New HTHP Cutter Technology Coupled with FEA-Based Bit Selection System Improves ROP by 60% in Abrasive Zubair Formation
Mohannad Al-Muhailan, Iqbal Hussain, Kuwait Oil Company; Harish Maliekkal, Osama Ghoneim, Prakash Nair, Mustafa Fayed, Smith Bits/Schlumberger.

Abstract
Efficiently drilling the abrasive Zubair sandstone is one of the Middle East’s most daunting challenges. Adding to application complexity, the pyritic formation is also interbedded with hard shale streaks and has a compressive strength that ranges between 3-10kpsi. In Kuwait, the formation is first encountered at a depth of approximately 9000ft and has been drilled with mixed performance results based on bit diameter. Generally, the large diameter PDC bits are still struggling to achieve the durability objective with some wells requiring more than two PDCs to complete the short 1400ft hole section. In the smaller hole sections, technological advances have overcome the cutter/bit durability issue but with no significant improvement in ROP. The objective of an intensive bit optimization effort has focused on increasing penetration rates while striving to improve overall bit life/cutter durability.

To accomplish the operator driven objectives without time-consuming field trials, the drilling team used a software system to calibrate rock strength. This data was used in conjunction with an advanced FEA-based modeling system to analyze different PDC cutting structures to select a PDC bit with the blade count and shearing configuration that would produce dynamically stable drilling. The bit body would be equipped with a new O2 cutter to increase abrasion resistance and maintain temperature at the cutter tip by using: 1) enhanced HTHP sintering process; 2) refined post-pressing process to improve thermal stability 3) optimized hydraulics to maximizing cutter cooling.

The authors will discuss the bit selection process and modeling system which eliminated costly field trials and the new manufacturing processes that produced the HTHP cutter technology that increased ROP by 60% in the 8-1/2” hole section. The new PDC bit achieved the operator’s objective of drilling shoe to TD eliminating several trips for new bits while delivering a significant reduction in drilling costs.

Introduction
This paper is discussing the modern reliable bit selection process and modeling system which can eliminate traditional field trial and error product development system, which is very costly especially when the formation to be drilled is highly abrasive and Pyritic sand formations, where cutting structure durability is very crucial. Thermal stability of the PDC cutters are of great importance, as quick cutter wear or diamond table loss are caused by high temperatures at the cutter tips while drilling through such highly abrasive formations. This paper will be looking into the new generation thermally stable PDC cutter developments that helped to double the PDC cutter durability and further rate of penetration improvements, through a case study of drilling through highly abrasive Zubair formation in Kuwait which quite often Pyritic.

Zubair Formation Geological Characteristics
Zubair formation is highly abrasive sandstone interbedded with hard silty shale. This formation is often observed with pyrite which adds to the complexity and difficulty in drilling this section. Zubair starts at a depth of about 9000ft and has almost 1400ft thickness. This formation is part of lower Cretaceous sequence in between the Shuaiba and Ratawi Shale formations (Figure 1). The compressive strength of this formation is ranging from 5 to 15 Kpsi with occasional peaks of up to 20Kpsi (Figure 2).
The formation contains four major horizons named Upper Zubair shale, Upper Zubair Sand, Middle Zubair Sand and Lower Zubair Sand. In order to understand the depositional features and sand distribution/geometry of Zubair, a sedimentological study was carried out. This study impacted the well locations, injectors and producers\(^2\). Generally, the field has gentler sloping sides over the northeast area.

The Upper Zubair shale was deposited in a wave/shore face and offshore-dominated environment resulting in sand channels that extend East-West across the anticline.

The Upper Zubair sand was deposited in a tidal/estuarine environment in which the sand channels are stacked. The sand is prevalent everywhere across the field.

Middle Zubair sand was deposited mainly in a tidal/estuarine environment. Three channel trends are observed. They are in vertical communication; however, they occur geographically in different areas. Lower Zubair sand was deposited in a fluvial/mouth bar dominated environment.

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>FORMATION</th>
<th>LITHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary</td>
<td>Kuwait Series</td>
<td>Sands and Gravels</td>
</tr>
<tr>
<td></td>
<td>Dammam</td>
<td>Highly fractured Limestone</td>
</tr>
<tr>
<td></td>
<td>Rus</td>
<td>Anhydrite with Limestone</td>
</tr>
<tr>
<td></td>
<td>Radhuma</td>
<td>Dolomitic Limestone</td>
</tr>
<tr>
<td></td>
<td>Tayarit</td>
<td>Dolomitic Limestone with Shale</td>
</tr>
<tr>
<td></td>
<td>Hartha</td>
<td>Medium hard Limestone</td>
</tr>
<tr>
<td></td>
<td>Sadi</td>
<td>Soft to medium vuggy Limestone</td>
</tr>
<tr>
<td></td>
<td>Mutriba</td>
<td>Medium hard Limestone</td>
</tr>
<tr>
<td></td>
<td>Mishref</td>
<td>Medium hard Limestone</td>
</tr>
<tr>
<td></td>
<td>Rumaila</td>
<td>Medium hard Limestone</td>
</tr>
<tr>
<td></td>
<td>Ahmadi</td>
<td>Shale with interbedded Limestone</td>
</tr>
<tr>
<td></td>
<td>Wara</td>
<td>Shale with interbedded Limestone</td>
</tr>
<tr>
<td></td>
<td>Mauddud</td>
<td>Limestone w</td>
</tr>
<tr>
<td></td>
<td>Burgan</td>
<td>Sandstone</td>
</tr>
<tr>
<td></td>
<td>Shuaiba</td>
<td>Highly fractured Dolomitic Limestone</td>
</tr>
<tr>
<td></td>
<td>Zubair</td>
<td>Sandstone interbedded with Shale</td>
</tr>
<tr>
<td></td>
<td>Ratawi Shale</td>
<td>Shale</td>
</tr>
<tr>
<td></td>
<td>Ratawi Limestone</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td>Minagish</td>
<td>Dolomitic to Oolitic Limestone</td>
</tr>
<tr>
<td></td>
<td>Makhul</td>
<td>Hard Limestone</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Hith</td>
<td>Anhydrite interbedded with Limestone</td>
</tr>
<tr>
<td></td>
<td>Gotina</td>
<td>Anhydrite and Salt layers</td>
</tr>
<tr>
<td></td>
<td>Najmah</td>
<td>Fractured Limestone</td>
</tr>
<tr>
<td></td>
<td>Sargelu</td>
<td>Limestone to Calcareous Shale</td>
</tr>
<tr>
<td></td>
<td>Marrat</td>
<td>Oolitic Limestone with thin Shale</td>
</tr>
</tbody>
</table>

**Application Background**

The general casing design for the Zubair wells (Figure 3) is drilling a total depth of 10,500ft into top of Ratawi Shale formation. The surface hole is set in Dammam formation with 18-5/8” Casing, then 16” hole section is set at about 6000ft in Mutriba formation. The 12.25” section drills through Mutriba formation to top of Zubair in a depth of approximately 9000ft, and the 9-5/8” casing is set there. The 8 1/2” hole section which we are discussing in this paper is drilling through approximately 1300ft of Zubair formation and another 100ft of Ratawi Shale formation which is comes after the Zubair.
Zubair Application Challenges

Zubair consists mainly of highly abrasive sand which is quite often infested with pyrite. As the formation is showing interbedded nature with sand and shale patches the drill bit performance and durability optimization has been a great challenge to all the bit manufacturers and the operator.\textsuperscript{3-5}

Drillability concerns with this formation has been well recorded by the industry experts and different solutions and technologies introduced in order to address the prime concern of durability of the cutting structure. Even though larger diameter bit size applications through this Zubair formation demands multiple PDC bit or combinations of PDC/TCI bits to drill this 1300+ft, latest PDC bit technologies did help to improve the durability of the bit and to finish the section with one PDC bit in the 8½” bit size application.\textsuperscript{3-4}

Still latest bit design and component factors available until recently did keep the penetration rates in lower ranges or without much progress in improving it (Figures 5 & 6).
Based on previous PDC runs in these sections, areas of concern were identified:

- PDC impact damage caused by improper bit force balance
- Loss of diamond table due to impact damage or formation abrasiveness (presence of pyrite)
- Accelerated PDC cutter wear related to loss of diamond table
- BHA impact damage from downhole vibration caused by formation characteristics
FEA Modeling/PDC Design Iterations
KOC engineering team wanted to quantitatively determine the root cause of drilling dysfunction, without relying on the costly and time-consuming trial and error process. Additionally, the operator wanted to avoid making iterative bit changes on the rig while incurring daily drilling costs. To accomplish the operator’s objective, a comprehensive FEA-based engineering program was used to model the total drilling system. The design tool accurately predicted the drill bit’s performance and behavior as an integral part of the total downhole system. The first step was to select a PDC design based on the operator’s application requirements and analysis of offset performance (Figures 7-9).

**Figure 7 - Bit center trajectory output comparison**

**Figure 8 - Static ROP analysis with four different bit designs**
HTHP Cutter Development

Conventional PDC cutters fail quickly due to abrasive wear/spalling and/or delamination of the diamond table. The situation has caused stagnation in PDC performance and limited additional gains in total footage and rate of penetration (ROP). Recent scientific studies have indicated that thermal fatigue of the diamond table is the main contributing factor leading to cutter failure and is restricting further advancement of PDC drilling in northern Kuwait. To improve cutter performance the industry must:

1) Manufacture a cutter to resist abrasive wear and retain a sharp edge for an extended amount of footage;
2) reduce/maintain temperature at the cutter edge to minimize thermal fatigue.

To further advance cutter technology, an R&D initiative was launched to enhance the properties of the base diamond material especially wear resistance and thermal stability by redesigning diamond grit mixing, pre/post-processing treatment in addition to high temperature/high pressure (HTHP) sintering. Laboratory experiments were preformed to study the wear mechanism and the progression of the wear flat under different conditions with various synthetic polycrystalline diamond (PCD) materials. Testing revealed the following:

- The base diamond quality plays a very important role contributing to the life of a cutter. High quality diamond table increases cutting efficiency in terms of slowing wear flat progression in the initial mechanical wear mode.
- When the wear flat grows past a certain threshold, the cutter is forced into thermal/mechanical wear mode and this condition will have a detrimental effect on cutter life.

Armed with the knowledge, engineers refined and implemented several new processes to increase abrasion resistance and maintain temperature at the cutter tip. The O2 technology platform includes:

- Enhanced two-step high temperature/high pressure (HTHP) sintering process
- Refined post-pressing process to improve thermal stability
- Optimized hydraulics to maximize cutter cooling

In laboratory experiments, the next generation O2 cutter has demonstrated a 15% improvement in resistance to abrasive wear compared to the previous generation of premium O1 cutters (Figure 10).
Hydraulics Analysis

Laboratory tests also confirm that optimizing cutter cooling would enhance the life of the new shearing element. This was achieved by modifying the bit’s hydraulic design. Figure 11 compares different hydraulic configurations on a 9-7/8” 6-bladed bit used for comparison purposes. The change is designed to improve cooling efficiency on the cutters that generate large wear flats. The new hydraulics design delivers higher velocity flow adjacent to the cutters in the shoulder region (arrows) where wear flats develop faster due to high work rate. The optimized configuration produces an average velocity increase of approximately 30% for each blade compared to the baseline design (Figure 12). The majority of the increase is related to higher flow velocity on the cutters in the shoulder area. This in turn has significantly increased cuttings evacuation as well as cooling efficiency.

Figure 10 - Wear comparison of leached O1 and O2 cutters

Figure 11 - Comparison of fluid velocity at hole bottom between baseline and proposed designs
Based on recommendations from the FEA modeling system and offset analysis a new-style seven-bladed PDC bit, fitted with latest HTHP 16mm O2 cutter technology was manufactured in an attempt to increase ROP (Figures 13 & 14).

The new bit design was run in Raudhatain well RA-471 and made 1490 ft of hole from the casing shoe to TD in one run. The new PDC design had an average ROP of 46 ft/hr, 61% faster than the best offset of 28.5 ft/hr drilled with another manufacturer’s PDC bit (Figure 15). The increase in ROP also set another field record for lowest 8 ½” cost/ft. The bit came out of the hole in excellent dull condition and will be run again in a similar application.
Conclusions
KOC’s Drilling Team, working in conjunction with the service provider, set a new performance benchmark for drilling the 8 ½” vertical hole section utilizing teamwork and new PDC bit/cutter technology.

- Using the advanced dynamic FEA engineering software systems helped prevent BHA and formation induced vibrations, associated failures and trips by providing dynamically stable BHA and PDC bit combinations.

- The application specific bit design was tested and certified according to the operator’s requirements through the use of dynamic simulations and rock laboratory tests. The result saved the operator rig time and reduced drilling costs by eliminating the traditional trial and error improvement/optimization process.

- The new HPHT PDC cutters have reduced accelerated cutter wear and diamond table loss enhancing penetration rates and bit durability.

- The performance improvement suggests other KOC deep drilling teams could benefit from the latest FEA based bit selection process and HPHT cutter technology for improved PDC bit performances.

Acknowledgements
The authors would like to extend their thanks to The Manager, Development Drilling Group –KOC, and the engineering team. Their efforts led to the success discussed in this paper. Special thanks to Craig Fleming, Smith Bits, for his technical writing and editorial contributions.

References


