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Monobore completion design: Classification, applications, benefits and limitations

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MONOBORE COMPLETION DESIGN: CLASSIFICATION, APPLICATIONS, BENEFITS AND LIMITATIONS

by

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ABSTRACT

A monobore completion is a simple completion design that uses the same internal diameter from the bottom of the well to surface. This may be accomplished by cementing a string of casing in a well, or by having tubing stabbed into a polished bore receptacle on a casing liner the same size as the tubing. Monobore completions have been applied extensively in oil and gas fields around the world, both onshore and offshore, from very low reservoir flow to extremely high production rates, since the late 1980s. They have proven beneficial due to their simplicity and cost savings. This study summarizes an extensive literature review of monobore completions and categorizes the monobore completions as slimhole, big bore or special function applications.

This study also evaluates the well inflow impact of the 4 1/2-in. openhole multistage sleeve monobore completion employed in the North Kuwait Jurassic Gas field for HPHT wells compared to the previous completion using 3 1/2-in. tubing and 5 1/2-in. liners. The inflow evaluation was made for both volatile oil and gas condensate fluids found in this reservoir. Reservoir depletion was modeled to determine flowing life for the conventional completion versus the monobore design.

The results of the modeling indicate production rate for the volatile oil case is the same in both completion designs, conventional and monobore, while in the gas condensate case the production rate is slightly higher for the monobore completion. As the monobore completion is larger, it reaches an unstable flow condition more quickly than the conventional design. However the multistage completion methodology allows all zones to be stimulated and contribute to flow, and can be equipped with a velocity string to sustain flow.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Page

LIST OF TABLES

NOMENCLATURE

Symbol	Description
AOF	Absolute Open Flow
BBL/d	Barrel per day
BCPD	Barrel Condensate per Day
BOPD	Barrel Oil per Day
BTC	Buttress Thread Casing Coupling
CNRF	Contoured Non-Resilient Flapper
EOS	Equation of State
GL	Gas Lift
HCCV	Hydrostatically Closed Circulating Valve
HPHT	High pressure High Temperature
ID	Internal Diameter
IPR	Inflow Performance Relationship
KOC	Kuwait Oil Company
LTC	Long Thread Casing Coupling
MM	Middle Marrat
MMSCF/d	Million Standard Cubic Foot per day
NKJG	North Kuwait Jurassic Gas
OD	Outer Diameter
OHMS	Open Hole Multi-Stage
PBR	Polished Bore Receptacle
P_c	Critical Pressure

PVT	Pressure Volume Temperature
R	Ideal Gas Constant
SCSSV	Surface Controlled Sub-Surface Safety Valve
SPM	Side Pocket Mandrel
SSD	Sliding Sleeve Door
T_c	Critical Temperature
TRBP	Tubing Retrievable Bridge Plug
TRSV	Tubing Retrievable Safety Valve
VLP	Vertical Lift Performance

1. INTRODUCTION

Well completion design refers to all of the equipment, materials and processes required to establish production (or injection) from a well after drilling, casing and cementing conclude. Because the scope of well completions is so broad, one must be knowledgeable in a wide range of subjects, such as completion equipment (including setting and removal), tubing sizing, completion fluids, perforating, acidizing, hydraulic fracturing, completion installation procedures, artificial lift, sand control, and workover technology (wireline work and full tubing removal), plus the myriad of safety and environmental issues related to these topics. The role of the completions engineer is to understand these subjects thoroughly, and to develop a completion design which optimizes production given any specific functional requirements (e.g. must use a downhole safety valve offshore) and any design constraints (e.g. equipment availability). Figure 1.1 depicts some of the sources of data used in well completion design.

Completions are the interface between the reservoir and surface production. Whatever happens during a well completion greatly impacts the well's ability to produce and overall economics of a field development. For example, if perforations do not extend beyond a well's damage zone, then inflow is reduced. If a gravel pack operation is performed poorly, the screen may ultimately fail, jeopardizing the well's ability to continue producing. These are only two examples of hundreds of completion activities that can compromise the well's flow immediately or years later.

While completion expenditures may be a relative small proportion of the total capital costs in some fields (e.g. offshore), completions may have a disproportional effect on revenues and future operating costs. Some of the basic economic considerations are shown in Figure 1.2

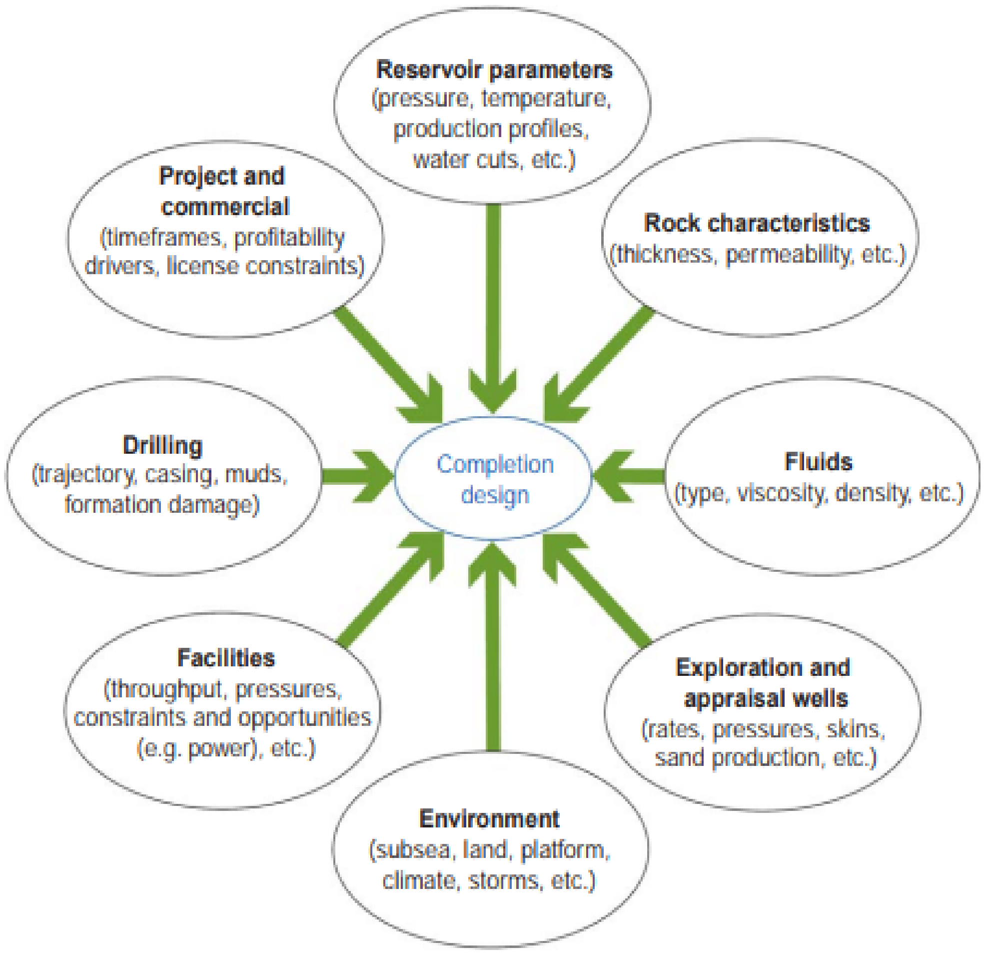

Figure 1.1. Data sources for completion design. (Bellarby 2009)

A well's completion is normally planned in accordance with the drilling program. The typical land well will have multiple casing strings, with either a full production casing run to total depth, or a liner. The completion activities such as circulating, perforating, stimulating are then conducted through the final casing/casing liner. Tubing and completion equipment are set and the well is readied for production. Figure 1.3

depicts two common drilling and tubing arrangements for (a) normally pressured and (b) abnormally high pressure wells.

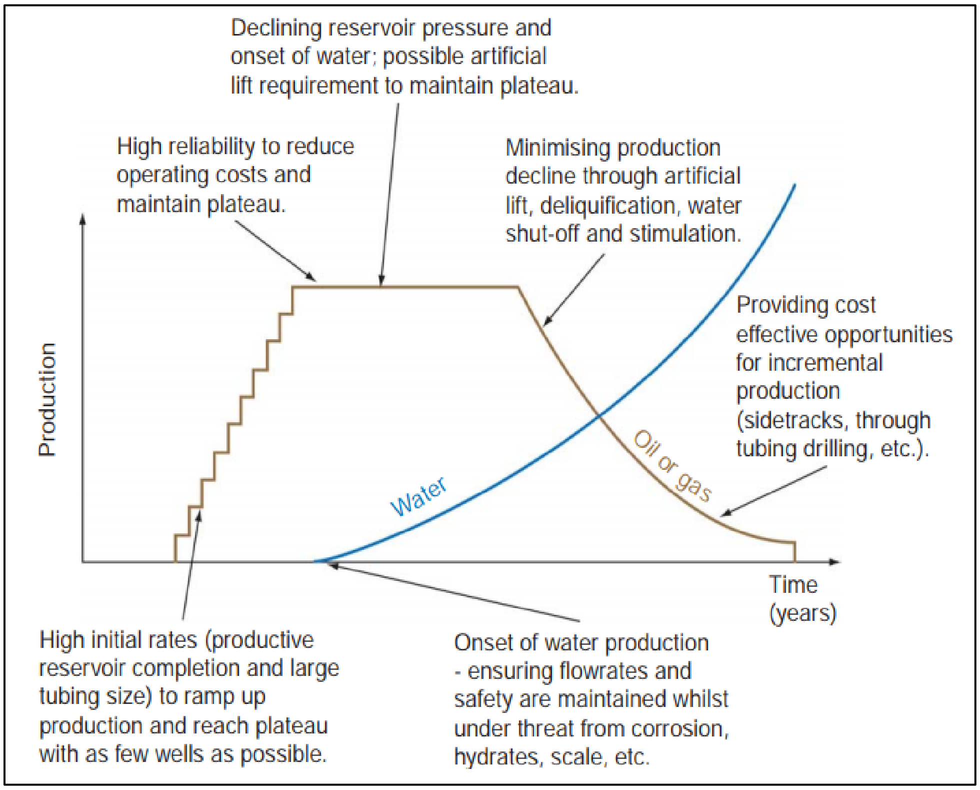

Figure 1.2. Economic influence of completions. (Bellarby 2009)

In a well completion, tubing size is determined according to a well's inflow potential. Wells with large flowrates of oil/gas require larger tubing sizes than wells with low productivity. However, there is also a temporal aspect to sizing tubing, because reservoir pressure decreases with time, thereby decreasing the reservoir's flow potential with time. In addition, more water may be produced with time, increasing overall fluid density and requiring more pressure to produce fluids to the surface. As flow rate decreases the initial tubing size may be too large for stable flow. Hence, a completion needn't necessarily be designed to survive the field life. It may be optimum to design for tubing replacements. An economic comparison is always necessary in determining selecting completion alternatives.

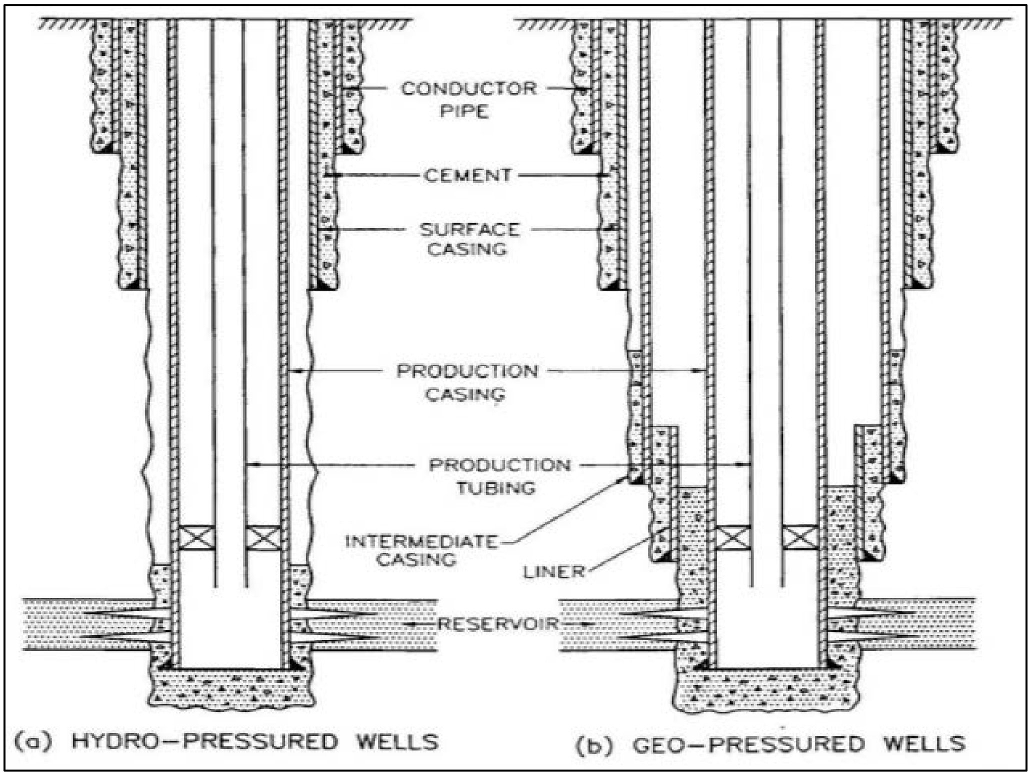

Figure 1.3. Example casing designs for (a) normally pressured wells and (b) abnormally high pressured wells. https://www.slideshare.net/akincraig/petroleum-engineering-drilling-engineering-casing-design

Table 1.1. summarizes an economic comparison for three different field scenarios: a land well, a well located on an offshore platform and a subsea well. The choice illustrated is whether to spend an additional million dollars on a corrosion resistant completion or to install a cheaper completion that is expected to be replaced in 10 years' time. If the completion fails, a rig has to be sourced and a new completion installed; this costs money and a delay in production. The time value of money reduces the impact of a

cost in 10 years. In the case of the onshore well producing at lower rates where a workover is cheaper, the workover cost is less than the upfront incremental cost of the high-specification metallurgy. However, for the platform wells, and especially the subsea well, the high cost of the workover places greater economic emphasis on upfront reliability. (Bellarby, 2009). This type of analysis is conducted for completion design alternatives.

Table 1.1. Economic example of completion design decision. (Bellarby, 2009)

	Land Well	Platform Well	Subsea Well	
Sustained production rate	250	2500	5000	bpd
Value of *accelerated* oil after opex and tax	20	20	20	$/bbl
Capital cost of 13Cr completion (includes installation)	3	6	15	$ million
Incremental cost of upfront duplex completion	1	1	1	$ million
Delay in production before rig can perform workover	3	2	6	months
Cost of workover	1.5	2	10	$ million
Impact of completion failure	1.95	5	28	$ million
Discount factor	8%	8%	8%	
Net present cost of failure in 10 years' time	0.8	2.2	12.2	$ million

Well completions can be described or categorized according to their location, overall geometry, openhole vs cased hole, the need for sand control, the need for stimulation (proppant or acid) or according to the number of zones completed. Figure 1.4 shows some of the options in the lower (reservoir) completion while Figure 1.5 shows some upper completions methods. These two Figures depict only vertical wells.

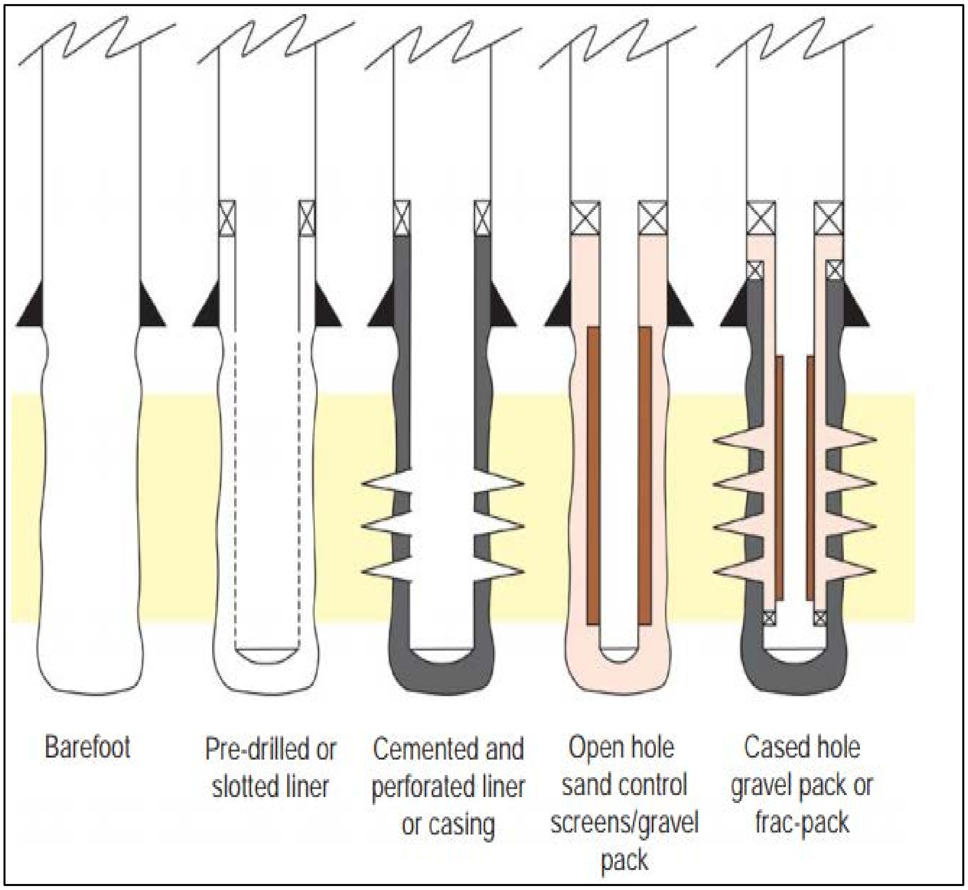

Figure 1.4. Reservoir completion alternatives. (Bellarby, 2009)

Most wells drilled for unconventional (shale) or tight reservoirs utilize horizontal wells, with multistage hydraulic fracturing stages along the lateral portion of the well. These wells utilize either perforated and cemented casing (plug-and-perf), openhole liners with packers and balldrop sleeves (openhole sleeve systems) or cemented sleeve systems. Figure 1.6 is a sleeve type horizontal multi-stage well completion.

Industry constantly strives to improve well drilling and workover operations, develop new completion designs, and innovate equipment changes to enhance production and reduce well cost. In the 1980s industry introduced the concept of a ‘monobore completion’. These completions were developed to have a uniform internal diameter with no barriers or restrictions, so the well can be constructed with less time and material cost, and potentially provide easier workover operations, resulting in more economical production. Figure 1.7 depicts a general comparison between a conventional completion and a monobore completion.

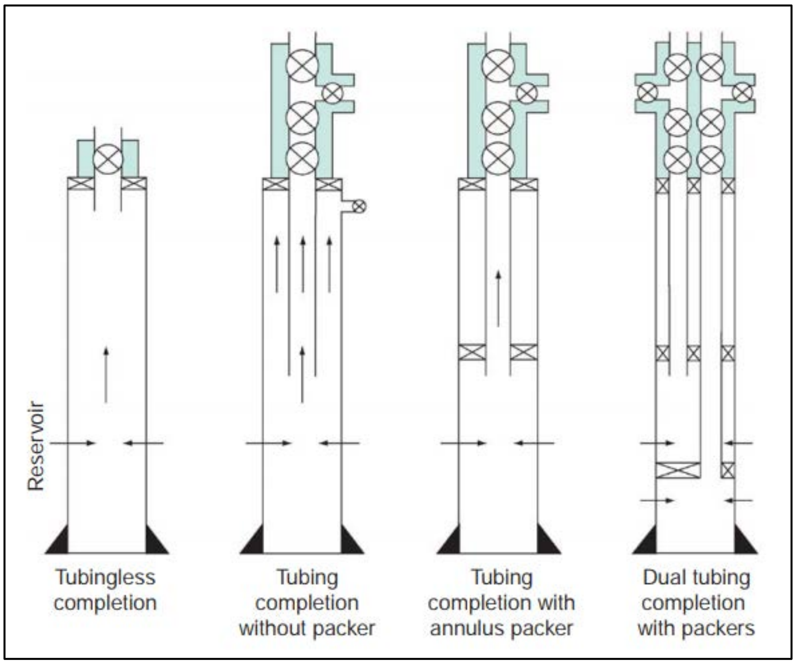

Figure 1.5. Common upper completion configurations. (Bellarby, 2009)

The use of monobore has become widespread across the industry in an attempt to save on exploration and field development costs while maximizing production. The literature contains numerous references to these completions. This work provides a classification system for monobore completions, coupled with a historical review and compilation of monobore case studies.

Recent applications of monobore completions include wells completed in the North Kuwait Jurassic Gas field, which is a deep, high pressure high temperature (HPHT) reservoir, with tight carbonate layers of varying permeability. This monobore design also combined multistage hydraulic fracturing stimulation methods in the completion design. The design was developed by Kuwait Oil Company (KOC) and Shell Kuwait E&P.

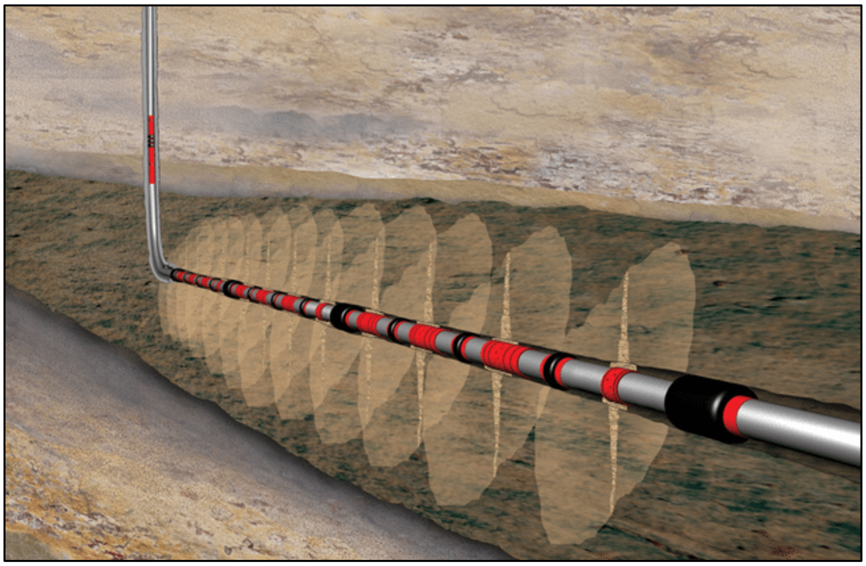

Figure 1.6. Sleeve type horizontal multistage hydraulic fracture well completion. Image credit Halliburton. https://info.drillinginfo.com/well-completion-well stimulation/

In this work, well productivity software (PROSPER) has been used to model the monobore well production with reservoir pressure decline, to investigate the impact of the monobore compared to conventional completion design.

In this study there are two main objectives. The first objective is to perform a literature review of the historical monobore completion design case studies and to develop a classification system for these monobore completions. This review includes summaries of the advantages and disadvantes of the monobore completions. This work is intended to provide a comprehensive and progressive overview of monobore completions, to determine how these completions have been used over nearly the past four decades. No such review of monobore completions exists.

The second objective is to investigate the well productivity impact of the monobore completion used in North Kuwait's Jurassic Gas compared to a conventional completion with the same stimulation applied. This modeling work is intended to demonstrate that for a HPHT gas condensate field, a monobore completion does not limit the production capability of the well.

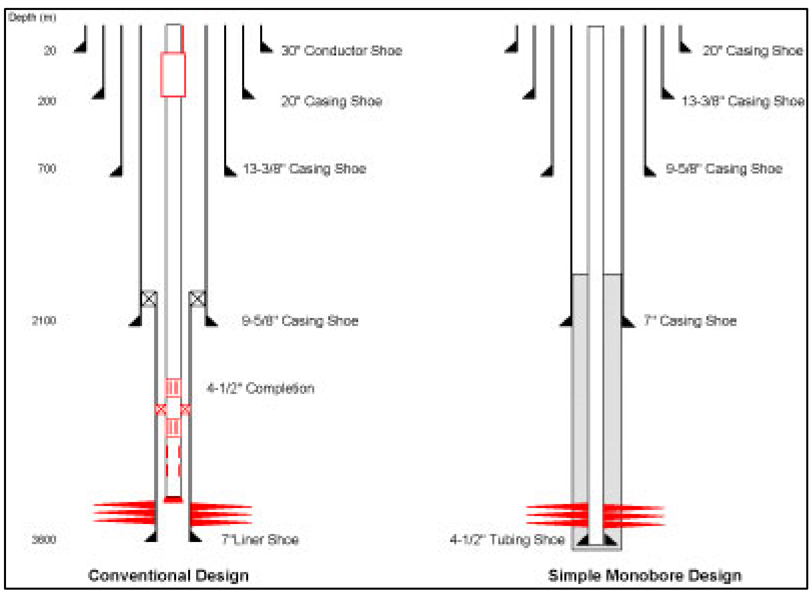

Figure 1.7. Comparison between conventional vertical single completion and a monobore completion. http://www.drillingcontractor.org

2. MONOBORE COMPLETION

Operational efficiency and cost-cutting have been the twin objectives that have driven the oil industry. These often conflicting requirements have led to many innovations encompassing almost every aspect of hydrocarbon exploration and production. One such innovation is the monobore completion, which essentially consists of a single internal diameter well from the top of the well to the very bottom, including into the producing zone. The monobore was established by Shell UK Exploration and Production incorporation with various service companies in 1987.

Monobore completions have proven beneficial in many ways, but also have demonstrated limitations. Early implementation of monobore completions eliminated the intermediate casing and replaced it with a single hole size from the reservoir to the surface. This strategy had a high impact on the well cost by simplifying the well construction and reducing the overall cycle time, thus reducing the cost by 15-30%.

This section reviews the characteristics of monobore completions, their operational requirements, and where applicable, specific improvements over existing completions. It also discusses a few appropriate case studies to determine potential benefits and limitations of monobore completion technology.

2.1. CONVENTIONAL COMPLETION TO MONOBORE COMPLETION DESIGN

This section introduces and describes several early examples of how existing well completion designs were altered to become monobore completions. A number of operators have switched from conventional to monobore completion or have implemented innovative new designs in the monobore well drilling process, and these innovations have led to operational improvements as well as the discovery of new issues. Some of the more important challenges facing oil producers and the necessary operational conditions are discussed in this section.

At first, the operators were trying to optimize the completion design by reducing the capital and operating expenditure for the new drilling wells without affecting the operation and to produce economically. To achieve this purpose, the idea of monobore completion design was developed by eliminating one casing (intermediate casing) and installing a cemented production liner that is one size smaller and the same size as the tubing to have an even internal diameter ID from the top of the well to the very bottom, including into the producing zone (Figure 2.1). The key advantage is to have a clear wellbore without any permanent restrictions such as restrictive nipples or locator seal assemblies. Furthermore, the monobore design facilitates the workover operation and well intervention because all the restrictions are removed and the work can be done rigless through the existing production tubing without having to pull it in order to service the producing intervals and increase the economical production, which would play an instrumental role in reducing the cost.

In 1990, the completion optimization concept was applied in Gullfaks field in the Norwegian sector of the North Sea to overcome the operational issues due to low formation strength, rapid pore pressure build-up and shallow gas sand. Originally, Gullfaks wells were completed with a 7 in. liner and 5 ½-in. tubing. Then, the completion design went through continuous improvements to manage the reservoir and enhance the production ending with the 7 in. monobore completion with a gravel pack option where 7 in. tubing connected to the top of the 7 in. liner, giving a smooth internal bore from the surface to the bottom including the pay zone. This completion design increased the production, facilitated the workover operations through the tubing and allowed the lower completion to be easily installed with snubbing units or coil tubing without needing the rig, which would reduce the cost. In 1993-94, an alternative casing program for Gullfaks field was created to achieve a more confident operational plan.

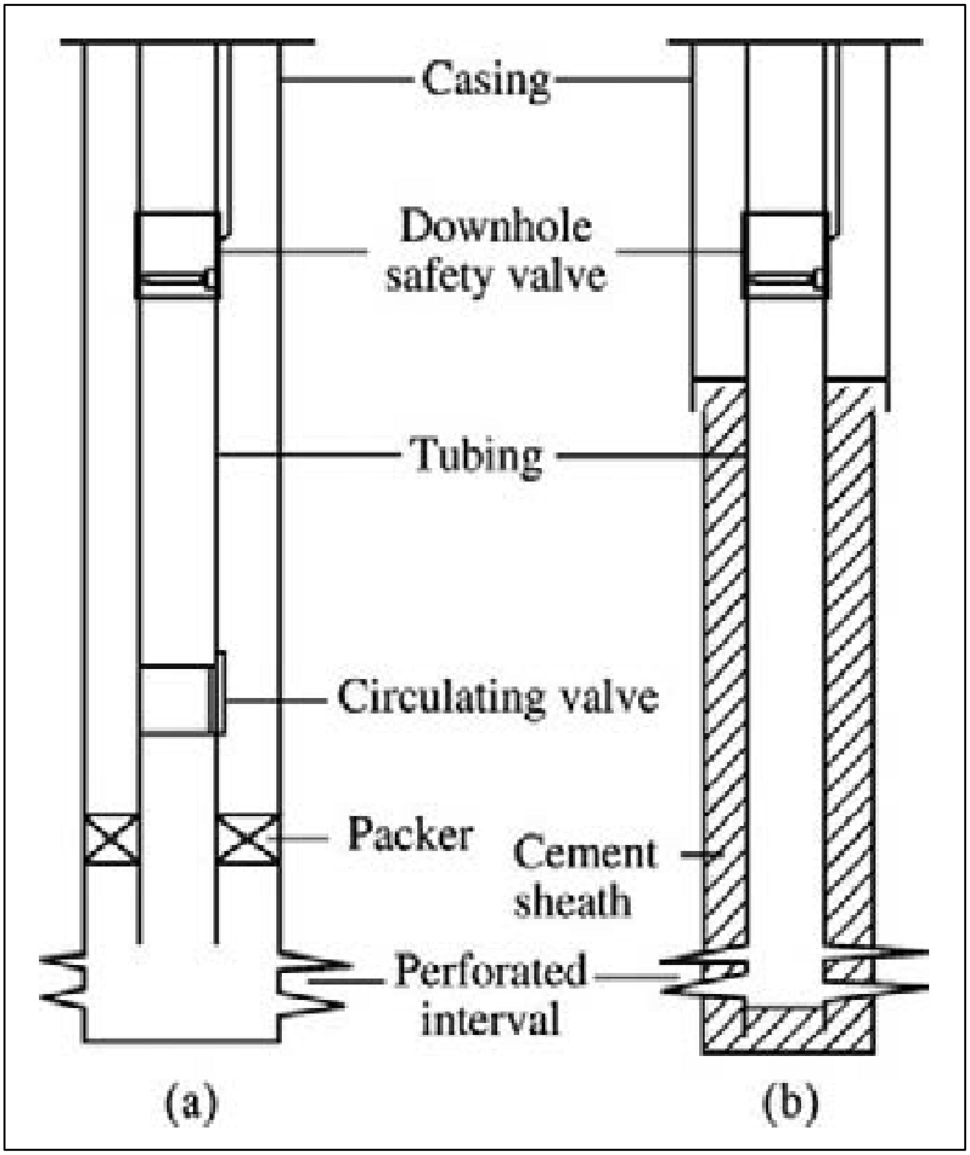

Figure 2.1. Conventional completion (a) vs. monobore completion (b). (Renpu, W. 2011)

Figure 2.2 shows the improvement of the casing design, Figure 2.2a illustrates the primary monobore completion design with the existence of the two intermediate casings, and Figure 2.2b illustrates the monobore completion design after eliminating the 26 in. casing. The three alternative casing designs are shown in Figure 2.2c, 2.2d and 2.2e.

In Alternative 1 (Figure 2.1c), the well was completed with a 7 in. monobore completion. One intermediate casing was eliminated, and the other two intermediate casing diameters were reduced. This design is optimal for wells with a small reservoir thickness with initial or near initial pore pressure. Alternative 2 (Figure 2.2d) was planned to complete the well as a 7 in. monobore completion with a 7 in. liner in the first reservoir section, and a 5 in. liner in the second reservoir section. One intermediate casing was eliminated, and the other two intermediate casing diameters were reduced. This design is useful for wells with long reservoir sections and reservoirs of different degrees of depletion. In Alternative 3 (Figure 2.2e), the wells were planned to be completed with a 5 in. monobore completion. One intermediate casing was eliminated, and the other two intermediate casing diameters were reduced. As the second alternative, this design is suitable for wells with long reservoir sections and reservoirs of different degrees of depletion. The main limitations of the 5 in. monobore completion are the restrictions on the rates of injection and production.

The Statfjord field, which is located in the North Sea on the boundary between the United Kingdom and the Norwegian sector, is another example where the operators optimized the completion design gradually until they approved the monobore completion design in late 1980s as the most beneficial completion design.

The original completion design was 32 ppf, 7 in. L80 carbon steel production tubing with a 5 ½-in. restricted tail pipe run into the liner as shown in Figure 2.3. A 9 5/8-in. production packer was set in the top of the liner and 164 ft above the reservoir in case there was not a liner. Around 900 ft below the surface, a nipple for the wireline retrievable subsurface safety valve was set. Due to the restrictions and operational limitations on the insertion of the workover tools, the operators retrieved the tubing to proceed with the workover, which increased the operational expenditure by around 2 MMUSD with a total cost of 82 MMUSD for all the workovers performed. The initial completion design restricting the perforating guns to 3 3/8-in. with a density of 6 spf , which needs two runs to perforate 12 spf that would affect the perforation distribution, sand production, and productivity. As a result, the well performance was delayed. In order to speed the workover operation and lower the cost, the operators upgraded the workover to be performed through tubing by installing inflatable plugs and cement plugs. Nine jobs were done with a drilling rig with a cost of 1 MMUSD per well, and five jobs used snubbing or coil tubing. The results were unsatisfactory because, there were some failures due to setting the plugs in a 9 5/8-in. casing. After that the operators agreed to apply pre-installation equipment for future isolation in case workover was needed, such as isolation packers and straddle packers with nipple profiles and sliding sleeves, which were installed between the different zones. This method cost 40,000 USD using a workover rig to pre-install a packer. Some issues such as misruns, were experienced while trying to open the pre-installed sliding sleeves and when setting wireline plugs in nipples. These issues were due to scale or corrosion, so the pre-installation method needs a good reservoir behavior.

To achieve the main purpose of enhancing the productivity with lower cost while considering all the limitations of the initial completion and the reservoir condition, the monobore completion was approved to be a standard design in the Statfjord field after it was successfully applied for the first time in 1989. Figure 2.4 shows the monobore completion design in Statfjord.

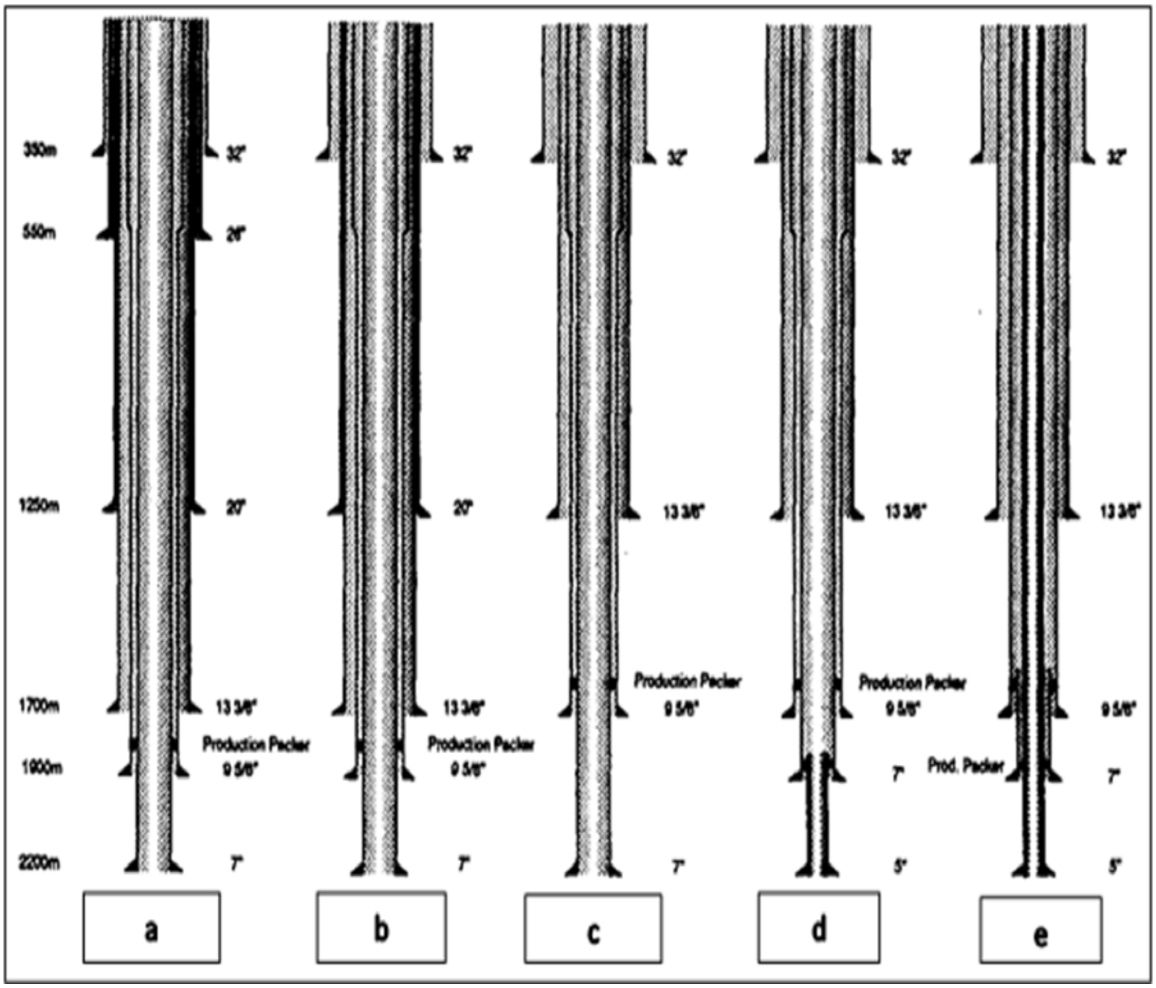

Figure 2.2. The improvement of the casing design in Gulfaks field. (O. Skogseth 1995)

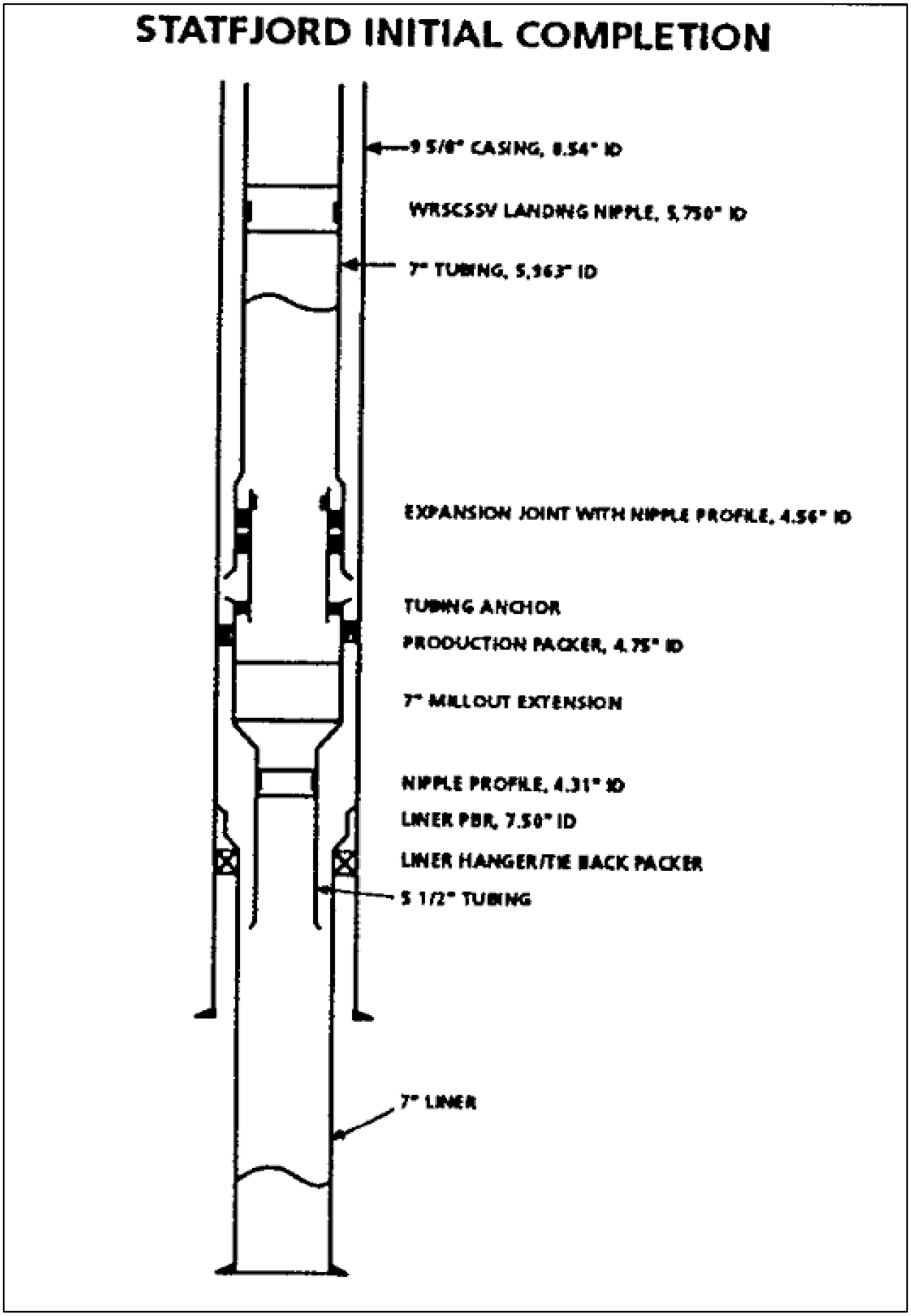

Figure 2.3. Conventional completion design in Ststfjord field. (P. Kostol 1993)

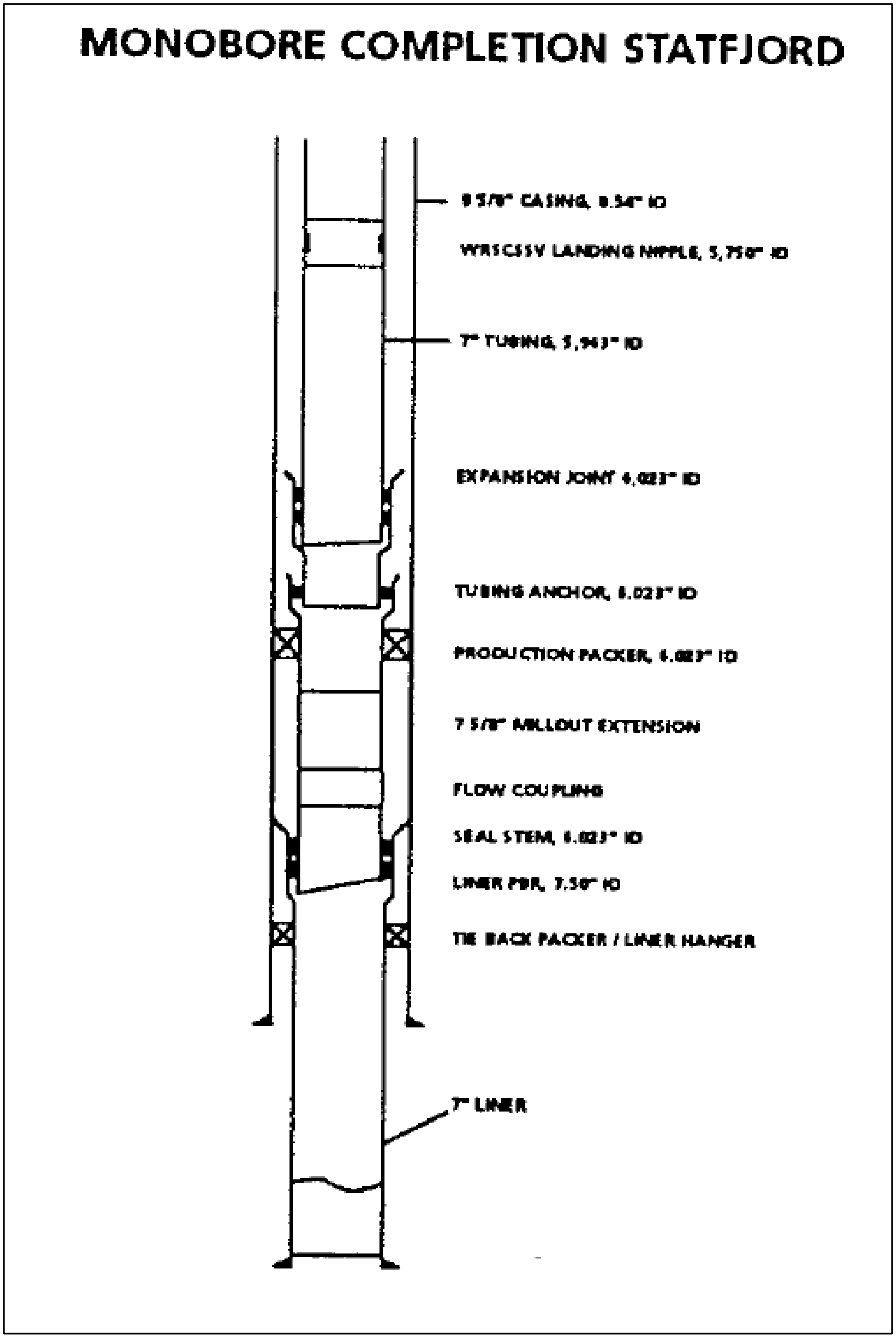

Figure 2.4. Monobore completion design in Ststfjord field. (P. Kostol 1993)

The South Australian Cooper and Eromanga Basin oil and gas fields are low permeability (<10mD) and low porosity (8-14%) sand stone multi-layered gas reservoirs. The wells were initially completed with 7 in. production casing and 2 7/8-in. production tubing (Figure 2.5). With the purpose of cost saving in completion and fracture stimulation treatment, the researchers in different disciplines improved the completion design to the monobore completion as a standard completion design by elimination the intermediate casing and ending with two string monobore design (Figure 2.6), which saved the cost by 10% compared with the conventional design.

In the mid-1990s in the Gulf of Thailand Bongkot offshore field, a big evolution in developing the completion design to monobore completion design using 3 ½-in. or 2 7/8-in. cemented production casing in a 6 1/8-in. hole (Figure 2.7). With this design, all further jobs could be done rigless, this design has dramatically reduced the well cost by almost 50% and increased the gas recoverable reserves on the field by 5% (M.J. Horn 1997). Figure 2.8 shows the significant reduction in time and cost by applying the monobore completion in the Gulf of Thailand, which would improve the oil and gas production.

Another case of adopting the monobore completion design is in An Aike-Barda Las Vegas field, Argentina. The wells were originally designed with a 13 3/8-in. surface, 9 5/8-in. and 7 in. casings, and completed with 4 ½-in. tubing. The operators reviewed some monobore completion designs for similar fields, and optimized the well completion design considering the cost and safe well intervention. The decision taken was reducing the diameter of each section and installing a 4 ½-in. monobore completion, which resulted in cost savings of 30% and reduction in the operation time.

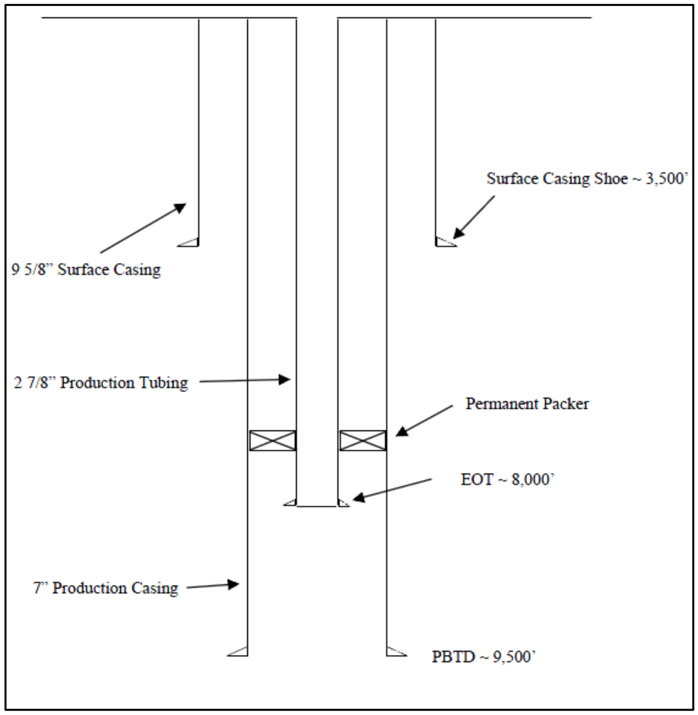

Figure 2.5. Conventional completion design in South Australia field. (M. S. Macfarlane 1998)

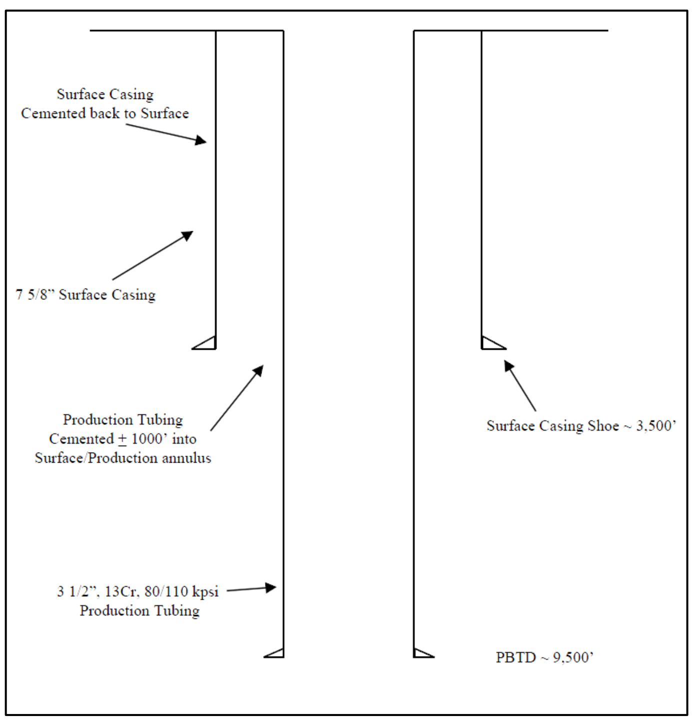

Figure 2.6. Monobore completion design in South Australia field. (M. S. Macfarlane 1998)

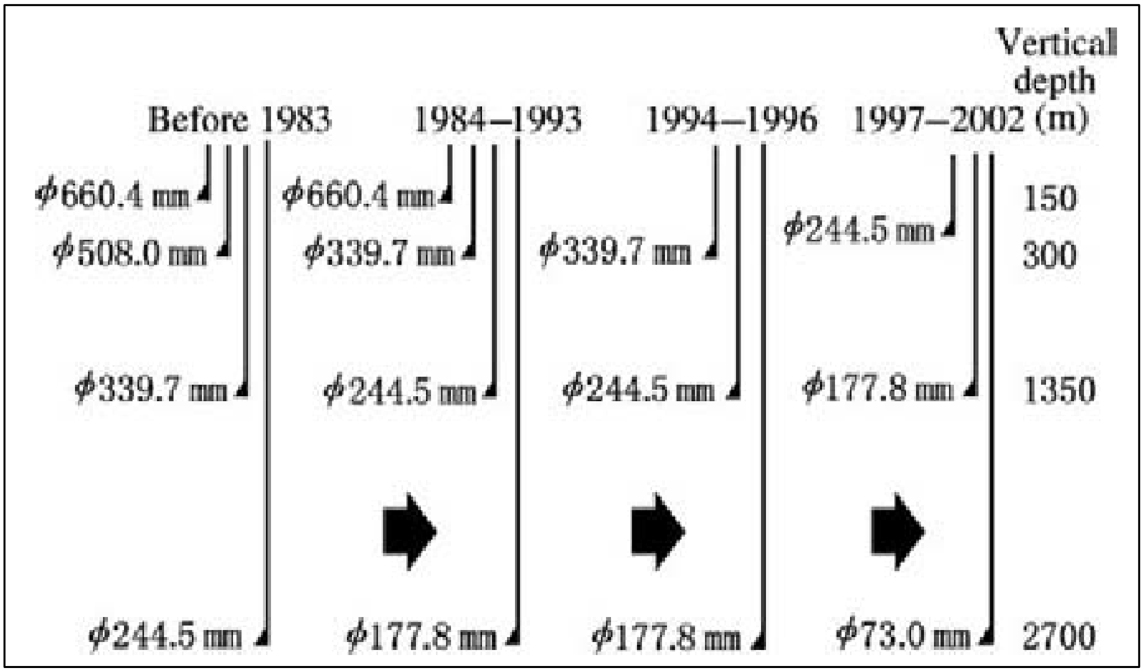

Figure 2.7. Well design improvement in the Gulf of Thailand. (Renpu, W. 2011)

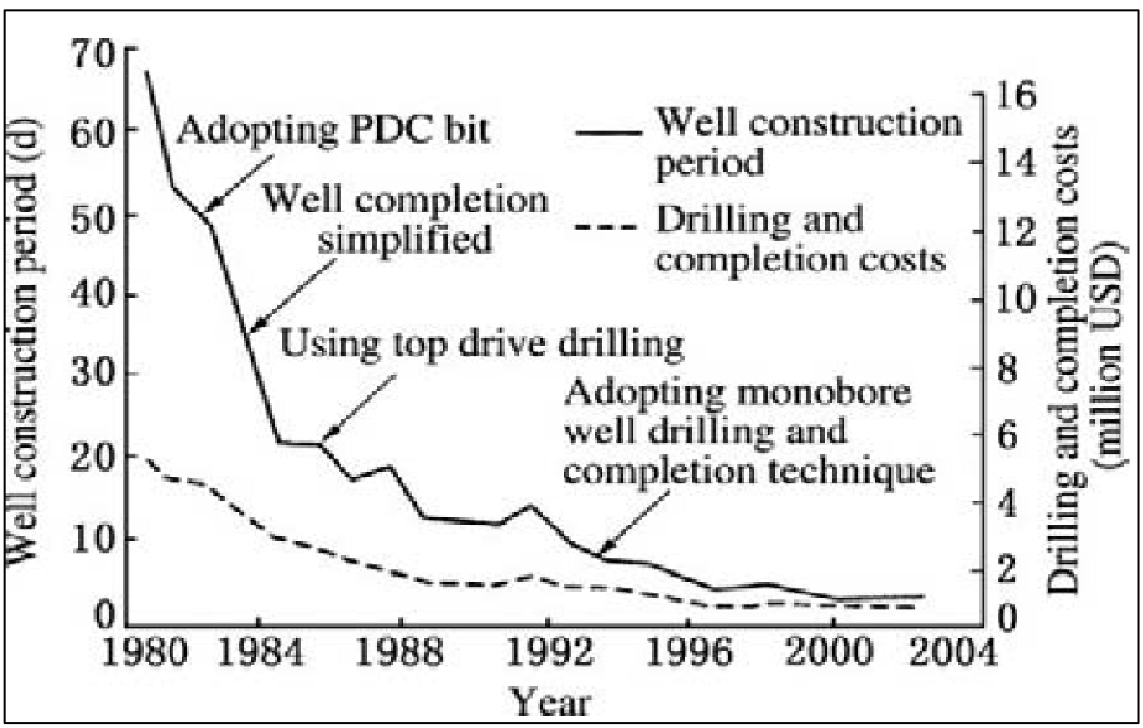

Figure 2.8. The operational improvements and the well construction period and cost in the Gulf of Thailand (1980-2004). (Renpu, W. 2011)

Since the late 1980s, the monobore completion design has succeeded in many oil and gas fields because it is a simple design that uses available materials. Nevertheless, the monobore design does pose challenges in terms of designing downhole components because the smaller diameter clearance means that conventional subsurface flow-control devices cannot be implemented in monobore wells without impacting other required downhole functions. Thus, researchers have improved the completion equipment and some accessories such as the wireline set retrievable straddle tools, and wireline set retrievable bridge plugs. These tools are effective in isolating and securing the lower zones in workover operations. Moreover, they assist in controlling the spills of fluids from undesirable zones and thief zones by simplifying the zone shutoff operation. The main advantages of these tools include being retrievable and cost-effective. Figure 2.9 shows the typical monobore completion with the tools. Another example is the landing nipple/lock mandrel configuration that has been reconfigured to create a nipple-less lock system that can operate anywhere in the tubing, can be set and retrieved through standard slick-line procedures, and can withstand pressure reversals operating in a high-pressure environment. In monobore completion, a landing profile is utilized for flow control devices such as SCSSV and SSD to have a full-bore access, as the landing profile does not inhibit inner diameter.

Monobore completion can often, though not always, mitigate the asphaltene deposition problem during the lifetime of a well operation. Known by the generic term of SARA (saturated hydrocarbons, aromatics, resins and asphaltenes), these deposits usually occur downstream of a choke during the early field life and along the entire well length with a downward moving window at a later stage till the deposition point reaches the reservoir and poses a serious challenge to the continued operation. As a result, conventional operations try to avoid restrictions such as nipple profiles or safety valves (especially the wireline retrievable type) in the asphaltene deposition window. Mechanical removal of these deposits is much easier in a monobore design due to the ability of the well interventions, especially if a nipple profile is not used at all. (Bellarby 2009)

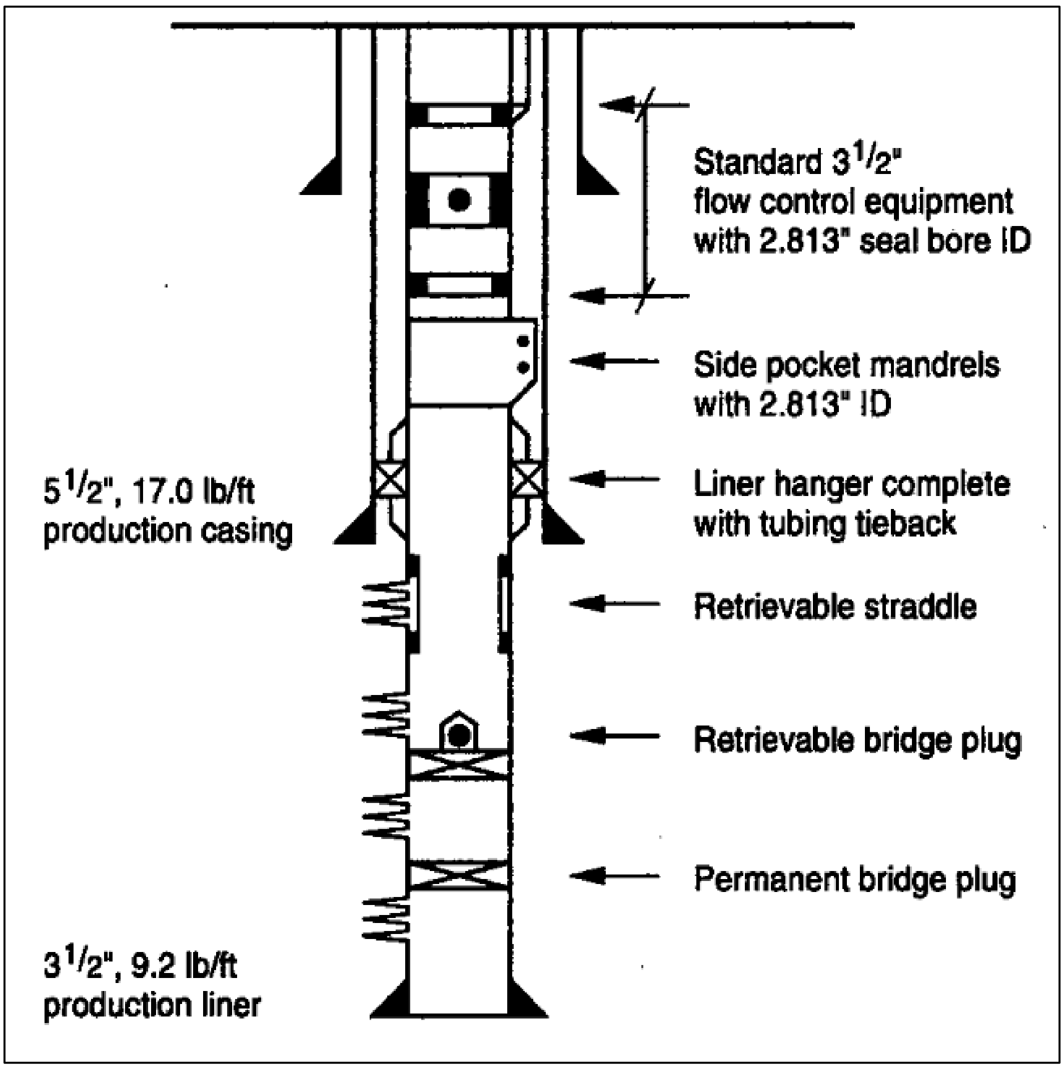

Figure 2.9. Typical 3 ½-in. monobore completion. (B.R. Ross 1992)

2.2. MAJOR CLASSIFICATIONS OF MONOBORE COMPLETION

Many early monobore completions employed smaller tubing diameters (< 4 in.) compared to the tubing sizes discussed in the preceding section. Some of these design changes were driven by reservoir depletion and coupled with slimhole drilling programs. Alternatively, some monobore completions retained the use of larger tubing sizes even as large as 9 5/8-in., particularly in high-flow volume gas fields such as the Arun gas field, Sumatra and at Statfjord field, North Sea (Kostol and Rasmussen 635, 1993). In these cases the larger tubing diameters allow operators to accelerate recovery. In this study, completions with tubing sizes greater than 6 5/8-in are referred to as "big bore" monobore completions. The following are details of each monobore design with the benefits and limitations including some field cases.

2.2.1. Slim-Hole Monobore Completion. After the great success in implementing slimhole drilling with a hole size less than 6 ¼-in. diameter, which associated with an optimal economic and operational impact, in the late 1980s the operators strove to apply a fit to purpose slim monobore completion to overcome some production limitations and maximize the full potential in addition to enhancing the well life in less expense. Experts from different disciplines decided to select a 3 ½-in. slim monobore completion size as a base case for low-pressure, low-temperature wells due to design simplicity and the availabilities of the completion equipment. The vast majority of the production wells are fitted with this design mainly the wells that produce below 3000-5000 bopd in oil wells or less than 50 MMSCF/d in gas wells. Furthermore, 3 ½-in. completion size can be run in a 4 ½-in., 5 in. or 5 ½-in. production casing and the liner can fit in a 4 1/8-in. or 4 ¾-in. slim hole. While some of the completion equipment is available for the slim monobore design, a number of challenges faced the equipment designers since the traditional components were not convenient with the slim monobore design criteria. Developing the downhole equipment and applying proper technologies helped in adopting the majority of the wells toward the slim monobore completion with a great degree of confidence.

Slim monobore completion has been successfully applied in Duyong Field, Offshore Peninsular Malaysia, in an attempt to deepen one of the wells to the new high-pressure tapis sand reservoir after the depletion of the shallower sand reservoir. Many challenges were faced due to severe gas migration through the opened channels, which affect the shallow unconsolidated sandy layers also the obstruction of the shale formation above the interesting zone. After several studies and based on engineering planning, a 3 ½-in. monobore completion was the best option to fill all the operational gaps, such as water cut and comingled production from upper zones. Furthermore, it has the benefits of easier future penetration, remedial operation, and minimizing the cost. (Mohammad, and Maung, 2000)

Oil and gas wells in the offshore North West Java (ONWJ) Field in Indonesia is another example of successfully applying slim monobore completion. The wells were completed in 3 ½-in. or 2 7/8-in. monobore completion with many advantages, such as reduction in cost, simplicity in workover, and well intervention operations. However, the operators have noticed some limitation in applying slim monobore completions. Most of the problems in the slim monobore completions were due to cement stringers and gun debris. Cement debris was caused by poor cement displacement, which was enhanced by installing T-line valves before cementing the heads to remove the cement slurry left behind the plug, and pumping sugar water after the wiper plug to elongate the setting time of the cement that passes through the wiper plugs during displacement. Gun debris is one of the critical problems in slim monobore completion, to avoid this issue, a hollow carrier type gun was preferred over the usual expendable gun. Thus, the type of perforating gun is a crucial thing to consider while designing the slim monobore completion. The well production in this completion type has no difference from the conventional wells.

The slim monobore completion design may not be applicable in highly productive wells. Therefore, the design was developed and improved to cater many reservoirs and well criteria.

2.2.2. Big-Hole Monobore Completion. In the early 1990s, many operators agreed to use big monobore completions as a profitable design; this design was beneficial for highly productive reservoirs since it eliminated the gas turbulence areas and facilitated the using of technologies that reduced the wellbore restrictions and the associated risks. All the mentioned benefits are saving the costs and improving the net present value of overall project economics.

Big monobore completion is applicable in deep-water, horizontal, extended reach, HPHT, cemented liners, or gravel packed/sand control wells.

Many projects in the North Sea have proved the success of big monobore completion when using 7 in. or even 9 5/8-in. tubing and tree instead of 5 ½-in., which increases the production while decreasing the total cost. The net present value of the project is increased when using a tubing with a larger ID, which enabled the reservoir depletion two years earlier than a 5 ½-in. completion and just over one year earlier than a

7-in. completion. Most of the large-bore completions were with 7 in. or 7 5/8-in. tubular. However, 9 5/8-in. completions were used since the 1990s in the gas fields in Western Europe and Indonesia.

Qatar's offshore Khuff formation is one of the best examples of optimized big monobore completion. It is rated as the largest single accumulation of natural gas in the world with an estimated reserve of 504 TCF. The conventional design was a 5 ½-in. x 5 in. production tubing with a production rate of around 50 MMscf/day (Figure 2.10) in the early 1990's then the design was developed to be 7 in. monobore completion with a production rate of 90 MMscf/day (Figure 2.11). The most recent design is the optimized big monobore completion using 9 5/8 by 7 5/8 by 7 in. resulted in production rate of 150 MMscf/day (Figure 2.12). Based on study was made by Khosravanian, R and Wood, D., 2016 to compare 7 in. monobore, 9 5/8-in. big-bore monobore, and 9 5/8 by 7 5/8 by 7 in. optimized big-bore completions and their effect on high-rate gas wells, optimized big-bore completion has the highest production rate and the lowest risk. (Khosravanian, and Wood, 2016).

Another case where improvements in the big monobore design have successfully reduced operational time is the South Pars, a large deposit in the Arabian Gulf. It has an existing high production rate of 80 MMscf /day, and engineers had already utilized monobore completion with 7 in. tubing and cemented liners so that downhole corrosion of equipment was avoided in the absence of diameter restriction. However, because of reliability and pressure container concerns, the completion sequence had three stages. The liners were run with cementing behind liners (Stage 1), the tie back production packer was tied using anchor latch and seal stem (Stage 2), and the completion string was run with a seal stem to complete the well (Stage 3). This procedure had several challenging aspects, such as possible mechanical damage to the upper stem during installation, lengthy and complex space out operation, and consequent well control issues. Some of these challenges were resolved by combining Stages 2 and 3, by replacing mechanical setting packers with hydraulic or hydrostatic set production packers, and by combining the packer run with the upper seal stem/mechanical run so that the seal stem received additional protection during the installation phase. This was achieved in several steps that involved reducing sources of error in the conventional monobore process and increasing the accuracy of space out. The downhole equipment manufacturer used shear pins to design a new seal stem mechanism inside the liner hanger polished bore receptacle (PBR). This innovation resulted in a saving of 1.5 rig days in a highly deviated wells, yielding a cost-cutting of more than $200,000 for each well. (Ghayoomi et al. 2012)

2.3. DEVELOPMENT AND INNOVATIONS IN MONOBORE COMPLETION

More recently, several new developments in monobore completion technology have been achieved.

2.3.1. Openhole Multistage Completion (OHMS). An openhole multistage completion refers to the well completions commonly used in developing unconventional oil and gas plays. The majority of these completions are made in horizontal laterals in North America, where many stages of hydraulic fracturing are applied with sleeve systems to produce from extremely tight shale plays (Figure 2.13). More recently, the multistage concept has been applied in HPHT carbonate reservoirs horizontal/deviated wells in the Middle East.

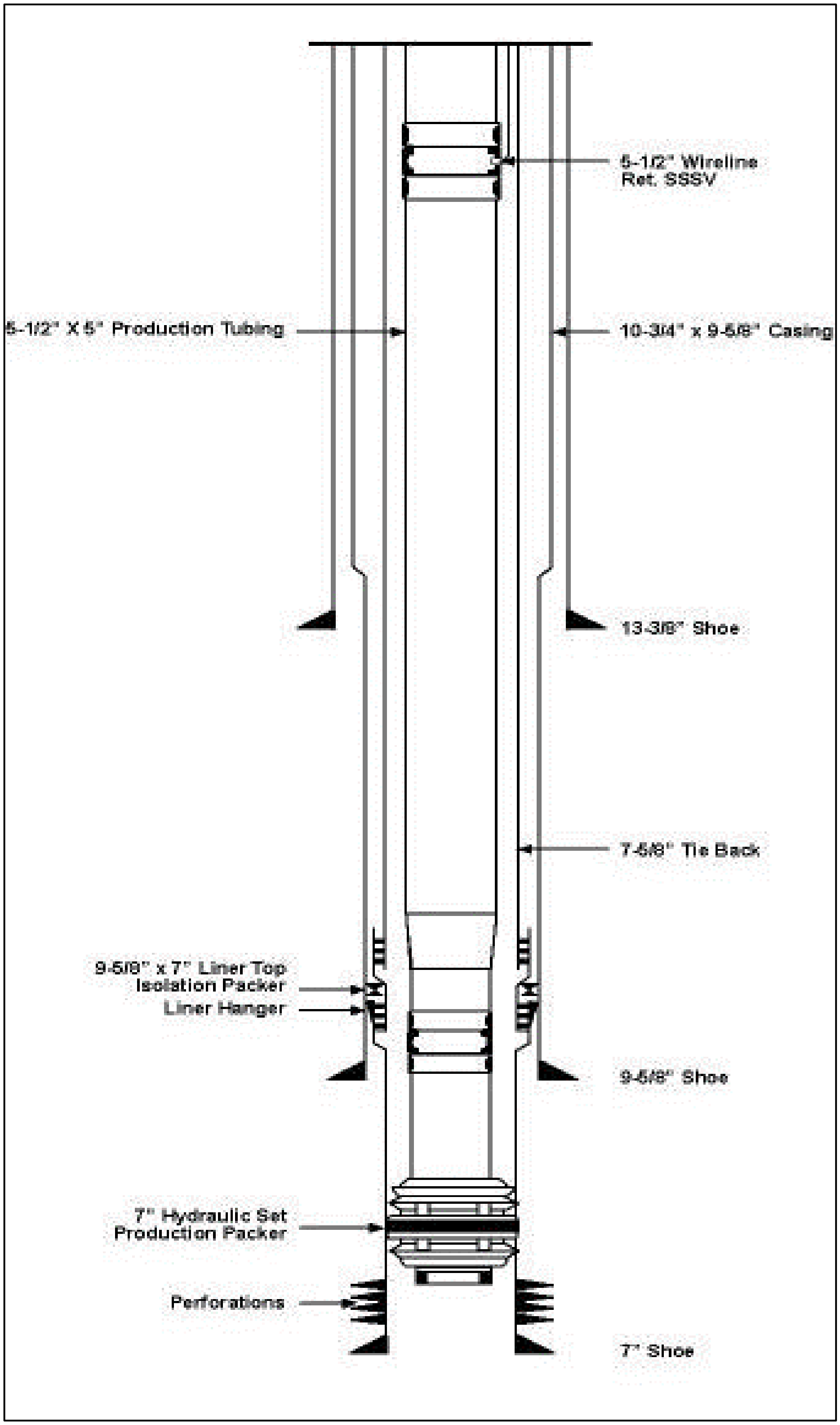

Figure 2.10. 5 ½-in. x 5 in. conventional completion (approx. 50 MMscf/day). (K. Almond 2002)

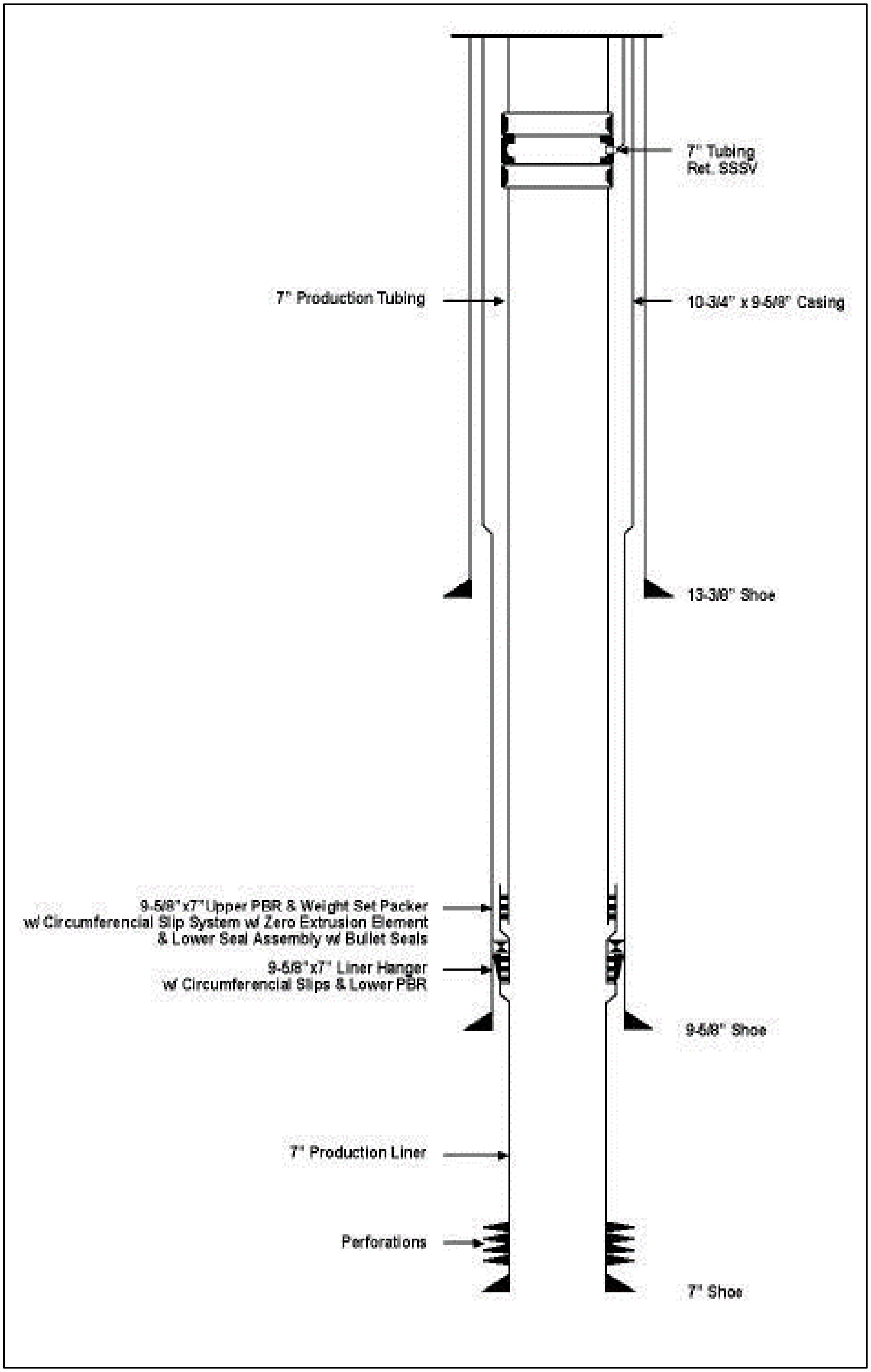

Figure 2.11. 7in. monobore (approx. 90 MMscf/day). (K. Almond 2002)

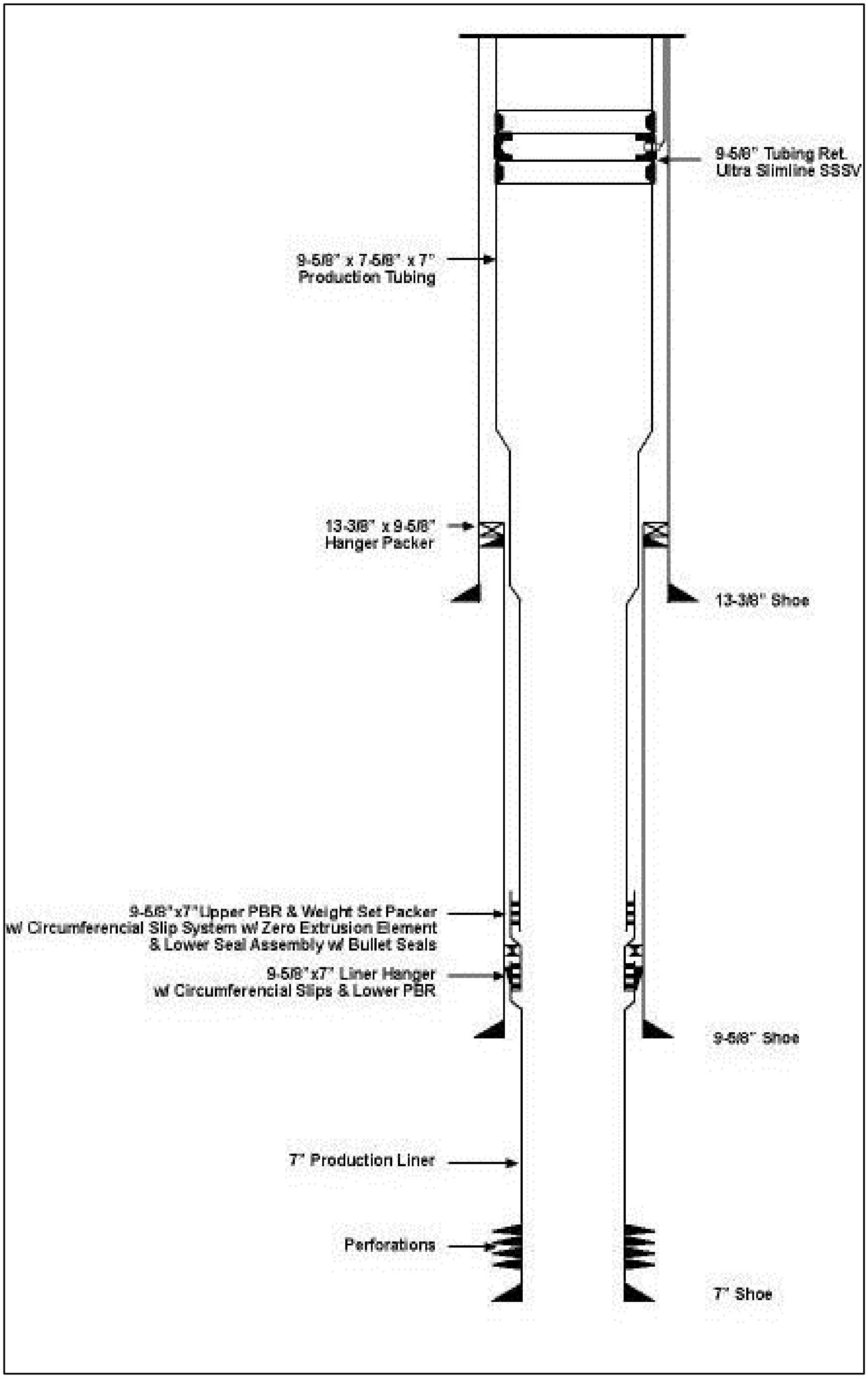

Figure 2.12. 9 5/8-in. x 7 5/8-in. x 7 in. big monobore (approx. 150 MMscf/day). (K. Almond 2002)

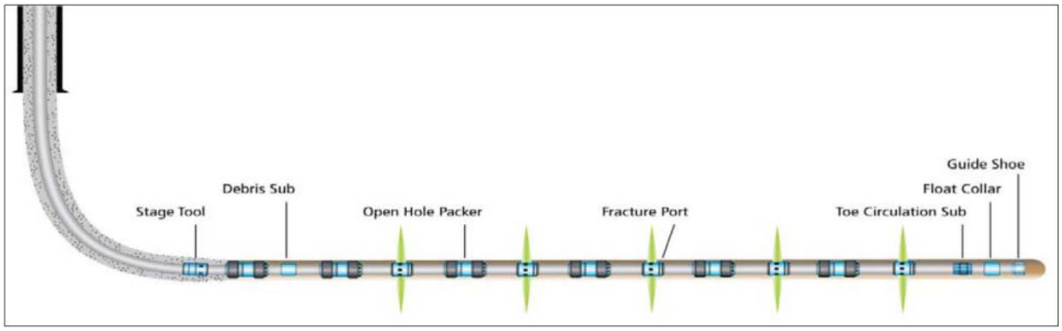

Figure 2.13. Openhole multistage completion.

Monobore completions have proven their feasibility in multistage completions and fracture wells. Utilizing a cemented back monobore completions with OHMS will optimize the operational time and cost by eliminating the intermediate casing and cement completion string from the horizontal section back to surface. Accordingly, the number of trips needed to install OHMS system will be minimized. The concept is to use a new stage tool after installing the liner and cement the buildup section of the wellbore back to the surface (Figure 2.14). The new mechanically closed cementing stage collar was designed to compensate the use of plug/dart to open/close the stages for isolation purpose. This design was successfully used in many shale formations in United States and Canada and in high pressure carbonate formations in Saudi Arabia.

Another reliable example of the monobore multistage completion is in Jurassic tight gas reservoirs in North Kuwait. Due to the variation in permeability layers, the reservoirs layers need to be stimulated selectively. A 4 ½-in. multistage ball activated completion and stimulation was the typical design that overcame the issues associated with stimulating within the highest permeable reservoir, and used instead of a 4 ½-in. cemented completion "plug and perf," which required a long process to selectively stimulate individual zones.

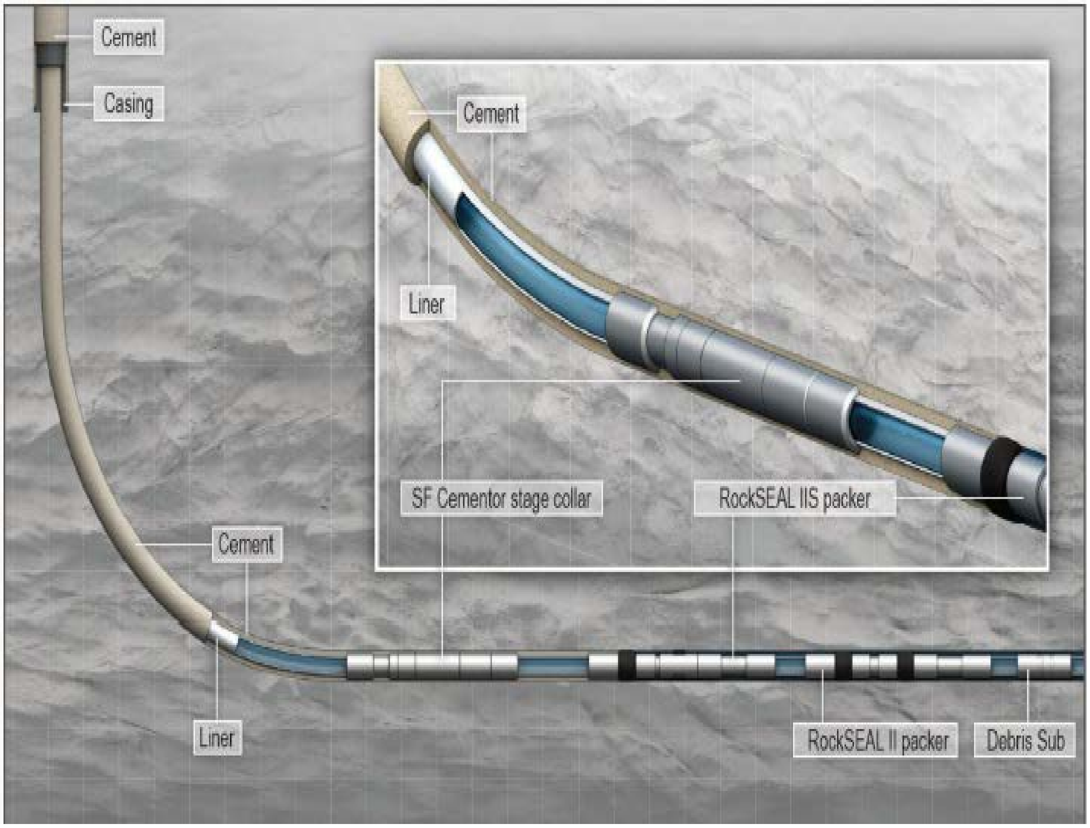

Figure 2.14. Principle of the cemented stage tool in an openhole multistage completion. (Siham, et al. 2015)

2.3.2. Monobore in Heavy-Oil Shallow Reservoirs. Randell, 2012 reported the implementation of newly designed near-vertical steamflood producers by Chevron at its Midway-Sunset (MWSS) near Bakersfield, and the use of lean six sigma techniques to identify non-value-added steps while converting its existing slotted liner well designs into monobore ones. The operational time for the drilling rig could be significantly lowered by replacing the two hole sizes and casing strings of the earlier slotted liner design with a single hole and casing string of the monobore design and this also reduced the wellbore delivery time since it was on the project critical path. While the author identified a number of conversion or elimination steps from the slotted liner to the monobore completion, the most salient ones are discussed briefly in Table 2.1.

The 5 ½-in. monobore casing combo string utilizes several design improvements and new components, such as a blank casing, a cross-over between the BTC casing and LTC tools, annular casing packer to create a hydraulic seal redundant cement basket, aluminum insert baffle plate, etc..This design is feasible for shallow, low-pressure, heavy-oil reservoirs. However, the design is not suitable for wells with subnormal pressures or unstable surface intervals and needs to cement the casing string before penetrating the reservoir. Furthermore, 5 ½-in. casing combo string in monobore well design cannot be sidetracked because of the minimum clearance requirements. (Randell, 2012).

2.3.3. Cemented Casing Monobore. Another interesting case study is the use of a full monobore 4 ½-in. completion at several unconventional gas plays that are being tested by Saudi Aramco. The target reservoirs involve tight sandstone from the Ordovician Era and are interbedded with shale and siltstone sections causing a contrast in the pore pressure and fracture gradients, and the tight sands require hydraulic fracturing in order to be accessed for the hydrocarbon potentials. A typical completion type for wells targeting tight sandstones so far has been to run and cement a 4 ½-in. liner across a 5 7/8-in. hole section, covering the target zone, hanging the liner from the previous casing with a liner hanger and a polished bore receptacle (PBR), tie-back the 4 ½-in. completion tubing seal assembly to the liner hanger polished bore receptacle, and make a 4 ½-in. full monobore completion.

Table 2.1. Differences in steps taken while converting from conventional slotted liner to new monobore completion by Chevron. (Randell 2012 adapted from Table 1, p. 2)

Slotted liner completion	**Monobore completion**
Drill 8¾-in. holes to casing point to approximate 1500 ft depth	Drill 7 7/8-in. holes to 1500 ft depth
Lay down 8 ¾-in. drilling assembly	Eliminated
Run and cement 7 in. production casing, change fluid system from surface mud to drill-in fluid	Eliminated
Drill 6 ¼-in. hole to Total Depth of 2000 ft	Continue 7 7/8-in. holes straight to 2000 ft depth
Lay down 6 ¼-in. drilling assembly and create 5 ½-in. liner with 2 3/8-in. tubing inner string	Lay down 7 7/8-in. drilling assembly and create 5 ½-in. monobore combination string with slotted casing, specialty tools, and blank casing
Set Steel-Seal Assembly (SSA) and displace inside of liner to breaker fluid	Inflate Annular Casing Packer (ACP) and pump cement
Lay down drill pipe and tubing inner-string, set and test Retrievable Bridge Plug (RBP)	Eliminated
Pick up 2 7/8-in. tubing and retrieve RBP, lay down tubing	Pick up drillout assembly, cleanout track, lay down tools
Proceed to completion	Proceed to completion

Aramco decided to test the new cemented casing monobore technology because it is a proven technique that can potentially reduce completion costs along with well delivery days without affecting safety and well integrity. Another factor was that cemented tubing completions have already been used successfully worldwide and are the preferred completion type for wells planned for high-pressure, high-rate hydraulic fractures stimulation because of the design’s lack of sources of weak points (leak areas). In the cemented completion concept, the operator runs the completion string and cements it straight into the 5 7/8-in. open hole after the well is drilled to cover the target reservoir. After performing all the required pressure tests, the rig is released to the next location; all the required testing and fracturing operations are then performed rigless. However, while undertaking the project the company was faced with several challenges related to the cementing operation, stimulation, and general business considerations. Challenges related to cementing operations included performing the cementing job with the restricted annular area, achieving cement column with enough height and compressive strength to contain the target formation, and the quality of annular completion fluid (leaving a frac-friendly completion fluid inside the string with a corrosion-free fluid in the annulus). Challenges related to well stimulation included withstanding the high axial loads during stimulation job due to a lack of ability to release the resulting stresses by tube movement and meeting the barrier policies at all times for well control compliance. Some of the challenges were addressed through process improvements and innovations, such as using cement heads linked directly to the casing instead of to the drill-pipe, landing the tubing hanger in the tubing spool, and sealing the annular space before starting the cementing stage. (Almasmoom et al. 2015)

2.3.4. Artificial Lift in Monobore Completion. Monobore completion is a reliable example for enhancing the well economic production, the potential for substantial success is the consideration of the well life by adding the appropriate equipment and applying a suitable design, which would help boost the production of the well. Specially designed cement-through components, including safety valves and gas lift (GL) equipment, are some of the most feasible components in enhancing the production in the monobore completions wells. The concept of the cement through system is to install entire completion with cement-friendly components (a safety valve, cement-through SPMs, hydrostatically closed circulating valve (HCCV), hydraulic packer, and landing collar/shoe track) into the wellbore, pump the cement in single-trip, clean, and test the components integrity. The purpose of the cement through single trip system is to complete the wells with a 3 to 5 year life expectancy in order to enhance the production and extend the life of the well by using a proven gas lift (GL) system, which brings economic benefits. This process will reduce the completion time from approximately 60 hr to an average of 17 hr per completion, which will significantly reduce the rig, manpower, and non-productive times. Figure 2.15 illustrates the cost comparison in each completion type.

This type of completion is successfully applied in many wells in the Gulf of Thailand, and it is proven to be the most preferred method of completion there. Also, this type is beneficially used in the water injector wells in the North Sea as an economical design that reduced four days from the rig time. Although this design is simple, there are a few things to consider, such as formation characteristics, cementing efficiency, and the potential longevity of the well.

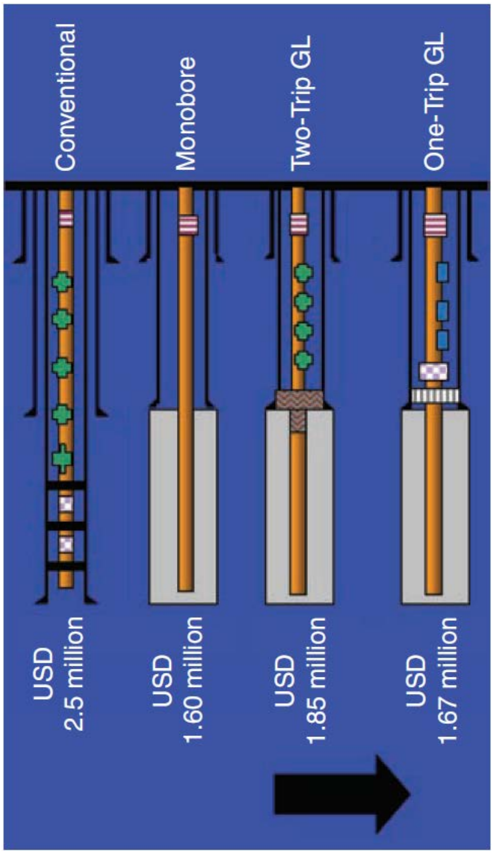

Figure 2.15. Completion types. (Don Ingvardsen 2009)

From the case studies and the preceding discussion, several benefits and drawbacks of monobore completion can be inferred. The benefits include lower cost and higher project profitability due to increased activity levels, as well as the ability to extend existing installations. Monobore also often lead to a reduced location size (particularly true for slimbore designs) and wastes, thereby reducing the environmental impact. Monobores are ideally suited to completions through several reservoirs where these are produced and abandoned from the bottom up or where production can be commingled. Sometimes the monobore design also increases wellbore stability, for example in fractured shales, and underbalanced coiled tubing drilling may create sidetracking opportunities from existing wells while minimizing impairment. On the other hand, well control may pose difficulties and require advanced equipment to deal with higher annular pressure drops and lower annular capacities, as well as better training of personnel. Commitment is required from operator management as well as service companies, and people with rich and varied experiences are often required to achieve a successful completion. Table 2.2 summarize the advantages and disadvantages of the monobore completion design.

Table 2.2. Advantages and disadvantages of monobore completion.

Advantages	**Disadvantages**
Allows a large production conduit, flexibility in diameter to produce more and longer.	Contingency string options may be limited
The number of specialist completion services can be significantly reduced, saving on well construction costs and logistical issues	Restrictions on maintenance & intervention operations
May eliminate one casing/liner string and reduce the size of the other strings which will result in a significant saving in wellhead equipment, mud, casing, cement and drill bit costs.	Installing completion components may not be possible
Cost saving	The specification and cost of the monobore production string may have to be higher than in the conventional well

3. LITERATURE REVIEW

Numerous case studies on monobore completion design have been published, to date more than 140 literatures were specifically discussed monobore completion design and compared it with the conventional completion design. The cases were diversified in onshore and offshore fields in different reservoir types and for different well conditions. In this section, 63 papers excluding the duplications were reviewed, classified, and summarized to specify the main points that need to be considered in monobore completion design, in addition to the advantages and disadvantages of the monobore completion design, and in what type of fields it is most applicable. These papers were grouped as the classification in Section 2.2 based on the completion size, also the cases with modifications and development in the monobore completion design are summarizes.

The purpose of this historical review and summary is to provide a record where the operators can refer to in case of completing new well or re-completing an existing well with monobore completion design, or development of an applied monobore completion design such as adding a new tool or changing the completion size.

3.1. SLIM-HOLE MONOBORE COMPLETION DESIGN

This type of monobore consider to be the earliest completion applied after the success of the slim-hole drilling, the slim-hole completion stated in slim-hole wells where the tubing diameter is less than 4 in. diameter. This type of completion was applied successfully in many fields with different reservoir types. However, it is not aplicable for wells with high production rate. Furthermore, the completion equipment size and the type of perforation guns used in the normal design need to be reconsidered to fit for slim-hole monobore completion design. Table 3.1 summerizes the field cases that applied the slim-hole monobore completion.

Table 3.1. Published papers in slim-hole monobore completion.

SPE Number - year	Subject	Field	Objective	Limitations
77943-2002	Slimhole Completion Experience in Java Sea, Indonesia: A Look Back on of the First 40 Slimhole Wells	Java Sea, Indonesia	To look back over the slim-hole monobore completion cases applied in the offshore Java field in Indonesia (3 ½-in. or 2 7/8-in.)	The most frequent problem is the cement obstruction in the liner section due to the weak cement displacement. Commonly in deep and deviated wells
63042-2000	Artificial Lift for Slim Holes	_	Compare the artificial lift methods and determine the best applicable for slim-hole completions	_
35664/ 57717-1996	The Use of Slimhole Drilling and Monobore Completions To Reduce Development Costs at the Kuparuk River Field	Kuparuk River Field, Alaskan Arctic, USA	Switched the normal 5 ½ casing and 3 ½-in. tubing completion to 3 ½-in. slim-hole monobore, and discuss field cases that successfully applied slim-hole monobore completion including critical cases as injector wells and compare the cost	Developments and innovations in completion, perforation, and cementing tools is required
OTC 7885-1995	New Subsurface Safety Valve Designs For Slimhole / Monobore Completions	_	Discuss the improvements of subsurface safety valve equipment (CNRF) to match the slim-hole monobore completion design and address the challenges while using the normal SSSV flapper "flat plate", "curved flappers", and "ball valve designs"	CNRF designed to overcome the limitations in the conventional SSSV equipment, it combined the best features from the flapper and ball valve.
OTC 7551-1994	Monobore Completions for Slimhole Wells	Many oil and Gas fields	Discuss the enhancements of the completion equipment to fit the slim-hole monobore completion	Challenges faced due to small size diameter and reconsidering the design of the new equipment
27601/ 29217-1994	Monobore Completions for Slimhole Wells	Many oil and gas fields	Overview on the suitable completion equipment used in slim-hole monobore completion and enhancement of some tools to boost the production and eliminate restrictions	Challenges faced due to small size diameter and reconsidering the design of the new equipment
7330- 1993	Nippleless Completion System for Slimhole/ Monobore Wells	offshore North Sea	Implementation of nippleless monobore completion to eliminate the wellbore restrictions using production bridge plug, retrievable slimhole straddle system, and disappearing plug	More developments for the equipment to minimize the hole restrictions
24981-1992	Innovative Slim-Hole Completions	Many fields included	The applications and limitations of slim-hole monobore completion (3 ½-in.). Evaluate the inflow performance as a function of wellbore diameter, slim-hole monobore completion has minimal impact on the inflow performance	Completion tools and equipment need to be redesigned to fit the slim-hole monobore completion design (3 ½-in. or 2 7/8-in.)
24965-1992	An Evolutionary Approach to Slim-Hole	Many offshore and onshore fields	To review slimhole drilling and completion system development in many fields by Shell	Completion tools and equipment need to be developed to fit 3 1/2 –in. slim-hole monobore completion

3.2. BIG-HOLE MONOBORE COMPLETION DESIGN

This type of monobore completion represents wells completed with 6 5/8-in. OD tubing and larger, it can reach 9 5/8-in. in some cases. The larg-bore monobore completion mostly applied in offshore fields with high production rate mainly for gas producer wells. The key benefits of the big-hole monobore completion are:

- Give a full access for the tubing and the production liner, which would facilitate the perforation and stimulation.
- Eliminate the restrictions on service and intervention tools, no restrictions on production as well.
- Maximize the production rate.
- Eliminate the gas turbulence areas.
- Minimize the completion equipment accessories.

Table 3.2 summerize the field cases that applied the big-hole monobore completion.

3.3. DEVELOPMENT AND INNOVATIONS IN MONOBORE COMPLETION

Further developments and advanced opomization were applied in the existing monobore completions, the operators did some upgrads in the existing designs. In this section, Table 3.3 summerizes several cases in different domains. The cases include adding artificial lift to enhance the production, applying cemented monobore completion by installing the production casing in the open hole and cement it without the need of the liner, improving multistage perforation and stimulation operations using the monobore completion design in openhole multistage well type, and solving complicated reservoir condition.

Table 3.2. Published papers in big-hole monobore completion.

SPE Number - year	Subject	Field	Objective	Limitations
105509-2007	Design, Construction, and Optimization of Big-Bore Gas Wells in a Giant Offshore Field	Giant Offshore Field, Qatar	Optimize the previous 7 in. monobore and 9 5/8-in. big-bore monobore completions, using 9 5/8 by 7 5/8 by 7 in. tubing (7 in. tubing installed in the reservoir section), and compare the three designs	*Need to increase the diameter of each hole and casing string. *increase number of days to 6 days comparing with 7 in. monobore completion
77519-2002	Improving Production Results in Monobore, Deepwater and Extended Reach Wells	North Sea, offshore Mexico, East Coast of Canada, western Europe, Indonesia, Qatar	Study and analyze the field applications of big-bore monobore completion design over 20 year (more than 350 cases) to determine the best practices and assist the operators to apply the best design for their case	Challenge of the well control due to high production rate was mitigated by advancing the subsurface equipment
68217-2001	Considerations for the Design, Development, and Testing of an Integrated Large Monobore Completion System to Facilitate High-Rate Production	Western Europe & Arun field, Indonesia	The development of 9 5/8-in. big-bore monobore completion design and improvement of the component used	Avoid the limitations by improving the component to manage the risk from the high rate production
OTC-11880/ 64279-2000	Development of a Large-Bore Monobore Completion System for Gas Production	High rate Gas Reservoir (Indonesia & Qatar)	The advantages of development the 9 5/8-in. big-hole monobore completion in gas wells. Production rate and cost analysis of different sizes of monobore completion (5 ½-in., 7-in. & 9 5/8-in.)	Limitations were addressed in development of some components to withstand the high production rate (wellhead plug and back pressure valve, TRSV, High Load Permanent Packer, Disappearing Plug, TRBP, & Liner Hanger)
29429-1995	Cost Effective Design Change in the Drilling Program for the Gullfaks Field	Gullfaks Field, North Sea	Discuss the implementation of 7 in. monobore completion design and 3 other alternatives with eliminating one and two intermediate strings.	The alternative designs mitigated the effects on safety, environment, economy, production, and lifecycle time
28559-1994	Completion and Workover of Horizontal and Extended-Reach Wells in the Statfjord Field	Statfjord Field, North Sea	Development of Statfjord field, successfully used the 7 in. monobore completion in horizontal and extended reach wells.	Challenges in the wells profile, torque and drag, inserting the equipment, and sand control
OTC 7328-1993	Arun Indonesia: Big Bore Completion Tool Design	Arun Gas Field, Indonesia	To discuss the planning of the first big-hole monobore completion in Arun field, and its benefit in boost the production.	*Reduce the capabilities of directional drilling. *require a higher torque, drag and pump capacities. *High Volume of drill cuttings.
OTC 7327-1993	Optimized Well Completion Design in the Statfjord Field, North Sea	Statfjord Field, North Sea	To review the limitations of the original completion (5 ½ tubing x 7-in.liner) , and discuss the improvements in the monobore completion design by applying 9 5/8-in. big-bore monobore completion in deviated, horizontal and extended reach wells	Limitations in using the conventional completion equipment that restrict the operations and production. SSSV, and other flow control components need to be modified to withstand the high flowrate

Table 3.3. Published papers in development of monobore completion.

SPE Number - year	Subject	Field	Objective	Limitations
187591-2017	Successful Installation of 1st 15K Multistage Completion System in North Kuwait Gas Well	Kuwait	Switch the conventional completion 5-in. cemented liner and 3 ½-in. tubing with 4 ½-in. monobore completion to enable the selective stimulation and perforation	Consider the hole cleaning, using heavy oil base mud
187580-2017	First Successful Multistage Completion Paves the Way for Optimized Field Development of the Jurassic Formations of North Kuwait	Kuwait	To develop the completion from plug and perf to 4 1/2" openhole multi-stage monobore completion to stimulate different zones with high permeability contrast, the result was enhance production and lower the cost	Deep sour HPHT wells
184805-2017	Novel Technique Applied to Lock Open SCSSV Installed in Monobore Subsea Completion in Deepwater GOM	Gulf of Mexico (GOM)	Installation of through-tubing expandable hanger assembly in the tubing pup joint above the SCSSV using wireline for locking open SCSSV without the landing nipple profile in the monobore completion	Remediation if improperly set would be difficult.
178867-2016	Utilizing Short Bit-to-Bend Motor Technology Enables Monobore Wells to be Drilled in the Niobrara Unconventional Shale Play with a Single Drilling Assembly	Niobrara shale play	Using Positive Displacement Motor (PDM) with short bit-to-bend technology to drill monobore horizontal well in one run and compare it to conventional well design wrt build-up rate, ROP, and number of days	Consider the drilling fluid while changing formations, consider the RPM in the buildup section
178675-2015	Cemented-Back Monobore Reduces Well Cost and Frac Time in the Wolfcamp	Wolfcamp Shale in Permian Basin, USA	Cemented-back monobore completion enhance hydraulic fracture for 38-stage system in open hole multi-stage horizontal well	Specially designed stage collar need to be used for cemented-back method
178114-2015	Case History: Largest Hydraulic Fracturing Jobs of India in KG Basin and Successful Production Test with Underbalanced Slim Hole Selective Completion in HPHT Environment	India	Develop the completion of the wells in HPHT low permeable reservoir from 7-in. liner then reduced to 4 ½-in monobore to reach 2 7/8-in. production tubing slim-hole selective completion as a best option to enable the high load hydraulic fracture	Small clearance of 2 7/8-in tubing
177977-2015	A New Completion Approach in Saudi Aramco for Unconventional Gas Wells Using Full Monobore 4 1/2" Cemented Casing Completion	Saudi Aramco	Applying of cemented casing completion in a tight gas reservoir to reduce the cost and time of running a liner	Challenges in performing the cement, in stimulation where the cement has to withstand the high loads from stimulation job, and economical challenges in case of cement failure

Table 3.3. Published papers in development of monobore completion (cont.).

177208-2015	Well Completion with Monobore Technology for Gas Production in the B6 LL 370 Reservoir in the Tia Juana Field, Lake Maracaibo, Venezuela	Tia Juana Field, Lake Maracaibo, Venezuela	5 ½-in. monobore completion was applied to replace 7-in. production CSG and 2 3/8, 2 7/8or 3 ½-in. tubing conventional design, the result was increasing in production rate with less fluid loading, higher perforation efficiency and decreasing of cost and time.	–
174955-2015	Comparing Openhole Packer Systems with Cemented Liner Completions in the Northern Montney Gas Resource Play: Results From Microseismic Monitoring and Production	British Columbia, Canada	Compare openhole multi-stage with cemented liner completions, the study performed for monobore wells.	–
175384-2015	Unique Application of a Cementing Stage Tool with an Open Hole Multistage Completion System in Saudi Arabia	Saudi Aramco	Redesign the cementing stage tool to be second contingency closure tool to facilitate the cementing and stimulation without restrictions	Overcome the challenges with previous stage tools
171585-2014	Reducing Cost and Risk with Cemented-Back Monobore Well Construction in the Cardium Formation	Cardium formation of central Alberta, Canada	Cement-back wellbore from heel to the surface using mechanically operated cementing stage tool, to isolate vertical section while fracturing horizontal OHMS section	100% success
170489-2014	First Achievement Using Water Shutoff Polymer in Monobore Well Completion, Gulf of Thailand	Gulf of Thailand	Utilizing a water shutoff polymer technique to isolate the water producing zone in monobore well completion without using mechanical sealing. The result was 50% decreasing in water production and it is successfully applied for long term water shutoff	Consider the gelation time where 20% safety factor added to ensure that the gel sets properly
170476-2014	An Innovative Approach to Cementation of Monobore Completion Tubing to Maximize Access to the Bottom Most Reservoirs	Tunu field, Indonesia	Develop the cement job in monobore well completion by utilizing a specially designed calibration plug with proper burst disc pressure rating, to determine the cement displacement volume prior the cement job by monitoring the pressure spikes on the rig floor	Successfully applied in cementation of completion strings in many wells where the reservoir targets close to the tubing shoe
168187-2014	Perforating Monobore Completions Offshore: An Efficient, Safe and Optimal Approach	Gulf of Thailand, Australia, and Indonesia	Optimization of perforation methods in monobore wells and utilization of Dynamic Underbalance method (DUB) considering the economic, technical, and safety aspects. The result was reduction in time and boost the production by 40%	The result may be different depending on the formation characterization
166450-2013	Reducing Drilling Costs Through the Successful Implementation of a One-Run Monobore Well Strategy	Western Canada	Switch the completion of the horizontal wells to monobore completion in one run process using special designed BHA and drill bit	Consider the directional well plan and the new designed bit
163887-2013	Restoring Monobore Well Life with Novel Coiled Tubing Gas Lift Dip Tube in a Highly Corrosive Environment	Gulf of Thailand	Using a high chromium steel coil tubing gas lift (corrosion resistive) in slim-hole monobore completion	Consider the well control by increasing the number of barriers while installing the gas lift string (3 barriers from quad BOP and a shear-seal ram which makes 5 hydraulic rams and killing fluid barrier)
OTC 23628-2012	Case Study: Optimization in Intervention Monobore Design in Completing Horizontal Gas Producing Wells in Malaysia	Malaysia	Applying of new technologies such as tubing hanger profile, fluid-loss device, and glass reinforced epoxy (GRE) in large-bore 7-in. monobore completion	Minimal reduction in production while using GRE. It's a big challenge to be the first field applying GRE technology
161947-2012	A Break Through In Monobore Completion System by Using New Design "One Run" Upper Completion System	South Pars gas field, Iran	Combination of two runs (running the Tie Back production packer with PBR and running completion string with upper seal stem) while installing the monobore completion to avoid seals damage and well control issues	Minor concerns due to highly deviated wells

Table 3.3. Published papers in development of monobore completion (cont.).

155095-2012	Comparison of Production Results from Open Hole and Cemented Multistage Completions in the Marcellus Shale	Marcellus Shale, USA	Apply the monobore technique in open hole multi-stage horizontal well by cement back the upper part of the lower completion to facilitate multi-stage stimulation and compare it with plug'n perf technique	Cleanout run in some of the wells couldn't reach the TD and needs more reamer trip
154145-2012	Technology Challenges and Emerging Solutions	North America	Implementing monobore system with one size ball to replace cased and cemented plug and perf system to enhance the multi-zone fracture	Beneficial for multi-stage fracture
154013-2012	Monobore Well Design: Utilizing Technology to Improve Well Execution Efficiency	Midway-Sunset field & Cymric field, Central California, USA	Convert slotted liner completion to monobore completion in steam flood heavy oil producer well, in order to eliminate non-value-added steps	This design is not suitable for wells with subnormal pressured or unstable surface intervals and needs to cement the casing string before penetrating the reservoir- can't be sidetracked
15267-2012	Developing a Stage Tool for Cemented Back Monobore Completions with Open Hole Multi-Stage Systems in the Montney	Montney play in northeastern British Columbia, Canada	Use special stage collar to cement back the wellbore in OHMS completion after installing the liner, the stage collar designed to work without the need of plug-dart. This technique enables installing the frac string in one trip	Consider the strength of formations overlaying the target formation to withstand the mud while drilling the horizontal section
14255-2012	Monobore Solid Expandable Liners – Redesigning Wells for a More Economical and Operational Benefit	Gulf of Mexico, offshore West Africa, the Middle East, Asia Pacific, Australia, Brazil, and the North Sea	Innovation of monobore solid expandable liner enables the operator to increase the efficiency and minimize the risks while drilling hard formations without reducing the ID	Applied successfully in many fields
147903-2011	Developing Oil in Monobore Well Completion Using Permanent Coil Tubing Gas Lift Application	East Kalimantan, Indonesia	Innovation of Permanent Coil Tubing Gas Lift (PCTGL) in monobore completion wells to enable running gas lift system without needing the rig and enhance the oil production	–
144970-2011	Dare to CHOP: Resources Development Cost Holistic Optimization	Malaysia	Applying a monobore well completions as an economic way to develop marginal fields in Malaysia, and change the design and production strategy such as using ICD & ICV for enhance commingle production from multi-layer reservoirs to produce economically	Continuous examination and improvement in yearly basis
128394-2010	Monobore Design Optimises Slimhole Raageshwari Deep Gas Development	India	Slim hole monobore completion (3 ½ or 4 ½-in.) was successfully applied to switch 5 ½ or 7- in. liner completion in deep tight gas reservoir with multi-stage hydraulic fracture , the result was long term producing and lowering the cost	–
124797-2009	Monobore Completion System Provides Low-Cost Completion Option	Gulf of Thailand & North Sea	Enhance monobore completion system in short life wells by adding specially designed cement-through components, including safety valves and gas lift. This technology can be applied in producer and injector wells	Considering the formation characteristics, the integrity of cement, and the well life.
121548-2009	Innovative Retrievable Lock Mandrel Extends Monobore-Completion Potential	Indonesia	Optimize the sealing elements in the bridge plugs by using mechanical expandable sealing ring with different materials than rubber (Kinematic Seal) to replace the conventional rubber sealing in monobore well completion	Successfully applied in many wells in harsh environment

Table 3.3. Published papers in development of monobore completion (cont.).

113315-2008	Using Monobore Systems to Lower Completion Costs in Short-Life Wells	offshore wells (Gulf of Thailand-North Sea-Barnett Shale, Texas)	Improvement of monobore completion in short life wells to support the use of artificial lift system. (Disposable monobore completion, cement through completion system, monobore injector wells, and gas well unloading)	Considering the well life and the economical side.
OTC 19008-2007	Mitigating Subsalt Rubble Zones Using High-Collapse, Cost-Effective Solid Expandable Monobore Systems	Gulf of Mexico, offshore West Africa, the Middle East, and the North Sea	Development of the monobore solid expandable liner with over twice collapse than the conventional without reduction in hole size to overcome the challenges while drilling the salt formations	Applied successfully in many fields
107433-2007	New Approach To Ensure Long-Term Zonal Isolation for Land Gas Wells Using Monobore Cemented Completion	Netherlands	Implementing a cemented monobore completion method where the tubing is cemented in place to reduce the time and the cost of running the liner and its accessories. 3 cases success using 3 ½-in. and 5-in. tubing	Analyze and simulate the cement behavior and zonal isolation prior the application
103668-2006	Case History of One-Trip Monobore Completion System-2 Years of Cement-Through Monobore Completions in the Gulf of Thailand	Gulf of Thailand	The design of monobore one trip cement through completion system to run GL components safely in monobore wells	Considering the cement efficiency
OTC 17458-2005	Interventionless Monobore Technology Used for Offshore Horizontal Gas-Injection Wells	Amenam/ Kpono oil field, Nigeria	Optimization of the well completion equipment in HPHT deep offshore wells (gas injector well completed with 5 ½-in. monobore completion with 5 ½-in. wire-wrapped screens) to allow running completion equipment without slickline	Challenging horizontal gas injector
97668-2005	Disposable Wells: A Monobore One Trip Case Study	Gulf of Thailand	Adding artificial lift to short life monobore wells, using one trip cement-through completion system	Ensure the sealing tools to prevent the cement precipitations in the annulus.
88525-2004	Hybrid Monobore Completion Design: An Application for Multilayer Reservoir	Semberah Field, Indonesia	Combination of the 3 ½-in. dual selective conventional and 3 ½-in. monobore completions to produce from 2 different zones to overcome the reservoir depletion and liquid loading of the reservoir	Additional cost compared to 4 ½-in. normal monobore completion, but still less cost than the conventional completion
OTC 16545-2004	Using Cement –Through Completions to Improve Productivity and Safety in Short-Life Wells	Gulf of Thailand	Improve the production in short life wells by implementing mono-trip cement through completion system, which support the use of GL in economical way using cement friendly components.	To avoid any limitation, the fluid dynamics was simulated to ensure smoothly flow of the fluids without residual cement.
84267-2003	South Texas Hybrid Monobore High Pressure, High Temperature Well Design	South Texas, USA	Successfully utilize the Hybrid Monobore, modified tubingless, design in HPHT wells, where installing the production string in the openhole and cement it in place then CRA tied back to the surface and cemented in place	Consider cement job integrity, cement plug clearance
69498-2001	Optimizing Development Costs By Applying A Monobore Well Design	An Aike–Barda Las Vegas field, Argentina	To optimize and develop the existing completion 7-in. production casing and 4 1/2-in tubing (gas reservoir) by using 4½-in. monobore completion and reduce each section by one size to lower the cost	Consider the connection devices for 4 ½-in. string and device for precise cement job.

Table 3.3. Published papers in development of monobore completion (cont.).

54475-1999	Utilizing 4 ½-in. Monobores and Rigless Completions to Develop Marginal Reserves	Gulf of Mexico	Utilization of monobore completion with some modification in operation and equipment to enable sand control system and be suitable for the reservoir condition	Washing problems, gel damage, and near wellbore turbulence were appeared in one of the cases. However, the production was improved with no sand production
50046-1998	Monobores-Making a Difference to the Life Cycle Cost of a Development	South Australia	Switch the initial completion design 7-in. casing and 2 7/8-in. tubing with 3 ½-in. cemented monobore completion design to lower the cost, increase the well life, and enhance the fracture job	Cement clean-out, perforating debris due to perforating the tubing with high power, post frac clean-out, and placing cement inside the production annulus
37616-1997	New Well Architectures Increase Gas Recovery and Reduced Drilling Costs	Bongkot Gas Field Gulf of Thailand	Implementation of monobore completion to optimize 3 casing design with 3 ½-in. multi-zone completion to tubingless monobore completion design	High CO_2 concentration, consider the water production and the ability of installing artificial lift.
29820-1995	A New Tubing-Conveyed Perforating Method	USA, offshore Scotland, offshore Australia	Enhancement in the perforation process in monobore well completions by using an automatically released gun hanger, and a modular gun system	Applicable in almost all the types of monobore completion
28916-1995	Monobore Completions and Novel Wireline Perforating of High-Angle Wells in the Nelson Field	Nelson Field, North Sea	Apply monobore completion with dual tubing to enable the gas lift system safely in highly deviated offshore wells	Complex completion to enhance the safety system
26743-1993	Everest and Lomond Completion Design Innovations Lower Completion and Workover Costs	Everest and Lomond gas condensate fields, North Sea	Complete the wells with 5 ½-in. monobore completion to eliminate hole restrictions and facilitate the well intervention without pulling the completion strings	Consider the perforation method and the well control
25054-1992	The Gullfaks Field Development: Challenges and Perspectives	Gullfaks Field, North Sea	Switch the standard 7-in. liner and 5 ½-in. tubing completion to 7-in. monobore completion to have smooth well path for the frequent intervention operation due to well complexity	Complex reservoir, sand control, and well control

4. EVALUATION OF INFLOW CAPABILITY OF MONOBORE COMPLETION IN KUWAIT HPHT JURASSIC GAS RESERVOIR

As a part of Kuwait Oil Company (KOC) strategic plan to develop gas production in North Kuwait Jurassic Gas (NKJG) project and as agreed under the Enhance Technical Services Agreement (ETSA) with Shell, a monobore design was developed and selected to complete deep HPHT gas wells.

Optimizing the economical production and enhancing the life of the well are the main purposes where all the operators in multidiscipline aim to achieve behind the monobore design. After numerous precise engineering analyses and a success pilot well, 4 ½-in. monobore design had been chosen as an optimum design for NKJG reservoirs to enable the technical challenges with high pressure sour volatile oil/gas condensate.
The idea of implementing and adopting the monobore completion for future wells is to improve productivity considering the cost effective and facilitate the well intervention and testing by;

a. Enable selective underbalanced perforation and stimulation of smaller intervals (20-40 ft.) without having to kill the well.
b. Delivering maximum value of information, improving reservoir characterization, validation of open hole logs leading to optimized selection of future well targets.
c. Providing full-bore access to the Middle Marrat and eliminate time consuming tubing retrieval and kill operations to access reservoir sections.
d. Simplify the workover and testing operation; with monobore completion workover and testing would be possible to achieve rigless. That will also reduce the HSE exposure associated with rig operations.

e. Minimizing the need to use inflatable tools which usually comes with limited differential pressure ratings.

The objective of this work is to compare and contrast the current standard design which consist of 3 ½-in. upper completion hung above a 5 in. production liner set across the Middle Marrat reservoir with the new 4 ½-in. cemented liner into the 6-in. reservoir section and 4 ½-in. upper completion monobore design. The flow work was done by using an integrated system Model via PROSPER software using a data for a well in each design and fixing all the parameter except the design of downhole equipment.

4.1. GEOLOGICAL BACKGROUND

The area of interset is locted in the northern part of Kuwait. A part of much larger Arabian plate, which through the geological time has undergone many tectonics and geological proceeses that control the sedimentation processes in the area.

North Kuwait Jurassic Gas (NKJG) reservoirs covered six major fields with an area of about 1,800 Km^2 and thickness of about 2,200 ft (Figure 4.1), distributed in five major formations as Najmah, Sargelu, Upper Marrat, Middle Marrat and Lower Marrat.

The Middle Marrat formation consists of carbonate rocks deposited in low relief shelf where any minor change in the relative sea level led to major change in the depostional environment. Therfore, the depositional environments for Middle Marrat are slope, outer shelf, inner shelf, shoal, lagoon, and sabkha. Through time, Middle Marrat limestone was partialy dolomitized, creating secondary porosity and permeability. The natural fractured zones in Middle Marrat have the most producing potential. Consequently, Marrat reservoir has the best reservoir properties.

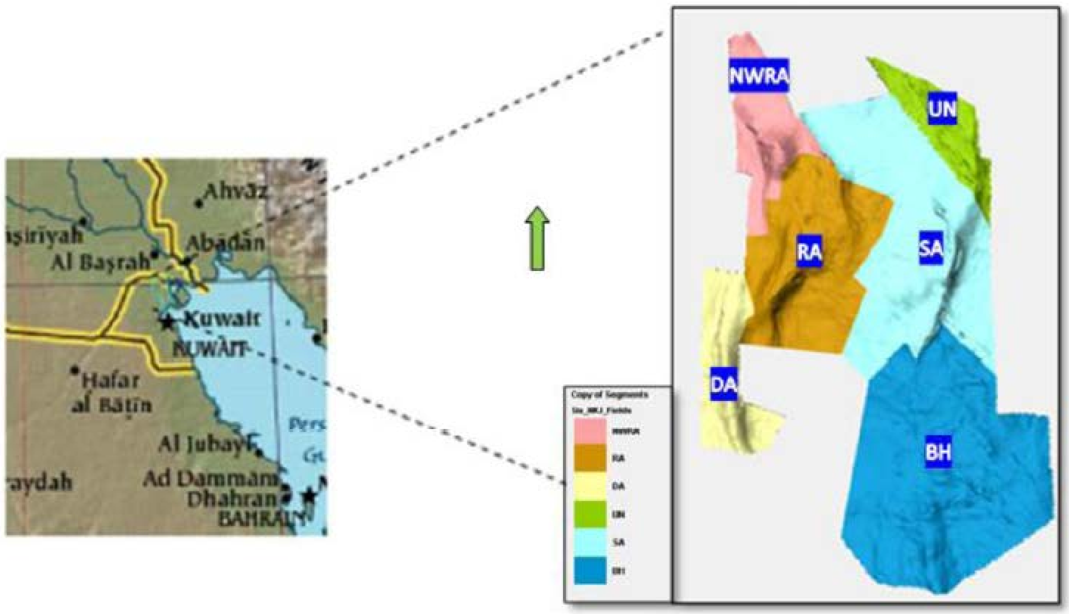

Figure 4.1. North Kuwait Jurassic fields. (Fava et al. 2015)

4.2. RESERVOIR DATA AND FLUID PROPERTIES

Jurassic deep carbonates reservoirs have dual low porosity and low permeability. The porosity range is 3% to 24%, and permeability range is 0.001 md to 100 md. The reservoirs are characterized by high pressure and high temperature conditions rangeing from 10,500 psi to 12,000 psi and 225 to 290℉. The hydrorbons are considered to be sour as the H_2S is high with 2.9 %, and CO_2 concentration is 1.5% (S. Packirisamy, 2010) (S. Malik, 2012). The reservoirs are recognized as heterogeneous due to very complex compartments and high contrast in permeability as a result of the natural fracture connectivity, which is connected perfectly in some areas and poorly in other areas. Therefore, a big challenge in completion design was to identify a well completion and stimulation strategy to maximize the flow from the multiple zones and enhance the production in order to meet the country's gas production strategy. The large hydrocarbon fluids content of volatile oil and condensate gas makes it profitable to produce over all the challenges faced. Figure 4.2 shows the summary of the Jurassic gas reservoirs.

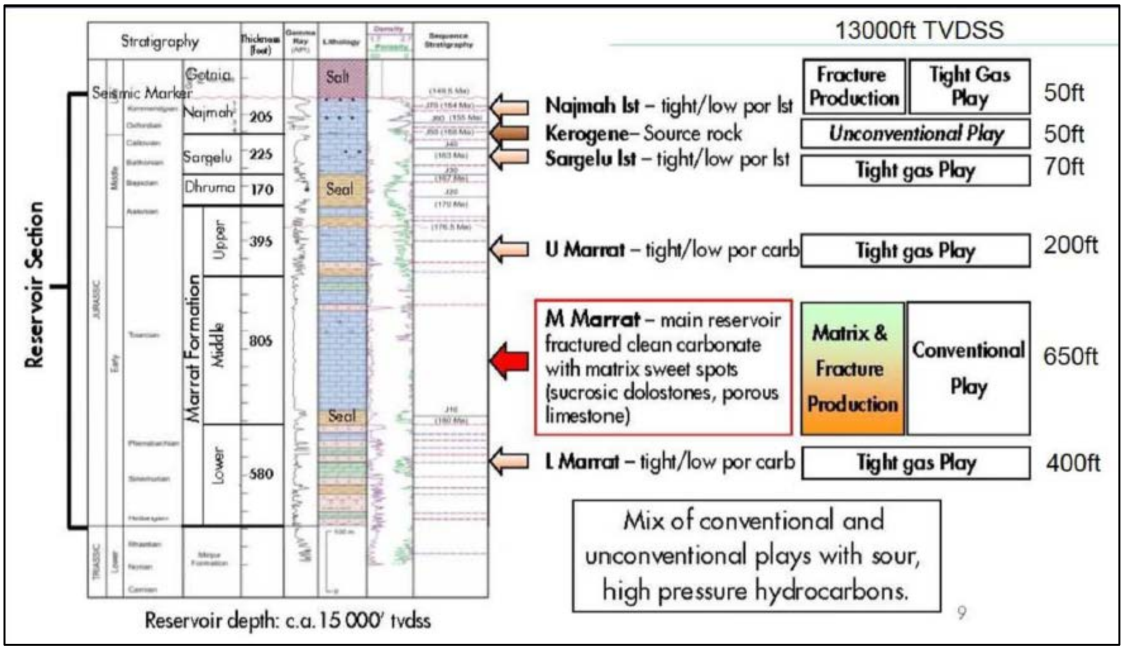

Figure 4.2. Summary of the Jurassic Gas reservoirs. (Ahmed et al. 2017)

Due to the 2-3 orders of magnitude difference in permeability contrast between the different reservoir flow units, a well completed across the entire Middle Marrat pay would really only prduce from the most productive zones. Further, any acid stimulation applied (bullheading acid) would also only reach the most permeabile zone (zone 2, Figure 4.3), leaving a large portion of the net pay within the well unstimulated. Initially that was the only way the reservoir could be developed, with individual wells targeting a single permeability layer and bullheading acid to that one layer, anticipating that other layers would be opened and a later time, once the first layer was depleted. However, it was estimated that this approach was producing only 65% of the total reservoir flow capacity. (Ahmed et al. 2017)

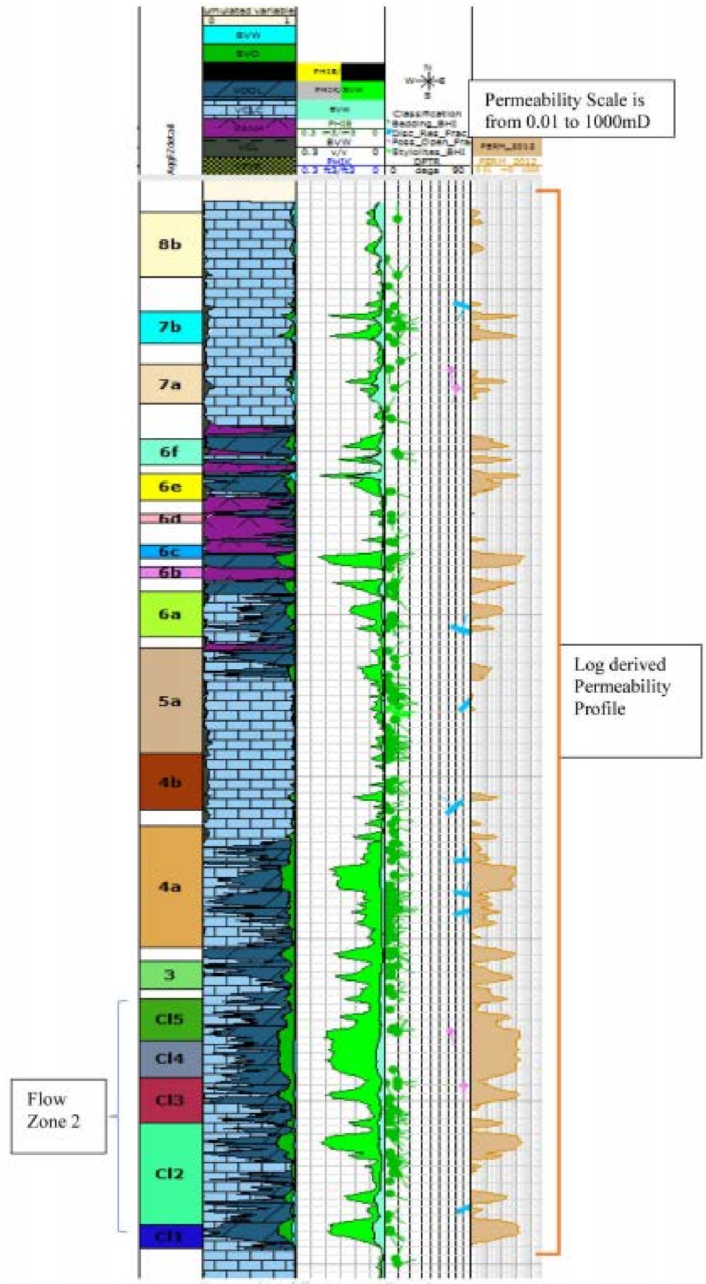

Figure 4.3. Middle Marrat Type Log. (Ahmed et al. 2017)

Forty percent of the total gas in place in the North Kuwait Jurassic (NKJ) asset is concentrated in Middle Marrat reservoirs in RA and SA fields. In RA field, the produced fluid considered as volatile oil after analyzing 16 PVT samples while the fluid produced from SA field is described as Gas-condensate. Where 7 samples from 12 PVT samples show Gas-condensate behavior, and the rest show volatile oil behavior. Whereas the volatile oil samples in SA field are not separated from the gas condensate wells by any barrier and the initial reservoir pressure is much higher than the saturation pressure. Many studies and models have described the fluid behavior in SA field and proven that the coexisting of the oil and Gas-condensate is due to geological complixity such as the sharp change in depostionl environments and lithology as well as post depostional proceeses. Gas and oil distribution in deep reservoirs led to changes in the fluid composition (Fava et al. 2015). Figure 4.4 shows the distribution of the volatile oil and gas condensate wells in RA and SA fields.

4.3. GAS PRODUCTION IN NORTH KUWAIT

Marrat formation is the main and primary reservoir with high potential drainage of hydrocarbon fluids. The current production rates are 50,000 BBL/d light oil and 120,000 MMSCF/d gas (F. Clayton 2012), typical per well production rates are up to 5,000 BOPD/BCPD and 10 MMSCF/d. The secondary reservoir targets (Najmah/Sargelu formations) can be achieved by applying 4 ½-in. monobore completion which will facilitate the stimulation for multiple zones and enhance the production simply with less time.

During the early phases of the reservoir the natural fractures played an instrumental role in enhancing the production. However, due to high pressure high temperature reservoir condition and the need of using heavy mud(18-20 ppg), some formation damage appeared, which required acid stimulation to enhance the production. Acid fracture job is performed in almost all the wells.

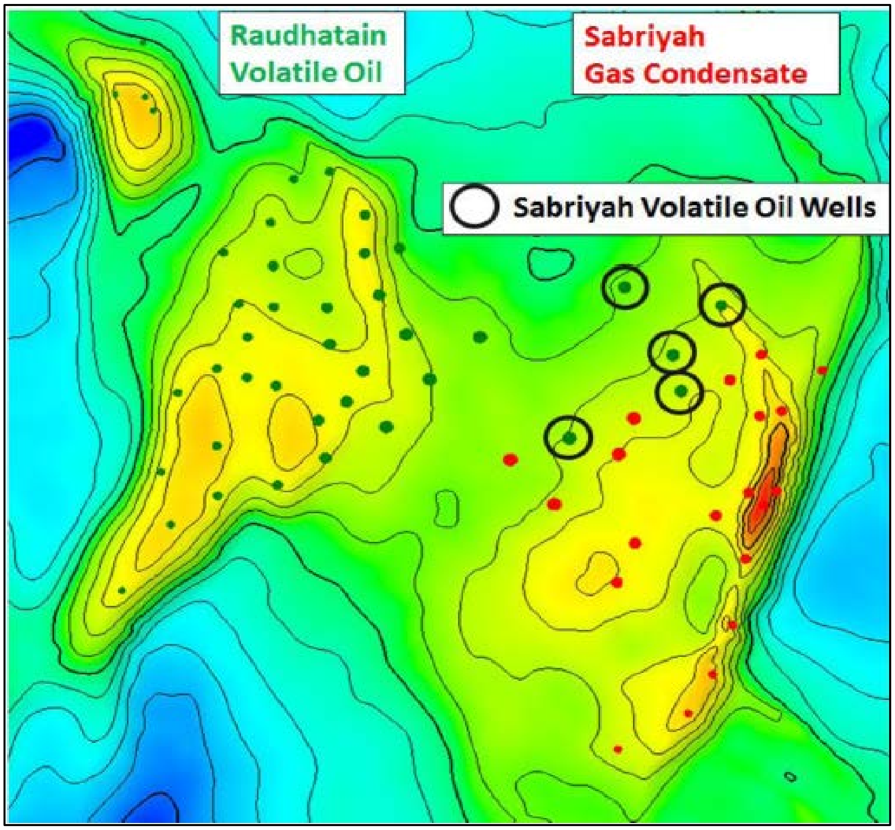

Figure 4.4. Volatile oil wells in RA and SA fields (RA green dots, SA green dots with black circle) and Gas condensate in SA field (red dots). (Fava et al. 2015)

4.4. COMPLETION DESIGN

In line with exploration and development of many unconventional reservoirs and with the high demand of gas production in the market, operators strive to improve the existing technologies and innovate new technologies and designs to overcome the technical and operational challenges. Monobore completion design is became essential after many success implementations in oil and gas industries as it demonstrate the simplicity and flexibility in well completion, testing, production and intervention.

In North Kuwait Jurrasic reservoir, the main purpose of applying the monobore completion was to enable the openhole multistage completion and isolate the upper completion to facilitate installing of stimulation string and enhance the fracture process. Hence, the whole layers in the reservoir will be produced and the asset's production targets can be achieved.

4.4.1. Conventional Design. The current standard design consists of 3 ½-in. upper completion set on a 5 in. production packer across the Middle Marrat. The 5 in. production liner is hosted by a 7 5/8-in. drilling/production liner set below the Najmah/Sargelu and extended to surface with a tie-back string required to withstand the production loads.

4.4.2. Monobore Design. The monobore completion design was developed and implemented in NKJG pilot well and has been proven for the future wells to optimize production and recovery factor in the Marrat reservoir. The openhole sleeve system allows highly varying tight permeability layers in the Middle Marrat (MM) carbonate reservoir to be acid stimulated individually and commingled for production.

The optimum monobore completion size for NKJG wells is 4 ½-in. (Figure 4.5). The concept involve running the 4 ½-in. liner into the 6 in. reservoir section and cemented in place. The 4 ½-in. upper completion with 4 ½-in. Safety Valve Landing Nipple (SVLN) is then stabbed into the PBR of the integral PBR/tie back packer assembly positioned on top of the liner hanger assembly.

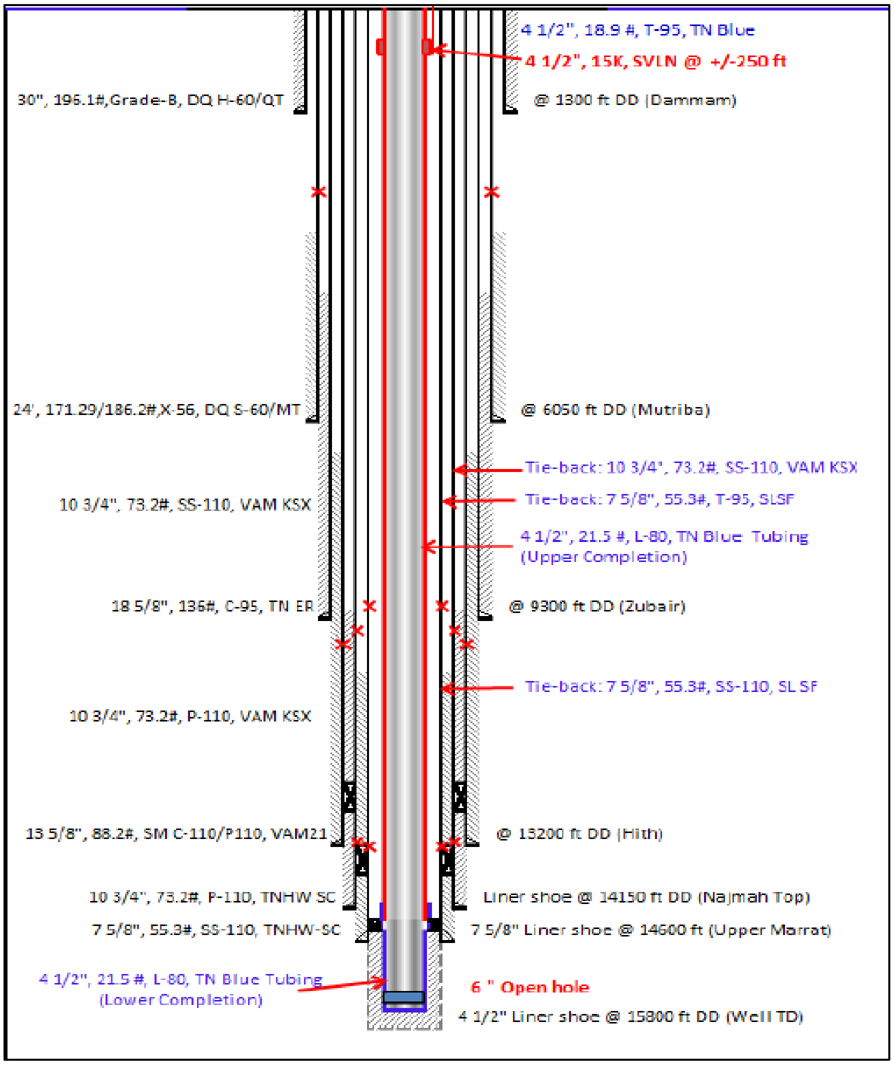

Figure 4.5. 4 ½-in. monobore completion schematic. (Shell Kuwait internal Report)

4.5. STIMULATION

North Kuwait Jurassic reservoirs is naturally fractured, which make it beneficially in the primary production. However, due to the high pressure high temperature nature the wells are drilled with high specific gravity mud that caused a formation damage and reduction in permeability in some areas. Acid fracture is needed in carbonate formation of the Jurassic field to reconnect the natural fracture systems (Packirisamy et al. 2010).

At the beginning, single stage bullhead matrix acid stimulation was performed, which were treating only the highest permeability zone. The high contrast in the permeability between the zones in the Jurassic formations makes it challenge to produce from multi layers at a time. Then, the operator applied 'plug and perf' completion to stimulate multi layers selectively, but this type of completion has some disadvantages such as the time consuming needed to mill out the plugs and the high cost.

In order to optimize the stimulation strategy, an alternative design was implemented with positive results. The alternative was to stimulate with 4 ½-in. multistage ball activated sleeve completion system. Thus, 4 ½-in. monobore completion design was implemented to facilitate the usage of ball and sleeve multi stage completion.

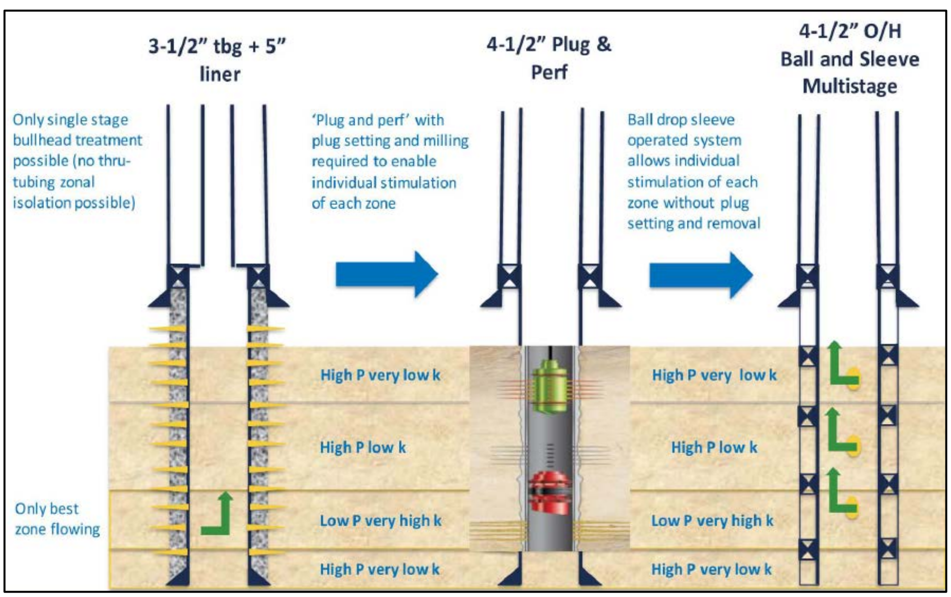

Figure 4.6. Completion designs in North Kuwait Jurassic gas reservoir. (Z. Ahmad and Y AL-Otaibi 2017)

5. INFLOW PRODUCTION MODELING OF MONOBORE COMPLETION IN KUWAIT HPHT JURASSIC GAS RESERVOIR

The main objective of this work is to evaluate the well performance at two different completion designs, conventional vs monobore completion design, using actual PVT lab data, reservoir data, and design of a deep HP HT well in North Kuwait Jurassic Gas (NKJG) project. PROSPER software was used to achieve this objective by nodal analysis method.

Two models were built for wells W-A and W-B, which are located in North Kuwait Jurassic field and produced from MM formation. Well W-A is producing a volatile oil under reservoir pressure of 8,500 psi, while well W-B is producing a gas-condensate under reservoir pressure of 11,000 psi, more details in reservoir data is in Section 5.1.3. For each model the reservoir data is fixed except the reservoir pressure, the variables are the reservoir pressure and the well design (tubing size and depth).

5.1. PROSPER WORKFLOW

PROSPER is one of the most powerful tools that can predict the well performance and the production capability, through building a well model using the major well aspects such as PVT (fluid characterization), VLP correlations (for calculation of flow-line and tubing pressure loss) and IPR (reservoir inflow). In addition, operators can evaluate the well life and optimize the production and the well design prior taking any crucial decision (artificial lift). Prosper software enables design modeling for all types of the well profiles considering the reservoir parameters, surface and subsurface tools, and the type of reservoir fluids. PROSPER's name came out of "advanced PROduction and

Systems PERformance analysis software" PROSPER supports well performance, design, and optimization applications such as (Prosper User Manual Version 11.5, 2):

- Design and optimize well completions including multi-lateral, multilayer and horizontal wells
- Design and optimize tubing and pipeline sizes
- Design, diagnose and optimize Gas lift, Hydraulic pumps and ESP wells
- Generate lift curves for use in simulators
- Calculate pressure losses in wells, flow lines and across chokes
- Predict flowing temperature in wells and pipelines
- Monitor well performance to rapidly identify wells requiring remedial action
- Calculate total skin and determine breakdown (damage, deviation or partial penetration)
- Unique black oil model for retrograde condensate fluids, accounting for liquid dropout in the wellbore
- Allocate production between wells.

PROSPER allows the engineer to match different components of the model viz, PVT, flow correlations and IPR with measured data. The matching procedure is followed by quality checking options, on the basis of what is possible physically.

- ➢ PVT correlations can be matched to laboratory flash data.
- ➢ Vertical lift and flowline correlations can be automatically tuned to match measured flowing pressure surveys.
- ➢ Flow Correlations can be tuned to fit up to 10 tests simultaneously, using a multi-dimensional non-linear regression.

The matching process is a powerful data consistency check. Figure 5.1 illustrates the workflow used in this research with PROSPER software.

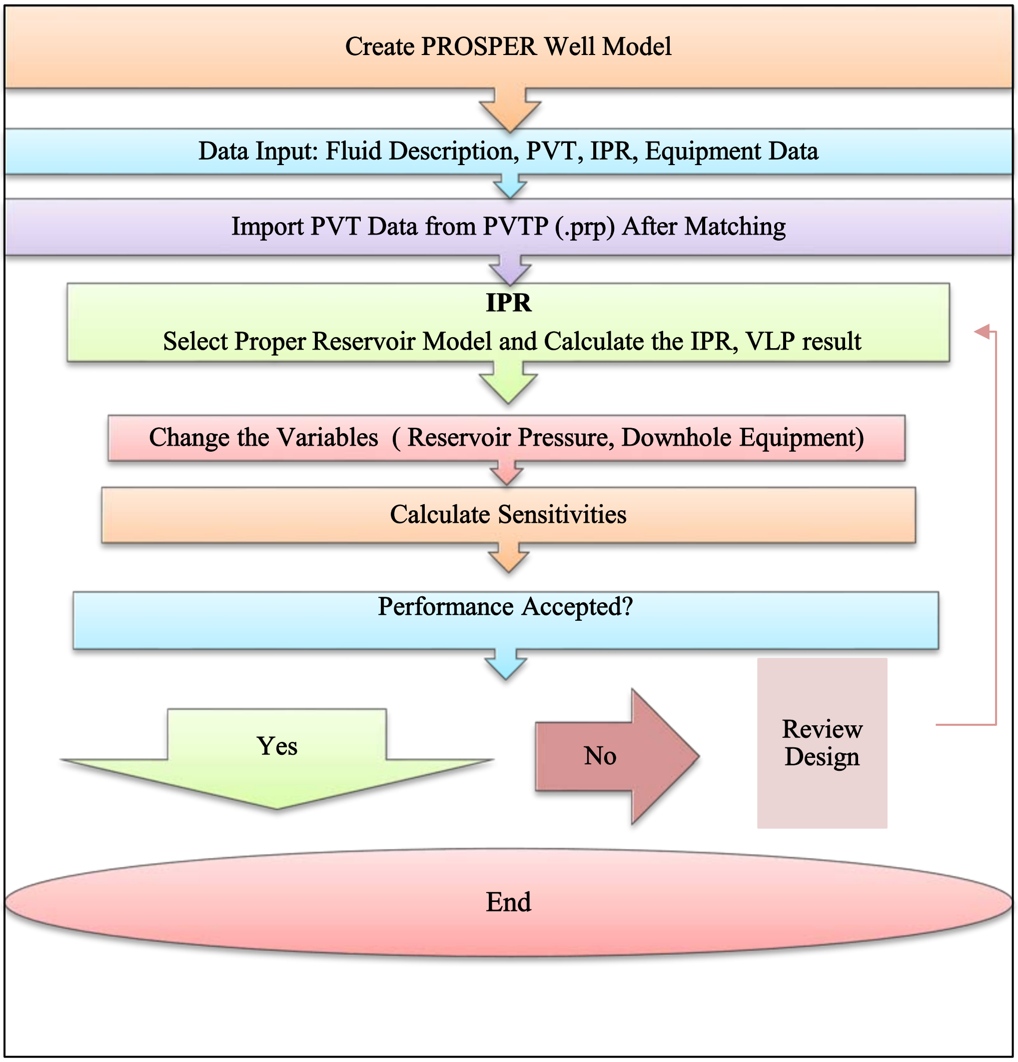

Figure 5.1. Work Flowchart using PROSPER.

5.1.1. Fluid Description Method. Two models were built for volatile oil and gas condensate wells, due to rich gas fluid nature in the utilized wells, the models were built for retrograde condensate fluid type. The produced hydrocarbons passed through multi-stage separator (3 stages) therefore, separator train was used as a separator calculation method.

Equation of State (EOS) fluid model is recommended for the compositional hydrocarbon reservoir, thus Peng-Robinson Equation of State has been used as a PVT fluid model due to its simplicity and solvability in representation of volumetric and phase equilibria (Wei et al. 2011).

Peng-Robinson Equation of State is a modified EOS, which applied for predicting the real gas behavior and the fluid properties in the vicinity of the critical region.

The Peng and Robinson Equation of State

$$P = \frac{RT}{V_m - b} - \frac{a\alpha}{V_m^2 + 2bV_m - b^2} \tag{5-1}$$

$$a = \frac{0.45724R^2T_c^2}{P_c} \tag{5-2}$$

$$b = \frac{0.07780RT_c}{P_c} \tag{5-3}$$

(5-4)

$$\propto = (1 + (0.37464 + 1.54226\omega - 0.26992\omega\text{^}2)(1 - T_r^{0.5}))^2 \tag{5-5}$$

$$T_r = \frac{T}{T_c}$$

Where ω is the acentric factor for the species,

P_c is critical pressure,

T_c is critical temperature.

The ideal gas constant R = 8.314413 J/mol-K

5.1.2. PVT Data. In this study, two fluid samples for different fields have been used. One is a volatile oil sample while the other is gas condensate sample, both from HPHT reservoir with a high percent of H_2S gas.

PVT Modeling is the process of describing the phase behavior of hydrocarbon fluids by mathematical equations (i.e.; EOS) based on lab measurements. Usually, the EOS needs to be matched with lab data by changing the pseudo-components' properties, which are considered as tuning parameters due to their low reliability and using the volume shift mode for the full composition to calibrate the data. However, the tuning process can be complicated and challenging. PVTP software was used to calibrate the lab PVT data (lab measurement) and match it with the calculated data using the proper EOS and plot the phase envelop for each fluid sample, Figures 5.2 and 5.3 show the phase envelope for the used fluid samples in the studied fields. After matching the lab measurement, the resultant data saved in PRP format and the data table was imported in to PROSPER PVT.

PVTP is Petroleum Experts' advanced Pressure Volume and Temperature analysis software. It is a thermodynamic fluid characterization tool that can assist production, reservoir and process engineers in modeling the fluid PVT behavior and predicting the effect of process conditions on the composition of hydrocarbon mixtures with accuracy and speed.

5.1.3. IPR and the Reservoir Data. Inflow Performance Relationship (IPR) is a method where well deliverability is determined by the relationship between the production rate and the bottom hole flowing, which is called an inflow performance. Due to complexity of the multi-phase reservoir fluid, back pressure reservoir model is applied for the gas condensate well model with assumed skin of zero, while Forchheimer was used for volatile oil reservoir . Table 5.1 includes the input data for both models.

After adding the data, the software will calculate and plot the IPR and the AOF will appear as an output.

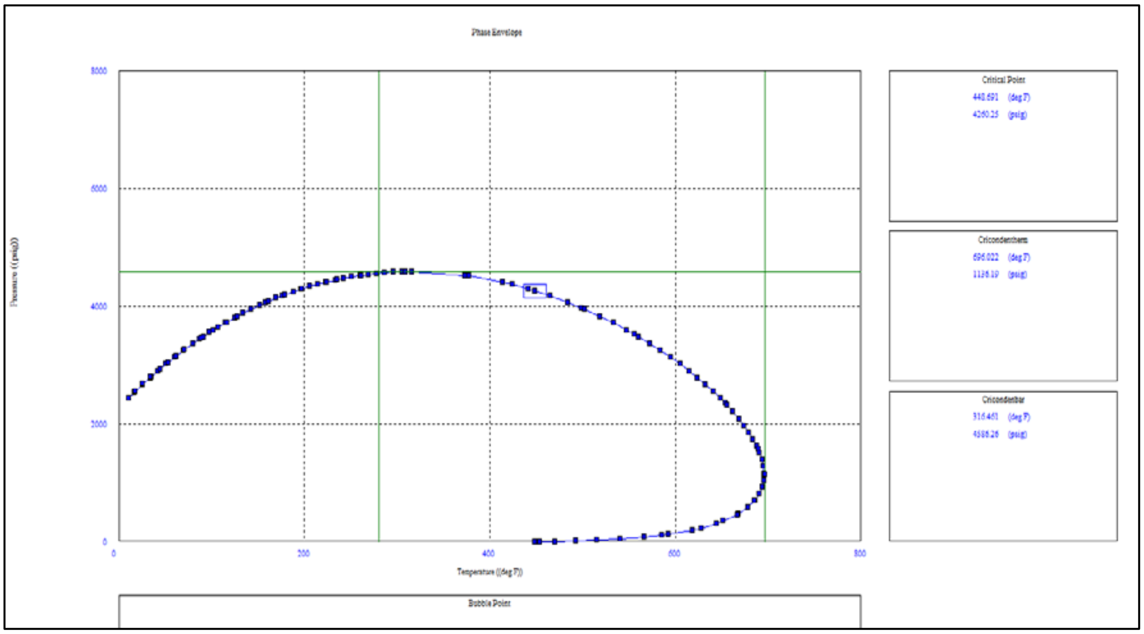

Figure 5.2. Volatile Oil phase envelope.

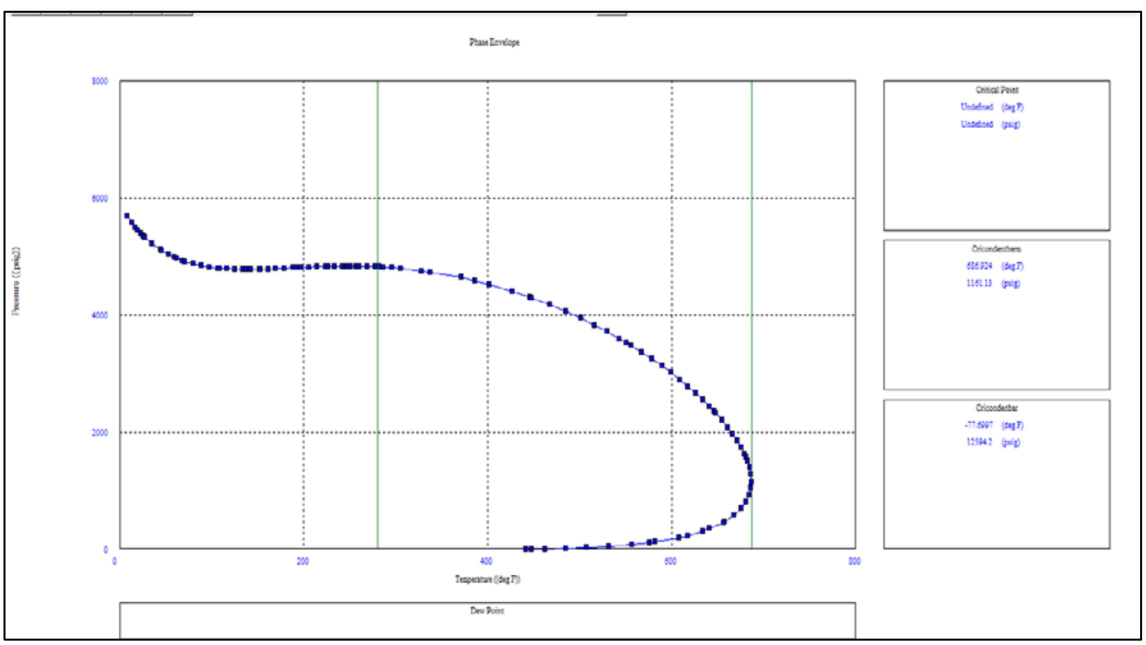

Figure 5.3. Gas Condensate phase envelope.

Table 5.1. Reservoir data for wells W-A and W-B.

Reservoir Data	W-A	W-B
Reservoir Permeability (md)	10	10
Reservoir Thickness (feet)	45	45
Drainage Area (acres)	_	288.34
Dietz Shape Factor	_	30.9972
Wellbore Radius (feet)	0.25	0.25
Exponent n	_	0.5
Non-Darcy Coefficient	0.214	_
Darcy Coefficient	211.454	_
Reservoir pressure (psi)	8500	11,000
Reservoir temperature (℉)	280	280
Water Gas Ratio (STB/MMscf)	0	0
Total GOR (scf/STB)	2972	4059.8

5.1.4. Equipment Data. In this section, the actual well data such as downhole equipment design and setting depths, surface equipment design (tree, separators..etc.), well deviation survey, geothermal gradient and heat capacities are required. These data are crucial in predicting the flow.

- Deviation Survey: the deviation survey can have its origin anywhere: well head, sea-bed, platform, RKB and so on, the key thing is to describe all the equipment in the well in a manner consistent with the origin selected. The well head depths does not have to coincide with the origin of the deviation survey.

- Surface Equipment: All equipment located downstream of the well head are part of the surface equipment. The surface equipment can include: well head chokes, risers, flow lines, fittings, and so on.
- Down Hole Equipment: The down hole equipment include the tubing, casings, nipples, Sub-surface Safety valves ...etc.
- Static Geothermal Gradient: The geothermal gradient expresses the rate of increase in temperature per unit depth. The geothermal gradient is independent of the well flow rate.

5.2. ANALYSIS SUMMARY

In PROSPER, the data entered can be analyzed and the sensitivity can be determined using more than two variables up to 10 sensitivity variables. The software enables to calculate the inflow by nodal analysis with different variable, thus the user can compare the output data and analyze the result. Furthermore, the user can change the variables in every run and observes the result easily and in a short time until the best integrity is reached.

6. STUDY RESULTS

6.1. RESULT OF THE MONOBORE HISTORICAL OVERVIEW

Over the period of more than 30 years, the monobore completion was applied in many oil and gas fields in the world. Vast majority of the monobore wells have proven its effective in different types of reservoir. Operators strove to improve the monobore completion design to overcome many operational challenges and enhance the production in economical way. Monobore completion is used now with more confident.

6.2. RESULT OF THE INFLOW CAPABILITY

This section includes the inflow result and nodal analysis plots for two wells located in adjacent fields and producing from the same reservoir, thus both wells have the same reservoir data except for the reservoir pressure and slight difference in the total depth. The two wells have two different hydrocarbon fluid type, one produces volatile oil while the other produces gas condensate.

The result show the performance of each well in two different cases.

Case 1: Performance of Well W-A (volatile oil fluid) using the original completion design with 5-in. liner and 3 ½-in. tubing vs. 4 ½-in. monobore completion design.

Case 2: Performance of Well W-B (gas condensate fluid) using the original completion design with 5-in. liner and 3 ½-in. tubing vs. 4 ½-in. monobore completion design.

6.2.1. Result of Monobore Completion in Volatile Oil Reservoir in Kuwait.

The preliminary result after adding all the reservoir data and applying the proper model, shows that the AOF is the same in both completion designs, which is equal to 17.887 (MMscf/day). Figure 6.1 shows the IPR plot.

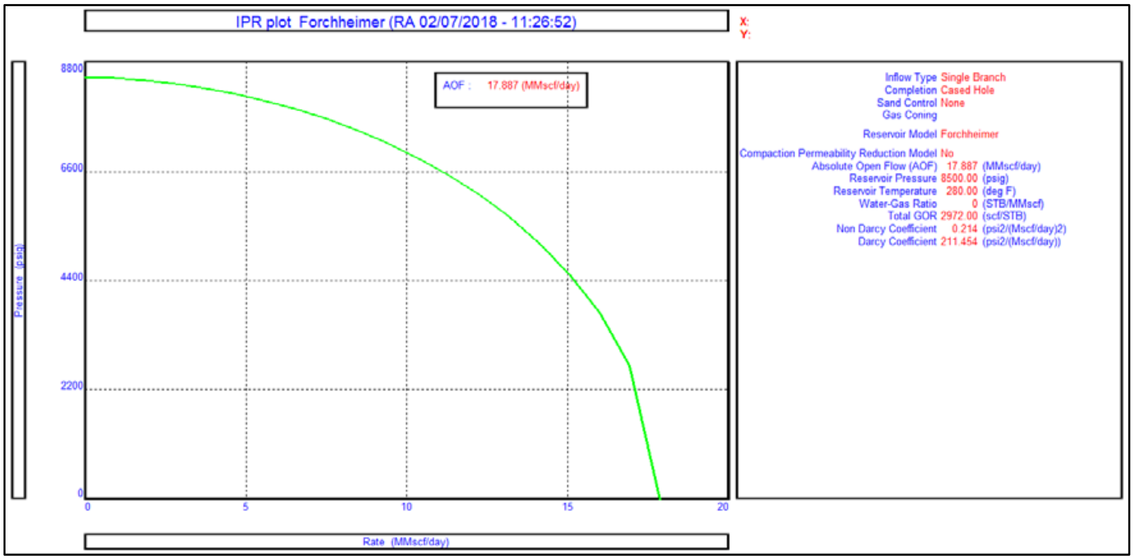

Figure 6.1. IPR plot for well W-A.

For the original completion design the well will produce gas at rate of 4.622 (MMscf/day) and oil rate of 1324.6 (STB/day). Further, it will deplete at pressure less than 2350 psig. The following Figures (6.2, 6.3) show the IPR vs. VLP plot and the sensitivity at different reservoir pressures respectively.

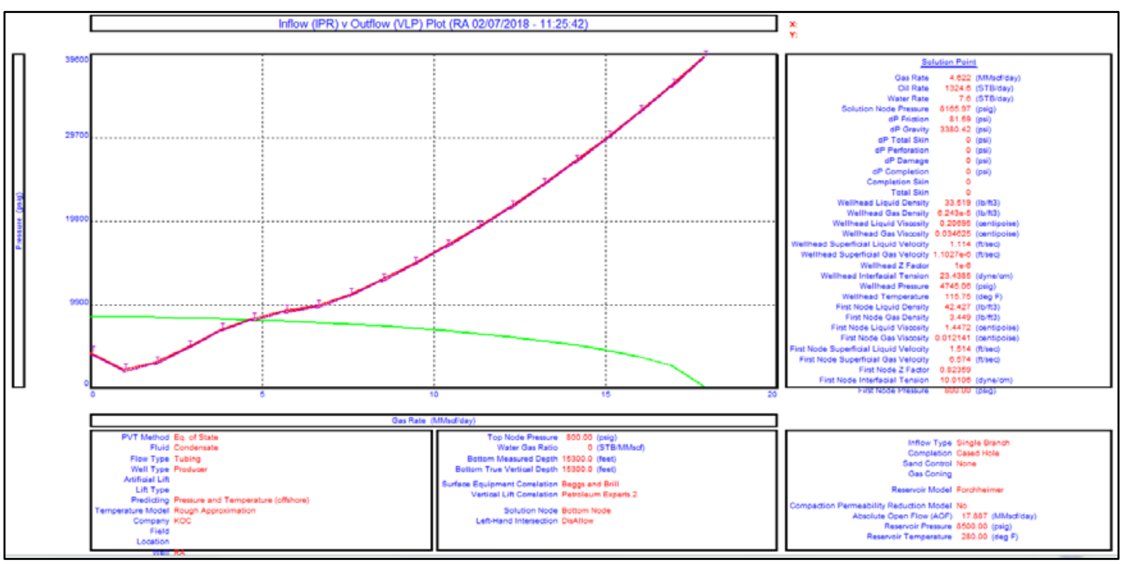

Figure 6.2. IPR vs. VLP for well W-A at the original completion design.

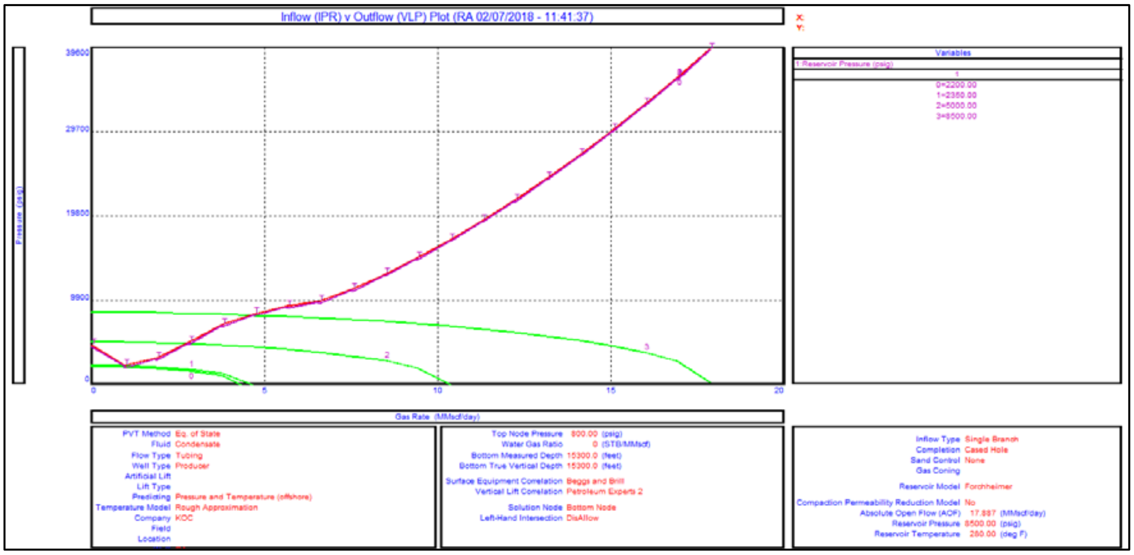

Figure 6.3. Reservoir pressure sensitivity for the well W-A at the original completion design.

When applying the monobore completion design for the same well the gas and oil rate will be 4.618 (MMscf/day), 1323.4 (STB/day) respectively. The well will deplete at pressure below 2350 psig as shown in the following Figures (6.4, 6.5).

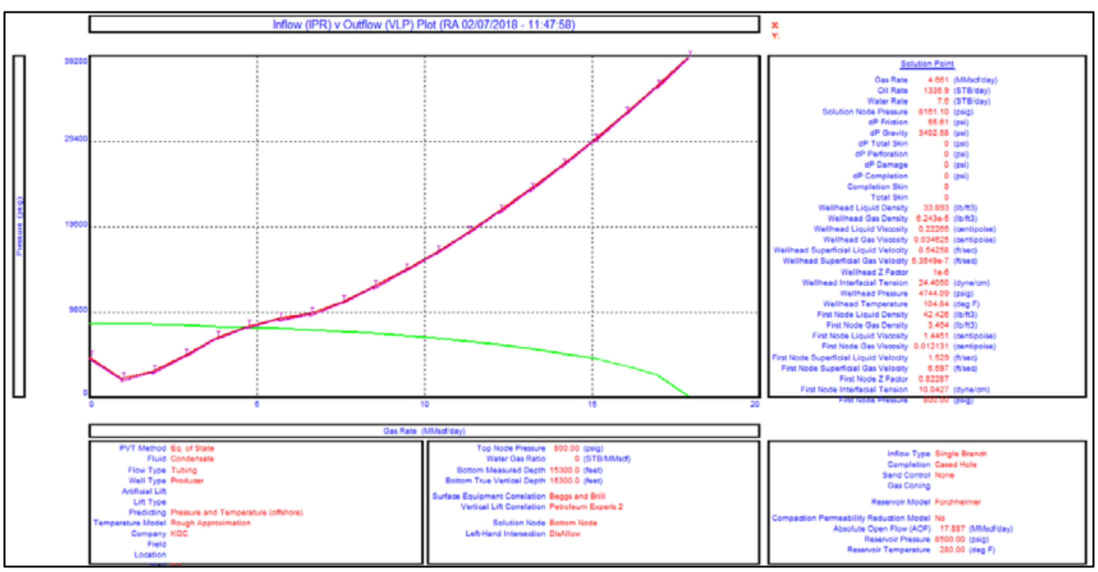

Figure 6.4. IPR vs. VLP for well W-A at the Monobore completion design.

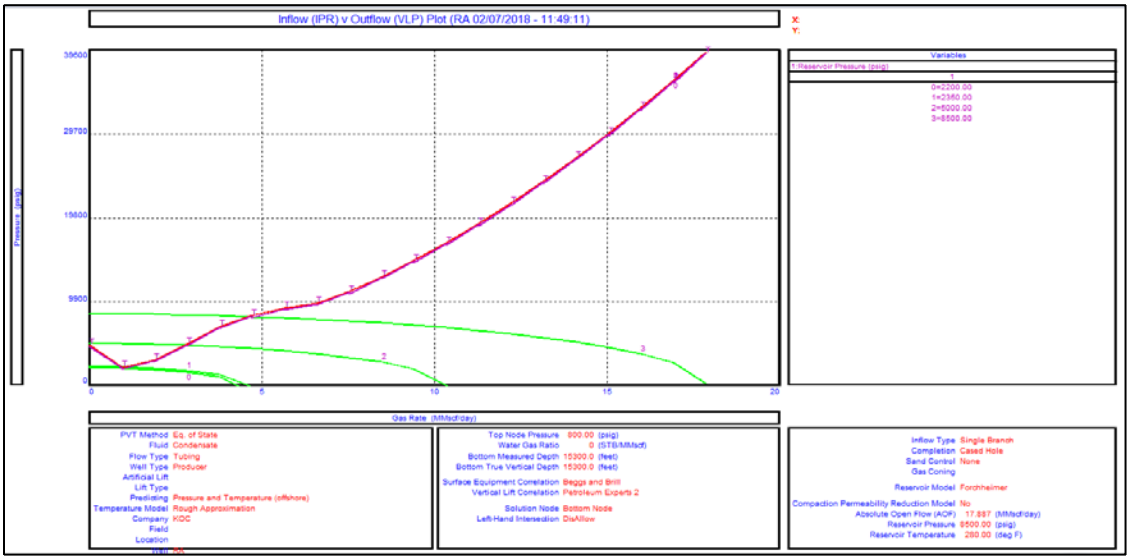

Figure 6.5. Reservoir pressure sensitivity for the well W-A at the Monobore completion design.

Figure 6.6 shows the IPR vs. VLP plot for using the two variables (reservoir pressure and downhole equipment) for well W-A.

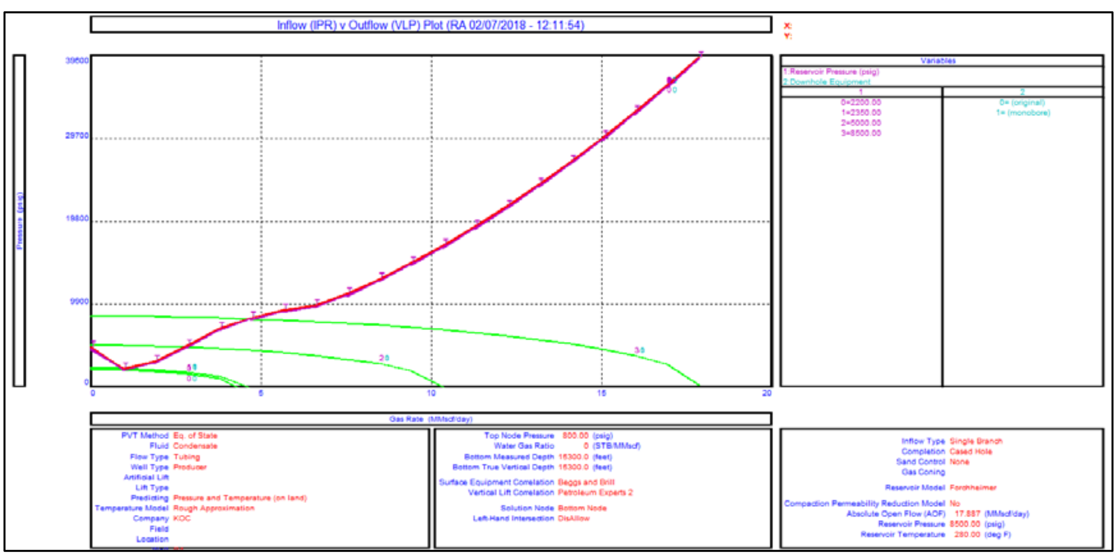

Figure 6.6. IPR vs. VLP plot for using the two variables for well W-A.

6.2.2. Result of Monobore Completion in Gas Condensate Reservoir in Kuwait. The preliminary result after adding all the reservoir data and applying the gas condensate reservoir model is given in Figure 6.7, where the AOF for both design in the well W-B is the same and equals to 29.447 (MMscf/day).

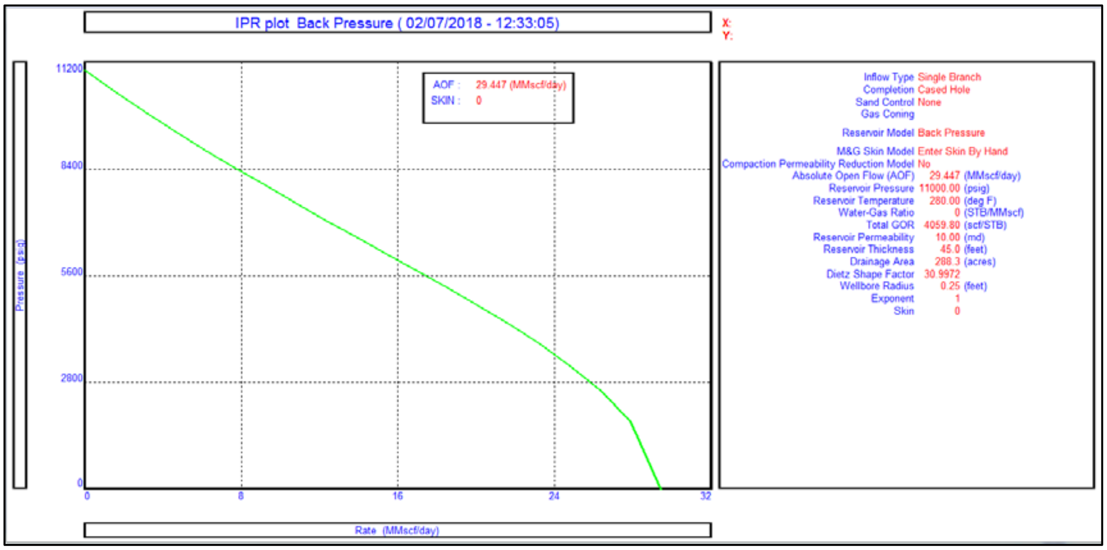

Figure 6.7. IPR plot for well W-B.

In the original well design the gas production is 5.657 (MMscf/ day) and the oil rate is 1691.4 (STB/day) as shown in Figure 6.8, and the depletion pressure for this well is below 3950 psig shown in Figure 6.9.

In the Monobore completion design case the well will produce 5.795 (MMscf/day) of gas and 1732.5 (STB/day) of oil. The depletion pressure is below 4250 psig Figures (6.10, 6.11). Figure 6.12 shows the IPR vs. VLP plot for using the two variables (reservoir pressure and downhole equipment) for well W-B.

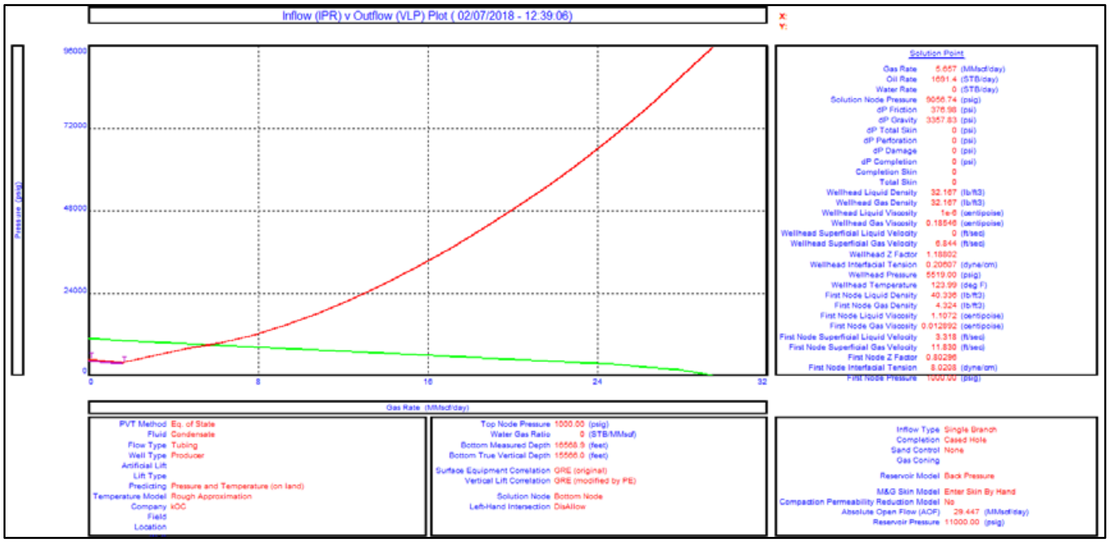

Figure 6.8. IPR vs. VLP for well W-B at the original completion design.

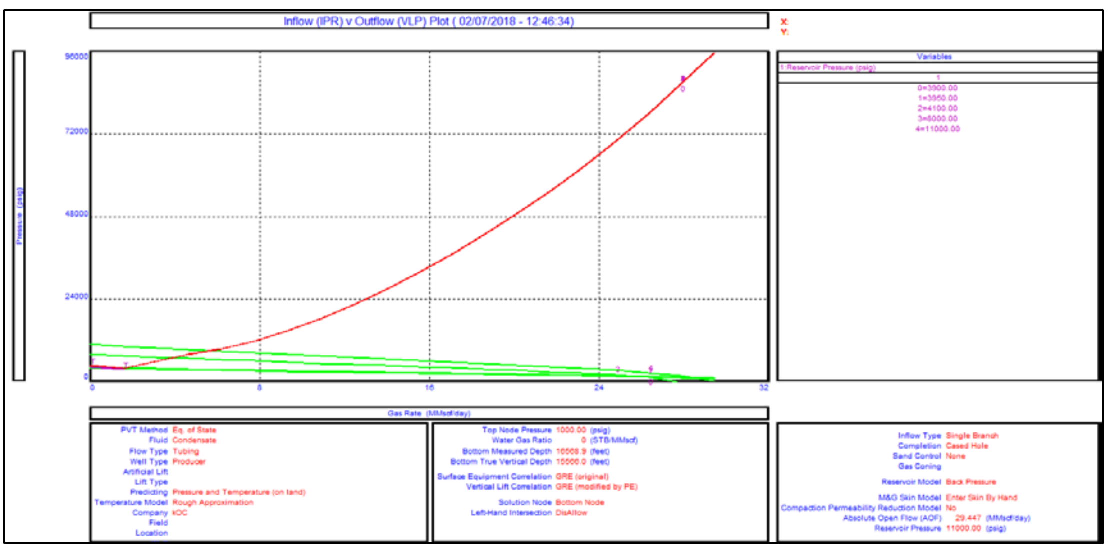

Figure 6.9. Reservoir pressure sensitivity for the well W-B at the original completion design.

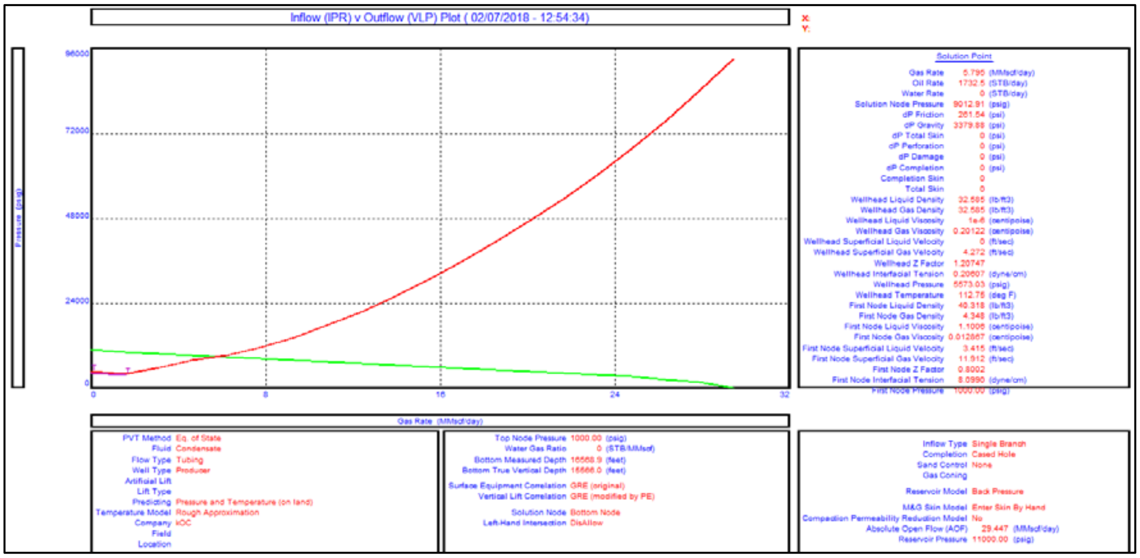

Figure 6.10. IPR vs. VLP for well W-B at the monobore completion design.

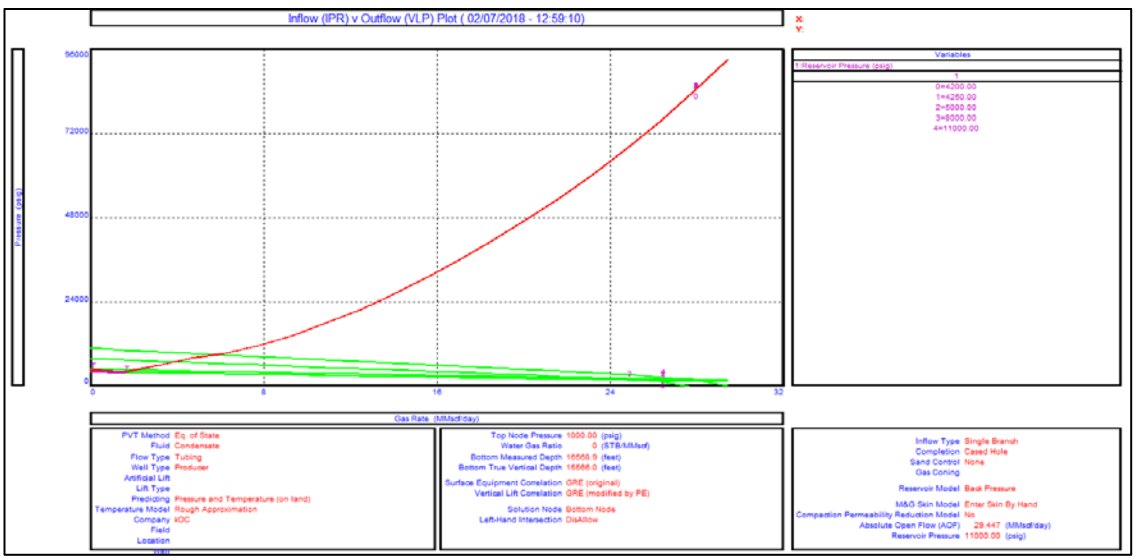

Figure 6.11. Reservoir pressure sensitivity for the well W-B at the Monobore completion design.

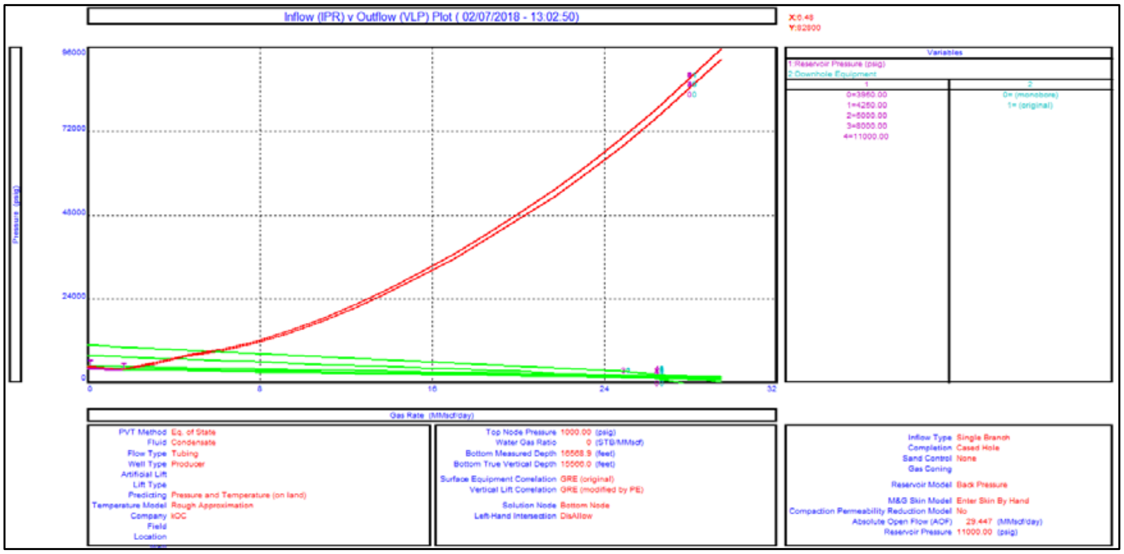

Figure 6.12. IPR vs. VLP plot for using the two variables for well W-B.

7. DISCUSSION

Based on the result of modeling and investigating the effect of monobore completion at two cases of different fields, it has been proved that a minor change in the production rate between the original completion design and monobore completion design in the gas condensate well, while in the volatile oil well the change in the rates is too small that can be neglected. However, the well with original completion design has a longer life when compared to the well completed with monobore in gas condensate well, and it is the same in the volatile oil well. The reason behind that is the size of tubing, which is smaller in the original completion with OD of 3 1/2-in. (ID 2 3/4-in.) while the tubing OD in the monobore completion is 4 ½-in. (ID 3 1/2in.). Accordingly, the production rate and the well life are considered to be the same in both cases. Table 7.1 summarize the details of the comparison between the two cases. Whereas Tables 7.2 and 7.3 include the results of sensitivity study of reservoir pressure for wells W-A and W-B.

Table 7.1. Summary of the results.

Case	**Volatile Oil (W-A)**			**Gas Condensate (W-B)**		
	Gas Rate at Pr (MMscf/day)	Oil Rate at Pr (STB/day)	Depletion pressure (psig)	Gas Rate at Pr (MMscf/day)	Oil Rate at Pr (STB/day)	Depletion pressure (psig)
Original Completion	4.622	1324.6	2350	5.657	1691.4	3950
Monobore Completion	4.618	1323.4	2350	5.795	1732.5	4250
% Change	0.0865	0.091	0	2.44	2.43	7.6

Table 7.2. Result of sensitivity study of reservoir pressure for well W-A (volatile oil).

Case	**Original Completion**		**Monobore Completion**	
Pr (Psig)	Gas Rate (MMscf/day)	Oil Rate (STB/day)	Gas Rate (MMscf/day)	Oil Rate (STB/day)
8500	4.588	1314.8	4.618	1323.4
5000	2.741	785.6	2.767	792.9
2350	0.977	279.9	0.998	286

Table 7.3. Result of sensitivity study of reservoir pressure for well W-B (Gas Condensate)

Case	**Original Completion**		**Monobore Completion**	
Pr (Psig)	Gas Rate (MMscf/day)	Oil Rate (STB/day)	Gas Rate (MMscf/day)	Oil Rate (STB/day)
11000	5.657	1691.4	5.944	1777
8000	3.924	1173.1	4.074	1217.9
4100	1.7	508.3	1.608	480.8

The monobore completion is beneficial in many ways such as facilitate the operation, workover jobs and the well stimulation without affecting the production, or with enhancing the production in some cases depending on other factors.

8. SUMMARY AND CONCLUSIONS

Monobore completion is a type of well completion where the ID size of tubing and the production liner is the same, or in some cases for tubingless design the production casing is cemented in place, which makes the wellbore smooth without any restrictions. In most wells completed with monobore completion, the intermediate casing is eliminated. Also many completion accessories can be eliminated, and compensate with specially designed equipment to avoid any trammels inside the hole. That would help in facilitate the completion operation and workover jobs with less time and cost. Monobore completions have proven to be a cost effective design for producing from wells both initially and during reservoir depletion.

The monobore completion have proven its feasibility in many fields around the world, onshore and offshore, including fields with HPHT reservoirs. Early monobore completions are readily categorized on their size - as either slim hole or big hole. Recent monobore completions combine multistage isolation and stimulation. Other recent instances show installation improvements such as cement through/single trip. Modern case studies can be categorized on these enhancements or applications (heavy oil/artificial lift).

Operators in Jurassic field in Kuwait have applied a monobore completion design for HPHT wells in this area, after the successful application of the monobore completion design in the adjacent regions in Middle East. Monobore completion in Kuwait Jurassic field enable the openhole multistage, ball drop sleeve system completion, which enhance the multi-zone stimulation.

Two cases from Jurassic field in Kuwait have been modeled and investigated to determine the effect of the monobore completion in the production performance using PROSPER software. From the result of this study it has been conclude that for volatile oil the monobore has little impact on inflow performance, whereas for gas condensate there is a slight inflow improvement gained from the monobore design. However, the monobore completion design simplifies the stimulation for small intervals, addresses operational issues, and reduce completion and workover costs, which will pave the way to be applied in all the wells at this area safely, considering the reservoir characterizations and pressure tests.

9. FUTURE WORK

Economical and functional comparisons of different completion designs for the Kuwait Jurassic reservoir could be made if more data became available.

If more data can be collected from the industry, it would be possible to construct a completions database with reservoir and completion information. This could support statistical studies in the future.

A parametric nodal analysis study could be made to develop charts that indicate flowrates where there are differences between conventional and monobore completions for different types of reservoir fluids. Comparisons of monobore completion design options can be made if cost data is obtained.

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