The History and Impact of Synthetic Diamond Cutters and Diamond Enhanced Inserts on the Oil and Gas Industry

D.E. Scott
Hughes Christensen, 9110 Grogan's Mill Road, The Woodlands, Texas 77380 USA

The PDC cutter for oil and gas drill bits was introduced commercially in 1976, after three years of development work and market testing. This paper will discuss the market conditions, technical challenges, and milestones in the past three decades of the PDC drill bit and diamond enhanced rolling cone drill bit for oil and gas wells. After a period of very slow growth, the bits entered a period of sustained growth through the 1990s driven by technology improvements in the cutters, inserts, and bit technology. The author will highlight the significant growth in the market for oil and gas drill bits, and PDC bits in particular in the past 5 years, and demonstrate the impact of this technology on the superabrasives industry as well as the bit industry.

Introduction (1)

Since the invention of the carbide supported polycrystalline diamond cutter (PDC) by General Electric in 1971 [1] this technology has made substantial changes in many material removal industry segments. This paper will trace the history and significant milestones of the PDC cutter and diamond enhanced insert (DEI), and PDC and roller cone bit technologies on the oil and gas well drilling industry through the last three decades. The author will focus on advances in synthetic diamond cutters and inserts and other factors which have significantly increased drill bit performance and drilling efficiency to a point where PDC bits have made significant headway into applications once dominated by the venerable rolling cone bit introduced by Howard Hughes Sr. and the Hughes Tool Company in 1909. Diamond enhancements on the roller cone have also became a significant segment of the bit industry, although gradually, after their introduction by MegaDiamond in 1986.

The key bit company customers have insisted on pushing the technology and performance envelope, not allowing these cutters to become a commodity item. As a result, PDC cutters and DEI are now, arguably, one of the largest segments of the super abrasives industry, and this technology is playing a significant roll in changing how and where oil and gas wells are drilled.

Early PDC Cutter Development and Market Conditions (2)

After being first introduced into the drilling industry at Hughes Tool Company (HTC) by GE Carboloy in late 1972 (private notes at HTC) the PDC cutter and bit technology progressed slowly for several years as a wide variety of issues were being addressed. The first public introduction of the PDC cutter for oil field drill bits was in the technical manual "Compax® Diamond Blanks, Progress report of General Electric Company Compax diamond drill blanks for oil and gas drill bit applications" [2] in the fall of 1973. To support the manual, technical presentations were made to the established drill bit manufacturers, and in many industry forums.

The early cutter was available as a carbide disc 0.330 inches (8.38 mm) diameter by 0.110 inches (2.8 mm) thick, with a 0.020 inches (0.5 mm) thick PDC layer that was un-chamfered. A Compax "slug system" that later became known as the stud cutter was also available where the PDC blank was brazed to a carbide stud for easier attachment into steel body bits to allow design freedom (Figure 1).

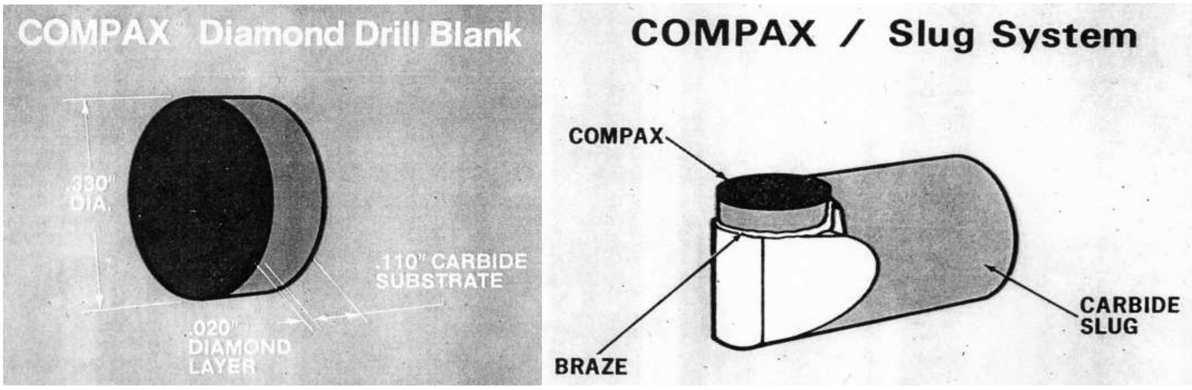

Fig 1. Schematic of early PDC diamond layer and substrate taken from Compax Manual.

The braze alloy, BAg-1, was chosen for this attachment to keep the temperature of the cutter below the thermal degradation temperature of the PDC layer. The Compax technical manual contained detailed results of the testing of the PDC drill blank cutters conducted at the University of Tulsa Drilling Engineering Department with the work supported by GE and was intended to help jump start the use of this innovative new technology with data from an independent University laboratory recognized within the oil industry. A wide variety of wear and impact test were run and reported in the manual along with the photos of the test samples before and after the testing. Much of the initial laboratory testing demonstrated that the cutter could replace the natural diamond “surface set’ bits that were then used in the hardest and most abrasive rocks. The focus switched in the next couple of years to the more conventional and much larger market; the soft to moderate formations typically considered “steel tooth roller cone rocks” at the time. This manual also highlighted the first Laboratory drilling tests of the early plate style bits at the University of Tulsa, in 1973, and the initial field trials by Exxon on the fabled King Ranch in July of 1973.

A year before the PDC cutter was introduced to the oil exploration industry, there had been the major introduction of the innovative “O” ring sealed journal bearing tungsten carbide insert (TCI) bit by the Hughes Tool Company. This new bit was providing a step change in performance with bit life, and reliability increased several fold [3,4]. The other established roller cone bit companies were focusing their technical staff on introduction of their own versions of the sealed journal bearing TCI bit. It was revolutionizing the way wells were drilled and had quickly dominated the market place. These bit companies were making large capital expenditures in technology, and on plants and equipment to produce this new journal bearing bit. The surface set bit companies were looking at both of these new technologies as serious threats. These innovations were both introduced at the time when the oil drilling industry had been in a steady declining market for the past 15 years (Figure 2).

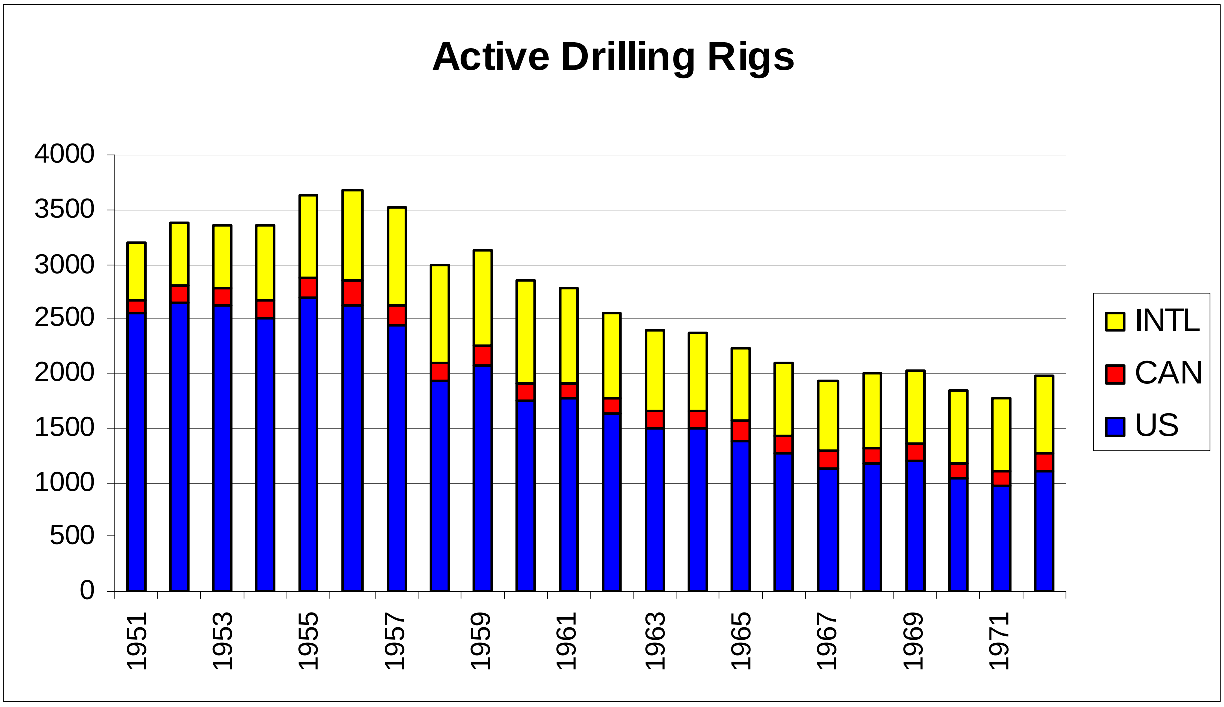

Fig 2. Bar chart of worldwide drilling activity (1951-1972)

With the discovery and ongoing development of the large oil fields with high volume production rates in the Gulf of Mexico, Persian Gulf countries, North Africa, and other places the need to drill wells in the heavily explored North American basins was less attractive. It was hard to absorb both drill bit innovations with the same technical and economic resources, and the improved TCI bit employed known application and drilling technology and was readily accepted by the drilling industry customers.

First PDC bit runs and early commercial development (3)

The first oil industry publication of PDC bit results in commercial oil wells was by Bower, Eaton, and Martis in 1975 in the Journal of Petroleum Technology [5]. At that point testing of the PDC cutter, as well as the initial flat face bit design concept had been conducted at the University of Tulsa Drilling Research Center. There had been three limited commercial trials conducted by GE designed bits with key oil field companies in the United States. The roller cone and natural diamond bit companies had not yet embraced this technology nor conducted any field trials, but some were busy conducting their own proprietary laboratory test and making their own proprietary conceptual bit designs. There were many problems with the early cutters and bit designs and these had to be solved. Progress was slowed by the market factors mentioned above, and the technical factors covered below.

In July 1973, GE had arranged for the first test run of one of their early bit designs to be made on an Exxon well on the fabled King Ranch in South Texas. Bit cleaning was thought to be an issue in portions on the run, three of the cutters failed at their braze joint, and two cutters broke through the carbide studs. These premature braze joint failures had been seen in the earlier Tulsa drilling test as well. Subsequently, a second bit with improved hydraulics to focus on the cleaning of the cutters was run in Hudson, Colorado, where it was reported to have drilled fast in a sand – shale sequence, but it deviated significantly from the prescribed well path, and again suffered several lost cutters do to suspected braze joint problems.

In April of 1974, the third bit was run in San Juan, Utah. It had an improved stud design and improved bit profile. It replaced three mill tooth bits on an offset well, but suffered from a lost nozzle, and damage to the bit, thought to have occurred at the end of the run from running into a hard formation. A fourth bit, this time a mineral exploration core bit, was run in early 1974 in an iron mine in Upper Michigan, drilling into hematite strata, where the offsets were typically natural surface set diamond bits. This run was reported at a Canadian mining conference in April 1974 [6].

Through 1974-76, cutter improvements were evaluated with a few key customers within the bit companies and entrepreneurs. Many of the issues that had been identified in the early laboratory and field were addressed as well as those observed in the continued testing. The solutions were incorporated into the Stratapax® product line of PDC cutters which were introduced commercially by GE in December 1976. The product line included the original 8mm and new 13mm cutters and a longer substrate (LS Bonded®) design which facilitated attachment onto bits and provided a more impact resistant cutter. Several shapes and configurations were now commercially available [7] (Figure 3).

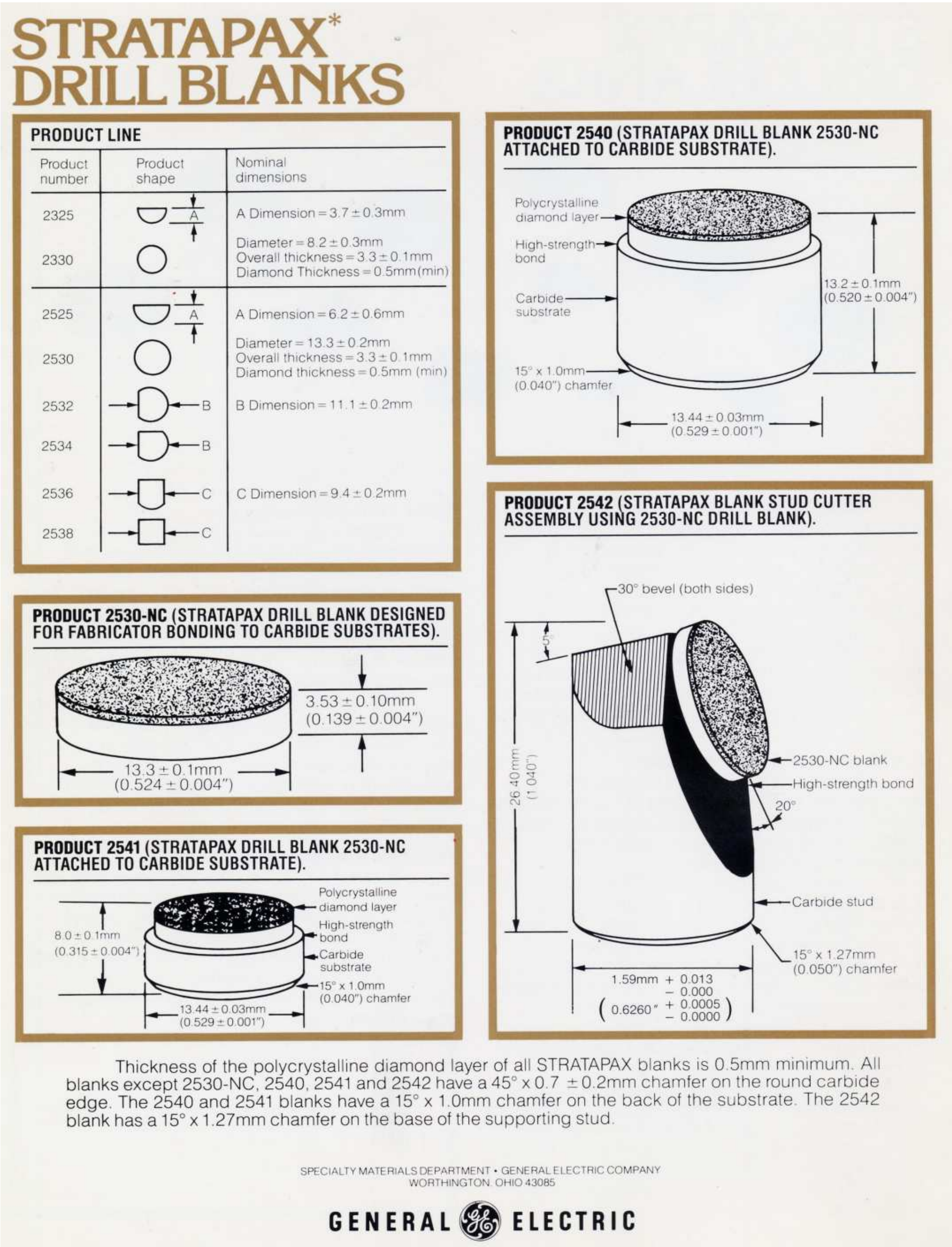

Fig 3. GE's Stratapax cutters available at product introduction, 1976.

The name change from Compax to Stratapax helped to eliminate the confusion in the bit industry between bits with tungsten carbide compacts, and diamond Compax. Many bit companies were now aggressively working on their own improvements in brazing, and attachment technologies, as well as PDC bit designs and applications knowledge.

While the PDC cutter was introduced at a low point in the drilling market, the new PDC bit was now being introduced against the backdrop of a major shift in drilling activity. There was a boom in the drilling industry as the world looked for more secure sources of energy. The number of active rigs drilling for oil and gas in 1977 was at a 20 year high (3444 in December 1977), rapidly rising to near double the recent low of 1764 in 1971. It would continue to rapidly increase for another four years (Figure 4).

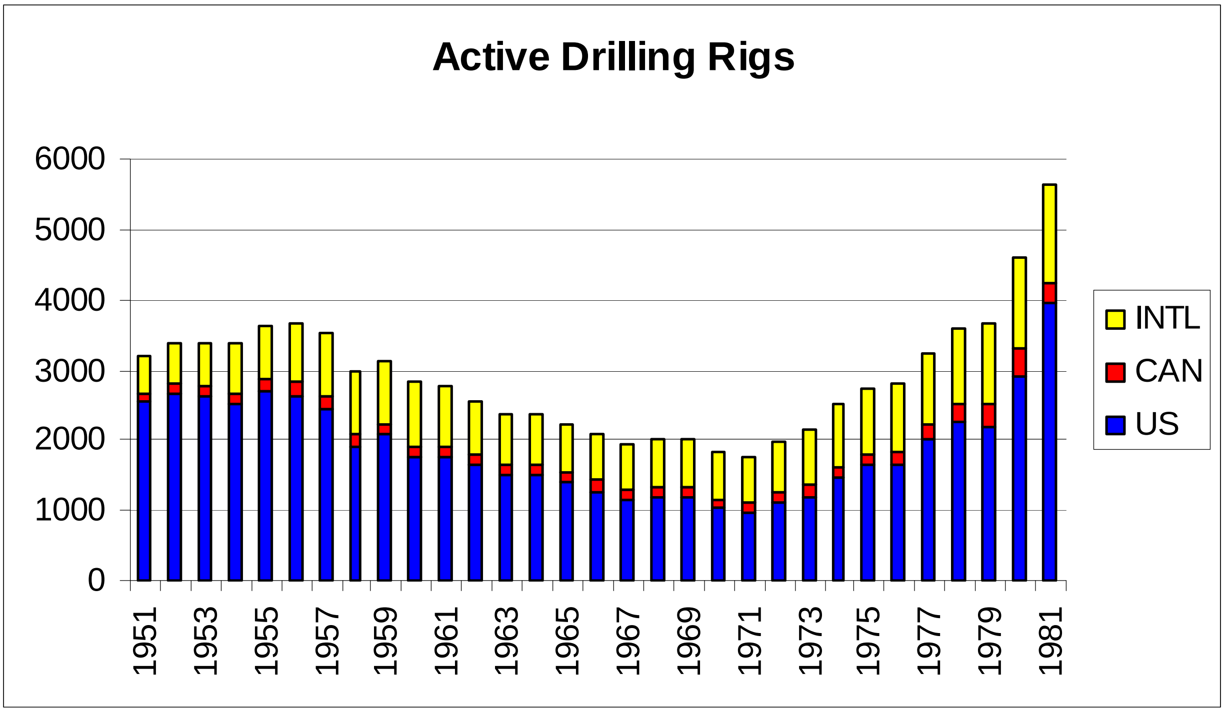

Fig 4.

Many early successes and studies were being reported at the drilling industry technical conferences and in their associated literature between 1977-1979 [8-16]. Most of the more successful runs reported were in evaporites that contained little shale or hard and abrasive streaks. Although soft, drilling shale and similar rocks were a source of significant problems for PDC bits and development efforts to solve this will be discussed later.

One industry estimate was that 2% of the bits consumed in 1977, the first year of full commercial use, were PDC. The same source estimated the potential growth to be up to 20% of the market by 1981. That growth rate would be hard to manage given the issues of trying to introduce new technology which still had some technical limitations into such a divers and global market. Another source from a major bit manufacturer forecast a conservative slow growth for the PDC with a potential of 25% of the drilling market by 2000, assuming problems with the early cutters were overcome. The actual market growth will be discussed later in the paper. Review of the Hughes Christensen world wide bit record data base revealed that as late as 1980, less than 2% of the footage was being drilled by PDC bits.

The United States Department of Energy (DOE) was also very active in supporting the development and understanding of these new cutters and innovative bit designs employing them with support provided by GE [17-19]. The DOE involvement was driven by the oil shortages and the price spike brought on by the geopolitical factors and resulting oil boycott of the mid 1970s and the U. S. Government's new interest in developing the U. S. energy resources. I am sure many people remember the high prices, shortages, and long lines at gasoline filling stations. The DOE was very active at publishing their results of laboratory testing, bit modeling, and thermal modeling of cutters over the next several years, while the bit companies and customers were publishing the results of their actual drilling applications.

Many individuals and companies were experimenting with this new PDC cutter, and developing bits to utilize them. Diamant Boart reported some limited success in drilling salt formations in the Persian Gulf and the North Sea in 1974 and 1975, while the cutters were still in their infancy and developments were on going. Entrepreneurs Davis and Hicks experienced some success in South Texas sands in the late 1970's. The first widely applied PDC bits were developed by Drilling & Service (D&S) lead by John Barr in the U.K. North Sea and Stratabit led by Mahlon Dennis and Bill Mauer in the U.S. Eastman Christensen had some success in prototype bits in the North Sea as early as 1976, adapting the cutters to the matrix used in the surface set bits and continued the development of a standard PDC product line to augment their leadership position in surface set natural diamond bits.

Innovations like chamfered cutters, non planer interfaces, fishtail bits, and rental and repair of the bit versus sale of the bit, were pioneered by Stratabit [20,21]. Stratabit was later to be come part of Diamant Boart, and eventually Halliburton's Security DBS operation, D&S became part of Hycalog, now part of Grant Prideco, and Eastman Christensen merged with Hughes Tool Co. and is now part of Baker Hughes. Numerous other start-up companies and divisions of the major oil field service companies were introducing a PDC product line during or shortly after this period. Major oil companies like Shell were conducting their own research and working with bit suppliers to develop bits and to understand the best way to apply this new technology [10]. It was a period of much innovation and learning, although the rate of penetration of PDC technology into the drill bit market was still slow and steady.

Problems which were identified and still had to be resolved for the full potential of the PDC cutter to be recognized included: understanding and managing residual stress in the cutter, improving overall cutter durability, eliminating edge chipping, improving thermal degradation during drilling, drilling through interbedded formations, bit balling in water based drilling fluids, improved design tools and bit designs, and improved understanding of the applications and formations which these cutters could be successfully used in.

Expansion and Competition of the Cutter Market (4)

Many innovations in drilling practices, bit designs, hydraulics, and the cutters were introduced in the late 70s and through the late 80s. These improvements and better cutter technology helped pave the way for the wider commercial success of the PDC cutter. Competition in the cutter field and a growing bit market also entered the picture and helped drive the technology forward.

Valdiamant, the PDC department of Valeron, started in 1979, and by the early 80s was supplying prototype cutters to the bit companies. Their entrance to the market was as a supplier of cutters custom made with input from the bit companies and they were instrumental in the development of the first commercially successful non planar interface (NPI) cutter, the Claw Cutter®, which was introduced into the market by Stratabit in 1984. This cutter dealt with the troublesome residual stress problems thought to be responsible for some of the table delamination of cutters and generally detrimental to cutter performance. Valdiamant was also the first to introduce the 19mm cutter, now an industry standard. Valdiamant was acquired by GE, now Diamond Innovations, in 1987.

Now know as Element 6, DeBeers Industrial Diamond Division (DEBID) entered the PDC cutter market in 1981 with both stud and cylindrical cutters, and all of the major synthetic diamond suppliers and bit companies were now well engaged in the pursuit of commercializing the PDC cutter in drilling for oil and gas. The typical PDC cutter from DEBID had a 0.040"

(1mm) thick diamond table which was substantially thicker than previously available, and the increased diamond volume and perceived improved toughness and wear resistance proved to be a benefit in certain applications and they made significant market penetrations by the end of the 1980s. DEBID became a significant supplier to the drilling market in the 1980s. By 1986, they had introduced PDC cutters up to 50 mm in diameter. There was a flurry of activity among some of the bit companies to develop very aggressive light set bits that could drill soft sticky formations and could make use of the ultra large cutters. Some designs even resembled the fishtail drag bits which the Hughes rolling cone bit had made obsolete some 75 years earlier. Later, in conjunction with a major bit manufacturer, they pioneered the development and introduction of a layered diamond table cutter with a hard wear resistant diamond feed on the face, backed up by a tougher diamond feed on a stress engineered non-planer interface. This cutter feature became the foundation for a market leading drill bit product line [22]. They remain a leading supplier in the industry today.

US Synthetic entered the PDC cutter market in 1983. Through customer driven proprietary cutter development programs focused totally on the drilling market from 1991 forward, they became the market share leader in 1997. They are a leading supplier focused only on the drilling market. They were the first to commercialize tough durable cutters with what was the thickest and most impact resistant diamond tables in the industry at the time, and the first company to be predominately customer driven in their development activities [23].

Other suppliers like MegaDiamond, Novatek, Dennis Tool, and Phoenix Crystal each were involved in supplying PDC cutters, rolling cone inserts, and diamond bearings to the bit companies and others making down hole tools. Some forged strong ties with a particular end customer, became a significant factor, and were eventually integrated into their customers. There has been sporadic interest in drilling from the Russian, Chinese, and Japanese suppliers from time to time, but none are major suppliers of cutters into the current premium PDC cutter markets.

The number of rigs actively exploring for and developing oil and gas deposits had continued to increase and hit an all time high of 6227 in December 1981, with 4520 of these just in the US. This is more than 3X the number of potential drilling customers just 10 years earlier. Bit companies were rapidly introducing the improved bit technology to the drilling customers, and the customers were becoming receptive to the new technology, but many technical challenges remained to be solved with the PDC bits. The bad news for PDC bits was that only a very small portion of the US market was PDC drillable with the technology available at that point in time, and the roller cone bit continued to be a dominating force in the market place. Through the early 1980s the diamond tables delaminated from the substrate too often, the bits lacked durability in many markets with spalled, broken, and chipped cutters dominating most dulls, and the economics still favored the roller cone bits in most markets with hard or interbedded formations. Bit hydraulic and cleaning improvements were still issues that were getting attention with significant advancements yet to be made. Thermal stability issues were identified and many developments were conducted in that technology as well.

Commercial Success, Bit Developments, and Wide Spread Application (5)

There was a rapid growth in drilling activity in the late 70's and early 80's, and a subsequent rapid fall driven by surplus supply and low oil prices in the mid 80's (Figure 5). In this period of substantial contraction in the drilling industry, cutter and bit developments continued and the amount of hole drilled by PDC bits showed a slow steady rate of increase to 5% of the market by 1990 (Figure 6). Part of this % increase was from the virtual collapse of the U.S. land drilling.

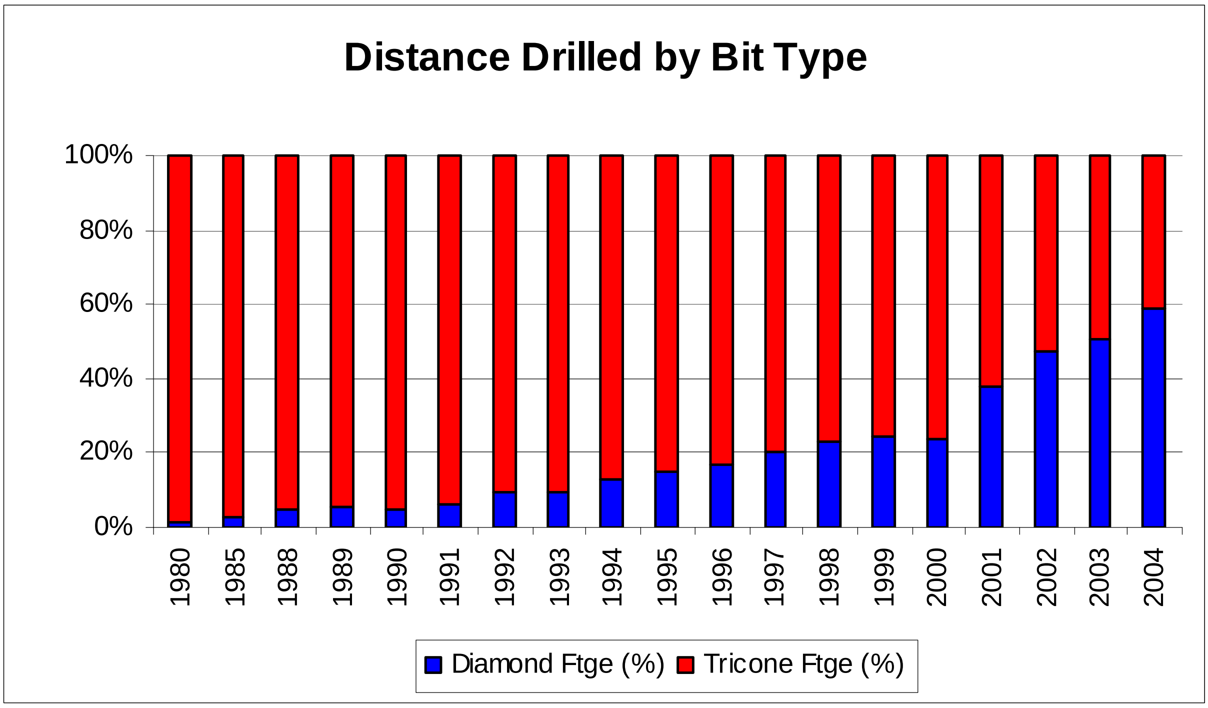

Fig 6.

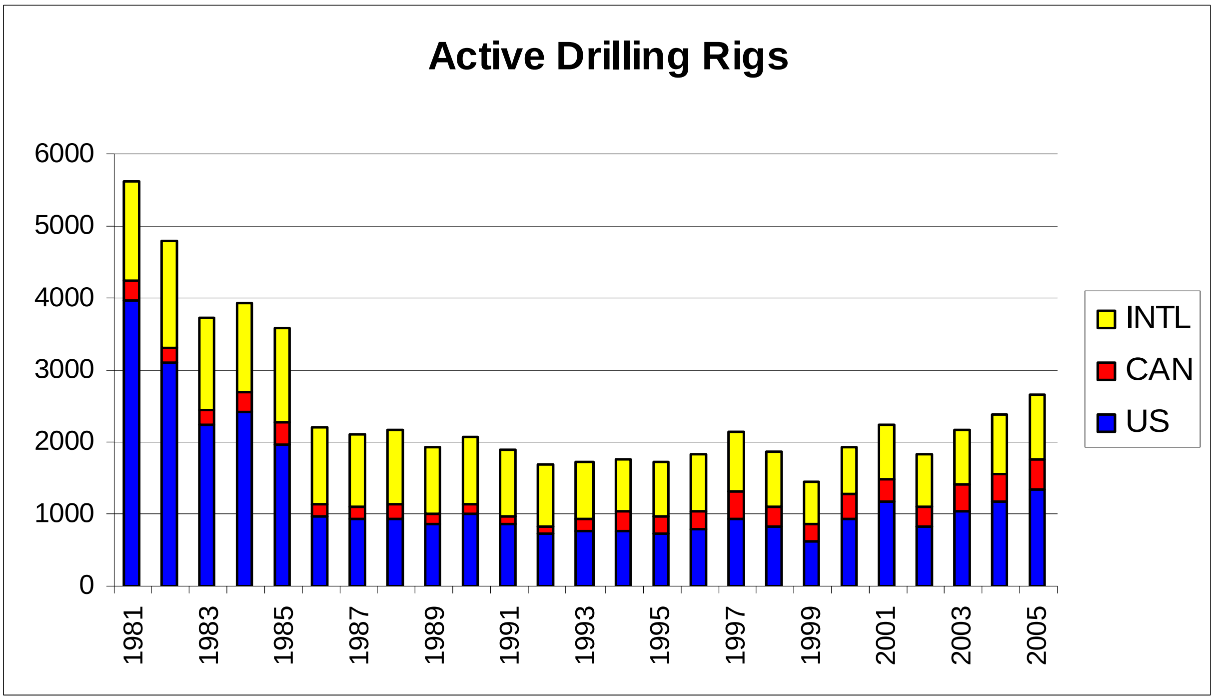

Fig 5.

During this time of severe market disruption, the US domestic drilling market reached a new historic low in 1989, again in 1992, and nearly collapsed in 1999. Many of the drilling contractors went bankrupt and the oil companies were consolidating. Companies in the bit business were also consolidating into a smaller, but more financially viable number of competitors with more technical resources. These companies continued to develop and introduce new technology and improved drill bits to a very depressed market place. The major bit suppliers all compete in a highly charged market place, where a technological or market lead can be fleeting. The properties of the cutters were gradually improved and the long substrate cutter that had been introduced was much more adaptable to the matrix style bit technology which was adapted from the surface set bits and became favored for PDC bits. The ability to predict where these bits would work best was gaining momentum as application expertise was improved. Top Engineers at the major oil companies were publishing their insights on the PDC bit's technology limitations, areas for improvements, and applications knowledge [24-28].

Improved Hydraulics (6)

Most major oil companies were working with the bit companies to develop new PDC drill bits, improved application techniques, and to identify the formations in which they could be successfully applied. Cutter and bit suppliers were also working to help provide this guidance to the customers. Opinions varied significantly on what established a successful run, and the best target applications [29,30]. In general, long homogeneous sections of non sticky formations with no hard and abrasive streaks were required for a successful run with the PDC bits of the middle to late 1970s and early 80s.

Drilling through shale intervals could be problematic and many papers dealt with a variety of solutions to this problem. Since most drilling involves significant shale intervals, and because of the potential benefits to lowering well costs if this problem was solved, the problem was being worked on in Universities, the major oil companies, the DOE, the bit suppliers, and the PDC suppliers themselves. The studies and improvements in this area were continued well into the 1990s with improvements to the drilling fluids to control the bit balling phenomenon encountered in shale playing a significant impact on the eventual success. Innovative patented bit designs were also keys to success in some of the applications. Many papers were published on the issues and improvements, and opinions varied significantly on the optimized solution to the technology challenges [31-40].

Today most of the major bit manufacturers use computational fluid dynamics (CFD) as a part of their bit hydraulics design process. Bits may be optimized for cleaning, erosion, or cooling depending upon the demands of a particular application. Hughes also runs newly designed bits through a full-scale high pressure drilling simulator to more adequately evaluate the effects of the CFD on cleaning.

Bit Stability (7)

By the late 80s the problem of fractured cutters and their terminal effects on bit life were being researched on a more global scale than just the cutter properties. Bit vibration and drilling dynamics were being studied by many in the industry including Coy Fielder at Stratabit, and Joe Kelly at Hughes through proprietary in-house efforts at their respective companies. A whirling bit drills a multisided, polygon shaped hole instead of a round one. The result is frequently severe impact damage to the cutters. Figure 7 shows a bottom hole pattern of an unstable bit which is drilling an oversize hole in a phenomenon know as bit whirl.

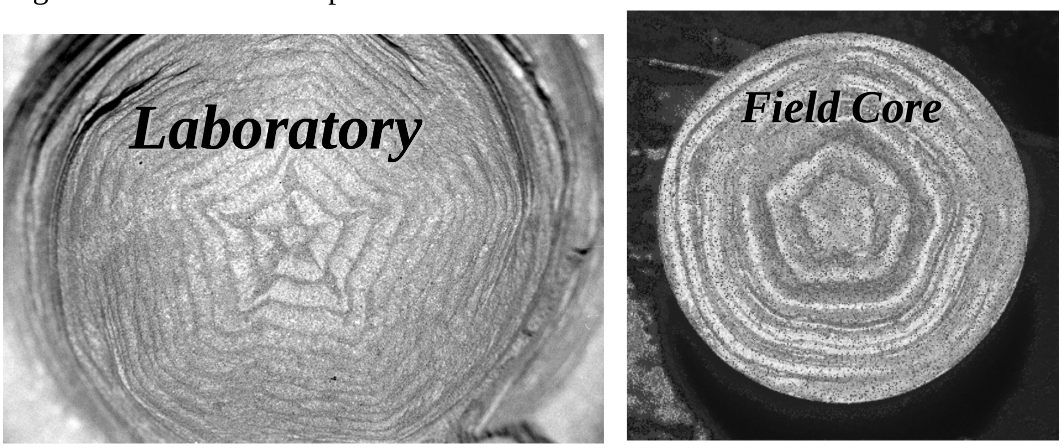

Fig 7. Bottom hole pattern drilled by unstable (whirling) PDC bit

At Amoco Drilling Research in Tulsa, Oklahoma, a team led by Tommy Warren was also researching the issue of cutter damage and bit performance. This team published seminal papers in the oil field literature describing the problems, observations, and their patented solutions, and received significant recognition in the industry for their efforts [41-44]. Eastman Christensen commercialized these Amoco patents in an Anti-Whirl ® product line under an innovative license arrangement. The royalties were used by Amoco and EC to fund a jointly managed PDC bit research and development program to further the introduction of improved technology [45-47]. The need for further improvements in bit technology were seen by Amoco to far overshadow the benefits of collecting and banking the royalties at the corporate headquarters, and this innovative use of royalties was a far cited venture by the end user for providing a mechanism for furthering bit improvements.

With the introduction of a stable bit frame, the benefit of improved cutter technology finally could be exploited. The improved bit gave the cutters a chance to drill with out suffering high and catastrophic loads leading to massive cutter fracture. A step change in reported footage was seen in the industries bit records and the PDC bit market saw a step in growth with the introduction of this technology and the improved non planer cutters that shortly followed it. Between 1990 and 1992, with the introduction of the Anti Whirl® bits, PDC bits moved from 5% to 9% of the footage drilled. Most bit suppliers in the industry utilized the work of Amoco, or developed some other alternate method to provide stable bits and there were many patents and publications over the next several years [48-58].

Further developments continue to this day with a significant effort on computer modeling of the bit's expected behavior, cutter work rates, cutter loads, etc. in the drilling environment. A patented depth of cut control design process which helps control a bits torque response while drilling, Smooth Cut®, has been found by Hughes to add stability to a bit, especially in highly interbedded applications. Hughes runs a newly designed bit through a full-scale laboratory drilling test to verify and quantify the stability of the bit before it is sent to the customer's well site. Both the improved modeling and the full scale testing before the bit is released for sale have helped to dramatically increase the success rate of a new design.

Computer Modeling (8)

Another contributor to the success of the PDC cutter was the development of computer models which helped in the design, and understanding of the behavior of PDC bits. Many dealt with balance forces on the bit, the rock – cutter interaction, and the drill string behavior and influence on the bit. A wide variety of these models were developed by Universities, the DOE, oil companies, and the bit companies. They continue to be refined and used to reduce the time to market for new products and to increase the potential for a bit to be successful in it's application. The more recent, more complex models developed and used by the major oil service companies combine influences of all of the above factors and are coming into wide use [59-66]. A significant amount of study, largely with computer modeling and some laboratory verification, was conducted on the thermal behavior and thermal management of the cutters [67-73]. CFD is used extensively in the bit industry, as is FEA for cutter design, bit body strength, and manufacturing processes.

Cutter Improvements (9)

With the development of the stable bit, efforts could now be concentrated on improving the cutters in the 1990s. The understanding of the role residual stress played in cutter performance and how to measure, and manage it was coming into its own in the early 1990s [74]. Finite element modeling became the standard practice for understanding cutter behavior and cutter developments. A typical solid model and FEA output is shown in Figure 8.

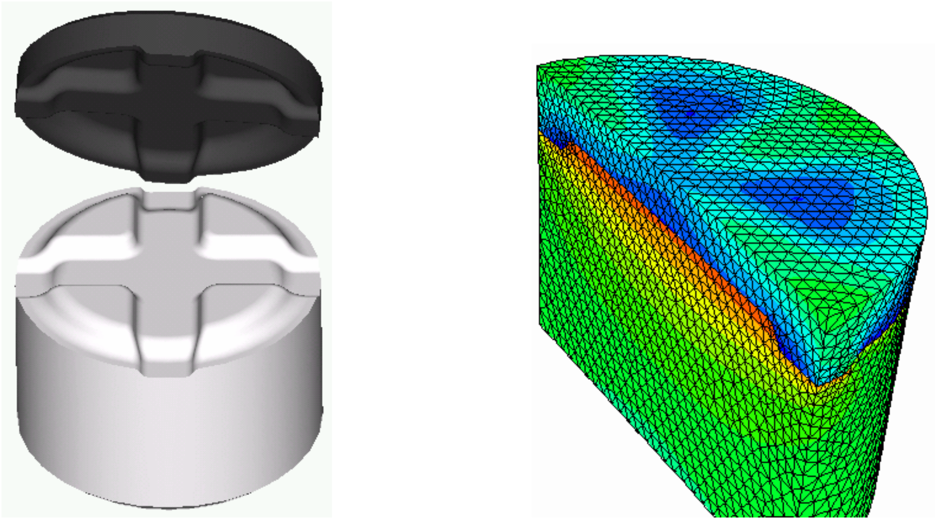

Fig 8. Solid model FEA Model of new style cutter technology

Proprietary cutters with non-planer interfaces and better residual stress management have become the norm in the industry with a plethora of interfaces being patented by the suppliers, the bit companies, some oil companies, and individuals.   Managing the residual stress through heat treatments, and manipulating the carbide properties have been patented and commercialized [75]. Much of this work was driven by the bit companies in joint efforts with the PDC suppliers in a very competitive market for both. It took several years however to go from the initial NPI cutter in 1984 to where multiple users and suppliers were willing to entertain the idea of “designer” cutters, or signature cutters, and dealing with the effects it presented to the market.   Another step change was seen in bit performance with the widespread introduction of the NPI cutters to the stale bit frames in the early 1990s and by 1995 the PDC bits were drilling nearly 15% of the footage, up from 9% just three years earlier.

Many improvements to the diamond table were introduced from the 1990s and up to today, which have raised the durability, wear resistance, consistency, or extended the application range of PDC bits. Cutters with diamond tables over 4mm thick were introduced. These had the durability to extend the life of the bits through interbedded formations. A peripheral ring of diamond on the outside of a non-planer interface became a popular and near standard feature on many cutters used recently [76-79].

While most early cutters used a uni-modal diamond feed, multimodal feeds became the norm in the 1990s. A unique layered diamond table cutter was commercially introduced in 1999, where a fine, abrasion resistant layer was backed up by a coarser impact resistant layer over a stress engineered interface.   This is still a broadly applied cutter technology. A typical example is shown in Figure 9. These layered cutters offered further potential in abrasive and high impact applications and were part of the basis for a new product line by a major bit company.

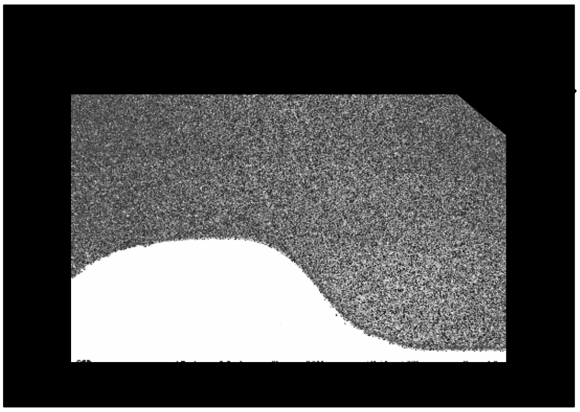

Fig 9.

Highly engineered application specific "signature" cutters are now the norm for many bit companies. Being able to tailor the performance of the cutters though managing the residual stress, load carrying capacity of the cutter, table thickness, wear resistance, etc. allowed for application specific cutters to be utilized in particular parts of the bit to optimize the performance and is protected by patents [80]. Application specific cutters are now commonly utilized all over to optimize the bit for a given type of drilling, formation, or application. Many papers were presented in industry forums highlighting the performance gains being made by this package of these new cutters and bit technologies [81].

Improvements in chamfer technology and the use of multiple chamfers, patented by Hughes in 1995 became wide spread in the mid 1990s [82-85]. When properly utilized, the fracture resistance of a cutter during drilling increased by 100% with a corresponding significant increase in a bit's durability and length of run. Another innovation was the introduction of a patented polished cutter for drill bits by Hughes in 1995. Research in the laboratory had shown a marked reduction in friction of the cutter in certain formations and this was proven in full scale drilling tests, and in field trials. Bit performance was measurably improved and this feature is still widely employed [86,87].

Some companies decided to explore backwards integration in terms of the research into the material properties and basic cutter technologies, with Norton Christensen, Diamant Boart, Hughes Tool Co., Hycalog, Smith International and others acquiring HTHP apparatus (aka diamond synthesis presses) or a cutter supplier outright in order to conduct their own cutter research,. At times there was a certain level of frustration by what they perceived as continued performance limitations with the current cutters on the market and resistance to development of signature or proprietary cutters. Others believed there may be cost benefits from integration. There were also some efforts by the bit companies to jointly develop improved and proprietary cutters with the PDC suppliers. Many of the bit companies were determined not to have this product turned into a commodity, and kept the focus on improved bit life and performance. Lower cost generic products were generally not seen as the key for successful growth in this market. There were many smaller specialty PDC suppliers as well who made inroads into the market, often concentrating their efforts with one or two bit companies. Two of the drill bit companies have since backwards integrated through mergers and acquisitions and are supplying a portion of their own cutters.

One industry estimate in 2003 was that the bit industry used $155M of PDC cutters and diamond inserts, with about 60 % coming from the major suppliers, and 30% from captive sources. Growth through 2007 was projected at an annual rate of 4% to $182M [88]. It is felt by some leaders in the industry today that number and projected growth rate was conservative and the market is substantially higher than that in 2005 driven by several factors which will be discussed later.

Development of the Global PDC Bit Market (10)

As shown in Figure 6 the growth rate for PDC has been relatively slow until the recent few years. Step changes or changes in the rate of growth in PDC bits in drilling were generally preceded by introductions of new technologies or market forces.

The first commercially successful runs known were by test bits designed by Diamant Boart in the Persian Gulf and North Sea in 1974 and 1975. Developments continued in most market areas, but with a concentrated effort in the North Sea applications, and many of the successes in the late 1970s were in this high cost market, where high cost-high reward innovations which reduced drilling cost could be implemented. However, in spite of the large amount of publicity and hype, in 1980 less than 2% of the footage in the world was drilled by PDC bits.

Through the 1980s the focus moved to the Gulf of Mexico which also had a relatively high cost operating environment, and by 1988 the Gulf surpassed the North Sea in terms of the units used, but the North Sea still led in terms of the market revenue. In 1988, approximately 1200 PDC bits were run in the North Sea, with nearly 1300 in the Gulf of Mexico, but the revenue was approximately $25M in the Gulf, and $34M in the North Sea. These were the two largest markets at the time. PDC bits accounted for less than 5% of the total footage drilled hat year, and just over 5% by 1990 [89].

Two studies were published in the late 1990s highlighting the technology and performance advances in the roller cone and PDC product lines. The studies analyzed the industries largest data base of over 100,000 bit records from all manufacturers, and clearly demonstrated that both product lines had delivered improved performance and value to eth customers during the study period. Rate of penetration was increased 11% for the roller cone bits, and 57% for the PDC bits. Bit life improved for both product lines, with footage up 19% for the roller cone, and a staggering 115% for the PDC bits. What made this study counter intuitive was that even with the PDC bits replacing tricone bits in the soft to medium formations, taking much of the faster and softer (long runs) markets, the rolling cone products had still yielded an improved performance in the remaining hard rock markets [90,91].

As mentioned above, the combination of the stable bit and improved cutter technologies through out the 1990s, along with significant improvements in drilling applications knowledge led to improved performance and an increased rate of growth for the PDC bit, with it accounting for 24% of the footage drilled by 2000. This is a much higher rate of growth than in the 1980s. The original estimate by a major bit company in 1975 was right on target.

Market Impact Now: New Technology and Twenty-first Century (11)

As can be seen in Figure 6, PDC bits rapidly expanded in application in the last four years. The variety of features to provide a more stable bit which had been introduced by the bit companies was becoming more widely used. Formations considered un-drillable by PDC bits a few years earlier were now being drilled economically and reliably. The bits were now able to penetrate formations with hard interbedded streaks. The rule of thumb for identifying the applications of an upper limit of 20 ksi unconfined compressive strength in the rock, if the drilling practices were managed well, was being broken.

Application specific bits with improved design and application review processes were introduced by the bit companies. Hughes pioneered the process of running new bit designs through their drilling laboratory to confirm the design objectives for rate of penetration and stability were met, before the bit was shipped to the customer. These application specific, customer focused efforts further extended the reliability and life of PDC bits [92,93].

Improvements to modeling of the Bottom Hole Assembly (BHA), or down the hole tool components which are required to drill the wells, was instrumental in the understanding and management of torsional oscillations and other modes of bit vibration which could lead to bit damage. Managing the bit vibrations though better BHA design has helped to extend the application range and reliability PDC bits.

Other design improvements provided a step change in steerability for bits used in directional wells. Most offshore and many land wells are drilled using steerable assemblies to direct the bits to the target formations. Some of these wells employ a complex well geometry such as an s-curve and are targeting oil reservoirs that may be only a few meters thick with a horizontal entry. Roller cones had traditionally been used for much of this as they are very easily steered, while the traditional PDC bit with a higher operating torque had limitations in this area. The new PDC bit with the patented steerable features has been shown to markedly reduce drilling cost and reliably meet the customer's objectives. It is rapidly growing in application [94,97].

The drilling industry has undergone another growth spurt as the global demand for energy has increased, driven by a marked increase in Asian demand. The rig count is currently at a 20 year high, driven largely by the US and Canadian markets as shown in Figure 5. In 2004, PDC bits accounted for approximately 50% of the revenue in the bit industry and nearly 60% of the footage drilled,. Growth is expected to continue in the coming years. An increased conversion the past few tears to PDC bits was accompanied with the step change in performance after the introduction of a variety of improved cutter technologies coupled with the above mentioned bit features and a focus on specific applications. Several papers have been presented in industry conferences. With the ability to drill hard and abrasive formations, and formations with hard interbedded streaks, PDC bits are now being used in nearly all of the North American land drilling applications, and this is the dominate segment in the current drill bit market.

Diamond Enhanced Inserts in Roller Cones (12)

The first diamond enhanced carbide inserts were provided by GE, through their Carboloy Division, to the Hughes in 1968. An additional effort was made and initial patent protection taken, but only limited testing and commercial development was pursued [98]. This effort did not progress beyond the initial step, and their efforts were later directed to the PDC cutter developments. Nearly two decades passed until the first commercial parts were introduced in the industry by MegaDiamond in 1986 and they were widely reported in the industry conferences and publications [99,100]. These first inserts were based on the multi layering stress management concept patented by MegaDiamond and were reported to be successful at modifying the residual stress in complex shaped parts like a rolling cone insert [101]. The first parts were ovoid shaped inserts and were the same size and shape of the carbide counterparts they replaced. They were also used in percussion as well as rolling cone bits, and were slowly to change the rolling cone bit technology. In the next two decades a wide variety of interfaces and multilayer technologies were developed as more companies got involved in this market, the shapes got more complex, and the demands on the inserts increased [102,106]. Fig 10 shows an example of the wide variety of sizes and shapes available today. These are readily available today for enhancing roller cone bits in hard or abrasive applications not suitable for PDC bits.

Fig 10. Typical diamond enhanced inserts used in rolling cone bits today.

In 1989, Hughes began its efforts to utilize diamond as an active shear cutting element on a roller cone bit. The patented elements projected somewhat from the cone steel on the gage surface, to actively engage and remove the rock on the borehole wall as the cone rotated [107]. The first runs in a very demanding application in Southern Italy, were an immediate success and this feature started to grow [108,109]. These were used on the gage and were shown to provide better gage holding capability, improved seal life, and increased rate of penetration. To make them even more active, and to remove a rubbing component they were set with a patented relief angle [110]. These patented features were frequently employed with the innovative metal face seal (MFS) package developed and introduced by Hughes on the premium rolling cone bits through out the 1990s, and are still a mainstay of the in the industry today, 15 years later. In spite of the accelerated growth of the PDC bits in to the drilling market, rolling cone bits with a diamond enhanced gage make up a higher % of the product mix today that in the past, reflecting on the continued potential for diamond to play a part in the future of all drill bits.

In 1993 Hughes developed the patented diamond trimmer shear cutting insert and moved the shear cutting action into the cutting elements on the roller cone bits. These inserts went against common wisdom, and utilized a sharp ground edge to actively engage the borehole wall and were much more successful than their initial test parts with a rounded, more durable shape. This innovation was reported and described in the diamond and energy industry's literature [111-114].

One of the main issues with diamond enhanced inserts on rolling cone bits has been their cost relative to the carbide inserts they are replacing. Initially with a cost factor of 50 or 100:1 over carbide, there was a significant cost to benefit ratio that had to be overcome for them to become commercially viable. As with the PDC cutter, the relative cost of these inserts has dropped over time, and their performance has improved. Increased competition and higher volumes have been a factor as well as a series of joint projects between the diamond insert manufactures and the bit companies to develop and commercialize this technology. All of the major rolling cone bit companies now have some form of diamond enhanced insert available for use in the gage and cutting rows. This high performance segment of the drilling industry has further opportunity for growth, as the PDC bits continue their growth into the standard TCI and steel tooth applications and the demands for energy take us into more demanding drilling applications.

Summary (13)

After their introduction in the middle 1970s and their initial slow growth, PDC cutters have helped change the oil and gas exploration bit industry. PDC bits are now over 50% of the bit market, and are still growing. Diamond enhanced rolling cone bits are a significant sector of the roller cone bit market and their acceptance is continuing to grow.

Diamond elements for use in the bit industry has been one of the fastest growing segments of the super-abrasive industry in the past five years now accounting for a potential market, counting captive sources, well in excess of $200M by some estimates. It is now one of the largest segments, partially do to the substantial commoditization and price erosion in saw grits and wheel grits in the past few years.

References (14)

[1] Wentorf, R. H., etal, “Diamond Tools for Machining”, US Patent 3,745,623, , December, 27, 1971

[2] “Compax Diamond Blanks, Progress report of General Electric Company: Compax diamond drill blanks for oil and gas drill bit applications”, 1973

[3] “The J8 Journal Bearing Bit: new-tough-dependable-consistent”, Hughes Rigway Magazine, Summer, 1970

[4] J.C. Cook etal, “Development and Application of Journal Bearing Bits”, IADC Rotary Drilling Conference, February-28-1973.

[5] B. A. Eaton, SPE 5068, “Manufactured Diamond Cutters Used in Drilling Bits”, Journal of Petroleum Technology, May, 1975

[6] Ratterman, E., etal, “Core Drilling of Hematite With Compax Diamond Drill Blanks”, Canadian Diamond Drilling Association 31st Annual Meeting, Toronto, Canada, April 7-9, 1974

[7] Offenbacher, L. A., “Recent Developments in Strtapax Blank Bits”, ASME Petroleum Mechanical Engineering Conference, Tulsa, Oklahoma, October 28-30, 1979

[8] Daniels, W. H. etal, “Fabrication and Laboratory Testing of a Bit Containing Diamond Compacts’, SPE 6713, SPE Annual Meeting, Denver Colorado, October 9-12, 1977

[9] Daniels, W. H. etal, “”Design, Fabrication, and Field test Performance of Slug Type Diamond Compacts on oil Bits”, Journal of Energy Resources Technology, Vol. 101, March, 1979

[10] Feenstra, R, etal, “New Generation of Oilfield bits – Laboratory and Field Test Results”, SPE 6712, SPE Annual Meeting, Denver, Colorado, October 9-12, 1977

[11] Radtke, R. P. etal, “Stratapax Drill Bit for Gulf Coast Drilling”, Paper 77-PET-74, ASME 1977 Energy Technology Conference, Houston, Texas, September 18-22, 1977

[12] Hibbs, L.E. etal, “Diamond Compact Cutter Studies or Geothermal Bit Design”, ASME 1977 Energy Technology Conference, Houston, Texas, September 18-22, 1977

[13] Hibbs, L.E. etal, “Geothermal Compax Drill Bit Development”, General Electric Report No. SRD-78-048, April, 1978

[14] Hibbs, L.E. etal, “Simulated Geothermal Drilling Rock Drilling Using Stratapax Diamond Compacts”, ASME Energy Technology Conference, Houston, Texas, November 5-9, 1978

[15] Huff, C.F., etal, “Design of Special Performance Bits Utilizing Synthetic Diamond Cutters”, SPE 7515, SPE Annual Meeting, Houston, Texas, October 1-3, 1978

[16] Cheatham, J.B., etal, “A Study of Factors Influencing the Drillability of Shale: Single Cutter Experiments with Stratapax Drill Blanks” ASME Energy Technology Conference, Houston, Texas, November 5-9, 1978

[17] Huff, C.F., etal, “Single Point Rock Cutting Strength and Fatigue Evaluation of Gas Pressure Bonded Stratapax”, Sandia Laboratories Report No. SAND-77-1962, Albuquerque, New Mexico, April, 1978

[18] Jellison, J.L., etal, “Gas Pressure Bonding of Stratapax” Paper 77-PET-72, ASME 1977 Energy Technology Conference, Houston, Texas, September 18-22, 1977
[19] Ashmore, R.F., etal, “Stratapax Computer Program” Sandia Laboratories Report No. SADSN-77-1994, Albuquerque, New Mexico, April, 1978
[20] Dennis, M.D., “Drill Bit”, U. S. Patent 4,323,130, April 6, 1982
[21] Dennis, M. D., “Cutting Element having Composite Formed of Cemented Carbide Substrate and Diamond layer and Method of Making Same”, U.S. Patent 4,784,023, November 1988
[22] Phall, C. Etal, ‘Tool Component”, U.S. Patent 4,861,350, August 29, 1989
[23] www.ussynthetic.com/milestones
[24] Feenstra, R. “Status of Polycrystalline-Diamond-Compact Bits: Part 1-Development”, Journal of Petroleum, June 1988
[25] Feenstra, R. “Status of Polycrystalline-Diamond-Compact Bits: Part 2-Applications”, Journal of Petroleum, July 1988
[26] Glowka, D. A. “Discussion of Status of Polycrystalline-Diamond-Compact Bits: Part 1-Development”, Journal of Petroleum, February, 1989
[27] Zijsling, D.H. “Reply to Discussion of Status of Polycrystalline-Diamond-Compact Bits: Part 1-Development”, Journal of Petroleum, October, 1989
[28] Warren, T.W., etal, “PDC Bits: What’s needed to meet tomorrow’s Challenge”, SPE 27978, University of Tulsa Centennial Petroleum Engineering Symposium, Tulsa, Oklahoma, August 29-31, 1994
[29] Madigan, J.A., etal, “Applications for Strtapax Blank Bits from Analysis of Carbide insert and Steel Tooth Bit Performance”, SPE paper, SPE Annual Meeting, Dallas, Texas, September 21-24, 1980
[30] Keller, W.S., “Where and How Not to Run PDC Bits” , SPE 11387, IADC/SPE Drilling Technology Conference, February 20-23, 1983
[31] Salazar, J.A. “Development of a Predictive Model for Drilling Pressured Shale With Stratapax Blank Bits” General Electric Publication, 1980
[32] Glowka. D.A., “Optimization of Bit Hydraulic Configurations”, Society of Petroleum Engineers Journal, February, 1983
[33] Feenstra, R. etal, “The Effect of Bit Hydraulics on Bit Performance in Relation to the Rock Destruction Mechanism at Depth”, SPE 13205, SPE Annual Meeting, Houston, Texas, September 15-19, 1984
[34] Radtke, R.P. etal, “Optimization of Hydraulics for Polycrystalline Diamond Composite Bits in Gulf Coast Shales with Water-Based Muds”, SPE 11411, Journal of Petroleum Technology, October 1984
[35] Koskie, E. A. “A PDC Solution to Drilling Sticky Formations with Non-inhibited Water-Based Drilling Fluid: Experience in the Provincia Field Colombia” SPE 14430, SPE Annual Meeting, Las Vegas, Nevada, September 22-25, 1985
[36] Azar, J.J. etal, “Proper Nozzle Location, Bit Profile, and Cutter Arrangement Affect PDC-Bit Performance Significantly”, SPE 20415, SPE Drilling and Completion Journal, September, 1994
[37] Crouse, R. etal, Optimization of PDC Bit Hydraulics by Fluid Simulation”, SPE 14221, SPE Annual Meeting, Las Vegas, Nevada, September 22-25, 1985
[38] Knowlton, H. etal, “PDC Applications in the gulf of Mexico with Water-Based Drilling Fluids”, SPE Drilling Engineering, June 1988
[39] Tibbits, G.A. “Drag Bit for Drilling in Plastic Formation with Maximum Chip Clearance and Hydraulic for Direct Chip Impingement”, U.S. Patent 4,883,132, November, 28, 1989
[40] King, I, etal, “Hydraulic Optimization of PDC Bits”, SPE 20928, Europec 90, The Hague, Netherlands, October 22-24, 1990
[41] Warren, T.M., etal, “Bit Whirl-A new Theory of PDC Bit Failure”, SPE 19571, SPE Drilling Engineering, December, 1990

[42] Warren, T. M. etal, “Development of a Whirl-Resistant Bit”, SPE 19572, SPE Drilling Engineering, December 1990
[43] Brett, J.F., etal, “Low Friction Subterranean Drill Bit and Related Methods”, U.S. Patent 5,131,478, July, 1992
[44] Sinor, L.A., etal, “Field Testing of Low-Friction –gauge PDC Bits”, SPE 20416, SPE Drilling and Completion, March, 1993
[45] Pastusek, P.E., etal, “Directional and Stability Characteristics of Anti-Whirl Bits With Non-Axisymetric Loading “ SPE 24614, SPE Annual Meeting, October 4-7, 1992
[46] Pastusek, P.E., etal, “The Design and Testing of Anti-Whirl Bits”, SPE 24586, SPE Annual Meeting, October 4-7, 1992
[47] Bobrosky, D., Etal, “Anti-Whirl PDC Bits Increased Penetration rates in Alberta Drilling”, Oil and Gas Journal, July 5, 1993
[48] Clegg, J.M. “An Analysis of the Field Performance of Antiwhirl PDC Bits”, SPE 23868, IADC/SPE Drilling Technical Conference, New Orleans, Louisiana, February, 1992
[49] Weaver, G.E. “Diamond Drill Bit with Varied Cutting Elements”, U.S. Patent 4,602,691, July 29, 1986
[50] Keith, C.W., “Drill Bit with Vibration Stabilization”, U.S. Patent 5,090,492, February, 1992
[51] Keith, C.W., Etal, “Drill Bit with Improved Insert Cutter Pattern”, U.S. Patent 5,265,685, November, 1993
[52] Weaver, G.E., etal, “ A New PDC Cutting Structure Improves Bit Stabilization and Extends Application Into Harder Rock Types”, SPE 25734, IADC/SPE Drilling Technical Conference, Amsterdam, The Netherlands, February 23-25, 1993
[53] Clayton, R.I., etal, “Development of Whirl Resistant PDC Bits”, SPE 26954, Latin American/Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina, April 27029, 1994
[54] Roberts, T.S., etal, “Rotary Drills with Extended Bearing Surfaces”, U.S. Patent 6,129,161, October 10, 2000
[55] Schell, E.J., etal, SPE 79797, “New Stable PDC Technology Significantly Reduces Hard Rock Cost per Foot”, SPE/IADC Drilling Technical Conference, Amsterdam, The Netherlands, February 19-21, 2003
[56] Mensa-Wilmont, G., Etal, “Drill Bit and Cutting Structure Having Enhanced Placement and Sizing of Cutters for Improved Stabilization”, U.S. Patent 5,607,025, March 4, 1997
[57] Mensa-Wilmont, G., Etal, “Innovative Cutting Structure Improves Stability and Penetration Rate of PDC Bits Without Sacrificing Durability”, SPE 39310, IADC/SPE Drilling Technical Conference, Dallas, Texas, March 3-6, 1998
[58] Doster, M. L., etal, “Drill Bit with Lateral Movement Mitigation, and Method of Subterranean Drilling”, U.S. Patent 6,575,256, June 10, 2003
[59] Miska, S., etal, “Mathematical Model of the Diamond-Bit Drilling Process and Its Practical Application”, Society of Petroleum Engineers Journal, December, 1982
[60] Brett, J.F., Etal, “Method of Modeling and Building Drill Bits”, U.S. Patent 4,815,342, March 28, 1989
[61] Warren, T.M., etal, “3D PDC Bit Model Predicts Higher Cutter Loads”, SPE 21928, SPE Drilling and Completion, December, 1993
[62] Glowka, D.A., “Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part 1- Development of a PDC Cutting Force Model”, SPE 15619, Journal of Petroleum Technology, August 1989
[63] Glowka, D.A., “Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part 2- Development and Use of the PDC WEAR Computer Code”, SPE 19309, Journal of Petroleum Technology, October, 1989
[64] Hanson, J. M.., etal, “Dynamics Modeling of PDC Bits”, SPE 29401, IADC/SPE Drilling Technical Conference, Amsterdam, The Netherlands, February 29-March 2, 1995

[65] Dykstra, Dr. M. W., etal, “Improving Drilling Performance by Applying Advanced Dynamics Models”, SPE 67697, IADC/SPE Drilling Technical Conference Amsterdam, The Netherlands, February 27-March 1, 2001
[66] Pastusek, P. E., etal, “A Model for Borehole Oscillations”, SPE 84448, SPE Annual Technical Conference, Denver Colorado, October 5-8, 2003
[67] Glowka, D.A. Etal, “Frictional Heating and Convective Cooling of Polycrystalline Diamond Drag Tools During Rock Cutting”, SPE 11061, Society f petroleum Engineers Journal, April, 1984
[68] Glowka, D.A. Etal, “Effects of Thermal and Mechanical Loading on PDC Bit Life”, SPE 13257, SPE Annual Meeting, Houston, Texas, September 15-19, 1984
[69] Zijsling, D.H., “Analysis of Temperature Distribution and Performance of Polycrystalline Diamond Compact Bits Under Field Drilling Conditions”, SPE 13260, SPE Annual Meeting, Houston, Texas, September 15-19, 1984
[70] Glowka, D.A., ‘Implications of Thermal Wear Phenomena for PDC Bit Design and Operation”, SPE 14222, SPE Annual Meeting, Las Vegas, Nevada, September 22-25, 1985
[71] Glowka, D.A. Etal, “Thermal Response of Polycrystalline Diamond Compact Cutters Under Simulated Downhole Conditions”, SPE 11947, Society of Petroleum Engineers Journal, April, 1985
[72] Appl, F.C., etal, “Temperature Distribution in Synthetic Diamond Cutters During Orthogonal Rock Cutting”, SPE 17268, SPE Drilling Engineering, June 1989
[73] Appl, F.C., etal, “Measurement of Forces, Temperatures, and Wear of PDC Cutters in Rock Cutting”, Wear, 169, 1993
[74] Smith, R.H.., Etal, “Residual Stresses in Polycrystalline Diamond Compacts”, Journal of the American Ceramic Society, 77 (6) 1562-68, (1994)
[75] Butcher, T.N., etal, “Polycrystalline Diamond Cutters Having Modified Residual Stresses”, U.S. Patent 6,220,375, April 24, 2001
[76] Dennis, M.H., “Cutting Composite Formed of Cemented Carbide Substrate and Diamond Layer”, U.S. Patent 5,120,327, June 9, 1992
[77] Bertagnolli, K.E., Etal, “Polycrystalline Diamond Compact Cutter Having A Stress Mitigating Hoop at the Periphery”, U.S. Patent 6,408,959, June 25, 2002
[78] Adia, M. Etal, “Abrasive Body”, U.S. Patent 6,149,695, November 21, 2000
[79] Meiners, M.J., etal, “Superabrasive Cutter Having Optimized Table Thickness and Accurate Table-to-Substrate Interfaces”, U.S. Patent 6,527,069, March 4, 2003
[80] Tibbits, G.A., Etal, “Stress Related Placement of Engineered Superabrasive Cutting Elements on Rotary Drag Bits”, U.S. Patent 5,605,198, February 25, 1997
[81] Clark, L.A., Etal, “New PDC Designs Doubles ROP on Kingfisher Project Well, Central North Sea”, AADE 01-NC-HO-15, AADE 2001 National Drilling Conference, Houston Texas, March 27-29, 2001
[82] Meany, N.C., etal, “Diamond Cutting Structure for Drilling Hard Subterranean Formations”, U.S. Patent 5,460,233, October 24, 1995
[83] Cooley, C. H., etal, “Diamond Cutters have Modified Cutting Edge Geometry and Drill Bit Mounting Arrangement Therefore”, U.S. Patent 5,437,343, August 1, 1995
[84] Cooley, C.H., etal, “ The Development o a Fracture Resistant PDC Cutting Element”, SPE 28312, SPE Annual Technical Conference, New Orleans, Louisiana, September 25-28, 1994
[85] Lund, J.B., etal, Superabrasive Cutting Elements with Cutting Edge Geometry having Enhanced Durability, Method of Producing Same, and Drill Bits so Equipped”, U.S. Patent 6,935,444, August 30, 2005
[86] Lund. J. B., etal, “ Superabrasive Cutting Element Having Reduced Surface Roughness and Method of Modifying”, U.S. Patent 5,447,208, September 5, 1995
[87] Smith, R.H., etal, “Drilling Plastic Formations Using Highly Polished PDC Cutters”, SPE 30476, SPE annual Technical Conference, New Orleans, Louisiana, October 22-25, 1995

[88] Jaruzelski, B. “Oil and Gas Industry Drill Bit Insert Market” Booze, Allen, Hamilton Study completed in summer of 2004. Used with permission of US Synthetic
[89] Warlick and Associates., “Strategic Evaluation of the Diamond Drill Bit Market”, A special Study for Eastman Christensen, September, 1988
[90] Turner, E.C. “Bit Improvements are Cutting Drilling Costs”, World Oil, April, 1996
[91] Turner, E.C. “Field Specific Analysis Reinforces Role of Bit Technology in Improving Overall Drilling Economics”, SPE 37642, IADC/SPE Drilling Technical Conference, Amsterdam, The Netherlands, March 4-6, 1997
[92] Shaji, T., etal, “Expanding Application of PDC into Harder, More Abrasive Formations: Performance Step Change in Saudi Arabia”, SPE 92435, IADC/SPE Drilling Technical Conference, Amsterdam, The Netherlands, February 23-25, 2005
[93] Mohd, J.A., etal, Kuwait Oil Company Sets Drilling Record Completing the Zubair Section in one Run”, SPE 97364, IADC/SPE Middle East Drilling Technical Conference, Dubai, U.A.E., September 12-14, 2005
[94] Al-Suwaidi, A.S., etal, “New PDC Design Process Solves Challenging Directional Application in Abu Dhabi Onshore Fields,” SPE 79796 presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands, 19-21 February 2003
[95] Sinor, L.A., etal, “Drill Bits with Controlled Cutter Loading and Depth of Cut,” U.S. Patent 6,298,930, October 9, 2001
[96] Dykstra Dr. M.W., etal, “Drill bits with reduced exposure of cutters,” U.S. Patent 6,460,631, October 8, 2002
[97] Dykstra Dr. M.W., etal, “Drill bits with controlled exposure of cutters,” U.S. Patent 6,779,613, August 24, 2004
[98] Bovenkerk, H.P., Rotary Drill Bit”, U.S. Patent 4,109,737, August 29, 1978
[99] Salesky W. J., etal, “Preliminary Field Tests of Diamond Enhanced Inserts for Three Cone Bits”, SPE 16115, SPE/IADC Drilling Technical Conference, New Orleans, Louisiana, March 15-18, 1987
[100] Salesky W. J., etal, “Offshore Tests of Diamond Enhanced Rock Bits”, SPE 18039, SPE Annual Technical Conference, Houston, Texas, October 2-5, 1088
[101] Hall, D.R., etal, “Composite Polycrystalline Diamond Compact”, U.S. Patent 4,604,106. August 5, 1986
[102] Hall, H.T., etal, “Carbide Metal Composite Material and Process Therefore”, U.S. Patent 5,304,342, April 19, 1994
[103] Dennis, M.D., “Cutting Element for Drill Bits”, U.S. Patent 5,544,713, 1996
[104] Jensen, K.M., etal, “Attachment Geometry for Non-Planar Drill Inserts”, U.S. Patent 5,871,060, 1999
[105] Tank, K., “Composite Abrasive Compact”, patent application, WO 03/064806, August 7, 2003
[106] Scott, D.E., “Earth Boring Bits with Super-hard Cutting Elements” U.S. patent 6,135,219, October 24, 2000
[107] Grimes, R.E., etal, “Rolling Cone Bit With Shear Cutting Gage”, U.S. Patent 5,287,936, February 22,1994
[108] Scot, D. E., etal, Development of Roller Cone Bits with Active PDC Cutting Elements Improves Gage Holding Ability”, SPE 25736, IADC/SPE Drilling Technical Conference, Amsterdam, The Netherlands, February 23-25, 1993
[109] Besson, A. etal, “Optimization of the Drilling Performance in the 17 ½” Section of an Exploration Well in the Over-thrust of Southern Italy”, SPE 23910, IADC/SPE Drilling Technical Conference, New Orleans, Louisiana, February 18-21, 1992
[110] Scott, D.E., etal, “Free Cutting Gage Insert with Relief Angle”, U.S. Patent 5,407,022, April 18, 1995
[111] Scott, D.E., etal, “Earth Boring Bit with Improved Cutting Structure”, U.S. Patent 5,351,768, October 4,1994

[112] Scott, D.E., etal, “Earth Boring Bit Having Shear Cutting Elements”, U.S. Patent 5,752,573, May 19, 1998
[113] Scott, D. E., etal, “Earth Boring Bits with Super-hard Cutting Elements”, U.S. Patent 5,758,733, June 2, 1998
[114] Scott, D.E., etal, “Diamond Enhanced Shear Cutting Elements on Roller Cone bits”, Intertech 2000, Vancouver, Canada, July 19, 2000

Personal Author Information (15)

D.E. Scott has 35 years experience with Hughes Christensen and is currently the Group Leader - Hard Materials Research. Prior to this position he served in various research and engineering roles largely involved with cemented carbide and diamond cutter research, development, and application, and served as carbide plant metallurgist, Manager of Manufacturing Research, Chief Metallurgist, Manager of Materials R&D, and Manager of Product Development. He holds 55 U.S. Patents, has 20 publications, and is a Fellow in ASM International, and has served on the IADC/SPE Drilling Technical Conference Program Committee since 1992. He holds a Registered Professional Engineer and has a Degree in Metallurgical Engineering from the University of Missouri at Rolla.

Acknowledgements (16)

I would like to thank the Management of Hughes Christensen Company for allowing me to publish this paper, the Diamond at Work conference committee for inviting it, and Earl Koske, Bob Frushour, Joe Connolly, and Gary Weaver for sharing their reflections, documents and comments. I want to thank Craig Fleming for his assistance with the preparation of the manuscript