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Original article

Application of underbalanced tubing conveyed perforation in horizontal wells: A case study of perforation optimization in a giant oil field in Southwest Iran

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Abstract:
Underbalanced perforation can substantially reduce formation damage and improve the efficiency of production operation. The field in question is a giant oil field in Southwest Iran, with over 350,000 bbl/day production rates. Reservoir X is the main reservoir of the field and includes 139 horizontal wells out of the total of 185 production wells drilled in the field. Despite its technical difficulties, under-balance perforation has been proven to result in high productivity ratios and has been shown to reduce workover costs if appropriately conducted. Therefore, this study investigated a customized underbalanced tubing conveyed perforation to enhance oil production. First, post-drilling formation damage was estimated using Perforating Completion Solution Kits. Next, high-density guns (types 73 and 127) with high melting explosives were selected based on the reservoir and well specifications. By conducting a sensitivity analysis using schlumberger perforating analyzer program, shot angles of 60° and 90°, shot densities of 16 and 20 shots per meter, perforation diameters of 8 and 10 mm, and helix hole distribution were selected as optimized perforation parameters and resulted in productivity ratios up to 1.18. The current study provides a case study of applying a combination of two previously proven technologies, tubing convoyed and underbalanced perforation, in Iran's giant oilfield. The method used and the outcome could be used to analyze the efficiency of applying the technology in other green or mature fields.

1. Introduction

Perforations are holes in the formation that establish a connection between the wellbore and production zone to achieve optimum productivity (Dastgerdi et al., 2020). Perforation operation typically involves creating several openings from the wellbore through the casing and the cement behind it into the hydrocarbon-bearing zone. This technique has been widely used in onshore and offshore completions of hydrocarbon reservoirs and geothermal wells (Marbun et al., 2021). The global energy demand has led to a marked increase in the development of unconventional hydrocarbon resources. Most

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unconventional resources are low to ultralow permeable, so directional drilling and high-efficiency completion methods are inevitable (Liu et al., 2014).

Moreover, perforation in injection wells is also of great significance. Waterflooding has been the most frequently used improved oil recovery method (Hofsaess and Kleintz, 1998; Ahmed, 2010). Perforations directly affect well injectivity, and productivity (Abobaker et al., 2022). Hence, an optimized perforation program is required to ensure the desired injectivities are attainable. Conventional drilling often causes damage to the formation due to infiltration of the drilling mud into the surrounding permeable formation. Hence, when conventional (overbalanced) perforation is conducted, the existing debris in the formation can cause suboptimal perforations that are partially filled with debris. Various researchers have acknowledged the presence of this damage zone due to perforation and stated that it could significantly reduce the permeability of the formation and inhibit production (Wang et al., 2021). Overbalanced perforation results in substantial formation damage, increased workover costs, and ultimately loss of productivity, specifically at directional and horizontal wells. To achieve high-performance perforations, it is necessary to understand the sophisticated interactions between explosive charges, perforation guns, wellbore characteristics, and reservoir properties. The literature has reported up to 70% reduction in permeability due to conventual drilling (Klotz et al., 1974; Krueger, 1988). The latter is more severe when drilling low permeable unconventional resources where permeabilities are often less than one millidarcy (mD). Formation damage can be mitigated via an underbalanced perforation operation (UBP) in which an under balance is established between the formation and wellbore pressures. Afterward, the perforation guns are fired to create a controlled entrance of reservoir fluids into the wellbore. This results in better cleaning of the perforations and improving the well's productivity and injectivity (Bale and Satti, 2020), and if completed successfully, minimizes the formation damage near the perforation zone (Abobaker et al., 2021). In UBP, the perforations are immediately back surged; this results in the debris being expelled into the well upon entrance of formation fluids to the wellbore.

Underbalanced perforation is often conducted via a tubing conveyed perforation assembly (TCP). Recently, advances in well production technologies, which enable higher-shot densities and larger perforating guns, have resulted in the more frequent application of TCP combined with well testing in modern completion designs. The assembly often comprises a perforating gun, shock absorbers, packer, and several instruments (Gilliat et al., 2014). Underbalanced perforation has become an essential part of well testing, specifically when a drill stem test (DST) is involved (Deng et al., 2020). UBP is ideal as DST includes hardware that enables underbalance and perforation using high shot density guns. This assembly also offers proper well control and often saves time because the perforating guns are run below the test string.

The performance of perforations mainly determines the productivity of the well. Hence, a gun/charge system must be selected to provide the required production rates and operation safety in a particular well environment. This is mainly based on a good understanding of rock and fluid properties, drilling damage, and well type. UB-TCP was chosen as the default perforation technique for the field to ensure hole safety, increase the success ratio, and minimize formation damage. Hence, the main aim of the current study is to achieve high perforation efficiency by implementing UB-TCP in a giant field, specifically reservoir X (the actual name of the reservoir is changed to X due to confidentiality of the data). Before selecting perforation parameters, the extent of formation damage in the reservoir was estimated. The formation damage estimation and pay zone characteristics were used to choose a suitable perforation assembly. Lastly, to obtain optimum results, an analysis of perforation parameters, including perforation density, perforation diameters, hole distribution, and phase angle, was conducted to achieve quality perforation and ultimately enhance productivities from the giant field (reservoir X) in Iran.

2. Field and reservoir characteristics

The giant oilfield is located west of Ahwaz city, in Khuzestan province SW Iran. The alluvium of the Holocene age completely covers the field. The penetrated formation from top to bottom is Aghajari, Gachsaran, Asmari, Pabdeh, Gurpi, Ilam, Laffan, Sarvak, Kazhdumi, Dariyan, Gadvan, Fahliyan. The field has four main reservoirs named W-Z due to confidentiality. Reservoir X contains black oil with an API of 19.9° and holds over 90% of the field's reserve and hence is the chief producible reservoir of the field. The lithology of the existing wells mainly consists of limestone, claystone, and is interbedded with anhydrite, salt bed, and shale. The permeability of most reservoirs in the field is 30-36 mD. The black oil from reservoir X has viscosities up to 4 cp. The primary driving mechanism of the reservoirs is rock and fluid expansion, and the formation is mainly homogeneous (Dastgerdi et al., 2020). The reservoir characteristics of the field is shown in Table 1.

Analysis of pressure-volume-temperature data from offset wells, pressure, and temperature for major reservoirs in the field was estimated as shown in Fig. 1. The formation pore pressure coefficient is 1.02-1.26 in X, Y, and W. However, Z formation shows an abnormal pressure with FPCC between 1.3-1.6. All the reservoirs show a normal temperature gradient in the range of 2.3-2.6 °C/100 m (11.1-11.2 °F/ft).

The original oil in place of the field is over 25,340 MMSTB and reservoir X, being the primary reservoir, holds about 92% of it (23,251 MMSTB) (Liu et al., 2013). The current target production level of the field is over 350,000 bbl/day for phase one of the field development. From the 185 wells to be drilled in the field, 139 are horizontal production wells in reservoir X. The horizontal section in the reservoir is from 600 to 800 meters. Given the high number of wells to be drilled and the large horizontal sections, increasing productivity through perforation optimization is significant. Reservoir X is completed with 4-1/2" production liners in horizontal wells in X3 & X8 (formations of reservoir X) and 7" production liners in X4 & X6. Due to the importance of the reservoir in the giant field of interest, this study is focused

Table 1. Rock and fluid properties of formations X-Z of the giant field.

Reservoir	X	W	Y	Z
Reservoir depth (m)	2,709-2,850	3,436-3,610	3,750-3,875	3,995-4,088
Netpay (m)	118	12.7	15	100
Pressure (psi)	4,600-5,029	4,992-5,438	6,010-6,300	7,800-9,300
Lithology	Carbonate	Sandstone	Sandstone	Sandstone
Permeability (mD)	34.2	35.8	366.0	29.5
Crude oil gravity (API)	19.95	30.85	32.24	33.3
GOR scf/STB	267-441	916-1,589	706-1,391	1,090-1,996
Oil viscosity (cp)	4.40-5.40	0.32-0.52	0.33-0.58	0.29-0.53

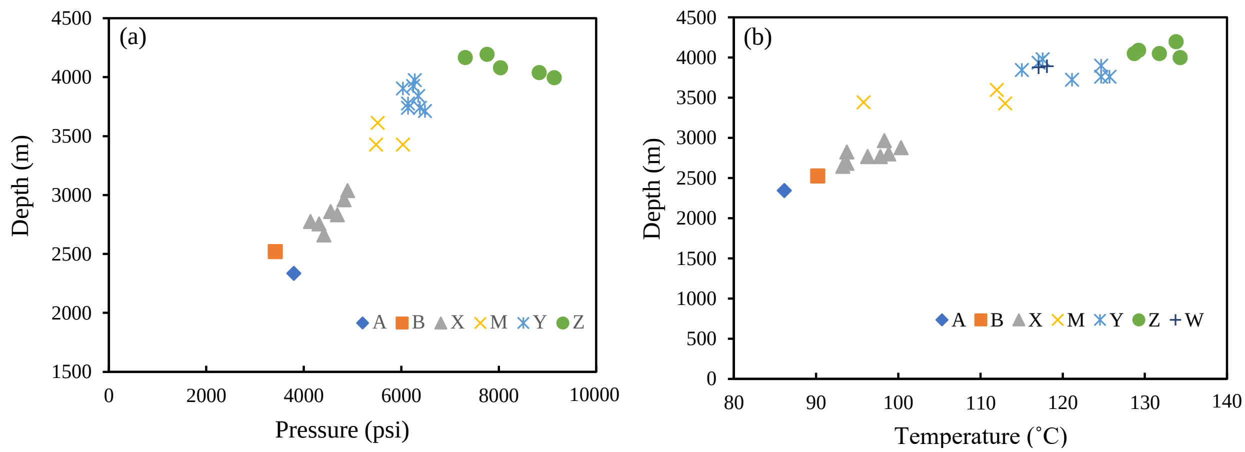

Fig. 1. Pressure and temperature gradients of the field.

on perforation of horizontal wells in X reservoir.

3. UB-TCP assembly

Fig. 2 shows the schematic of a simplified TCP assembly that is to be used for perforation operation in the field (in Reservoir X). TCP is often used with several accessories that enable various operations such as testing, workover, and a controlled underbalanced condition required for UB-TCP. The accessories can regulate the post-detonation surges in the formation as well. The main accessories included with the UB-TCP assembly are packers, circulating sub, dropping bar firing head, tubing, screen sub, and shock absorber. Packer is an essential part of the assembly. A 7" RTTS packer made by Halliburton is used in the intermediate casing to isolate the production zone. The RTTS packer is often accompanied by a circulating valve that can be used as a bypass valve. As the packer sets, the circulating valve locks in the closed position. During testing or squeezing operations, the lock prevents the valve from being pumped open. The shock absorber is installed above the gun to lessen the impacts caused by gun detonation. A sleeve sub is used to connect the annulus and tubing when necessary. Activated Vent is used to enabling the primary underbalance conditions UB-TCP operations. The drop-bar firing head consists of an internal firing pin and a drop bar. With the impact of this drop bar, hydrostatic pressure is applied

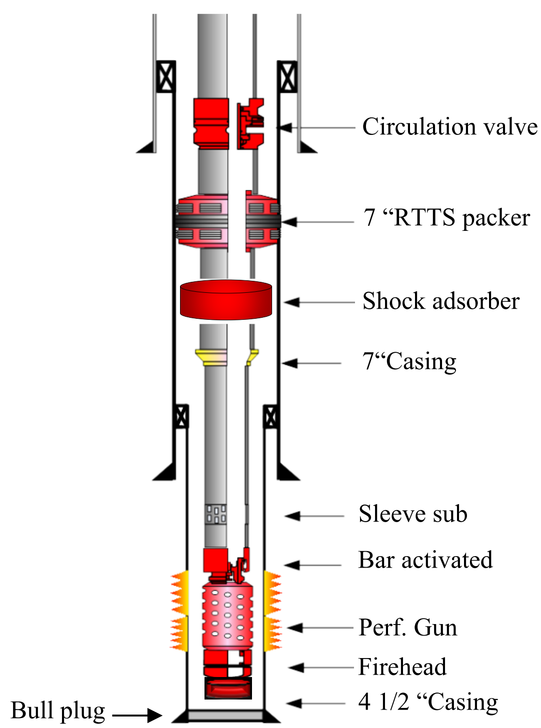

Fig. 2. Schematic of UB-TCP assembly to be used in reservoir X.

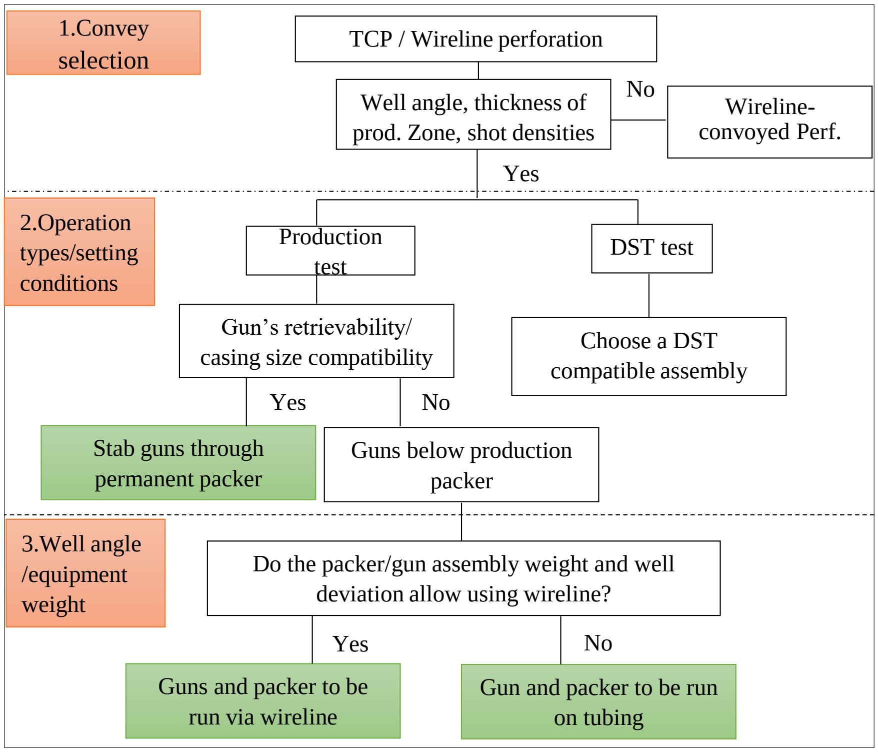

Fig. 3. TCP/ wireline perforation selection procedure.

to increase the pressure in shear rings, which release the balls. This type of head is mainly used in deviated and vertical wells. Lastly, a bull plug is attached to the string to isolate the assembly where no-fluid entry is required.

Performing tubing convoyed underbalance perforation requires careful assessment of various parameters. Fig. 3 illustrates the steps for choosing proper underbalanced perforation equipment (Cosad, 1995). It begins with checking sets of conditions, including well inclination (deviation $> 59°$), shot densities above five spf (shot per foot), the need for perforation of a long production zone, and compatibility of equipment with the hole size. If these conditions were rejected, wireline conveyed perforation operation is suggested. However, since the focus of the current study is horizontal wells in the reservoir, the above conditions are met. UB-TCP is achievable both for DST and the production phase. In the case of the DST test, the firing equipment is integrated with DST assembly and run into the hole. For production perforations, the following essential criteria are diameter and retrievability of the perforation gun. If the latter is not satisfied, conveying the gun with a wireline is assessed based on well deviation and hole angle.

4. Methodology

Fig. 4 illustrates the workflow of optimization of parameters used in this study. Phase one starts with estimating formation damage resulting from drilling in the reservoir of interest. To do this, PCSK^{TM} was utilized. The software uses reservoir rock and fluid parameters and drilling parameters to estimate the formation damage (skin) extent. The depth of formation damage versus operation (drilling) duration is estimated for the reservoir of interest. Moreover, the formation damage in rock matrix and well-developed fractures are assessed. Lastly effects of drilling parameters such as mud density, formation pressure and permeability on extent of damage is quantitatively predicted. The next step is to choose a perforating assembly (gun, charge, and bullets). This is based on the estimated formation damage, well characteristics, and desired perforation plan (required depth, diameter, and the number of perforations).

In the next phase, a sensitivity analysis is used to find optimum perforation parameters based on the selected perforation assembly. The schlumberger perforating analyzer program (SPAN) is utilized to estimate optimum shot density, perforation diameter, and phase angle. Once the optimized values were selected for the above parameters, the required underbalance is calculated based on optimized perforation parameters and the formation's rock and fluid properties. In the last step, the required underbalance pressure is calculated for reservoir X. To quantify the critical (the minimum) value of the underbalanced required for near-zero perforation damage, Eq. (1) for permeabilities over 100 mD, and Eq. (2) for those below 100 mD is utilized (Behrmann, 1996):

$$P = \frac{687D^{0.3}}{K^{1/3}} \tag{1}$$

$$P = \frac{1480D^{0.3}}{K^{1/2}} \tag{2}$$

where K is permeability in mD, D is perforation diameter in inches, and P is pressure in psi. Majority of commercial

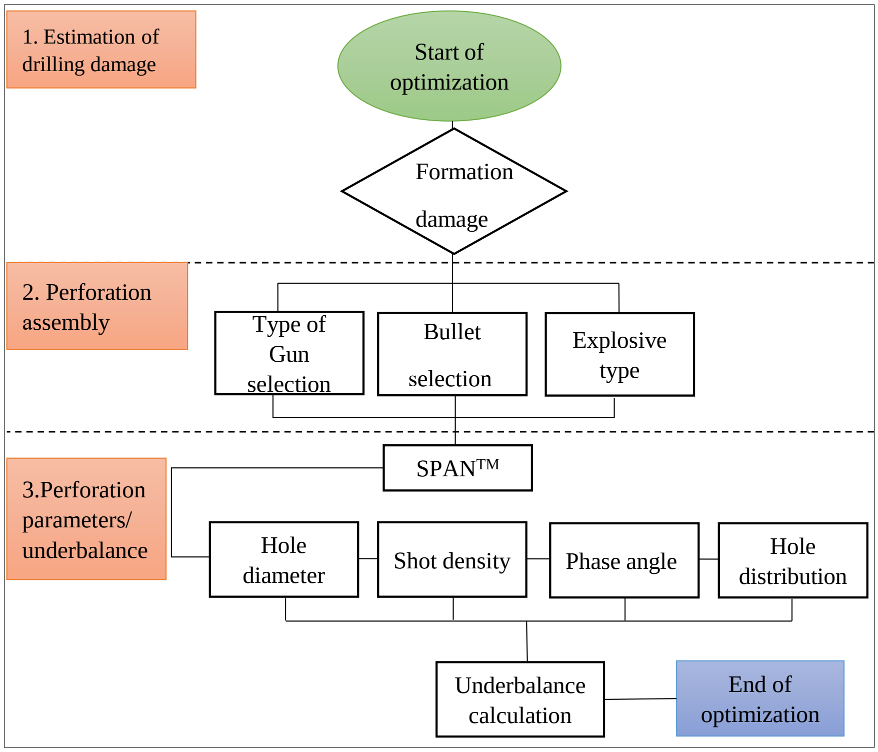

Fig. 4. Perforation optimization flowchart.

software, including SPAN, use the same equations to predict underbalance, as was the case in the current study.

5. Results and discussion

Several perforating parameters control the productivity of the perforated wells; perforation length, perforation diameter, degree of the damage around the perforation tunnels, shot density, and perforation phasing angle (Abobaker et al., 2021). Some of the listed parameters are easy to quantify and control. For instance, shot density and phasing angle may be readily determined and controlled from the surface. However, there is no means of measuring the perforation parameters such as the degree of damage around the perforation tunnels, perforation length and diameter under subsurface conditions. The common practice is to measure the perforation length, diameter, and perforating damage on the core targets in laboratory conditions and correct the lab measured values for subsurface conditions. The success of any perforation operation is mainly dependent upon choosing suitable equipment that meets the field production demands and is compatible with reservoir properties, i.e., sand production, formations with overpressure, and high-temperature gradients (Moradi et al., 2020).

The first step in choosing the perforation operation is to consider the general interaction of the reservoir and the perforation. Hence, the process in this research started with formation damage estimation. In addition to formation damage, estimating differential pressure between reservoir and wellbore, ideally, an underbalanced condition, is preferable for an optimized perforation job. The next step is choosing the proper perforation method based on the type of well completion and sand management requirements (if necessary). The next part is the gun selection and explosive selection. Once those are chosen, penetration tunnel length, shot phasing, shot density, and perforation entrance hole diameter can be determined. Lastly, the perforation parameters are chosen for the selected gun and charge, leading to an optimum productivity.

5.1 Formation damage estimation

Zone of altered permeability, aka damaged zone (zone of positive skin), is caused by infiltration of fluid and solids components of drilling and cementation operation to the formation. An accurate estimation of skin factors is essential for optimizing perforating parameters. Oil production will increase significantly if the charges penetrate beyond the damage zone (Bennion et al., 1996; Ezenweichu and Laditan, 2015). Although direct evaluation of the formation damage is often challenging, it can be estimated for each well type based on the fundamental data from its reservoir and drilling parameters such as density, viscosity, pH, filter loss, mudflow rate (Kang et al., 2014). The expected mud system used for drilling wells in reservoir X is water-based drilling fluid ($CaCO_3$ + KCl + polymer).

In reservoir X, the mud density is 1.2-1.3 g/cm^3; the mud invasion time is approximately 40 days. The change of damage depth with invasion time under given formation properties and drilling operation parameters is shown in Fig. 5. It can be seen that wellbore damage increases over time. The damage reaches a depth of 492 mm on day 40. By controlling mud density and the mud invasion time within approximately 18 days, the mud invasion depth in X can be limited to about 357 mm. However, due to the presence of well-developed fractures, the magnitude of the damage could be as high as three times that of the matrix. Hence the uncertainty in the assessment of formation damage significantly increases.

The drilling damage of the target oil layer was assessed using PCSK^{TM} based on rock and fluid properties and drilling mud parameters. The results are shown in Fig. 6. It should be noted that the results need to be rectified if the mud parameters during the drilling operation differ significantly from that of the design process. As is apparent from the figure, the formation exhibits well-developed fractures and matrix damage due to the invasion of drilling mud. The results indicate that the average formation damage of reservoir X is 65 mm.

Various factors such as permeability, formation pressure, and mud density largely contribute to the extent and degree of formation damage due to the drilling. Figs. 7(a)-7(c) illustrates the effect of formation permeability, formation pressure, and density of drilling mud on the depth of the (drilling) damage in the reservoir.

As expected from Fig. 7(a), higher mud densities result in higher skin factors. This could be attributed to the higher concentration of solids in heavier muds that increase the migration of fine particles to near-wellbore permeable areas and leads to more formation damage (Fattah and Lashin, 2016). As seen in Fig. 7(b), formation pressure directly affects the formation damage. The invasion of solid particles and mud filtrate is higher in high-permeability zones around the wellbore. Hence, higher permeability formations have higher skin factors. If microfractures develop in a well, the effect of mud invasion damage on productivity will be more severe.

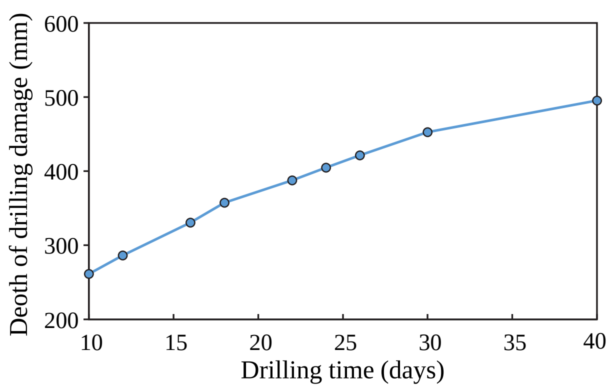

Fig. 5. Drilling damage versus mud invasion time.

Wellbore damage evaluation is crucial in choosing shaped charges and productivity prediction.

Similarly, under the given condition of shaped charge properties, we can design reasonable mud parameters and drilling speed to assure that the shaped charge will penetrate the damage zone more efficiently. Lastly, formation pressure's effects on formation damage are reverse permeability and mud density (Jilani et al., 2002). In formations with higher pressures, lower formation damage is expected. This is mainly due to the higher resistance the mud filtrate and solids face as they infiltrate the near-wellbore formations.

5.2 Charge and gun selection

The perforation depth is a function of formation strength, perforation gun, bullet, and the type of explosive. The perforation efficiency depends on length and diameter, the type and extent of the formation damage, shot density, and the phase angle. High shot density guns are specifically designed for each casing size to enhance shot density, hole size, penetration, and phasing (Cosad, 1995). All TCP operations in the field are conducted with high shot density guns selected by considering the temperature gradient of the reservoir and the casing size and grade used in the area (4-1/2 and 7" production casings in reservoir X). The highest allowable diameter of perforation guns and bullets was considered. To fulfill the high production quota of the field (350,000 bbl/day), deep penetration perforations are required. Hence, the following were selected for each reservoir:

- Type-73 (73 mm) perforation gun is recommended for 4-1/2" casing.

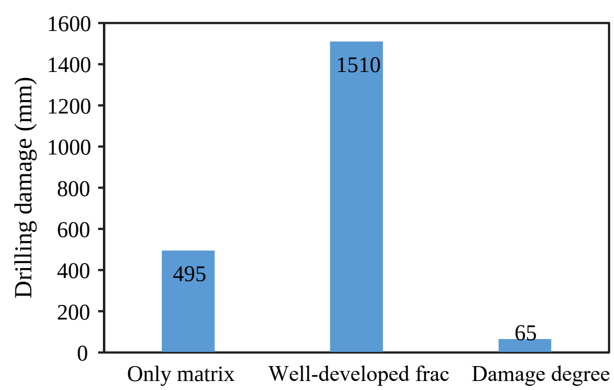

Fig. 6. Drilling damage in the matrix, well-developed fracture, and damage degree in reservoir X.

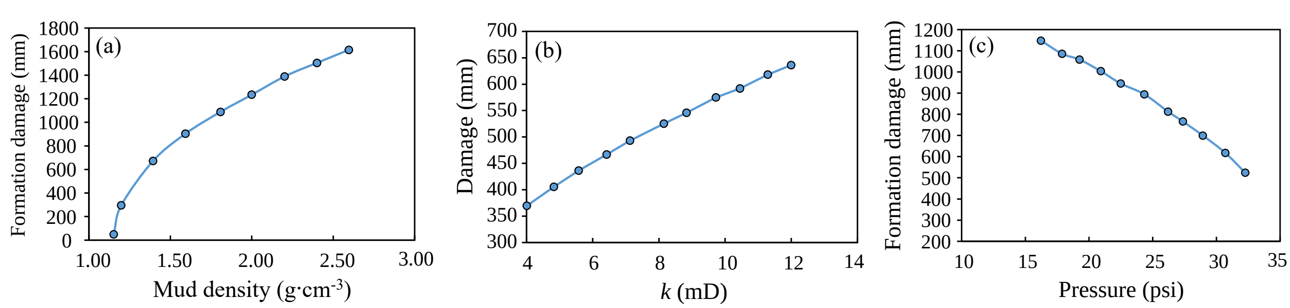

Fig. 7. Formation damage versus mud density (a), permeability (b), and formation pressure (c) in reservoir X.

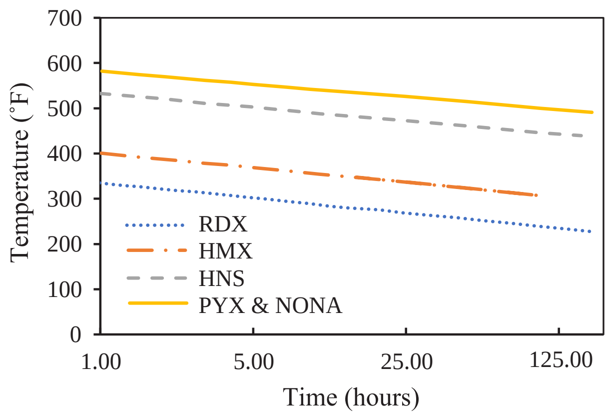

Fig. 8. Explosive temperature resistance curve (Bellarby, 2009).

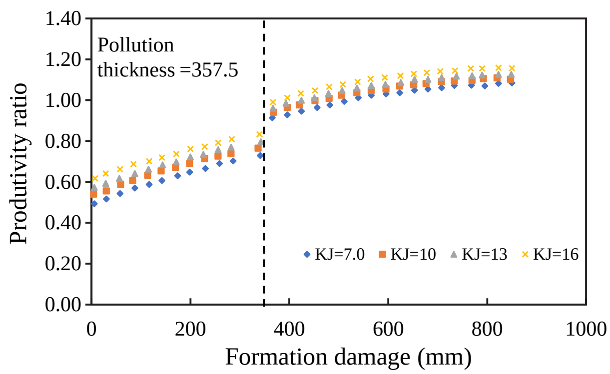

Fig. 9. Relation between perforation diameter and productivity ratio.

- Type-127 (127 mm) perforation gun is recommended for 7" casing.
- The deep penetrating bullet is recommended for all the wells.

Factors such as cement slurry remaining in the internal casing, wellbore inclination, gun burr, and gun deformation that may cause gun sticking problems should be considered carefully to ensure the safety of perforating operation (Tang et al., 2009). However, the final decision of perforator system should be made based on the evaluation of well productivity, technical requirements, and economic feasibility. Considering the high pressure and high temperature (150 °C) in some of the reservoirs in the field, the internal pressure strength of the gun needs to be at least 120 MPa to reduce the expandability and burr height of the gun.

When selecting shaped charges, two factors need to be considered. First, the selected charges should be able to withstand the high-temperature environment without degradation long enough to complete the perforating job. Second, the charge performance fulfills penetration requirements to get the expected well productivity. High melting explosives (HMX) and royal demolition explosive (RDX) cyclotrimetyl trinitramin are the most frequently used explosives choices for perforation (Cosad, 1995). HMX survives up to 100 hours at around 300 °F, whereas RDX only lasts two hours at the same temperature. Fig. 8 illustrates the temperature rating of different explosives. Reservoir temperatures up to 293 °F (145 °C) were measured in the field. RDX explosives will be unstable at those temperatures. Hence, HMX explosives were chosen for the perforation of all production wells in the field.

5.3 Perforation parameter optimization

In this section, a sensitivity analysis is conducted to better understand the relationship between perforation parameters and productivity ratio (PR). PR represents the flowing efficiency of actual completion well, or the communication effectiveness between formation and wellbore. Based on the drilling formation damage analysis, the depth of formation damage is 357.5 mm in reservoir X.

5.3.1 Perforation diameter

A sensitivity analysis was conducted to analyze the relationship between perforation diameter and productivity ratio, as shown in Fig. 9. As expected, the productivity ratio of oil wells increases with perforation depth and diameter. The figure showed that a perforation diameter of 16 mm (shown as KJ) resulted in the highest PR at all perforation depths. Notably, productivity increases substantially once the penetration goes beyond the drilling damaged zone. However, in areas too far away from the damaged zone, the slope of the increase in the PR and perforation depth slows down in all series (perforation diameters). Therefore, the economic viability of the operation lastly determines the optimum penetration depth at distances far beyond the damaged zone.

Based on the selected gun and charge specifications for different reservoirs in the field the following recommendations could be made:

- Peroration diameters over $\geq$ 8 mm and $\geq$ 10 mm is recommended for type-73 and type-127, respectively.

5.3.2 Shot density

A sensitivity analysis was conducted to find the optimum shot density with shots ranging from 8-40 shots per meter (SPM). Fig. 10 illustrates the perforation depth versus productivity ratio for various shot densities. It can be observed that the productivity rate (PR) increases as shot density increases. At the pollution thickness of 357 mm, the productivity ratio for SPM of 8 and 40 (minimum and maximums of the range) is 0.70 and 0.85, respectively. The increase in PR is significantly higher at depths beyond 357.5 mm, at which formation damage (pollution damage) due to drilling exists. However, the slope of the increase in PR reduces at high perforation depths. Therefore, considering the limitations of the selected perforation gun, the following shot densities are suggested:

- 20 holes/m for type-73 perforation gun in Reservoir X.
- 16 holes/m for type-127 perforation gun in Reservoir X.

5.3.3 Phase angle

A sensitivity analysis was conducted to choose the optimum phase angle (from 0 to 180°). The results are shown in Fig. 11. It can be seen that the perforation degree of 180 results in the lowest PR (at least 13% reduction in PR) along

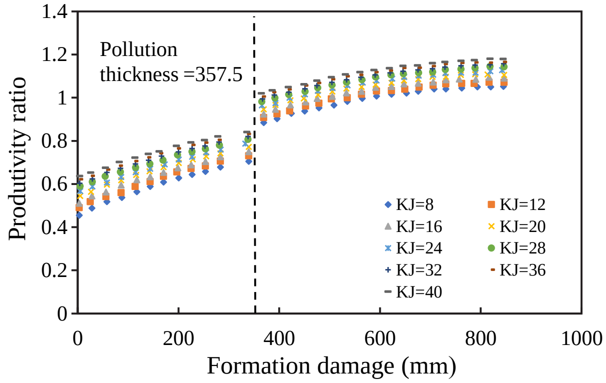

Fig. 10. Relationship between perforation depth, shot density and productivity ratio.

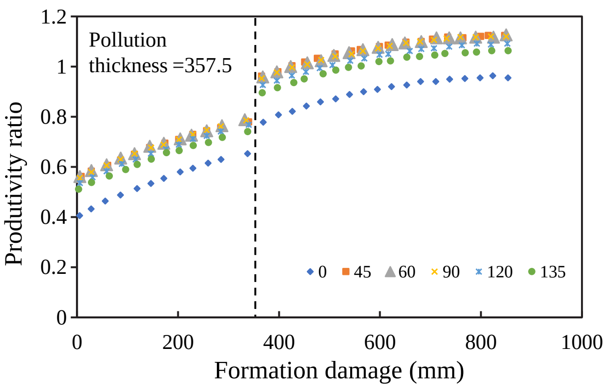

Fig. 11. Relation between phase angle and productivity ratio.

all the perforation depths. On the other hand, PR fluctuates in a narrow range of (0.75-0.76) for the rest of the phase angles. Although the optimum PRs can be observed in phase angles 45°, 60°, and 90°, based on the selected gun (type-73, and 127), the following was recommended:

- Phase angle 60° with type-73 perforation gun in Reservoir X.
- Phase angle 90° with type-127 perforation gun in Reservoir X.

5.3.4 Hole distribution (perforation pattern)

Helix perforation is often the most frequently applied perforation (hole) distributed method specifically in horizontal and deviated wells (Xie et al., 2018). This technique allows the largest vertical distance between holes (casing strength guaranteed), resulting in a uniform downhole pressure, minimum distortion of the perforating gun's body, and safer operation (Zhang et al., 2018). Hence, it was recommended for reservoir X. Fig. 12 shows a schematic of helix hole (perforation) wellbore and number 2 shows the perforations into the formation.

5.4 Underbalance pressure estimation

The required under balance for perforation varies based on lithology, production fluid, and the zone of interest permeability. A general range was proposed based on studying data from more than two thousand fields worldwide (Bell, 1982). Based

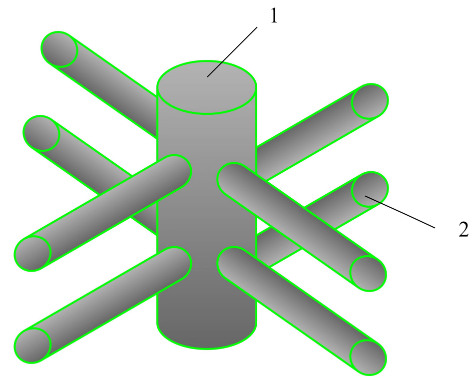

Fig. 12. Helix perforation distribution. (1) illustrates the wellbore and (2) shows the perforations made into the formation.

Table 2. The underbalanced values of perforation.

Permeability (mD)	Underbalance value (psi)	
	Oil reservoir	Gas reservoir
$K > 100$	200-500	1,000-2,000
$10 < K \leq 100$	1,000-2,000	2,000-5,000
$K \leq 10$	$> 2,000$	$\geq 5,000$

on Bell's recommendation, for an oil reservoir that has permeability less than 100 mD, the underbalanced pressure between 1,000 and 2,000 psi is recommended. Table 2 shows the required values of underbalanced based on permeability based on Bell's recommendation. A heterogeneous formation (large variations in permeability) also acts like a damaged formation, in which none of the perforations are likely to result in the same flow. Those with higher permeability values respond better to low pressure differences and hence will clean up more readily than low permeability zones, or zones in which skin is higher. By adjusting well pressure based on the cleanup of all perforations, only perforations from high permeable zones will result in an optimum flow rate. Hence, the effective shot density is reduced, and as a result, PR reduces, too (Bell, 1982). An underbalance of 1,500 means that if the formation pressure is 4,000 psia, the hydrostatic pressure needs to be lowered to 2,500 psia to have an optimized perforation operation.

Using diameter of 0.83, porosity of 0.16 and permeability of 34.1 mD at the formation of interest, Behrmann's equation is used to estimate the minimum underbalance of 46.68 psi. Behrmann's equation is frequently used in the industry and is also included in SPAN^{TM} program. Lastly, a summary of optimum perforation parameters obtained for reservoir X is summarized in Table 3.

6. Conclusion

To enhance productivity and minimize formation damage, the application of UB-TCP was studied in reservoir X, which has numerous production wells with extended horizontal sections (up to 800 meters). First, to design suitable perforations, the drilling formation damage was estimated as a function

Table 3. Summary of perforation parameters in reservoir X.

Perforation gun					Bullet			
Gun OD (inch)	Shot density (SPM)	Hole diameter (mm)	Phase angle (°)	Hole distribution	Penetration depth (mm)	Explosive type	Explosive weight (g)	Underbalance pressure (MPa)
5	16	≥ 10	90	Helix	≥ 800	HMX	23-38	7-14
2-7/8	20	≥ 8	60	Helix	≥ 800	HMX	16	7-14

of reservoir characteristics and drilling parameters (type and density of mud, formation pressure, and permeability) using PCSK™ software. The formation damage can be limited to 357 mm in the drilling period of 18 days in reservoir X. In the next part, HDS perforation guns (73 and 127 mm) and temperature-resistant explosives of HMX types were selected for the reservoir based on the high production quota expected from wells and well characteristics.

Lastly, a sensitivity analysis was conducted using SPAN™ to find optimum hole distribution, phase angle, shot density, and the range of overbalance required for the reservoir. The minimum necessary underbalance was calculated using the optimum perforation parameters and formation properties. The highest productivity index could be achieved when shot spacing is 16 and 20 shots in the reservoir. By choosing the optimized values of 60° and 90°, for phase angle and perforation diameters of over 8 and 10 mm, PRs up to 1.18 were attainable.

By carefully estimating formation damage, selecting compatible perforation assembly, and conducting a thorough analysis of the perforation parameters, low drilling damage and high productivities can be obtained when applying UB-TCP to reservoir X.

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Conflict of interest

The authors declare no competing interest.

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