Underbalanced drilling of oil wells in Saudi Arabia: case history and lessons learned

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UNDERBALANCED DRILLING (UBD) has been accepted as an enabling technology for its various benefits. UBD can avoid or minimize drilling-related issues like stuck pipe and lost circulation and increase rate of penetration.

Saudi Aramco has identified the minimization of fluid losses, formation damage and reduction of nonproductive time (NPT) as key well design objectives. Based on these premises, UBD was accepted as an enabling technology to implement in the Ghawar Field (Muqeem, 2006).

OIL WELL PILOT PROJECT

After drilling 15 PWI wells underbalanced, Saudi Aramco extended the UBD campaign to oil wells. Three oil wells were drilled in the Arab D carbonate of the Uthmaniyah Field. The oil wells, like the PWI wells, were all high-pressure reservoirs (≥ 2,890-psi reservoir pressure); therefore all wells were drilled using the flow drilling (single phase) technology.

A closed/semi-closed loop diesel/native crude oil circulating system was used while applying the flow drilling technique to drill UBD Oil-1, UBD Oil-2 and UBD Oil-3. While drilling UBD Oil-1 and UBD Oil-2, all fluid returns from the well (including any produced fluid) were centrifuged, then passed through the settling tank farms before being used as drill fluid. In drilling UBD Oil-3, however, the centrifuge was removed from the loop. All fluid returns from the well passed through three settling tank farms and two additional tank farms, which served as storage and shipping for the produced oil. The excess volume of produced fluids was exported via a temporary flowline (COFLEXLITE) to the nearby gas-oil separation plant (GOSP).

All three wells were drilled according to the UBD program prepared, ensuring that bottomhole circulating pressures were engineered to be below the reservoir pressures at all times. Detailed surface separation setup and training and procedure development is covered elsewhere (Muqeem, 2006; Hallman, 2007).

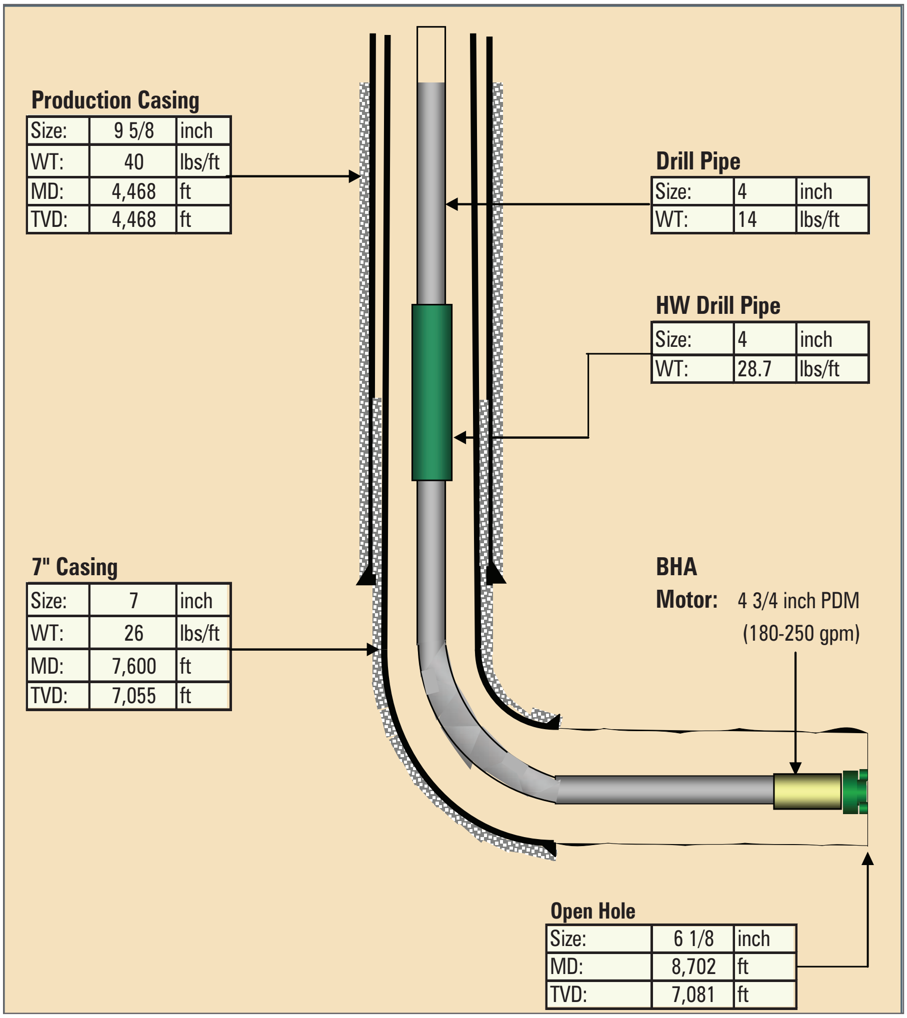


Figure 1: Well configuration for the first oil well drilled underbalanced in Saudi Arabia — UBD Oil-1. The 6 1/8-in. reservoir lateral was drilled from 7,600 ft MD/7,055 ft TVD to a total depth of 8,702 ft MD/7,081 ft TVD. The 1,102-ft lateral was drileld in 16 hours.

The first oil well drilled underbalanced in Saudi Arabia was UBD Oil-1. The 6 1/8-in. reservoir lateral was drilled from 7,600 ft MD (7,055 ft TVD) to a total depth of 8,702 ft MD (7,081 ft TVD). The 1,102-ft lateral length was drilled in 16 hrs, resulting in an on-bottom rate of penetration (ROP) of 69 ft/hr. Production while drilling was 4,679 BOPD.

The second underbalanced oil well drilled was UBD Oil-2. The 5 7/8-inch reservoir lateral was drilled from 8,057 ft MD (7,078.6 ft TVD) to a total depth of 9,500 ft MD (7,121 ft TVD). The 1,443 ft lateral length was drilled in 24.7 hours, resulting in an on-bottom ROP of 58.3 ft/hr. Production while drilling was 6,912 BOPD.

The third underbalanced oil well drilled was UBD Oil-3. The 6 1/8-in. reservoir lateral was drilled from 7,342 ft MD (6,564 ft TVD) to a total depth of 9,067 ft MD (6,586 ft TVD). The 1,725-ft lateral length was drilled in 20 hrs, resulting in an on-bottom ROP of 86.3 ft/hr. Production while drilling was 5,856 BOPD.

These key performance indicators were achieved while drilling the reservoir sections of wells underbalanced:

- Drilled underbalanced horizontal oil producer lateral; 1,102, 1,443 and 1,725 ft long, in the targeted zones of the Arab D reservoir for wells UBD Oil-1, UBD Oil-2 and UBD Oil-3 respectively.

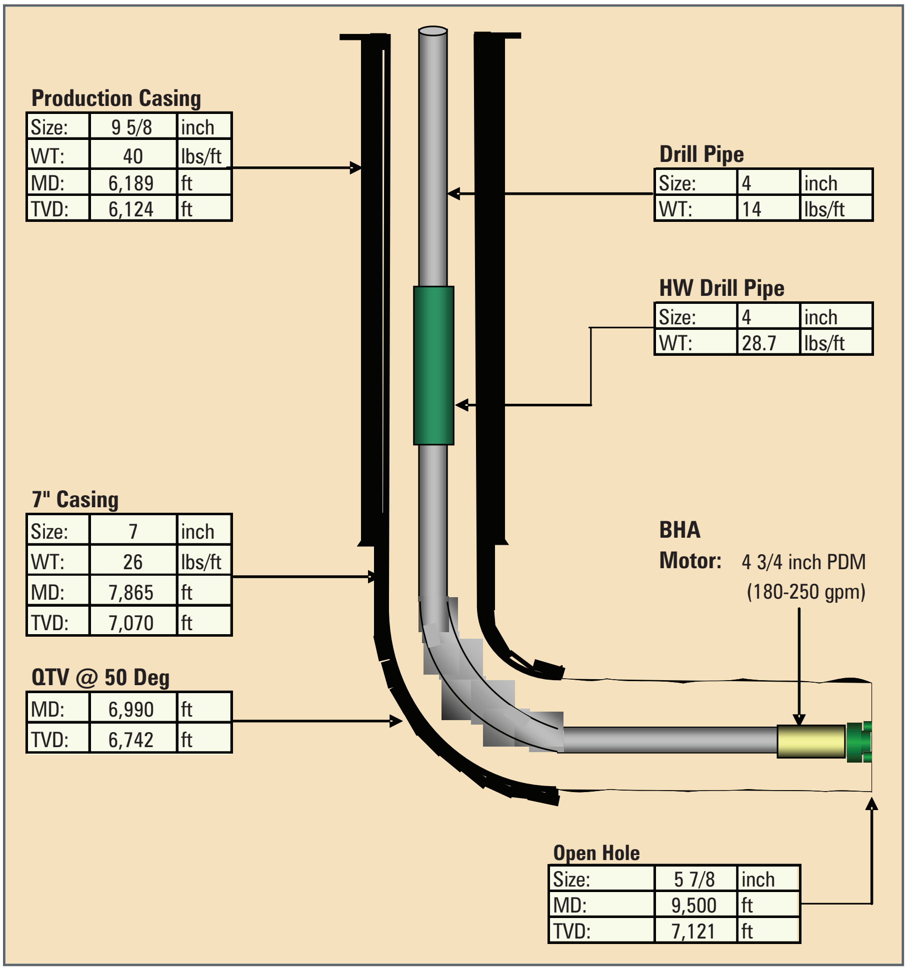


Figure 2: The second UB oil well drilled in Saudi Arabia, UBD Oil-2, required 24.7 hours to drill the 1,443-ft lateral, which kicked off from an MD of 8,057 ft (7,079 ft TVD).

- Improved ROP while drilling: Total on-bottom hours drilled for UBD Oil-1, UBD Oil-2 and UBD Oil-3 were 16, 24.7 and 20, with on-bottom ROPs of 69, 58.3 and 86.3 ft/hr, respectively.
- Achieved the maximum sustainable capacity (MSC) target by adding 5,000 BOPD to the GOSPs.

WELL PROFILES AS DRILLED

The objectives for drilling this well underbalanced were to maintain underbalanced conditions throughout the drilling operation and to minimize the environmental impact of any flared or released H_2S through the use of recycling and recovery technology and techniques.

UBD Oil-1

The well configuration for UBD Oil-1 is depicted in Figure 1. It consisted of a vertical 9 5/8-in. casing string and a 7-in. casing string set through a build section to 82° degrees and cemented at a depth of 7,600 ft MD (7,055 ft TVD). A **Halliburton** Quick Trip Valve (QTV) was run integral with the 7-in. 26-lb casing, but unfortunately the casing became stuck on the first attempt and was unable to be freed. This resulted in cutting the casing and fishing job, and the 8 ½-in. section had to be sidetracked and redrilled. The subsequent 7-in. casing string was then run without the QTV valve. The BHA was made up of a 6 1/8-in. PDC bit, a 4 ¾-in. positive displacement motor (PDM), logging and pressure measurement tools. The drill pipe and heavy weight pipes were 4-in. XT39 types.

UBD Oil-2

The well configuration (Figure 2) consisted of a vertical 9 5/8-in. casing string and a 7-in. casing string set through a build section to 86° and cemented at a depth of 7,865 ft MD (7,070 ft TVD). A second Halliburton QTV was run integral with the 7-in. 26-lb NVAM casing, but unfortunately the shifting sleeve pins could not be sheared on several attempts.

Eventually, the QTV flapper was milled, and drilling proceeded without a QTV valve. The BHA was made up of a 5 7/8-in. PDC bit, a 4 ¾-in. PDM, logging and pressure measurement tools. The drill pipe and heavy weight pipes were also 4-in. XT39 types.

UBD Oil-3

The well profile (Figure 3) consisted of a vertical 9 5/8-in. casing string and a 7-in. liner set through a build section to 83° and cemented at a depth of 7,342 ft MD (6,564 ft TVD). A 7-in. tie back seal was run with a **Weatherford** Downhole Deployment Valve (DDV) in a 7-in. 26-lb NVAM casing as part of the casing string to surface. The BHA was comprised of a 6 1/8-in. PDC bit, a 4 ¾-in. PDM, logging and pressure measurement tools. The drill pipe and heavy weight pipes were 4-in. XT39 types also.

H_2S CONTROL

Rawabi United Safety provided the H_2S monitoring system all around the rig site to check H_2S levels and ensure that H_2S readings were within permissible levels. WFT 9809, an oil-soluble scavenger, was the primary scavenger for the UBD Oil-1 oil fluid system. WFT 9801, a water-soluble scavenger, was used in water wash of the cuttings once they were removed from the centrifuge system. It was also subsequently used in the passive scrubbers after the aqueous ammonia being used became spent. The aqueous ammonia was not effective in knocking out the H_2S, which was vented from the tank farms. Three H_2S rig musters occurred during drilling due to the wind direction change, thus blowing back vented gas across the rig structure. H_2S was not effectively controlled on UBD Oil-1.

The experience from UBD Oil-1 necessitated changes to be implemented on UBD Oil-2 as far as H_2S control was concerned. Rawabi United Safety again supplied the H_2S monitoring system around the rig site to check H_2S levels to ensure that H_2S did not exceed the permissible levels. The WFT 9809 was again used as the primary scavenger in the fluid system.

Four passive scrubbers were installed as part of the venting system of the tank farm and were filled with WFT 9801. A back pressure was created in the 4-in. hoses connecting the scrubbers to the tanks farms, thereby popping open the atmospheric vents. This vented higher concentrations of H_2S around the tank farms while drilling. The scrubbers were therefore only partially effective in knocking out the H_2S with the WFT-9801 scavenger.

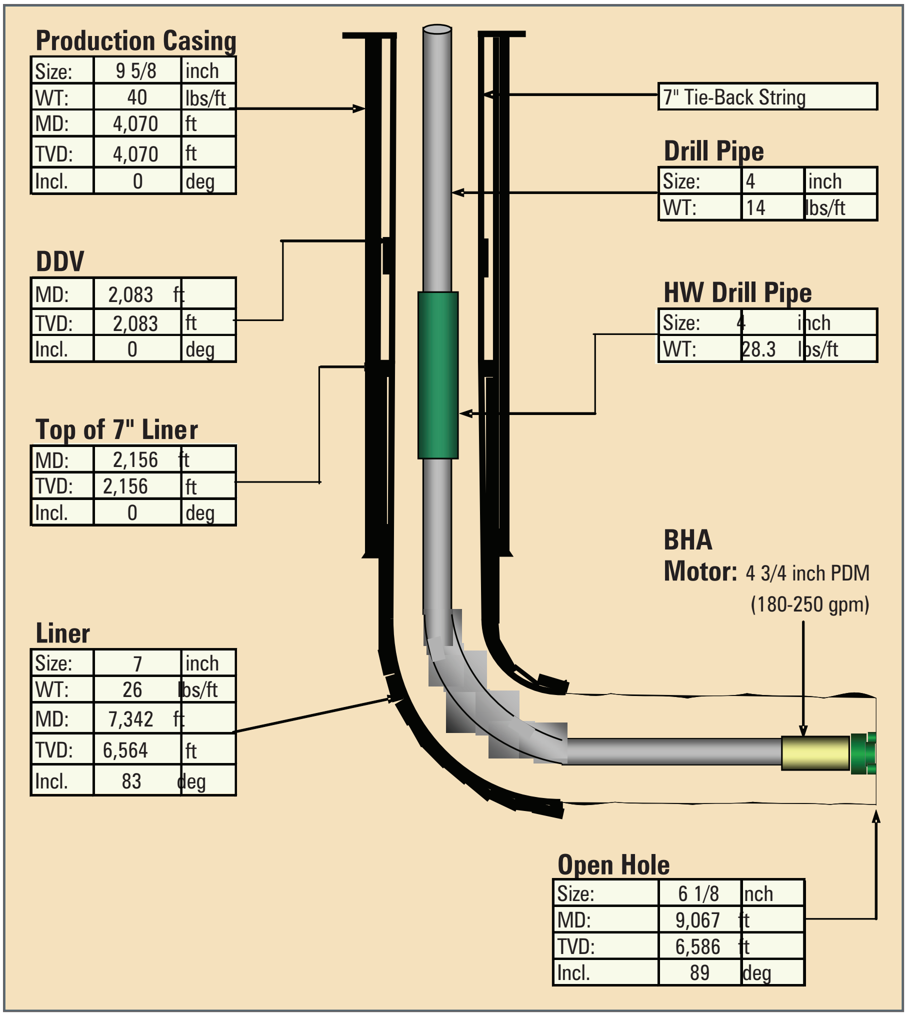


Figure 3: UBD Oil-3, Saudi Arabia's third UB oil well, featured the longest lateral (1,725 ft), drilled in 20 hours, producing the highest on-bottom ROP (86.3 ft/hr).

Two additional active (zero back-pressure) scrubbers were brought in to deal with H_2S problems while drilling UBD Oil-3. These scrubbers were installed as part of the venting system of the tank farms and were very effective in knocking out the high concentration of H_2S produced from the well.

Rawabi United Safety again supplied the H_2S monitoring system all around the rig site. Due to logistical supply reasons, WFT-9809 was not used on UBD Oil-3. Instead, H_22 + MCS (scavenger and surfactant additive), aqueous ammonia and WFT 9801 were used. The ammonia and WFT 9801 are water-soluble and were used in the scrubbers, which were connected to the tank farms. The HS2+MCS were the primary H_2S scavenger used in the power fluid. The highest concentration of H_2S recorded from the inlet of active scrubber was 10,300 ppm and outlet was 380 ppm when it had WFT-9801. The highest concentration of H_2S in the power fluid was 10 ppm. H_2S was effectively controlled while drilling UBD Oil-3.

ISOLATION VALVE

One objective of any well drilled underbalance is to maintain the underbalanced condition. This is necessary to eliminate the introduction of foreign solids into the zone of interest. Killing the well is one way of tripping drill string into and stripping out of the well. This defeats the purpose of utilizing underbalanced technology in the first place.

Current methods of achieving and maintaining underbalance conditions primarily involve the use of a snubbing or hydraulic workover unit to pull out of the hole or run in the hole with drilling tools and equipment. This process increases tripping times, adding appreciable operational complexity and expense. In addition, the snubbing unit cannot seal around complex completion assemblies (Grayson, 2004). As new technology evolves, we look for better, safer, and more cost-effective means of achieving the end objective.

One evolving means of maintaining underbalance is with a downhole isolation valve, either mechanical or hydraulic. Both types were tested to determine if they could be used as a downhole mechanical barrier and eliminate the need for a hydraulic workover unit. A total of four (1 PWI + 3 oil) wells served as our test platform for both tools. The mechanical downhole isolation tool (Figure 4) was run in three wells to determine if it was suitable and could be classified as a barrier and eliminate the requirement for a hydraulic workover unit. In each case, the mechanical downhole isolation tool was run with the 7-in. casing. The tool required no external control lines, utilized a flapper valve and used metal to metal seals.

The tool was run initially with a cementing sleeve installed to protect the flapper valve during the cementation process. This sleeve is then retrieved, allowing the flapper to close, thus isolating the reservoir in an underbalance state. Another sleeve is run in the hole with the drilling assembly and locks into place across the flapper valve to protect the valve while the drilling tools are tripped below the valve. Table 1 shows the conditions in which the downhole isolation tool was run.

PWI- 1 challenges

The 7-in. liner could not pass 7,020 ft. and was pulled out of the hole, and the hole was reamed. The 7-in. liner was run and could not pass 7,475 ft and was pulled out of the hole, and again the hole was reamed. Finally, on the third attempt, the liner was run and cemented at the hole depth. The cementing sleeve was found packed with cement when inspected at the surface. The downhole isolation valve failed to seal, and it was assumed that residual cement in the lower valve cavity caused the valve not to function as planned.

UBD Oil-1 challenges

The 7-in. casing was run to 6,920 ft, and the pipe became stuck. Several attempts to free the pipe were unsuccessful. Finally, the liner was backed off above the valve, and the well sidetracked. The section was re-drilled, and the decision was made not to run another valve in this section. The large outer diameter of the tool was thought to have contributed to the difficulties getting the casing to bottom.

UBD Oil-2 challenges

As a result of having difficulties getting the tool down in the previous two wells, the hole was drilled and opened simultaneously to 9 7/8 in. The 7-in. casing with the valve was run, and there was no difficulties going into the hole or cementing the casing. Additional measures such as spotting acid to remove any residual cement were performed. Several unsuccessful attempts were made to engage and open the valve. Eventually the valve was milled prior to drilling to TD.

Hydraulically operated downhole deployment tool

The hydraulically operated downhole deployment tool (Figures 5 and 6) was run into the last oil well to determine if it was suitable and could be classified as a barrier and eliminate the requirement for a hydraulic workover unit. The hydraulically operated downhole isolation tool was run with a 7-in. tie-back string after running and cementing the 7-in. liner. The tool required two control lines and utilized a flapper valve. The valve is functioned by pumping hydraulic fluid down the control line. Table 1 compares the conditions in which the hydraulic downhole isolation tool was run, along with the mechanical downhole isolation valve.

UBD Oil-3 challenges

There were no problems encountered with the running of the tool in the 7-in. tie-back string other than the necessary pre-planning required to enable the control lines to be run in circumstances that were not normal to the standard operation. Initial tests showed the tool held underbalance pressures. However, after completing of drilling the section underbalance and pulling the drilling string above the tool, the tool failed to hold pressure for a period of time. The valve was flushed with fluid and finally held pressure. It was suspected that there may have been some debris in the flapper valve allowing the well pressure to bypass the valve.

CHALLENGES AND LESSONS LEARNED

The lessons learned are provided as occurred on the three wells, although by the end of UBD Oil-3, almost all problems have been resolved.

H_2S control on UBD oil wells

The wellbore fluid in UBD Oil-1 had a higher concentration of H_2S than originally thought. The chemical program was designed to handle 700 ppm, but over 4,000 ppm was observed regularly at the separator outlet. This triggered surface release of excess H_2S gas during fluid surges, causing tripping of the

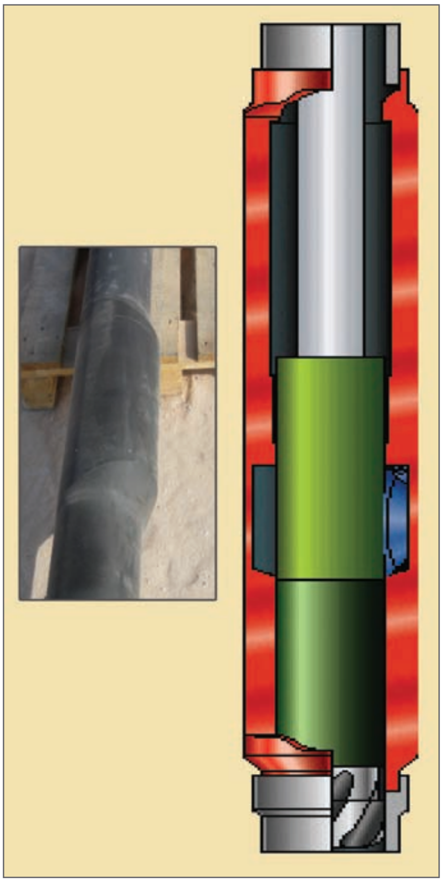


Figure 4: The mechanical downhole isolation tool was designed to serve as a mechanical barrier and eliminate the need for a hydraulic workover unit.

H_2S alarm systems. The wellbore fluid in UBD Oil-2 also had a higher concentration of H_2S than planned. The chemical program was designed to handle 6,000 ppm, but over 14,500 ppm was observed frequently at the separator outlet (Hallman, 2007).

Gas venting on UBD oil wells

There were too many vent points in the overall system design for UBD Oil-1, and they were too close to the surface control equipment. This led to release of gas at various positions when fluid influx was at its highest. The high wellbore fluid returns increased the volume of gas breaking out in the storage tanks; this caused the cold vent points in the UBD Oil-2 system to still release H_2S-laden gas when the vacuum breakers lifted. The installation of the "zero-backpressure" scrubbers in the system design of UBD Oil-3 enabled the handling of all the venting effectively without causing the vacuum vents to release any H_2S. The scrubbers dealt more efficiently with the H_2S as well, and no H_2S alarms occurred during the drilling of the well.

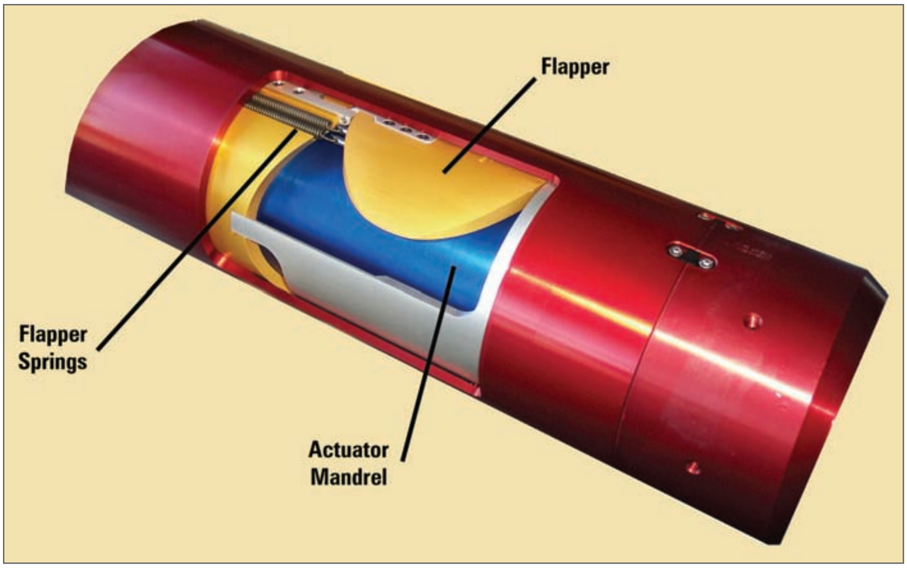
Pressure spiking due to bumping of drillstring float

The bottomhole circulating pressure spiked as a result of drillstring float bumping to establish the accurate standpipe pressure. This is not a common practice in underbalanced drilling. This procedure has to be done at low injection rate with good monitoring of the standpipe and wellhead pressures.

Completion

The three oil wells were completed with downhole packers and tubing. Since, the first two oil wells were killed with clean filtered brine due to various mechanical isolation valve problems, it was decided to drill and complete the last well fully underbalanced utilizing the rig assist snubbing unit. **High Arctic** provided the 120K rig assist snubbing unit for this project.

In the second oil well, the snubbing unit was rigged up, and dry simulation runs were conducted to make operational personnel familiar with the snubbing operation. In the last oil well, it was rigged up to snub out the BHA and snub in the completion with the well in an underbalanced state. Extensive and thorough planning and written work instructions were prepared to ensure a safe and



Figures 5 (above) and 6 (right): The hydraulically opened downhole deployment tool was evaluated in the last well for suitability as a barrier and to eliminate the need for a hydraulic workover unit. Table 1 (below) summarizes run conditions for the mechanically operated downhole isolation valve (PWI-1, UBD Oil-1, UBD Oil-2) and the hydraulic downhole isolation tool (UBD Oil-3).

	PWI-1	UBD Oil-1	UBD Oil-2	UBD Oil-3
Hole Size (in.)	8-1/2	8-1/2	8-1/2 x 9-7/8	8-1/2
Hole Depth (ft.)	7,717	7,600	7,865	7,342
Inc. at Hole Depth (deg.)	±87	±82	±86	±83
Tool Setting Depth (ft.)	6,137	6,240 (stuck)	6,989	2,083

smooth snubbing operation. Although it took longer to rig up/down the snubbing unit, all completion operations were conducted safely and according to the plan.

Cost

Since UBD was implemented in the 6 1/8-in. reservoir section of the three wells, only incremental costs were tabulated (Table 2). Due to the sour nature of the produced crude, extra safety and precautionary measures were taken early in the campaign. Afterwards, the equipment requirements and layout, as well as operational procedures, were redesigned and optimized based on the post-mortem and lessons learned exercises. This resulted in cost reduction as the campaign progressed. Furthermore, Saudi Aramco was testing new tools and technology in a live-well situation; therefore, extra time was spent training the rig and other field personnel.

UBD PROJECT ANALYSIS

A three-well UBD pilot project to deliver single lateral-horizontal oil-producing wells was completed in May 2006. The reservoir objectives were:

- Assess the extent of reduction of invasive formation damage across the UBD penetrated reservoir section.
- Achieve oil production along the entire length of the horizontal wellbore.
- Deliver a single-lateral horizontal well requiring minimum pressure drawdown along the horizontal section to produce desired oil target rate, thus reduce water coning and prolong dry oil production from the well.
- Optimize oil inflow into the horizontal wellbore to promote optimum reservoir drainage/sweep and oil recovery.
- Avoid the need for well stimulation.

All three UBD wells have been in production since October 2006. Several HPPT well-rate tests have been conducted on the three since production start-up; downhole production logging surveys were also completed on the three subject wells. Results of the UBD wells' performance along with comparison to the offsetting conventionally drilled horizontal oil producers are shown in Table 3.

Because of considerable distance (+25 km), separating UBD wells UBD Oil-1 and UBD Oil-2 from UBD Oil-3, results of UBD wells performance shown in Table 3 are split into two groups. Group-1 wells representing the GOSP-6 area where UBD Oil-1 and UBD Oil-2 were drilled underbalance and wells Offset-1 and Offset-2, which were conventionally drilled, are included for performance comparison. Group-2 wells represent well UBD Oil-3 and offsetting conventionally drilled wells Offset-3 and Offset-4 to provide comparative well performance data.

Within Group-1, the two UBD wells, UBD Oil-1 and UBD Oil-2, have superior PI values compared with Offset-1 conventionally drilled well. The very high PI observed in well UBD Oil-1 is produced by a very high capacity zone at 8,495 ft - 8,515 ft. Production logs for the two UBD wells, UBD Oil-1 and UBD Oil-2, show fluid entry along the entire horizontal sections for each well. Measured pressure draw-down for the UBD Oil-1 and UBD Oil-2 was 19 and 41 psi respectively. The recorded rising water production from UBD Oil-1 and UBD Oil-2, notwithstanding good PI values, low pressure draw-down and uniform production inflow profiles, is affected by a thin oil column (about 30 ft) at the two wells locations. Production inflow profile analysis and water entry identification for Offset-1 will be addressed pending production log assessment.

Within Group-2, UBD Oil-3 was drilled underbalanced along with conventionally drilled wells, Offset-3 and Offset-4, and is included for well performance comparison. PI values and pressure draw-down, 114 bbl/d/psi with delta-pressure of 62 psi for UBD Oil-3 and 120 bbl/d/psi and delta-pressure of 63 for Offset-4 indicate that UBD operations on UBD Oil-3 did not produce superior well performance as a result of underbalanced drilling. UBD Oil-3 well inflow production profile shows that the well produces along its entire horizontal length. The major factor affecting the overall performance of the three wells in Group-2 is the oil column thickness.

In summary, UBD of three horizontal oil producing wells in Arab-D highly pressured good quality reservoir did achieve the following:

1. Equivalent or higher PI values compared with conventionally drilled horizontal oil producers.
2. Uniform inflow profile along the entire horizontal section of the UBD wells.
3. Lower pressure draw-downs during production.

CONCLUSIONS

Three oil wells were successfully drilled underbalanced in the Ghawar Field using flowing drilling technology. While drilling UBD Oil-1, average oil production was 4,679 BPD with an associated

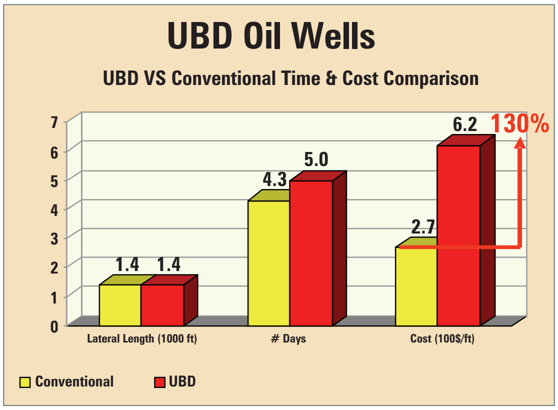


Table 2: Only incremental costs were tabulated because UBD was implemented in the 6 ⅛-in. section.

gas rate of 2.5 MMscfd. The average oil production while drilling UBD Oil-2 was 6,912 BPD with the associated gas rate of 2.0 MMscfd. UBD Oil-3 produced an average of 5,856 BOPD with an associated gas rate of 2.6 MMscfd. There was no water production in any of the wells.

Underbalanced conditions were maintained and continuously monitored throughout the drilling of the reservoir section of all three wells.

It was strongly recommended in both cases to carry out flow tests for at least one hour immediately after the drillstring has been pulled back to the casing shoe. This data is vital as a key performance indicator (KPI) for the UBD program.

Killing an underbalance drilled oil well by bullheading brine is not a good practice and defeats the objective somewhat. A move to using downhole valve arrangements was attempted to improve on this unsatisfactory arrangement.

The first two wells used Halliburton's Quick Trip Valve and, in both cases, severe problems were encountered that resulted in both wells being ultimately killed with brine. The third oil well ran a Weatherford Downhole Deployment Valve. This proved a success, and the well was drilled and completed in an underbalanced state with no need for well kill operations. With more DDV usage, confidence will increase, ultimately eliminating the need for a snubbing unit.

No HSE or LTIs were recorded during the underbalanced section of UBD Oil-1 and UBD Oil-2. There was one minor HSE incident while drilling the UB section of UBD Oil-3.

It has been proven on UBD Oil-3 that the efficiency of WFT 9801 in knocking out H_2S from the produced gas is far greater than aqueous ammonia.

The downhole installations of the mechanically operated isolation valve failed to prove its reliability. However, the hydraulically operated isolation valve was very successful in isolating the wellbore and should be acceptable for consideration as a downhole barrier with more field trial.

There were no fluid losses, no formation damage and no NPT. It was also demonstrated that a closed/semi-closed system could be utilized properly and safely to undertake UBD in the Ghawar field.

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To view the paper's references, please go to www.drillingcontractor.org.

	Well No.	Horizontal Length (ft.)	Porosity (%)	Oil Column (ft.)	Latest Rate BOPD	Latest Water-cut (%)	PI bbl/d/psi	Total Skin
Group-1	Offset-1	525	21	30	1887	48	4	129
	Offset-2	846	28	30	5963 R	6.7	-	-
	UBD Oil-1	1102	25	30	4240 R	17.7	371	-
	UBD Oil-2	1443	22	30	3337 R	32.4	110	-
Group-2	Offset-3	1400	20	30	2938 R	33.7	53.5	-
	Offset-4	1200	26	90	7922 R	0	120	6.1
	UBD Oil-3	1725	25	60	3063 R	3.4	114	-

Table 3: Comparison of UBD wells and conventionally drilled offset horizontal oil producers.