Underbalanced Drilling as a Tool for Optimized Drilling and Completion Contingency in Fractured Carbonate Reservoirs


Abstract

Maintained pressure management and fracture network mapping are key issues for successful well construction in fractured carbonate reservoirs. Prediction and characterization of the fracture network prior to drilling is very difficult and challenge optimized well direction and placement in respect to the fractures. Avoiding productivity impairment by loss of drilling fluids is another major challenge.

Later stimulation of a micro-fractured reservoir invaded by drilling mud is extremely difficult or even impossible. Open hole completion is generally preferred in these type of reservoirs. Underbalanced drilling (UBD) is therefore an interesting option for enhanced data acquisition, avoiding reservoir impairment and achieving completion contingency for optimized well production and added value.

Locating and characterizing the natural fractures while drilling is a vital issue for appropriate well placement and selection of completion options during the field development strategy. Depending on the opening and extension of the fractures, the mud loss rates and volumes can differ from low to high. The associated fracture network is the main parameter contributing to well production.

Underbalanced drilling is one of the main recommended technologies for further development of fractured carbonate reservoirs in South-West Iran. Flow drilling, allowing the hydrocarbons to flow to surface while drilling, will be advantageous. With sufficient reservoir pressure, this method enables better fracture characterization and a dynamic decision process can be applied for drilling horizontal wells with optimized well trajectory intersecting more fractures. Formation damage can be avoided and dramatically reduce unsuccessfully drilled wells.

Introduction

UBD is a drilling practice where the dynamic wellbore pressure intentionally is less than the formation pore pressure. Underbalanced drilling may improve drilling efficiency and enhance well productivity. However, for operational safety overbalanced drilling is generally preferred and the value of UBD is not yet fully acknowledged. At the same time UBD is increasingly used in many parts of the world. The technology involved is matured and the experience is increasing. UBD may be the only solution to unlock further drilling in depleted reservoirs with abnormal pressure ramps. UBD is applied for a variety of reservoir types at different complexity levels.

For field development projects in Iran, underbalanced drilling has a great potential and the National Iranian Oil Company (NIOC) has initiated a UBD technology program. UBD projects are related to some partially depleted fields in the south of Iran. The motivation is to increase the drilling efficiency and to enhance production. Normal drilling procedures, even with minimum conventional mud density (0.8 s.g) is not possible in many of the fields due to heavy to complete mud loss. In practice, drilling horizontal wells with heavy mud loss creates two severe drilling challenges:

- Stuck pipe due to cutting accumulation
- Loss of data transmission

In fractured carbonate reservoirs commonly found in Iran, non-producing wells are a major challenge either due to formation damage by loss of drilling fluids or not appropriate well placement and direction to intersect the fractures. The key aspects for promoting UBD in Iran are:

- Improved drilling performance
  - Avoiding drilling fluid loss
  - Improved ROP
  - Less bit wear and tripping time
- Improved reservoir fracture productivity
  - Early and improved fracture detection
  - Avoiding reservoir impairment
  - Allowing open hole completion
  - Reduced need for well stimulation

This paper discusses the above mentioned challenges to Iran and in relation to underbalanced drilling as a tool for optimized drilling and completion contingency in fractured carbonate reservoirs. Data and experience from West-Zagross fields located in South-Western part of Iran have been used as a basis for the study.
Underbalanced Drilling Technology

The UBD methodology involves two major technologies:

- Types of UBD fluid; gas, foam, gasified- and one phase liquids
- Circulating system; open system, closed loop system and snubbing unit

There are two ways to create underbalanced conditions which are also dependant on the formation pore pressure:

- Artificially underbalanced
- Naturally underbalanced

Artificially underbalanced operations apply to depleted reservoirs where the pore pressure gradient is less than the water pressure gradient. Gas is then required and mixed with the drilling fluids. Natural underbalanced operations mean that the reservoir pressure is able to flow the well by itself. However, starting the underbalanced condition, the mud column of the well has to be unloaded by a lighter fluid. The method is referred to as “flow-drilling”.

UBD systems are modular and self-contained and can in principle be installed independently of the drilling rigs. Some extension of the surface pad is needed for the equipment involved. Top-drives are advantageous, avoiding the square extension of the surface pad is needed for the equipment. A standard UBD package is designed as a closed loop system. Flexibility is a key issue allowing production while drilling and reservoir testing. Drilling with volatile fluids (high GOR) and managing H₂S environments are important safety issues.

Well Construction Challenges in Fractured Carbonates

Maintaining underbalanced in both drilling and completion is a complex and challenging operation. Due to this complexity, some underbalanced drilled wells may be completed in overbalance and the initial production capabilities of the well may be lost. Underbalanced conditions are important for all phases of the well construction comprising:

- Drilling
- Tripping (in and out)
- Logging and formation testing
- Running casing and pumping cement
- Perforation and completion

Hard rock drilling and low rate of penetration (ROP) is a common challenge in the Middle East. In tight carbonated reservoirs in Iran an ROP of one meter per hour has been experienced. This low ROP impacts the drilling costs and is also very relevant to the formation damage issue due to increased time of exposure of mud to the reservoir. The bit life is generally low and several bit runs are required. UBD can dramatically reduce drilling time and up to 10 times improvement has been reported.

Abnormal pressurized salt water formations and depleted and fractured reservoirs need to be carefully addressed. Logistic is a very important issue and impacts the drilling efficiency and the ability to handle critical well operations. With UBD it is possible to manage unforeseen pressure regimes and mitigate the logistics challenge related to heavy mud loss.

Mud losses occur when fractures are encountered ahead of the bit. Depending on the fracture characteristics the mud loss rates can vary. Dyke described three types for fracture apertures. With micro-fractures (less that 250 µm) mud will block the fracture near the wellbore without any detectable mud loss. Fracture openings between 250 and 500 µm can be detected by monitoring the mud loss, but will be blocked by the mud after some time. When the fracture opening is larger than 500 µm, mud can not seal the fracture by itself and lost circulation material (LCM) may be required to stop losses. However, using LCM can destroy the conductivity of the fractures damaging the production potential of the well. This risk need to be balanced with the potential drilling hazards such as stuck pipe and gas blow out. In some cases the data acquisition programme has to be cancelled due to mud loss. During well completion, back flushing is generally carried out to clean the well. A successful clean up or stimulation of the fracture network is hard to achieve. This is demonstrated with field data in the further discussion.

Optimized well direction and placement in respect to the fracture network pattern is very important. Experience has shown that predicting and characterizing the fracture network prior to drilling is very difficult. UBD can assist for early detection and assessment of the fractures.

Field Study

90 % of the discovered fields in Iran are in carbonate reservoirs putting Iran as one of the largest carbonate producers in the world. The normal production mechanism of carbonate reservoirs is through natural fracture networks with high conductivity. The dense matrix usually feeds the fracture network. If the well trajectory does not intersect any fractures, production will be low or even absent. In such cases, field experiences have shown that stimulation efforts like acidizing often are unsuccessful.

New master development plans (MDP) have been developed for upgrading of seven Iranian oil fields in south west of Iran. A location area map is shown in Figure 1. Although the production history has been poor, the potential of the fields have been found to be high, but dependent on efficient exploitation methods like horizontal wells, underbalanced drilling and smart data acquisition programs.

The Dehluran (DH) field is a relevant field for UBD operations because of the nature of the field and the long and problematic production history. DH is located in the southwestern part of Iran close to the Iran-Iraq border. The field is 20 km long and 9 km wide with an average reservoir thickness of 300 m. The DH field map is presented in Figure 2. The field was discovered in 1970 and 22 wells have been drilled so far. Only 13 wells have reached the reservoir target. The rest of the wells have been abandoned due to serious drilling challenges like high salt pressure and also due to the Iraq-Iran war (1980-1988). The estimated recoverable oil is 15 % by natural depletion. So far only 10 % of recoverable oil is produced. To date, horizontal wells have not been drilled.

The integrated study showed:

- The majority of wells has poor production history
- General lack of fracture knowledge
• Uncertainties apply with respect to reservoir compartments and fluid contacts

Only a few wells have shown a reasonable production potential. It is assumed that the exposure to the fracture network govern the well productivity. It was not possible to explain the production capabilities from the available petrophysical log data.

Fractures can be identified and characterized by different methods. With formation image logs the fractures can be visualized directly. Accurate mud loss detectors combined with annulus pressure sensors near the drill bit can give a continuous log of minor to severe losses. Small fractures may however be difficult to detect by this method. The microfractures will be filled and blocked by mud within few seconds when the mud is non-Newtonian.

Mud loss logs or image logs were not available for the Dehuran field. Mud loss data, extracted from the daily drilling reports was thus studied as an approach to characterize fractures. Four types of mud losses can be distinguished based on severity of mud losses. The wells were ranked with respect to mud loss rate as follows:

- No mud loss (zero)
- Partial mud loss (1 to 9 bbl/hour)
- Moderate mud loss (10 to 49 bbl/hour)
- Severe mud loss (50 bbl/hour to total mud loss)

The results are shown in Table 1 together with the cumulative production. The mud loss distribution is summarised in Figure 3 and shows that 65% of the wells had no mud loss to partial mud loss while 35% of the drilled wells had severe to moderate mud loss. The rapid and unexpected mud loss observation is the main indication for existence of fractures. The complete mud loss probably happened when large fractures were hit.

The productive wells and the mud loss history are indicated on the field map in Figure 2. A correlation is found between the mud-loss and production history. It seems as the northern part of the field has higher probabilities of fractures. No systematic regional fracture pattern can however be deduced.

Fracture Interpretation in Well DH-5. Out of the 13 wells reaching the reservoir in the DH field the well DH-5 has been selected for an in-depth study. A simple well sketch is shown in Figure 4. This well was chosen due to the following:

- A successfully drilled well with a reasonable production rate
- Available production tests with draw-down and build-up tests and production logging (PLT)
- Available cores
- Complete drilling history with daily mud loss data
- Production rate history

The entire mud loss history of the pay zone was interpreted. The net thickness of the pay zone was about 350 m. 2600 bbl mud was totally lost in this interval by 250 bbl/day average loss rate and with 15% solid by volume. The mud properties are summarized in Table 2. The mud rheology is non-Newtonian and can be considered as Bingham fluid.

600 sacks of LCM (mica) were pumped to reduce the mud losses.

The mud losses experienced in DH-5 are shown as two charts in Figure 5 and Figure 6. The first chart is the actual daily mud losses versus well depth in the reservoir section extracted from the drilling report. Peak mud losses were observed when the well drilled through fractures. The mud loss rate was close to constant until the well was intersecting new set of fractures. Obviously, the total mud loss is a share of two set of fractures. The second chart is described as “differential mud loss” which is defined as the difference between old and new observed losses given by:

$$\Delta Q_{\text{differential}} = Q_{\text{new}} - Q_{\text{old}}$$

Differential mud loss can be both positive and negative. If the well intersects new fractures the differential mud loss will be positive. On the other hand, if the losses are treated, the differential mud loss will be negative.

There are five mud loss peaks at different depths which are assumed to represent fractures. They are named fracture 1 to 5 in the figure. There is a possibility that only one fracture (fracture 1) is present, being opened in succeeding time periods. Therefore, the fracture interpretation was done for two cases; one case which considered only one fracture and a second case with five independent fractures. The well was perforated in five intervals. Perforation intervals were probably selected mainly from petrophysical logs with porosity indications. However, only one perforation interval was placed exactly against fracture indications (fracture 1) taken from the mud loss analysis. The PLT log showed that 95% of total flow was produced from this perforation. The second perforation interval produced 5% and the rest of the intervals did not contribute to any production. The length of both producing perforation intervals is 21 m.

A temperature survey also indicated an anomaly from 4040 to 4070 mMD which corresponds to fracture 1. Therefore, the first fracture was verified from four sources:

- PLT log
- Mud loss
- Temperature survey
- Well test

A production test, including draw-down and build-up tests in three periods, was carried out in well DH-5 after well completion. The calculated result showed negative skin (-3 to -5) which indicates fracture conductivity. The corresponding fracture permeability is 70 to 120 mD. As the mud losses continued for a long period we assume the fracture networks can be treated as infinite acting conductivity.

The fracture permeability, fracture porosity and fracture extension are essential parameters for the reservoir evaluation and the field development. In addition, these parameters are vital for the driller to select LCM and to design the well trajectory.

Muskat and Jones have shown that the fracture permeability ($k_f$) and porosity ($\phi_f$) for parallel fractures spreading horizontally are given by:
\[
k_{fp} = \frac{w^3}{(24 \, \delta_f)}
\]  
(2)
\[
\phi_f = \frac{w}{\delta}
\]  
(3)
whereas the permeability for conjugated fracture pattern is given by:
\[
k_{fc} = \frac{w^3}{(12 \, \delta_f)}
\]  
(4)
The average fracture spacing can be obtained by dividing the net pay zone thickness with the number of fractures. Since five fractures were indicated during drilling 350 m of pay zone, the average fracture spacing in DH-5 is 70 m. The reservoir geology is layered with interbedded shale. The main producing interval is 100 m thick and the first fracture was indicated in this layer. The well test was also carried out here. Therefore, in the well DH-5 case the fracture spacing can be 100 m. It has been shown that there is a relation between fissure pseudoskin and fractures spacing in the absence of mud loss and LCM. This skin is only related to the nature of the fracture network and is always negative.  
\[
S_f = \frac{\pi}{2} (1 - \frac{2 \, r_w}{\delta}) + \ln (2 \, r_w / \delta)
\]  
(5)
When the fracture spacing is known, fissure pseudoskin can be obtained. The obtained value for skin will be between -4 to -5 by using fracture spacing 70 to 100 m which is in good match with the well test result.

During overbalanced drilling most of the fractures will be immobilized by mud or LCM. To make all the fractures produce it is required to perforate all fractured intervals and to stimulate the different fracture systems individually. It is assumed that lack of perforation as well as insufficient stimulation is a major contribution to poor productivity in many of the DH wells.

**Dehluran Logistics.** The drilling logistic issue is very important when operating in remote and desert areas like the Dehluran field. Rough terrain with long access roads and also military regulations due to the closeness to the Iraqi border is a challenge. The logistics are related to both human support and securing of needed equipment and materials. A downtime analysis from daily drilling reports shows that while hole condition problems was the major issue for early wells, the logistics are the major area of concern for the later wells. The major factors involved for the logistics are transportation and the availability and quality of materials and spare parts. Figure 7 shows downtime analysis of nine DH wells. The downtime is caused by severe mud losses and securing water supply is the most predominant issue and impacts the ability to handle critical drilling operations.

**Validating Underbalanced Well Construction**

Different field and formation characteristics need to be screened with respect to the potential benefits of underbalanced well construction:

- Fields or formations where UBD can obviously offer advantages; depleted formations, hard rock formations and formations subject to damage.
- Fields or formations where potential benefits of underbalanced drilling are obvious; deformed formations, macro-fractured formations and abnormal pressurized formations.
- Fields or formations which need in-depth evaluation; low permeable formations, very permeable formations, macro-fractured formations and abnormal pressurized formations.
- Fields or formations where UBD is not recommended; highly unconsolidated formations and swelling formations.

Before commencing drilling operations the following considerations need to be carefully addressed:

- Wellbore collapse or enlargement
- Drilling operation safety
- Net present value (NPV)
- UBD operations should be evaluated for different contributions to validate the enhancements:
  - Short-term enhancement related to drilling ability and ROP achievements
  - Long-term production enhancement related to improved well productivity.

In the seven fields study UBD solutions for production enhancement have been addressed. The fields have been screened and drilling and production histories were evaluated for UBD applications. Fracture characteristics and pressure gradients have been analysed and Table 3 summarizes the findings. Three out of the seven fields have more than 5 wells drilled while the rest still are in an exploration phase. Recommendations with respect to UBD application in the seven fields are summarized in Table 4.

**Flow Drilling.** Flow drilling is a UBD technique where the well is left flowing while drilling. This technique is applicable for reservoirs with sufficient pore pressure to overcome hydrostatic pressure in the well.

In fractured reservoirs, the reservoir fluid can flow easily when exposed to an underbalanced condition due to the high flow conductivity of the fractures. The observed reservoir pressures in DH are between 414 – 428 bar at the datum depth of 3900 mss. Normally 10% overpressure in the reservoir is required to achieve underbalanced conditions.

For safety issues criteria for hole collapse and procedures for surface handling of the fluids need to be clearly defined. The open hole production history in the field shows that the rock is generally stable and the use of crude oil fluid should be acceptable and recommended both with respect to reservoir evaluation and rock compatibility. Surface handling of fluids need to be carefully assessed by the service contractor.

**Fracture Characterisation by UBD.** The Dehluran study showed the importance of precise positioning and characterization of the intersected fractures. This is of special importance if the reservoir section is completed with a casing and the production intervals are perforated.

When the flow-drilling method is applied, influx to the well will increase rapidly after the bit intersects fractures. By monitoring the rate of flow at the surface fracture interpretations can be made. This evaluation may be integrated with data from the Logging While Drilling tool (LWD) in real time and comprehensive fracture knowledge can be achieved. Micro-fractures which are difficult to detect by overbalanced mud loss may be observed by flow-drilling.
Completion and Stimulation. Later stimulation of a micro-fractured reservoir invaded by drilling mud is extremely difficult. Open hole completion is generally preferred in these competent formations and type of reservoirs due to larger reservoir exposure. Drilling overbalanced contaminates the fractured reservoir and open hole stimulation is difficult. An effective treatment requires selective stimulation of each fracture. To perform this in open hole time consuming straddle pack operations are required. A liner is normally set and perforated. In natural fractured reservoir one needs to perforate in the exact position of the fractures which is very difficult to achieve. Underbalanced well construction will help to avoid reservoir impairment maintaining the option of an open hole completion. Moreover, production diagnoses are simpler in complex fields by applying UBD and flow-drilling. With UBD, fracture monitoring can be done while drilling and it is possible for completion and reservoir engineers to make dynamic decision how to complete the wells.

Logistics with UBD. Downtime due to logistics problems represents a challenge as shown in the Dehluran field. UBD can help to reduce this downtime if an appropriate technique is selected. For example, using foam as the UBD drilling fluid does not need conventional water amounts. A closed UBD system will minimize waste of drilling fluids and improve environmental issues.

The specific field locations need attention as an UBD equipment package needs some extra space. However, assembling an UBD system onshore is simpler than offshore due to less space limitations.

UBD operations require a more careful planning than a conventional drilled well. It is therefore possible to reduce the downtime significantly and to improve the drilling efficiency and safety. As discussed before the root causes of mud losses or blowouts are unknown or not well-known fractures and associated pore pressure. UBD is an operation which plays with the well hydraulics, and thus adjusts the well pressure to the pore pressure.

UBD Time and Cost. Introducing UBD will add service cost to the drilling campaign. However, simple time and cost estimates can also illustrate potential cost savings in addition to improved well performance. Table 5 compares estimated rig days with conventional drilling and with UBD for a DH well and Table 6 compares the total drilling costs for the same well. It is assumed that rate of penetration with UBD will be twice compared to conventional drilling. Furthermore, it is assumed that additional daily rates of UBD is comparable to a rig rate of 25000 $$. Saved time on drilling and tripping in the reservoir interval without stimulation needs sums up to 12 rig days saved and a total cost almost equal to a conventional drilled well.

As most of the advantages of UBD come in the production phase a reasonable net present value calculation of UBD should be as a lifetime calculation of the well.

Conclusions

In the evaluation of productivity improvements of fractured carbonate reservoirs in Iran UBD technology has been identified as a promising tool. The value has been found to be mainly related to:

- Improved fracture network identification and characterization
- Improved well productivity avoiding fracture contamination
- Avoiding time consuming and risky stimulation operations
- While drilling decision support for optimized well placement and completion contingency
- Less need for drilling water supply and mitigating logistics related to mud materials
- Faster drilling with less rig days

A pilot program for a suite of wells may be needed to justify the associated mobilization costs.

Acknowledgment

The authors would like to thank Iranian Central Oil Field Company and SINTEF Petroleum Research for their support for the work and approval of publication.

Nomenclature

\[ Q = \text{mud loss rate (bbl/day)} \]
\[ w = \text{fracture opening, m} \]
\[ \delta = \text{fracture spacing, m} \]
\[ r_w = \text{wellbore radius, m} \]
\[ S_f = \text{fissure pseudoskin, dimensionless} \]
\[ k_f = \text{fracture permeability, mD} \]
\[ \phi_f = \text{fracture porosity, percent} \]

Subscript

\[ p = \text{parallel} \]
\[ c = \text{conjugated} \]

Reference


### Table 1 - Dehluran cumulative production and mud loss

<table>
<thead>
<tr>
<th>Well</th>
<th>Cumulative production (MMSTB)</th>
<th>Average daily rate (BOPD)</th>
<th>Mud loss</th>
<th>Mud type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>19.4</td>
<td>3796</td>
<td>Severe</td>
<td>WBM</td>
</tr>
<tr>
<td>3</td>
<td>9.7</td>
<td>1898</td>
<td>0</td>
<td>OBM</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>4110</td>
<td>0</td>
<td>WBM</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>7828</td>
<td>Severe</td>
<td>OBM</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
<td>2</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>11</td>
<td>0.14</td>
<td>27</td>
<td>0</td>
<td>OBM</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>OBM</td>
</tr>
<tr>
<td>14</td>
<td>0.004</td>
<td>1</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>16</td>
<td>0.75</td>
<td>147</td>
<td>Severe</td>
<td>WBM</td>
</tr>
<tr>
<td>17</td>
<td>0.004</td>
<td>1</td>
<td>Moderate</td>
<td>WBM</td>
</tr>
<tr>
<td>18</td>
<td>0.46</td>
<td>90</td>
<td>0</td>
<td>WBM</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>OBM</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>10</td>
<td>Partial</td>
<td>OBM</td>
</tr>
<tr>
<td>21</td>
<td>0.02</td>
<td>4</td>
<td>Partial</td>
<td>OBM</td>
</tr>
</tbody>
</table>

Table 2 - Mud properties in well DH-5

<table>
<thead>
<tr>
<th>Mud density</th>
<th>Plastic viscosity</th>
<th>Yield point</th>
<th>Solid</th>
<th>Oil / water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 s.g</td>
<td>19 cp</td>
<td>8 lb/100 sq.ft</td>
<td>15 %</td>
<td>70 / 30</td>
</tr>
</tbody>
</table>

### Table 3 - Summary of seven fields screening for UBD application

<table>
<thead>
<tr>
<th>Field</th>
<th>Number of wells</th>
<th>Production activity</th>
<th>Development status</th>
<th>Size of fracture</th>
<th>Frequency of fractures</th>
<th>Pressure gradient (Kpa / m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>Yes</td>
<td>Partially develop</td>
<td>Small to medium</td>
<td>low</td>
<td>11.8</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>Yes</td>
<td>Limited develop</td>
<td>Small to medium</td>
<td>very low</td>
<td>11.8</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>Yes</td>
<td>Limited develop</td>
<td>Small to medium</td>
<td>low</td>
<td>11.8</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>Limited Exploration</td>
<td>Large</td>
<td>very low</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>Limited Exploration</td>
<td>Large</td>
<td>NA</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>Limited Exploration</td>
<td>NA (sandstone)</td>
<td>NA</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>No Exploration</td>
<td>Large</td>
<td>NA</td>
<td>9.8</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4 - Results and recommendations after fields study

<table>
<thead>
<tr>
<th>Field</th>
<th>UBD Fluid</th>
<th>UBD Method</th>
<th>UBD Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>one phase</td>
<td>Flow drilling</td>
<td>Formation damage</td>
</tr>
<tr>
<td>2</td>
<td>one phase</td>
<td>Flow drilling</td>
<td>Formation damage</td>
</tr>
<tr>
<td>3</td>
<td>one phase</td>
<td>Flow drilling</td>
<td>Formation damage</td>
</tr>
<tr>
<td>4</td>
<td>two phase</td>
<td>Foam</td>
<td>Mud loss and safety</td>
</tr>
<tr>
<td>5</td>
<td>two phase</td>
<td>Foam</td>
<td>Mud loss and safety</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>7</td>
<td>two phase</td>
<td>Aerated</td>
<td>Mud loss and safety</td>
</tr>
</tbody>
</table>
### Table 5 - Historical conventional drilling operation time compared to plan UBD in DH field.

<table>
<thead>
<tr>
<th>Items</th>
<th>Nomenclature</th>
<th>Unit</th>
<th>OBD case</th>
<th>UBD case</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBD interval length</td>
<td>L</td>
<td>m</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Rate of penetration in reservoir interval</td>
<td>Rr</td>
<td>m / hour</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Total drilling time</td>
<td>T</td>
<td>hour</td>
<td>333</td>
<td>167</td>
</tr>
<tr>
<td>Tripping time in reservoir interval</td>
<td>Ttr</td>
<td>hour</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>UBD installation time</td>
<td>Tsubd</td>
<td>hour</td>
<td>NA</td>
<td>24</td>
</tr>
<tr>
<td>Stimulation time</td>
<td>Ts</td>
<td>hour</td>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td>Completion time</td>
<td>Tc</td>
<td>hour</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Total reservoir drilling time</td>
<td>Td</td>
<td>hour</td>
<td>597</td>
<td>311</td>
</tr>
<tr>
<td>Saved rig - days</td>
<td>Delta T</td>
<td>day</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6 - Historical conventional drilling operation cost compared to plan UBD in DH field.

<table>
<thead>
<tr>
<th>Items</th>
<th>Nomenclature</th>
<th>Unit</th>
<th>OBD case</th>
<th>UBD case</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBD service cost</td>
<td>Cubd</td>
<td>$ / day</td>
<td>NA</td>
<td>25 000</td>
</tr>
<tr>
<td>Rig cost</td>
<td>Crig</td>
<td>$ / day</td>
<td>25 000</td>
<td>25 000</td>
</tr>
<tr>
<td>Location cost</td>
<td>Cloc</td>
<td>$ / well</td>
<td>150 000</td>
<td>200 000</td>
</tr>
<tr>
<td>Stimulation cost</td>
<td>Cs</td>
<td>$ / well</td>
<td>50 000</td>
<td>NA</td>
</tr>
<tr>
<td>UBD service cost</td>
<td>Cubd</td>
<td>$</td>
<td>NA</td>
<td>323 611</td>
</tr>
<tr>
<td>Rig cost</td>
<td>Crig</td>
<td>$</td>
<td>622 222</td>
<td>323 611</td>
</tr>
<tr>
<td>Total reservoir drilling cost</td>
<td>Crez</td>
<td>$</td>
<td>822 222</td>
<td>847 222</td>
</tr>
<tr>
<td>Additional cost</td>
<td>Delta C</td>
<td>$</td>
<td>25 000</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1 - Location of the seven fields area. The Dehloran field was selected for evaluation.
Figure 2- Dehluran field map showing wells with mud loss (red circle) and production wells (blue circle). Wells not reaching the reservoir are indicated with pink squares.

Figure 3- Mud loss type distribution in the DH field wells (reservoir section)
Figure 4- Well sketch with perforation intervals and fracture depths.

Figure 5- Drilling mud loss in the pay zone of well DH-5 (actual mud loss).
Figure 6- Drilling mud loss in the pay zone of well DH-5 (differential mud loss).

Figure 7- Analysis of root causes for drilling downtime.