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About the cover: December 1995. Fully integrated jackup platform in offloading site near Stavanger, Norway, before towout to installation in BP Exploration's Harding field, offshore UK, following 54-Day, 12,000-mile dry tow from South Korea. Photograph courtesy British Petroleum.

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Bit improvements are cutting drilling costs

A study of bit records indicates that better design and selection of roller cone and fixed drill bits have reduced worldwide drilling costs as much as 35% since 1989

Evan Turner, Director of Marketing Services, Hughes Christensen Company, Houston.

More than 100,000 bit records, including those from all bit manufacturers, were analyzed and subsequently confirmed the widely held assumption that drill bits, while representing a small portion of base well costs, can have a dramatic bearing on the eventual overall well costs. As documented in the examination of the records, technological advancements in both fixed cutter and roller cone bits and sophisticated, often computer-generated, application techniques have combined to steadily improve drilling economics.

As measured by cost per foot drilled, drilling expenses for wells employing fixed cutter bits, primarily PDC designs, have reduced cost per foot an average of 35%, while those running roller cone bits have seen drilling costs decline 8% on the average.

Subsequent to earlier reviews by Kissler, et al.,¹ and Shepherd, et al.,² this latest research into the relationship of bit performance to total well costs shows drill bits having an unprecedented impact on the bottom line of a well. Drilling cost reductions resulting from improved bit performance for the study period are shown in Fig. 1.

BIT PERFORMANCE MEASUREMENT CRITERIA

The above conclusions were derived by analyzing bit performance from 1989 to mid-year 1995, as documented in a bit record system. The database, which contains worldwide bit run information, included performance data from every manufacturer. With the large sample size, concerns about sampling errors in drawing industry-wide

conclusions are eliminated.

Bit life and rate of penetration (ROP) are the barometers used to ultimately define impact of the drill bit on overall drilling costs. Bit life is measured as footage drilled per bit, while ROP is feet drilled per rotating hour. Bit life affects the number of trips that must be made to change out the bit, whereas ROP directly influences the number of drilling hours needed to complete a given hole interval. While in some applications, bit life may have more of a direct bearing on drilling costs than ROP, and vice versa, both directly impact the number of rig hours required to drill a well and, hence, its total cost.

A trend line was established by separately analyzing roller cone and fixed cutter bit performance for each year in

lated with the following commonly used equation:

$$C_d = [C_b + C_r(T_t + T_d)]/D \quad (1)$$

where:

C_d = Drilling cost, \$/ft

C_b = Bit cost, \$

C_r = Rig cost, \$/hr

T_t = Trip time, hr

T_d = Drilling time, hr

D = Distance drilled, ft.

Bit cost per well was estimated by dividing average well depth for each year by average bit life for each year. The resulting number was the units used per well, which was then multiplied by the average base price per bit for both roller cone and PDC bits in each respective year.

Drilling hours per well were estimated by dividing the average well depth by the average ROP achieved by each bit. Tripping hours per well were estimated by dividing the average well depth by the average bit life to determine the number of trips, which was then multiplied by the average tripping hours per round trip. Average tripping hours per well each year in the study period were estimated by assuming a tripping rate of 1,000 ft/hr for the median well depth.

For each year of the study, rig rates were held constant at \$800/hr; however, to isolate the true cost impact of bit performance, bit prices were inflated to reflect actual operator costs.

Further, a sensitivity analysis was performed to determine what impact varying rig rates might have on the conclusions. As such, rig rates were varied from a low of \$200/hr to a high of \$4,000/hr. The overall variance from the base case conclusion was slightly over one percentage point, thus confirming the validity of base case conclusions.

ROP AND BIT LIFE VERSUS COST PER FOOT

It is generally recognized that changes in ROP have a much greater impact on drilling costs than do simi-

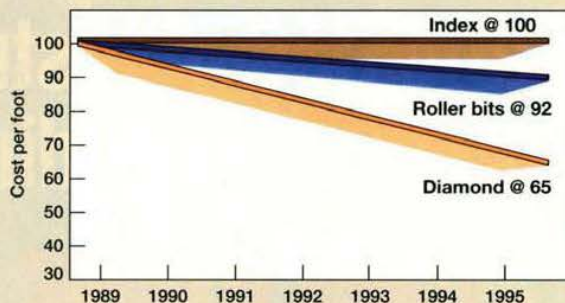


Fig. 1. Drill bits have had an unprecedented impact on well costs. Drilling cost reductions resulting from improved bit performance for the study period are shown as an index for both roller cone and fixed cutter bits.

the study period. Roller cone bits include both steel tooth and tungsten carbide insert (TCI) designs. Conversely, polycrystalline diamond compact (PDC) bits dominate the fixed cutter, or diamond, category, therefore the performance data largely reflects PDC performance.

DRILLING COST EQUATIONS

Average drilling cost improvements were estimated by calculating drilling cost per foot for each year (1989 to mid-1995). Average cost per foot was calcu-

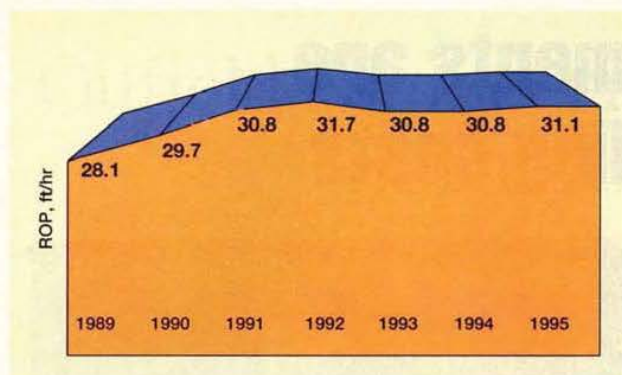


Fig. 2. Roller cone bit penetration rates have increased by 11%, rising from an average of 28 ft/hr in 1989 to 31 ft/hr in 1995.

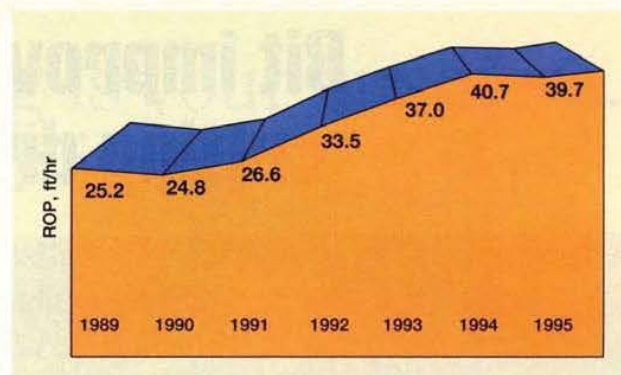


Fig. 3. Improvements in PDC bit hydraulics and cutter technology since 1989, have allowed average ROP to soar by 60%, reaching a current average of 40 ft/hr.

lar percentage changes in bit life. This is especially true in high-cost rig environments, such as offshore and deep onshore applications, where the total dollar impact can be enormous.

The magnitude of the impacts that improved ROP and bit life have on overall drilling cost per foot was quantified by expanding Eq. 1 to isolate, for comparison purposes, the two effects separately. Consequently, bit life and ROP became separate variables by defining T_t and T_d in those terms:

$$T_t = [(D/BL)(D/2)]/1,000 \quad (2)$$

$$T_d = D/ROP$$

where:

BL = Average bit life

ROP = Average penetration rate.

The average tripping rate was assumed to be 1,000 ft/hr. Thus drilling cost is calculated with the following expanded equation:

$$C_d = \{C_b + C_r[(D^2/2,000 BL) + (D/ROP)]\}/D \quad (4)$$

The impact of changes in bit life and ROP on drilling costs can be isolated by

(3) taking partial derivatives of the drilling cost equation with respect to each of these variables. This results in the following relationships:

$$\partial C_d / \partial BL = -C_r D / 2,000 BL^2 \quad (5)$$

$$\partial C_d / \partial ROP = -C_r / ROP^2 \quad (6)$$

By using the 1995 average values calculated for D , BL and ROP , and assuming an average rig cost of \$800/hr, relative change in the drilling cost per foot with a change in bit life or ROP can be determined.

Should bit life and ROP both increase

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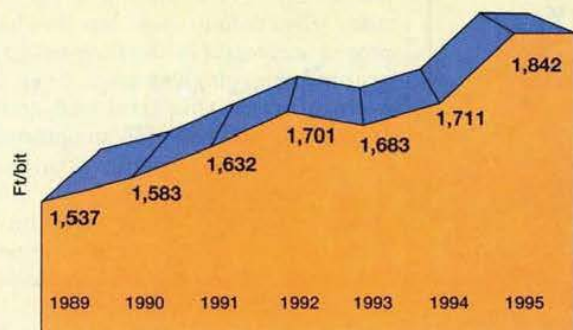


Fig. 4. Average life of a roller cone bit increased to 1,842 ft from 1,537 ft between 1989 and mid-1995—an aggregate 20% increase, or 3.1% per year.



Fig. 5. Since 1989, PDC bit life has increased 115% to an average of 3,629 ft by mid-1995.

a hypothetical 10% from current values and everything else remains constant, the faster drilling rate would have a much greater impact on overall drilling costs than would the longer operating life of the bit. With the 10% assumption, calculations using Eqs. 5 and 6 reveal that the assumed increase in bit life would decrease drilling cost per foot by 0.4%, whereas a 10% increase in ROP would decrease overall drilling costs by 8.9%.

The assumed rig rate impacts magnitude of the response to the extent that the higher the rig rate the more favor-

able the response. However, the basic relationship of ROP to drilling costs, which is an order of magnitude greater than the benefits achieved with longer bit life, is maintained within a fairly narrow band of values. This would indicate that efforts to lower overall drilling costs could best be accomplished by focusing future technical development on improving ROP.

It is important to keep in mind that the above results are averages that apply to general drilling conditions. The exact response in any given well could differ significantly.

IMPACT OF BIT DESIGN, SELECTION TO WELL COSTS

Obviously, technological advancements in designs, which will be discussed in greater detail, must be considered fundamental to the authenticated value-added performances generated by fixed cutter and roller cone bits during the study period. Correspondingly, design advancements recorded since Shepherd's 1989 study² have been complemented with new methodologies and mechanisms to properly match the drill bit to the targeted formations

Historically, bit programs for a pro-

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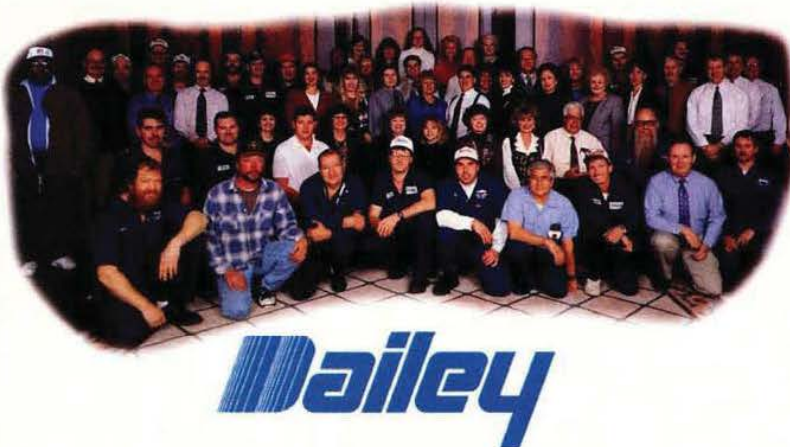
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posed well were developed by merely using offset data to select bits that had proven successful in the targeted geographic or geological area. Even in mature areas, this trial and error approach often prevented an optimum bit program from being attained, because historical records do not indicate whether another bit would have performed better than the one selected. Hence, the most cost-effective bit-to-formation match was not achieved.

During the past five years, technologies have emerged that better enable the bit programmer to properly match formations to be encountered with the most cost-effective drilling tool. These computer-generated technologies, which primarily center on methods of determining compressive strengths of the targeted intervals, have been well-documented in the literature.^{3,4} Complementing this knowledge is the emergence of computer tools that assist in selecting the bit best suited to the defined compressive strengths.⁵

The complex refinements in bit selection go hand-in-hand with steady technological advancements that have greatly improved both ROP and bit life.

ROP: ROLLER CONE BITS

As mentioned, even small increases in ROP can have a major impact on well economics, especially in high-cost drilling environments. Fig. 2 shows that roller cone bit penetration rates have increased by 11%, rising from an average of 28 ft/hr in 1989 to 31 ft/hr in 1995.

Generally, one would think that as bits last longer, the time spent drilling with dull teeth would increase, thereby, reducing overall ROP. In truth, a number of technical improvements have provided for both longer lasting bits and faster overall ROPs.

For steel tooth bits, technical improvements that have resulted in higher ROPs include better hard facing and tooth geometry to maintain an aggressive cutting structure. Tungsten carbide insert (TCI) bits now employ carbide inserts with more wear resistant carbide grades and improved geometric shapes that resist dulling or premature breakage, thereby allowing for longer and more aggressive inserts. Further, better hydraulic schemes have enhanced cuttings removal to prevent the re-drilling of cuttings. In 1995, introduction of gauge trimmers and more efficient strategies for cutting the corner of the borehole have combined to create cutting structures that are more aggressive and cost-effective.

Continued

ROP: PDC BITS

Major improvements in PDC bit hydraulics and cutter technology have paved the way for a step change in rates of penetration achievable with PDC bits. Since 1989, average ROP has soared 60% to reach a current average of 40 ft/hr, Fig. 3.

Initially, PDC bits were applied exclusively in softer environments, but even then, poor hydraulic designs characteristic of those earlier versions inhibited the realization of their full ROP potential.

The latest generation of PDC bits employs thinner, yet stronger, blades, which permit large junk slot areas and increased face volume to more efficiently handle the large cuttings typical of these bits. Rear impact hydraulic schemes and the incorporation of chip breakers into the designs have made for more efficient chip creation and PDC bits that are more resistant to bit balling than their earlier counterparts.

With the advent of chamfered edges, buttress support, improved carbide interface geometries and polished surfaces, today's PDC cutters remain intact and sharper much longer than prior designs. Durability aside, the polished cutter (a feature where the diamond surface receives a mirror finish designed to reduce frictional forces between cutter face and cuttings) also serves to reduce drilling torque. Less torque increases cutting efficiency by preventing the creation of a built up edge during the cutting of ductile acting formation.

BIT LIFE: ROLLER CONE BITS

As shown in Fig. 4, the average life of a roller cone bit increased to 1,842 ft from 1,537 ft between 1989 and mid-1995. This represents an aggregate 20% increase over that period or an increase of 3.1% per year, when compared to the 2.75%/year rate of increase recorded in the prior decade.

A number of technical improvements are responsible for the improved durability of roller cone bits, many of which center on the bearing and seal package—the heart of a roller cone drill bit. Today's bearing technology has advanced well beyond that of just a few years ago. Most manufacturers have improved bearing performance and seal reliability through better sealing mechanisms such as metal face seals,^{6,7} improved elastomers, better greases and grease compensator systems, and improvements to the bearing surface itself. Silver coatings on the bearing surface work as a solid lubricant and

help dissipate heat. All these factors have improved seal reliability and bearing life, while at the same time expanding the operational range of these bits into more demanding applications and/or operating parameters.

For both TCI and steel tooth bits, longer bearing life has been complemented with proportionate increases in the effective life of the cutting structure itself. During the past five years, slow demise of the steel tooth bit has been reversed dramatically with major improvements in cutting structures. New hard facing materials and improved base metal tooth geometry for mill tooth bits have extended cutting structure life threefold in some cases. Coupled with better gauge protection through the use of carbide gauge inserts, including actively cutting diamond gauge inserts,⁸ the life of steel tooth bits is often much longer than previously thought possible.

For TCI bits, new carbide grades and geometric shapes have made them more durable and have allowed teeth to be lengthened to facilitate soft formation drilling at acceptable penetration rates without compromising durability.

BIT LIFE: PDC BITS

Improvements in the life of PDC bits have been even more impressive than those achieved by roller cones. Since 1989, PDC bit life has increased 115% to an average of 3,629 ft by mid-1995, Fig. 5. The 13.7% annual increase in the average operational life of a PDC bit clearly explains the growing popularity of these tools.

Major technological enhancements that have driven the improved PDC bit life are tougher, more abrasion and fracture resistant cutters,⁹ new dynamically stable bit designs,¹⁰ tougher matrix materials and better hard facing for steel bodied bits.

A number of factors have spurred the improvements in PDC cutter durability. Manufacturing improvements in the sintering of polycrystalline diamond have led to better diamond crystal bonding, thus improving the ability of a cutter to resist abrasion. Higher fracture toughness has been achieved by improving interface geometries between the diamond table and the carbide backing to reduce residual stresses. Further improvement in the overall toughness of the diamond has been attained by providing better support for the diamond table by buttressing the cutter, or providing a carbide supported edge.

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fering characteristics has come the ability to engineer the placement of cutters on a bit so as to optimize overall performance. In concert with the development of cutters with different load carrying abilities, has come a better understanding of the stress state of the borehole. Combining this knowledge in the design of the bit profile and the placement of different types of cutters has greatly enhanced both durability and performance of fixed cutter bits.

Another area where technology has been effectively applied to enhance PDC

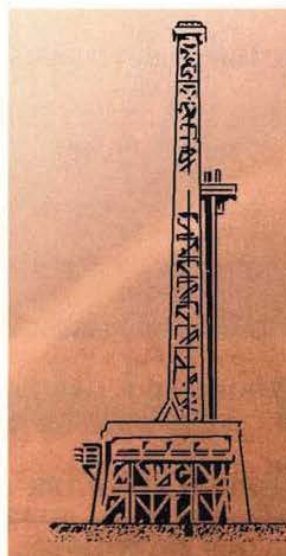
bit performance is in stability and drilling dynamics. One of the key pieces of information discovered recently is the tremendously detrimental impact that vibration and off-center running have on a diamond drill bit. Anti-whirl and low friction bit gauge designs that promote bit stability and resist whirl have led to bits that last longer and drill more consistently.

THE FUTURE

Roller cone bit performance will likely continue to benefit from advances in

material technology. Super-hard materials, such as diamond, are already making their way into roller cone products. This trend will continue to the benefit of bearing and cutting structure life, as well as rates of penetration. Further roller cone enhancements are expected in the areas of improved hydraulics and more dynamically stable products.

In the future, PDC bits will no doubt benefit from improved cutter technology aimed at further expanding their application range into harder formations. Research is just now beginning to unlock the key to PDC cutting mechanics. Down the road, the truly optimal PDC bit will be one that combines the right hydraulic design, with the right cutter layout and cutter selection to match the cutting forces required to optimally drill a formation. It is also likely that more compatible downhole motor and bit combinations will emerge.



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