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REVIEW

Potential implementation of underbalanced drilling technique in Egyptian oil fields

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Abstract The need to increase productivity and to reduce drilling damage favors the use of underbalanced drilling (UBD) technology. In highly depleted reservoirs, extremely low-density fluids, such as foams or aerated mud, are used to achieve circulating densities lower than the pore pressure. In such cases, the induced modification of the in situ stresses has to be supported mainly by the rock, with little contribution from the drilling fluid pressure. The application of underbalanced drilling depends on the mechanical stability of the drilled formation, among other factors. In general, poorly consolidated, depleted formations are not suited for that technology.

In this paper, 23 UBD worldwide cases have been analyzed; two of which are from Egyptian fields and the others are from Iran, Algeria, Kuwait, Oman, Texas, Mexico, Indonesia, Canada, Libya, Middle East, Qatar, Saudi Arabia and Lithuania. From these analyses, the reasons of failure or success have been stated. The reasons of success included depleted reservoirs and highly fractured carbonates formation while, the reasons of failure include over pressurized shale, highly tectonic stress areas, and downhole failures. The main attractive application of this technology was proposed to be only in the reservoir section, and the target was to prevent the reservoir damage and hence increase the productivity and recovery factor.

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A proposed underbalanced drilling program is developed based on these analyses to be used in the three main regions in oil and gas producing Egyptian fields. The aerated mud was selected as a drilling fluid to drill the reservoir section in Western Desert and Gulf of Suez region whereas the single phase fluid was selected as a drilling fluid in the Nile Delta region.

Contents

1. Introduction

Drilling cost is considered one of the major components of operating cost in the petroleum industry. Improving the penetration rate of drilling operation and reducing drilling problems, such as pressure differential pipe sticking and lost circulation, have long been considered an effective way of decreasing drilling costs. The overbalance pressure, generally recognized as the most important among the many factors affecting penetration rate, is often defined as the pressure differential between the borehole pressure and formation fluid pressure (Murray and Cunningham, 1955; Eckel, 1957; Cunningham and Eenink, 1959; Gamier and van Lingen, 1959; Vidrine and Benit, 1968; Bourgoyne and Young, 1974; Black and Green, 1978). Formation pressures lower than the static pressure of a column of fresh water require the use of a lighter fluid, such as air, injected with liquid to obtain lower overbalance pressure to enhance penetration rate and to minimize lost circulation and pipe sticking as well as formation damage. Therefore, aerated mud drilling "implies the use of air or natural gas as the circulating medium instead of the regular mud" is becoming an attractive practice in some areas. The commercial use of aerated mud drilling began only in recent years (Rankin et al., 1989; Claytor et al., 1991). Low-density drilling fluids used in underbalanced drilling consist of air, mist, stable foam, and aerated mud foam with back pressure. Whereas the term "aerated mud" implies the simultaneous introduction of air and mud together into the standpipe in order to drill special types of formations (Godwin et al., 1986; Boyun and Rajtar, 1995; Salah El-Din and El-Katatney, 2009).

The main advantage of air as a circulating fluid is that being the lowest density fluid. It imposes minimum pressure on the formation to be drilled. High penetration rates have been achieved in hard and dry formations with the use of air as a circulating fluid. In addition to high penetration rate, longer bit life results through the use of this medium as compared to mud. Drilling rates as high as 90 ft/h have been attained in shales. Air drilling, however, is restricted to areas where high volume water sands are not present ahead of the producing zone. The rate of water influx that can be handled in the case of air drilling is also not well known. Other inherent disadvantages of using air or natural gas as drilling fluids include possibility of downhole fires and explosions, and sloughing of formations due to underbalance of stresses around the wellbore. Possibility of downhole explosions are of particular concern in air drilling operations. Small dust-like particles are generated as a result of rock cuttings (chips) being ground and pulverized by the drill string in the annulus, and collision of cuttings with each other, the tool joints, and the wall of the borehole due to the high velocity forces. In the presence of moisture, seal rings may form at tight places in the annulus, which create pressure chambers. With additional influx of natural gas from gas-bearing zones being penetrated by the bit, an explosion may easily occur.

Besides having formations suitable for air drilling, the most important consideration in drilling with air is the volume of air required. Air drilling often fails because of insufficient volume of air necessary to clean the hole efficiently under certain conditions, e.g., wet hole, sloughing shales, and influx of formation water. A practical rule of thumb for determining adequate air volume is that the volume required achieving 1000 ft per minute annular velocity to clean the hole properly (Godwin et al., 1986; Boyun and Rajtar, 1995).

Drilling with foam has some appeal due to the fact that foam has some attractive qualities and properties with respect to the very low hydrostatic densities, which can be generated with foam systems (Hooshmandkoochi et al., 2007; Moore and Lafave, 1956; Maurer, 1998; Bentsen and Veny, 1976). Foam has good rheology and excellent cutting transport properties. The fact that foam has some natural inherent viscosity

Table 1 Change in BHCP versus mud rate and N2 rate.

Duration (h)	Mud rate (GPM)	N_2 rate (SCF/m)	N_2 (%)	SPP (psi)	BHCP (psi)	ECD (kg/lit)	Gain (bbls)	MWD Signal
1.5	250	250	4.8	2250	2887	0.86	31 mud	Ok
3.0	250	500	9.1	2250	2660	0.79	34 mud	Ok
2.0	240	500	11.4	1800	2652	0.79	0	Ok
1.5	230	500	13.2	1600	2620	0.78	0	Ok
1.5	210	500	15.5	1450	2590	0.77	0	Ok
1.5	180	500	21.6	1120	2549	0.76	0	Ok

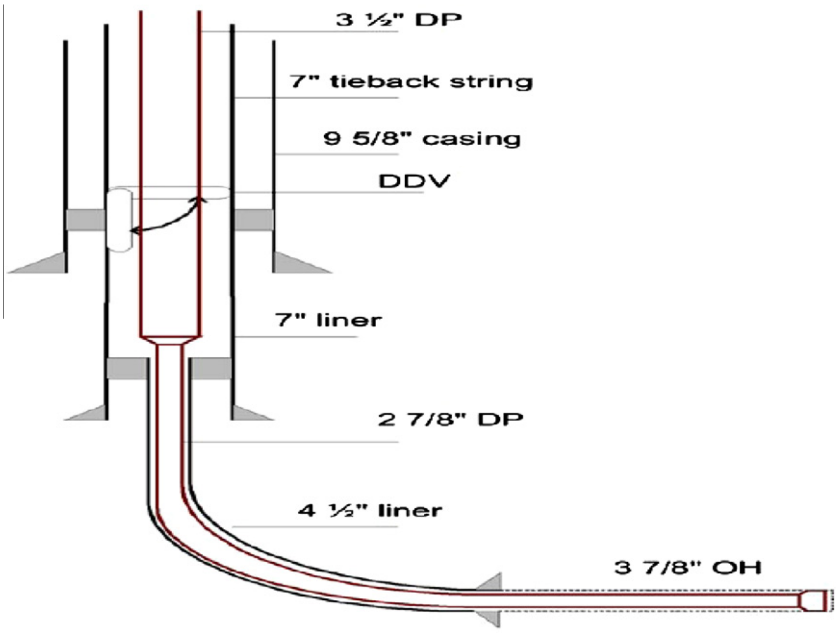


Figure 1 Well profile diagram for case 2: western desert gas field area.

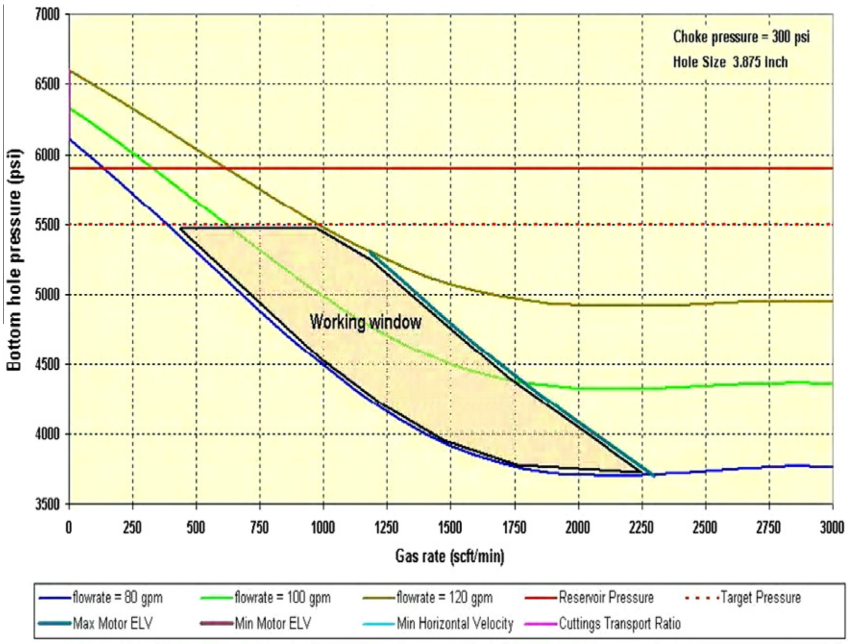


Figure 2 Working window for case 2: western desert gas field area.

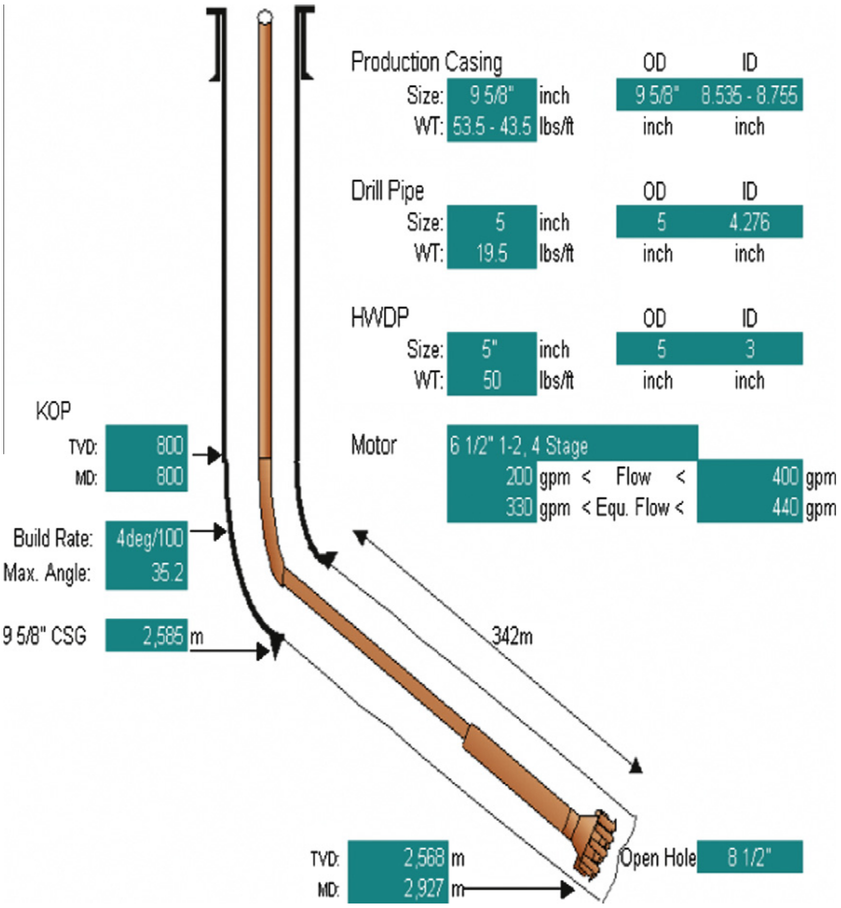


Figure 3 Well profile diagram for case 3: Iranian oil field area.

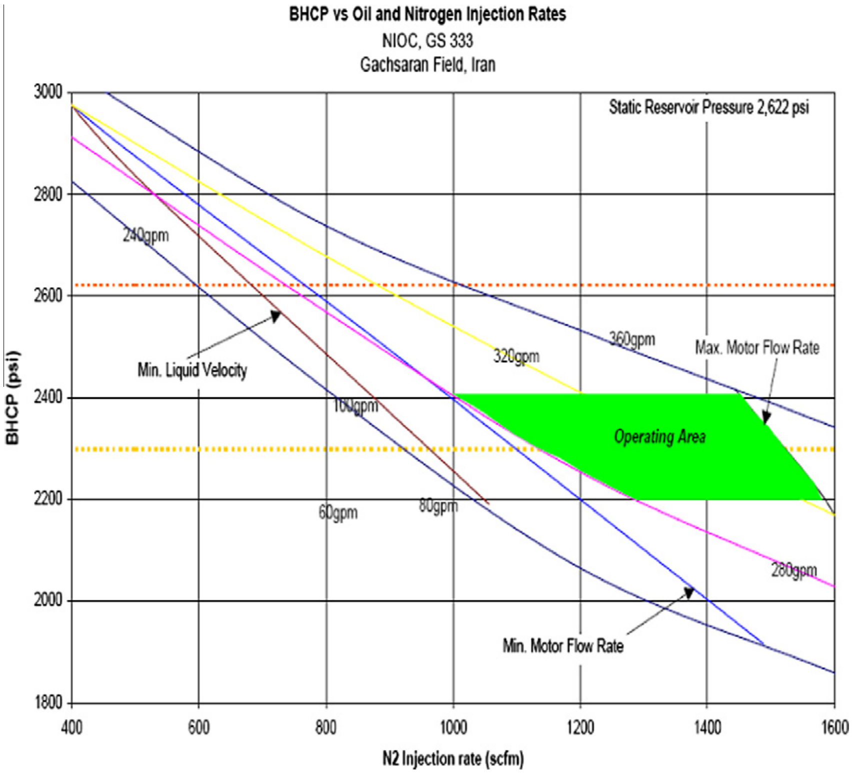


Figure 4 Operational envelope – native crude for case 3: Iranian oil field area.

Table 2 Recorded ROP in Algeria.

Algeria sandstone reservoir		
Well number	ROP overbalanced (ft/h)	ROP underbalanced (ft/h)
1	10.4	19.5
2	10.4	17.6
3	19.3	22.5
4	19.5	22.3
5	13.5	45
6	17	26.6

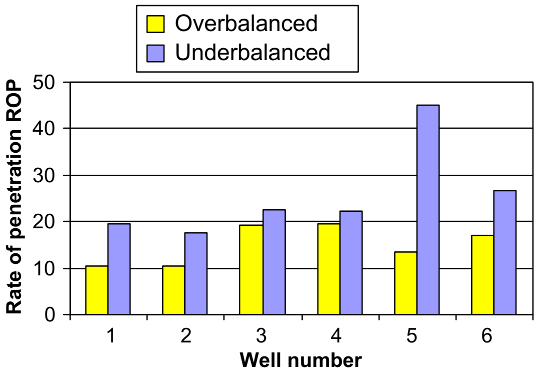


Figure 5 Comparison between ROP in OB and UB cases.

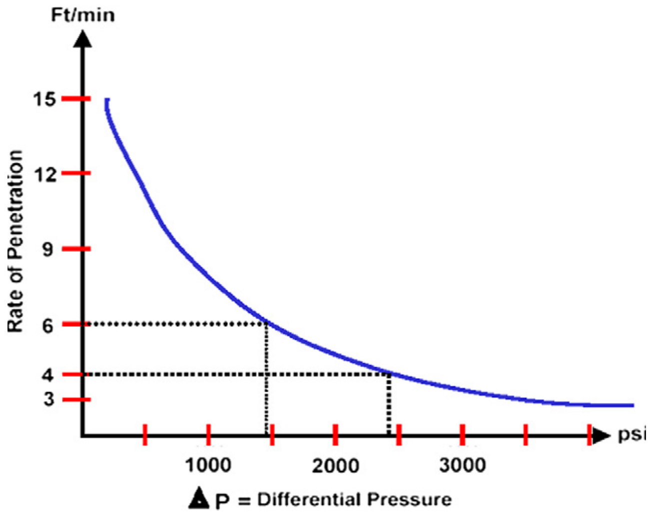


Figure 6 Relationship between ROP and pressure drop.

Table 3 ROP versus pressure drop for UBD wells.

Reservoir pressure (psi)	Pressure drop (ΔP) (psi)	Rate of penetration (ft/h)	Lithology
2900	290	45	Sandstone
3000	360	38	Sandstone
1350	540	16	Sandstone
3200	640	27	Sandstone
5500	990	30	Sandstone

Table 4 Recorded data for UBD wells.

Pressure drop (psi)	ROP (ft/h)	Production while drilling (%)	Production after test (%)	Lithology
290	26.6	0	1.2	Sandstone
320	44.7	0.8	3.9	Sandstone
350	19.45	1	2	Sandstone
406	22.5	1.5	1.8	Sandstone
435	17.6	2.7	3.4	Sandstone

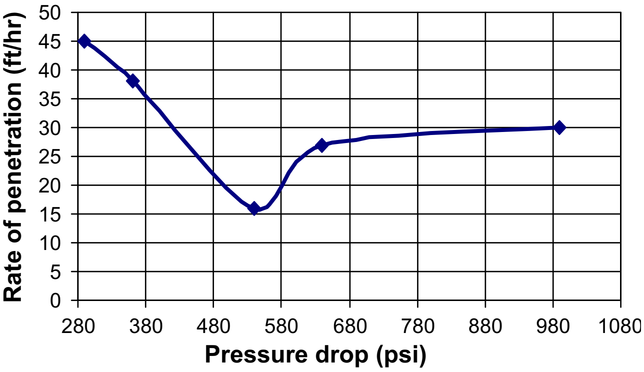


Figure 7 ROP versus pressure drop for UBD wells in different reservoirs.

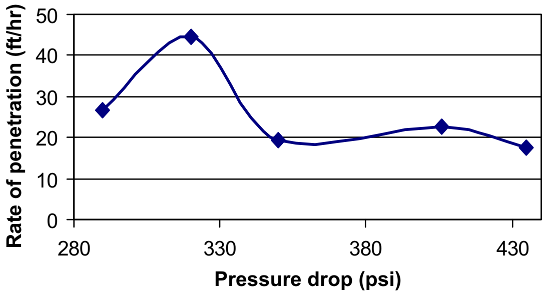


Figure 8 ROP versus pressure drop for UBD wells in one reservoir.

as well as fluid loss control properties, which may inhibit fluid losses, makes foam a very attractive drilling medium. During connections and trips, the foam remains stable and provides a more stable bottom hole pressure. It is a particularly good drilling fluid with a high carrying capacity and a low density. The foam normally remains stable, even when it returns to the surface, and this can cause problems on a rig if the foam cannot be broken down fast enough. In earlier foam systems, the amount of defoamer had to be tested carefully so that the foam was broken down before any fluid entered the separators. In closed circulation drilling systems, stable foam could cause particular problems with carry over. The recently developed stable foam systems are simpler to break, and the liquid can also be refoamed so that less foaming agent is required and a closed circulation system can be used. These systems, in general, rely on either a chemical method of breaking and making the foam, or the utilization of an increase and decrease of pH to make and break the foam. The foam quality at surface used for drilling is normally between 80% and 95%.

The quality of foam means that the system is 80–95% gas, with the remaining 5–20% being liquid. Downhole, due to the hydrostatic pressure of the annular column, this ratio changes as the volume of gas is reduced. An average acceptable bottom-hole foam quality (FQ) is in the region of 50–60%. Fluid densities for foam range from 1.6 ppg to 6.95 ppg (0.2–0.8 S.G.) (Godwin et al., 1986; Boyun and Rajtar, 1995). The density ranges are adjusted with the make up of the foam by adjusting the Liquid Volume Fraction (LVF) through the injection of liquid and gas by adjusting the backpressure on the well. The backpressure adjusts the downhole pressure and slows down the velocities in the annulus. Experience has proven that foam is able to handle over 100 bbl/h of water influx (Godwin et al., 1986; George and Waston, 1956; Boyun and Rajtar, 1995).

So, the objective of this research work is to investigate and analyze many worldwide applications of underbalanced drilling and state the reasons of success or failure of this application. Based on these analyses, a proposed underbalanced drilling program is developed. In this proposed program, the method of selecting the appropriate technique to be applied for these candidate areas are selected according to the geology of the area and the bottom hole conditions inside the wells.

2. Studied cases

In this section, three case studies from Egyptian fields and other places are analyzed in detail and a summary of 20 cases from other worldwide fields are given with a brief discussion about their objectives, problems and results (Salah El-Din and El-Katatney, 2009).

2.1. Case 1: gulf of Suez area

The well is located at onshore Belayim oil field. The well target was sandstone of zone III (Belayim formation, Feiran member) at a total depth of 2335 m TVD, 2854 m MD. The pressure in Zone III (sandstone) was estimated to be 3000–3500 psi (0.3917–0.4569 psi/ft). The objectives of UBD were to increase rate of penetration, enhance Well control, reduce occurrence of lost time incidents, and increase well productivity. The 20 m of the new hole at 7 in. liner shoe at 2659 m MD was drilled with only mud, then the MWD signal test was performed (inflow test and also to test the optimum rate combination for better MWD signal) as shown in Table 1. Based on this test, the formation pressure was estimated to be less than 2500 psi that was confirmed at 2400 psi from vacuum test and the MWD can work up to 21% nitrogen. Nitrified mud (500 SCFM + 230 gpm diesel) was applied while close balance drilling the six in original and side-track lateral section. The six in hole was drilled to depth 2830 m utilizing UBDS and power-pack motor of 1.15° BH c/w MWD Impulse, VPWD, ADN tools (inclination at bit, annulus and string pressure, GR resistivity, density-neutron) with 2 × 3-1/2 in. W.FORD float valve + motor restriction sub (nozzle 14/32 in.) for improving MWD signal. The analysis of this well results showed that, The ROP was enhanced drastically in sand from 4 m/h while sliding to 50 m/h, and in anhydrite was 8–10 m/h (experienced 2–4 m/h in normal overbalance drilling), the use of rotating head helped to control well while tripping and also in case of separator carry over problems, and the Crew acquired UBD work experience.

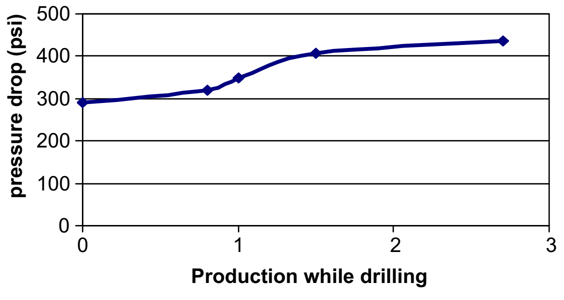


Figure 9 Production while drilling versus pressure drop for UBD wells.

2.2. Case 2: western desert gas field area

The well is located at the central part of the western desert block. The well target was to drill 3-7/8 in. × 500 m horizontal

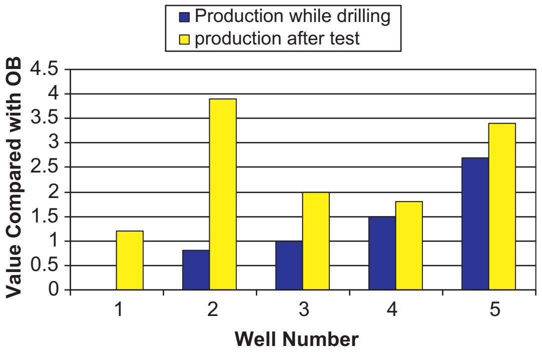


Figure 10 Comparison of production while and after UBD drilling.

Table 5 Drilling time and cost savings for 8-1/2″ hole section drilled underbalanced conditions.

Well	Real cost		Clean cost (just drilling)	
	Days	K$	Days	K$
8-1/2″ hole – conventional				
1	27	1171	27	1171
2	25.7	1146.3	24.4	1114
3	30.4	2125.3	21.6	1771.9
4	19.3	1360.1	17.6	1230.8
5	31.9	2215.7	16.7	1629.3
6	23.3	1058.5	22.4	1035
7	31.4	1385.1	23	1005.6
8	21.6	1241.5	17.8	989.9
9	20.7	899.1	17.2	667.4
10	34.1	1551.6	30.3	1300.1
Average	26.5	1415.4	21.8	1191.5
8-1/2″ hole – underbalanced				
1	20.5	1652	14.8	1395.6
2	19	1458	13.7	1243.5
3	21.2	1998.6	16.5	1541.5
4	17.8	1193.6	15.7	728
5	12.9	597	12.2	553.9
Average	18.3	1379.8	14.6	1092.5

section in unit 3 of the Mesozoic Lower Safa reservoir. They are composed of low to medium permeable (1–500 md) micaceous sandstones deposited in a strong tidally influenced estuary, Fig. 1. Lower Safa formation comprises a high-energy sequence of Estuarine deposits with a total average thickness of 110 m in the area where is planned, although only 29 m of these thickness are considered productive. The objective of UBD was to prevent reservoir damage. Gasification was through drill pipe injection technique.

The well was completed as open hole. Average ROP during overbalanced drilling operations on offset wells has been historically 2–3 m/h in the horizontal section. Historical data for UBD wells suggested that there will be an improvement in ROP due to the elimination of the chip hold-down effect. It was estimated that the ROP will be between 5 and 10 m/h. The drilling fluid of choice was produced water. The drilling fluid could be separated from the produced hydrocarbons and re-used. Due to the CO_2 content of the reservoir (up to 9%) and the use of nitrogen (up to 5% O2), corrosion mitigation was required. Once the well started to produce during the drilling phase, the N_2 was stopped, which in turns eliminated excessive use of corrosion inhibitors. Water and nitrogen gave the desired underbalanced margin when kicking off the well, and water was treated with suitable chemicals for corrosion mitigation. It became apparent that the Lower Safa formation was normally pressured. Hence by using just water, the BHP will be 260 psi underbalanced. Nitrogen was required to create a greater draw down than the 260 psi as it is unknown at what draw down the matrix starts to contribute to the inflow.

Table 6 Drilling time and cost savings for 6-1/2″ hole section drilled underbalanced conditions.

Well	Total cost		Drilling cost	
	Days	K$	Days	K$
6-1/2″ hole – conventional				
1	9	886.6	9	886.6
2	11.8	591.8	11.8	591.8
3	20.7	1186.4	18.1	1082
4	29.6	1596.7	17.8	644.7
5	33.5	2074.1	20	1531.9
6	21.9	928.1	19.7	779.9
7	19.1	995.5	17.8	938.3
8	14.1	778.5	11.8	650.6
9	16.4	800.8	16.4	800.8
Average	19.6	1093.2	15.8	878.5
6-1/2″ hole – underbalanced				
1	7.4	507.8	6.6	471.9
2	24	1664.6	11.9	998.9
3	22.4	1804	17.2	1057.7
4	14.8	545.1	10.8	387.57
5	9.5	580.6	9	560.6
Average	15.6	920.4	11.1	695.3

Table 7 Gulf of Suez reservoir characteristics.

Parameter	Belayim	Kareem
Pressure	1500 psi	1700 psi
Temperature	180 °F	190 °F
Gas–oil ratio (GOR)	15–17 SCF/STB	20 SCF/STB
Porosity (md)	18–20%	20–22%
Permeability	200 md	500 md
API^0 gravity of oil	20–23	20–30
H_2S concentration	No	No

As soon as the well produced, nitrogen was cut down to zero rates. Nitrogen injection was required again every time the drill string tripped through the Down-hole Deployment Valve (DDV) to remove the water from the reservoir section.

Fig. 2 shows the working window (operating envelope) for the well (case 2) with no reservoir inflow for, 3-7/8 in hole, 3-1/2 in. × 2–7/8 in. drill pipe design, 2 × 500 m legs, and bit at TD. Also plotted on the operating envelope, are the various constraints that must be fulfilled during underbalanced drilling operations. After drilling 200 m, the drilling had been stopped due to failure of downhole equipment due to high temperature**.**

2.3. Case 3: Iranian oil field

The target reservoir for this well was Asmari formation, the formation was fractured carbonated formation. The reservoir drive mechanism was gas cap. Shale strings were not expected in this formation. Expected reservoir pressure and temperature were 2622 psi and 141 °F, respectively. Reservoir fluid was oil with API gravity of 25°, GOR 564 SCF/STB, and H2S concentration of 240 ppm. The permeability of the reservoir was 0.1–1000 md with a porosity of 9% (Hooshmandkoochi et al., 2007). The well was drilled from m (9-5/8 in shoe depth) to a total depth of 2938 m MD (2567 m TVD), Fig. 3. The primary objectives of this underbalanced drilling project were to: minimize drilling induced formation damage, eliminate drilling fluid losses, and improve drilling performance. The drilling fluid selection was one of the most critical decisions in planning an underbalanced well. The right fluid(s) selection will not only lead to suitable BHCP but will also minimize pressure transients and thus eliminating/minimizing formation impairment. The deviated underbalanced section of this well was to be drilled with a Gachsaran field native crude oil and a membrane nitrogen generation circulating system. Liquid Phase, the native crude oil, was chosen over Diesel and other drilling fluids because it is the natural reservoir fluid for this well. This minimized chances of formation

Table 8 Gulf of Suez formation characteristics.

Formation	Lithology	Top (m)	Thickness (m)	Pore pressure (psi)
Belayim				
Hammam Faraun	Shale-sand	2160	35	
Ferran	Shale-sand	2195	140	
Sidri	Mainly sand	2335	65	1500
Babaa	Anhydrite	2400	15	
Kareem	Limestone	2415	195	1700

Table 9 Underbalanced drilling design parameters for Gulf of Suez area.

Rig modification	• No essential modifications to be made on the rig to suite UBD operations • The substructure has to be high enough to allow Rotating Control Head (RCH) to be installed on top of the Hydril
Well plan	• As shown in Fig. 11
Drill string design	• Use a 5″ DP and 5″ HWDP on 6-3/4″ DC
BHA	• The BHA consists of 6-1/2″ mud motor and MWD to drill 8-1/2″ hole • An 8-1/2″ bit size of 3 × 13/32″ nozzles
Drilling fluid selection	• The deviated section will be drilled using an oil bas mud and a membrane nitrogen generation circulating system
A-liquid phase	• Drilling fluid is native crude oil with density 7.6 ppg (0.91 S.G. or 20° API) • Liquid flow rates were selected to achieve a drawdown from the reservoir pressure
B-gas phase	• Nitrogen was selected as the injection gas • Nitrogen will be obtained from the surrounding air and generated onsite
Operating envelope	• A minimum drawdown at the bit of 100 psi is required to ensure adequate underbalanced conditions in the well • Using 300 gpm and more than 2400 scfm of Nitrogen will provide maximum 100 psi drawdown from the expected reservoir pressure, as shown in Fig. 12 • In case the real reservoir pressure will result below the expected value, then the liquid injection rate should be reduced increasing the risk for a hole cleaning issue
Hole cleaning	• Minimum annular liquid velocities in deviated holes of 210 ft/min when crude oil is used as the drilling fluid to ensure that the drilled cuttings are effectively removed from the wellbore • A wiper drilling trip will help clear the problem of hole cleaning
Motor performance	• The motor should be suitable for oil/nitrogen two-phase application • A maximum Equivalent Liquid Volume through the motor of 600 gpm was used as reference • A pressure loss of 800 psi between downhole motor and MWD was considered • The motor should not have a bypass valve on top of it
Production sensitivity	• As more reservoir fluids (oil and gas) introduced into the wellbore, the bottomhole circulating pressures (BHCP) will decrease • BHCP will therefore be controlled by increasing liquid injection and/or decreasing nitrogen injection, based on real-time BHCP data from the MWD tool • BHCP could also be controlled with surface backpressure • Choking will be necessary in stabilizing the circulating system during and after drill string connections
Data acquisition	• The software for the rig data acquisition has to be able to interface with the UBD equipment software
Completion	• The well can be completed with barefoot completion technique, or installing a slotted liner completions

damage in event of pressure transients and/or from fluid imbibitions. The well was displaced with the produced fluid after getting enough oil production. Gas Phase, nitrogen, was selected as the injection gas because of its inert nature, economic availability and suitability for this specific underbalanced drilling project. Nitrogen was obtained from the surrounding air and generated onsite, by nitrogen production unit (NIOC's). The multiphase flow behavior in the wellbore during underbalanced drilling was very complex. The response of the downhole conditions to changes in various flow parameters must be characterized prior to the commencement of underbalanced drilling operations in order to maximize chances of success. Fig. 4 contains a plot of the bottom hole circulating pressures induced by a variety of nitrogen rates and the Gachsaran native crude oil injection rates. This plot was referred to as the operating envelope. Also plotted on the operating envelope, are the various constraints that must be fulfilled during underbalanced drilling operations. The range of flow rates that satisfy all of the constraints, defined the acceptable operating region. A minimum drawdown at the bit of 200 psi was required to ensure adequate underbalanced conditions in the well, with a maximum drawdown of 300 psi to minimize any near wellbore depletion effects. The target bottom hole circulating pressure at the bit for this well was 2300–2400 psi.

UBD on this well experienced some typical logistical and start up problems associated with a steep learning curve, this being the first such operation in Iran. Despite all the problems encountered in this well, the following performance had been achieved: drilled to 308 m of total open hole depth, no loss circulation was encountered while drilling, successfully implemented UBD technology, and no Quality, health, safety and environment (QHSE) incidents were recorded. Data for case 4 to case 23 are given in the Appendix A (Azeemddin, 2006; Bates, 1965; Bennion et al., 1998; Dorenbos and Ranalho, 2002; Gordon, 2005; Gray, 1957; Hongren et al., 1999; International Association of Drilling Contractor, 2005; Kuru, 1999; Louison et al., 1984; Maclovio, 1996; Meng, 2005; Moore et al., 2004; Nas, 2004; Negra et al., 1999; Parra et al., 2003; Qutob, 2007; Qutob and Ferreira, 2005; Sunthankar, 2001, Weatherford Company, 2006; Westermark, 1986; Whiteley and England, 1986; Zhou, 2005).

2.4. Data analysis

The following analysis is carried out based on some actual wells drilled underbalanced worldwide. As mentioned before, the main advantage of underbalanced drilling techniques is to increase the rate of penetration as compared with overbalanced drilling techniques.

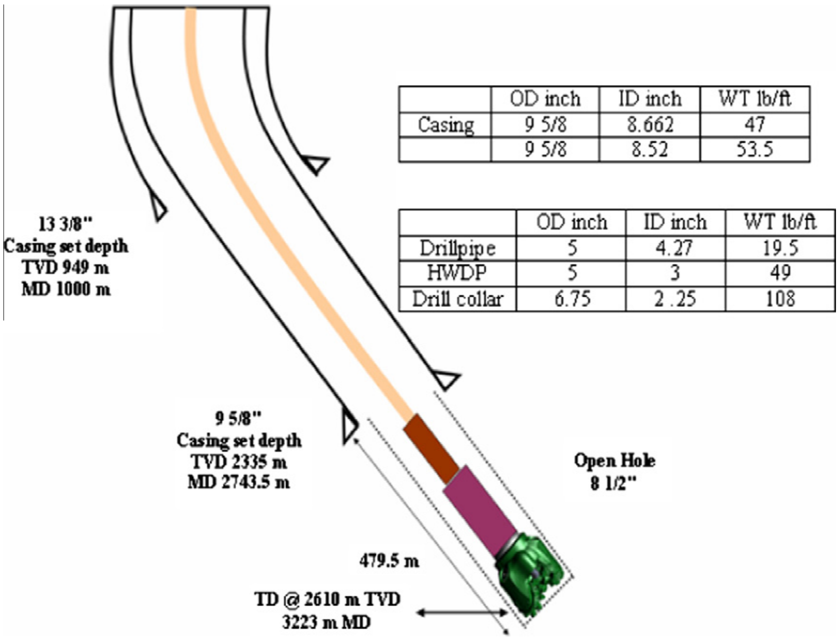
Table 2 gives the recorded data that were collected from successful underbalanced drilling cases in which the aerated mud was used to drill sandstone reservoir sections (Moore and Lafave, 1956).

From Fig. 5, there is an observed increase in ROP in all cases that were drilled by underbalanced techniques. In underbalanced drilling, ROP was increased due to the disappearance of chip hold-down effect. So the normal trend includes that an increase of the ROP resulted from a decrease in the hydrostatic pressure of drilling fluid as compared with the pressure of the formation that drilled by UB, as shown in Fig. 6.

Table 3 gives the recorded data of ROP (ft/h) and pressure drop (psi) for different reservoirs that were drilled by aerated fluid as an UBD drilling fluid. These reservoirs have the same lithology but having different reservoir pressure.

Table 4 gives a recorded data for different wells drilled by aerated fluid in a reservoir that has a constant pressure and same lithology compared to those wells drilled in overbalanced environment (Moore and Lafave, 1956).

Fig. 7 illustrates that ROP initially decreases with an increase in pressure drop and increases with further increase in pressure drop. Whereas, Fig. 8 shows that ROP has no



	OD inch	ID inch	WT lb/ft
Casing	9 5/8	8.662	47
	9 5/8	8.52	53.5

	OD inch	ID inch	WT lb/ft
Drillpipe	5	4.27	19.5
HWDP	5	3	49
Drill collar	6.75	2 .25	108

Figure 11 Well schematic of Gulf of Suez oil field area.

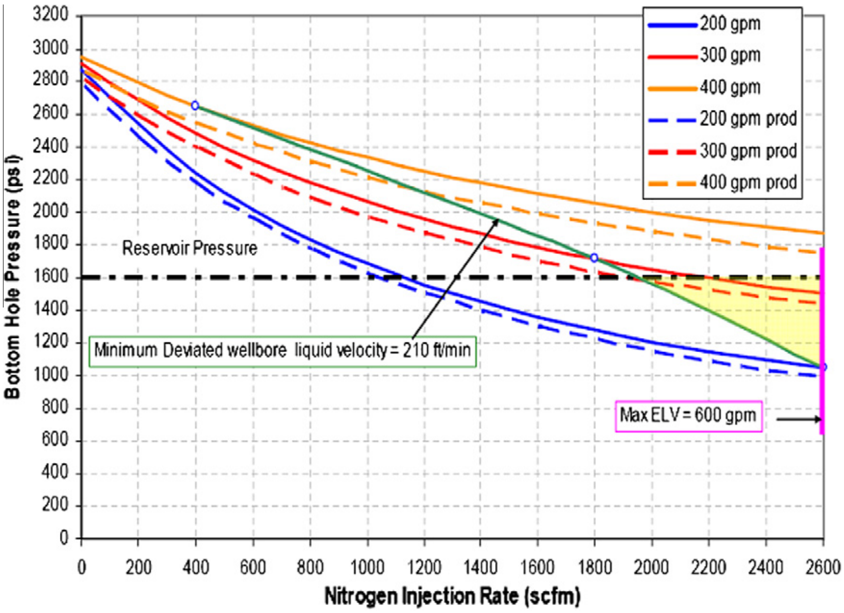
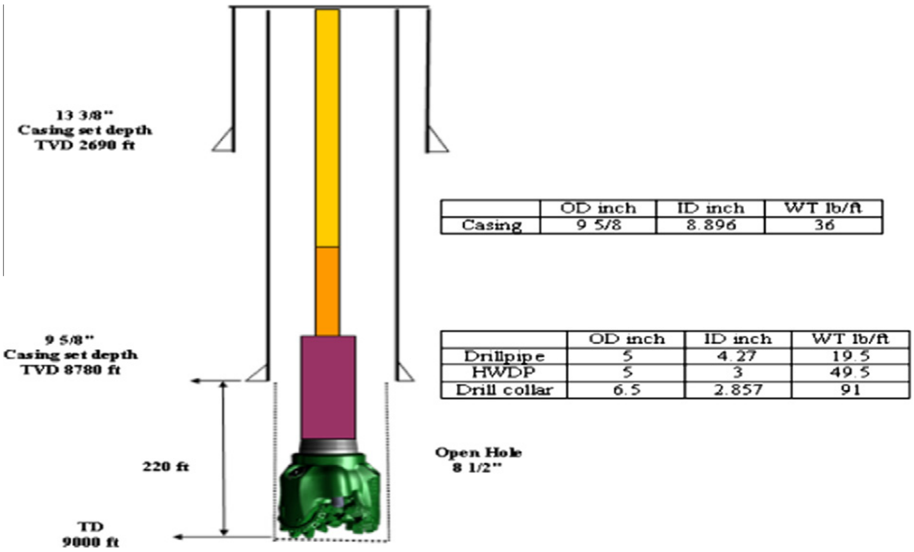


Figure 12 Operating window, multiphase fluid injection of Gulf of Suez oil field area.

Table 10 Underbalanced drilling design criteria for western desert area.

Rig modification	• No essential modifications to be made on the rig to suite UBD operations • The substructure has to be high enough to allow Rotating Control Head (RCH) to be installed on top of the Hydril
Well plan	• As shown in Fig. 13
Drill string design	• Use 5″ DP, 5″ HWDP and 6.5″ DC
BHA	• No downhole motor used • An 8-1/2″ bit size of 3 × 13/32″ nozzles size
Drilling fluid selection	• Based on the pore pressure and formation depth, the reservoir formation is below the normal pressure regime • The subnormal pressure requires the use of a multiphase (liquid + gas) drilling fluid system in order to obtain on Underbalanced drilling condition
A-liquid phase	• Drilling fluid is native crude oil with density 6.84 ppg (0.82 S.G. or 41.7° API) • Liquid flow rates were selected to achieve a drawdown from the reservoir pressure
B-gas phase	• Nitrogen was selected as the injection gas
Operating envelope	• It is displayed as the area of the graph between the targets BHCP's, bound by the maximum motor throughput, the minimum annular liquid velocity, Fig. 11 • Using 300 gpm and more than 2200 scfm of Nitrogen will provide maximum 200 psi drawdown from the expected reservoir pressure
Hole cleaning	• Depends on several variables such as cutting size and shape; liquid properties; drill string rotation; liquid velocities; flow regime, etc. • Minimum vertical annular liquid velocities of 180 ft/min when crude oil is used as the drilling fluid to ensure that the drilled cuttings are effectively removed from the wellbore
Hydraulic modeling	• Using a multiphase hydraulic simulator, the required underbalanced drilling parameters could be evaluated in detail • Graphs can be created to incorporate the limiting factors of minimum annular liquid velocity required for hole cleaning and the desired BHCP range
Pressure while drilling	• When the maximum gas volume fraction (GVF) inside the drill pipe is bellow, 20% conventional mud pulse tools (MWD/LWD/PWD) can be used • Otherwise, electromagnetic transition tools have to be used in order to obtain downhole data real time
Data acquisition	• The software for the rig data acquisition has to be able to interface with the UBD equipment software
Completion	• The well can be completed with barefoot completion technique, or installing a slotted lined



	OD inch	ID inch	WT lb/ft
Casing	9 5/8	8.896	36

	OD inch	ID inch	WT lb/ft
Drillpipe	5	4.27	19.5
HWDP	5	3	49.5
Drill collar	6.5	2.857	91

Figure 13 Well schematic of western desert oil field area.

definite relation with pressure drop if other drilling parameters are ignored. However a continuous increase in formation fluid production while drilling was observed with the continuous increase in pressure drop as shown in Fig. 9.

Fig. 10 illustrated that all wells drilled by UBD have an increased in fluid production rate compared to those wells drilled in overbalanced environment. In addition, there is no clear relation between the amount of fluid production while drilling and the amount of fluid production after the well is put on production as shown in Fig. 10.

Table 5 highlights the savings in total rig days and cost for conventional versus underbalanced drilling wells in Iran (Roving and Reynolds, 1994). It is clear that big savings in drilling cost was realized.

The cost savings ranged between $90,000 and $110,000 for 8-1/2 in. hole section and between $170,000 and $190,000 for the 6-1/2 in. hole size (Table 6). A total of approximately

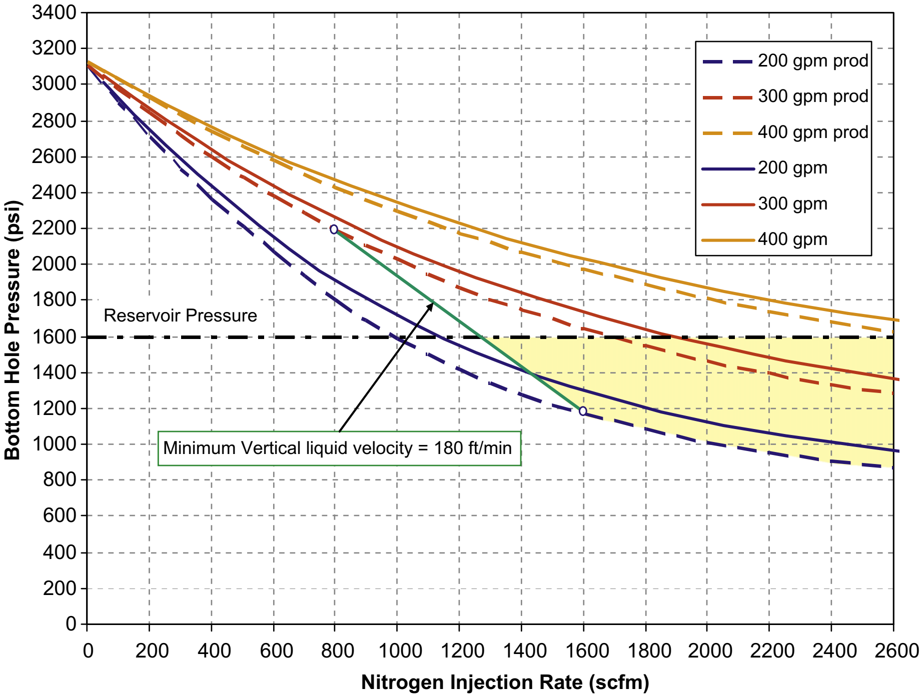


Figure 14 Operating window, multiphase fluid injection of western desert oil field area.

Table 11 Proposed UBD program in Nile Delta area.

Rig modification	• No essential modifications to be made on the rig to suite UBD operations • The substructure has to be high enough to allow Rotating Control Head (RCH) to be installed on top of the Hydril
Well plan	• As shown in Fig. 15
Drill string design	• Use a 5″ DP, 5″ HWDP and 6.5″ DC • An 8-1/2″ bit size of 3x13/32" nozzles
BHA	• The BHA consists of 6-1/2″ PDM mud motor and MWD to drill 6″ hole • If MWD signal doesn't observed, use electromagnetic MWD tools
Drilling fluid selection	• Water based fluid (flow-drilling operation) • Drilling fluid is water with density 8.75 ppg (1.05 S.G.) • Liquid flow rates and surface choke backpressure were selected to achieve a drawdown from the reservoir pressure
Operating envelope	• It is recommended to pump at least 400 gpm of liquid phase to avoid any operational problem related with hole cleaning • The drawdown is 200 psi to prevent wellbore collapse
Motor performance	• A maximum equivalent liquid volume through the motor of 600 gpm was used as reference • A pressure loss of 800 psi between downhole motor and MWD was considered
Hole cleaning	• Minimum annular liquid velocities in deviated holes of 180 ft/min to ensure that the drilled cuttings are effectively removed from the wellbore • A wiper trip will help clear the hole cleaning problem
Tripping	• Some type of snubbing device can be used, or a downhole isolation valve can be installed • Balancing the well for trips seemed the simplest and least expensive method
Data acquisition	• The software for the rig data acquisition has to be able to interface with the UBD equipment software
Completion	• The well can be completed with barefoot completion technique, or installing a slotted lined

$1.4MM has been saved (drilling only) and about $1MM (overall), for the five wells drilled.

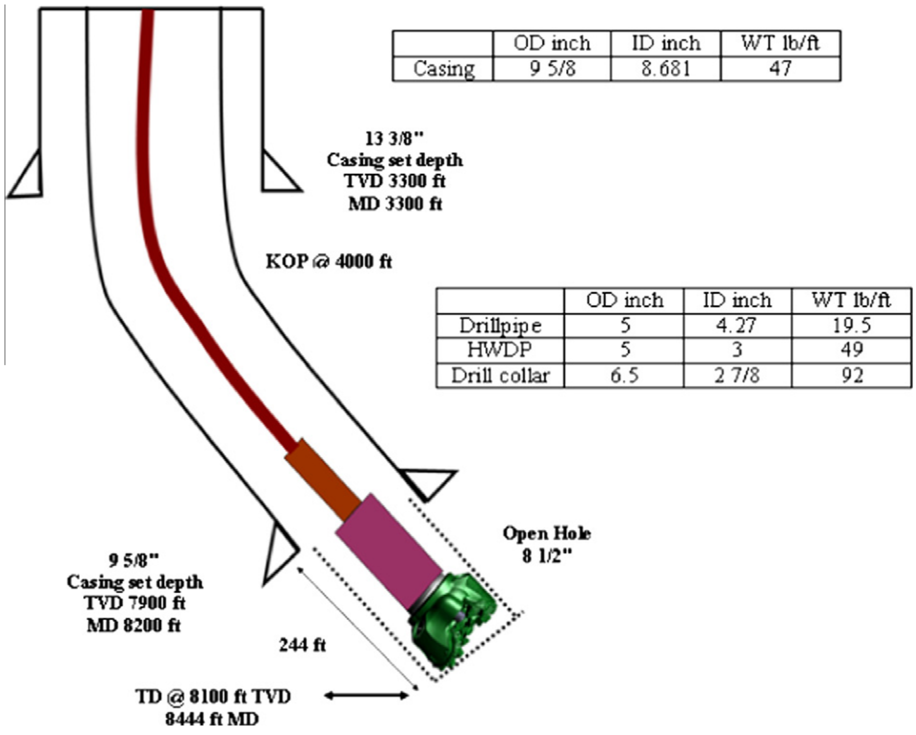
3. Proposed UBD program to be implemented in Egyptian fields

Based on the experience and the problem faced discussed in the previous discussions, a proposed UBD program is given here-below.

3.1. Gulf of Suez oil field area

The selected example includes drilling through the reservoir section, which consists of two production formations (Belayim and kareem formation from Miocene age). The reservoir and formation characteristics are given in Tables 7 and 8.

The selected reservoir can be drilled by underbalanced drilling technique and the proposed UBD program is given in



	OD inch	ID inch	WT lb/ft
Casing	9 5/8	8.681	47

	OD inch	ID inch	WT lb/ft
Drillpipe	5	4.27	19.5
HWDP	5	3	49
Drill collar	6.5	2 7/8	92

Figure 15 Well schematic of Nile delta oil field area.

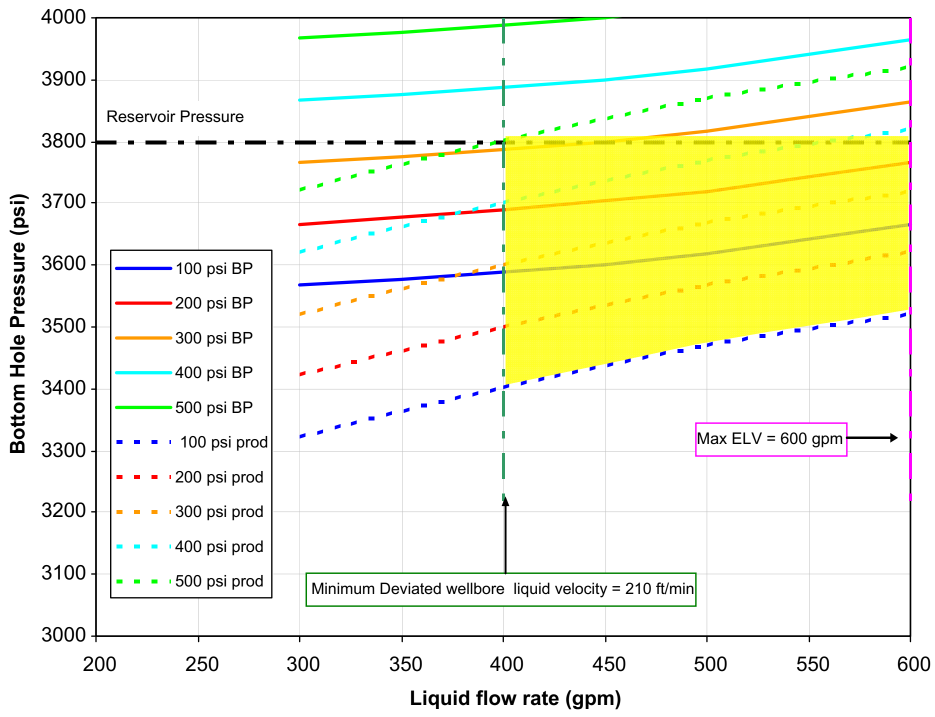


Figure 16 Operating window, flow-drilling operation for Nile delta oil field area.

Table 9. Fig. 12 shows the operating window, multiphase fluid injection of Gulf of Suez oil field area.

3.2. Western desert oil field area

The selected example includes drilling through the reservoir section, which consists of Alam El Buieb formation of Cretaceous age. The lithology of this formation is sandstone with depleted reservoir pressure 1600 psi, reservoir temperature 219 °F, porosity 19%, permeability 200 md, GOR 95 SCF/STB, 41.7° API gravity of oil, and there is no H_2S concentration. The selected reservoir can be drilled by underbalanced drilling technique as given in Table 10. Fig. 14 shows the operating window, multiphase fluid injection of western desert oil field area.

Table A.1 Summary data of case 4 to case 23.

Information		Objective(s)	Results
Case 4 – SE (U.S.) area			
Location	SE (U.S.) area	Improve production rate by eliminating formation damage	Production rate increased from 6 MMcfd to 24 MMcfd
Formation	Smackover & norphlet carbonates		
Depth	18,300 ft TVD	Reduce/eliminate fluid losses to expedite well clean-up	Hostile operating environment (H_2S and 350 °F BHT) safely drilled using UBS techniques (no QHSE incidences)
Pore press	2700 psi		
Well type	Vertical New Drill		
Hole size	6-1/2		
Case 5 – Texas Panhandle area			
Location	Texas Panhandle	Remove barium sulfate scale from liner/ perforations to restore production	Increased gas production rates from 800 Mcfd to over 5000 Mcfd
Formation	Hunton limestone		
Depth	±22,000 ft TVD	Avoid fluid losses to formation	Minimized tubular corrosion in the presence of CO_2 and H_2S
Pore press	1100 psi, + 380° F		
Well type	Vertical cleanouts	Carry metal cuttings back to surface	
Hole size	3-1/16 in.		
Case 6 – Texas Panhandle area			
Location	Texas Panhandle	Mist drill 400 in. new hole to eliminate formation damage	Successfully drilled target interval in fewer days than planned
Formation	Hunton limestone		
Depth	19,322 ft TVD/19,700 ft MD	Minimize corrosion by effective implementation of corrosion program	Project cost $1,000,000 less than budgeted
Pore press	800–1000 psi		Gas production rates substantially higher than previously drilled wells in the same field
Well type	Horizontal re-entry	Capture real-time surface flow and pressure data	
Hole size	4-3/4 in.		
Case 7 – West Texas (Pecos County) area			
Location	West Texas (Pecos County)	Sidetrack and drill lateral section in a severely depleted gas reservoir	Maintained underbalanced environment in a deep, 550 psi reservoir using UBS techniques
Formation	Ellenburger		
Depth	13,100 ft to 14,100 ft TVD	Minimize fluid losses and differential sticking	Encountered no lost circulation or stuck pipe, using nitrogen mist systems
Pore press	550 psi		
Well type	Horizontal, ee-entries	Increase rate of penetration over conventional methods	
Hole size	6-1/4 in. and 4-1/2 in.		
Case 8 – NE (U.S.) area			
Location	NE (U.S.)	Increase ROP relative to conventional techniques	Vertical deviation controlled
Formation	Hard rock (surface hole)		
Depth	3900 in.	Minimize footprint of surface equipment to reduce location size in an environmentally sensitive area	Hammer drilling increased rates of penetration from 10 ft/h to more than 50 fph in 28-1/2 in. hole. Realized up to 75 ft/h ROP in 24 in. interval
Well type	Vertical new drill, gas storage		
Hole size	28-1/2 in. and 24 in.	Minimize vertical deviation	
Case 9 – Permian Basin, Texas area			
Location	Permian Basin, Texas	Maintain an underbalanced condition in a depleted sandstone reservoir while drilling 1000 foot lateral	No fluid losses recorded during underbalanced horizontal drilling operation
Formation	Keystone field (Holt)		
Depth	5634 ft TVD	Reduce/eliminate formation damage due to fluid loss	Realized a 66% increase in rate of penetration compared to previous well drilled conventionally
Well type	Horizontal re-entry		
Hole size	6-1/8 in.		

(*continued on next page*)

Table A.1 *(continued)*

Information		Objective(s)	Results
Case 10 – Lea County, New Mexico area			
Location	Lea County, New Mexico	Minimize formation damage due to fluid losses	Fluid losses reduced by 50% compared to wells drilled conventionally
Formation	Greyburg sandstone		
Depth	4100 ft TVD	Maintain underbalanced conditions in depleted sandstone reservoir with pore pressure of 200 psi	Realized up to 97% increase in rate of penetration, with average rig time per well reduced by 22%
Well type	Multiple vertical new drills & re-entries		
Hole size	4-3/4 in. re-entry deepenings; 7-7/8 in. New Drills		
Case 11- Java, Indonesia area			
Location	Java, Indonesia	Drill 500 m lateral out of 7 in. liner while maintaining underbalanced conditions using nitrified water	Significant decrease in formation damage due to maintaining BHCP less than pore pressure in the lateral section
Formation	Jatibarang (Volcanic)		
Depth	2287 m MD	Minimize formation damage due to lost fluids and solids invasion	
Well type	Horizontal (New Drill)		Lateral section terminated at 175 m displacement due to limitations of customer production facilities to handle production during drilling
Hole size	6 in.		
Case 12 – Gargzdai Field, Lithuania area			
Location	Gargzdai field, Lithuania	Increase reservoir productivity by minimizing formation damage	The IP estimated to be 3250 BOPD. Stable production after 3 months exceeded 2700 BOPD
Formation	Cambrian sandstone + siltstone		
Depth	1976 m TVD, 2426 m MD	Complete well while flowing	To eliminate need of snubbing unit during completion, reservoir pressure was balanced with 134 bbl of formation fluid. Well started flowing after running 21 joints of 2.875 in tubing. Finished running tubing with well flowing
Well type	Horizontal – Type 1 New Drill		
Hole size	6 in.		
Case 13 – Central Alberta, Canada area			
Location	Central Alberta, Canada	Underbalance drill the lateral section in a severely depleted gas reservoir	Gas rates as high as 22 MMcfd productions while drilling
Formation	Elkton		
Depth	9700 ft MD (8400 ft TVD)	Increase well productivity compared to conventional methods	Nitrified diesel drilling fluid was very compatible with the formation
Well type	Horizontal, coil tubing		Significant production increases over offsetting vertical and horizontal wells drilled overbalanced
Hole size	4-3/4 in.	Minimize fluid losses and differential sticking	
Case 14 – Indonesia area			
Location	Indonesia	Underbalance drill the lateral section an under-pressured oil reservoir	Oil rates as high as 400 BOPD production while drilling
Formation	Upper bata		
Depth	6249 ft MD	Minimize fluid losses and differential sticking	Significant (± 10-fold) production increases over offsetting vertical and horizontal wells drilled overbalanced
Pore press	< 650 psi	Formation evaluation and real-time fracture identification	

Table A.1 *(continued)*

Information		Objective(s)	Results
Well type	Directional, oil	Increase well productivity compared to conventional methods	Nitrified diesel-mist fluid was very compatible with the formation
Hole size	6 in.		
Case 15 – OME area			
Location	OME	Minimize fluid loss and NPT while drilling	Total production of 12,757 bbls oil while drilling
Formation	Asmari		
Depth	2241 m MD (2212 m TVD)	Eliminate the use of drilling fluid additives	No additives or LCM added to the drilling fluid (formation oil) while drilling
Pore press	2240 psi		
Well type	Deviated	Minimize formation damage	Saved approximately 10 days of drilling time
Hole size	8-1/2 in		
Case 16 – Libya area			
Location	Libya	To eliminate/minimize possible lost circulation	First ever dual lateral to be drilled UB in Libya
Formation	Beda C, Facha C	To access the required reservoir	Wells drilled with zero LTI's
Depth	7000–8900 ft	To eliminate any impairment of the reservoir formation by any-non native fluid or material	Successfully drilled the wells to TD
Pore press	1050–3000 psi		
Well type	Oil wells	To increase PI compared to other conventionally drilled wells	Positive results helped in promoting UBD technology in Libya
Hole size	6 in.		
No. of wells	2	To evaluate and characterise the reservoir production and to increase ROP	
Case 17 – Eastern middle east area			
Location	Eastern middle east	Increase production rate by reducing formation damage	1st UBD campaign consisting of 3 wells was successfully completed in February 2003
Formation	Thebes, Risha and Dubeidib		
Depth	3300 m TVD	To increase ROP relative to conventional drilling Capture real-time surface flow and pressure data	Increased production rates & Reduced formation damage Excellent safety and operational performance led the operator to plan for a 2nd UBD campaign
Well type	Deviated		All the wells delivered safely with zero LTI's
Hole size	5-7/8 in.		ROP reached a maximum of 9 m/h as compared to an average of 2 m/h for conventional drilling
No. of wells	6		
Case 18 – Hassi Massoud oil field – Algeria area			
Location	Hassi Massoud oil field – Algeria	To increase oil production by minimizing formation damage	To date 18 wells have been drilled using UBD technique
Formation	Re Cambrian/Cretaceous		
Depth	Up to 4581 m MD	Increase ROP compared to conventional overbalanced drilling	Significant increase in ROP compared to offset conventional wells
Well type	Deviated		Successfully spread the UBD technology in the North Africa region
Hole size	6 in.	Eliminate NPT associated with conventional drilling problems	Encouraging production rates were observed while drilling and conducting production flow tests. The best of 27.5 m^3/h has been observed so far while drilling the well MDZ 550

(*continued on next page*)

Table A.1 *(continued)*

Information		Objective(s)	Results
Case 19 – Offshore – Qatar area			
Location	Offshore – Qatar	To create moderate under balanced conditions necessary to achieve returns to surface while drilling the 24 in surface hole through massive loss zones	An air injection rate of 750–850 scf/m via the parasite string created an appropriate level of UB conditions to eliminate losses in the UER formation and other zones
Formation	UER, Simsima, Fiqa, Halul, Laffan		
Depth	1000–3000 ft	To achieve UB conditions by utilizing air injection via parasite string on the 30 in conductor pipe set at 500 ft	To date 9 wells have been drilled using the air drilling technique
Pore press	600–1200 psi		
Well type	Gas well		The low degree of UB conditions successfully avoided massive sour water flows from flow zones and limited bore hole instability problems
Hole size	24 in.		
No. of wells	9		
Case 20 – Ghawar field – Saudi Arabia area			
Location	Ghawar field – Saudi Arabia	To eliminate formation damage caused by the loss of conventional drilling fluid to the formation and therefore avoids differential sticking	Increased Injectivity rates by more than 2 to 3-fold
Formation	Arab D		
Depth	11,400–11,850 ft (MD)		To date 4 power water injection wells have been drilled Underbalanced
Pore press	3520–3735 psi		
Well type	Horizontal	Maximizing water injectivity	
Hole size	6-1/8 in.	To increase "on bottom" rate of penetration	All wells were delivered safely without LTI's
No. of wells	3	To increase bit life	
Case 21 – Greater Oman area – North East Syria			
Location	Greater Oman area – North East Syria	Reduce typical drilling non-productive time (NPT) by depleting the Shiranish Gas zone while drilling	13 wells have been drilled using the Flow Drilling technique
Formation	Shiranish/Mulusa		
Well type	Straight & deviated	Eliminate an intermediate casing string from the drilling program	Average drilling rig time of 45 days, has been reduced to an average of 21 days
Hole size	6 in. & 8.5 in.		
		Develop UBD technology, practices and procedures for future Syrian activity	Intermediate casing string has been eliminated
			ROP improvements and excellent bit performance were experienced All wells were delivered safely with zero LTI's
Case 22 – North East British Columbia, Canada area			
Location	North East British Columbia, Canada	Increase well productivity through	PIWD as high as 4 MMscf/d/1000 psi
Formation	Jean Marie	Technical management of bottom hole pressure	
Depth	2,047 m MD	Minimize fluid losses and differential sticking	Gas rate up to 1.5 MMscfd

Table A.1 *(continued)*

Information		Objective(s)	Results
Pore press	4560 kPa	Monitor reservoir through PIWD	
Well type	Horizontal	Evaluation while drilling	
Hole size	156 mm		
Case 23 – Lithuania area			
Location	Lithuania	Increase reservoir productivity by minimizing formation damage	IP estimated to be 3250 BOPD. Stable production after 3 months exceeded 2700 BOPD
Formation	Sandstone		
Depth	6480 ft. TVD; 7960 ft. MD	Complete well while flowing	To eliminate need of snubbing unit during completion, reservoir pressure was balanced with 134 bbl of formation fluid. Well started flowing after running 21 joints of 2.875 in tubing; finished running tubing with well flowing
Well type	Horizontal new drill in-fill		
Hole size	6 in.		
No. of wells	3		

3.3. Nile delta oil field area

The selected example includes the reservoir section, which consists of one production formation (Qawasim from Miocene age). It has a sandstone lithology with reservoir pressure 3800 psi, reservoir temperature 185 °F, GOR 1100 SCF/STB, average porosity 25%, average permeability 400 md, gravity of oil 50° API, and there is no H_2S concentration.

The selected reservoir can be drilled by underbalanced drilling technique as given in Table 11. Fig. 16 shows the operating window, multiphase fluid injection of nile delta oil field area.

4. Conclusions

Planned and applied correctly, underbalanced drilling technology can address problems of formation damage, lost circulation and poor penetration rates. The ability to investigate and characterize the reservoir while drilling is another important benefit of under balanced drilling. Based on the analysis of the real cases studied during the research, the following conclusions could be cited:

1. Underbalanced drilling technique is a very useful technique especially when applied in reservoir section. It prevents formation damage, increases ROP, increases reservoir productivity and reduces the total cost of the well.
2. Candidate screening is a rigorous and is a critical first step in the design of a successful underbalanced drilling operation. Although UBD has many advantages, it is not a magic solution for all fields or drilling problems. Poor screening and planning would result in an over-enthusiastic misapplication of the technology, and possibly failure.
3. Many issues must be considered when designing an underbalanced drilling project including but certainly not limited to rock properties, reservoir pressure, borehole stability, drilling fluid type, injection method for gas assist, effect of compressible fluid on MWD, downhole motor requirements, bit type, corrosion, equipments availability, separation and fluid handling requirements especially when dealing with hydrocarbon drilling fluid, tripping procedures, data acquisition and completion procedures. Proper planning and design work, addressing these parameters, is essential to successfully conduct an underbalanced drilling project.
4. UBD with stable foam through depleted reservoirs can be conducted safely and successfully in both vertical and horizontal wells. Drilling with foam has some appeal because foam has some attractive qualities and properties with respect to the very low hydrostatic densities, which can be generated with foam systems. Foam has good rheology and excellent cutting transport properties.
5. Real time capture of production data while drilling should provide information about the reservoir not otherwise available.
6. A proposed UBD program to be implemented in Egyptian fields is developed.

Appendix A

See Table A.1.

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