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POLY-CRYSTALLINE DIAMOND DRILL BIT DEVELOPMENT

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ABSTRACT: The development of directional drilling in the coal industry has been enhanced by access to Poly-Crystalline Diamond (PCD) bit technology. This technology has been developed in the oil industry with ongoing improvements driven by the need for improved drilling rates, more robustness for longer life and ability to penetrate a wider range of strata types. Although the underground drilling applications require smaller bit diameters, the technology has been applied with modifications to create suitable smaller bits. This paper describes PCD and bit design technology and identifies a range of drill bits now available and their applications in the underground in-seam directional drilling industry.

INTRODUCTION

As in-seam drilling of gas drainage boreholes became an established aspect of gas management, the technology in drill bit design and construction has also evolved. The early bits used for in-seam drilling in the coal were fitted with tungsten carbide cutters. These bits were usually "home-made" or produced by bit manufacturers for the surface drilling industry rather than being specifically designed for in-seam drilling applications (Hungerford, 1995).

Most drill bit technology has been driven and financed by the oil and gas industry with the flow on effect benefiting other drilling industries with that technology being adapted to suit differing needs. Improvements in the technology have benefitted the underground drilling industry with improved drilling performance in an increasing array of drilling applications.

INTRODUCTION OF THE PCD BIT

A key development in bit technology in Australia was the access to poly-crystalline diamond (PCD) bits through an experimental bit acquired by ACIRL from the USA in 1982. This "Terratek" 80 mm Stratapax bit (Figure 1) (Allen, 1982) was an early version of the PCD bits developed for the oil and gas drilling industry in the mid-1970's with PCD cutters mounted on tungsten carbide pillars secured into the face of a steel body. The PCD cutters penetrated both coal and stone without requiring the constant sharpening associated with tungsten carbide faced bits.

Figure 1 - "Terratak" 80 mm Stratapax PCD bit (Allen, 1982)

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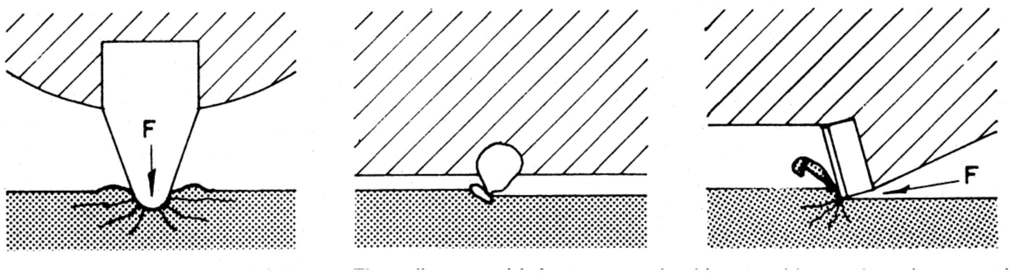
CUTTING ACTION

The comparative cutting action of the PCD cutter with other bits is demonstrated in Figure 2 (Triefus, 1982). The roller cone bit fractures rock with a crushing action, the natural diamond bit ploughs and grinds while the PCD cutter shears rock much like a lathe action.



Roller cone **Natural diamond** **PCD cutter**

Figure 2 - Cutting mechanics of various bit types (Triefus, 1982)

POLY-CRYSTALLINE DIAMOND TECHNOLOGY

The PCD cutter (Figure 3) (Brown, 2007) (usually referred to in the surface drilling industry as a PDC – Polycrystalline Diamond Compact) consists of a tungsten carbide blank (Substrate) which has a thin layer of synthetic diamond matrix (Diamond Table) bonded to it through a sintering process under high pressure and temperature in a synthesis press (Figure 4) (Brown, 2007). The matrix is formed from a mix of synthetic diamonds and a cobalt bonding agent with the diamond size, portions, temperature and pressure being regulated to produce improved diamond table.

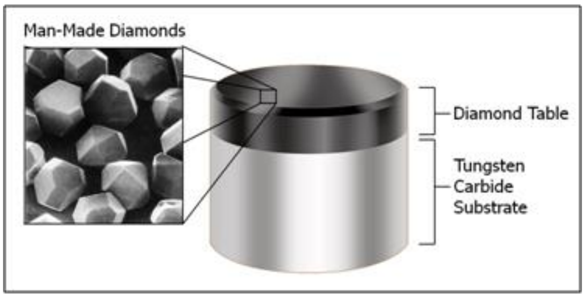


Figure 3 - PCD cutter (PDC - Polycrystalline Diamond Compact)

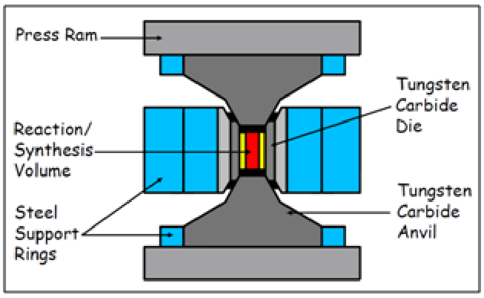


Figure 4 - Synthesis press for creating PCD cutters (Baker Hughes, 2007)

Continual evolution in the PCD technology has improved the matrix to be more robust to manage the abrasive and shock loading it is subjected to. Early PCD matrix was prone to flaking fracture failure (Figure 5) and occasional total failure of the bond with the tungsten carbide substrate. The PCD cutters are also sensitive to temperatures over 800°C and can be adversely affected during the process of silver soldering into the bit face.

Modern technology allows finite element analysis of load transfer and stress distribution (Figure 6) (Baker Hughes, 2007) from the cutting point of contact through to the mount in the bit face aimed at reducing the damaging stresses. The PCD / tungsten carbide interface is now modelled and analysed (Figure 7) (Mensa-Wilmot, *et al.,* 2003) with various substrate profiles (Figure 8) to reduce stresses in the PCD cutter and improve the bond strength. This improves resistance to chipping and/or fracturing. The modelling also considers various table thicknesses, interface shape and grade of tungsten carbide in the substrate to provide PCD cutters suitable for specific load applications. Further developments have included a chamfered edge and polished face on the PCD table to enhance the cutting action and removal of cuttings.

PCD cutters are available with diamond table thicknesses up to 3.5 mm and diameters up to 30 mm. The PCDs used in underground directional applications are usually 13 mm diameter with a diamond table thickness of 1.0-1.5 mm. PCDs are also available in 8 mm diameter (Figure 9). The general rule is that small cutters and high cutter count are chosen for hard and abrasive rock formations, whereas large cutters and a reduced cutter count are preferred for soft to medium formations.

Figure 5 - Fractured PCD table with eroded tungsten carbide substrate

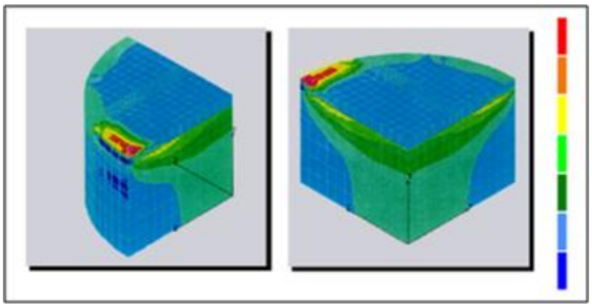


Figure 6 - Finite element analysis of stress distribution in a PCD cutter from contact point loading

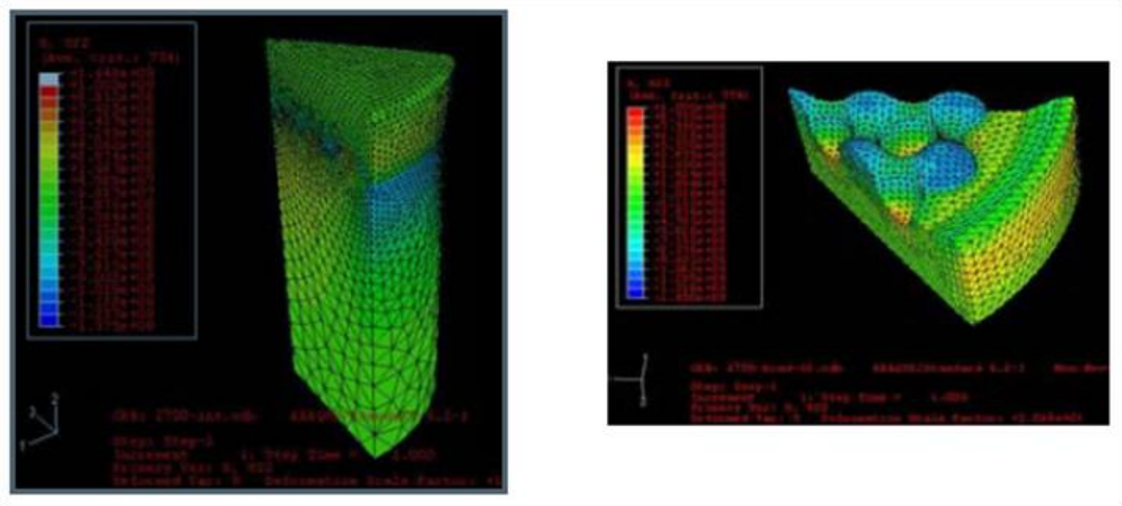


Figure 7 - Finite element analysis of tungsten carbide substrata and diamond table interface (Mensa-Wilmot, *et al.*, 2003)

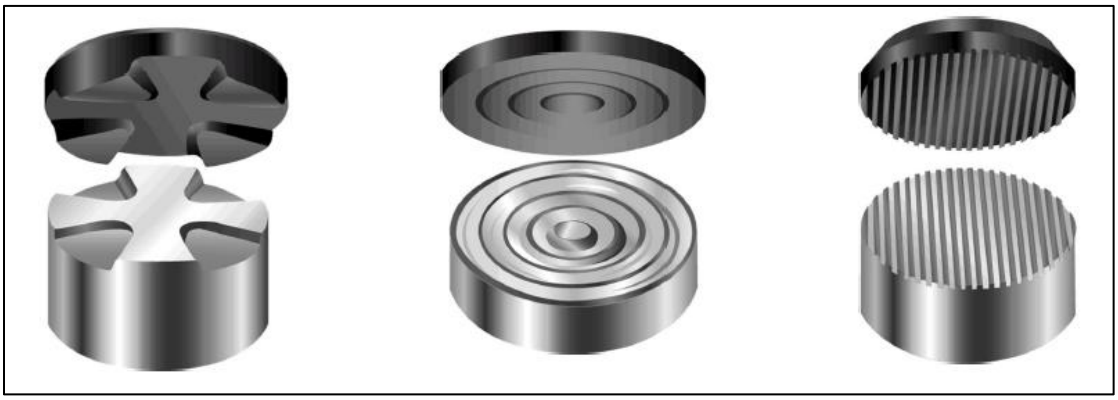


Figure 8 - Substrata profile - radial symmetry, axial symmetry and ripple (Baker Hughes, 2007)

The diamond Table is much harder but relatively brittle compared to the tungsten carbide Substrate. Progressive wear removes the tungsten carbide behind the diamond Table to present a leading cutting edge of PCD matrix (Figure 10). When the diamond Table fractures, the tungsten carbide Substrate is rapidly eroded to re-expose a cutting edge of PCD matrix (Figure 5).

BIT STRUCTURE

PCD bits are classified as either post (tungsten carbide posts mounted in a steel body) or cast matrix face (Figure 11) (Brown, 2007). With the latter, a mix of tungsten carbide and cobalt binding agent are cast and bonded at high temperature and pressure to a steel body. The face is designed with mounting recesses which position each cutter in a precise location at a prescribed angle. The cast matrix offers more resistance to erosion that that of a steel bodies bit. With improved technology, the matrix has become more robust with improved resistance to erosion and shock loading from vibration. In high erosion areas, tungsten carbide blocks or strips can be inserted in the cast to enhance erosion resistance.

Figure 9 - Flat faced bit with spiral layout of 8 mm PCD cutters

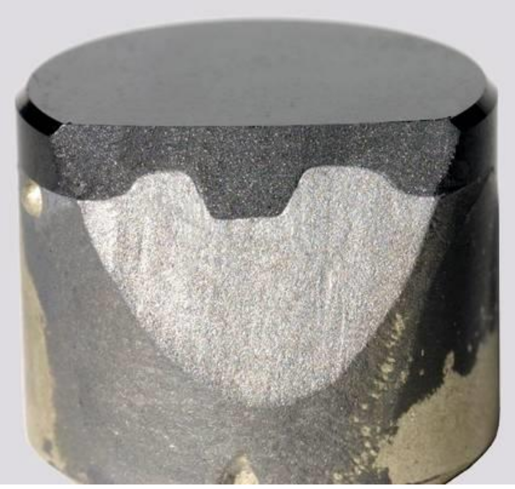


Figure 10 - Progressive wear of a PCD cutter

With relatively small diameter bits (96 mm) in use, there is insufficient space to design the usual blade face layout of larger diameter PCD bits (Figure 12) (Brown, 2007). The smaller bits are designed as flat or relatively flat faced (Figures 9 and 13) with the cutters arranged in a spiral from the centre outwards. The spiral layout assists in reducing torque vibration and promotes removal of cuttings towards the periphery of the bit. The coverage of the cutters is overlapped (Figure 13) to provide total coverage of the cutting face with the placement designed to generate balanced torque loading on the face. Outer cutters provide both axial and gauge cutting with tungsten carbide inserts providing passive gauge protection along the outside of the bit. Exposure of the outer cutters and a flat face are preferred elements to starting and propagating a lip for branching with directional drilling.

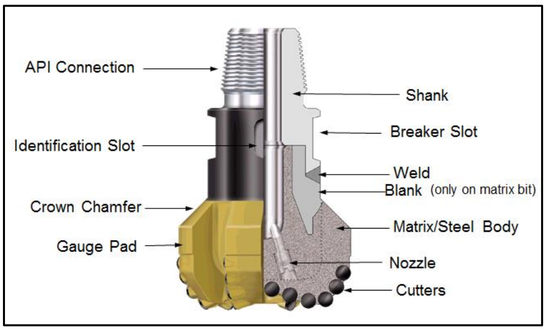


Figure 11 - PCD bit structure

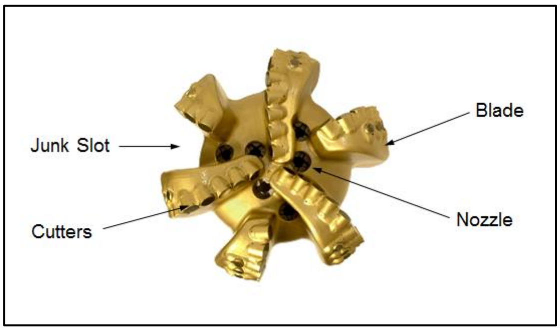


Figure 12 - PCD blade face layout

RAKE ANGLES

The PDC cutter characteristics, back rake angle, cutter layout, cutter count and cutter size are the main parameters that control the drillability of the bit. The PCD cutters are mounted at an angle relative to the axial direction of drilling/penetration. This is referred to as the back rake angle (Figure 14) (Triefus, 1982). This angle is required to present the cutting edge of the cutter in contact with the strata. It controls how aggressively cutters engage the rock formation. Generally, as the back rake is decreased, the cutting efficiency increases but the cutter becomes more vulnerable to impact breakage. A large back rake angle will result in lower rate of penetration but will give a longer PCD bit life. The general trend is for the inner cutter to have a back rake angle of 20-25^{o}with the angle reducing to 10^{o}for the outer cutters.

The side rake angle (Figure 14) aligns the cutter so that the back of the cutter is within the cutting circumference of that cutter (Figure 15) (Baker Hughes, 2007). It also enhances the shearing action of the cutter and helps to direct the cuttings toward the periphery of the bit.

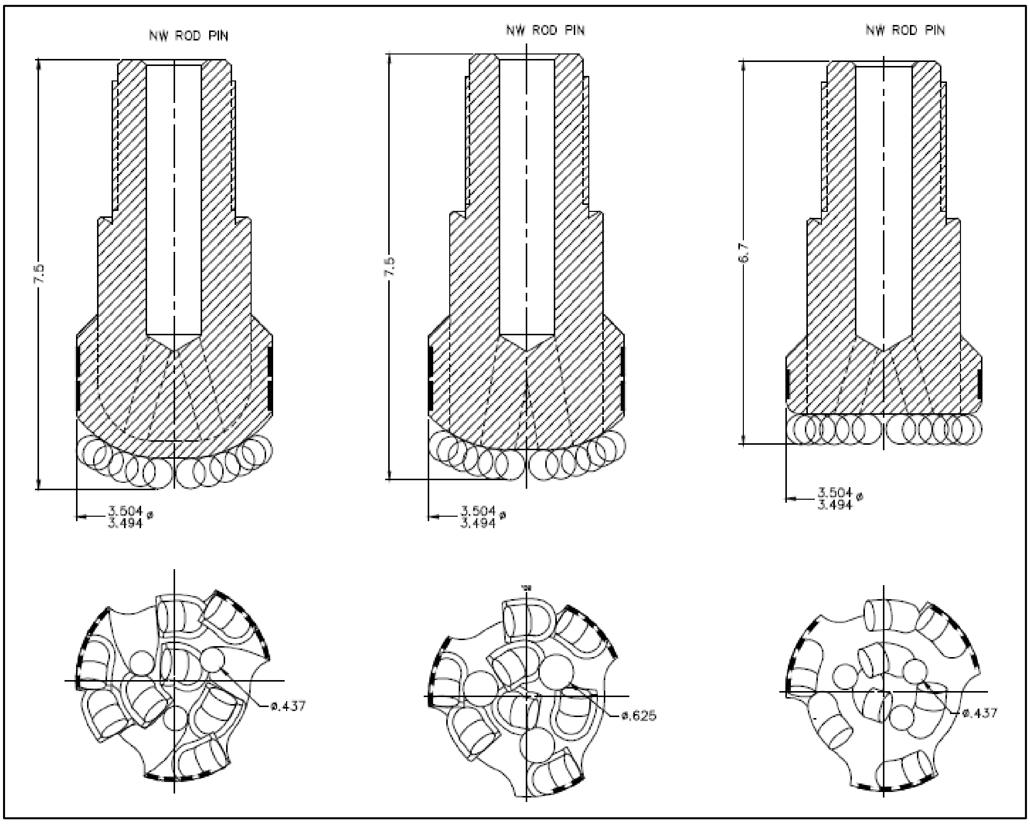


Figure 13 - PCD cutter layout and coverage

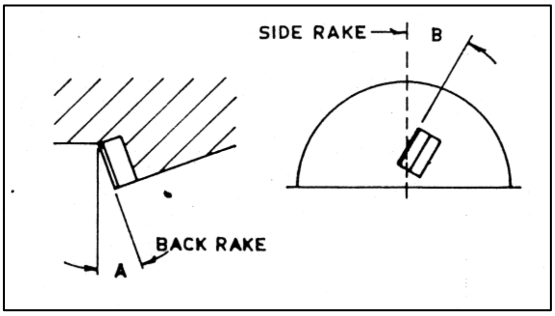


Figure 14 - Back and side rake angles of mounted PCD cutters (Triefus, 1982)

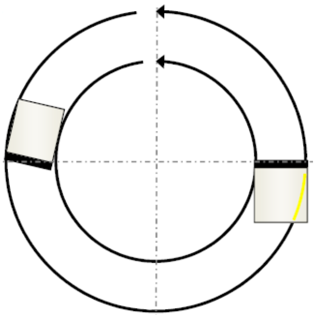


Figure 15 - Clearance provided by side rake angle (Baker Hughes, 2007)

DEVELOPMENT OF PCD BITS

Steel bodied PCD bits of similar design to the Terratek bit (Figure 1) were available for Down Hole Motor (DHM) drilling. As these were regarded as relatively expensive and with long delivery times from the USA, emphasis was directed towards developing a locally available product Longyear's had advertised cast matrix technology for drill bit construction so they were approached to design and manufacture a PCD bit with a cast matrix face. Tungsten carbide (T/C) inserts can be incorporated into the matrix at the casting stage to reinforce high erosion zones.

Longyear produced an 80 mm PCD rotary bit and an 89 mm flat faced PCD bit with exposed side cutting action for DHM drilling. The 80 mm design was used successfully for in-seam rotary drilling for exploration. The initial design of 89 mm bit was found to have design flaws, which had adverse influences on drilling performance and bit life (Hungerford, *et al.,* 1988). The problems were with the security of the outer cutters and uniform water flushing:

- The steep angle of the back of the cutter mounts (Figure 16) led to several break-out failures of the outer cutter mounts.
- Erosion under the outer mounts led to failure of the mount (Figure 16).
- The angled choke directly under the inner-most cutter mount in the central flushing port (from full round profile in the body of the bit to the half round profile as it exited the face adjacent to the inner-most cutter mount) was directing high water flow at an angle to the alignment of the DHM. This caused severe vibration of the DHM when operating.

Modifications proved successful and were adopted by Longyear (Figure 17). They were also incorporated into their rotary designed bits with semi-parallel sided gauge protection. Directional drilling eventually adopted rotary drill bits when the side cutting feature was regarded as not being essential for branching.

Asahi Pty Ltd Australia produced similar in their Claw bit series (Figure 18) with semi-parallel side gauge protection. These bits are reasonably aggressive and used extensively in underground gas drainage drilling. They are available with a non-return valve incorporated inside the threaded section.

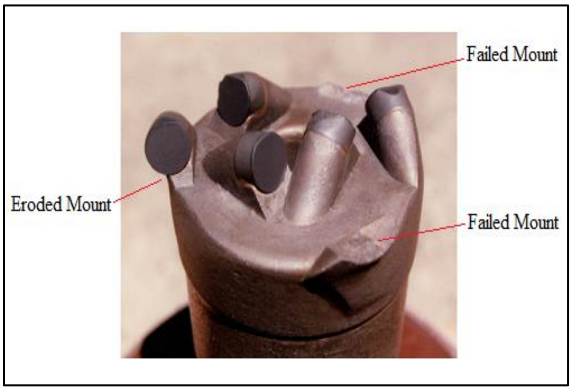


Figure 16 - Worn and damaged Longyear 89 mm bit

Figure 17 - Modified Longyear 89 mm DHM PCD bit

Several PCD bits are now more readily available from the USA. Their differing design and cutter configurations provide cutting characteristics suited to differing drilling environments and conditions. Smaller cutters (Figure 9) and recessed cutters (Figure 19) produce smaller cuttings and slower penetration rates more suited for longer boreholes or drilling in boggy conditions. The convex bit (Figure 20) with fully exposed 13 mm cutters is a very aggressive bit with very good penetration rates but is not conducive to branching.

To enhance the ability to drill back out of boggy conditions, back-cutting facilities have recently been added to bits in the form of tungsten carbide pieces (Figure 21) or PCD cutters with back-flushing port (Figure 22) and proved successful.

CONCLUSIONS

The development of PCD technology has been driven and financed by the oil and gas drilling industry. The technology has allowed improved drilling performance in an expanding number of drilling applications.

The key design aspects required for directional drilling bits are:

- Flat faced design with slightly exposed outer cutters to enhance the ability to branch,
- Complete coverage and balanced torque loading of PCD cutters on the face,
- Back rake angles determined to suit relative loading and frictional exposure,

- Axially balanced water flushing ports in the face to avoid vibration during rotation,
- Some form of back-cutting facility to assist recovery from boggy environments.

Drill bit design has also provided smaller diameter bits for use in underground directional drilling applications although most bits used are as provided by the manufacturers. Studying the performance of these bits can provide information to improve the design for specific applications.

Figure 18 - Asahi 96 mm PCD bit

Figure 19 - DPI flat-faced PCD bit with 50% recessed 13 mm cutters

Figure 20 - DPI convex-faced PCD bit with fully exposed 13 mm cutters

Figure 21 - Asahi PCD bit with tungsten carbide back-cutters

Figure 22 - DPI bit with PCD back-cutters and flushing ports

REFERENCES

Allen J, 1982. Private communication.

Baker Hughes, 2007, unpublished presentation.

Brown A, 2007. Product roadmap 2007, Company presentation, Baker Hughes Incorporated, Abu Dhabi, Nov, 2007.

Hungerford F, 1995. Status of underground drilling technology, keynote address, International Symposium cum Workshop on Management and Control of High Gas Emission and Outbursts, Wollongong 20-24 March, pp 397404 (Ed: R D Lama.) ISBN 0 646 22810 2. http://eis.uow.edu.au/outburst/pdfs/C3079%20Final%20Report.pdf.

Hungerford F, Saghafi A and Williams R J, 1988. In-seam and cross measure methane pre-drainage by long-hole drilling. *End of grant report NERDDP project No. 874*.

Mensa-Wilmot G and Penrose B, 2003. Advanced cutting structure improves PDC bit performance in hard and abrasive drilling environments, prepared for presentation at the SPE Latin American and Caribbean Petroleum Engineering Conference held at Port-of-Spain, Trinidad, West Indies, 27-30 April, 2003.

Triefus Pty Ltd, 1982 – Triefus product data sheet, Clore Drill Bits - Ref, No. BITS-REAMERS-4.