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Design of a Mixed-Zone Completion Using a Single Oil Production Column in a Non-Eruptive Well with Two Oil and Gas Reservoirs

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ABSTRACT The objective of this paper was to design a multi-zone completion to produce oil from a well designated PX (for confidentiality reasons). The well contains two reservoirs: one with non-eruptive oil and the other with eruptive deep-seated gas reservoir. Analysis reveals that the initial hydrocarbon reserves in the oil and gas reservoirs indicate that R7 oil reservoir contains $4.517396985 \times 10^{10}$ STB of initial oil, and the gas reservoir contains $29.04429927 \times 10^{6}$ MMscf of initial gas. A multi-zone completion scheme is design to extract oil from the deep gas reservoir using a single production column. After implementing the proposed completion, the R7 oil reservoir produces oil at a rate of 2,700 STB/d, with production attributed to the deep-seated R8 gas reservoir. Three oil prices per barrel were selected based on market price fluctuations over a period of 10 year (Low: Scenario 1, Medium: Scenario 2, and high: Scenario 3). The economic evaluation of the completion reveals that Scenario 1 has an NPV (1) of $328,7843 and an IRR (1) of 16.63%, Scenario 2 has an NPV (2) of $602.4843 and an IRR (2) of 12.14%, and Scenario 3 has an NPV (3) of $687.1949 and an IRR (3) of 9.62%. The production of oil from the oil reservoir powered by the deep-well gas reservoir remains a profitable regardless of the price per barrel.

KEYWORDS
Hydrocarbon recovery
Oil and gas reservoirs
Non-eruptive
Multi-zone completion
Nodal analysis
Economic evaluation

INTRODUCTION

The efficient and economical exploitation of hydrocarbon reservoirs is a major challenge for the oil industry (Amyx 1960; Craft 1991; Seyyedattar *et al.* 2020). Conventional development strategies often involve the sequential exploitation of individual reservoirs, potentially leaving significant reserves unexploited due to technical or economic constraints (Wattenbarger and Economides 1993; Bradley 1987; Zheng *et al.* 2017). This limitation is particularly pronounced in mature fields, where it is becoming increasingly difficult to achieve marginal production gains (Khor *et al.* 2017; Miller and Sorrell 2014; Wang *et al.* 2023). This paper addresses the challenge of how to produce oil from one reservoir using gas from another, all within the same well. It examines the challenge of improving hydrocarbon recovery by analyzing the feasibility of simultaneous oil production. It is based on producing oil from a shallow reservoir and gas from a deep reservoir within the same well to improve hydrocarbon recovery by exploring the feasibility of simultaneously producing oil from a shallow reservoir and gas from a deep reservoir within the same well (Bera *et al.* 2024; Lyons 2016; Malozyomov *et al.* 2023). Such integrated production approaches offer the potential to improve the overall economics of the field and reduce environmental impact (Holditch 2006; Jiang *et al.* 2019; Ericson *et al.* 2019). More specifically, it studies an innovative completion strategy designed to enable the extraction of oil from the deep gas reservoir. It had previously been considered unreliable for oil production while leveraging existing well infrastructure and minimizing the need for costly drilling of new wells (Beggs 2003; Brown 1967; Holdaway 2014).

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The growing interest in minimizing costs and maximizing energy efficiency, exacerbated by market volatility and environmental concerns, highlights the urgency of developing innovative solutions (IEA 2022; Farghali *et al.* 2023; Lv 2023). This paper aims to develop and evaluate a technically and economically viable completion solution that enables oil production from deep gas reservoirs, thereby increasing overall hydrocarbon recovery and maximizing asset value (Lake 1989; Alvarado and Manrique 2010; Maryam *et al.* 2024). It draws on a comprehensive al review of the literature on advanced completion techniques, multiphase flow in wellbores, and the economic evaluation of oil projects, in order to propose an original and pragmatic approach to solving this complex problem (Guo 2017; Allen 2016; Brill 1987; Kay and Nedderman 1974; Epelle and Gerogiorgis 2020; Wan 2011). The economic analysis includes a sensitivity analysis to assess the impact of fluctuations in oil and gas prices on the project's profitability. This design takes into account the challenges associated with multiphase flow and incorporates inflow control devices to optimize performance and minimize the risk of production problems.

The research question addressed: How can a suitable completion design be developed that effectively harnesses the high pressure of the lower gas reservoir to enable optimal production of the heavy oil contained in the upper reservoir via a production string? The overall objective is to identify a completion design that allows for the production of oil from the deep gas reservoir. To accomplish the purpose of this paper, three specific objectives were established: to quantify the hydrocarbons in place (oil and gas); to propose a completion design for producing this oil from the deep gas reservoir; and to simulate this completion design and perform an economic evaluation. To achieve these objectives, this paper is organized into three sections. Section 1 presents the introduction to the paper. Section 2 presents the data, the software used, the methodology employed to achieve the set objectives, and the various results obtained. Finally, Section 3 presents the results and discussion. Finally, Section 4 concludes the paper by summarizing the main findings, discussing their implications, outlining the study's limitations, and providing recommendations for future research.

MATERIALS AND METHODS

A number of equipment and tools was utilised for the analysis of data, including software such as PROSPER V15.0 and Microsoft Excel, in addition to field equipment and measuring instruments that were adapted to the particular domains of this study. The data made available for this paper consist of two categories: geological data and reservoir data, for which these data were obtained from national geological surveys, international open-access repositories, and direct field or operational measurements. Key methods include utilizing public government databases, accessing academic or commercial subsurface archives, and gathering direct well data. As illustrated in Figure 1, the geological data has been extracted from the logging data of the PX well.

Figure 1 presents an excerpt from the logging data of well PX. Well PX was drilled in 1981 (started on February 24, 1981; completed on April 10, 1981), and the document was modified on December 3, 2005. Its total depth is 1871. For the logging data, the figure displays logging traces such as density (RHOB), porosity (NPHI), resistivity (ROEEP), pseudo-VSH (shale volume), lithology (LITHO), and fluid type (FLUIDE). Tools, designed to acquire logging data are lowered into the borehole at the end of a cable that connects them to the surface instruments controlling the operations; these instruments are housed either in a truck or in a fixed cabin for offshore drilling.

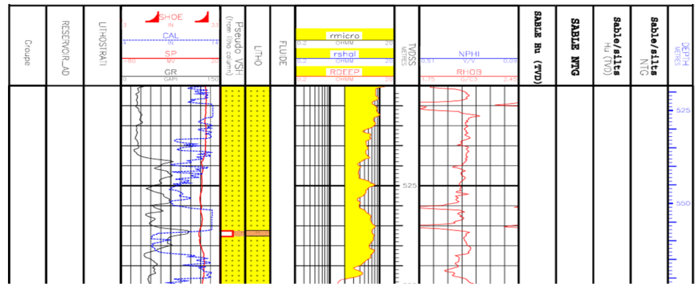

Figure 1 Geological data from the PX well

A multi-zone completion design is a method used to produce oil and gas from two or more separate layers in the same well. The main strategies are comingled flow, segregated production, and alternate zone production. This zone is designed and configured with a single-string comingled (which uses one pipe, mix fluids together, and is cheap but hard to control if pressures differ), single-string selective (which uses packers and sliding sleeves on one pipe to open or close zones one at a time), and a multiple-string (which uses two or more separate parallel pipes to produce each layer completely apart from the others). In addition, consist of zonal insolation packers set between layers to stop fluids from mixing outside the pipe, the flow control sliding sleeves or smart valves (intelligent well valves) for opening and closing holes to let oil in and the monitoring downhole sensors to track pressure and heat in each layer to check production rates.

Justification for the Completion Design

We propose using a multi-zone completion, mixed via a single production string in well PX, which has two reservoirs: one being the oil reservoir and the other the gas reservoir. The factors that will determine the design using a single production string are:

Number of reservoirs: There are two production levels in reservoir R7, which contains gas, oil, and water; it should be noted that the fluid in this reservoir is highly viscous. In addition to reservoir R7, there is also reservoir R8, which contains only gas;

Available pressure data: The tube wall thickness must be strong enough to withstand bottom pressures. Two failure modes must be considered: bursting and collapse. The tube must not be subjected to pressures exceeding its nominal pressure divided by 1.1 for the tube's collapse resistance and internal yield pressure. The collapse design factor must not be less than 1.0 based on the actual differential pressure that could be applied, for example, a full annular fluid column with an empty tube column;

Length and force variations due to temperature effects depend on the variation in the average temperature within the production column. During initial completion (static condition), the average temperature of the tubing is equal to the bottom-hole temperature plus half the surface temperature. This will serve as the reference case for determining the effect of changes in force and length due to an increase or decrease in temperature;

Tubing generally constitutes the main conduit connecting the production interval to the wellhead production facilities. Consequently, the proper selection, design, and installation of tubing are essential elements of any completion system. The tubing must be sized to allow for efficient production;

The string must be designed to prevent failure due to tensile forces, internal and external pressures, and the corrosive nature of the well environment; assembly: the components of the string must be installed without damage to ensure pressure tightness.

Water salinity refers to the concentration of dissolved salt in the water and can lead to several consequences, such as corrosion, which is generally considered the factor with the greatest negative impact on the service life and integrity of completion equipment and components. In harsh environments, components deteriorate extremely rapidly, often with dramatic consequences and requiring costly recovery or retrieval operations; fouling is caused by the accumulation of deposits on equipment due to the presence of dissolved salts. Density can be affected by the presence of salts, which can impact the operation of measurement and control equipment.

The economic factors presented go beyond the scope of the technical preparation for well completion design. However, they undeniably influence the sector. Consequently, a basic understanding of these factors and their interaction with those mentioned above is beneficial: market forces (including seasonal fluctuations and fluctuating production); taxation (including tax obligations or tax breaks); availability of investment; and, consequently, the various configurations created using the PROPER V15.0 software. In the absence of a downhole choke, since gas pressure is higher than oil pressure, the gas will rise while preventing the oil from rising.

RESULTS AND DISCUSSION

The reservoir data are presented in Table 1.

Table 1 Data for the two reservoirs of well PX

Layers	Reservoir R7	Reservoir R8
Fluids	Oil + water + gas	Gas
Sg (psi/ft)	0.403	0.307
Roof (m)	1079	1305
Base (m)	1140	1350
Pressure (psi)	1,400	3200

Table 1 presents the second set of data on the two reservoirs (S7, S8), including fluid type, specific gravity (Sg), top depth (TOP) and base depth (Base) in metres, and pressure (in PSI). After analysing the collected data, we must consider tools to enhance understanding and approach. Nodal analysis and economic evaluation are used to carry out this work. The hydrocarbon volume in the two reservoirs, R7 and R8, is estimated based on their petro-physical properties, as illustrated in Table 2.

Based on the volumetric method, Table 2 shows that the amount of oil in the R7 oil reservoir is $4.517396985 \times 10^{10}$ STB, and that of gas in the R8 gas reservoir is $29.044299270 \times 10^{6}$ MMscf.

Simulation results

All results from the simulations were obtained using PROSPER V15.0 software for each reservoir. Figure 2 shows the oil reservoir's nodal analysis curve before implementing the proposed completion.

Figure 2 consist of two curves: the VFP (Vertical Flow Performance) curve of the well and the IPR (Inflow Performance Relationship) curve of the reservoir. The R7 oil reservoir has no operating point (the IPR and VFP curves do not intersect) and is therefore non-eruptive (see Figure 3 for the gas reservoir IPR curve).

Table 2 Results of the estimation of the oil and gas volumes in reservoirs R7 and R8

Parameters	Oil reservoir (R7)	Gas reservoir (R8)
Thickness (m)	61	45
Porosity	RHOB : 1.980 RHOS : 2.600 RHOF : 0.870 ; Ø : 0.358	RHOB : 2.084 RHOS : 2.600 RHOF : 0.400 ; Ø : 0.235
Water resistivity (R_w)	0.7	0.6
Formation resistivity (R_t)	12.2	5.8
Water saturation (S_w)	0.446935233	0.320176957
Oil/gas saturation (S_O/S_G)	0.553064766	0.679823043
OOIP/OGIP	$4.517396985 \times 10^{10}$ STB	$29.044299270 \times 10^{6}$ MMscf

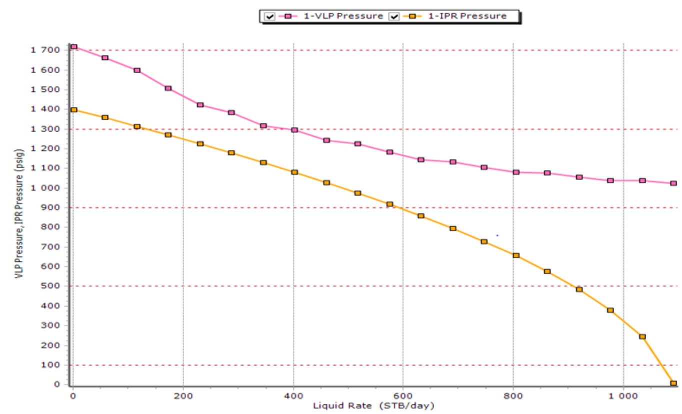

Figure 2 Nodal analysis curve of the R7 oil reservoir prior to implementation of the proposed completion

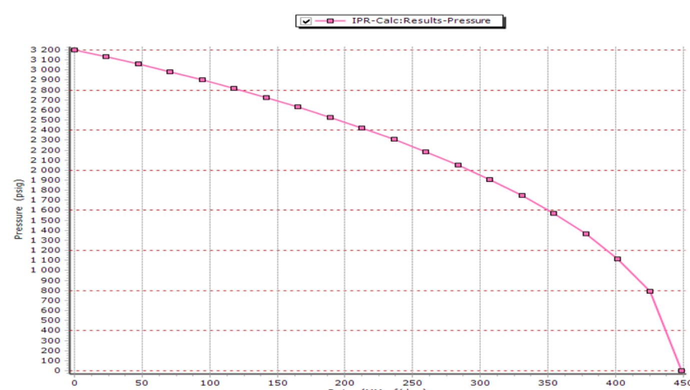

Figure 3 IPR curve for gas reservoir R8

Figure 3 shows the IPR curve for gas reservoir R8. This curve illustrates the relationship between a well's production rate and reservoir pressure. It reveals that the maximum rate that gas reservoir R8 can deliver is 448.681 MMSCF/day. Figure 4 shows the nodal analysis of gas reservoir R8.

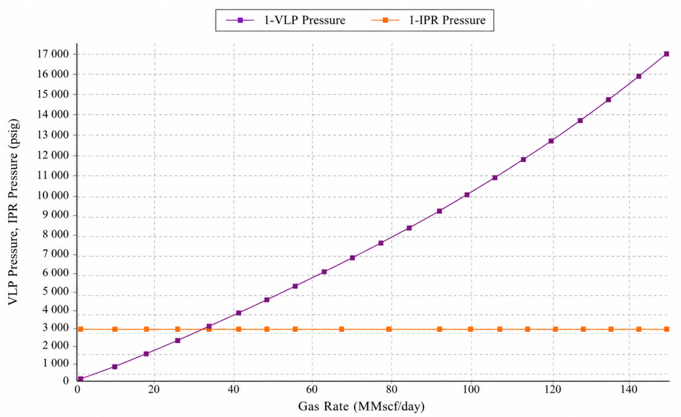

Figure 4 Nodal analysis of the R8 gas reservoir

Figure 4 consist of two curves: the VFP curve of the well and the PR curve of the reservoir. It shows that the R8 gas reservoir has an operating point where the VFP and IPR curves intersect, making it gush-prone. It can produce 35 MMscf/day. Figure 5 presents the proposed completion specification generated using Prosper V15.0, in which the goal is for the R7 oil reservoir to produce in connection with the R8 gas reservoir.

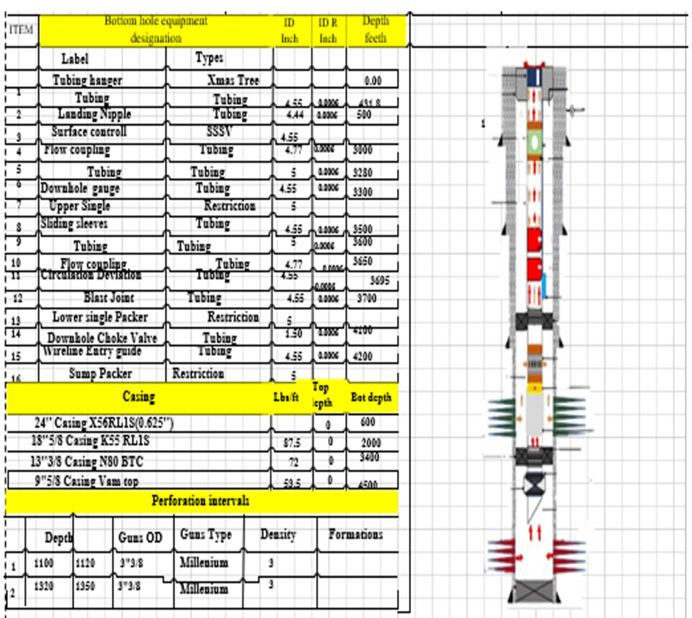

Figure 5 Proposed completion design sheet generated using Prosper V15.0

Figure 5 shows the PX well that extends into two reservoirs. The second reservoir allows the oil to rise to the surface via the downhole choke valve, which controls the flow rate of gas rising to the surface. The gas then mixes with the oil, which is highly dense. Figure 6 presents the R7 oil reservoir's nodal analysis.

Figure 6 shows the R7 oil reservoir produces oil with credit to the R8 gas reservoir. The drop in pressure as the flow rate increases indicates a possible production capacity limitation. The red curve shows how pressure changes with flow rate. A downward slope indicates a decrease in pressure as flow rate increases. The operating point is where the two curves intersect, shows that pressure and flow rate are in equilibrium for a maximum production of 2,700 STB/d as compared to the investigation of Abeed and Khalleefah on nodal analysis calculation for the estimation of the best operating conditions using two wells for which the operating flow rate is 2500 standard barrels per day and the pressure below the well is 2200 psi in the Nafoora Field of Arabian gulf oil.

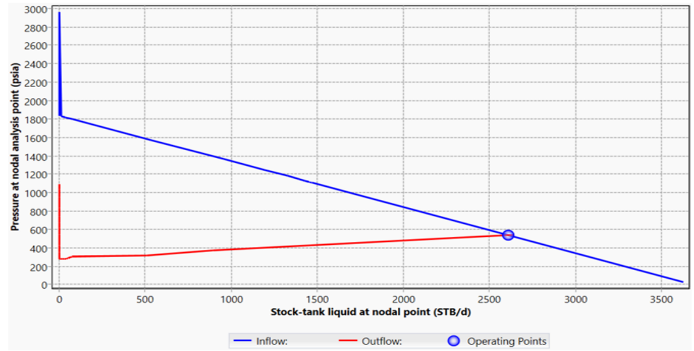

Figure 6 Nodal analysis of the R7 oil reservoir after implementation of the proposed completion

Results of the Economic Evaluation

The project's economic evaluation determines the returns for the investor. Capital and operating expenses must be considered, with revenue based on oil production, prices, taxes, the project period and costs. Table 3 shows the costs of equipment, operating expenses and capital expenditures for the proposed completion in the PX well.

Table 3 Economic model parameters

Parameters	Scenario 1	Scenario 2	Scenario 3
G & G	0.0	0.0	0.0
Facility Costs	16.0	20.0	24.0
CAPEX	1.0	3.0	4.0
OPEX per year	20.8	21.9	23.0
Drillex (for Well)	50.0	60.0	120.0
Maintenance cost every 3 years	3.0	6.0	9.0
Reserves (million barrels)	5.0	12.0	20.0
Oil Price	40.0	60.0	70.0
Production decline rate	100.0	0.0	0.0
Initial average daily	2,700.0	0.0	0.0
Discount rate	0.15	0.0	0.0

The economic evaluation is conducted for the three scenarios in Table 3. The oil prices per barrel for each scenario were selected based on market price fluctuations over a period of 10 years. Each of the three scenarios is defined as follows:

Scenario 1: The price per barrel of oil is estimated at $40, based on a pessimistic outlook regarding price fluctuations on the international market;

Scenario 2: The price per barrel of oil is the current price on the international market, i.e., $60;

Scenario 3: The price per barrel is estimated at $70, reflecting an optimistic outlook on the increase in the cost per barrel on the market.

Figure 7 shows the parameter estimates for the three scenarios presented in Table 3.

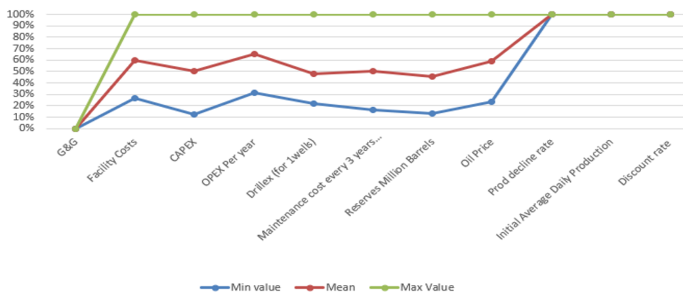

Figure 7 Estimated parameters for the three scenarios: Low (Scenario 1), Medium (Scenario 2), and High (Scenario 3), using oil production from the R7 oil reservoir via the deep-lying R8 gas reservoir

As demonstrated in Figure 7, in Scenario 1 (blue), the price per barrel of oil would be the lowest; in Scenario 2, the price per barrel of oil is the current price (brown); and in Scenario 3, the price per barrel of oil would be as high as possible (green). Tables 4-6 present the economic evaluation of the project for the three scenarios.

Table 4 Economic Evaluation of Scenario 1

Year	Prod.	Price	Revenue	CAPEX	OPEX	Cash Flow	Tax	Net CF	NPV
	(bbl/Y)	($)	(M$)	(M$)	(M$)	(M$)	15%	(M$)	(M$)
1	3.65	40	0	2.4584	21.97	-24.4284	0	-24.4284	**328.7843**
2	3.10	40	124	2.4584	21.82	99.7216	14.9582	84.76336	
3	2.70	40	108	2.4584	21.95	83.5916	12.5387	71.05286	
4	2.30	40	92	2.4584	22.28	67.2616	10.0892	57.17236	
5	1.90	40	76	2.4584	22.90	50.6416	7.59624	43.04536	
6	1.60	40	64	2.4584	22.25	39.2916	5.89374	33.39786	
7	1.40	40	56	2.4584	22.57	30.9716	4.64574	26.32586	
8	1.20	40	48	2.4584	23.59	21.9516	3.29274	18.65886	
9	1.00	40	40	2.4584	23.99	13.5516	2.03274	11.51886	
10	0.90	40	36	2.4584	24.98	8.5616	1.28424	7.27736	

Tables 4 to 6 show the NPV (net present value) for each scenario over 10 years: Scenario 1 has an NPV (1) of $328.7843, Scenario 2 has an NPV (2) of $602.4843, and Scenario 3 has an NPV (3) of $687.1949. The IRR (Internal Rate of Return) formula yields the rate of return for each scenario: Scenario 1 has an IRR (1) of 16.63%, Scenario 2 has an IRR (2) of 12.14%, and Scenario 3 has an IRR (3) of 9.62%. The cash flow is already much greater than the investment in the first year, indicating that the project remains highly profitable. The payback period is 0.8 months, or 24 days, for Scenario 1. The project is profitable.

The economic evaluation project summary for the three scenarios is presented in Figure 8 for over a period of 10 years.

Table 5 Economic Evaluation of Scenario 2

Year	Prod.	Price	Revenue	CAPEX	OPEX	Cash Flow	Tax	Net CF	NPV
	(bbl/Y)	($)	(M$)	(M$)	(M$)	(M$)	15%	(M$)	(M$)
1	3.65	60	0	2.4584	21.97	-24.4284	0	-24.4284	**602.4843**
2	3.10	60	186	2.4584	21.82	161.7220	24.2582	137.4634	
3	2.70	60	162	2.4584	21.95	137.5920	20.6387	116.9529	
4	2.30	60	138	2.4584	22.28	113.2620	16.9892	96.27236	
5	1.90	60	114	2.4584	22.90	88.6416	13.29624	75.34536	
6	1.60	60	96	2.4584	22.25	71.2916	10.69374	60.59786	
7	1.40	60	84	2.4584	22.57	58.9716	8.84574	50.12586	
8	1.20	60	72	2.4584	23.59	45.9516	6.89274	39.05886	
9	1.00	60	60	2.4584	23.99	33.5516	5.03274	28.51886	
10	0.90	60	54	2.4584	24.98	26.5616	3.98424	22.57736	

Table 6 Economic Evaluation of Scenario 3

Year	Prod.	Price	Revenue	CAPEX	OPEX	Cash Flow	Tax	Net CF	NPV
	(bbl/Y)	($/bbl)	(M$)	(M$)	(M$)	(M$)	15%	(M$)	(M$)
1	3.65	70	0	2.4584	21.97	-24.4284	0	-24.4284	**687.1949**
2	3.10	70	217	2.4584	21.82	99.2160	14.9582	87.76338	
3	2.70	70	189	2.4584	21.95	192.7220	28.9082	163.8134	
4	2.30	70	161	2.4584	22.28	136.2620	20.4392	115.8224	
5	1.90	70	133	2.4584	22.90	107.6420	16.1462	91.49536	
6	1.60	70	112	2.4584	22.25	87.2916	13.0937	74.19786	
7	1.40	70	98	2.4584	22.57	72.9716	10.9457	62.02586	
8	1.20	70	84	2.4584	23.59	57.9516	8.69274	49.25886	
9	1.00	70	70	2.4584	23.99	43.5516	6.53274	37.01886	
10	0.90	70	63	2.4584	24.98	35.5616	5.33424	30.22736	

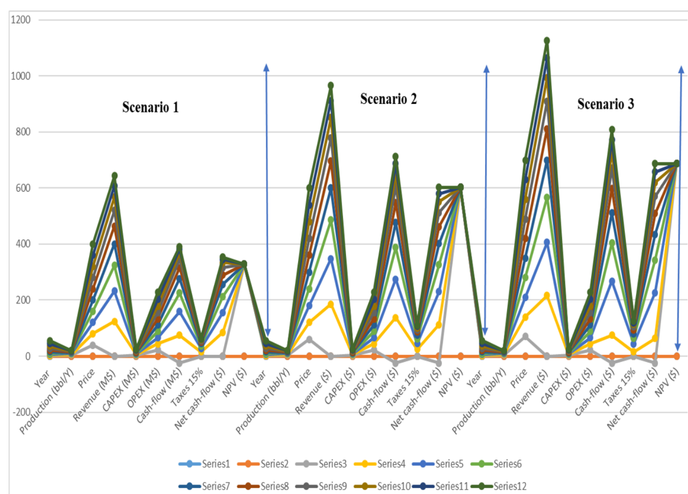

Figure 8 Economic evaluation project summary for the three scenarios

CONCLUSION

The aim of this paper was to produce oil from the PX well in the BX basin using its oil reservoir, aided by its deep-seated gas reservoir. The paper presented the data, tools, and methodology applied to address the productivity issue in the PX well, demonstrating the optimal completion design for this well. The results were then interpreted to explain the concepts discussed in the paper. The materials and methods used, including nodal analysis, economic evaluation, and the software Prosper v15.0 and Microsoft Excel, were then presented for data analysis, petro-physical analysis, porosity, water, oil, and gas saturation, water and formation resistivity, and the estimation of in-place oil and gas volumes in the R7 oil and R8 gas reservoirs of the PX well. The R7 oil reservoir of well PX has a thickness of 61 m, a pressure of 1,400 psi, and an initial oil of $4.517396985 \times 10^{10}$ STB. The gas reservoir of well PX has a thickness of 41 m, a pressure of 3,200 psi, and an initial gas volume of $29,04429927 \times 10^{6}$ MMscf. The nodal analysis of the R7 oil reservoir of well PX prior to the implementation of the proposed completion indicated that it is non-eruptive. The nodal analysis of the R8 gas reservoir indicated that it is eruptive and can produce 35 MMscf/day.

A multi-zone completion, mixed through a single production string in the PX well, was proposed to produce oil from the R7 reservoir and gas from the R8 reservoir. After implementation, the R7 reservoir produced 2,700 STB/d as compared to the investigation of Abeed and Khalleefah on nodal analysis calculation for the estimation of the best operating conditions using two wells for which the operating flow rate is 2500 standard barrels per day and the pressure below the well is 2200 psi in the Nafoora Field of Arabian gulf oil. The economic evaluation showed that Scenario 1 had an NPV (1) of $328,7843 and an IRR (1) of 16.63%, Scenario 2 had an NPV (2) of $602.4843 and an IRR (2) of 12.14%, and Scenario 3 had an NPV (3) of $687.1949 and an IRR (3) of 9.62%. The payback period was 0.8 months (24 days) for Scenario 1. It was shown that oil production from the R7 reservoir is profitable, regardless of price.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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