Department of Environment Land and Infrastructure Engineering

Master of Science in Petroleum and Mining Engineering

Master of Science Thesis

New Technologies and Protocols Concerning Horizontal Well Drilling and Completion

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ABSTRACT

For the last century, petroleum industry was advancing with development of new technologies. Step by step, drilling operations reached the milestones achievements in technological advancements, eliminating environmental hazards, improving safety of personnel with reduced cost expenditures. Non the less significant achieved progress, everyday companies, scientists and engineers, strive to improve technologies according to operational needs, with the worldwide energy demands and fluctuation of petroleum market.

Evolution of oil and gas industry first was seen in Directional Drilling, which opened a path for efficient production of reservoir fluids. However, restrictions regarding with the complexity of operations posed a big risk of failures, mainly with Horizontal Directional Drilling. Drilling wells in greater depths under a high degree of inclination in certain areas were impossible.

In the last 10 years however, technological advancements in Horizontal Directional Drilling and Completion operations raised the bar of achievement and opened a great deal of possibilities, with drilling operations becoming safer, efficient whereas completion operations became faster, profitable, and environmentally safer. In this thesis, advancements in Horizonal Directional Drilling and Completion operation were presented with dedicated case studies.

SUMMARY

1 INTRODUCTION

Advances in technologies used for well drilling and completion have enabled the energy industry to reach new sources of oil and natural gas to meet rising demand around the world.

New technologies have also helped reduce the environmental impact of energy production by allowing more oil and gas to be produced with fewer wells. Advances in technologies will play a critical role in meeting global energy demand because they enable the discovery of new resources, access to harsh or remote locations and the development of challenged reservoirs that previously were not economic to produce. Well completion is the final step of the drilling process, where the connection to hydrocarbon-bearing rock is established.

Again, advances in technology have enabled more oil and natural gas to be recovered from the length of each well, improving production and reducing the environmental footprint of energy production.

For example, by combining extended reach drilling capability with advanced stimulation technology, oil companies can optimize how and where stimulation fluid interacts with rock, allowing sustained production rates along the length of the wellbore. Companies are pushing completions in excess of 3,000 meters (9,842 feet) in length, compared to a typical completion of 30 meters a couple of decades ago.

These types of drilling and completion technologies have also enabled the recent growth in production from shale and other unconventional oil and gas reservoirs in many parts of the world, using a combination of hydraulic fracturing and horizontal, extended reach drilling [1].

2 DIRECTIONAL DRILLING

High demands in the world's economy and fluctuation of oil and gas market required advanced way of drilling for the world's prosperity. That's when Directional Drilling improved its potential. Method had a breakthrough in the oil and gas industry in the early 1970s, by Titan Construction Company, Sacramento, California, which later implemented Horizontal Directional Drilling. Starting from then, drilling operation jumped on a whole ne step. The possibility of drilling the wells to capture hydrocarbons in high depths, under deviated direction became groundbreaking for drilling industry, considering reduction operation time, financial expenditures and production efficiency.

But with all the benefits that Directional Drilling provides, difficulties come along in proper management of the operations, such as "maintaining stability of the wellbore", "proper direction of the drilling string", "safely completing of the well without major problems that may cause difficulties in remediation or completely ruin the well" and etc.

Directional drilling is the practice of drilling non-vertical bores under certain degree. **Directional drilling**, also referred to as **horizontal directional drilling** (**HDD**) is defined as the practice of controlling the direction and deviation of a wellbore to a predetermined underground target or location. Given section describes why directional drilling is necessary, the sort of well paths that are implemented, and the equipment and methodologies that are employed to drill those wells. Directional Drilling can be divided into 4 main categories: Oilfield Directional Drilling, utility installation directional drilling (which is horizontal directional drilling), directional boring, and surface in seam (SIS), which horizontally intersects a vertical bore target to extract coal bed methane [2].

2.1 History of Directional Drilling

Horizontal Directional Drilling can be traced to the early 1990s. Initially, when oil industry was created, only vertical wells were drilled. However, there was no way of telling if the drilled well was actually vertical or deviated at random angle. No survey instruments were developed at that time to monitor the progress of the drilled wellbore.

Only in the 1920s, people discovered that initially drilled vertical wells were, in fact, deviating through drilling process at their own will, with the inclinations up to 500 from their path. Since reservoirs were located deep under the earth, intermediate soil and rock strata with faults and dips, caused drilling bit to take deviation. Additionally, applied weight on bit caused drill string to bend and deviate under certain angle, [3].

In the 1980s, technologies such as steerable motors, PDC drill bits and MWD systems were developed and introduced to Directional Drilling, enhancing the productivity and performance of the drilling process, keeping accuracy of the deviated well according to plan. With implementation of these tools, operators eliminated the requirement in continuous changing of the BHA. Nevertheless, some constraints were detected as well. Frequent requirement of exchanging between the drilling modes while using steerable motors. The introduction of required tool adjustments were troublesome, particularly in longer sections, as well as cleaning the hole without the rotation of the drill string.

That's when Rotary steerable systems were developed, enhancing the well bore quality with drill string rotation allowed adequate hole cleaning, deviation of the tools according to plan with real time information while drilling. In the 1990s, Power-Drive system was developed by Schlumberger, which was huge development and progressed Directional Drilling on the new path.

Nowadays, Directional Drilling becoming more efficient and economical by development of new equipment, protocols and enhanced software, [4].

2.2 Definitions and Terminology

Directional drilling is used to reach determined objective below under specific inclination of the well. In order to properly execute given task, engineers must plan the trajectory of the well to complete the task in a safe and efficient matter.
Vertical wells are usually defined as wells with an inclination of ± 5^0. Wells with inclination more than 60^0 defined as highly deviated and well that are 80^0 and more as horizonal wells. There are set of parameters that are outmost important while drilling deviated wells:

- Azimuth: The angle between the north direction and the plane containing the vertical line through the wellhead and the vertical line through the target.
- Build-up rate: The angle from the kick-off point is steadily built up. The built-up rate (^{0}/30m) is the rate at which the angle is built.
- Drop-off point: The depth where the hole angle begins to drop off.
- Displacement: The horizontal distance between the vertical lines passing through the target and the wellhead.
- Inclination: Angle made by the tangential section of the hole with the vertical.
- Measured Depth: Depth (length) of the well along the well path.
- Tangent Section: Section of a well where the well path is maintained at a certain inclination with the intent of advancing in both TVF and vertical section. Short tangential sections are built for housing submersible pumps for example.
- True vertical depth: Vertical distance between Kelly bushing and survey point.
- Vertical Section: Pre-defined azimuth angle along which the VS is calculated, usually the angle between the north and a line uniting the wellhead and the total depth, measured on a plan view.
- Well path: The trajectory of a directionally drilled well in three dimensions.

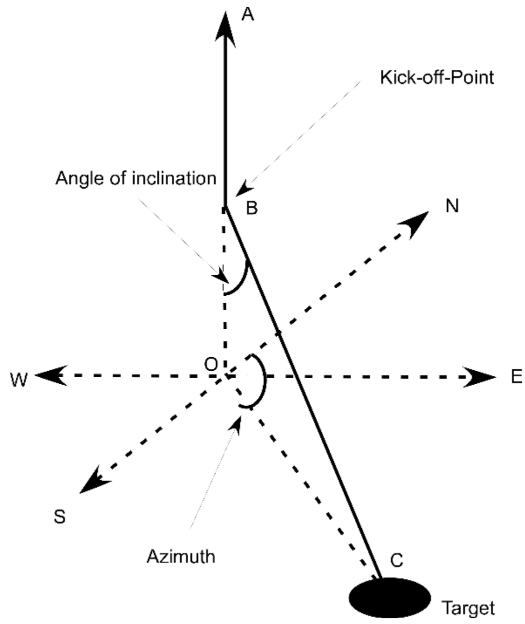


Figure 2.1: Measurement Parameters of a directional well, [5].

2.3 Planning of Well Trajectory

The directional well is planned along pre-planned trajectory in order to reach a target depth. Target may even be adjusted in real time according to Logging While Drilling measurements.

Directional wells are usually drilled in order to reach highly difficult targets, to increase the production from several reservoirs at the time. Some of the applications are shown in the **Figure 2.2**, [5].

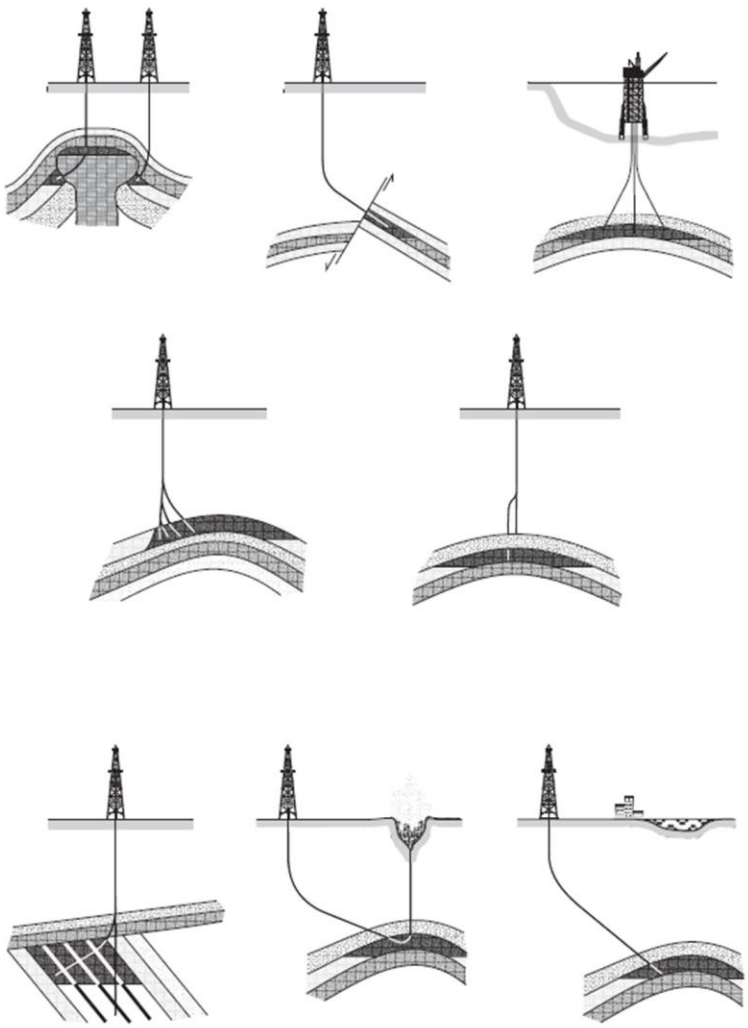


Figure 2.2: Directional Drilled wells, [6].

Geologists and reservoir engineers decide the optimal place of the wellbore to be drilled. They may determine a single target, which often will be tolerance of 100m around a certain target point. The angle at which well reaches the target may have various degrees of deviation from the plan, since the plan requires to hit one target. However, it might be necessary for well to penetrate more than one targets, with the final target being increasingly complex. For this purpose, we require a "geosteering". For this reason, drilling engineer needs to examine potential surface locations and design a well path which will meet the optimal requirements at relatively lowest possible cost expenditures, [6].

Well Profiles

Well profiles can be divided into two main groups, which are 2D and 3D designs

- **2D Well Profile Design:** is a profile which inclinations are changed in order to hit the target but without any change in azimuth, (**Figures 2.3,**)

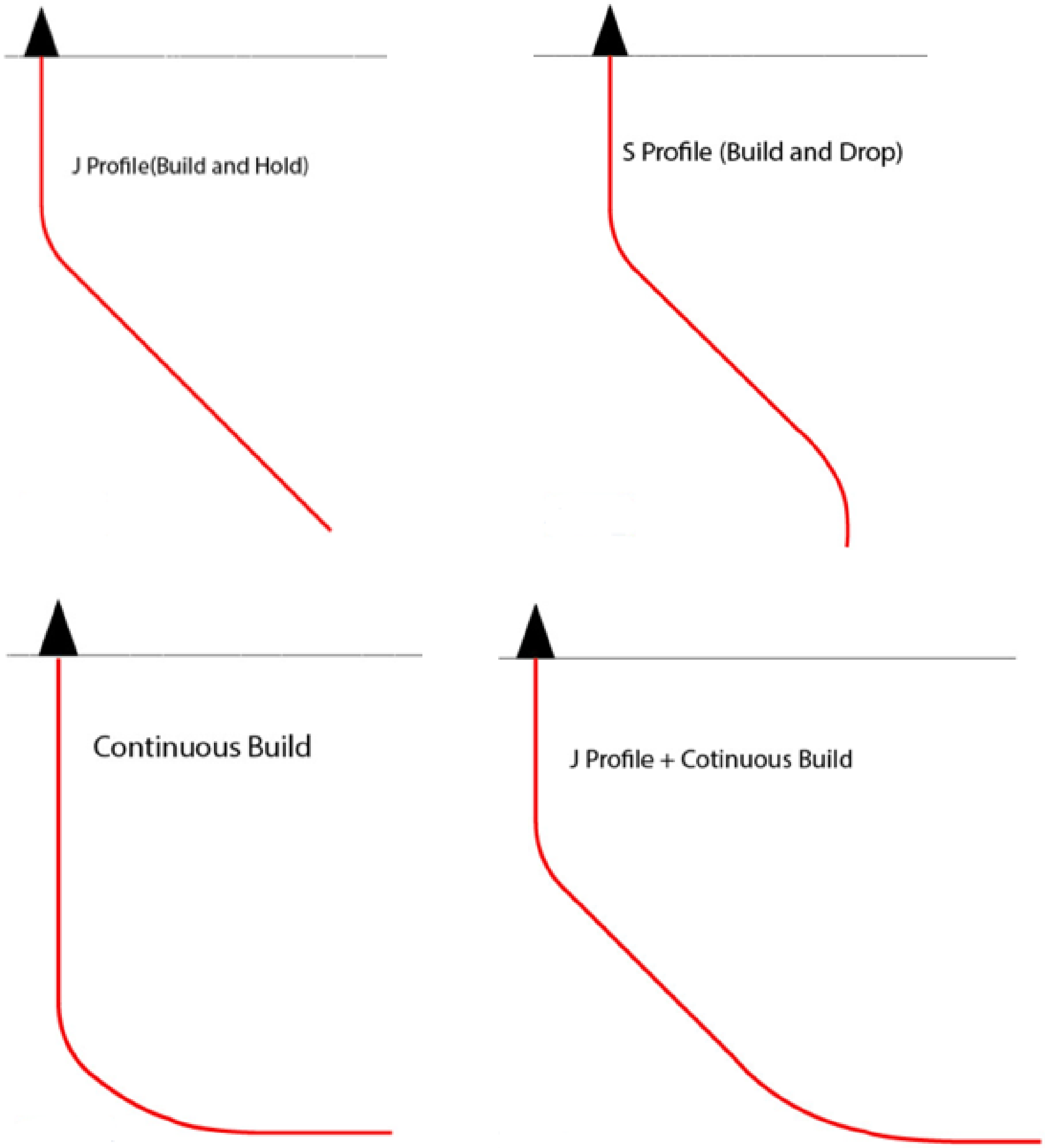


Figure 2.3: 2D Well Profiles, [7]

- **3D Well Profile Design:** in 3D Profile design, we may see changes in both azimuth and inclination. The example of 3D well profile shown in **Figure 2.4**:

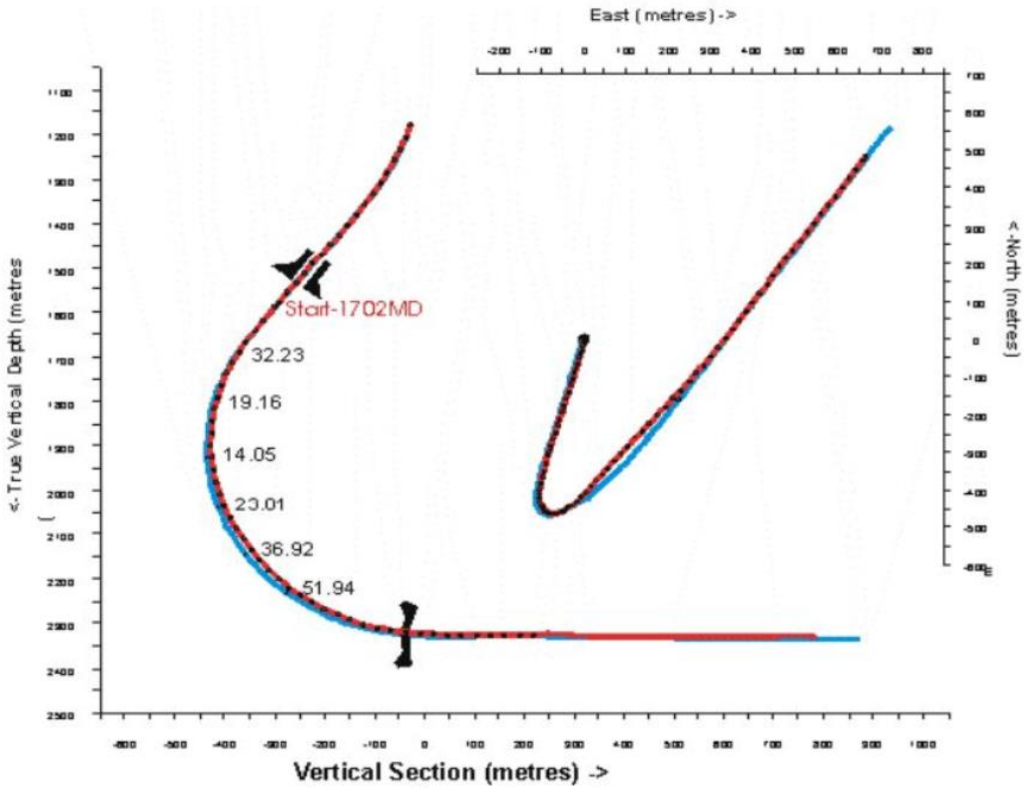


Figure 2.4: 3D Well Profile, [7].

Example of Well Planning

The final planning (**Figure 2.5**) of a well profile include vertical view and a plane view. Relatively simple directional well, with the design of hitting 2 targets. J-shaped profile wells, which is a build and hold to the target, are considered the easiest type of directional wells, [7].

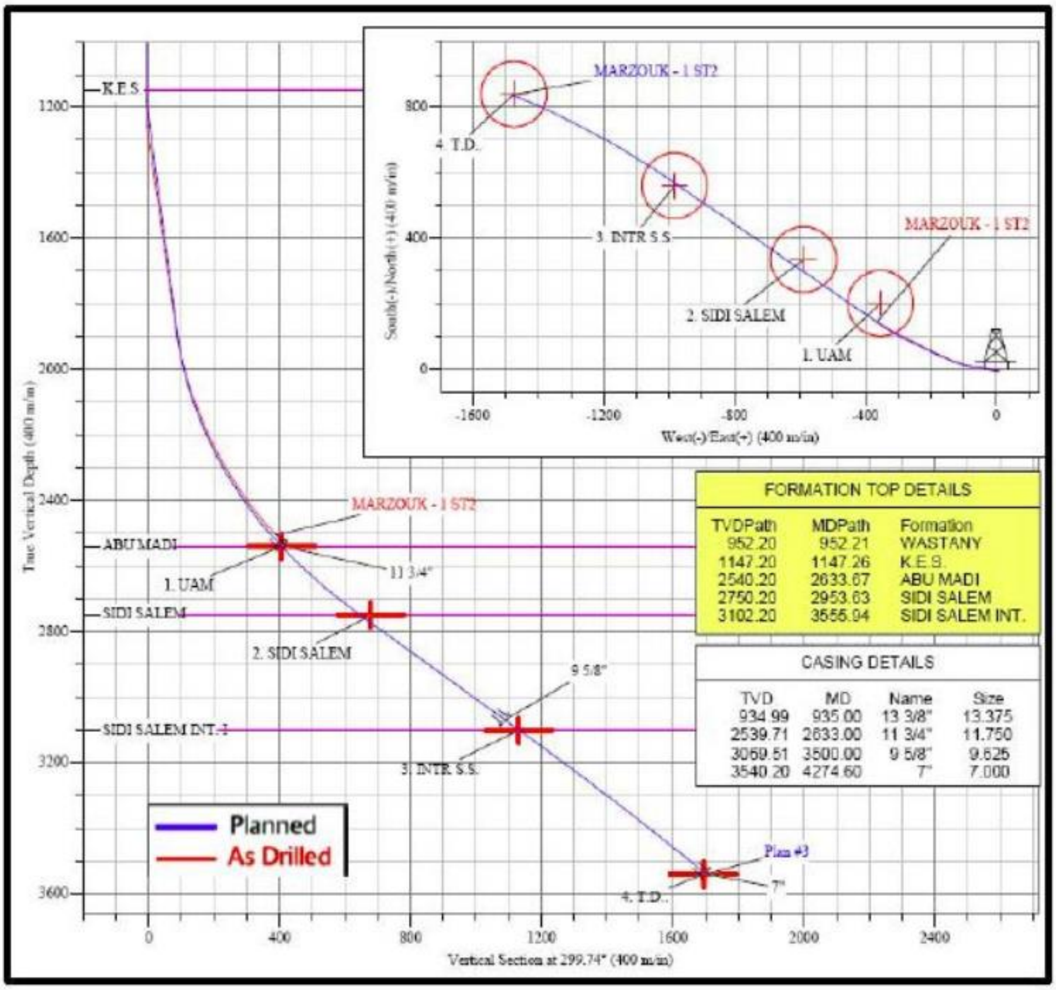


Figure 2.5: J Profile Directional well plan (Jones et al., 2008), [7].

Applications of Directional Drilling Sidetracking

While drilling operations, the drilling string may get stuck due to the hole instabilities or can be lost in hole due to string failure. The stuck equipment is addressed as fish. Some cases, where drillers unable to retrieve the fish, the well has to be sidetracked. It starts by setting cement plug several meters on top of the fish, to allow a foundation upon which the kick off of the well bore will commence. Next, whipstock or positive displacement motors will be used with MWD tools. Sidetracking may also be performed in a cased hole, where window is milled and the wellbore is directed across this window, [8].

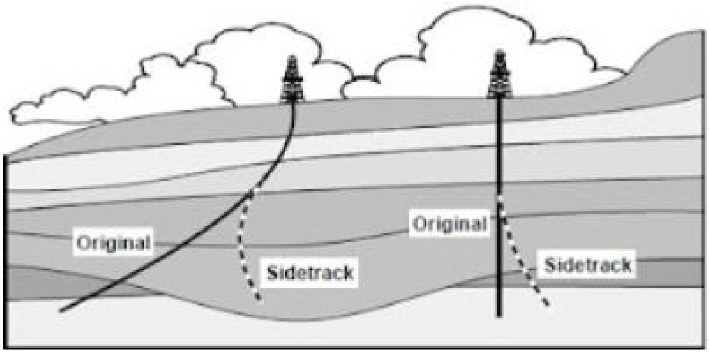


Figure 2.6: Sidetracking

Overcoming Geological Problems

While drilling, some situations require different angle of approach. Difficulties in drilling due to types of formation such as passing through a fault or drilling through a salt dome. Major problems while drilling through a salt dome can cause large washouts, corrosion and loss of circulation. In the moments like this, directional drilling is used to bypass this type of formation structures. In case of inclined fault, drilling bit deflect, causing deviation and may result in high inclination which may lead to stuck of drill string and even lost in hole equipment. Using directional drilling, helps to drill perpendicularly towards the faulted formation without crossing the fault line, [8].

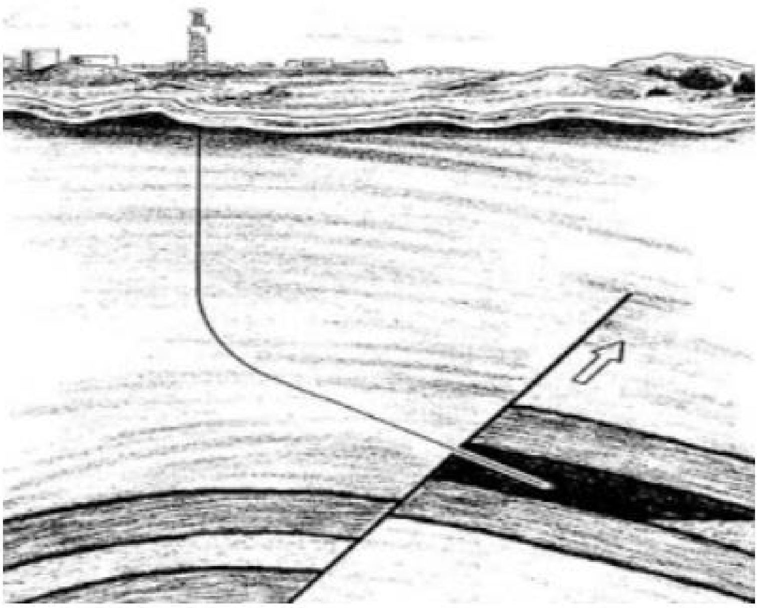


Figure 2.7: Fault drilling

Inaccessible Locations

Sometimes the target can't be reached by drilling vertical well. For reasons such as: inaccessible rig placement, infrastructural constraints, environmental endangered places where hydrocarbon reservoirs are preserved. Directional drilling may provide solution with accessing such reservoirs. The same solution can be applied for offshore drilling where locations can be restricted due to shallow gas zones or environmental issues, [8].

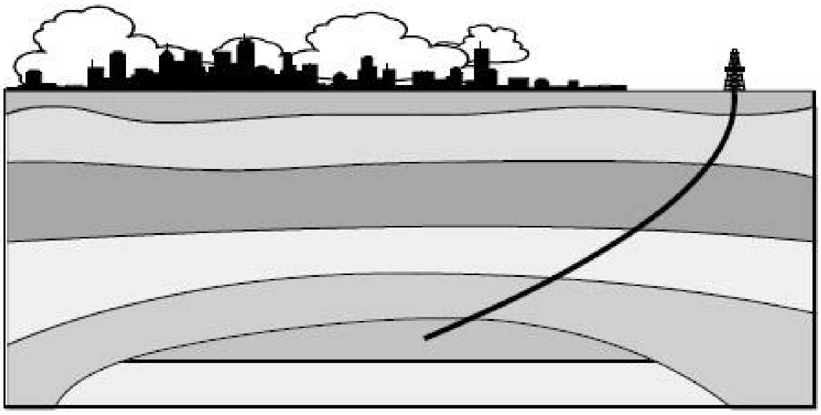


Figure 2.8: Inaccessible Locations

Multiple Wells from Offshore Location

In offshore, it is uneconomical and impractical to drill multiple well to reach several reservoirs beneath the seabed. With careful planning single wellbore may be sidetracked and provide production from given reservoirs, [8].

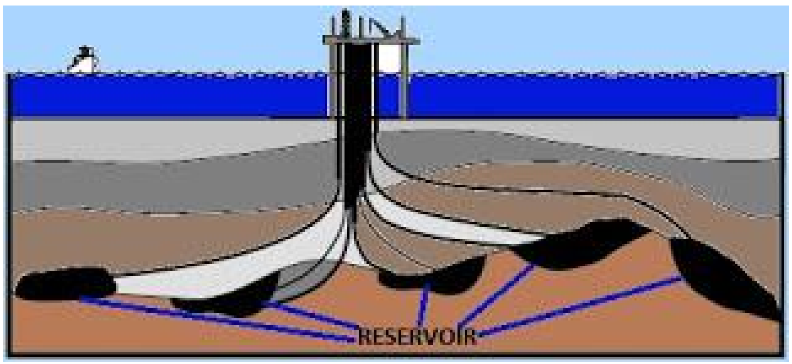


Figure 2.9: Multiple Wells

Horizontal Drilling

The wells that are inclined higher than 70^0 angle are considered horizontal wells. Drilling these types of wells may be complex which consecutively increase the drilling cost and rig time. However, horizontal wells provide many advantages, such as, [8]:

- Increasing drainage area
- Overcoming gas and water coning
- Increasing the contact area with reservoir
- Increasing the productivity by intersecting vertical fractures

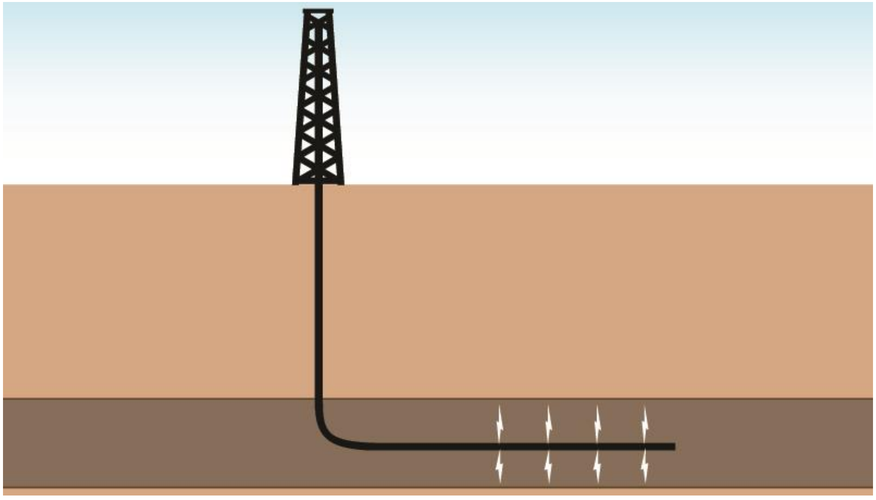


Figure 2.10: Horizontal Well, [8].

Relief Wells

Drilling is not an easy task to accomplish. As we progress deeper, pore pressure increases which may result in kick or even worse blowout. In case failure of well control equipment, resulting in blowout, a deviated well may be proposed as the solution. Deviated well is drilled from an adjacent surface location to the source of uncontrolled flow location as close as possible or even to the uncontrolled well itself. Once the target has been reached, a kill mud is pumped to acquire control, [8].

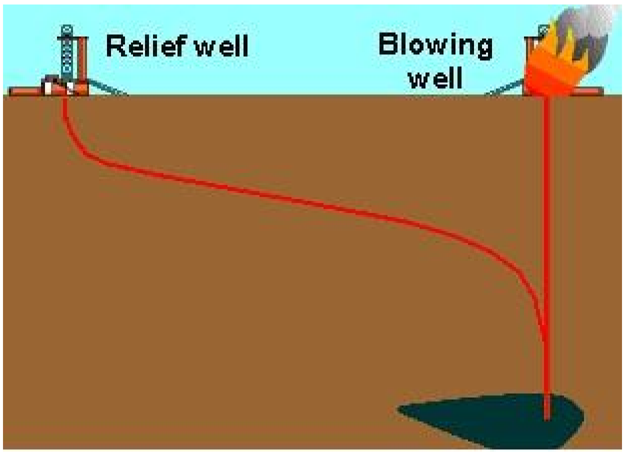


Figure 2.11: Relief Well, [8].

3 DIRECTIONAL DRILLING TECHNIQUES

3.1 Overview

While drilling deviated well, directional engineer must rely on magnetometer, accelerometer and gyroscope, in order to accurately pinpoint the direction of drilling well, in order to avoid consequential problems. By doing so, we minimize uncertainty of wellbore positioning, which is necessary for:

- Anti-collision with offset wells
- Relief wells
- High quality of logging data / geosteering in reservoir sections of the hole
- Accurate reserve estimation and optimized hydrocarbon recovery while drilling appraisal well

3.2 Measurements While Directional Drilling

Specific tools such as MWD (Measurement While Drilling), LWD (Logging While Drilling, PWD (Pressure While Drilling are used to transmit collected data from downhole to surface in real time, usually through drilling mud. The importance in borehole diameter measurement is to emit a sonic signal and measure two-way travel time, as the signal passes from downhole tool to the wellbore wall and back again. There are plenty of downhole complications, such as centering in the wellbore (**Figure 2.12**), but most of these complications are taken care of by integrated tool's algorithms. High level of gas in mud may interfere and alter the travel time significantly, resulting in major errors in measurement. In this case, sonic sensors will generally provide an early time warning in presence of gas, [6].

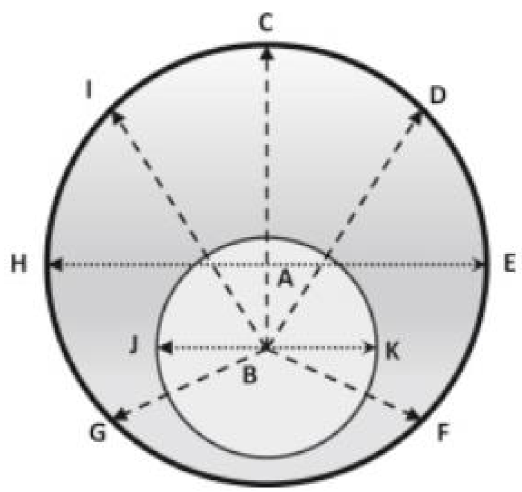


Figure 2.12: Tool centering in the wellbore, [6].

3.3 Directional BHA

3.3.1 Bottom Hole Assembly

The Bottom Hole Assembly (BHA) is a key component of the drilling system, consisting of various components and tools (including the drill bit itself) which operate at the bottom of the wellbore and physically drill the rock.

The bottom hole assembly is connected to drilling rig by interconnected drill pipes, an extendable hollow tube which conveys the mechanical and hydraulic energy and movement from the surface rig systems to the bottom hole assembly. Given complex set of tools varies considerably, depending on necessities, and can be extended up to 300 m long. BHAs became more and more complex over time to suit the needs of drilling operations and to accommodate different types of tools that have been developed. The main objective of BHA is to effectively load and control the drilling bit, however it also provides other functions as well, [9].

3.3.2 BHA Design

While designing the BHA, drillers must take into consideration that the operational objectives, rock characteristics that are being drilled, drilling parameters, and available tools. Objectives that should be considered include – drilling angle, directional and depth targets, the expected ROP, and achieving designed build/drop rate. The geological characteristics that should influence the design of the BHA include the abrasiveness and competency of the rock, bed dip angles, and the pressure regime in the hole being drilled. RPM range, desired WOB, torque, and the anticipated shock or vibration pattern must be planned while designing BHA, [9].

A drilling assembly (**Figure 3.1 a, b**) mainly consists of a surface drill rig and a downhole drill string, containing numbers of drill pipes, and a BHA, which comprises drill collars (DC), stabilizers, bit and additional downhole equipment. Drilling process of a wellbore is a complicated dynamical process— the high-speed rotating bit scraps the surrounding rocks, the BHA controls the orientation of the bit, the top drive system and drawworks work together to apply a rotational and downward force on drill pipes to drill effectively and deeper, and new drill pipes are mounted on from the rig floor to prolong the drill string. In other words, the drilling direction is a result of dynamics and control. The dynamics is resulted from the interaction between the bit and rocks, and flexible deformation of the bottom hole assembly and drill pipes; and the control comes from the manipulation of the top drive and drawworks. To obtain a satisfactory directional drilling performance, *fast* and *accurate* steerability prediction of a drilling assembly is a prerequisite, which is usually characterized by the build rate. The build rate is defined as the increase of the inclination of an advancing borehole after drilling every 30 mand, showed here as a quantitative parameter to analyze the steering ability of a BHA. Nonetheless, accurate prediction of the build rate is a challenging problem, as the steering performance will not only be influenced by different BHA configurations, such as the steerable motor assembly, conventional rotary BHA, and rotary steerable system (RSS) (**Figure 3.1c**), but also the drilling parameters and formation properties. Although great efforts have been made to propose various methods to evaluate the build rate, the state-of-the-art progress is still far away from satisfactory in engineering, and there remains vast space for improvement, [10].

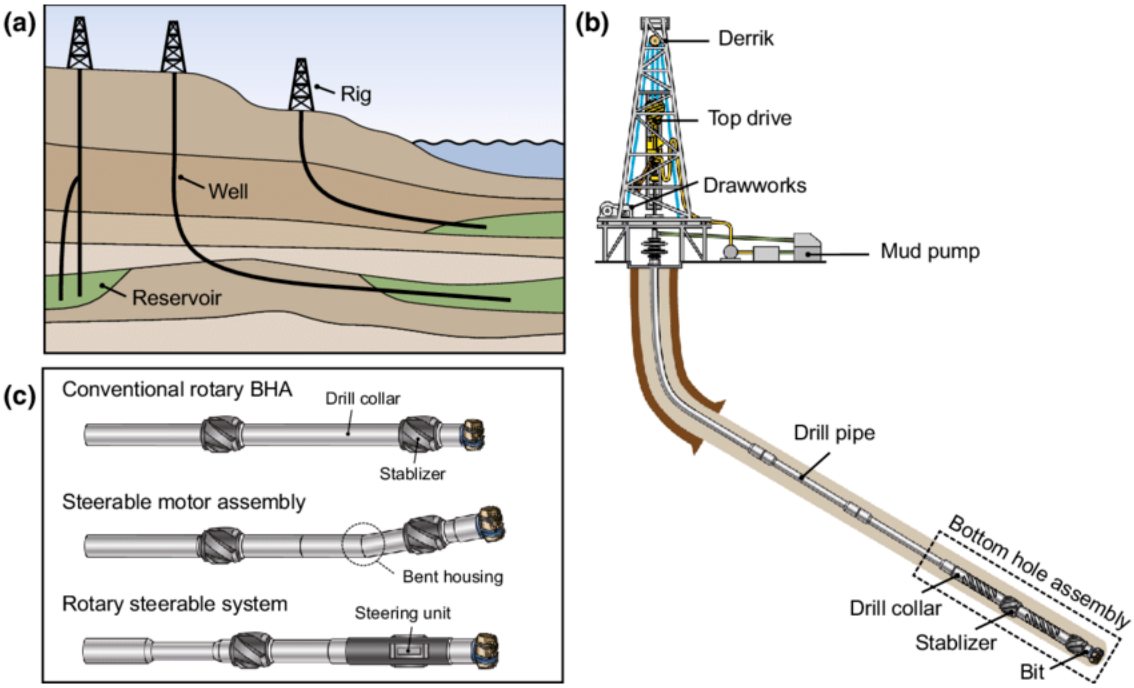


Figure 3.1: A) Applications of directional wells: single surface location for multiple wells, onshore drilling to an offshore reservoir, B) schematic representation of a typical drilling system, C) three typical kinds of BHAs widely used in the oil field, including the conventional rotary BHA, the steerable motor assembly, and the RSS, [10].

3.3.3 Directional BHA Components

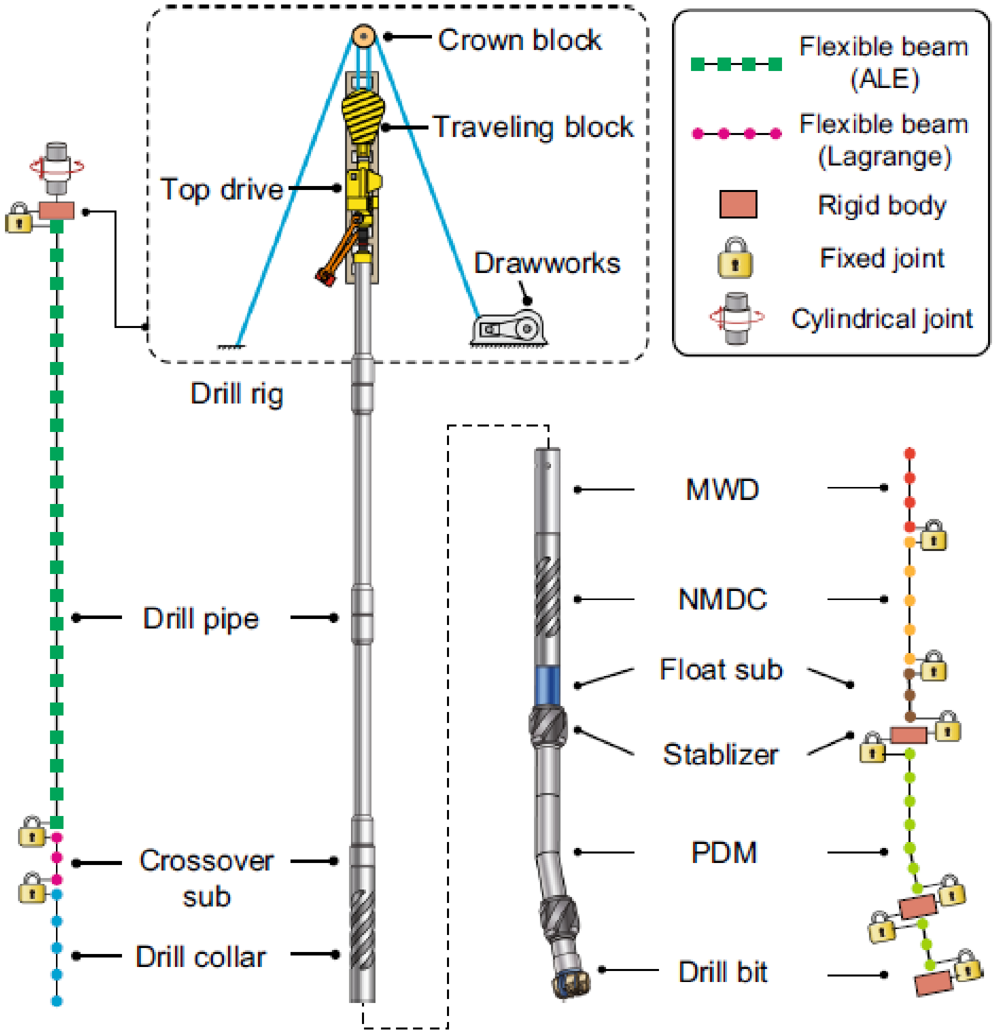


Figure 3.2: Schematic of the whole drilling system and its multibody dynamic model. The length of the drill pipes is greatly reduced to clearly illustrate such a slender system, [10].

Common BHA components that are used in Directional Drilling are shown in the (**Figure 3.2**). Each component of the BHA has an important role:

- **MWD:** MWD tools are generally capable of taking directional surveys in real time. The tool uses accelerometers and magnetometers to measure the inclination and azimuth of the wellbore at that location, and they then transmit that information to the surface. With a series of surveys; measurements of inclination, azimuth, and tool face, at appropriate intervals, the location of the wellbore can be calculated.

- **NMDC:** The primary purpose of non-magnetic drill collars is to reduce the interference of the magnetic fields associated with those sections of the BHA which are both above the below the magnetic compass contained in the survey tool with the earth's magnetic field.

- **Float Sub:** Float subs are adapters that are machined with float bore inside that allows to run a float valve. These are also available as a float crossover sub. Float subs are used ti house a float valve, also known as a back pressure valve.

- **Stabilizer:** A drilling stabilizer is a piece of downhole equipment used in the bottom hole assembly (BHA) of a drill string. It mechanically stabilizes the BHA in the borehole in order to avoid unintentional sidetracking, vibrations, and ensure the quality of the hole being drilled. It is composed of a hollow cylindrical body and stabilizing blades, both made of high-strength steel. The blades can be either straight or spiralled, and are hardfaced for wear resistance.

- **PDM:** A positive displacement motor (PDM) is a hydraulically driven downhole motor that uses the Moineau principle to rotate the bit, independent of drill string rotation. The PDM is made up of several sections:
  - By-pass valve or dump sub.
  - Motor Section.
  - Universal joint or connecting rod section.
  - Bearing section with drive sub.

- **Drill bit**: A drill bit is a tool designed to produce a generally cylindrical hole (wellbore) in the earth's crust by the rotary drilling method for the discovery and extraction of hydrocarbons such as crude oil and natural gas

3.4 Rotary Steerable Systems

The techniques of Directional Drilling can be summarized in two main points: POB (point-to-bit) and PUB (push-the-bit). POB is related to bending of the BHA into the desired direction during drilling, where as PUB is involved in pushing the bit in the directional perpendicular to the axis of the drilling string, achieving desired curved well. Downhole mud motors and bent subs were being implemented for many years now, since they showed their effectiveness, reliability and economical suitable solution for deviated wells. However, one of the main difficulty using mud motors is unavailability of rotation of Drill String, once the tool face is pointed to the desired direction, which may create problems such as pipe sticking or pack-off of tools, since cutting are not being rotated and could create a cutting bed, [11].

On the other hand, rotary steerable systems are designed to drill deviated holes with continuous rotation of the drilling string from the surface, greatly increasing the effectiveness in hole cleaning. RSSs have minimal interaction with wellbore wall, preserving hole quality, [12].

Two main components are included in RSS: the control platform and biasing mechanism. Control platform serves as a brain of the rotary guiding system, controlling the direction of the biasing mechanism. Where as biasing mechanism serves as an actuator for rotary steerable system. As a standard, RSS actuator is a 3-pad tool, which directs the string by pushing on of the pad against the formation, [11].

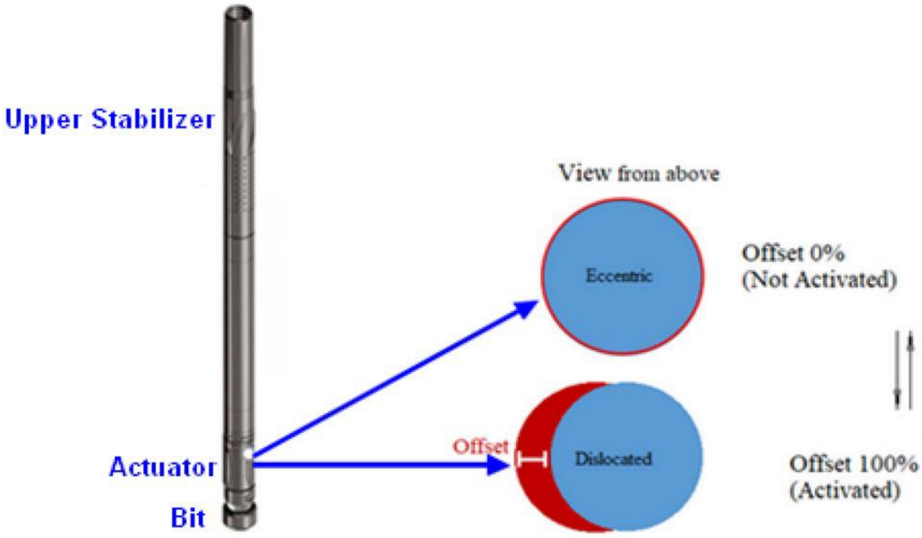


Figure 3.3: RSS work principle, [11].

Moreover, these two steering technologies can be further categorized into mechanical and hydraulic according to the offset mechanism. As (**Figure 3.4**) shows, the RSS technologies can be classified with different characteristic features such as non-rotating and strapdown, dynamic and static, and internal push and external push force.

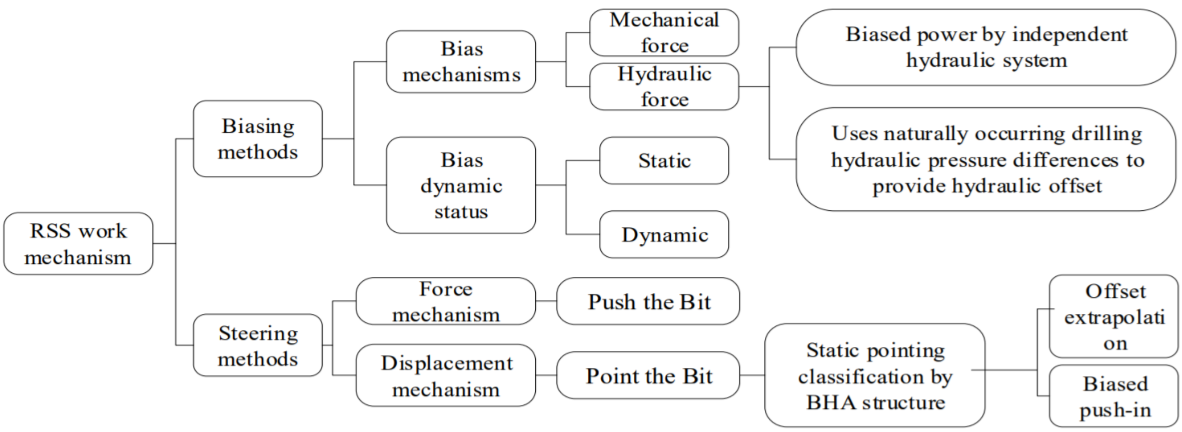


Figure 3.4: Classification of RSS Tools, [13].

According to the Market survey Spears, starting from mid-2012, RSS technology has occupied more than 50% of the DD market, and by 2020, quantity increased to more than 70%. (**Table 3.1**) shows the details of the classification of the rotary steerable system technologies, [13].

Table 3.1: Classification of the RSS Technologies, [13].

Company	RSS	Types of Mechanisms	Control Platform Type
Schlumberger	Archer	Hybrid	Geostationary
	Xceed	Push-the-bit	Strapdown
	PD X6	Push-the-bit	Geostationary
	ICE	Push-the-bit	Strapdown
Halliburton	Geopilot	Push-the-bit	Strapdown
Baker Hughes	Autotrac	Push-the-bit	Strapdown
Weatherford	Revolution	Push-the-bit	Geostationary
	Magnus	Push-the-bit	Strapdown
NOV	Vector	Push-the-bit	Strapdown
Terravici	Terravici	Push-the-bit	Strapdown
Gyrodata	Well Guide	Push-the-bit	Geostationary
APS	SureSteer	Push-the-bit	Strapdown
Sanvean	Scott	Push-the-bit	Geostationary

3.4.1 Comparison of RSS Tools

At present, the RSS technology of foreign oilfield service companies such as Schlumberger, Halliburton, Baker Hughes and Weatherford is relatively mature and advanced. A comparison of these RSS technologies is given in (**Table 3.2)**:

Table 3.2: Comparison of advantages and disadvantages of different RSS technologies, [13].

Type	RSS	Advantages	Disadvantages
Static push the Bit	AutoTrak RCLS	1 - For highly difficult horizontal wells, large-angle directional wells and ultra-large displacement directional wells, the drilling cost is lower. 2 - Long tool life. 3 - High precision of real-time direction control	1 - In wellbores where the borehole is enlarged, or the formation is soft and lacks sufficient support, the ribs tend to stick. 1 - The structure is complex, and the DLS is low. 3 - Due to the high friction, it is difficult to transfer weight to the drill bit.
Dynamic push the Bit	PowerDrive X6	(1) As the component rotates, the friction is reduced. 1 - The structure is relatively simple. 3 - Good directional performance.	1 - If the drilling pressure difference is small, it will cause insufficient thrust. 2 - The severe wear of the drill bit and its bearing will lead to a shortened service life of the drill.
Static bias extrapolation pointing	Well-Guide RSS, Revolution	1 - The guiding effect of the tool is not affected by the formation environment. 2 - More regular holes can be drilled to reduce spirals and protrusions.	1 - Due to a large number of rotating parts of the mandrel and the strict resistance requirements for the parts, the manufacturing cost and drilling cost of the drilling tool are relatively high. 2 - The mandrel is easily damaged by fatigue.
Static biased push-in pointing	Geo-Pilot, Power Drive-Direct		

In **(Table 3.3)**, we can see the comparison of key indicators of different 4.75-inch RSS tools. The outer diameter of the 4.75-inch rotary steerable system tool is the smallest, but the Dog Leg Severity value is relatively higher. Between the tools indicated above, the PowerDrive Archer 475 from Schlumberger can provide DLS at 18 degrees/100 feet, which is up to this day the highest DLS value. Temperature and pressure withstanding capabilities, Baker Hughes' 4.75" AutoTrak eXact is the favorite. Baker Hughes' eXact tool is tailor-made for high temperature and pressure applications, and is more suitable for drilling in high temperature and high-pressure zones than other companies' tools. Among the tools listed above, the sensor placement, Baker Hughes' eXact tool has a sensor distance between 5.9 ft (14.986 cm) and 11.25 ft (28.575). Majority of presented tools can be rotated to 250 RPM, except for Weatherford's Revolution 475 RSS, which can only reach 200 RPM. **Figure 3.5** shows the performance of these tools in a pentagon graph, [13].

Table 3.3: Comparison of key indicators of the different 4.75-inch RSS, [13].

Company	**RSS Series**	**Max DLS (^{0}/100 ft)**	**Maximum Temp (degC)**	**Max Pressure (psi)**	**Sensor distance (ft)**	**Maximum RPM (rpm)**
Baker Hughes	4.75 AutoTrak eXact	12	165	30,000	5.9	250
Gyrodata E	Well-Guide 4-100	12	150	20,000	11.25	250
Haliburton	Geo-Pilot XL RSS 5200 Series	14	150	20,000	10	250
Schlumberger	PowerDrive Archer 475	18	150	20,000	8.2	250
Weatherford	Revolution 475 RSS	10	150	25,000	9	200

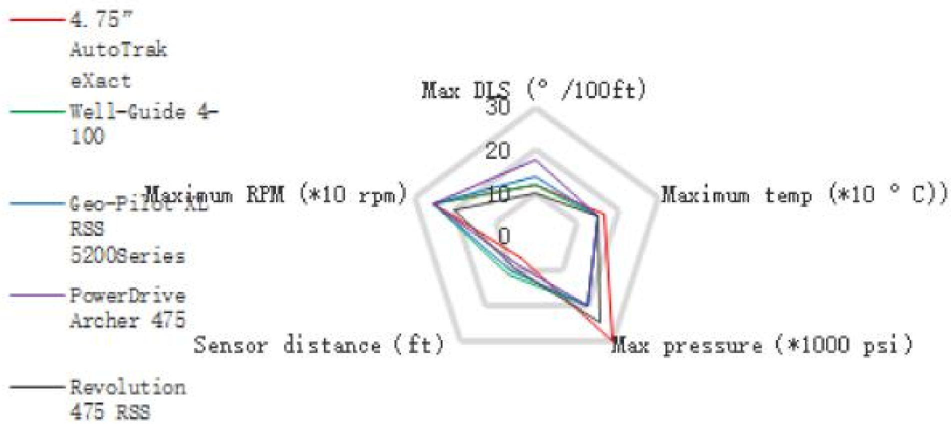


Figure 3.5: Comparison of performance indicators of 4.75-inch RSS Tools, [13].

Nowadays, RSS tools are essential part of equipment in the exploitation of oil and gas resources. However, this technology is only fully mastered by a several foreign oil service companies. Therefore, to expand the company's international market and maintain its leading position, major oil service companies keep continuously upgrading their technologies and replace their tools. The market share of several major oil service companies in the directional drilling market is shown in (**Figure 3.6**).

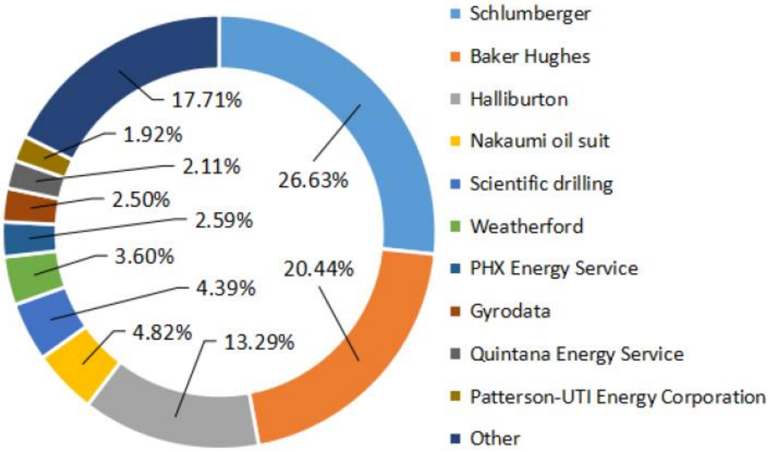


Figure 3.6: 2019 Petroleum Service Company's Rotary Steering Tool Market Share Comparison, [13].

From the perspective of market share in 2019, Schlumberger, Baker Hughes and Halliburton, the three major international oil service companies, account for more than 50% of the global directional drilling market, [13].

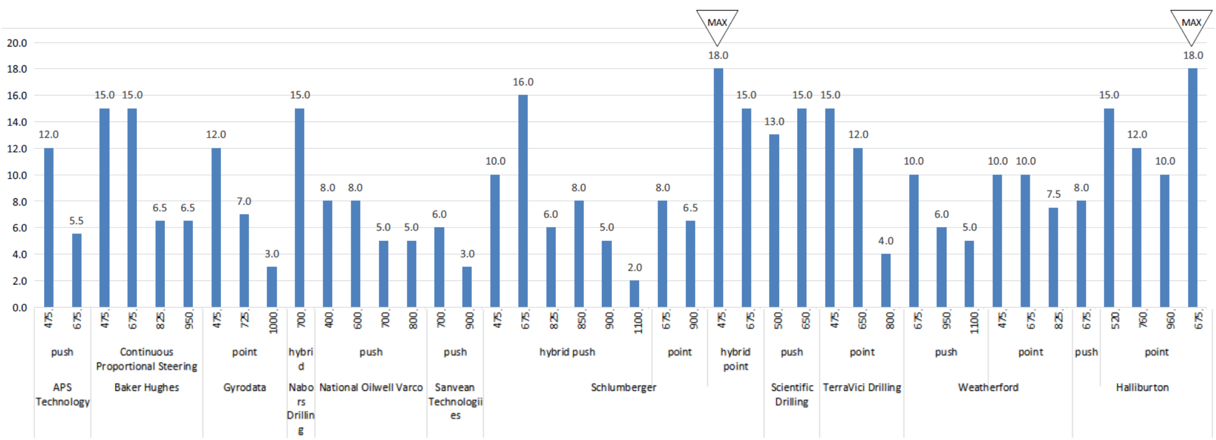


Figure 3.7: Comparison of the maximum dogleg of the RSS of the major oil service companies, [13].

3.4.2 Modelling of Steerability

Before drilling directional well, the modelling of the wellbore is performed in order to analyse the if the drilling performance (ROP, WOB, integrity of the pipes and connections) could withstand against the bending properties. Mainly, two models are analysed: mathematical model and analytical model.

Calculation of mathematical model includes: Defining Target Point, Calculation Offset, Calculation Natural Displacement, Calculation Forces on the Bit, Calculation Resultant Force on the Bit caused by the RSS on each place of reference, Calculation ROP Composition, Calculation TVD, MD, DLS, Inclination, Azimuth, Horizontal Displacement, North and East Coordinates, [11].

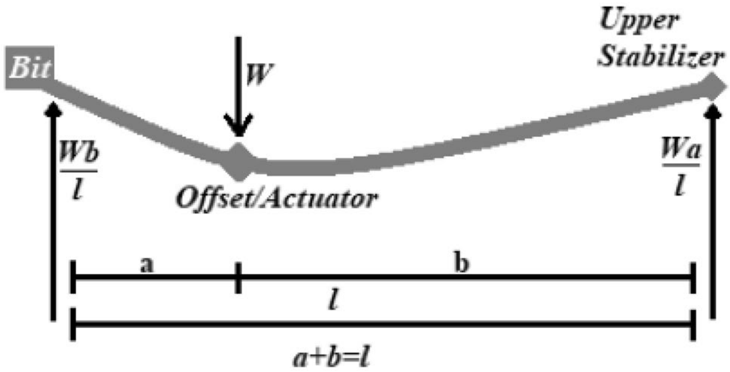


Figure 3.8: Beam bending analysis, [11].

After calculation of parameters, mathematical model can be expressed in 2D and 3D Coordinates.

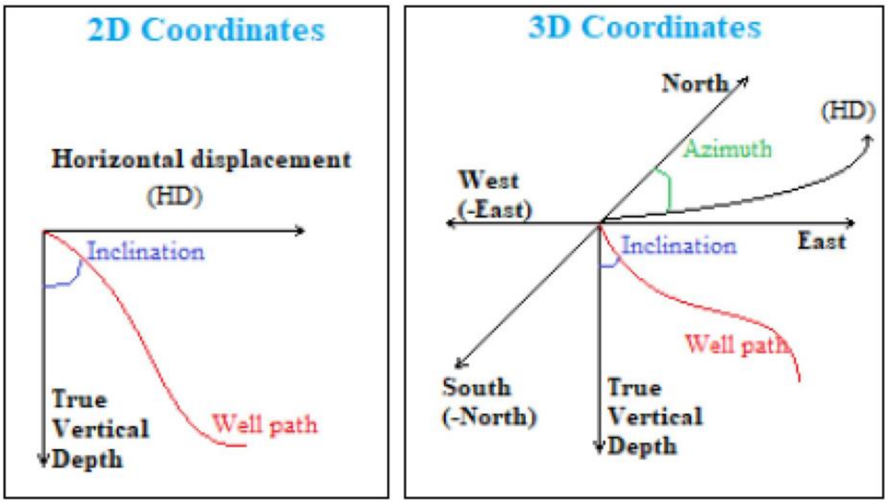


Figure 3.9: 2D and 3D cases for well path visualization, [11].

3D trajectory, aims to steer the bit to reach target inclination and azimuth. Whereas 2D scenario, model considers the inclination variations. Compared with 2D coordinates, 3D coordinate considers the offset displacement. **Figure 3.9** shows how these displacements look in 3D and 2D coordinates, [11].

4 HORIZONTAL DIRECTIONAL DRILLING

4.1 History of Horizontal Directional Drilling (HDD)

It is reported that the directional horizontal drilling process was developed in the United States and has become widely used for infrastructure development such as laying pipelines under man-made or natural obstacles, especially rivers, buildings, roads. This method revolutionized pipeline obstruction bypassing by dredging techniques or redirecting longer distances and crossing at a specific point on the bridge.

This method has revolutionized drilling technology. It was first developed in the 1970s by Titan Construction in Sacramento, California. The installation was performed in 1971 for Pacific Gas & Electric Co., with approximately 180m (600 ft) of 4 inch steel pipe was laid under the Pajaro River. The method was limited to short lengths up until 1979. However, in 1979, this method was taken over by Reading and Bates Const. company. Since that year, a multiple variety of pipe sizes made the possibility of installation, which was called state of the are.

In the period from 1971 to 1979, by applying this method, only 36 crossings were completed and all of which are located the USA. Over the next seven years, more than 175 crossings were completed globally. Nowadays, competition in the market is enormous, with the installed number of crossings reaching up to 500.

Horizontal drilling has been mainly used in the oil and gas industry on large-diameter transmission lines, which made pathways from country to country. But lately, with the increasing amount, horizontal drilling is being used for small diameter lines for gas distribution as well, mainly in suburban and urban areas. Additionally, telecommunication lines and water pipes are being extended thorough out the cities and even countries.

Horizontal directional drilling has become the optimal method for installation many pipelines and life-dependent utilities as it requires less cost and less environmental damage. The impact on the surface areas are decreased, thus proving that horizontal drilling is an ideal method not only for oil and gas industry but for infrastructural improvement as well, [14].

4.2 Application of Horizontal Directional Drilling

For drilling Horizontal Wells, several Directional Drilling technologies are applied in order to perform the job in an efficient way. These utilities vary from mud motor to Bottom Hole Assembly (BHA) with the addition of advanced RSS (rotary steerable systems) technologies.

But the main challenges that come with Horizontal Drilling are torque and drag and stick-slip. These challenges may jeopardize horizontal section of the well. Due to the acceleration and deceleration in cyclical rotation of equipment such as BHA, drilling bit or drill string, vibrations occur, which are called stick-slip. This challenge may decrease ROP significantly, damaging equipment along the way as well as wellbore stability and acquisition of data.

Horizontal drilling has typical applications in formations as, [15]:

- Fractured Carbonates
- Sandstones

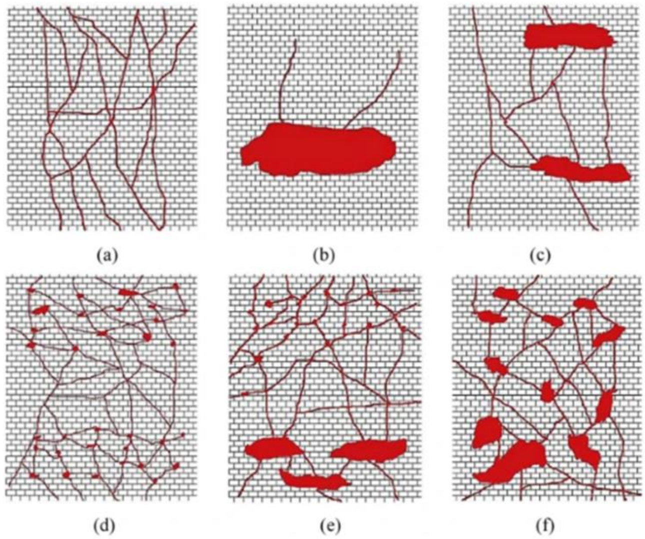


Figure 4.1: Different patterns of fractured-vuggy medium. (a) fracture network; (b) isolated cave; (c) cave-fracture-cave; (d) pore-fracture-pore; (e) pore-fracture-cave; (f) Cave network [24].

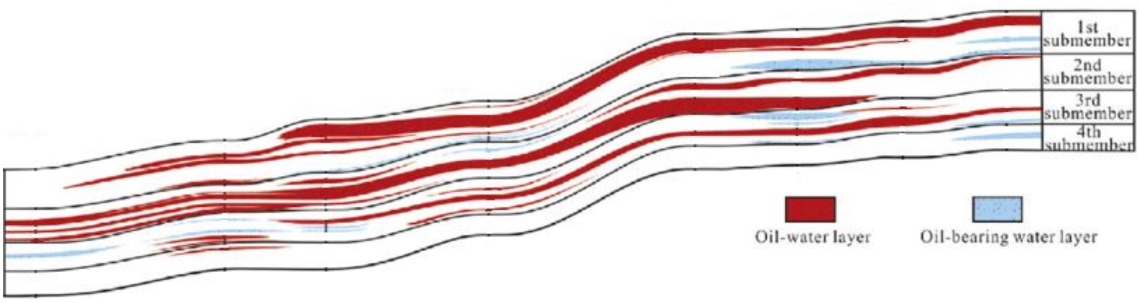


Figure 4.2: The quasi-continuous oil tight sandstone reservoirs, [15].

Given practice cannot be applied indiscriminately, but, it requires selected environments and gives the best results when applied to accurately screened scenarios.

Generally, Horizontal Drilling finds its application in:

- Naturally Fractured Reservoirs;
- Discontinuous Reservoirs;
- Water and Gas Coning Prone Reservoirs;
- Tight Sands and Carbonates;
- Heavy Oil Pools;
- Shallow or Thin Beds;
- Enhanced Oil Recovery Projects.

Drilling of horizontal wells however never comes cheap. The complexity versus to vertical wells exceeds for several times. Thus, the reason for implementing horizontal drilling techniques may be considered according to reservoir conditions for more and advanced production, [15].

The evaluation of reservoir characteristics, geological parameters, surface and downhole conditions with the inclusion of cost expenditures have to be carefully reviewed prior starting with the drilling process..

Geologists, Reservoir and Production Engineers are the most concerned in this phase of the project. Finding, processing and evaluation the suitable reservoir remain an outmost important task, in order to provide with the best outcome. Following parameters must be correctly assessed:

- Reservoir Characteristics;
- Reservoir Potential;
- Actual and Expected Production Rates;
- Production Decline Curve;
- Driving Mechanisms;
- Chances of Gas/Water Coning Problems;
- Thickness, Areal Extent and Geological Heterogeneities of the Reservoir.

Next phase foresees the involvement of the Drilling and Completion Engineers, whose task is to define:

- Hole Geometry;
- Drill String Design;
- Anticipated Hole Drilling Problems (Circulation Losses, Pipe Sticking, Hole Cleaning, Torque and Drag, etc.);
- Casing Design;
- Mud and Cementing Programmes;
- Hydraulic Programme;
- Bit Selection;

- Deviation and Orientation Equipment Selection;
- Completion, Stimulation and Work-over Requirements;
- Drilling and Completion Costs.

Table below shows the "Good Candidates" and "Poor Candidates" for Horizontal Drilling:

Table 4.1: Good and Poor Reservoir Candidates for Horizontal Drilling, [15].

Good Candidates	Poor Candidates
Gas or Water Coning Tendencies	Lease Constraints
Low Permeability	Low Productivity or Depleted Reservoirs
Low Virgin Formation Pressure	Severe Drilling and Completion Problems
Natural Vertical Fractures	Thin and Multilayered Reservoirs
Thin or Tight Reservoirs	Thick Pays with Low Vertical Permeability
Viscous oil Reservoirs	Marginal Economical Fields
Faulted / Discontinued Zones	

4.2.1 Advantages and Disadvantages of Horizontal Drilling

4.2.1.1 Advantages of Horizontal Drilling

Here are several advantages of Horizontal Drilling:

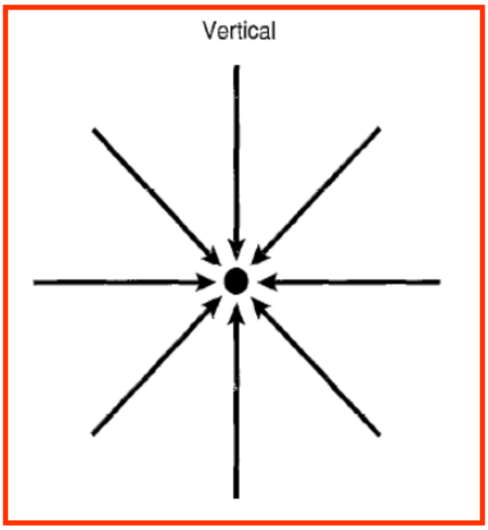
- Increased productivity because of a longer section of hole exposed
- Increased productivity through the connection of vertical or subvertical fractures
- Avoidance of problems by means of gas and water coning control
- Many other applications such as: drilling around topographical restrictions, production of gas from coal seams, minimization of environmental impact, EOR project enhancement, etc, [15].

Increased Productivity:

Horizontal wells provide with higher rates of production. Due to the higher exposure of horizontal section of the well to reservoir zone, horizontal wells may produce 20 times more compared to vertical or even directional wells.

Increased production can minimize the number of infilling wells required to develop a field and, consequently, the number and size of platforms and other infrastructures.

The productivity index rises according to the fluid flow and drainage patterns, that horizontal wells provide, such as uniform pressure drop and parallel flow. Where as vertical wells provide uniform pressure drops and radial flow. Thus, this brings to lower pressure drops all around the drilled wellbore, which determines less solid and fine particles migration and lower fluid velocities. Additionally, horizontal section of the well helps with the reduction of gas and water coning, [15].



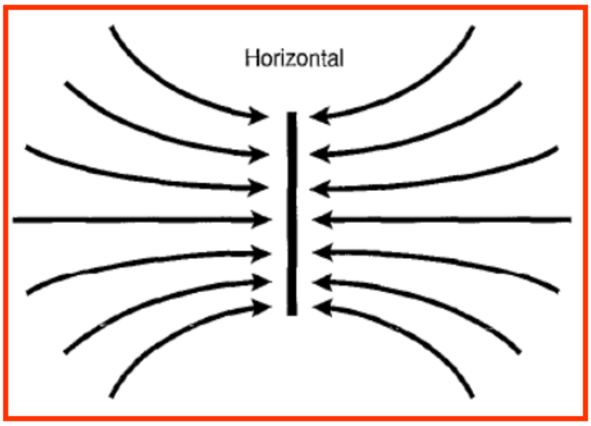


Figure 4.3: Comparison of flow geometries of vertical and horizontal wells, [15].

Factors influencing Horizontal Well productivity:

The main factors influencing horizontal well productivity are:

- Reservoir Thickness
- Lateral Length
- Reservoir Heterogeneities, such as: Faults, Shale Layers, Permeability
- Variations, etc.
- Ratio of Vertical to Horizontal Permeability
- Lateral Location within the Reservoir

In case of the pressure drawdown is equal in horizontal and vertical wells, and with the equal permeabilities between them, the J_h/J_v ratio decreases, just as the thickness of the reservoir increases: i.e., for a 25 ft (7.6 m) thick reservoir and for a horizontal section 1100 ft (335 m) long, the productivity of a horizontal well is more than four times that of a conventional well; but, if the reservoir thickness is around 122 m (450 ft), the productivity of the horizontal well is only 2 times greater. In general, it is stated that the optimum drainhole length is 10 times the formation thickness.

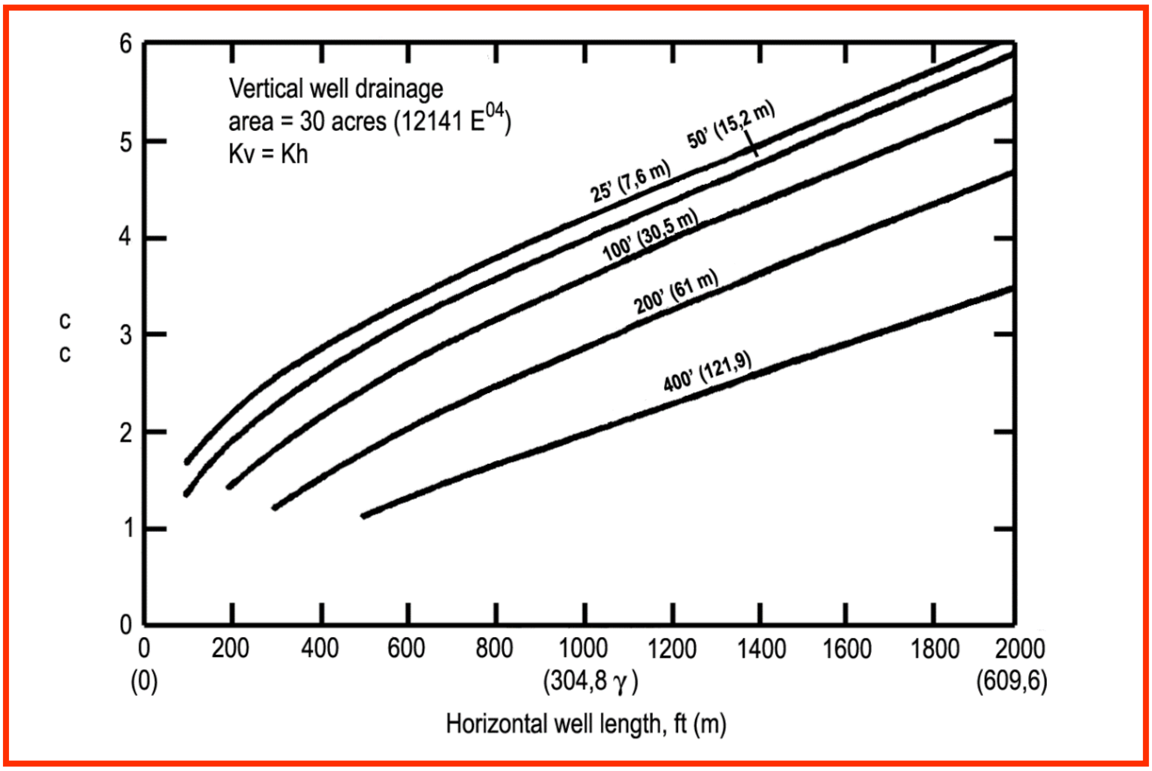


Figure 4.4: Horizontal/Vertical Well Productivity Index Ratio as a Function of the Reservoir Thickness, [15]

Vertical and horizontal permeability ratio is an important aspect in productivity expectations. Considered for vertical well, radial flow stays primarily horizontal, thus reduction in vertical permeability compared to horizontal one, does not affect to the performance of the well.

Where as in the horizontal wells, the flow travels from both top and bottom as well as from the aside. The productivity in this case depends on both planes. For example: for a horizontal section 240 m (800 ft) long, the productivity decreases from above 3 times more than that of a conventional well when the kv/kh =1 to only 2 times when kv/kh = 0,25.

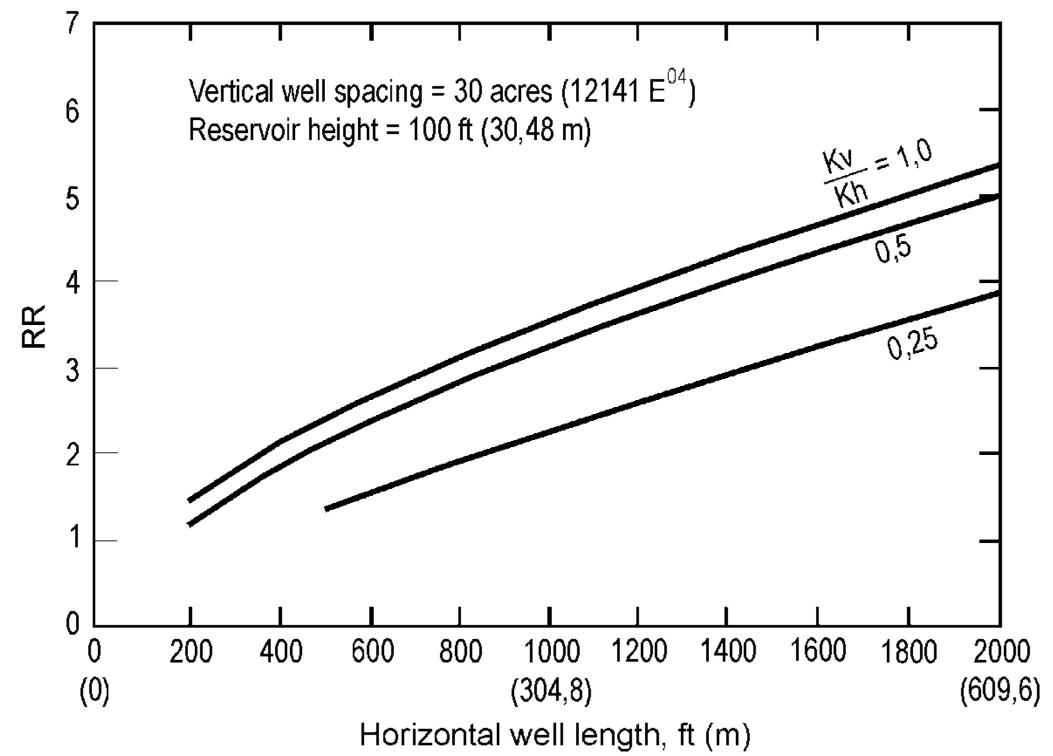


Figure 4.5: Horizontal Well Productivity as a Function of kv/kh Ratio, [15].

4.2.2 Difficulties in Horizontal Drilling

Operators experience difficulties while drilling deep horizontal wells, mainly with the vibrations, stick and slip and huge torque, which can greatly decrease drilling performance and lead to damaging of equipment and tools. Damaged tools, may lead up to bigger problems, and if not careful, the fish can be left inside of the hole with several thousands of meters drilling pipes and BHA, which may result in huge cost expenditure and additional time for remedial jobs.

"The severe speed variation, referred to as stick-slip, is known to be a major source of problems, such as fatigue failures, over-torqued drill pipe connection, bit wear, poor drilling rates, and damages on the electronic component of the downhole tools. Stick-slip motion is caused by the transition between static and kinetic frictions and are thus a dynamically unstable vibration. Due to the fact that downhole vibration can dramatically decrease the rate of penetration (ROP) in drilling operations. Stick-slip can significantly increase drilling cost. Stick-slip vibration in drill string also increases tool failures, adversely affects borehole quality, and can lead to the coupling of different vibrations. Stick-slip vibration is likely to occur in deep wells due to high rock strength and poor formation drill-ability. Therefore, understanding its causes and predicting its behavior on formation and knowing how to suppress it, are important in the drilling operation", [16]

4.3 New RSS Technologies

Technological advancements of RSS Tools continuously improving day by day to make drilling safer, efficient and productive. Here are shown some new RSS Tools that can improve our drilling processes on a higher level:

- **NeoSteer CLx (Schlumberger)**

"The NeoSteer CLx Extreme curve and lateral at-bit steerable system (ABSS) is uniquely developed for an efficient drilling of curves and lateral surfaces in a single run. Possibility of achieving high build rates and extend lateral lengths in unconventional drilling applications, especially where vertical, curve, and lateral sections are the same hole size, the NeoSteer CLx ABSS reduces non-productive time by eliminating the need to change out the BHA for every consequent section."

Figure 4.6: NeoSteer CLx, [17].

Accurate well placement in shale: Multiaxis measurements and automatic trajectory control.
Given tool includes comprehensive six-axis continuous inclination and azimuth measurements. The multiaxial component enables automatic hold inclination and azimuth (HIA) measurements for precise well positioning. This feature, along with self-steering capabilities, helps provide smooth tangents with minimized tortuosity. Near-bit extended-range gamma ray measurements provide additional well positioning data for improved real-time decision making.

Azimuthal image gamma ray for improved steering in the curve and lateral sections
The adjustments with The NeoSteer CLx can be performed with an onboard azimuth gamma cartridges to improve the percentage within the zone and provide control within the sweet spot of the reservoir. Equipped with a GR azimuth cartridge, which is located 6 feet above the cutting structure, the ABSS has the possibility to identify lithology changes earlier and make instant steering adjustments, [17].

Properties:
- Maximum Hydrostatic Pressure: 20,000 psi (138 MPa)
- Maximum Temperature: 302^{0}F (150^{0}C)
- Maximum Rotational Speed: 350 rpm
- Nominal OD (API): 6.75 in

Application:
- Pad and batch drilling operations
- Long lateral sectioned Horizontal wells
- Wells with high build rates and dogleg severity (DLS)
- Unconventional Wells

Benefits:
- Single run with single BHA for vertical, curve and lateral sections
- Achieves long lateral length and high build rates requirements
- Increases leverage of force applied to bit by placing pistons with the cutting structure
- Improves reaction time and control

Features:
- Smith Bits PDC bit design
- Non-magnetic steering body unit
- Hydraulically activated dual pistons
- Azimuth and inclination closed loops to provide advanced automated tangent control
- Proprietary high-endurance-strength connector
- Near-bit measurements, such as:
  - Inclination
  - Azimuthal
  - Gamma Ray
  - Azimuthal Gamma Ray
  - High-definition (HD) Surveying

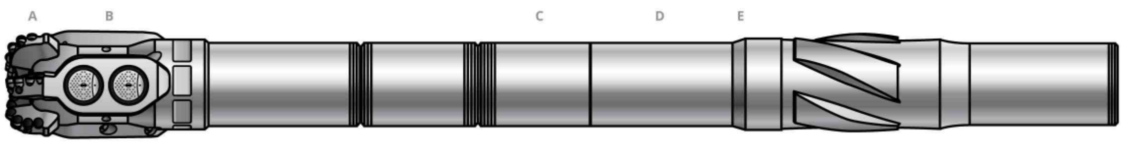


Figure 4.7: NeoSteer CLx RSS Tool Assembly, [17].

A: Cutting structure

B: Pistons push against wellbore wall to steer. They are integrated with the bit, which gives it better leverage to execute sharper turns

C: Inclination Sensor enables automatic hold inclination

D: Multiaxial component enables automatic hold inclination and azimuth measurements for precise well positioning and helps provide smooth tangents with minimized tortuosity

E: Azimuthal gamma ray cartridge is located just 6ft behind the cutting structure, enabling operators to proactively identify signs of changing lithology and enact instant steering corrections, [17].

NeoSteer CLx ABSS – Case Study: Drilling Three Sections in One Run Without Compromising ROP, Southwest Marcellus Shale

Extreme curve and lateral ABSS allowed to drill tangent, curve, and lateral sections, staying 91% in an extremely tight 4-ft target window, [40].

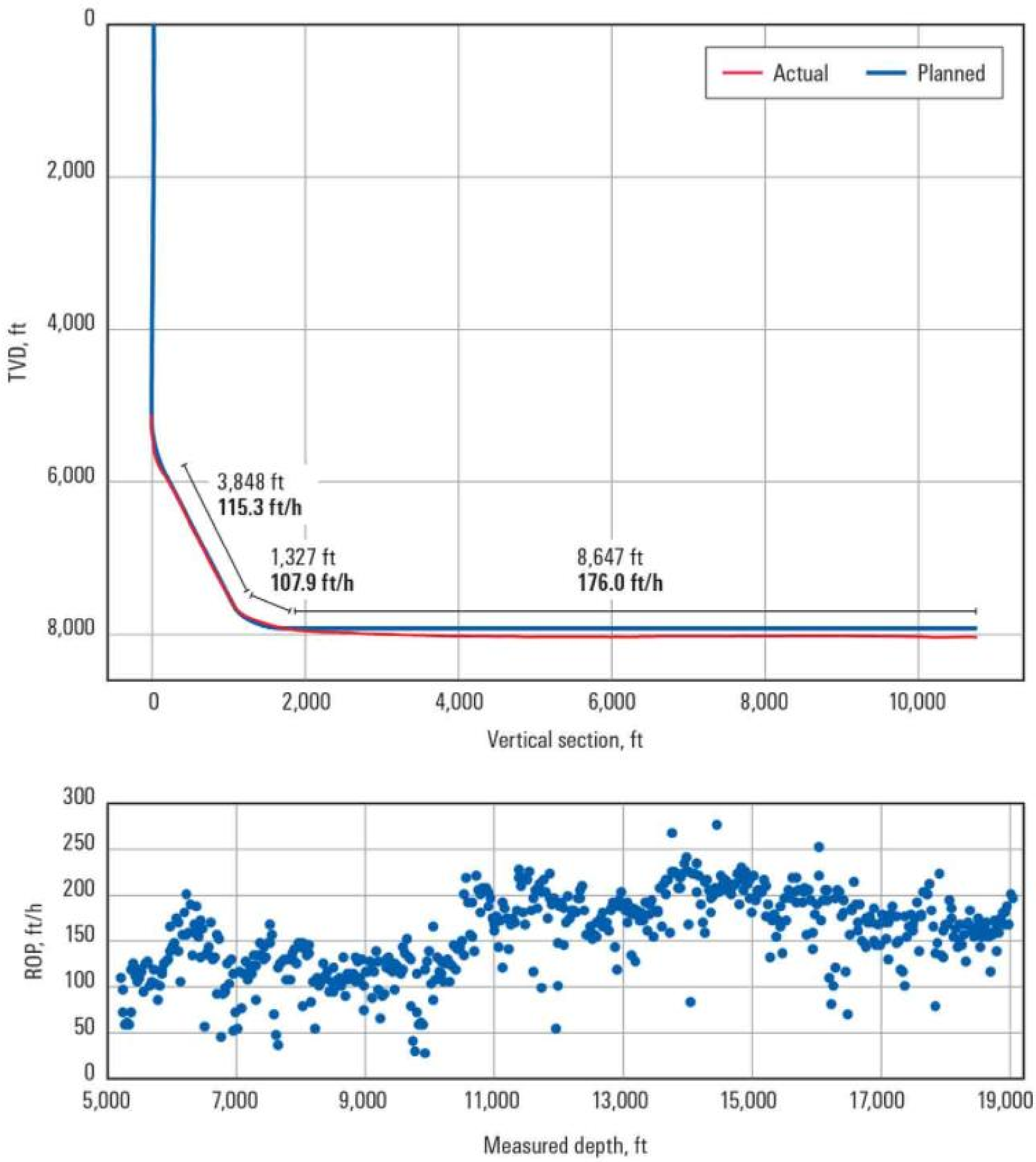


Figure 4.8: NeoSteer CLx Performance, [40].

"Operator Northeast Natural Energy, decided to use NeoSteer CLx ABSS to drill highly deviated horizontal well. Performance of the tool showed that the well was drilled 13,819-ft MD through all three sections and reduced the tortuosity of the complex well trajectory while staying 91% in a 4-ft zone, versus with most wells with a 10- to 20-ft window. This percentage includes the footage at the heel where the wellbore was soft landed. All the way through the drilling process, azimuthal image and dip picking helped the wellbore stay in zone through formation changes. Using the NeoSteer CLx ABSS instead of the traditional two-BHA strategy also enabled Northeast Natural Energy to maintain a high ROP because the operator was able to avoid sliding", [40].

- **PowerDrive Orbit G2 (Schlumberger)**

High-performance drilling with enhanced directional control
Highly versatile, reliable and tough PowerDrive Orbit G2 is an evolutionary steering tool. Reduction of drilling time and increased efficiency with the ability to steer at high BHA RPM. An advanced design of pad increases abrasion resistance with metal-to-metal sealing to withstand aggressive drilling fluids and severe downhole conditions for longer runs. Equipped with dual downlink options, including the QuikDownlink continuous-circulation downlink service, it fulfils all commands given from surface for any types of rig, provide with real time decision making, and excellent directional control

Accuracy in well placement
Given tool provides six-axis continuous hold of inclination and azimuth (HIA) measurements that optimize well placement and trajectory control for smoother tangents. An early identification of zones of interest is provided by its extended GR measurement. The PowerDrive Orbit G2 RSS increases DLS capability for much tighter curves, yet minimizes DLS in laterals and enables early control, [18].

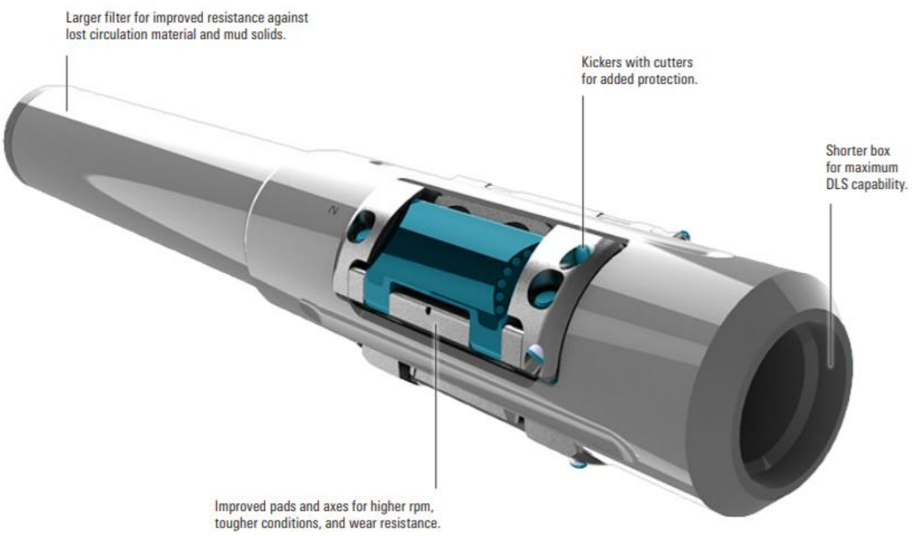


Figure 4.9: PowerDrive Orbit G2 Rotary Steerable System, [19].

Properties:

- Maximum pressure: 30,000 psi (207 MPa)
- High-performance drilling
- Maximum rotational speed: 350 rpm
- Maximum temperature: 302^0F (150^0C)

Advantages:

- Advanced pad design with metal-to-metal sealing to withstand corrosive drilling fluids and severe downhole conditions
- Higher dog leg severity capability in the curve, yet minimized dog leg severity in the lateral for smoother wellbores
- Six-axis continuous HIA measurements for accurate well positioning and better TVD definition
- Dual downlink options to fulfil all commands from surface for any rig type

Benefits:

- Improves abrasion resistance
- Increases DLS capabilities
- Minimizes overall well tortuosity by leveraging closed-loop automation
- Reduces CO_2 emissions by drilling more sections in one-run, [19].

VectorZIEL (NOV)

"The VectorZIEL™ RSS is an automatic steering tool for three-dimensional drilling. The tool provides higher ROP, improved hole cleaning and precise trajectory control. System helps to produce high quality boreholes at reduced operational costs. Based on a design that has been developed and refined over the past 20 years, given tool offers reliable and precise directional control in the most demanding applications.", [20].

Features

- Integrated MWD System for real-time feedback
- Near-bit inclination, azimuth and GR measurements
- Closed loop trajectory control, which requires minimal intervention from surface
- Automated downlinking using surface downlink skid
- Combination with MWD and LWD tools for an integrated directional drilling and logging BHA

Figure 4.10: VectroZIEL RSS, [20].

Specification of MWD System

- **Azimuth**
  - Sensor: X,Y, and Z-axis accelerometers
  - Accuracy: ± 1.0^0
  - Raw data to surface: G_x, G_y, G_z
  - Gtot quality check tolerance: ±0.005g

- **Direction**
  - Sensor: X,Y, and Z-axis magnetometers
  - Accuracy: ± 1.0^0
  - Raw data to surface: B_x, B_y, B_z
  - Btot quality check tolerance: ± 0.3 µT
  - Dip angle quality check tolerance: ±0.5^0

- **Logging**
  - Logging capability: Gamma Sensor

Components at Surface

- Data receiving unit
- Electro-hydraulic choke mechanism for downlink, [20].

4.4 Drilling Bits for Horizontal Directional Drilling

Drilling bits remain an essential part of every drilling operation. The innovation of unique designs and cutters placement helped revolutionize drilling technology on a higher level. Certain bits are designed to comply with the specifications for directional drilling, sidetrack drilling, reaming drilling, motor steerable drilling, rotary steerable drilling, core drilling, slim hole, air drilling, pilot drilling, casing drilling, etc. Thus, we can select the appropriate bits to conduct corresponding drilling.

4.4.1 Fixed Cutter Bits

Fixed cutter bits stand as a revolutionized development with conical diamond cutter. In comparison with the conventional PDC bits, fixed cutter bits advanced with twice the diamond thickness. Conical Diamond Element (CDE) has demonstrated numerous times the improvements in wear resistance and impact strength. CDE crushes and fractures rock for improved ROP. With the availability of placement multiple CDEs across the bit face, fixed cutter bits showed increased footage and improved toolface control when compared with conventional PDC bits.
In order to withstand to the hard abrasive formations, integrated diamonds provide with the durability and hardness to the bit. From the economical point of view, diamonds are expensive, however the effectiveness and the results justify the risks in order to complete the well in fast and safely manner, [21].

The advancement in improving drilling bits continue up to these days. Companies are focused in developing innovative technologies, by which drilling process can be performed with laser, ultrasonic, microwaves or thermal technology. Until such days will come, fixed cutter bits will remain the optimal cutting tool in oil and gas industry.

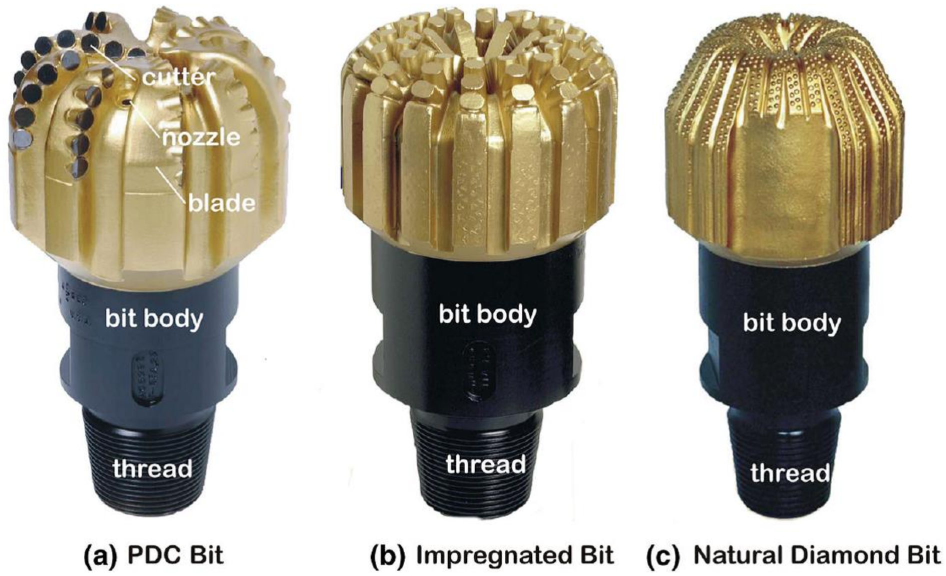


Figure 4.11: Fixed Cutter Drilling Bits

4.5 Technological Advancements in Drilling Bits for Horizontal Directional Drilling

With the expansion of Horizontal Drilling across the world, advanced drilling bits are being developed to withstand great compression strength, torsion, erosion and maintain effectiveness and condition of the bit. Some Companies have developed astonishing upgrades to drilling bits for Horizontal Directional Drilling.

- **VION PDC "Tangent" Drill Bit (Varel Energy Solutions)**

VION PDC "Tangent" Drill Bit series were developed specifically for drilling applications where drilling through formation transitions requiring durability and control. Designed to handle the increased operating parameters. Created with a balanced cutting structure profile adding greater bit stability to overcome durability challenges of drilling transition zones and abrasive formations with increased the ROP, [22].

Application

- Tangent, Intermediate drilling intervals
- For soft to hard and hard to soft formations with transition zones
- For all rotary and PDM applications

Features / Benefits

- Integrated with hydraulically optimized attributes with curved nozzles, webbed blades and designed junk slots improving performance in sticky formation applications
- Improved cutting structures lead to a toughened cone and strengthened nose and shoulder. With the balanced design, bit is more durable, faster in drilling and longer lived
- Steel body option leads to a design that is faster and more aggressive than a matrix body bit but retains the toughness of a VION

Figure 4.12: VION PDC "Tangent" Drill Bit, [22].

New cutting technology VENOM identifies the right PDC cutter to solve the key challenges for the application. Key diamond attributes can be enhanced to better match the demanding need. By selecting the diamond blend that best suits the need, the cutter will stay sharper, longer.

- **Abrasion**: Enhancing the abrasion attribute will target the hard sandstone and siltstone drilling environments. Higher diamond density keeps cutters sharp.
- **Impact**: Impact damage can abruptly stop a successful run. Diamond that does not crack and, if it does crack, it does not expand helps keep the bit in the ground.
- **Thermally Stable**: Focus on the thermal difficulties, allows integrated cutters to withstand higher temperatures for longer period. This is a key for long runs with high friction heat generation due to the rock and parameters.

- **Cutting Efficiency**: This upgrade can allow for improved ROP and/or durability. Modification of the physical shape of the cutter can enhance the cutting efficiency.
- **Shear Strength**: If the strength of the cutter is not able to handle the combination of rock interaction and application, the bit will fail quickly and premature trips happen. Matching this attribute to the need makes for consistent bit runs, [22].

IriSphere (Schlumberger)

"New technology for Drilling Bits, which was developed by Schlumberger company, allows to monitor the well while drilling. IriSphere* look-ahead-while-drilling service allows deep directional measurements with advanced automated inversion to precisely detect formation features ahead of the bit and land wells while managing drilling risks, optimizing casing placement and coring location. Using multifrequency transmitter and multi-receiver directional subs, this tool allows the capability of receiving the data in real time while drilling. Electromagnetic (EM) signals are sent from the transmitter into the formation and retrieved by the receivers to enable the enhanced look-ahead sensitivity and resistivity profiles", [23].

The ability of drilling with confidence and reduced uncertainties in real time. Applications include detection ahead of the bit of formation features with potential pressure differentials for integration in a standard pore pressure prediction workflow. Penetrating a high-pressure reservoir might result in stuck pipes, lost circulation, and other potential wellbore instability issues.

IriSphere service provides drillers with real-time mud properties management and enables optimized casing design and contingencies planning. IriSphere service differentiates between a thin high-resistivity stringer and a target reservoir, unlike the current geostopping technology available in the industry. Consequently, problems with premature casing seating or coring location are eliminated.

IriSphere service enables the driller to see far in front of the bit while drilling, providing enhanced formation tops mapping, improved landing capability, and better drilling hazard avoidance. The same workflow is applied to determine the reservoir bottom, completion optimization, and salt navigation, including salt entry and exit.

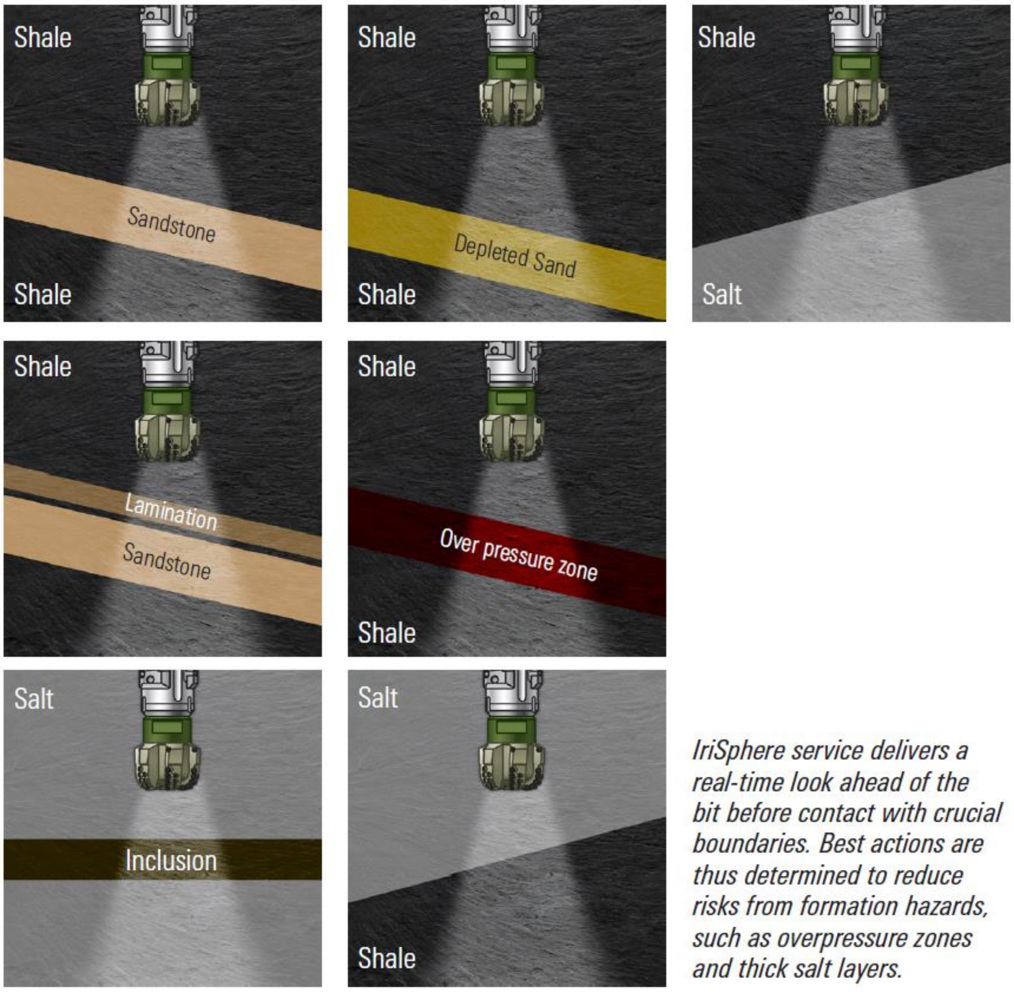


Figure 4.13: IriSphere Technology, [24].

Applications

- Deviated and Vertical wells
- Selection of casing improvement
- Salt navigation
- Optimized coring location
- Ahead-of-the-bit detection of
  - Early pressure transition
  - Formation tops
  - Formation stringers
  - Fluid contact

Benefits

- Higher drilling efficiency
- Reduced contingencies and Lower risk
- Avoidance and management of proactive hazards
- Improved casing sections through reduction, optimization or elimination
- Increased ROP
- Reduced BHA trips out of hole

Features

- Deep look ahead of the bit exceeding 100 ft (30m)
- Cloud-enabled automated solution
- Hole size availability from 5 5/8 in to 16 in, [34].

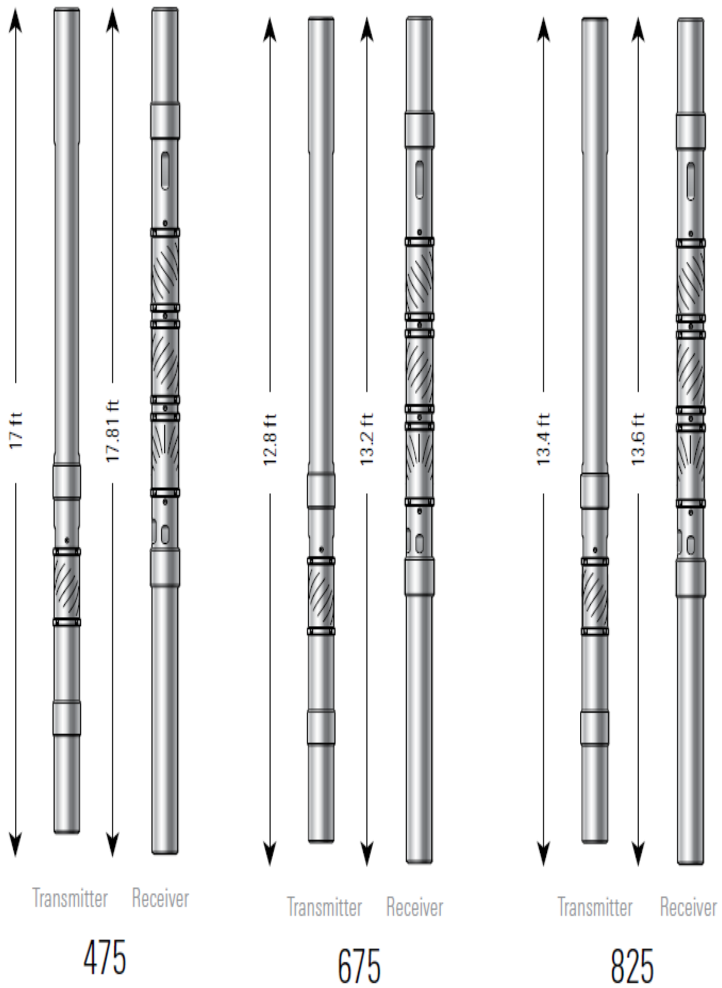


Figure 4.14: IriSphere tool size, [24].

Case Study: Elimination of Unplanned Sections and Cost Expenditures by implementing Real-Time Look Ahead While Drilling Technology, Sulawesi, Indonesia.

The plan was to drill a carbonate appraisal well on a gas reef to delineate the structure and reservoir while overcoming several challenges. There were no correlation markers in the thick shale above the formation, which resulted in low resolution seismic data, which lead in an error of ± 40 m to determine the top of the formation. Limestone stringers have been observed in offset wells, however conventional drilling equipment and correlation techniques might have misinterpreted stringers as a major carbonate formation. This could have resulted in setting 9 5/8 in. casing to early, which might have lead to an unplanned additional 6 in. wellbore section - at least $ 1.35 million in additional cost to the operator. Operator required clear reservoir picture to set up for accurate reserve calculation and future field development. Thus the 9⅝-in casing had to be accurately set 5 m above the top of the target formation to enable complete coverage for the subsequent coring, openhole wireline logging, and well testing program, [41].

IriSphere service first verified that the conventional indication of top of formation at 1,535-m MD was invalid. Then it enabled normal drilling ROP to 176 m deeper than the previously assumed formation top, avoiding time-wasting conventional spot samples at 5- to 10-m intervals because it also distinguished several thin limestone stringers from the target carbonate. At 1,703-m MD, IriSphere service detected the formation top 10 m ahead of the bit, enabling a 9⅝-in casing to be set at 1,706-m MD, approximately 4–5 m above the top of formation. IriSphere service enabled placing the well to optimize coring, openhole wireline logging, and a well testing program for accurate reservoir delineation, reserve calculation, and future field development. This confirmed the top of formation at 1,711-m MD. Thus, IriSphere service also avoided drilling an unplanned 6-in hole, [41].

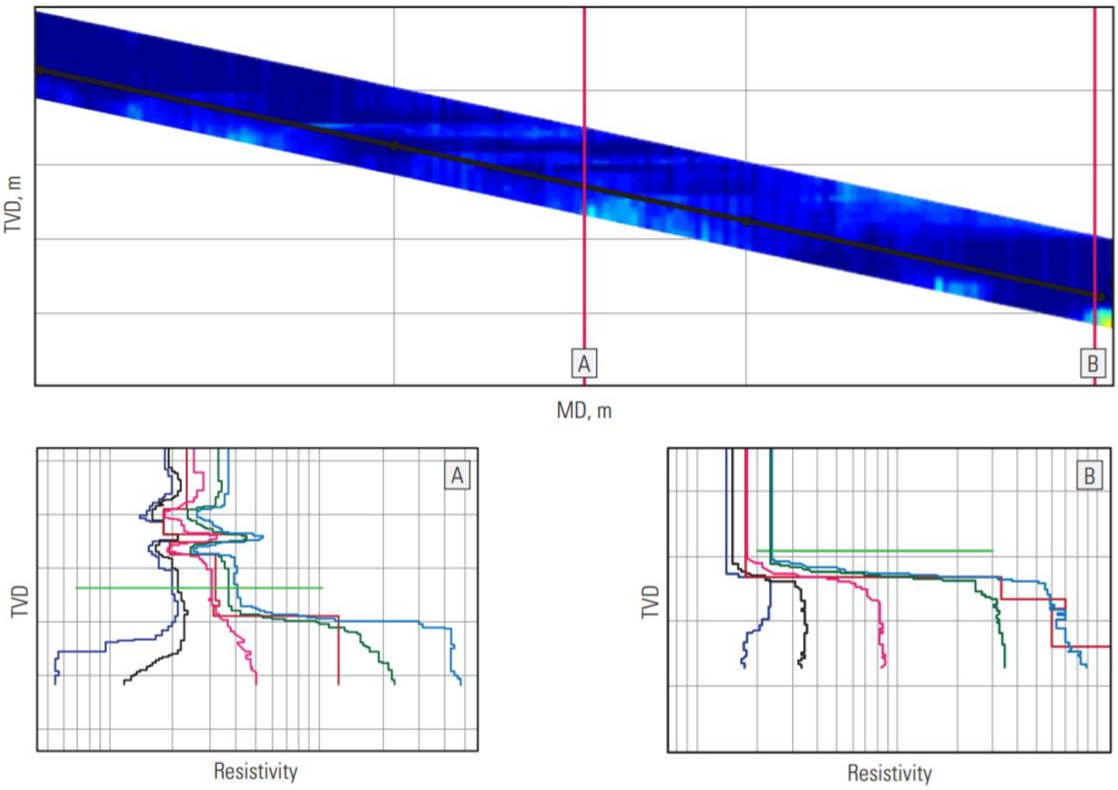


Figure 4.15: IriSphere service differentiated between stringers and the expected target carbonate in real time, [41].

- **AxeBlade – Ridged diamond element (Schlumberger – Smiths Bits)**

AxeBlade bits integrated cutting elements with a unique geometry that cut rock in an effective way — combining shearing and crushing. The cutting method achieves 22% deeper penetration, removing more formation to provide higher ROP while implementing same WOB and RPM applied to conventional PDC cutters. The diamond table on the element ridge, which is 70% thicker, gives the Axe ridged diamond element increased frontal impact resistance, meaning that the AxeBlade bit delivers improved durability and dull condition for maximum ROP throughout the drilling process.

Field performance of the AxeBlade ridged diamond element bit demonstrates up to 29% improvement in ROP compared with similar bit designs using conventional PDC cutters, significantly decreasing rig time and costs expenditures, [25].

The Axe element was an innovative leap in PDC bit performance, and from its success, Smith Bits engineers continue to develop effective new geometries using the ridged shape.

Axe Ultra element compacts shearing motion of a standard PDC cutter which is inserted in tungsten carbide insert (TCI). The ridged design enables more efficient cutting and heat dissipation, (**Figure 4.16**).

A B C

Figure 4.16: A) Axe Ultra. B)Axe TR. C)Axe SR, [25].

Applications

- For every sections
- Adjustable for all BHAs
- Applicable for Medium to Hard formations

Benefits

- Minimizes rig time and cost expenditures with faster, instantaneous ROP
- Maximizes production zone exposure and achieves direction objectives in less time

Features

- Axe ridged diamond elements combine crushing and shearing actions to cut rock more effectively
- Durability of cutters maximizing ROP
- Specific shapes of cutters minimize torque

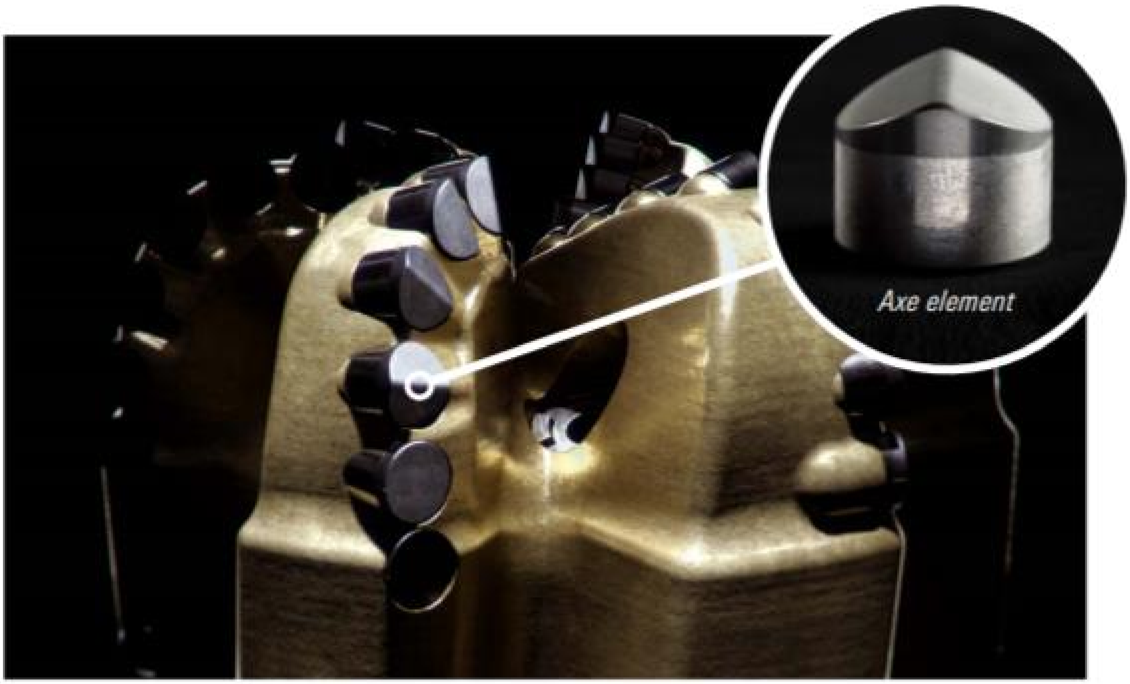


Figure 4.17: Axe blade element fitted in Drilling Bit , [26].

Case Study: 42% in improvement of ROP using AxeBlade Ridged Diamond Element Bit in a Single Run, Oman

In central Oman, an operator had undertaken an aggressive drilling campaign in a deep gas field. The first challenge consisted of finding an optimal technology in order to drill 12¼-in hole section in a single run, which historically required multiple runs. The section was geologically consisted with multiple different layers, [42].

AxeBlade was used in the deep gas field and fulfilled its purpos of drilling the entire 12¼-in hole section - Natih Limestone to the Al Khalata Sandstone. Drilling was finished in single run. Generated ROP was of 27.5 m/h [90.2 ft/h]. Exceeded normalized ROP was increased by 42%, but the operator also outperformed the existing field-best ROP by 18%, [42].

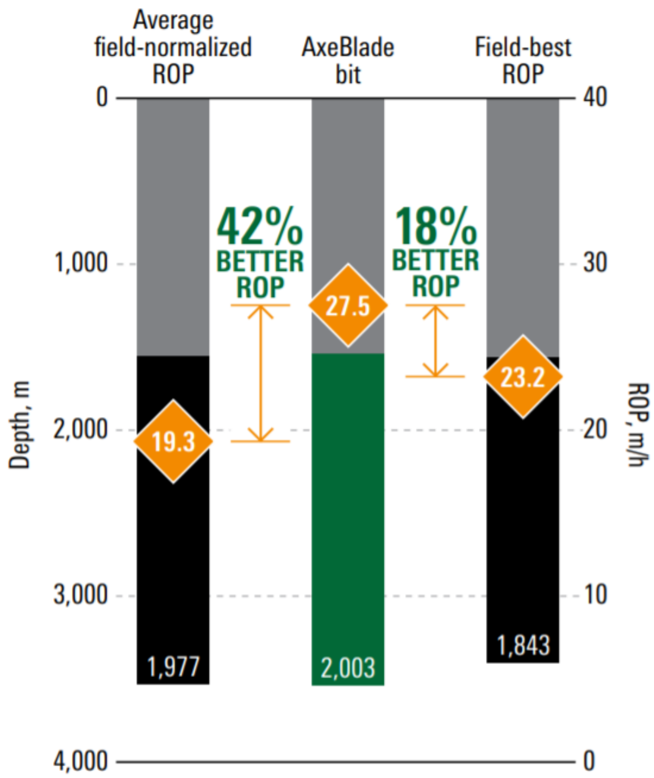


Figure 4.18: AxeBlade drilling bit performance, [42].

4.6 Innovative Casing Setting Technologies

4.6.1 Casing Setting Depth

Selecting the proper depths for setting casing cannot be overemphasized. Wrongly set casing may result in unplanned extension of additional casings, reduced production hole diameter and extended rig time with additional cost expenditures. Many wells have been engineered incorrectly, which resulted in economic failures because the casing program specified setting depths were too shallow or deep.

The drilling engineer must consider geological conditions such as:

- Formation pressures and fracture mud weights.
- Hole problems.
- Internal company policies.
- A variety of government regulations.

4.6.2 Types of Casings

Drilling environments require several casing strings to reach the total desired depth. Single hole diameter cannot be sustained, due to the increment of formation pressure. Thus, several casings must be set after certain period of depths. Some of the strings are:

- Drive, or conductor.
- Surface.
- Intermediate (also known as protection pipe).
- Production (also known as an oil string).
- Liners.

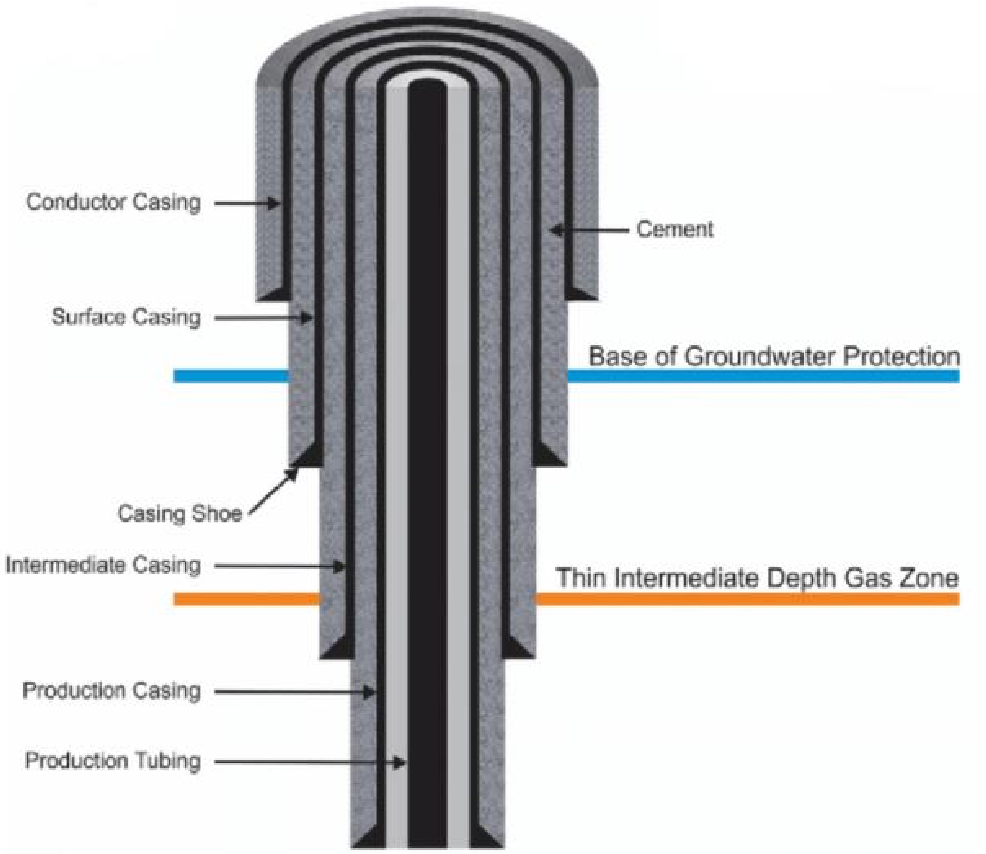


Figure 4.19: Wellbore Casing, [27].

Allegro XCD-Pro: Casing-while-drilling (Schlumberger)

"The Allegro XCD-Pro casing-while-drilling expert service provides an unconventional, comprehensive application analysis to identify and mitigate drilling risks. Leveraging a suite of software simulation solutions, including the IDEAS integrated dynamic design and analysis platform, the service evaluates conditions such as formation strength and bit-to-rock interaction to design an ideal bit cutting structure with unique diamond cutting elements.

With specific bit customization, given service delivers greater reliability and performance during casing-while-drilling operations," [28].

Increase Wellbore Strength

- Sloughing shales
- Tight holes
- Borehole bridges
- Lost circulation
- Large-diameter surface hole resulting in hard-to-remove cuttings from the annulus
- Damaged producing zones
- Stuck pipe.

Decreased risks and effective job is possible without loosing precious time. Drilling While Casing may reduce rig time by 3 times of the average.

.

Figure 4.20: Casing while Drilling.

Well Improvement

- Provides rotation and weight in bit during drilling operation
- Maximizes borehole stability and strength
- Prevents fluid migration into the casing

The Case Study: Kuwait Oil Company Saves 47 Rig Days Using Casing-While-Drilling Service, Kuwait

Kuwait Oil Company (KOC), by using XCD-Pro* casing-while-drilling service Managed to reach TD in the matter of days, thus saving 42 working standard days, [43].

Geological challenges were encountered in an offset wells, resulting in inefficient hole cleaning, wellbore instability, and stuck pipe. Operator lost in hole BHAs. NPTs were very large compared to company's standards. Operator decided to implement given service

A 12 1/4-in section with 9 5/8-in casing was drilled to TD in one run without any problem and lost-in hole BHAs, multiple cement plugs to stabilize the wellbore, or other hole complications. As a comparison, **Figure 4.22** shows the flat time between the subject well and an offset well with conventional drilling technique, [43].

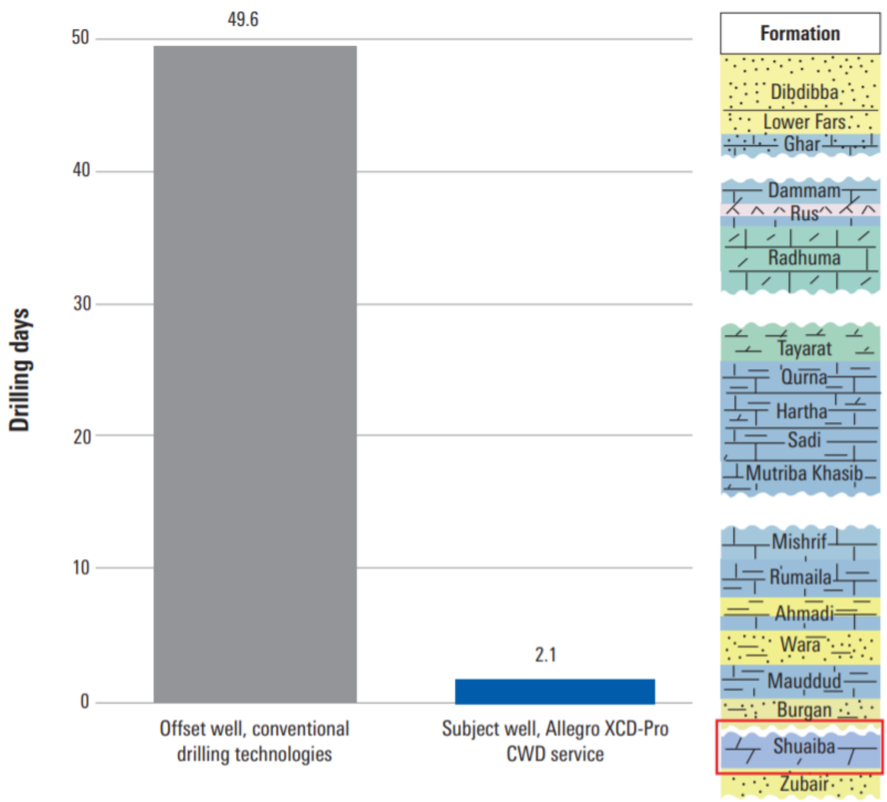


Figure 4.21: Comparison between Conventional Drilling Technology vs Allegro XCD-Pro, [43].

5 COMPLETION OPERATIONS

By the time operator completes with the drilling of the well, a decision has to be made, if the given well will be put into production or it will be plugged and abandoned (P&A), in case if the well turns out to be dry. In case of the first decision, completion operations are performed by introducing the newly drilled well into production by running in hole tubing string with particular sets of tools.

Transforming newly drilled well into producing one requires: casing setting, cementing perforating, gravel packing and installation of a production tree.

5.1 Types of Completions

Mainly there are 3 types of completion operations, which are open hole, liner, and perforated casing completions. Most of the time, single perforated casing completions are implemented in oil and gas industry. Planning completion operations strictly dependent on thorough analysed and coordinated reservoir management plan, in order to put the well in proper production. Additionally, engineering plan has to be analysed very carefully, such as equipment choice, which requires proper selection of size, grade and weight of the tubulars. In case of requirement of injection, stronger and more durable casings will be selected rather than standard production casings, [29].

5.1.1 Open Hole Completions

Not so long ago, open hole completion required a standard cable tools in order to complete the well, where as these days, after the drilling is completed, operators run and cement casings according to plan. Before casings were run in hole as a standard procedure, after penetrating formation during drilling, reservoir fluids started to flow and all operations were stopped and production commenced in an uncased hole. As the exploitation of rotary rigs began to drill, wells were completed with an open hole. In **Figure 5.1 (a)** The representation of an open hole completion is showed. Nowadays, this method is practically extinguished, for some particular exception in horizontal drilling, where a consolidated, fractured formation is left uncased and production commence in an open hole.

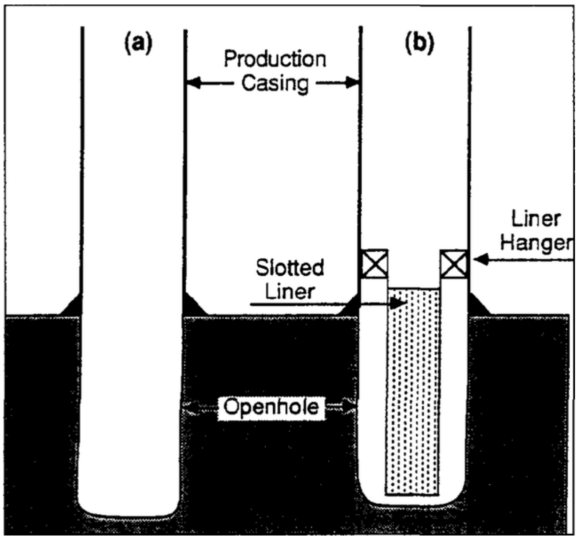


Figure 5.1: The diagram of a wellbore (a) open hole completion. (b) a slotted liner completion, [29].

Main disadvantage with an open hole completion is with unavailability of flow control, which comes from reservoir into the hole and vice versa. Additionally, sloughing zones can cave into the wellbore, thus restricting flow to the surface, [29].

5.1.2 Liner Completions

Given principle is similar to an open hole completion system, where a casing should be set before the producing interval. Afterwards, however, liner is run in hole and is set onto the previously cemented casing by using Liner Hanger. This brings an advantage in availability of using the drilling fluid, which won't damage the reservoir interval, due to its isolation. There are several types of Liners which are used in completion operations:

- Slotted liner
- Screen and liner
- Cemented liner

Liners which were previously perforated and represent a sort of holed pipes are called slotted liners. These types of liners are not required perforation. Application is similar to an open hole completion with its advantages and disadvantages. Main task of slotted liners are minimizing or completely preventing of sloughing of the formation into the hole **(Figure 5.1 (b))**. A screen and liner completions are relatively similar. The only difference is the placement of the gravel, which is sometimes is set behind the screen **(Figure 5.2 (a))**. Pros and cons remain the same just as for an open hole completion. Used mostly in unconsolidated formations, in order to prevent formation materials into the wellbore, which may restrict the flow of reservoir fluid.

The most common type of liners are cemented liners, which is set on previously cemented intermediate casing by using Liner Hanger **(Figure 5.2 (b))**. Intermediate casing provides with isolation support and is set mainly in pressure transition zones.

The advantage of cemented liner completion is that perforation can be selective according to the production or injection zones. However, the disadvantage of this liner is the difficulty in performing cementing job. Cement bond has to be good in order to proceed with the perforation, [29].

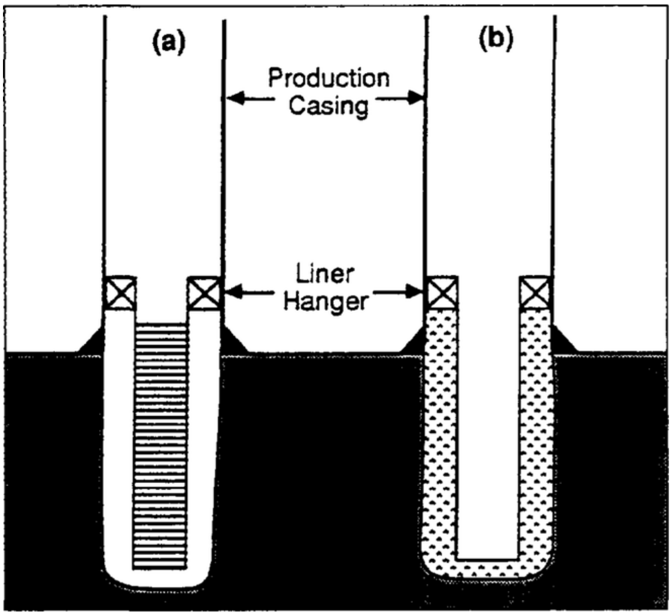


Figure 5.2: A. screen and liner completions. B. cement liner completion, [29].

5.1.3 Perforated Completions

Perforated casing is the common and most used completion application nowadays **(Figure 5.3 a)**. After performing logging operations and identifying producing intervals, necessary cost expenditure evaluation is performed. After the casing has been run and cemented, a CBL has to be performed in order to evaluate the cementation quality. In case of results form the cement bond log is satisfactory, a perforated gun will be run in hole and activate, punching holes and allowing formation fluids to flow inside the well for further production. Selective perforation may be done as well, in order to perforate desired intervals, in case needed. The application is very versatile, and can be adapted for alternate and multiple completions, [29].

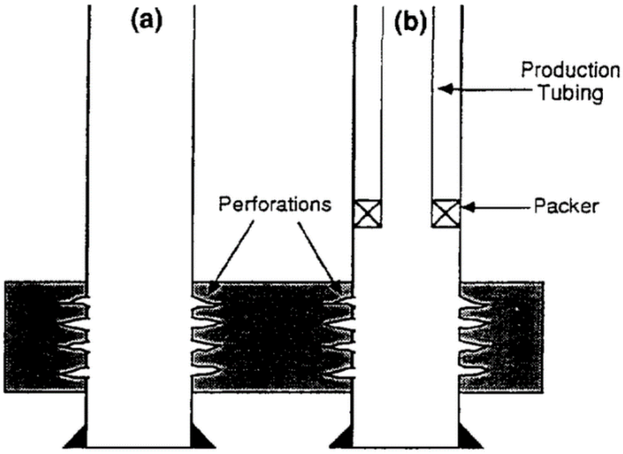


Figure 5.3: (a) perforated completion. (b) completion string inside perforated casing, [29].

5.1.4 Single Completion

The most common and preferable types of completions. Only one production string is run in hole. The production is carried out from one interval. Given method doesn't require complicated implementation, relatively simple and cost effective. In comparison with multiple completion, given method of completion may be done with relatively few operating problems. An ideal completion method for shallow wells or very deep wells, where reservoirs lay down deeper than 10,000ft, where multiple completion will be hard to sustain and operate. Usually implemented in onshore wells, [29].

5.1.5 Multiple Completions

The best control of reservoir operations may be achieved with multiple completions. Dual completion includes dual tubing strings and triple completion with three tubing strings, as illustrated in **Figures 5.4 and 5.5**.
As the complexity of the completion increases, the more difficulties engineers can expect in completion operations and in workover operations. Given methods should only be considered in special situations, such as areas where drilling cost expenditures are very high or where areas allocated for drilling wells with a big pay-zone.
With multiple completion, two or more reservoirs may be put into production simultaneously from the single wellbore. Completing the well with given technique in safest manner may be very profitable, however operating and workover expenditures may be high. All of these factors have to be considered prior implementing multiple completion method, [29].

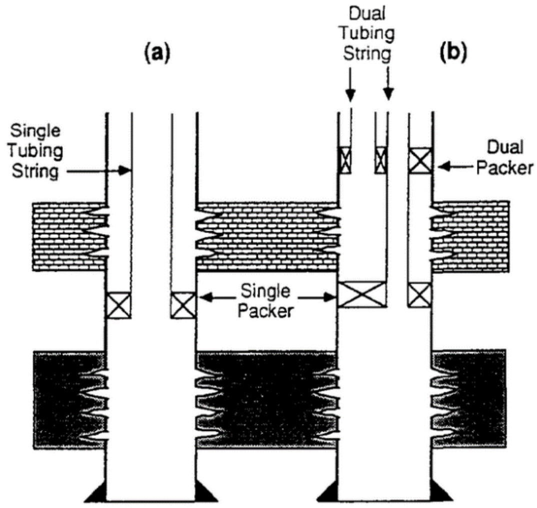


Figure 5.4: (a) casing-tubing dual completion. (b) completion with dual packers and dual tubing strings, [29].

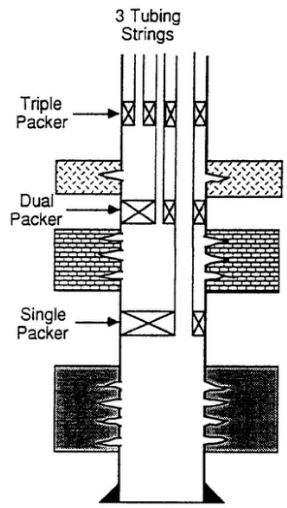


Figure 5.5: Wellbore diagram of a conventional triple completion, [**29**].

5.2 Gravel Pack

After the drilling operations are completed, a cleaning system is required, which will serve as a filtration system, by eliminating the sand out of the well stream. Gravel pack remains a common tool for given cases. Specific slurry is prepared with the appropriate consistency of gravel or coarse sand. Afterwards, slurry is pumped between sides of the wellbore and slotted liner. Further, the screens act as a filtration system, working together with gravel pack, cleaning out the sand which may corrupt the wellstream.

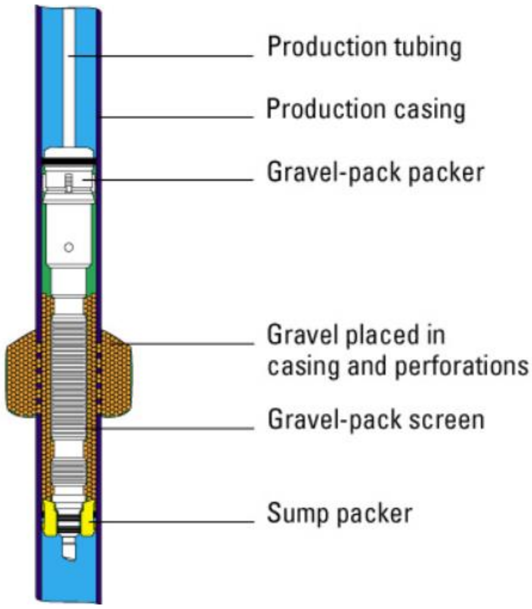


Figure 5.6: Gravel Pack, [30].

Gravel pack completion procedure includes drilling through the oil reservoir to design depth, running production casing to the bottom of the oil reservoir, cementing, and then perforating the oil reservoir. During perforation, in order to increase flow area, a high perforation density (30-40 perforations / m) and a large diameters 20-25.4 mm are required., [30].

5.3 Installation of Production Tree

The last step in completion is installation of a tree. Production tree or Christmas tree – a device with multiple valves including casing heads, for setting on a casing, and a tubing head, for setting on a tubing string. The equipment provides safety, isolation and surface control of the well.

There are 2 types of production trees: wet and dry production trees. First one is mainly used in onshore drilling whereas the second one in offshore. However, dry trees can be used in offshore as well, by installing above the water's surface, on the deck of the facility or a platform. The trees are attached below the water to the well. Wet trees are set on the bottom of the seabed and are tightly cased and isolated in a steel box for better protection of the valves and gauges. Afterwards, wet trees are connected to the platform via ROVs or hydraulic settings.

In addition, wells may have production flowing from multiple reservoir levels. Given wells require multiple completion systems, to sustain the production separately. Double-wing trees are installed on multiple reservoir levels.

The newly developed advanced trees are able to measure flow properties, such as pressure, rate and GOR, mainly these types of wells are called intelligent wells, [31].

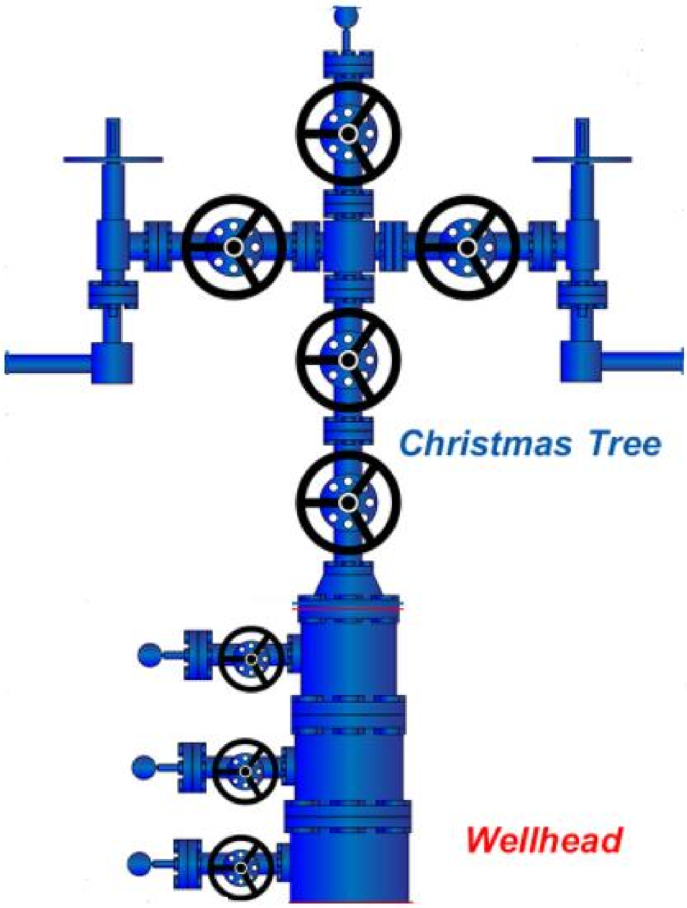


Figure 5.7: Wellhead and Production Christmas Tree diagram, [37].

5.4 Innovative Technological Advancements in Wellbore Completion

5.4.1 Completion of Multilateral Wells

Drilling of Multilateral wells increased rapidly worldwide as innovative drilling and completion technologies made possible constructing of laterals less costly and less technically challenging. Multilateral wells consist of more than one wellbore drilled from and connected to a main bore. After drilling, operators can leverage this approach to increase reservoir production by accessing several production zones or by increasing contact area between wellbore and formation with less cost expenditures on drilling and completion operations. Given technique massively reduces the impact on environment related to drilling rig installation, setting of production trees, specifically for land operations.

5.4.1.1 Multilateral Configurations – TAML Levels

From the beginning of 1950s, ML wells we implemented in the oil and gas industry and only by 1997, this method received new technological advancements in completion configurations, which were identified as TAML classifications (Technology Advancements of Multilaterals). In order to perform safer and categorized jobs of competition, they were devided into TAMLs. Completion of the junctions were categorized according to the connections of laterals to the main bore. 6 different classifications were developed. The increasing order of the TAMLs represent the complexity with pressure and mechanical capabilities of the junction (Figure). Therefore the cost, complexity and risk increase as well with ascending order of the TAMLs. (**Figure 5.8**), [32].

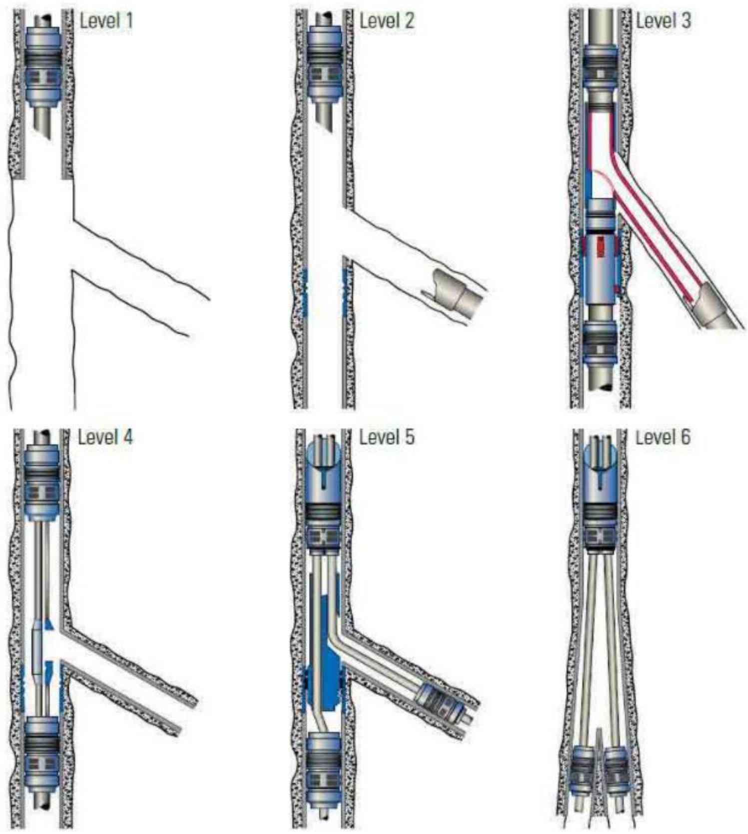


Figure 5.8: Multilateral standards classify junctions as TAML Level 1, 2, 3, 4, 5, or 6 based on mechanical complexity, connectivity, and hydraulic isolation, [32].

TAML 1: This classification represents uncased completion of junction, lateral and main bore. The main purpose of design of the given lateral is to improve drainage of reservoirs from consolidated formations. Generally, cost expenditures in drilling and completion are small, however reentry to the lateral and flow control coming from it is practically impossible, [32].

TAML 2: This classification represents uncased laterals with normally cased and cemented main bore. With the reduction of risk with cased and cemented main bore regarding collapse of the wellbore, provides with isolation. With this, operators have the possibility to produce commingle or singly by the installation and setting of sliding sleeves and packers, [32].

TAML 3: This classification represents cased and cemented main bore, to which lateral is connected with placed liner. However liner is not cemented, thus not cemented at the junction. This completion method is relatively low cost, which supports the option of reentering into the laterals. However, given method can be applied only in consolidated formations without the capability of hydraulic isolation, [32].

TAML 4: This classification represents cased and cemented of both main bore and laterals as well. This opens up a possibility of implementing given method in consolidated and unconsolidated formations. Due to cased and cemented laterals, given method provide options with access to the well, with the mechanical support. Nevertheless, cemented junction does not provide hydraulic isolation due to the integrity of the junction, which can support limited differential pressure, [32].

TAML 5: This classification represents of fully cased and cemented laterals and main bore. Hydraulic isolation is provided due to connected production tubing and packer are located in the wellbore just above the junction, packer in laterals, making level 5 the best option for completion, [32].

5.4.2 AICD Completions

Since 2011, Fluidic diode Autonomous Inflow Control Devices (AICDs) are being used and implemented in many applications, such as gravel packed completions in offshore and onshore fields, they include sandstone and carbonate formations. Up to this day, more than 65 AICD wells were completed, [44].

Given device adjusts restriction of the fluidic device according to fluid properties at downhole conditions. This technology is an improved version of ICD, which was developed for optimizing the flow profile and restricting water and gas production. The fluidic diode AICD uses fluid-dynamic components engineered on flow-path channels that self-direct the fluid through a low - or high-resistance flow path, depending on its properties. AICD tool consists of different designs:

Table 5.1: Fluidic diode, oil-viscosity and restricted fluid, [44].

Fluidic Diode AICD	Viscosity Range (cP)	Oil Type	Fluid Restricted
Range 1	0.3 to 1.5	Very light	Gas and water
Range 2	1.5 to 10	Light, medium	Gas and water
Range 3	3 to 200	Light, medium, heavy	Gas and water
Range 4	+150	Heavy, very heavy	Gas and water

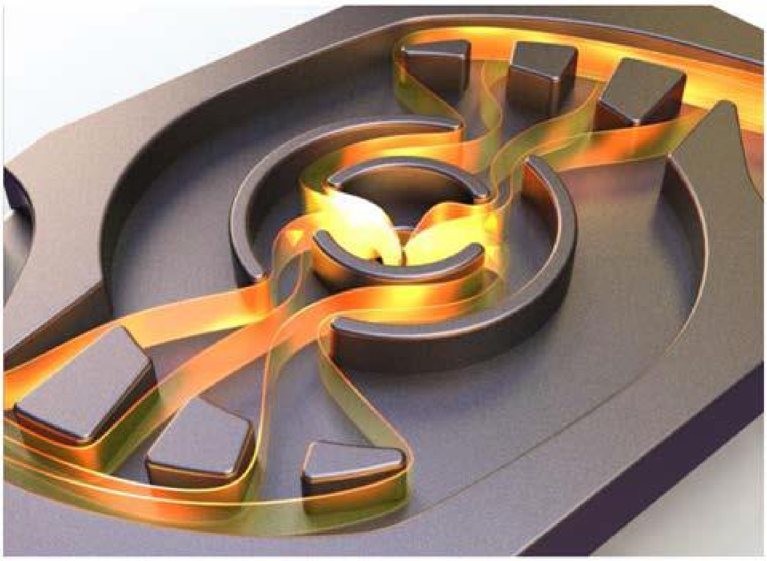


Figure 5.9: Fluidic diode AICD Range 3 oil-flow path, [44].

Below presented data taken from the real case studies on AICD performance published by operators from the different regions with differing formations:

- United Arab Emirates: 2.7 cP of oil with combination of water production problems. Workover was performed. Completion implemented fluidic AICDs. Cumulative oil production from given well increased 300% during a period of 2.5 years, and water cut (WC) reduced from 97 to 47%, (2015).
- Ecuador: heavy oil field (20 to 40 cP) sandstone formation in a mature oil field with an extremely rapid increase of water cut: Oil recovered to 500%. Much more than standard ICD completions., (2018).
- Brazil: A well was completed: added 50,000 m^3, 315,000 bbl on top of the gross reserves with the implementation of advanced AICDs. (2017).

The production increases massively while implementing given technology, which was proven globally. According to above presented case studies: increased oil production, slower WC increases, well life has been extended, [44].

5.4.3 Coiled Tubing

Drilling or workover rigs are not always required for drilling, completions or maintenance operations. Increasingly, the coiled tubing unit is used for many well intervention operations and certain drilling applications. *Coiled tubing* (CT) refers to a continuous length of small-diameter steel pipe and related surface equipment as well as associated drilling, completion and workover, or remediation, techniques. Initially, coiled tubing oilfield technology was developed for working on live, producing wells. Recently, given technology was mainly used by the operators for workover and drilling operations, due to its low overall cost. The trend toward extended-reach wells favours CT for its capability to drill or to convey tools and equipment in high-angle wellbores, [34].

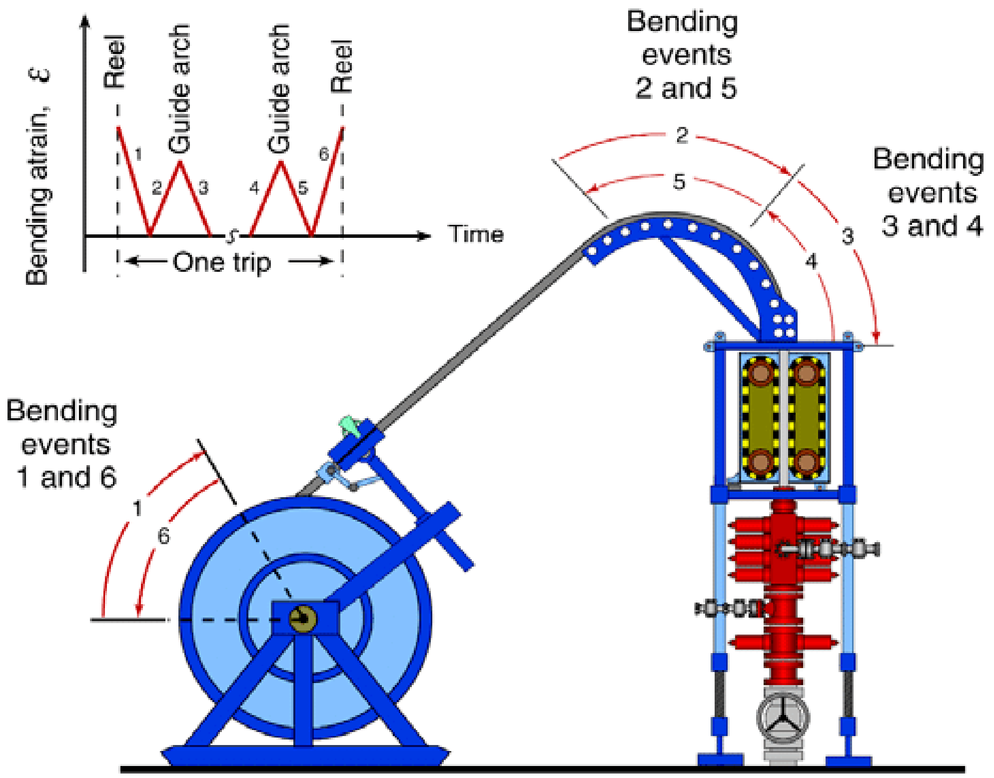


Figure 5.10: Coiled tubing method, [35].

With increasing worldwide demands, advanced equipment are being developed. Hybrid Coiled Tubing systems with diagnostic capabilities and intervention are the best example.

- **SPECTRUM® FUSION Real-Time Hybrid Coiled Tubing Service (Halliburton)**

An intelligent communication and power with an advanced fiber optics, SPECTRUM® FUSION revolutionised data acquisition method on a whole different level. Compatible with mechanical and wireline tools, given system provides with greater range of diagnostics, [36].

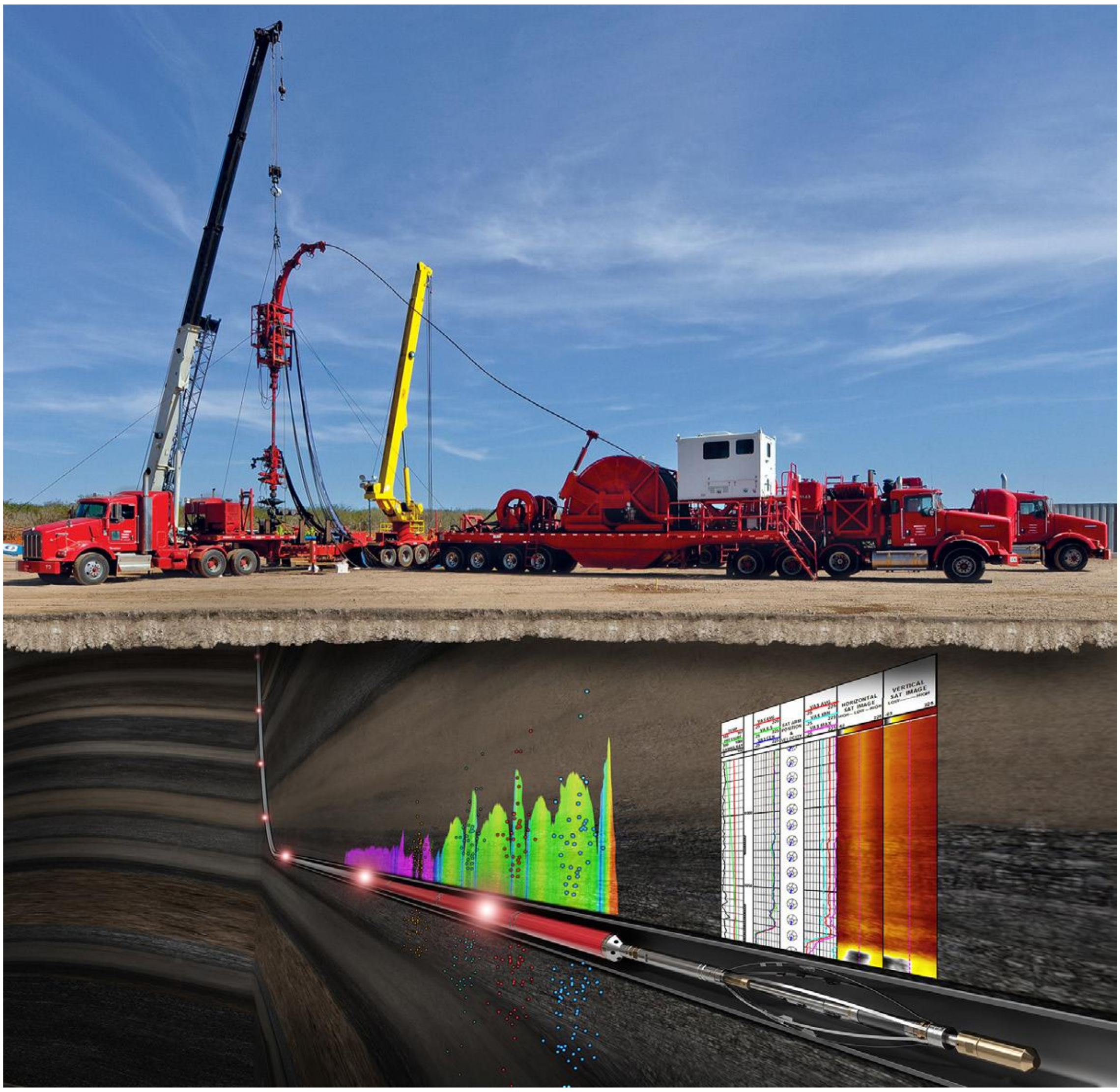


Figure 5.11: SPECTRUM® FUSION Real-Time Hybrid Coiled Tubing Service, [36].

Benefits

- Integrated logging capability – deployment of all cased-hole logging tools, in addition to distributed temperature sensing (DTS) and distributed acoustic sensing (DAS), for maximum subsurface insight.

- Open architecture – designed to be compatible with all electric and mechanical tools, helping provide the best solutions for solving industry challenges.
- Fast rig-up – rig-up efficiency with plug and play connections, eliminating non-productive time (NPT).
- Ability to work with all types of fluids.
- Combination of coiled tubing, service streamlines logistical work flows. Reduction in operation time with limited footprints on working area, [36].

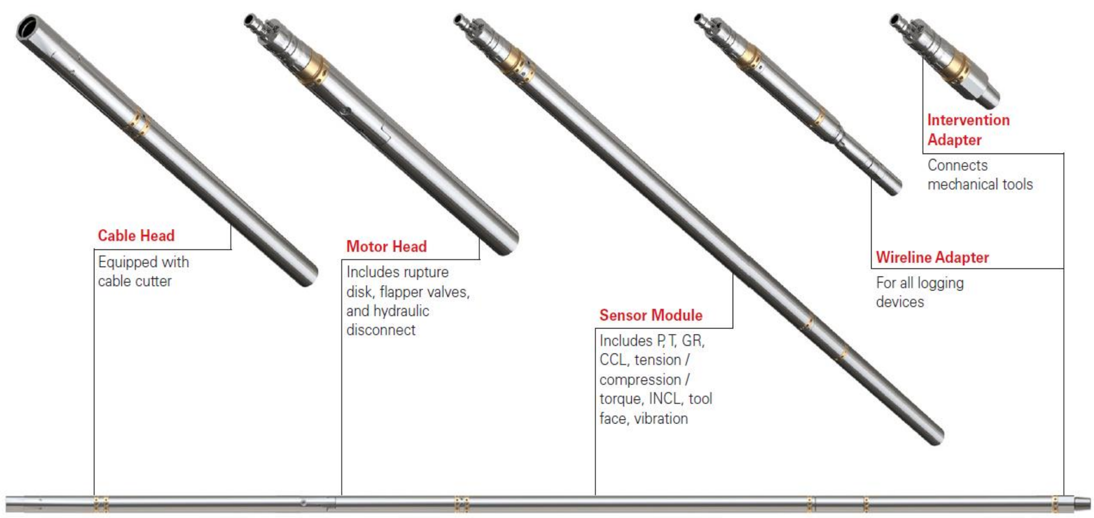


Figure 5.12: The industry's shortest real-time coiled tubing solution with full intervention and diagnostic capabilities, [36].

5.4.4 Production Packers

The key piece in downhole equipment in most of the completion operations, packer serves as a sealing device that isolates and prevents produced fluids and pressure within the tubing string. A protection equipment as well as sealing. An essential equipment, serving just as in production and injection wells. There multiple types of packers – cemented, hydraulic, mechanical. Depending on which kind of operation operator is performing, selection of packers are very important., [37].

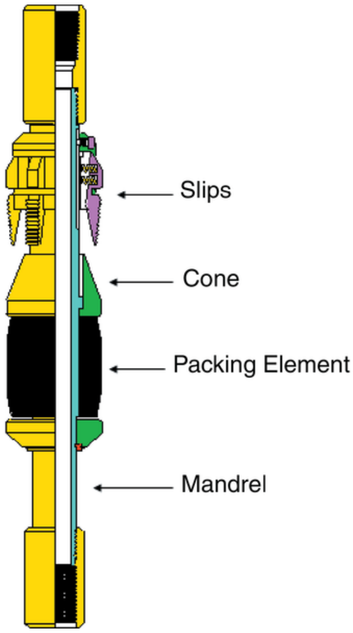


Figure 5.13: Production Packer, [37].

- **Halliburton SPECTRUM® inflatable isolation tool**

Electric inflatable packer SPECTRUM e-IP is an isolation tool to run with the SPECTRUM FUSION service suite. Flexible, modular design of the tool provides with multipurpose BHA configuration, which depends on required chemical treatment. Adjustable according to different straddle lengths. Has the possibility to run dual straddle packer or single packer. With the unique and durable design, given tool can be adjusted for necessary planned treatment, [38].

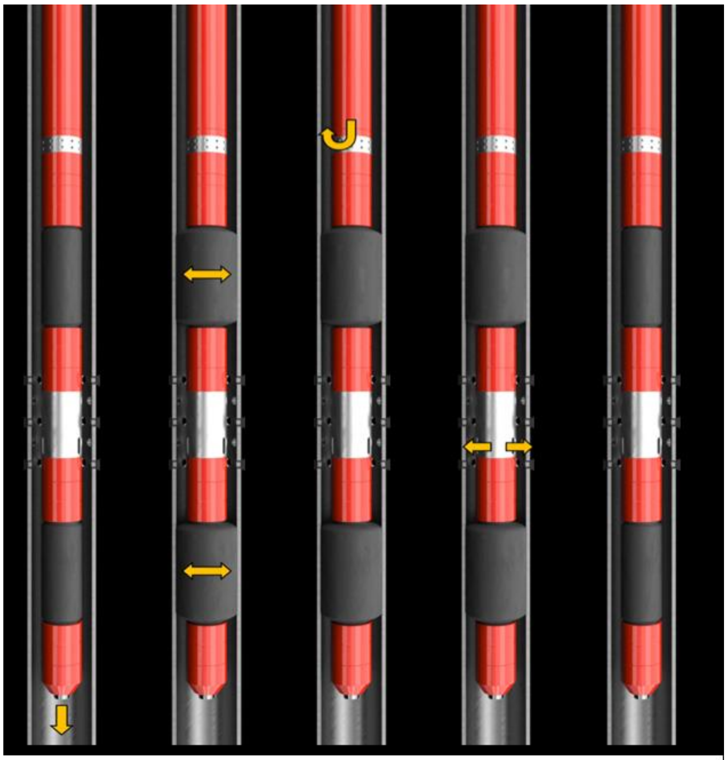


Figure 5.14: Electric inflatable packer SPECTRUM e-IP, [38].

Applications

- Selective Treatments
- For testing injectivity
- Evaluation of integrity of the casings
- Acid jobs
- Water and gas shut-off

Benefits

- Hole cleaning properties while RIH
- Continuation of circulation, without stopping the flow.
- Compatible with different kinds of chemicals
- May be use in a single run for multiple intervals.
- Equipped with camera for a realtime observation

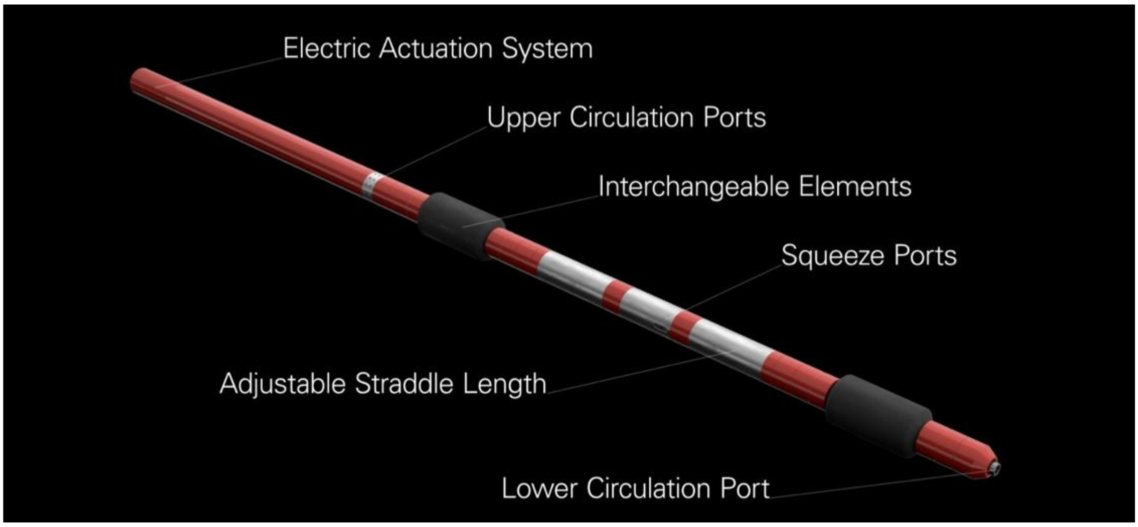


Figure 5.15: Specification design of SPECTRUM® e-IP electric inflatable packer, [38].

5.4.5 Hydraulic Fracturing of Horizontal Wells

For the past 30 years Horizontal Directional Drilling technology has been actively implemented in the oil and gas industry, however only in the last 5-10 years, we have seen the application of multistage hydraulic fracturing of horizontal wells. The reservoir productivity gains from multi-stage hydraulic fracturing of horizontal wells is causing a revolution in our industry. Nowadays, Completion Engineers have a variety of completion tools and techniques which can be applied to effectively stimulate horizontal wells.

- **SmartFleet™ Intelligent Fracturing System (Halliburton)**

Nowadays, almost every completion operation is performed with high uncertainty. Limitations in subsurface observation, may cause high risk and economical loss. With the advanced intelligent fracturing system SmartFleet™, operators may observe and control over fracture outcomes in real-time across every preferred stage, [39].

Control outcomes while pumping
Given tool is an intelligently automated fracturing system that provides with increased control over fracture outcomes, by keeping connected to the subsurface through real-time fracture measurements, live 3D visualization and real-time fracture commands.

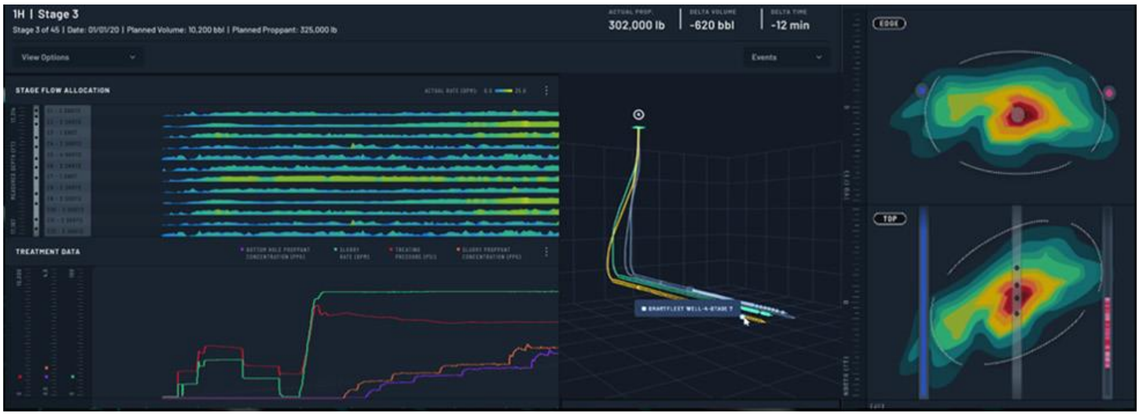


Figure 5.16: Monitoring of fractures in real-life time in 3D, [39].

- Connected to surface
    - o Equipped with subsurface sensing to autonomously adapt and respond to real-time reservoir measurements.

- Monitoring of fractures in real time
    - o The ability to see in real time the measurements of a fractures geometries

An Intelligent Fracturing System that

- Automatically responds to real-time fracture and reservoir measurements
- Provides real-time visibility of fracture behaviour and performance
- Gives you control over fracture outcomes while pumping

A System proven to

- Increase average production uplift between 10-20%
- Manage well interactions in real-time
- Increase stage length by up to 100%
- Optimize fluid volume usage
- Reduce screen-outs by 50%, [39].

6 CONCLUSION

New innovative technological advancements in drilling operations of horizontal wells, will open greater possibilities in performing drilling in time efficient, safely and effective manner. Companies all over the world are focused to provide best possible solution to eliminate errors and mistakes by bringing equipment that will make drilling in areas that were previously unreachable – affordable.

- RSS Technology NeoSteer (Schlumberger) showed that steerable system managed to drill tangent, curve and lateral sections while staying 91% in an extremely tight 4 ft tangent window in Southwest Marcellus Shale.
- Look-ahead-while-drilling technology IriSPhere (Schlumberger) allowed to identify formation to 10m ahead allowing proper setting of 9 5/8 inch casing without any NPT. (Sulawesi, Indonesia).
- AxeBlade drilling bit's (Schlumberger – Smith bits) statistics showed that according to Average field's normalized ROP and Field's Best ROP performance, given drilling bits outperformed Normalized ROP by 42% and Best ROP by 18%, in a single run while drilling 12 1/4 inch holewith generating 27.5 m/h ROP in Oman.
- Casing-while-drilling technology outperformed the conventional drilling technology by saving 47 rig days and large amount of cost expenditures while drilling 12 ¼ inch casing with 9 5/8 inch casing. The operation was completed without any problems. (Kuwait).

Technological advancements in completion operations are being developed and the progress in increasing immensely, such as advanced downhole completion equipment, completion strings, autonomous inflow control devices, production trees. Implementation of new technologies, showed us that formations with high reservoir pressures to more hostile development areas, can be conquered and completed without major problems and failures, decreasing environmental impact and cost expenditures. Technologies such as:

- Fluidic diode Autonomous Inflow Control Devices (AICD) was developed for optimization of flow profile and restriction of unwanted fluids such as water and gas production. Completed wells using AICD technology showed outstanding results in: United Arab Emirates by increasing the oil production up to 300% and restricting Water Coning from 97% to 47%; in Ecuador oil recovery increased up to 500%.
- Real-Time Hybrid Coiled Tubing Service is an revolutionized version of coiled tubing strings, which is equipped with all cased-hole logging tools, in addition to distributed temperature sensing (DTS) and distributed acoustic sensing (DAS), providing with a real-time onsite decision making for more precise execution and maximized well performance.
- TAML classifications from 1 to 5 for different kind of lateral junctions. Increasing the integrity and performance of multilateral wells. Classification TAML 6 is being developed: level differs from a TAML Level 5 well in that pressure integrity is provided by the main wellbore casing and a cemented or uncemented liner in the lateral.

LIST OF FIGURES

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