotary speed of 80rpm with 6.5tonnes weight on bit.

In order to stay on the drilling curve, weight on bit and rotary speed were compromised producing a lower penetration rate than that achievable with optimum parameters.

The new bit dull showed no sign of impact damage and each PDC cutter had formed an excellent diamond lip, see Figure 11. The cutters were worn to an IADC grade<sup>7</sup> 2. This implies that the bit was very stable through the hard stringers and had maintained a good cutting structure producing high penetration rates through the softer lithologies.

There was no evidence of heat checking, suggesting that the face hydraulics were cooling the cutters effectively.

The best comparison to illustrate the performance improvement of the new bit over previous designs is to compare the average performance over a period of time. All 12¼" runs in the Tunu Field between June, 1991 and April, 1997 were analysed and the two bits with the most offset information selected for comparison purposes. The first comparison bit is a standard design, with a total of 14 runs; the second, a conventional antiwhirl design, with a total of 42 runs. Both bits were the bit of choice at a particular stage of the Tunu Field development. The new bit has had a total of 20 runs.

The run length and penetration rates are compared in Figures 12 and 13. This comparison shows that the new bit drilled 180% further and 141% faster than the standard bit; and, 68% further and 70% faster than the conventional antiwhirl bit.

### Summary of Case History

Although alternative bit designs such as force balance concepts continue to be evaluated the new bit is now preferred to drill this section. Generally each run is a repeat performance of the first, demonstrating the consistent drilling rates achievable, by maintaining the bit in good condition to the end of the section.

The case history has illustrated that the new bit is capable of consistently drilling the interbedded formations in the Tunu Field, Indonesia. It can dramatically improve penetration rates over conventional anti-whirl bits.

The bit has demonstrated, by its dull condition, that it is also more stable than conventional anti-whirl bits; which in turn are more stable than conventional standard bits without an imbalance force and low friction pad arrangement.

The new bit consistently completes the interval, the primary objective.

### Further Developments

Detailed analysis of information collected from all bit runs indicate that the majority of cutters on each bit are worn only to an IADC grade 2. This suggests that the improved performance gained by the advances in stability could be transferred to a lighter set bit to complete the same section length.

A lighter set bit will offer two benefits. Firstly, a performance improvement since the bit would have less cutters and blades making a more aggressive bit. The bit will have an even higher face volume and junkslot area offering the opportunity to improve the bit cleaning substantially and potentially increase penetration rate.

The second benefit is the increased bit value as the bit will be cost less since it will have fewer cutters and wear more. An ideal bit would be pulled out of hole with the cutters worn to an IADC grade 3 or 4, provided the self sharpening diamond lip was maintained. If this life is acceptable the economics are improved.

At the time of writing this paper a lighter set version with the same design philosophy is being designed and built for field trial. The new version has two fewer blades, a larger low friction pad that encloses two junkslots, a larger junkslot area and fewer cutters.

The new bit dulls indicate that it was extremely stable. This suggests that cutters can be placed in the cutter devoid area without detriment to stability.

The 12¼" project was considered extremely successful. Last year a percentage of the drilling programs in the Tunu Field, Indonesia were redesigned as slimhole projects. Consequently, the 12¼" section was to be drilled in 8½" hole size. An 8½" new bit was designed in an attempt to confirm that the unique combination of PDC technologies described could be successfully transferred to other bit sizes.

At the time of writing, 28 smaller 8½" new bit designs have been field tested and the performance found to match the larger size design.

### Conclusions

1. An unconventional design with a unique combination of PDC technologies can competently drill interbedded formations.
2. The unconventional design is forgiving on entry into and departure from hard stringers, preventing immediate component damage.



3. The new bit dulls exhibit no impact damage. As it has large cutters it suggests that the technologies used to increase stability operate effectively.
4. A steel body is an effective material for combining PDC technologies, improving stability and penetration rate compared to conventional anti-whirl designs.
5. Improved stability through hard stringers enables lighter set designs to replace heavier set designs.
6. The unique combination of PDC technologies can be successfully transferred to other sizes to produce similar performance benefits.

### Acknowledgments

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Figure 1: Ringout experienced in the Tunu Field.

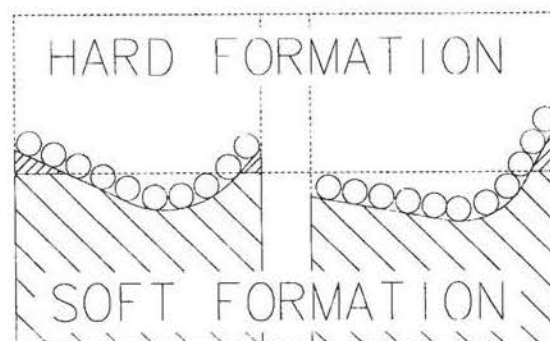


Figure 2: Matched cone and short external profile minimise PDC damage on exiting a hard formation.

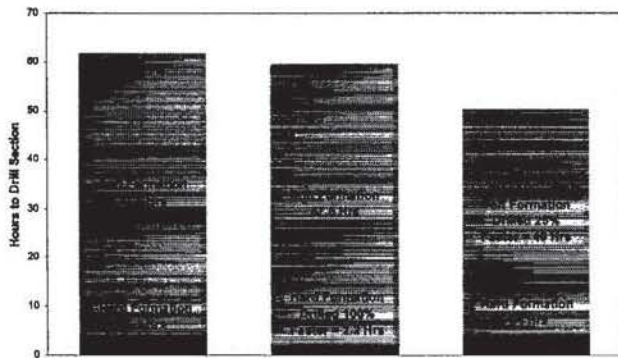


Figure 3: Benefits of improving penetration rates through the soft rather than the hard formation.

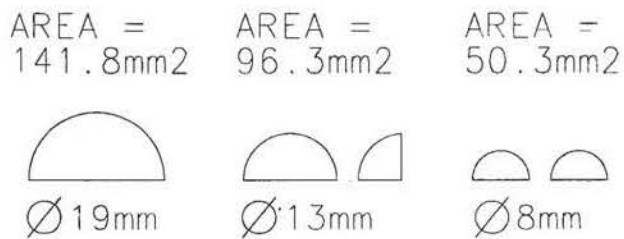


Figure 4: Diamond volume comparison between large and small cutters.

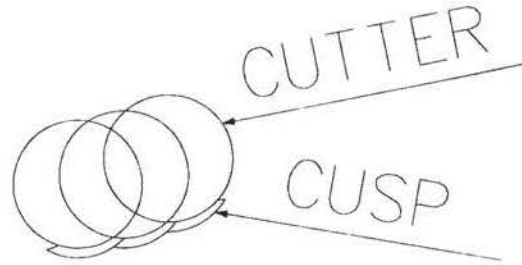


Figure 6: Cusp Definition.

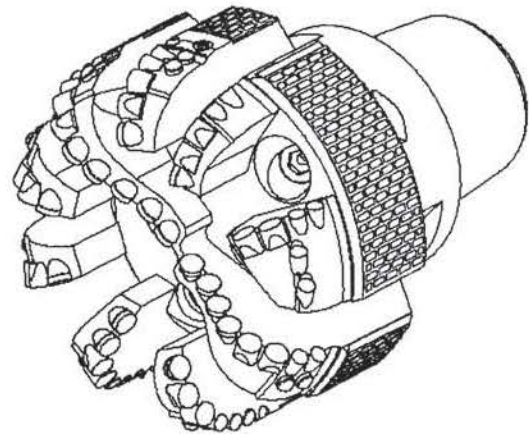


Figure 7: Tiled Gauge

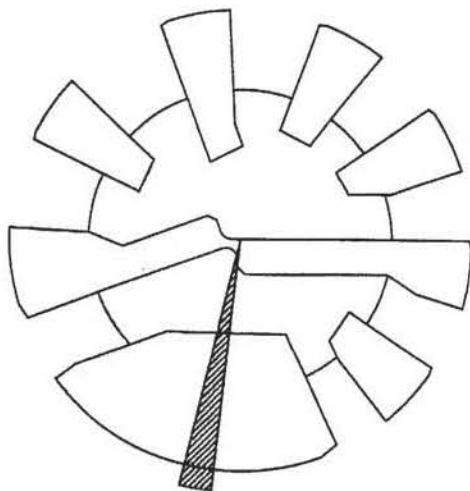


Figure 5: Resultant cutting force directed onto large unaggressive gauge pad.

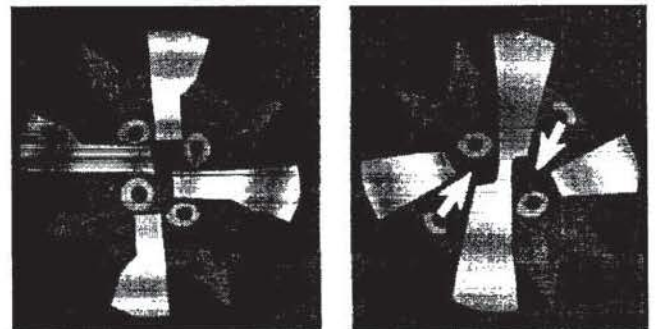


Figure 8: Comparison between conventional and cross flow hydraulic designs.

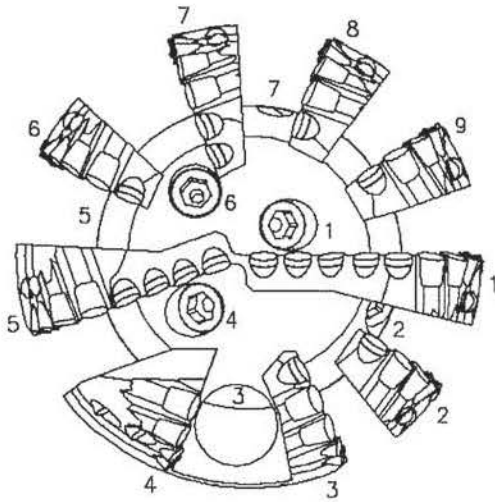


Figure 9: Enclosed junkslot.

	Standard	Conventional Antiwhirl	New Bit
Blade Count	8	10	9
Total Cutter Count	96	63	65
Cutter Size, (mm)	13	13	19 & 13
Nozzle Count	6	5	7
Junk Slot Area, (sq.cm)	182	110	205

Figure 10: A direct comparison between the standard, conventional antiwhirl and new bit.



Figure 11: No impact damage and formation of diamond lip.

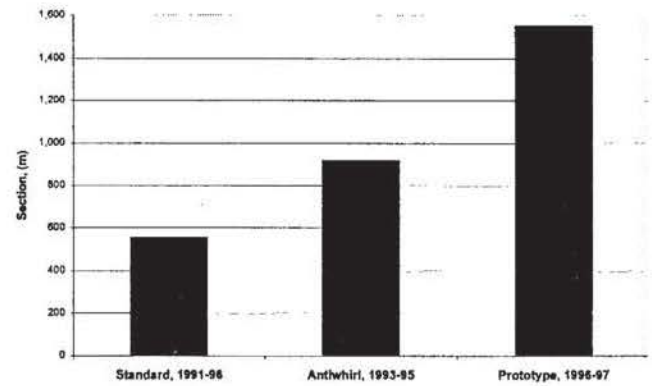


Figure 12: A comparison of run length between the standard conventional antiwhirl and new bit.

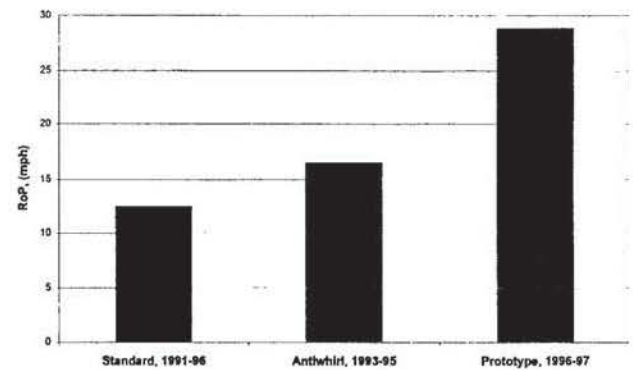


Figure 13: A comparison of penetration rate between the standard conventional antiwhirl and new bit.