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High Penetration Rates and Extended Bit Life Through Revolutionary Hydraulic and Mechanical Design in PDC Drill Bit Development

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Abstract

PDC drill bit developments have been made to achieve higher penetration rates and longer life, involving a compromise between open, light set, bits for speed and heavy set ones for durability. Developments are described which provided the benefits of both in a revolutionary hydraulic and mechanical design.

The hydraulic design causes mud to flow first towards the bit centre and then outwards. It was extensively flow tested using high speed photography to ensure that bit balling was prevented. It includes features to address bit whirl which were demonstrated in full scale laboratory testing to reduce the bit's vibration level.

The mechanical design maximises open face volume, known to benefit penetration rate, by using very high blades. However, the heights attainable can be limited by the bit body's mechanical strength. Steel was chosen to maximise blade strength and was coated with a newly developed hardfacing to improve erosion resistance. A programme of fatigue testing assured adequate strength.

Introduction

It is well recognised that each generation of PDC bits has produced better performance than its forebears, with one author claiming 60% improvement in ROP and 115% improvement in life between 1989 and 1995¹. These improvements have fueled the growth in use of this bit technology. However, this capability has in turn fed a demand for ever more difficult well programs which continue to

demand improvements in bit performance. The economic benefits of such well designs have been demonstrated by Barr & Clegg². One of the biggest challenges for the bit is to drill from shoe to T.D. through a range of formations from soft to hard and sticky to abrasive, or a homogenous formation of increasing hardness. Once this has been achieved, the design is developed to improve penetration rate through the interval. Typically a bit design is optimised for a particular application.

The bit designer has many ways of optimising a particular design for a given application. A feedback loop from analysis of field performance and dull condition has been shown many times to be a successful strategy in obtaining improvements. From this has come a growing recognition of important parameters. These include cutter count, hydraulic efficiency, and open face volume³. Unfortunately, these can conflict. For example, increasing the cutter count extends bit life but is difficult to achieve without reducing the hydraulic efficiency of the design and thus the rate of penetration. Many bit designs have been produced which alter the balance between these considerations but few attempt to resolve the inherent conflict.

Material Developments

The basic constraints within which the bit is designed are defined by the materials of which it is made. Most PDC bits today are manufactured from steel or an infiltrated matrix of tungsten carbide powder. These have very different properties. Matrix provides excellent surface properties, with an exceptional ability to resist fluid erosion. Fluid erosion is caused by loss of the soft binder alloy which then loosens the tungsten carbide powder grains from the matrix. The erosion resistance is increased by increasing the volume percentage of tungsten carbide but this in turn leads to problems. If this percentage becomes too high the poor transverse rupture strength of the tungsten carbide limits the mechanical stresses that the material will sustain, particularly in shock load conditions. In terms of bit design, this means that a matrix bodied bit will tend to have lower and thicker blades, reducing the open face volume that can be achieved.

It could therefore be argued that matrix bodied bits are best suited to long intervals of relatively slow drilling with correspondingly long periods of mud circulation and in which shock loads are avoided.

Steel, in contrast, has quite different mechanical properties. Its erosion resistance is relatively poor, particularly in fluid velocities above 100 ft/sec or when the fluid contains highly abrasive solids such as haemetite. However, its transverse rupture and impact strength are much higher than those of matrix. These properties allow steel bits to have higher, thinner, blades than matrix bits, with the consequent benefits to rate of penetration.

This suggests that steel bodied bits are best suited to applications where the open face volume can contribute to high penetration rates. The number of circulating hours to which the bit is exposed before completion of the interval is limited by the high rate of penetration, a virtuous circle.

The demands of today's well programs mean that it is neither practical nor desirable to distinguish applications so crudely. Accordingly bit manufacturers have sought to address the weaknesses of matrix by incorporating reinforcement into the matrix casting; to improve the surface properties of steel bits by cladding, or to seek alternative materials.

Cladding and reinforcing are alternative embodiments of the same basic concept - the structural strength of steel is combined with the surface properties of matrix. However, cladding is inherently more attractive because the coating of erosion resistant material can be thinner, thereby providing the bit designer with greater freedom to maximise the open face volume. Many claddings have been developed but two weaknesses are apparent in most. Firstly, the density of tungsten carbide powder is much lower than in infiltrated matrix, limiting the erosion resistance of the bit body. Secondly, the cladding does not intimately contact the PDC cutters because of a meniscus effect when it is laid down.

A new cladding has been developed with a density of tungsten carbide much closer to that of matrix and a process has been developed for eliminating the meniscus effect. The microstructure in fig.1 shows the original hardfacing cladding. It shows a few large particles of tungsten carbide and many small particles formed by reprecipitation from the molten form in which it is laid down. Particles so formed are much less resistant to erosion than the primary carbide. Fig.2 shows infiltrated tungsten carbide matrix. A much higher density of tungsten carbide is evident with a variety of particle sizes and shapes. Finally, fig.3 shows a section through the new cladding. The steel substrate forms one edge of the figure, the cladding the rest. As in fig.2 a good dispersion of tungsten carbide powder is evident. Comparison between the figures clearly shows the similarity between the new cladding and infiltrated matrix and the dissimilarity from the original cladding.

Previous cladding systems have suffered from a reducing thickness at edges. This is caused by the meniscus of the molten cladding material on the surface of the parent metal which causes the edges of these pools to be thin. Unfortunately these thin areas are often coincident with regions of high fluid velocity, such as those where mud flows around a cutter (fig.4). The solution adopted is described in detail elsewhere⁴. It involves inserting a wettable, sacrificial element into the cutter hole prior to cladding. The cladding wets this element and the meniscus effect then causes a local thickening of the cladding (fig.5). The insert is then removed and replaced with a PDC cutter.

The combination of these material developments paved the way for a new generation of aggressive drill bits.

Mechanical Design

Open face volume has been noted to correlate with increased penetration rate³. It was thus decided that the mechanical design of the bit should maximise the open face volume by using high thin blades. For the reasons described above, a clad steel body was selected to permit this.

High thin blades were expected to increase stress levels, over previous designs so a program of fatigue testing was initiated to examine the effect of blade root radius. A series of test bit bodies were made with various different blend radii where the blade joined the body. The two extremes selected were "sharp", (approximately 0.5mm) and "large", (a smooth 'U' shaped profile between two blades). Intermediate values of 2mm and 6mm, appropriate to various production capabilities, were also chosen. Each body in turn was clamped within a steel frame. Load was applied through a hardened steel roller to the two nose cutters on the blade. The direction of load was approximately parallel to the axis of the cylindrical PDC cutters. A sinusoidal bending load was applied at 5Hz frequency.

The data from the test (fig.17) fell into two groups. One was represented by the sharp corner and one by the large fillet radius. Curiously, and contrary to considerations of simple stress concentration factors, the 2mm radius then in use showed no benefit over the sharp corner and was thus rejected. In contrast the 6mm radius gave as much benefit as a completely rounded 'U' profile. The 6mm radius was therefore adopted as a design and production standard. One other notable aspect of the data is that the cladding process had no detrimental effect on the fatigue life of the bit.

Cutters are laid out on the bit face in one of two basic ways, described as spiral or tracking layouts. Tracking layouts were the earliest adopted⁵ and typically set cutters in concentric rings. Spiral layouts which set every cutter at a different radius came later⁶. In each case, the radial spacing is chosen to equalise the wear of the cutting structure.

One aspect of the cutter layout which is particularly applicable to tracking layouts is that by varying the angular spacing between cutters on each ring the rock removed at the radius can be apportioned unequally between the cutters. (figs. 6 & 7)

The advantage of this is that the bit can be designed so that the open face volume can be unequally apportioned between the cutter sets. The set generating the majority of cuttings produces them into a void volume more typical of a light set, high open face volume design. This is discussed further below.

At this point it is worth considering the role of the second set of cutters. Since they remove only a small proportion of the formation, they may appear to make little contribution to the bit performance. It has been shown⁷ that a bit whose cutting structure was a hybrid between PDC cutters and impregnated diamond elements benefitted from improved life and penetration rates. In that design the impregnated diamond elements formed such a set of cutters and produced these benefits despite the small volume of cuttings they generated. At the time of this paper the benefits were ascribed to the reduced cutter loading on the primary PDC cutters which reduced heat build up and the chances of impact damage. Today, with the greater insight into bit dynamics provided by Brett, et al⁸ we recognise the contribution of the secondary elements to the dynamic stability of the bit, reducing bit whirl, and thus impact damage to the PDC cutters.

Substituting PDC cutters for the impregnated diamond cutting elements provides the benefits of bit stability and increases the wear resistance of the bit. An example is shown from a well drilled in Southern Africa. In this case a hybrid PDC bit was modified by replacing the impregnated diamond cutting elements with PDC cutters. The typical wear pattern for the standard bit is illustrated (fig.8) by averaging data obtained from five dull bits of this design. The Southern African application required several sandstone stringers to be drilled and was chosen to test the concept. The resulting wear pattern clearly shows the influence of these secondary cutters. Instead of relatively uniform wear from cutter 35 to cutter 55 (the cutters were numbered from the centre outwards in radial order) this bit showed distinctly lower wear in the region where secondary cutters were located, cutters 44-65. In particular, wear here was graded 2 according to the standard method used in IADC coding⁹ whereas cutters in the region without secondary cutters were graded 8. In fact the bit was rung out here (Fig 9). The secondary cutters thus provide a means of extending the useful life of a bit. Unfortunately, such a design does not represent a general solution. Limited exposure of the secondary cutters invites cuttings build up in front of the secondary cutters and so it is unsuitable for formations prone to cause bit balling, where higher open face volume is required.

Weaver¹⁰ described how tracking cutter layouts provide a restoring force which inhibits bit whirl. We have confirmed

that these benefits can also be obtained with the unequal angular spacing described above. One such bit was tested at atmospheric pressure in Colton sandstone in a laboratory test machine. In this test the bit fig.10 drilled with a constant weight on bit whilst the rotary speed was gradually increased. The lateral acceleration of the bit was measured. The results fig.11 show a generally low level of vibration with a maximum of about 1g. The results from a whirling bit of the same size in a similar experiment are shown for comparison fig.12. These were much worse with acceleration levels up to 10g being recorded.

Hydraulic Design

Early PDC bits mimicked natural diamond bits with many blades of cutters and typically only one fluid port, the crow's foot. Over time, mud ports have been replaced by nozzles and increased in number, often now matching the number of blades. Further increases are typically not beneficial because limitations in available pump horsepower restrict the TFA and thus nozzle size to unreasonably low values. A common arrangement of these nozzles is to place one at the inner end of each blade, with the intention of cleaning that particular blade. Both field experience and laboratory study¹¹ have shown this to be effective. However, this approach leads to a number of difficulties. One is that matching the flow to the volume of cuttings generated by the adjacent blade can require the use of several different nozzle sizes placed in a prescribed manner. In practice, such prescriptions are rarely followed with only one or two different nozzle sizes being installed. Recirculation is almost inevitable where large changes in cross section of the flow path occur, as on exiting a nozzle, but the bit design should be such as to avoid zones of low velocity. This is relatively difficult to achieve when the impingement points of the free jets emerging from the nozzle are at similar low radii. King et al¹¹ have reported on the sensitivity of such designs to nozzle placement and orientation. A fundamental difficulty is that the volume of cuttings produced is greatest at large radius where the velocity of the wall jet is low because of its distance from the free jets' impingement point. fig.13

Such designs also tend to have a high degree of symmetry, leading to stagnant areas near the bit centre. It has been shown in studies of roller cone bits that penetration rate can be improved by breaking such symmetry, thereby introducing cross flow.¹²

This concept of cross flow has now been applied to PDC bits. fig.14. This is most simply considered in a four bladed bit but has been applied to eight and nine bladed bits with success.

Pairs of nozzles are arranged, one conventionally near the bit centre, the other near the bit gauge. The one near the bit centre produces an outward flow past the adjacent blade to the junk slot. In the vicinity of the jet a low pressure zone is formed¹¹. The nozzle near the bit gauge produces a jet which flows downwards and then inwards past the adjacent blade

towards the low pressure zone. It then merges with the other jet and flows past the other blade. The merging of these two streams minimises the turbulence in the low pressure zone. The hydraulic energy is better distributed around the borehole and recirculation is minimised.

One interesting consequence of this concept is that a much larger proportion of the borehole is swept by the high velocity jets as shown in fig.13. An additional aspect is that the volume of cuttings generated increases with radius. The outer nozzles of the new design sweep this area of the borehole more effectively.

It was noted above that a low pressure region occurs around the jet. For the inner nozzle this has the advantageous effect of assisting inward flow from the outer nozzle. For the outer nozzle the effect is to entrain fluid from the annulus. The volume of drilled solids in this fluid, and the volume of fluid thus entrained, are sufficiently low not to contribute to bit balling.

Synergy Between Hydraulic and Mechanical Design

One consequence of the crossflow concept is that some of the drilling fluid, typically about half, is used twice, once flowing in and once flowing out. This means that the flow rate past some blades can be effectively doubled, as compared with a standard bit.

A further refinement becomes apparent when this hydraulic design is linked with the concept of secondary cutters.

It was described above how the volume of rock removed can be unequally divided between cutters at the same radius. The hydraulic design permits the volume of fluid past each blade to be unequally distributed without detriment. The cutters which remove most rock are arranged on blades which have the highest flow rate. A synergy between the two concepts is thus achieved. These blades are the primary blades. Those which are cleaned by inward flow and which cut less rock are termed secondary blades. The table shows the effect when drilling at 118 ft/hr, with a four bladed 9.875" bit.

	Standard bit		Cross flow bit	
	Long blade	Short blade	Primary	Secondary
Number of nozzles	1	1	1	1
Flow (US gpm)	150	150	300	150
Cuttings generated (US gpm)	2.52	1.39	3.33	0.68
Cuttings in flow path (US gpm)	2.52	1.39	4.01	0.68
Volume concentration of cuttings in mud	1.68%	0.92%	1.34%	0.45%

In addition, side rake of the cutters on the secondary blades can be used to impart motion to the cuttings in the same direction as the mud flow¹³, towards the bit centre in this case.

The hydraulic design was examined in a flow simulation laboratory, using neutrally buoyant particles in water. Laser sheet lighting and high speed video photography were used to examine the flow pattern which is shown in fig.15.

It was apparent that the flow pattern was working as intended to provide a well structured flow inwards and across the bit centre. However, the lack of strongly turbulent flow was permitting beads to dwell in a region near the bit nose. Modifications to the bit body were made to increase the recirculating eddy in this flow pattern and, incidentally, further increase open face volume. The resulting flow pattern demonstrated (fig.16) that the dwell had been eliminated.

The design was validated by using the bit to drill Pierre Shale in a pressurised drilling machine. The rock and machine have been described elsewhere¹⁴ and need not be described further. The test procedure consisted of drilling into the rock sample with a constant weight on bit of 8000 lbf and rotary speed of 120 rpm until the penetration rate was demonstrably stable. The test was repeated at progressively lower flow rates until bit balling prevented the bit from drilling. A commercially successful four bladed "fishtail" bit was used for comparison. Both bits had four nozzles of 18/32" diameter and were 9.875" in size. The results are as follows:-

Flow (US gpm)	HSI	Standard bit ROP (ft/hr)	Crossflow bit ROP (ft/hr)
500	0.81	170	200 ¹
400	0.41	166	200
350	0.28	168 ²	175 ²
300	0.17	Balled up	Not tested
200	0.05	Balled up	185 ²

1. This ROP was reached at only 6000 lb weight on bit.
2. Some cuttings adhered to the bit face but penetration rate was stable.

The results showed an average increase in penetration rate of 14% and a reduction in minimum acceptable flow rate, defined as the flow rate required to continue drilling, of 43%.

Performance

Payne¹⁵ described the requirement to drill an exceptionally long tangent section for an extended reach well at Wytch Farm. This application was selected for the first trial of the concepts described. A 12.25" bit was designed, using eight nozzles and four pairs of blades. It successfully drilled the entire interval, setting a new record of 13170 ft for a single continuous interval. Following this initial success, many further bits were designed and run.

We have chosen examples of each important size range to illustrate these.

Run Ref.	Bit size	Depth out	Footage	Hours	ROP
1.	8 1/2"	9830	7275	29.9	243.3
2.	12 1/4"	20021	13443	205.5	65.4
3.	17 1/2"	11014	5484	248	22.1

1. Record ROP and footage drilled in 24 hours in Indonesia.

The DS70F+ 8 1/2" bit has proved itself to be both fast and durable in Indonesia. This bit has repeatedly broken the 24 hour footage record drilling through claystones, sandstones, siltstones and limestones.

2. World single run footage record.

The DS70HF+ 12 1/4" bit obtained the world single run footage record, drilling claystone marl sequences containing limestone stringers in block 211 of the U.K. sector of the North Sea.

3. Longest run in Cupigagua field.

In Colombia, the DS70HF+ 17 1/2" has demonstrated its superior performance capability in drilling both sticky mudstones and very hard, abrasive sandstones at high penetration rates. The bit drilled with water based mud through 945 feet of mudstone at ROPs in excess of 50 fph, progressing through 2967 feet of sandstone sequences finally drilling 1572 feet of hard and abrasive Carbonera C1 sandstone. The offset well required for the PDC bits to drill the same interval.

CONCLUSION

The performance records given above represent a small number of the many outstanding runs achieved and demonstrate the success of these revolutionary designs. In particular they highlight capability that these designs have to drill both hard, abrasive and soft, sticky formations efficiently.

ACKNOWLEDGEMENTS

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Fig.1

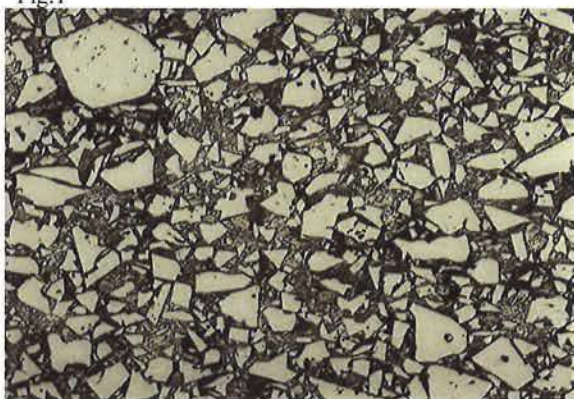


Fig.2.



Fig.3

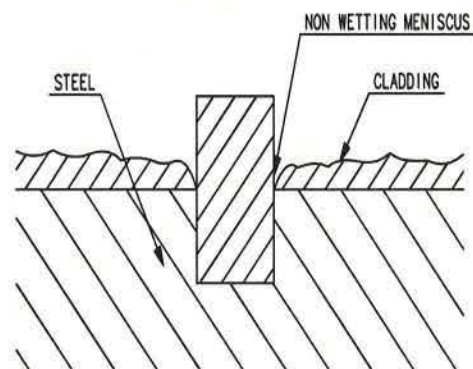


Fig 4

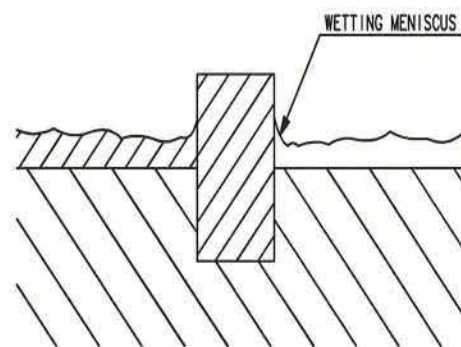


Fig 5

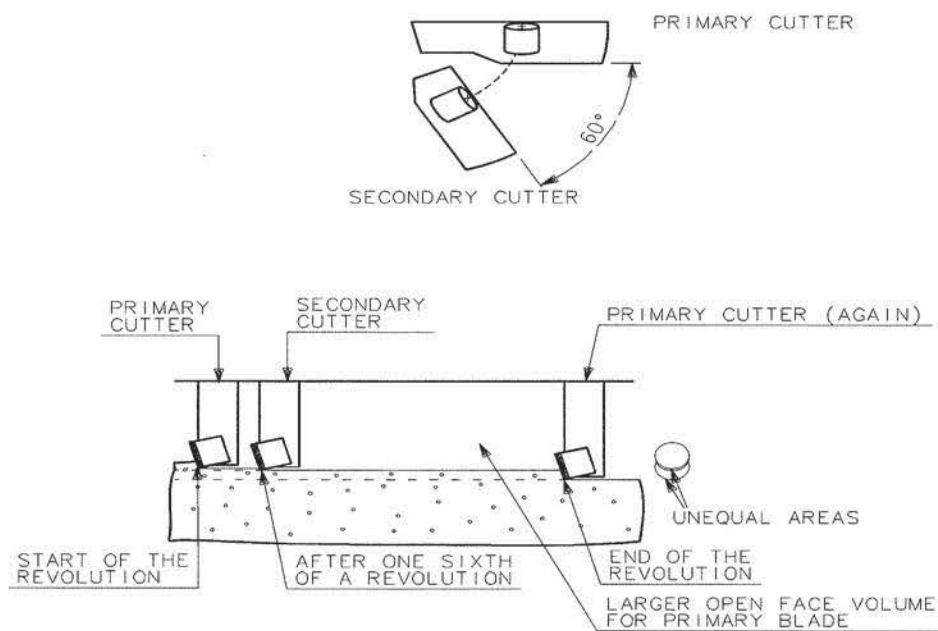


Fig.6

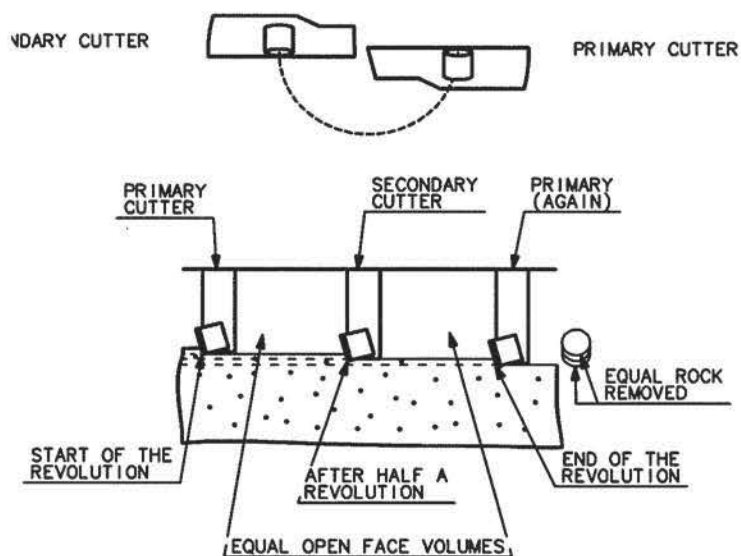


Fig.7

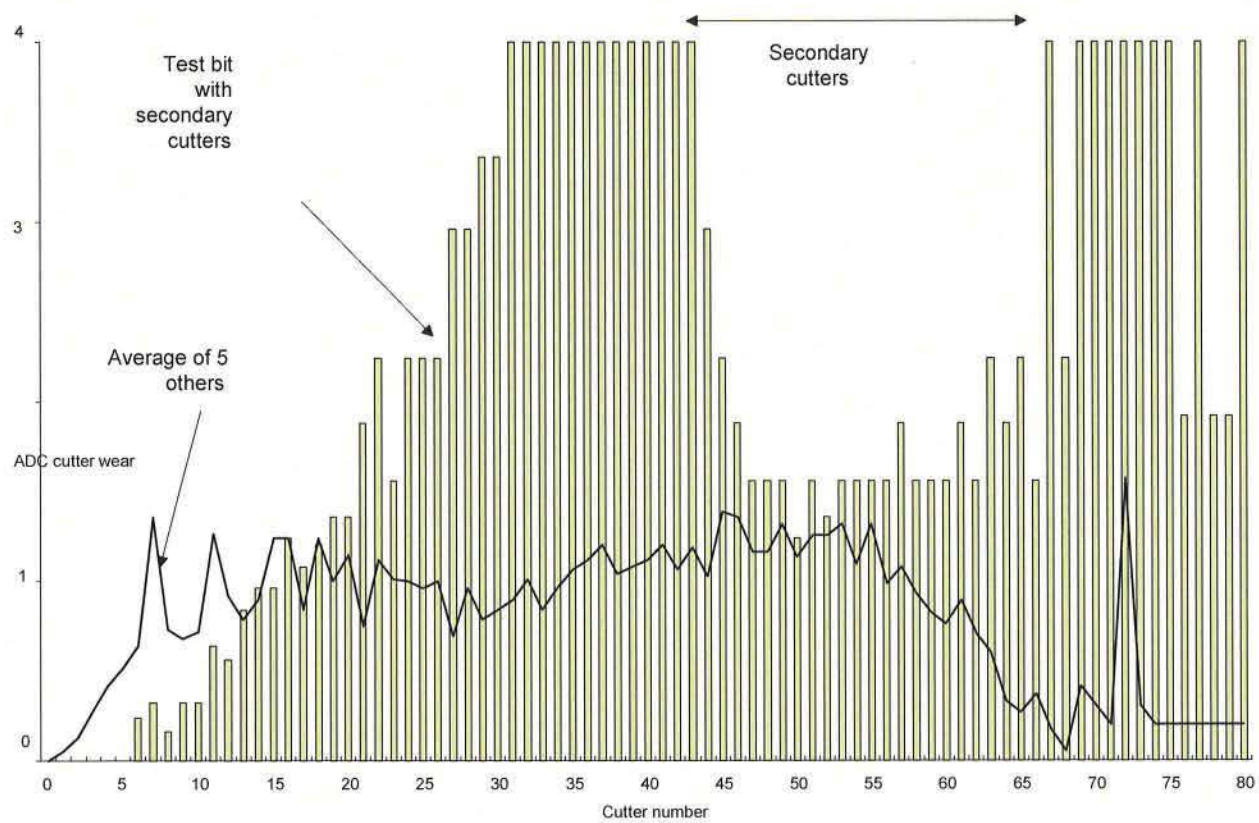


Fig 8



Fig 9

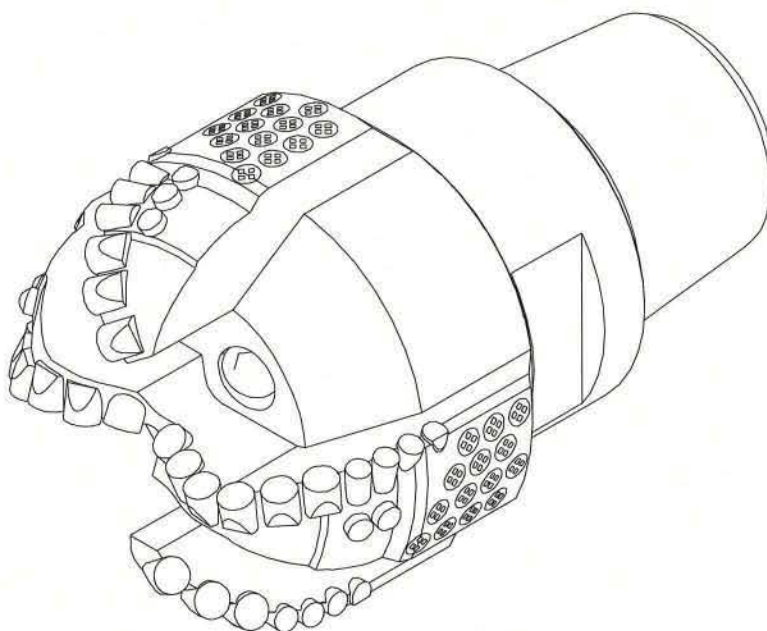
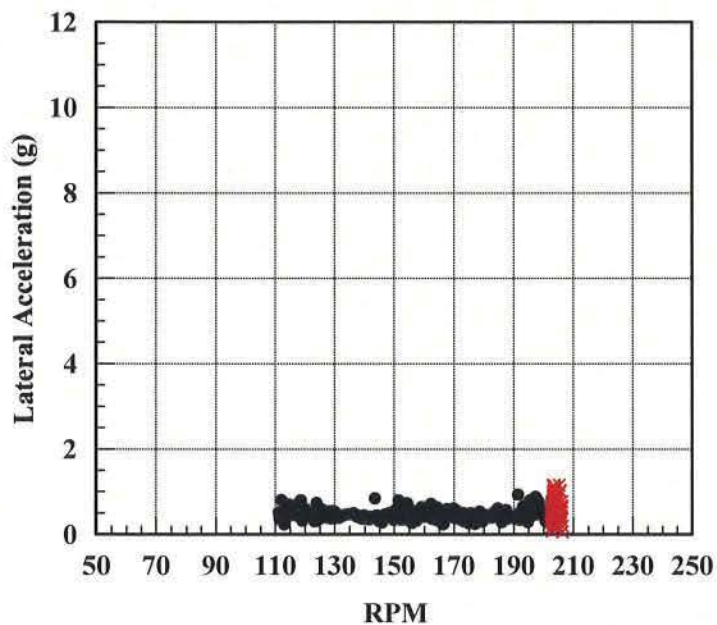
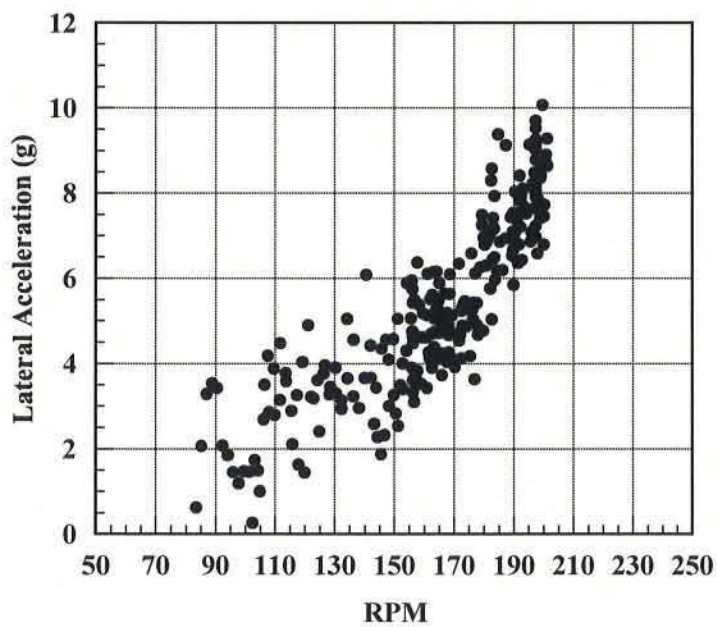


Fig 10

Figure 11: Test Bit of Figure 10**Figure 12: Whirling Bit**

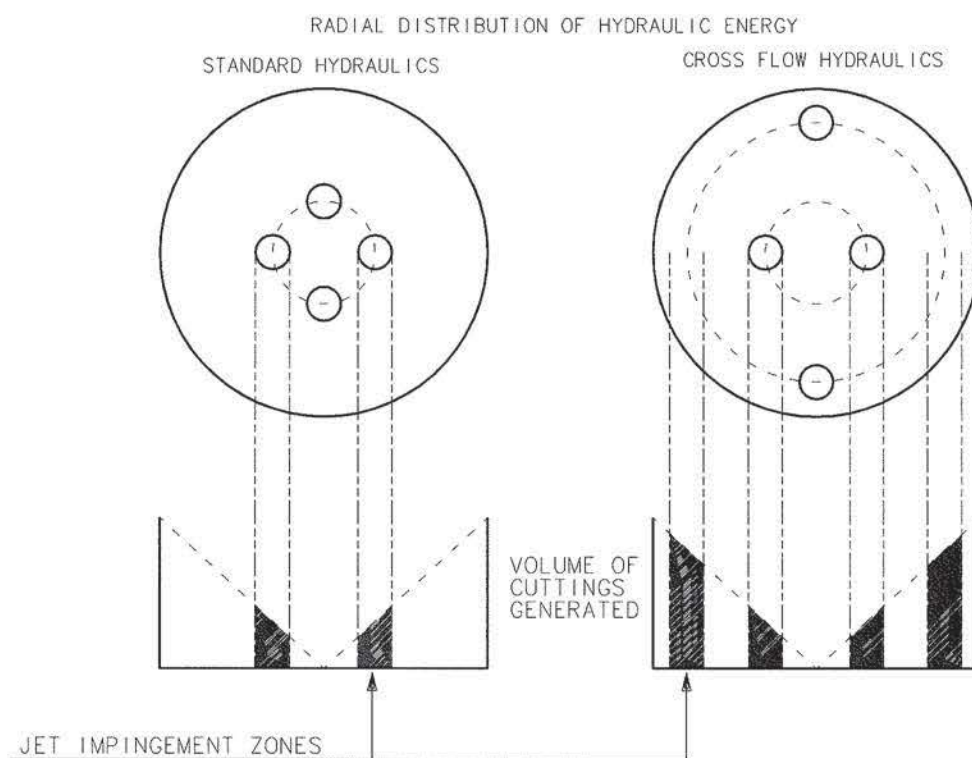


Fig 13

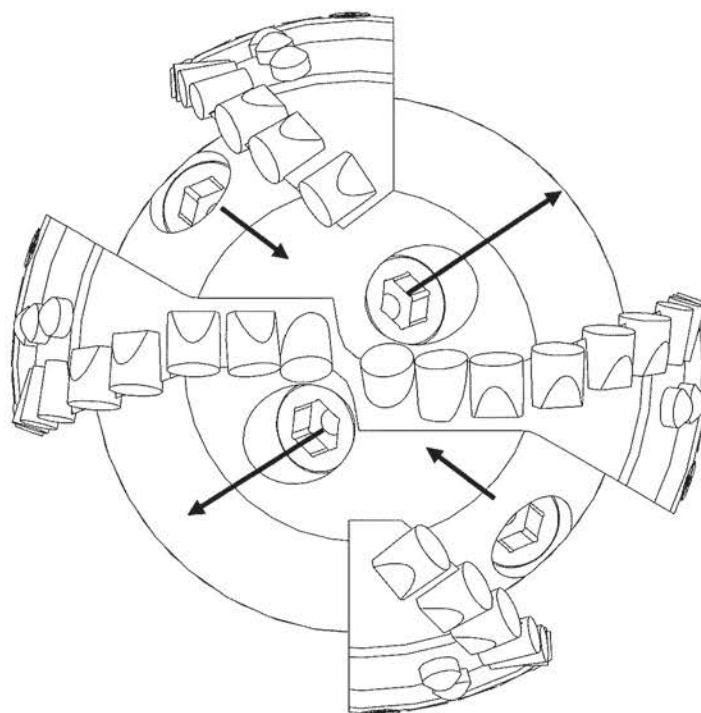


Fig 14

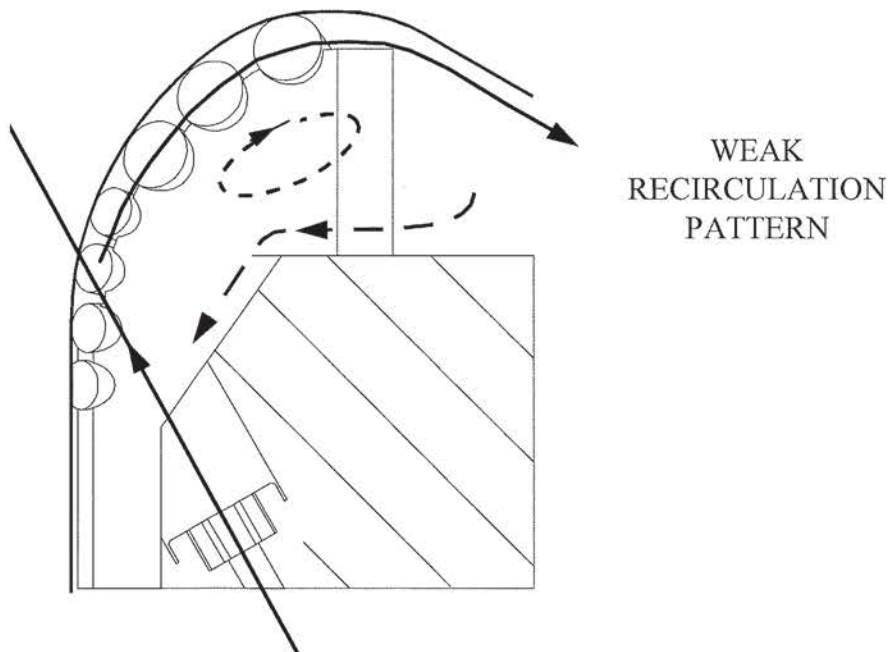


fig 15

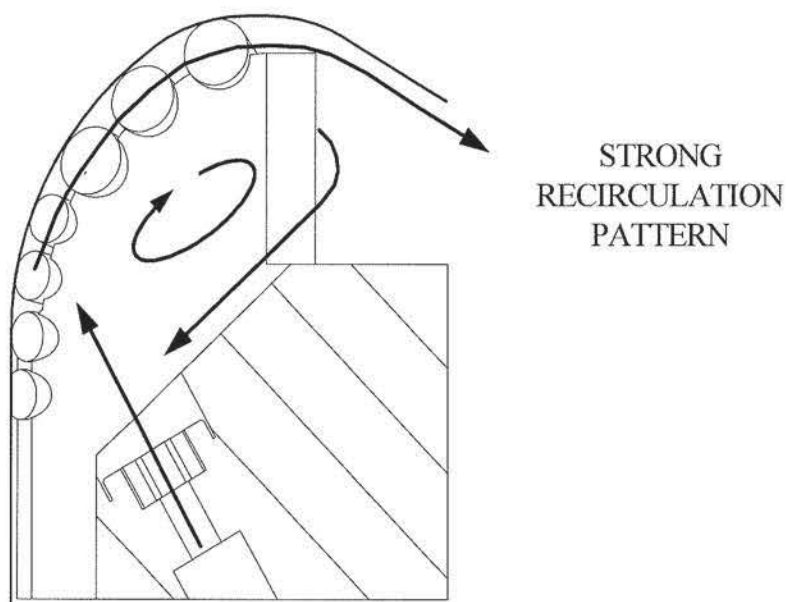


Fig 16

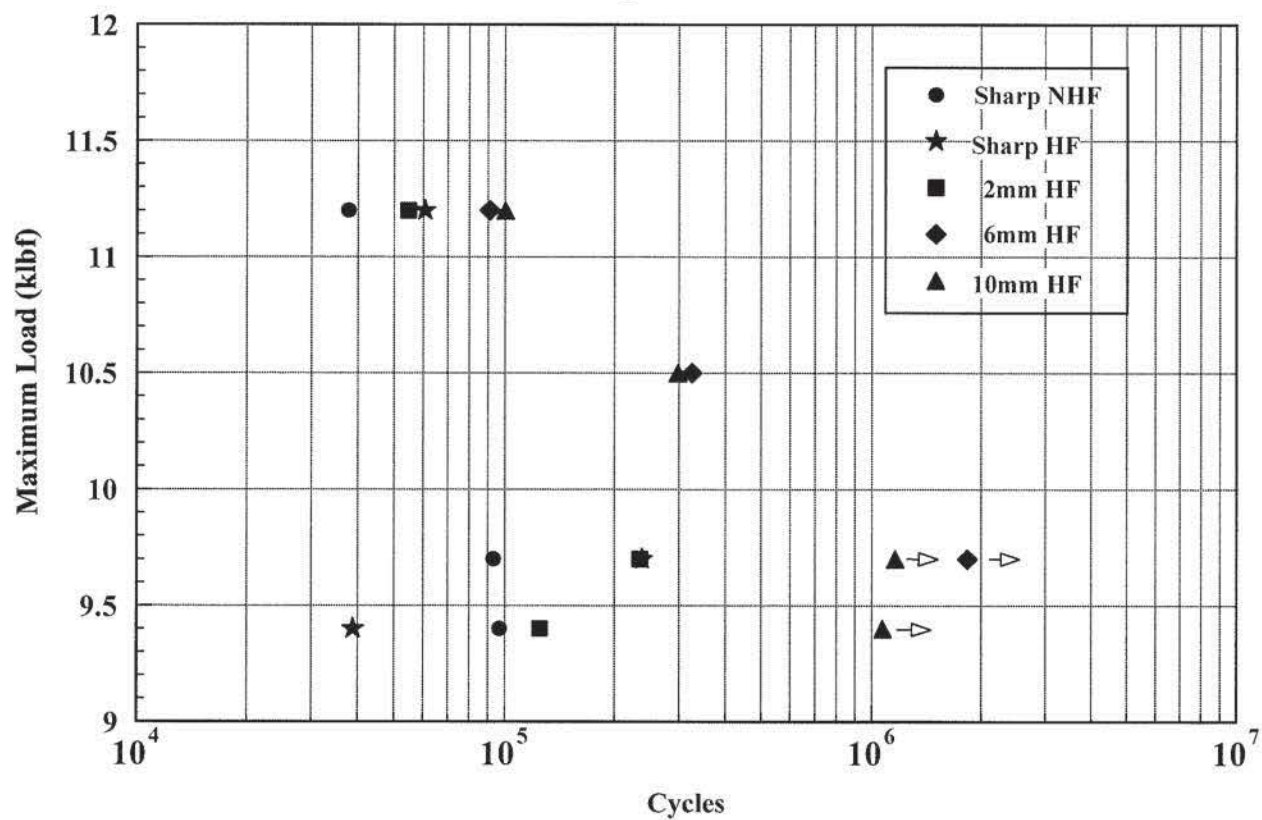


Fig.17