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ABSTRACT

Well integrity is an important safety aspect of a well. Lack of wellbore integrity can lead to challenges like wellbore collapse, stuck pipe, lost circulation and sloughing shales, which are all big problems for drillers. Loss of circulation and stuck pipe is a high cost problem and is affecting the drilling optimisation considerably. It is crucial to maintain the drilling operation and have minor downtime. The operational time is the most critical optimisation factor in the well process. With the new technology of programmable electronic circulating valves being developed, this can result in quicker and more efficient drilling. Cutting transport is a vital mechanism for an ideal drilling programme. When drilling holes, cleaning is a known problem and is frequently costly.

This master thesis is a study of different circulation tools and discusses if this new technology can lead to more efficient drilling, thus reducing downtime and optimising drilling to avoid undesired situations. The target is to create drilling tools that help reduce potential hole problems and eliminate unnecessary downtime.

The study was carried out by comparing the performance of several different tools with the same fundamental technical and drilling optimisation service, focusing on activation, operability, failure, and additional features. The work is based on literature reviews and additional information was acquired through communication with representation from the different companies. Based on the research, one of the tools excelled in several areas and is ideal for further technological development to help optimise drilling performance in the future.

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LIST OF ABBREVIATIONS

ADA	Alternative Diverter Dart
AVD	Annular Velocity Disconnect
AVOS	Annular Velocity Optimisation System
AVS	Annular Velocity Splitflow
AVT	Annular Velocity Tandem
BHA	Bottom Hole Assembly
BHP	Bottom Hole Pressure
CE	Circumferentially Enhanced
CFD	Computational Fluid Dynamics
ECD	Equivalent Circulating Density
ERD	Extended-Reach Drilling
ESD	Emergency Shut-Off Dart
HPHT	High Pressure, High Temperature
ID	Inner Diameter
LCM	Lost Circulation Material
LWD	Logging While Drilling
MPD	Managed Pressure Drilling
MWD	Measurements While Drilling
NCS	Norwegian Continental Shelf
NPT	Non-Productive Time
OBM	Oil Based Mud
OD	Outer Diameter
P&A	Plug and Abandon
PSA	Norwegian Petroleum Safety Authority
RFID	Radio-Frequency Identification
RFID	Radio-Frequency Identification
ROP	Rate of Penetration
RPM	Rounds per Minute
SDD	Standard Diverter Dart
SFD	Split Flow Dart
TD	Total Depth
TFA	Total Flow Area
UCD	Universal Closing Dart
USD	Ultra-Series Dart
WBM	Water Based Mud

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1. Introduction

In the past 30 years in the drilling industry the technology has evolved significantly. At the start on the Norwegian Continental Shelf (NCS), wells where designed to be located no more than 3 km from the actual offshore installation. Examples of these are the Statfjord and Gullfaks installations. If these fields had been developed within the last two decades, where the technical evolution has improved on many levels, construction costs would have been significantly reduced as directional drilling has reduced the need for both additional platforms in a field. One new installation could replace several platforms from a reservoir coverage point of view because today, it is possible to reach targets more than 12 km from the platform [1].

In 2019, a total of 90 exploration licenses were granted; in 2017 and 2018 there were, respectively, 75 and 103. We know that there are useful resources on the NCS that have not yet been located, and it is important to keep in mind that there were several companies that had looked at Utsirahøyden before Lundin found the Johan Sverdrup field. The directory of oil recourse report for 2018 estimated that about 4.000vstandard cubic metres of oil equivalent oil are yet to be located [2].

The improvement of drilling technology has led to the process of stimulating horizontal wells growing at a tremendous rate. A majority of the assets would not have been economically possible without this technology. This paradigm shift caused a flood in the market; however, this improvement has a downside: with the increased distance, there is additionally the increased risk of failure. The time requirements for the stimulation of single wells changed from several hours to several days. Due to the significant number of elements that need to be considered, it has been difficult to analyse this risk. Therefore, production companies have requested methods to make these horizontal wells more efficient.

To reduce this risk, standards have been developed to ensure safety for the petroleum industry. The two most common standards are from the Norwegian Petroleum Safety Authority (PSA), who prepared a guideline called NORSOK, and the American API. These are not only for safety but additionally value-adding and cost-effectiveness.

The definition of well integrity has several approaches, but a widely accepted definition is that "well integrity can in its simplest definition be defined as a condition of a well in operation that has full functionality and two qualified well barrier envelopes".

The most common definition given from by NORSOK D-010 is the "application of technical, operational and organisational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well" [3]. The operating companies have full responsibility for following these minimum requirements, but the guideline leaves it to the company's discretion which equipment and solution are to be chosen to meet the requirements. They have full responsibility for being compliant with the standard, and all operators on the NCS are obliged to follow these rules and requirements [1].

History can point to several critical unwanted events due to the loss of well integrity. The most commonly known event from the modern era is the Macondo blowout in the Gulf of Mexico in 2010, known as Deep Water Horizon shown in Figure 1.1. On the NCS, Phillips Petroleum's Bravo blowout occurred in 1977; Saga Petroleum's event occurred in 1989 near Ekofisk, and Statoil (Equinor)'s blowout occurred on Snorre in 2004.

Figure 1.1: The deep water horizon accident [4]

These incidents are a reminder of the dangers that can occur while drilling and shows the importance of focusing on the well integrity in the oil and gas industry.

NORSOK D-0101 specifies that "there shall be two well barriers available during all well activities and operations, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the external environment" [3]. This sets the basis for how to operate wells and maintain well integrity throughout the lifetime of the well. It is clear that well integrity should be prioritised, as issues that may not be critical can still lead to serious accidents.

1.1. Background

This thesis is written to ensure that newcomers to the topic can gain a basic understanding and general familiarity of the topic; information is additionally included for those more experienced in the field. Well integrity and drilling optimisation is a broad topic, and this thesis focuses on technology to reduce hole problems while drilling.

Since the initial discovery of oil and gas, there has been a massive research effort by the largest operators, such as Equinor, Conoco Phillips Shell, BP, Total and others, to attempt to understand the mechanism taking place in highly inclined and horizontal wells.

It is generally clear that problems take place while drilling a well, even in a properly planned well. A good example of this could be drilling a well in a known area, assuming the formation is similar and therefore using the same drilling practices. The operator believes that they will encounter the hole problems that have been reported in previously wells, but in reality, they are facing a non-homogeneous formation. This means that two close wells may have entirely different geological conditions.

The key is to create drilling tools to reduce potential hole problems. Since the expense of drilling is on the rise and drilling problems can be costly, it is important to improve drilling efficiency and decrease construction time. Severe problems occur which cost the oil industry several billion dollars yearly; therefore, oil companies attempt to avoid these problems to optimise the drill parameters, which reduces the risk or probability of these unwanted situations.

The operational time use is the most critical optimisation factor in the well construction process. Nevertheless, it is difficult to measure the precise effect of drilling optimisation on drilling operations. Improvements in drilling optimisation services should increase the rate of penetration (ROP), reduce non-productive time (NPT), and reduce failures [5].

The rotation per minute (RPM) is essential to lift the cuttings out of the well, but the mud weight transports the cuttings; hence, the annular velocity decides the efficiency of removal from the wellbore. If this is not done, the drill string may become stuck or another crucial issue can cause the operation to stop.

Cutting transport is a vital mechanism for an ideal drilling programme. When drilling holes, cleaning is a known problem and is frequently costly. If the removal of cuttings is unproductive, this can lead to several problems, such as bit wear, a slow drilling rate, increased equivalent circulating density (ECD), which may lead to formation fracturing, high torque, drag or a stuck pipe. If these problems are not solved, they may lead to side-tracking or, in a worst-case scenario, the loss of a well.

In order to achieve well cost control and reaching the target zone, it is essential to understand and predict drilling problems, their causes and planning how to solve them. Inadequate wellbore integrity can lead to challenges like wellbore collapse, stuck pipe, lost circulation and sloughing shales, which are all big problems for drillers. This thesis looks into possible solutions to several of these problems as well as providing preventive measures.

1.2. Objective

The overall objective of this thesis is to provide an understanding of the following:

- Describe the drilling technology used for drilling optimisation
- Give a short explanation of well integrity
- Present different tools
- Challenges related to new technology
- Discuss positive and negative aspects related to the technology and tools
- Draw conclusions about what we can learn from earlier studies and research

With the new technology being developed of programmable electronic circulating valves, could this technology have resulted in quicker and more efficient drilling, improved hole cleaning, quicker tripping, lower ECD's and fewer hole problems such as tight holes and stuck pipes? There have been different preventive measures against these issues, for example changing parameters, using pills with inhibitors in the mud to reduce friction, and so on.

In this thesis the effect that drilling optimisation has on drilling efficiency and time use has been studied. This was done by through comparison of several different circulation tools with the same fundamental technical and drilling optimisation service. It is discussed whether the different tools can lead to more efficient drilling, thus reducing downtime and optimising drilling to avoid unwanted situations.

1.3. Gullfaks Field

Gullfaks was allocated to Statoil (now Equinor), Norsk Hydro, and Saga Petroleum as operators. This was the first time the government chose a strictly Norwegian composition. The Gullfaks field lies in block 34/10 in the north part of the North Sea, as shown in Figure 1.2. The main field is built with three large production platforms with concrete substructures. The Gullfaks A-platform started production on December 22 in 1986. Gullfaks B started on the 29th of February 1988, and Gullfaks C started on November 4, 1989. A map of Gullfaks is shown in Figure 1.2. The oil that is produced is stored at the field, but the gas is transported in pipes for handling at the gas deposit in Kårstø; from here it goes to export [6].

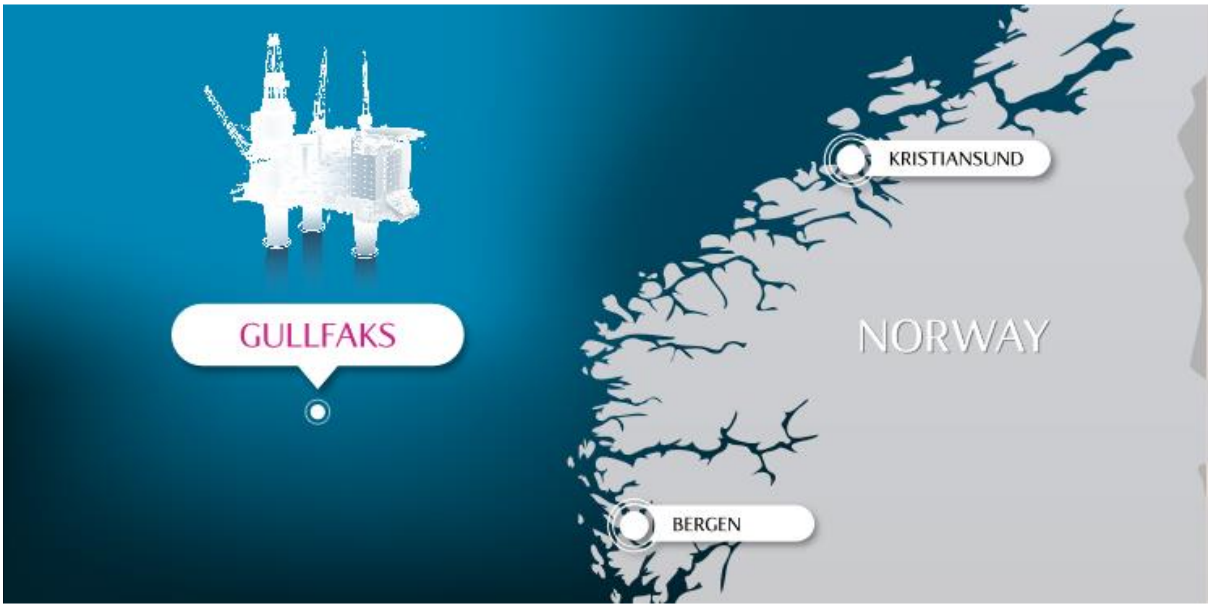

Figure 1.2: Location of the Gullfaks field [6]

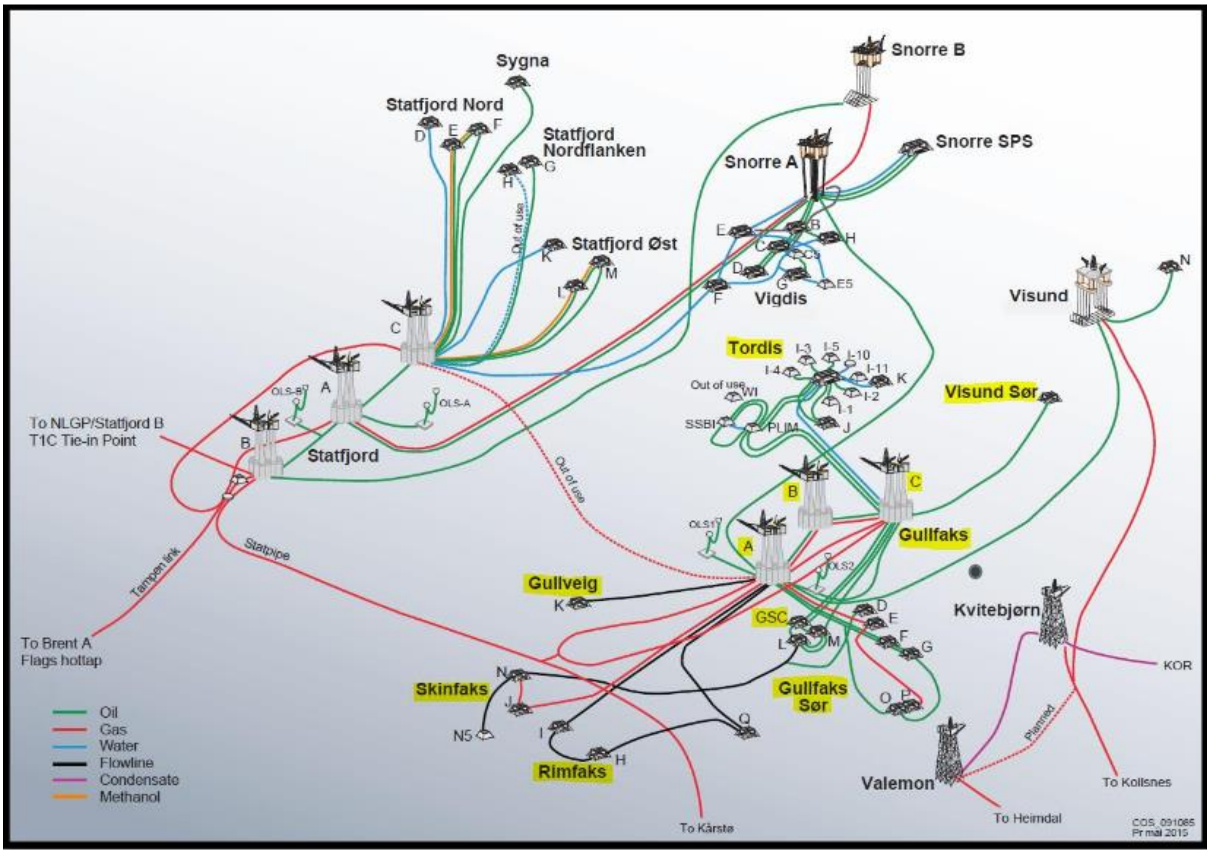

Figure 1.3: The Gullfaks field (except Sindre); Green lines: Oil; Red lines: Gas; Black lines: umbilicals [7]

Oil and gas from the field are transferred to A and C for treatment, storage, and export. The satellite fields for Gullfaks – Sør, Rimfaks, Skinfaks, and Gullveig – are built with subsea wells which are remotely operated from the Gullfaks A and C platforms as shown in Figure 1.3. The recoverable deposits amount to 59%, but the goal is to increase this to 62% [7].

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2. Theory

In this chapter the theory about drilling will be described and furthermore what drilling problems are and how to optimize them in an efficient way will be presented in detail.

2.1. Drilling

An oil and gas well have different phases throughout its life. Therefore, a short overview of the construction process is provided here. The construction quality impacts the profitability of the oilfield. The drilling system is performed similarly but with a few differences and can be divided into two single methods dependents on the type of rig.

- Fixed installation
- Floating installation

The central difference is where the location of the drilling equipment is. On a fixed platform, the equipment is placed below the drilling deck but on a floating device, it is generally on the seabed.

Prior to beginning drilling operations, all elements in the process must be reviewed. Location and all necessary and related information must be updated and included in the drilling programme for the selected well. Some of this information can be the casing programme, mud programme, directional drilling programme, bit programme, and other types of documents depending on the type of the well.

The drilling process consists of a rotating string with a drill bit positioned at the end. The lower part of the drill string generally consists of heavier pipes called drill collars, different equipment such as a mud motor, measuring equipment, and other specialised devices, as shown in Figure 2.1. This part is called the bottom hole assembly, shortened as BHA.

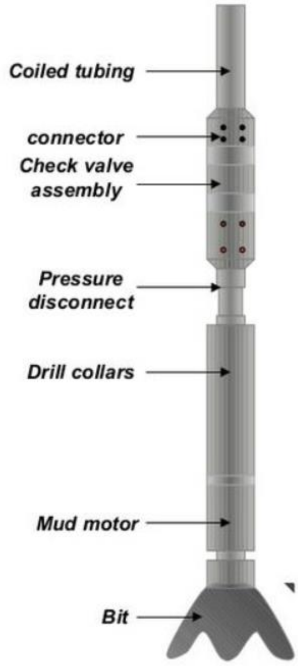


Figure 2.1: An example of a Bottom Hole Assembly, BHA [8]

The BHA consist of various components and tools with a complex arrangement of tools which vary depending on the requirements while drilling. The BHA serves many functions, but its main task is to efficiently load and control the drill bit. The BHA and string design need to be properly prepared to meet all safety parameters. The drill string needs to be designed to allow the highest ROP, and in several cases, the well path thaw has been initially planned cannot be drilled with the drill string or the equipment on the drilling ring; hence, the wall path is chanced due to its less expensive change cost instead of waiting for the necessary equipment.

While encountering various types of formation properties, the drilling bit bores the well hole by breaking, cutting, or crushing the subsurface rock formation into small pieces called rock cuttings, or simply cuttings. Drill bits vary in size, shape, and material and are determined by which section and which type of formation is being drilled. Figure 2.2. shows several different types of drilling bits.

Figure 2.2: Different types of drilling bits; Roller cones to the left and fixed cutters to the right [9]

Furthermore, drill bit types for a vertical well are probably not suitable for directional wells. Additionally, mud motors are required to provide a sufficient amount of power to the bit while drilling directionally.

The entire process must be planned and considered to make a final decision, and several of these issues can occur during the drilling process

- Drilling location (selection for centre of the well slot)
- Setting depth of casing and casing shoes
- Section size
- Mud parameters
- Type of rig and drilling equipment
- Data from wells in the area and identification of typical problems for the formation or area

2.1.1. Conventional drilling

The casing string is the steel tubular which is set into a well to protect it from its surroundings. Examples of casing string components are conductor casing, liners, and tubing. Different casings strings can be hung at different locations as shown in Figure 2.3. and have various functionalities. The main focus is to maintain well integrity and adequate well control, preventing contamination of formation fluid, reinforced with a cement programme to provide high-quality casing support and hydraulic isolation under given pressure and temperature settings. Tripping, or the tripping time, is the time taken to run equipment down or up a well. The annulus is the space around a pipe in a wellbore, the outer wall of which may be the wall of either the bore hole or the casing [8] [10].

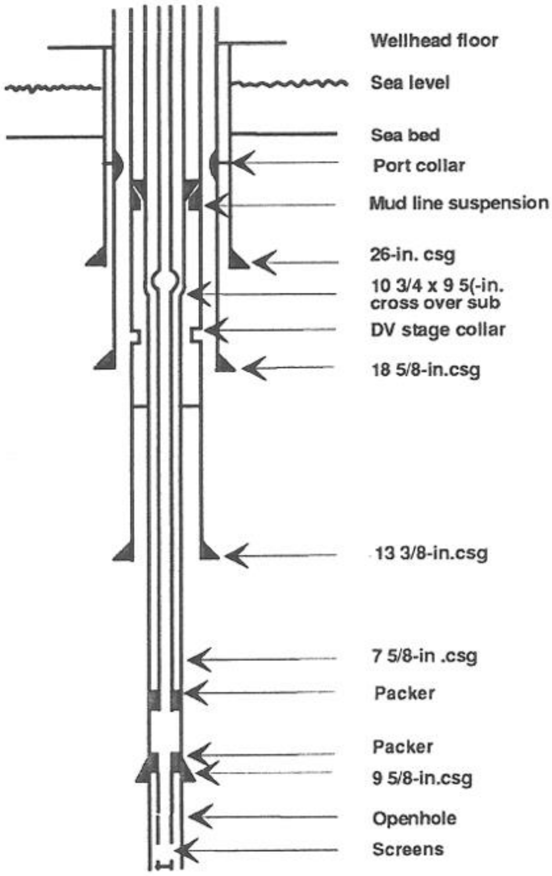


Figure 2.3: A simple overview of a wellbore [8]

While drilling, the use of drilling fluid is essential for the well. This drilling fluid, called mud, can be separated into two main types: oil-based mud (OBM) and water-based mud (WBM). The mud has a number of purposes, including but not limited to transporting cuttings, greasing the pipes, mud cake, cooling, lubricating, reducing friction, the cleaning of bits, and stabilising the well. The composition of the mud decides the density which enables adjustments to the hydrostatic pressure within the well. This is carefully planned to balance the formation pressure. Several zones may have different resistance levels to fracture, and the consequence of the use of incorrect pressure is that the well may collapse. The cuttings are separated from the mud, usually with a shale shaker, and are subsequently re-used in the well. The mud is developed for supplying the drilling fluid parameters for efficient wellbore cleaning, reducing damage to the formation, and developing the filter cake. [10]

While drilling, the evaluation of the process is crucial. Measurement while drilling (MWD) is a standard practice each time a well is drilled. The measurements are made downhole, contained in memory for a given time, then transmitted to the surface. The measurements are different from company to company, but MWD tools can measure formation parameters and several of the readings can additionally be called logging while drilling (LWD) [11].

There are additionally other types of drilling, among them being liner drilling and managed pressure drilling. Linear drilling can be defined as the casing not returning to the surface; in other terms, hung using a liner hanger from the bottom of the prior run casing [12].

As seen in Figure 2.4 (a), the liner is hung in the previous casing and the circulation starts. The liner is run on a drill pipe which screws into the liner hanger. Figure 2.4 (b) illustrates the casing and cement throughout a cementing job. After this, a ball or a dart is dropped to activate the wiper plug and shear off. After this, cement is filled into the annular, filling the area between the liner and the casing, as illustrated in Figure 2.4 (c).

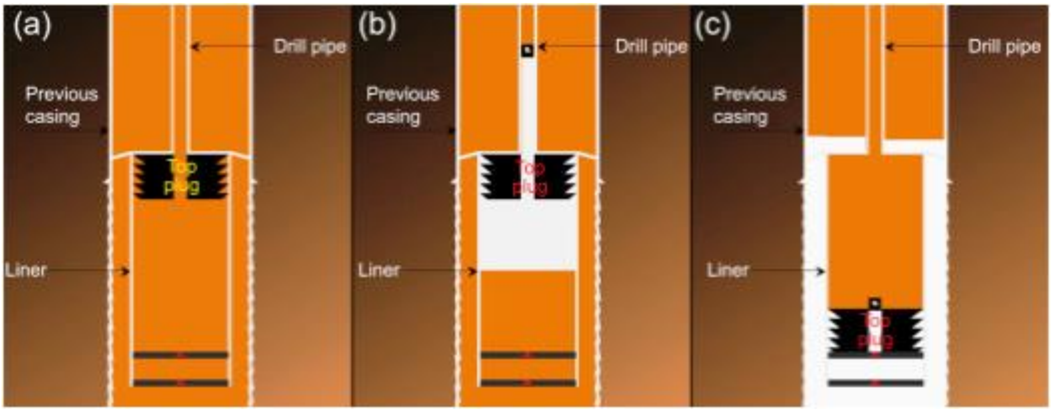


Figure 2.4: Liner cementing - (a) Liner hung and circulating; (b) During cement job; (c) Completion of cementing [13]

When all the above is completed and the tools are detached from the liner and removed from the well, the cement and internal liner hanger can be drilled.

In conventional operations, the system is open to the atmosphere at the top. There is no way to control the pressure by means of applying pressure on the surface. In managed pressure drilling (MPD), a rotating control device seals the annulus against the drill pipe, allowing pressure to be applied on the surface without any fluid spill. This allows for the use of gas as a fluid as well. Drilling choke valves are used to precisely control the pressure on the surface, allowing for the necessary changes in the pressure profile along the wellbore, as shown in Figure 2.5 [14].

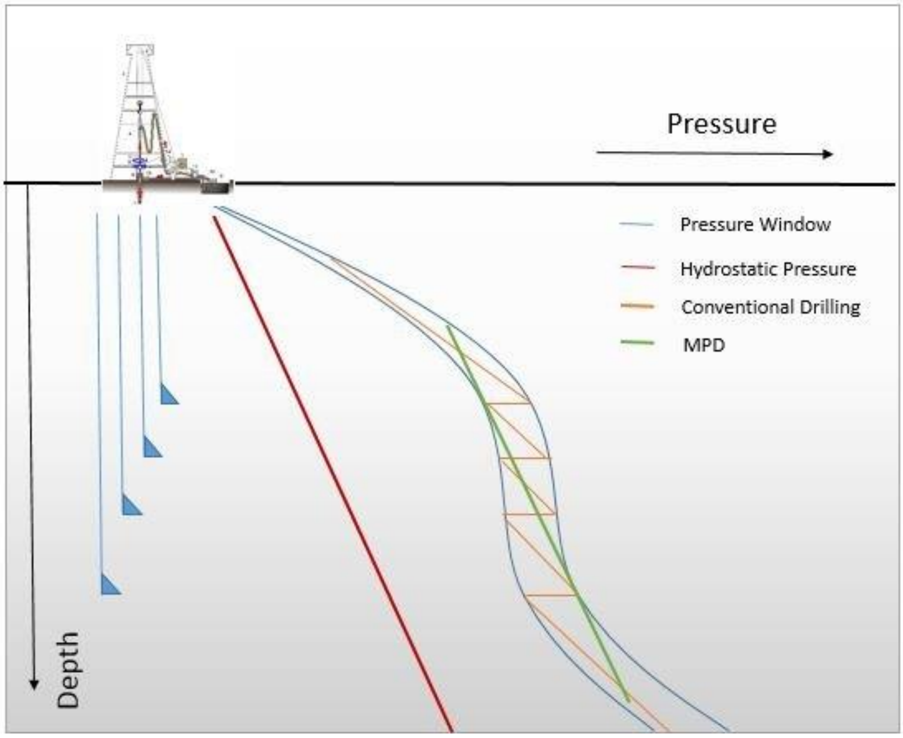


Figure 2.5: A rough sketch of MPD with constant bottom hole pressure [15]

2.1.2. Horizontal drilling

There are several profiles of directional wells, and the trajectories used include the following:

1 Slant-type well
2 J-type
3 S-type
4 Extended-reach drilling (ERD) wells
5 Horizontal wells

The majority of these can be combined if necessary [10].

2.1.3. Drilling Optimisation

The term drilling optimisation has been used for several decades and is currently used in all aspects of the drilling industry. It can be used in tools, software, procedures, and so on, either reducing time spent or the risk of facing a certain problem, enhancing any part of the drilling process to make it less expensive or more efficient. In 2004, D. C-K Chen from Sperry Drilling in Halliburton defined drilling optimisation as “a process that employs downhole and surface sensors, computer software, MWD, and experienced expert personnel – all dedicated to reduce trouble time and increase drilling efficiency” [16].

In general, a full drilling optimisation should consist of drill string integrity, hydraulics management, and wellbore integrity, as shown in Figure 2.6.

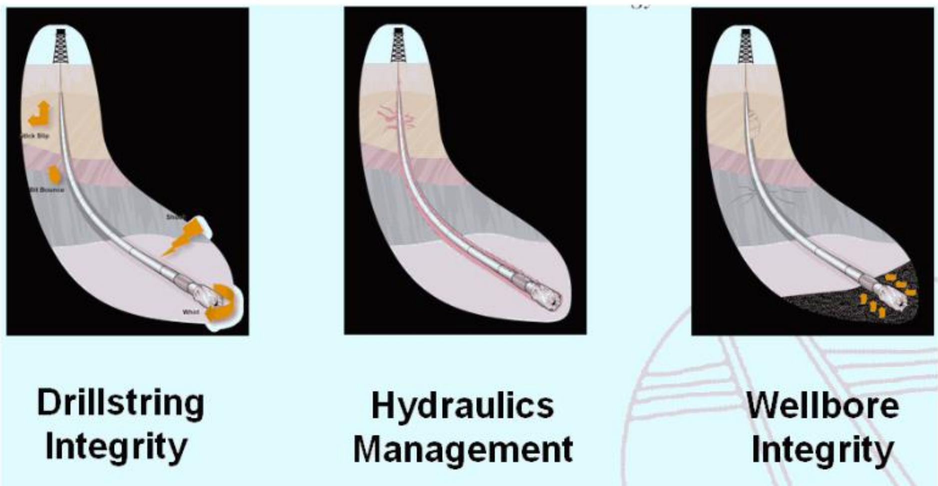


Figure 2.6: Contents of a comprehensive drilling optimisation system [17]

The cost throughout the drilling process has significantly improved, but there remains work to be done since 15–35 % of the well cost is due to NPT associated with wellbore integrity, drill string integrity, and downhole failure. Economical margins on each well are expected to continue shrinking as the significance of drilling optimisation increases [17].

The financial aspect of drilling is a critical factor for oil and gas companies. The financial return is the main focus and when operating costs increase, drilling challenges are more likely to occur. As mentioned, the key approach is to reduce NPT to its minimum, which could potentially result in large cost savings for the energy and petroleum industry. In several wells, particularly when the pore pressure and the fracture gradient are close, the wells require drilling optimisation to be completed. This is additionally an important factor that can lead to new wells in challenging drilling environments, which has been excessively expensive before [17].

2.1.3.1. Drill string integrity

Drill string integrity focuses on preventing or reducing mechanical forces to lower the risk of failure. The most critical concerns are downhole vibrations such as stick slip and bit bounce, BHA whirl, torque, buckling, and drag. Drill string integrity is for protection from fatigue, reducing unnecessary shock and vibration. For protection, the system should consist of the following:

- MWD (such as vibration sensors)
- Surface data logging
- Computer software – dynamic BHA modelling (for critical rotary speeds), static BHA modelling, and torque and drag modelling software
- Integrated rig site information systems [16]

2.1.3.2. Hydraulics management

Hydraulics management is about maintaining hydrostatic and dynamic pressure between critical upper and lower operating limits. It additionally focuses on optimising hole cleaning, circulating pressure, and clean-up cycles as well as optimising ROP and tripping without passing the pressure limits. For protection, the system should consist of the following:

- MWD (downhole of annular and bore pressures
- Surface data logging
- Computer software such as hydraulics modelling and hole cleaning modelling software
- Integrated rig site information system [16]

2.1.3.3. Wellbore integrity

Wellbore integrity concentrates on determining of the upper and lower wellbore pressure limits. These limits are prognostication of pore pressure, borehole collapse pressure, and fracture pressure.

Professionals make proposals to secure wellbore integrity and stability, extend target depth criteria, maximise ROP, and eliminate or optimise casing points. Scenarios like these are used to reduce the uncertainty in mud weight decisions and together with the hydraulics management service it can enhance performance conditions by selecting the correct mud weight and further contributing to provide a safe drilling operation [17].

For protection, the system should consist of the following:

- MWD measurements – downhole annular and bore pressure measurements
- LWD measurements – sonic, density, and resistivity and perhaps new sensors such as formation testing while drilling (FTWD) sensors
- LWD imaging tools
- Seismic well drilling, which has considerably increased the quality of optimisation services
- Surface data logging
- Computer software – pore pressure or fracture gradient modelling, and wellbore stability modelling software
- Integrated rig
- Site information system [16]

2.1.4. Technical limit

Technical limit is a term that defines the theoretical maximum in safety, efficiency, and production during the drilling processes. This limit is established for the times used to fabricate a theoretic well where all procedures are carried out without any flaws and under perfect conditions. It defines a given set of design parameters such as the following:

- Choosing a set of suitable reference wells
- Splitting the process of well construction into sections
- Determine the time used in each sequence

Removable time can be described as the difference between the technical limit time and the actual well period. It can be split into either invisible lost time or conventional lost or downtime. Invisible lost time can be categorised as the activities that would occur in a normal well, for example change of bit in-between section, wiper trips, BHA trips etc. [17].

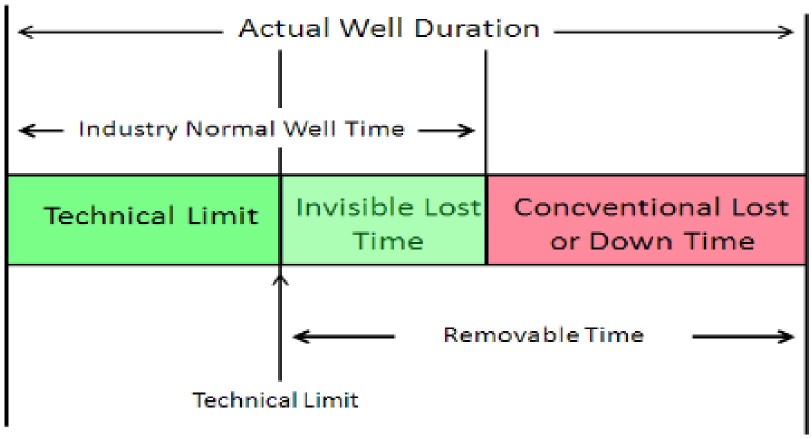


Figure 2.7: Schematic showing the relationship between the actual well duration and different phases within [18]

The point of the technical limit is to recognize the vulnerabilities and make improvements rather than accepting the flaws as permanently present.

2.2. Drilling challenges

In order to maintain an efficient drilling operation, one relies on acting and planning to avoid, ease, and control the challenges the created by the subsurface. The main challenge is that one cannot be certain of what problems may be encountered or what the subsurface will expose. The most common drilling challenges include the following:

- Pipe sticking
- Loss of circulation
- Hole deviation
- Pipe failures
- Borehole instability

- Mud contamination
- Formation damage
- Hole cleaning

2.2.1. Cutting transport

Transportation of cuttings a mechanism that is an essential factor for an efficient drilling schedule, and in directional and horizontal drilling hole, cleaning is a familiar and expensive challenge.

Unproductive removal of cuttings can have significant consequences, such as bit wear, a slow drilling rate, increased ECD, high torque, drag, and in the most severe case, the drill string can become stuck. If this type of situation is not properly managed, the problem can escalate to side tracking or the loss of the well. The transport of cuttings has many variables of effectiveness, for instance, inclination angle, hole and drill string diameter, RPM, drillpipe eccentricity, ROP, and cutting characteristics such as size and porosity. The fluid characteristics are important as well, such as the flow rate, fluid velocity, flow regime, and mud type [19].

2.2.2. Borehole instability

During drilling, costly wellbore problems due to unknown or unexpected behaviour of the rock may happen [20]. The geochemical and geomechanically properties of the rocks are interfered with while drilling, moving their state from equilibrium to be an unstable formation. The result of unstable formations can lead to parts of the wellbore collapsing and in a worst-case scenario, the entire hole may collapse. In other circumstances, the wellbore symmetry can be significantly altered due to a type of circular caving, reduction in the diameter, and elongated segments in parts of the well. These mentioned rock instability problems can result in a decrease in cutting transport efficiency and subsequently affect the quality of a cementing job [20].

It is important for the drilling engineer to understand the failure phenomenon. In order to understand them, compatible and specific criteria must be practiced [21]. Different formations tend to fail in different ways, where clay formations tend to fail by plastic deformation, and sand formations tend to fail by shear stresses. How the formations fail gives several scenarios with undesirable outcomes. Several of these outcomes are listed below [20]:

- A production case – comprehensive failure or pore collapse due to different or less fluid in the pore space
- Formation collapse due to tensile failure
- Cohesive failure or erosion

- Pore collapse due to plastic deformation
- Tight hole due to creep failure during drilling
- Shear failure with no significant plastic deformation present

Several empirical proofs have been advanced. The five most significant ones are the Von Mises, Mohr-Coulomb, Griffith, and Hoek-Brown failure criteria [20]. Each proof must be deeply understood before applying them to ensure that an appropriate failure criterion is selected for a specific problem. These failure criteria are used to generate a failure envelope showing the safe and unsafe regions.

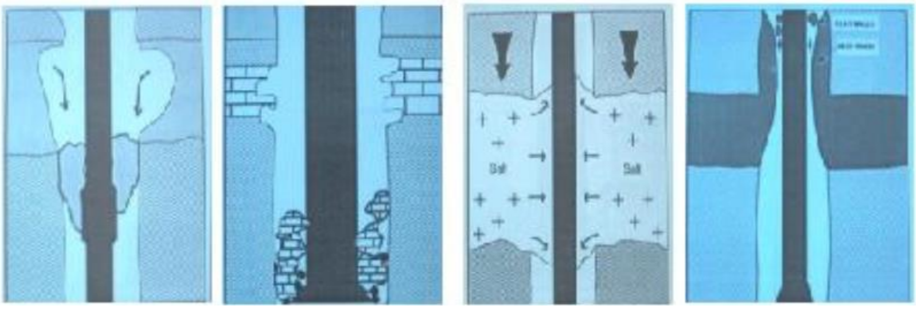


Figure 2.8: Drawing illustrating different wellbore instabilities [17]

As shown in Figure 2.8, from the right, there is a reactive clay consisting of few gumbo mud-balls; a plastic behaviour around the drill string invaded by a salt formation; a jammed drill string from fractured formations above; and formation collapsing into the drill string due to an unconsolidated formation [17].

2.2.3. Annular velocity

The annular velocity of a drilling process is selected to transfer cuttings from the bottom of the well to the surface. During this process, the concentration of cutting in the annulus within certain limits dictated by the drilling and formation conditions must be maintained. Two functions of the circulation of the drilling fluid are of primary importance to the drilling operation;

1. To jet the bottom hole and bit teeth clean of drill cuttings
2. To lift the drill cuttings through the annulus between the drill pipe and the hole wall

A solid particle tends to sink through a liquid of lower density at a velocity known as the settling velocity. There is much information in the literature on the settling velocity in Newtonian fluids, but only limited information is available for non-Newtonian fluids, and most drilling fluids are non-Newtonian in nature where the viscosity is not a constant [17].

2.2.4. Hole cleaning

How efficiently cuttings can be removed while drilling through a formation is called hole cleaning. Since the early 90s until today, there have been a large number of studies regarding hole cleaning, and the debate on how to achieve the ideal hole cleaning continues [22]. As mentioned in Section 2.2.2, it is essential for drilling engineers to understand this phenomenon and be able to optimise all parameters that can affect the hole cleaning, such as fluid rheology, RPM, ROP, drill pipe size, pump rate, annular eccentricity, and hole inclination. The recommendations on how to achieve a sufficient hole cleaning vary among experienced personnel, as well as among peer-reviewed scientific articles and can be broad. It is therefore important to conduct a thorough engineering study for each well.

In recent times, different scientific articles have identified that the consolidation of cuttings in the low-side of the annulus has a significant impact on hole cleaning usage of a circumferentially enhanced (CE) bond to address high-side channelling evaluated through computational fluid dynamics (CFD) modelling [22]. The consolidation of cuttings in the low-side of the annulus, alternatively called high-side channelling since the flow floods that path, has more impact as the inclination increases. This is due to the gravitation in the z-axis, working downwards and therefore attracting the largest particles, which tend to be cuttings. In recent years, new technology has arrived that addresses this problem, such as a CE-bond tool, additionally called a CE-bond, that lies around the drill string and re-defines the path of least resistance [23]. New technologies such as the CE-bond have not been subjected to practical evaluation of real wells but have been thoroughly studied with the use of computational CFD modelling.

Water- and oil-based drilling fluids behave differently [22], particularly in water-based drilling fluids that have low transportation abilities. Polymers are added to the fluid in order to increase its viscosity. The added polymers, to varying degrees, reinforce the adhesive ability water has and will couple cuttings together with water, resulting in small to large cuttings beds. Designing a drilling fluid as ideally possible is critical for the hole cleaning.

A cuttings bed is a consolidation of cuttings that accumulates and sticks around the drill string, as shown in Figure 2.9 below. From the figure, the cuttings bed is accumulated in the low-side channel of the annulus.

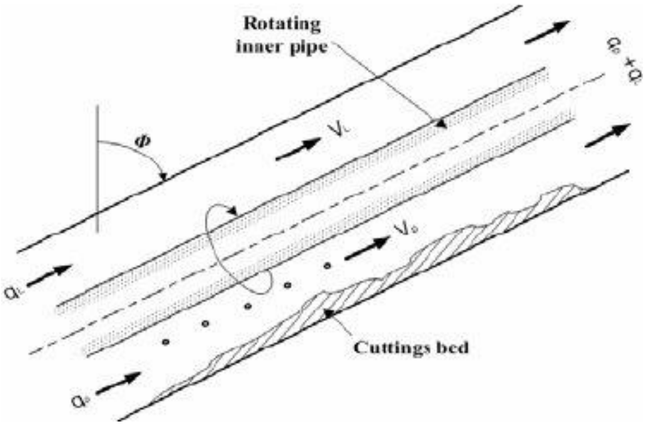


Figure 2.9: Cutting bed accumulation at the low-side of the annulus [24]

The drill pipe rotation, additionally called RPM, has an effect on hole cleaning and the presence of cuttings bed [22]. By increasing the RPM, the drag effect plays a role, and the centrifugal force increases. This results in the crushing and loss of cuttings beds. In addition to the increased centrifugal force, the cutting bed rapidly moves to higher ground in the annulus, where the velocity is higher compared to the bottom, further increasing the hole cleaning. The hole cleaning is additionally affected if the drill string is larger than normal, resulting in less annular volume and an increase in velocity, which increases the Reynold's number and turbulence. The drill string has a large effect on cutting transport and cannot be ignored when designing a wellbore.

2.2.5. Lost circulation

Each formation has a drilling window which has to lay inactive while drilling goes deeper to the space between formation pressure and fracture pressure. It is crucial to understand that they cannot be controlled although wellbore pressure, or hydrostatic pressure, can be. The mud weight must be more than formation pressure but less than fracture pressure. As one drills deeper, the pressure has to be adjusted if hydrostatic pressure exceeds fracture pressure. The most common place is generally immediately below the lowest casing. The casing shoe is where the lowest casing and formation meet. This is where the formation pressure is weakest. A fracture in the formation can lead to a loss of drilling fluid to the formation. Each drilling fluid is lost to a fracture in the formation, a situation called lost circulation occurs. The most obvious indication of lost circulation is a lack of flow, or no flow. The flow of the mud shakers (shale shakers) stops. Other indications of lost circulation include when the flow indicator decreases to zero, or string weight increases. Several other reasons include an increase in pump speed, which causes a loss of bottom hole pressure. When lost circulation occurs, the possibility of taking a kick is increased.

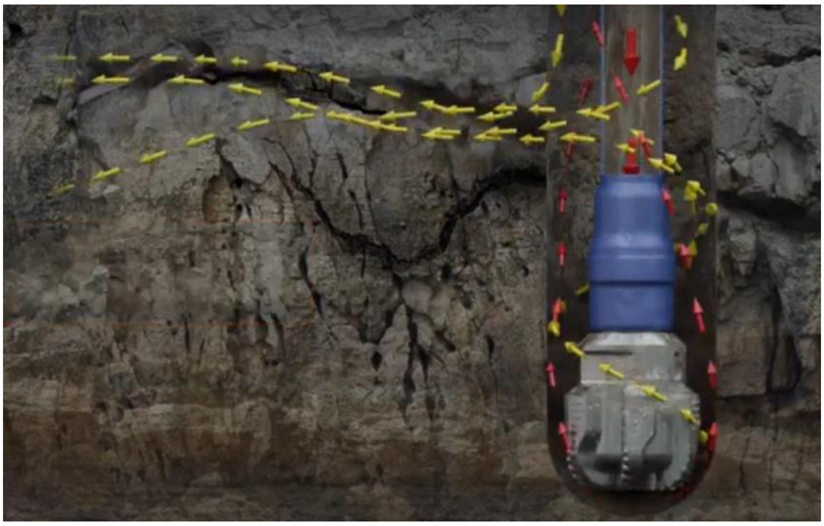


Figure 2.10: Illustration of lost circulation to the formation [25]

PetroWiki defines loss of circulation as “the uncontrolled flow of whole mud into a formation, sometimes referred to as a “thief zone” [26].

As shown in Figure 2.11 there is a partial and total loss to the formation; as mentioned, when there is the loss of circulation, flow goes out in the formation, and total loss is when all the mud flows into a formation with no return to the surface. This should be avoided at all times. For partial lost circulation, as seen to the left in Figure 2.11, the mud returns to the surface but there is partial loss to the formation.

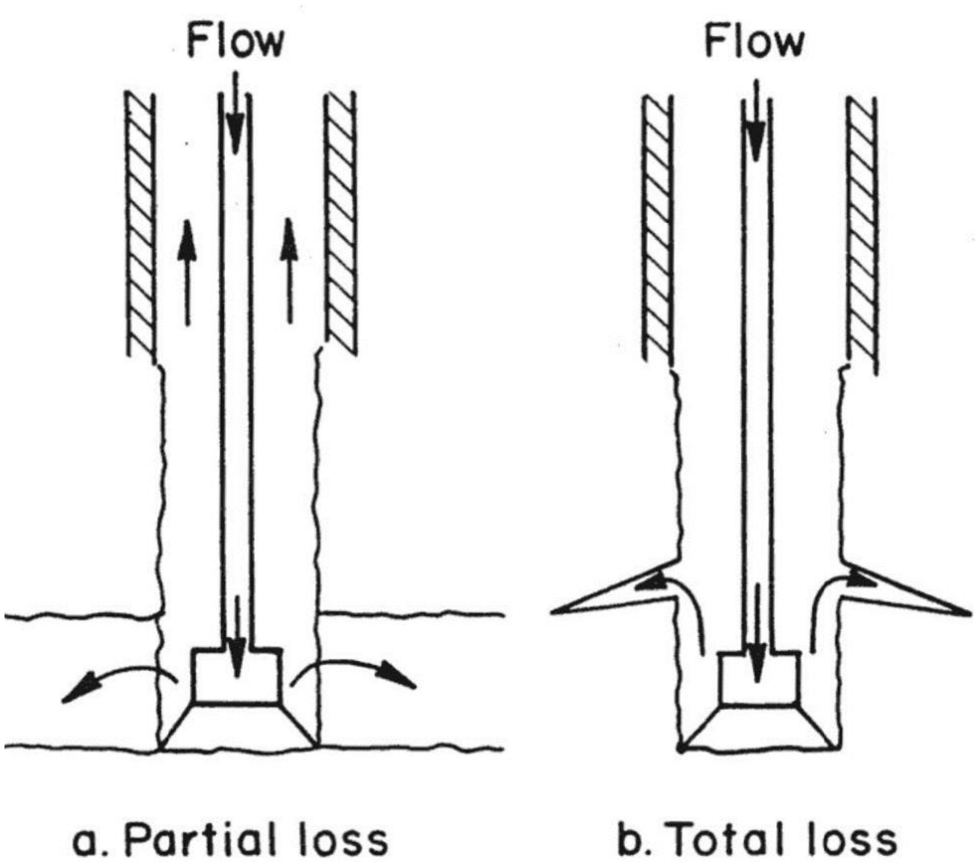


Figure 2.11: Drawing of lost circulation zones [26]

According to PetroWiki, the most common causes which can lead to lost circulation include the following:

- Formations that are inherently (induced) fractured, cavernous, or have high permeability
- Improper drilling conditions
- Induced fractures caused by excessive downhole pressures and setting intermediate casing to high [26]

It is simpler to prevent lost circulation than to cure it. Optimisation of drilling fluid properties and improved hole cleaning are crucial to prevent circulation loss. There are additionally different types of drilling methods that can reduce the risk of loss, such as casing while drilling, managed pressure drilling, and underbalanced drilling. As mentioned, when lost circulation occurs, it can happen for many different reasons. The highest concern is that the mud level in the annulus may decrease and accompanied by lost circulation, this may lead to reducing the mud-column to drop the mud hydrostatic pressure below pore pressure and invite kick occurrence.

When lost circulation occurs, it is traditional to add substances to the drilling fluid to cure losses. This is called lost circulation material (LCM), which generally includes fibrous, flaky, or granular materials [27].

2.2.6. Drop ball

For the terms drop ball and ball operated, Schlumberger glossary defines it as “a ball that is dropped or pumped through the wellbore tubulars to activate a downhole tool or device. When the ball is located on a landing seat, hydraulic pressure generally is applied to operate the tool mechanism. Describing a mechanism or system that is actuated by a ball that is dropped or pumped through the tubing string. Once located on a landing seat, the tool mechanism is generally actuated by hydraulic pressure” [28]. A solid sphere is dropped or pumped through the tubular in a well and activated by a ball operated tool through increased hydraulic pressure.

2.2.7. Stuck pipe

A stuck pipe is when the drill pipe cannot rotate or trip up or down. There are multiple causes of this, but the most common cause is an unstable formation. PetroWiki claims that complications related to stuck pipes are approximately half of the total well cost, which makes a stuck pipe one of the most expensive difficulties during a drilling operation. It is frequently linked with well control and lost circulation, which are additionally costly disruptions to the drilling operation [29].

If the drill string becomes stuck, fishing operations must be started, and in the worst-case scenario, requires the shooting off the string – the worst scenario if BHA is stuck. Then there is a likely need to take a side-track for the original well and plug the original. This operation is expensive and therefore, it can be profitable to not remove all the equipment in the well. Figure 2.12 is an example of a stuck pipe due to pack-off.

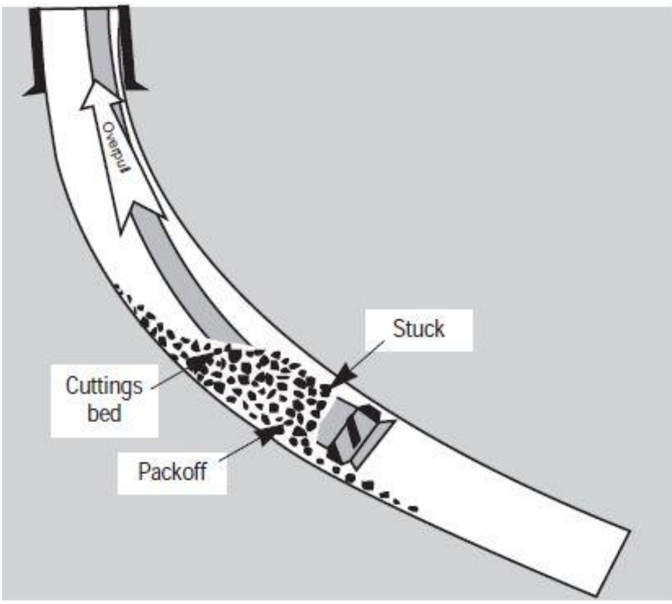


Figure 2.12: Stuck pipe due to pack-off [30]

Stuck pipes can occur for many reasons, occasionally man-made when hardware or equipment is placed in the well, but the main causes are mentioned in the sections above. In general, one could say that anything can pack around the drill string, or the BHA can lead to a unpleasant incident, but the most common phenomenon is called differential sticking, as shown in Figure 2.13.

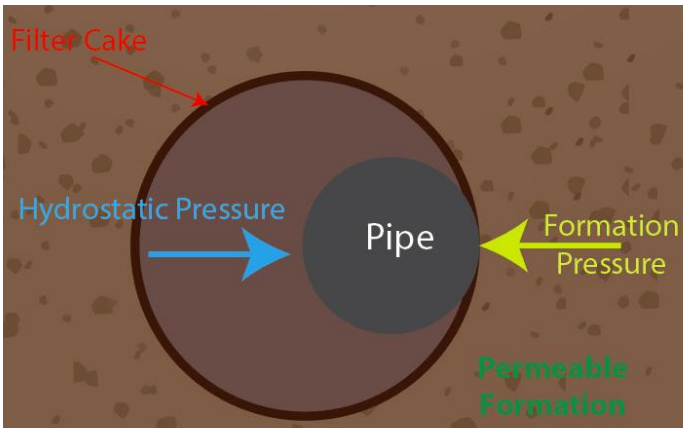


Figure 2.13: Top view of differential sticking [31]

This primarily occurs when the differential pressure is overbalanced and pushing the drill string and BHA into the formation [31].

2.2.8. Circulation valve

The Schlumberger oilfield glossary defines a circulation valve as “a downhole device that enables circulation through the tubing string and associated annulus” [32]. A circulation valve can be an accessory for circulation fluid or help with well kicks. They are frequently operated by different activation mechanisms, such as ball drops and darts, and are normally suitable for several opening and closing cycles before requiring service.

2.2.9. Equivalent circulating density

ECD is one of the parameters for avoiding kick and fluid losses, particularly in wells that have a slim window in regard to the fracture and the pore pressure gradient. The Schlumberger oilfield glossary has defined ECD as “the effective density exerted by a circulating fluid against the formation that takes into account the pressure drop in the annulus above the point being considered” [33]**.**

2.2.10. Kick

A kick can be defined as “a well control problem in which the pore pressure found within the drilled rock is larger than the mud hydrostatic pressure acting on the rock “ [34]. When this problem arises, the formation pressure forces the formation fluids into the wellbore, and if this is not brought under control, it expands while going up to the wellbore and to the surface, developing into a blowout. A kick state is not only a crucial situation when it comes to well control and safety but additionally when it comes to time consumption. There are several cases where a kick can occur, and kicks are initiated when the BHP decreases lower than the pore pressure. During drilling this may happen due to the following [17]:

- Insufficient mud weight
- Swab and heave effect
- Improper fill-up
- Gas or water cut mud
- Gas diffusion
- Lost circulation

How casual the kick is depending on a number of factors. The key factors are the pressure differential between the formation pore pressure and the mud hydrostatic pressure. This is additionally dependent on the permeability and porosity of the formation.

When this kick situation occurs, it is necessary to take action before it is safe to start drilling once more. The kick has to be circulated out of the well depending on the size of the kick and type of handling procedures each operator uses to produce well control, frequently called ‘kill the well’.

This is generally done in three different ways:

- Drillers method
- Wait and weight method
- Bull heading

2.2.11. Hole deviation

Hole deviation is the accidental change of the drill bit from a preselected well path. If the trend of the bit moves away from the planned path, it can lead to drilling problems, as shown in Figure 2.14 [35].

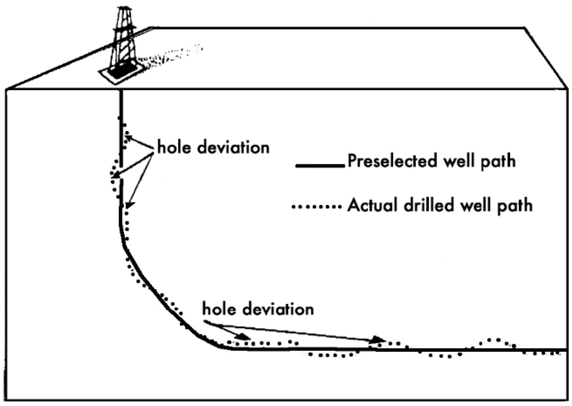


Figure 2.14: Image of a hole deviation [35]

3. Circulating Tools

In this chapter different tools and how they work will be presented. Where data have been accessible, field data will be presented.

3.1. Annular velocity optimisation system (AVOS)

The annular velocity optimisation system (AVOS) is designed and engineered by Intelligent Drilling Tools. Intelligent Drilling tools designs, manufactures, and builds at their facility in Sheffield, UK. Their goal is to develop downhole technology by producing useful, intelligent tools that tackle challenges with modern technology. AVOS stands for annular velocity optimisation system, and this is a family of electronic downhole tools.

They provide electronic, multi-position circulating valves and BHA disconnect systems. They have generally focused on three products: The AVS, AVT, and AVD.

These have several advantages, but the most significant advantage is the possibility of not using drop balls, as well as running unlimited cycles. Cycles can be run several times without removing darts or drop balls. Regarding the placement of the tools, they can be placed anywhere in the drill string, including below the MWD if this is desired. It has no restriction on time or ERD wells, concerning length and inclination.

This section focuses on the AVS, including a brief discussion on profitably with the AVT and AVD.

The most significant advantage of the AVOS is that it is activated by a signal sent from the rig. The system's tools are intelligent, which means that they are electronic with onboard sensors and power packs. It activates by a simple sequence of RPM followed by a pump on and off cycle. This system is called downlinking and can turn the pumps on and off as requested to place the AVOS tools in the corresponding position as desired. The pattern to activate this can be programmed before tripping down the tool. Activation needs no balls, darts, or any other mechanical devices to for pumping down in the drill string to activate the tool [36].

3.1.1. Annular Velocity Split-Flow Electronic Valve (AVS)

The AVS is a multi-position circulating valve controlled electronically and commanded by surface downlink and is illustrated in Figure 3.1. The AVS tool has three positions:

1. Through-bore
2. Splitflow
3. Bypass

As mentioned, the tool is highly flexible and accessible, that is, frequently through-bore, and the tools not being activated by drop balls darts or any other type of activation mechanism delivered from the rig. The AVS is electronic and intelligent, which means that its sensors are installed with logic and can respond to commands through a system called surface downlink. This is done by sending a type of signal to the tool with a pattern of on and off pumps and a specific RPM according to a function map. The AVS tool registers the signal and changes to the requested position.

This saves costs because a smaller amount of time is spent on tripping and occupied tight holes.

The foremost objective is to allow improved hole cleaning while drilling. When the tool is in splitflow mode, the technology improves the flowrate and results in an up to 20% increase in annular velocity. The total flow area (TFA) can be engineered to fit the requirements of the well using the diffuser nozzles. The tool has four nozzles with 4 in^2.

The tool monitors and reacts to a predetermined protocol of changes in RPM and on-off sequences by activating a mechanism that restricts the movement of a pressure activated piston. Ports in the piston and tool body become aligned at specific piston strokes to provide either a restricted flow to the annulus or a full bypass state. When pressure is lowered, the pistons return to a datum position, closing the ports [37].

Table 3.1: Features of the AVR Tool [37]

Features	**Benefits**
No drop balls, darts or RFID tags	Can be run in any inclination well
Command via surface downlink	Can be activated in horizontal wells
Simple and rapid commands	Can be run anywhere in the BHA or drill string
Through-bore at all times	Can be run below an MWD
Battery-powered; Low power draw	Splitflow maximises annular velocity
Splitflow position with variable	Up to 150ppb LCM through bypass
In excess of 200 cycles	LCM will not enter BHA in bypass
Bypass position with BHA shut-off	Cleans hole while drilling in splitflow
Four square inches TFA in full bypass position	No waiting for balls and darts to drop
Through-bore	Low power draw – in excess of 200 activations
Electronic, battery-powered	No balls or darts
Full-bore closure in bypass position	Works in an inclination

Rapid activation	Run multiple tools in the drill string
Splitflow and full bypass position	Customise nozzle size for well (BHA)
4x upward facing diffuser nozzles	Multiple applications

AVS APPLICATIONS

Table 3.2: Applications of the AVS Tool [37]

• Maximise hole cleaning while drilling	• Run behind reamer
• Pumping LCM	• Subsea riser or BOP jetting
• Jetting stabilisers prevent pack offs	• Hole cleaning with tapered string

Figure 3.1: The AVS Tool [37]

3.1.1.1. Through-bore

Through-bore is the same as the drill string; this is the normal position where all the drilling fluid flow goes directly through the tool to the AVS, BHA, and the bit. As shown in Figure 3.2, the flow goes directly through the wellbore.

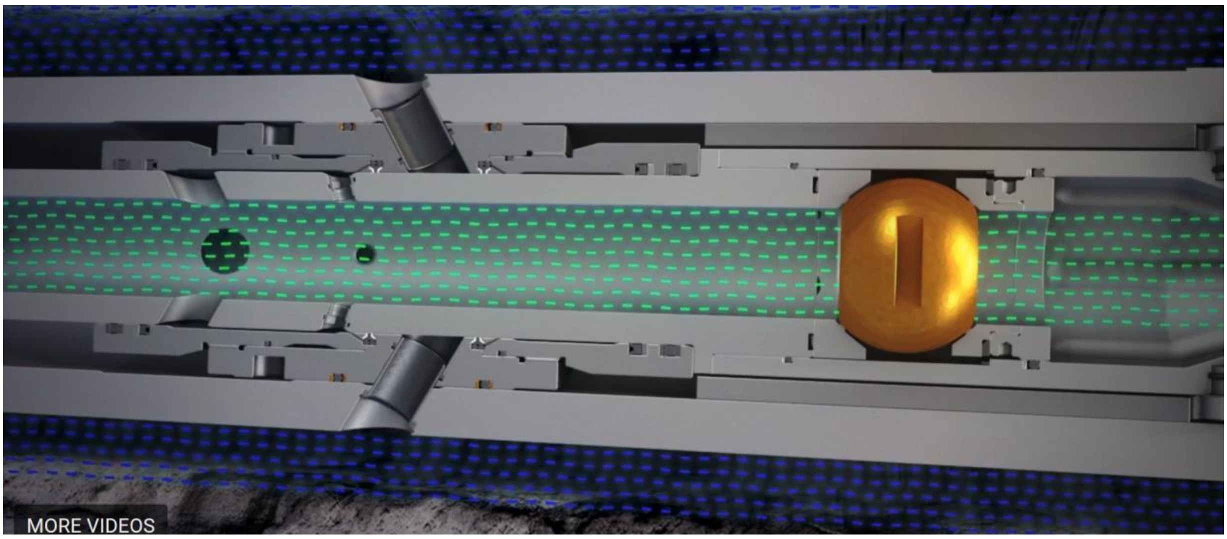


Figure 3.2: Illustration of the AVS Tool in Through-bore mode [38]

3.1.1.2. Splitflow

The splitflow mode is an open position where with nozzling, a ratio of the flow being pumped down the drillstring is side-tracked into the annulus. A percentage of drilling fluid bypasses the drillstring, reducing pressure losses, allowing a flow increase. This can be installed anywhere in the drillstring, but the most efficient location is above the BHA, where it bypasses the smaller inner diameters (IDs) of the drill collars and BHA tools. The ratio must be set to ensure that there is sufficient flow and back pressure through the BHA to power tools and provide bit hydraulics, normally set to a 70 to 30 split with 30% of the flow bypassing the BHA. This is done using Intelligent Drilling Tools's splitflow software to determine the minimum flow to power the MWD, RSS, motor, bit hydraulics, and so on. The remains go out to the annulus.

Doing this can maximise the annular velocity for a given surface pressure. With this technology, the available surface pressure can be maximised, increasing the overall flowrate. Using the splitflow software, the annular velocity could have an increase of up to 20% while drilling, which results in noteworthy hole cleaning enhancements. This position is open and can be nozzled to allow a controlled part of the flow to be transmitted into the annulus, passing by the BHA. In several sections, and at a certain total depth (TD), the AVS (or combined with the AVD) can be set in full bypass mode and four-square inches. The TFA can be opened to allow higher flowrates and annular velocities to be used. In Figure 3.3 there is an illustration of the AVS in splitflow position [39] [37].

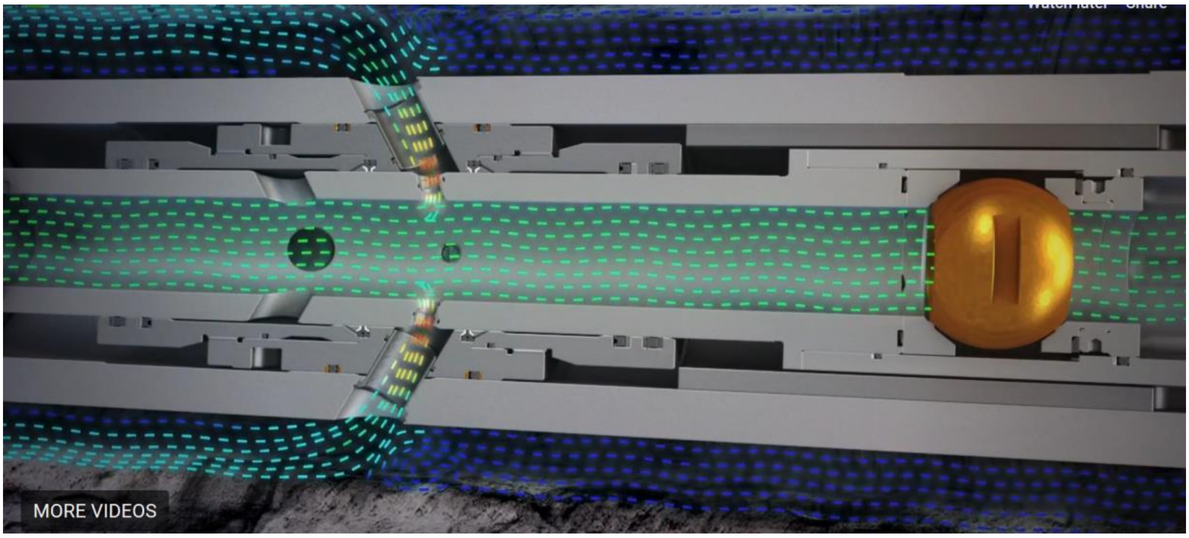


Figure 3.3: Illustration of the AVS Tool in splitflow mode [38]

As mentioned, effective hole cleaning is the deepening of hole angle, mud rheology, hole size, drill pipe size, drill string RPM, mud density, mud annular velocity, annular eccentricity, cutting size, and ROP [40].

Practical research has proven that the most efficient hole cleaning parameters are mud annular velocity and mud density. The higher the annular velocity, the more efficient the cutting transport. As seen in Figure 3.4, the AVS Tool shows examples for increased annular velocity and shows how the tool in splitflow mode with a 35:65 ratio maintains a sufficient amount of flow going through the BHA between 800 to 600 gpm. This maintains sufficient power to the BHA and bit components, but the total flowrate is 20% more than if the flow was led through the wellbore and to the bit.

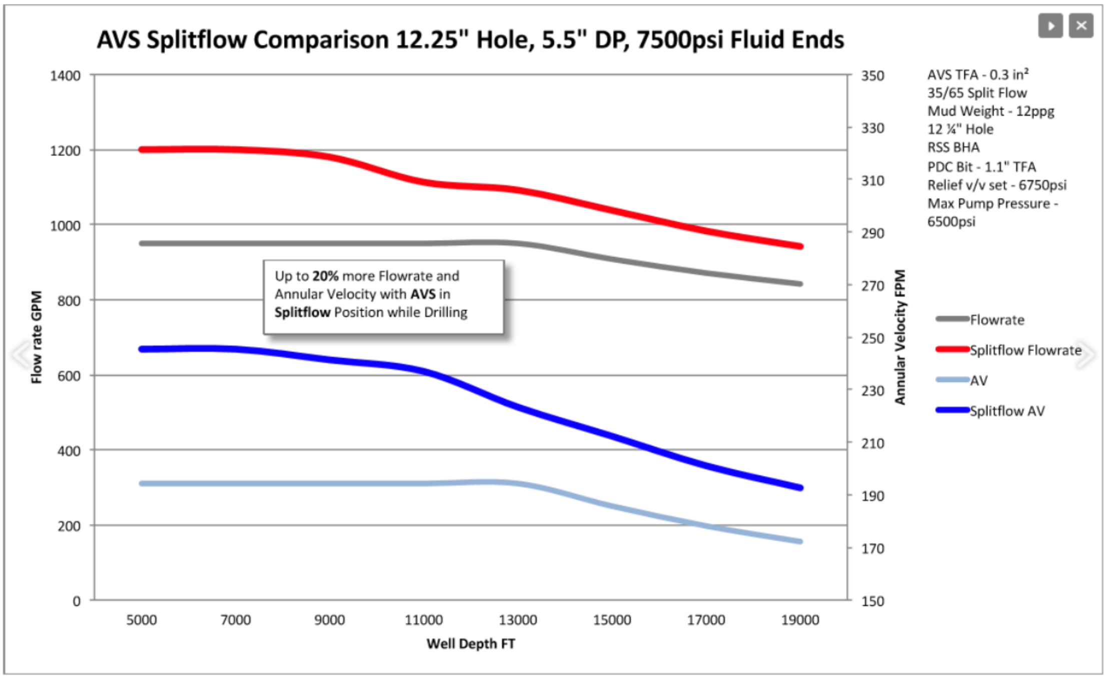


Figure 3.4: The AVS Tool splitflow comparison in the 12.25" hole [41]

Figure 3.5 shows a chart of the increase of cumulative volume pumped over the hole section. Here, 37,000 bbls of additional fluid can be pumped, meaning that 20% more cuttings are removed from the wellbore. Figure 3.4 and Figure 3.5 are examples of the increase in the annular velocity for the AVOS tools versus a conventional drilling string.

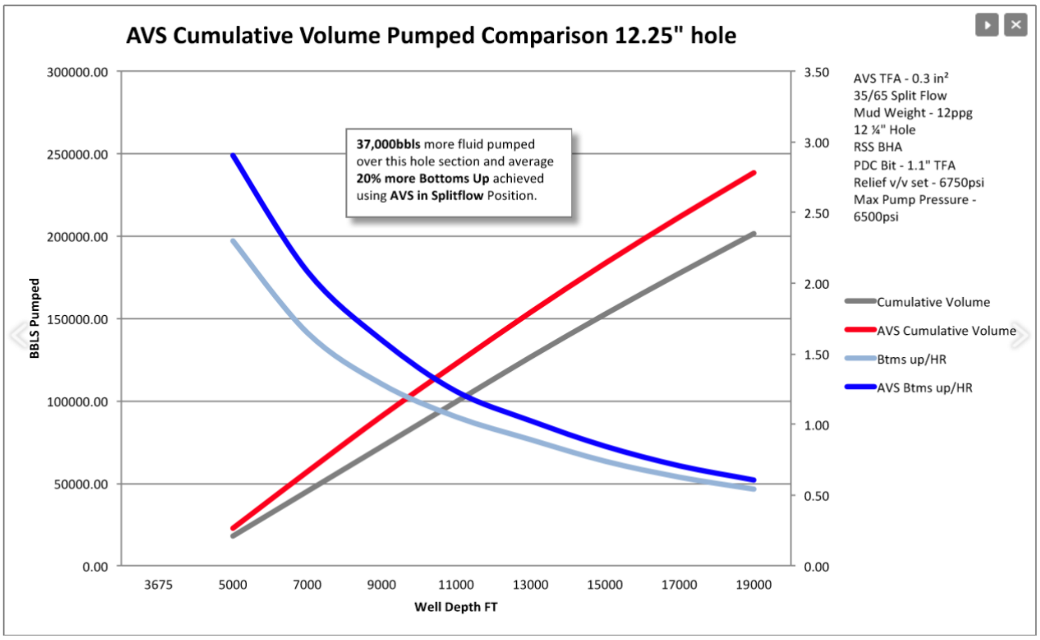


Figure 3.5: The AVS Tool cumulative comparison in the 12.25" hole [42]

The AVOS tools comes with exchangeable diffuser nozzles for the split flow position. The diffuser nozzles have a 15-degree angle in the inner body but in the main body, the angle is set to 30 degrees. The range of nozzles allows the flow to be divided in nearly any ratio depending on what BHA tools are being used and they type of bit hydraulics. Doing this allows the flow departing the nozzle to distribute energy against the tungsten carbide protective insert and make sure that flow is directed up the annulus without washing out the formation. In Figure 3.6, there is a model (animation) with computational fluid dynamics to prospect the flow trajectories when run in splitflow position [39].

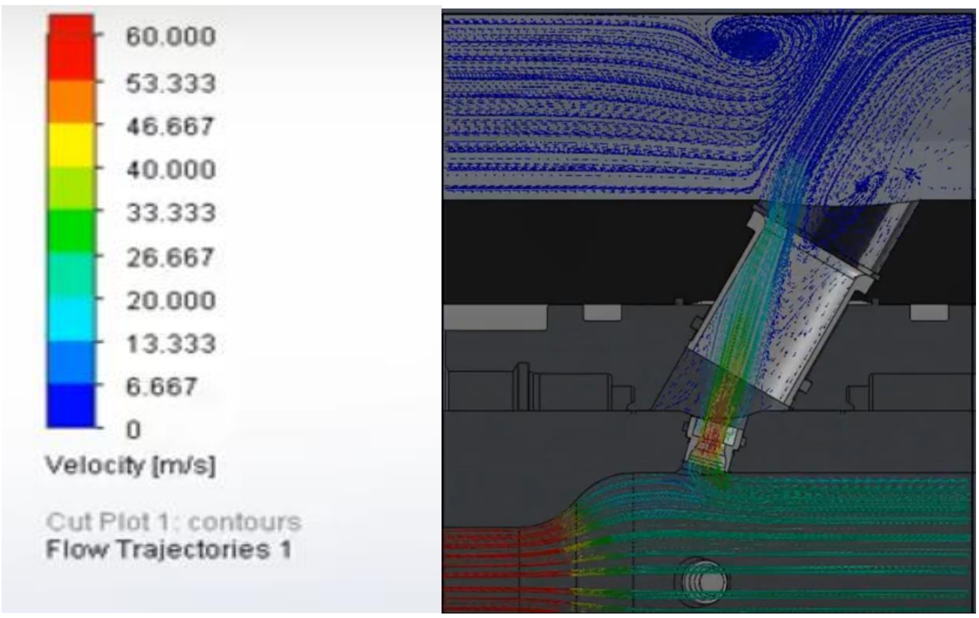


Figure 3.6: AVS Tool splitflow simulation of velocity [43]

This results in a higher annular velocity, which plays a key role for transporting cuttings and controlling concentration levels. Figure 3.7 shows a chart of how mud weight and annular velocity are key to the removal of cuttings.

Figure 3.7: Effect of mud weight on cutting bed height versus annular velocity [43]

3.1.1.3. Bypass

In full bypass mode, all valves are closed and the TFA opens for maximum flowrate to the annulus for the highest annular velocity at the lowest surface pressure, as illustrated in Figure 3.8. This means that there is no flow through the drill string below the AVD. This is for rapid wellbore clean-up or dumping of LCM. If there is a case where LCM is pumped, while the four large ports are opened, a ball valve closes off the bore to ensure that no debris can enter the drilling tools and that the bit does not become blocked by the LCM material; however, this closure is optional [37].

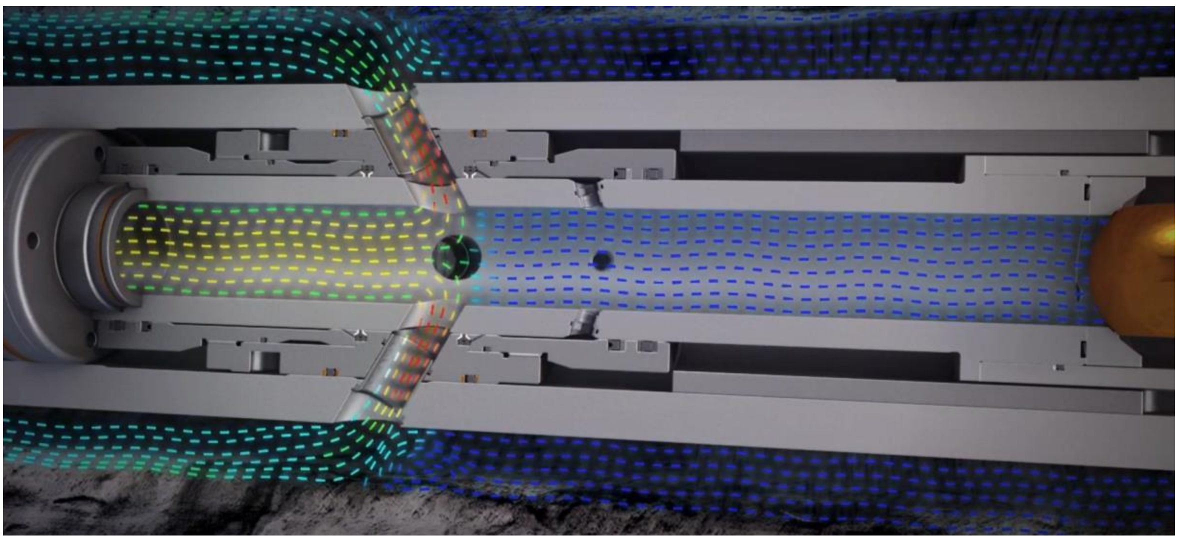


Figure 3.8: Illustration of the AVS in bypass position [38]

3.1.1.4. Supplementing Tools

In addition to the basic AVS Tool, it is possible to supplement with extra tools to increase the effect of the AVS Tool within different aspects of the drilling condition, for example for a long horizontal section or in a section where you have a certain dogleg. This will be described in detail in this sub-chapter.

3.1.1.4.1. AVT

The AVT is a single position electronic circulating valve designed for use in the drill string. It is run in combination with the AVS in a so-called tandem. As seen in Figure 3.9, it has the full bypass position and is intended for use in conjunction with the AVS in the BHA; there is no option to have full closure as in the AVS. This supplement tool is suitable for cleaning long, open hole sections. The AVS is run in the BHA, and the AVT is run in the drill string, ideally at the base of a built-up section, but this is up to the situation and where it is most strategic to put it. The AVT has two positions: through-bore and bypass, but in the bypass position, there is no full closure ball valve. The AVS goes to bypass position, initiating clean-up when the tandem downlink command is sent. When the cuttings are above the AVT, the AVT changes to the bypass mode, and the cuttings are transmitted up through the annulus. The operator can have a maximum rate and move the cuttings the fastest route. This is ideal for ERD type wells where sections of the hole are cleaned in turn to ensure maximum cutting removal in the least amount of time [44] [45].

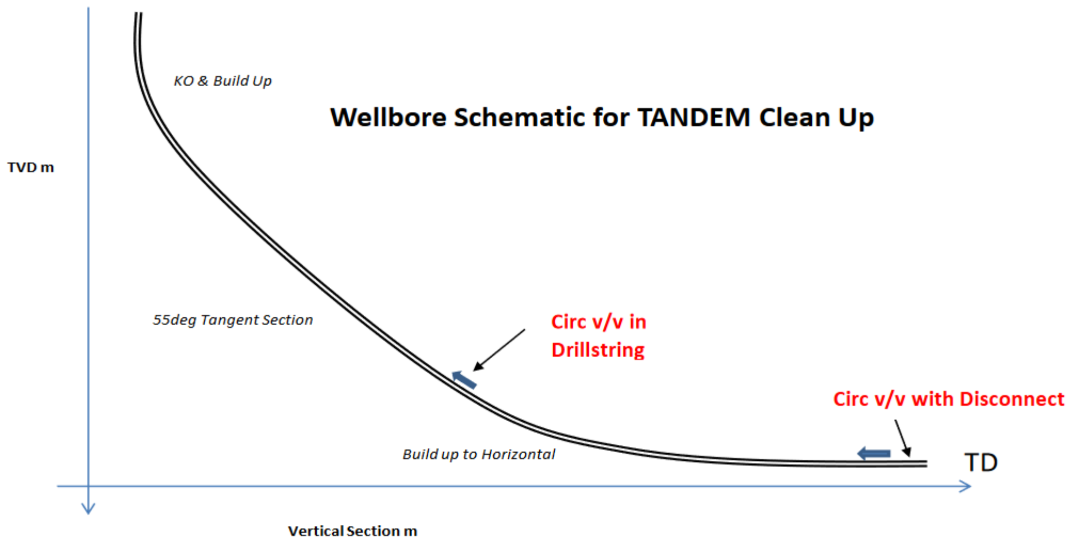


Figure 3.9: Illustration of the AVT and AVS Tool in a well schematic [44]

3.1.1.4.2. AVD

The function of the AVD is comparable to and performs the same functions as the AVS, but the main difference is that it has a unique BHA detach module which is fully integrated that allows the operator to separate the drill string from the BHA if it becomes stuck. AVD has, similar to the other tools, integrated sensors which measure pressure, accelerometers, and MEMS gyro to establish if it is stuck. When this is established, it goes through a process that is re-programmed beforehand, which can be customisable before it places itself in a position to receive the disconnect command from the surface. As mentioned before, this requires no balls, darts, or any other surface deployed system. A pre-defined Morse code is sent to the rig by moving the drill string up to full tension and then back to compression. As seen in Figure 3.10, there is a yellow spot which is activated by reading the signals that have been sent from the rig, and the electric power motors activate the mechanical clutch, which results in a full disconnect from the BHA. Figure 3.11 shows the disconnect module [46] [47].

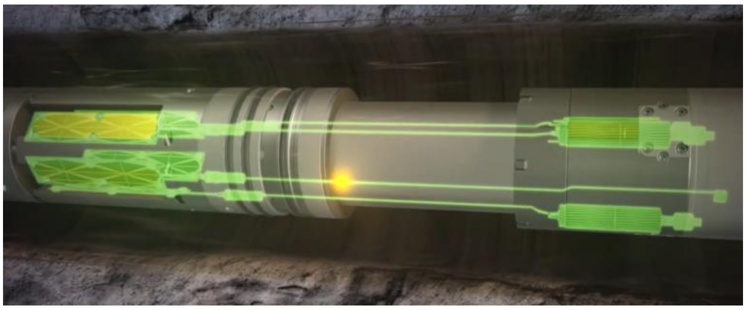


Figure 3.10: Illustration of the AVD Tool activation [48]

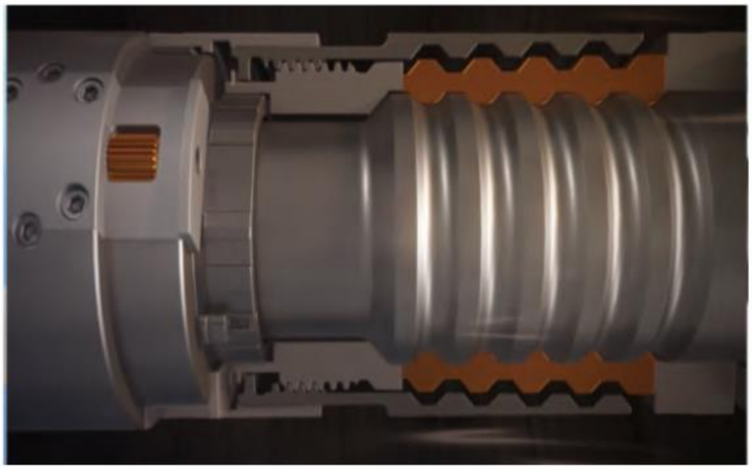


Figure 3.11: The disconnect module of the AVD Tool [48]

The upside of the AVD is that the entire process is controlled by the operator and there is no need for a specialist or equipment. The disconnect process is shown in Figure 3.12, taken from a real stuck pipe occurrence; the hook load, block position, flow, and RPM sensor are additionally from this incident [47].

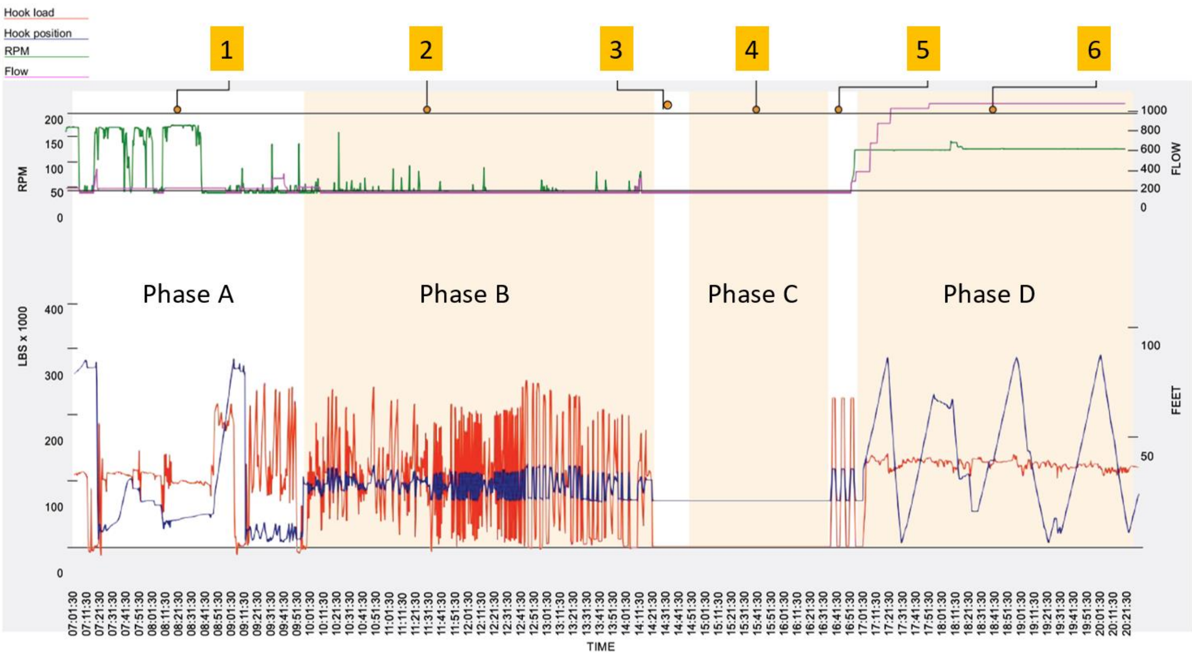


Figure 3.12: Plot of the different phases during disconnect [47]

The phases in Figure 3.12 explained directly from AVD Operational Procedure [47]:

1. **Phase A**

   For backreaming out the hole, nearly packed-off, there is limited flow but the ability to rotate and move the pipe up and down with large overpull and resistance. AVD three-axis accelerometers and MEMS gyro detect full-scale deflection in the X, Y, and Z planes through rotation, upward, downward, and lateral movement. Proximity sensor activates when picking up and down. The AVD is in active mode.

2. **Phase B**

   The pipe is stuck with no movement up or down, no rotation other than winding up to maximum torque. The pipe is packed off. Working on the string commences. A work single is added to give room to jar down. The rotating string weight prior to the stuck pipe is approximately 180k, jarring up with 150k overpull. AVD three-axis accelerometers detect partial or zero deflection in the X, Y, and Z planes. The gyro reading is 0 RPM. Proximity sensor cycling corresponds to jarring actions. AVD concludes it may be stuck and moves into listening mode looking for the signal to go into countdown. Any full-scale deflection on XYZ cancels listening mode, and AVD reverts to active mode.

3. **Listening Mode**

   AVD is in Listening Mode. There is no deflection from X Y or Z. Accelerometer and gyro is static. Proximity sensor reads continuous closed signal for 15 mins. AVD enters countdown mode.

4. **Phase C**

The driller slacks off brake and puts string into maximum compression. There are no string movements for 15 mins. This action signals the AVD to commence countdown. The string is not moved for 2 hrs. Any string movement cancels the countdown. AVD is in countdown mode. Continuous steady reading from proximity sensor and zero deflection from X Y and Z accelerometer and gyro for 2 hrs move the AVD into disconnect mode.

5. **Disconnect Mode**

   AVD is in disconnect mode waiting to receive the final confirmation to disconnect. Proximity sensor reads from closed to open three cycles within 20 minutes by lifting the string into tension and slacking into compression. This is the final signal to activate the electromechanical disconnect mechanism.

6. **Phase D**

   The driller picks up to max hookload and sets back down to previous hookload three times within a prescribed period, for example, 20 mins. AVD triggers, and the BHA is released. Full circulation and rotation and movement are then obtained. Hookload returns to free weight. AVD dual electric motors activate, and the collet latch is released. Electronics and sensor packages recover, leaving a slick mandrel for external catch with overshot or with Intelligent Drilling Tools's catch tool.

3.1.2. Design and software

Technical specification

Table 3.3: Technical specification for the AVD Tool [47]

Tool OD (in)	8.25
Tool ID, min (in)	2.36
Tool length (ft)	17
Tool Weight (tonne)	1.05
Total flow area (in^2)	
Pre-Activation TFA (through-bore)	4.37
Splitflow TFA (to Annulus, min/max*	0.20/0.44
Full bypass TFA (to Annulus)	4
Number of ports	4
Number of cycles	>200
Maximum flow rate (gpm)	1200
Minimum activation flow rate (water)(gpm)**	<400

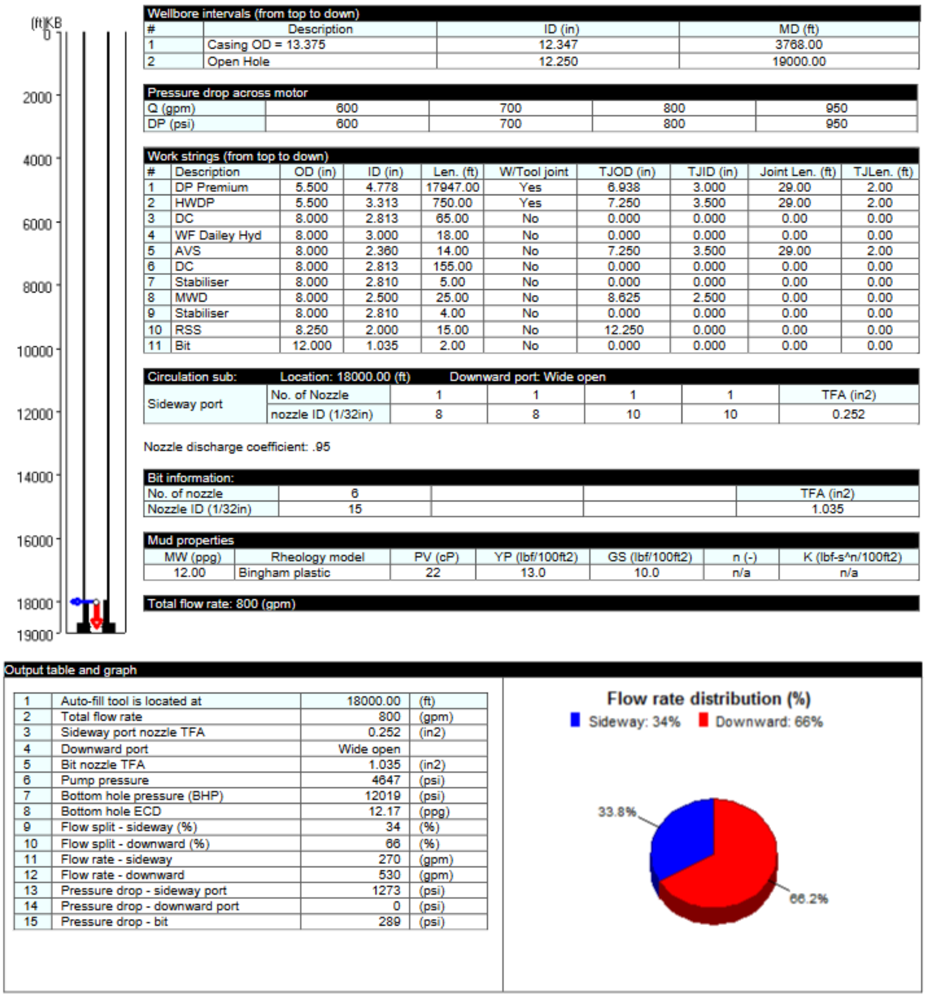
Maximum differential pressure (psi)	5000
Pre-activation pressure drop across tool (water) (psi)	45 @ 1000gpm
Maximum tensile load (lbs)	600,000
Maximum tensile load (lbs)	88,000
Make up torque (ft-lbs)	52,000
Tool joint end connection (box x Pin)	6 5/8 API REG
Temperature rating (degrees Celsius) max	150

* Nozzle TFA can be selected to fit split-flow profile.

* Depends on Bit TFA/Hydraulics.

3.1.2.1. Splitflow software

As mentioned before, the AVOS tools are electronic with sensors and power packs and are activated by a sequence of RPM followed by a cycle of on and off pulses. If there is a situation of pack-off and the circulation stops, there is a possibility of being able to break up the pack-off by sending a sequence of pressure pulses using the mud pumps. The software analyses the drilling hydraulics data given from the AVOS system in the drill string. It calculates the flow split between sideways nozzles and downward ports, and the overall hydraulics of different flow paths. Figure 3.13 is a picture of the software which can be installed on a computer or a tablet of any kind. Here, one has access to all the functions and data from the tools, as well as the settings from the operator’s commands [49].



Wellbore intervals (from top to down)			
#	Description	ID (in)	MD (ft)
1	Casing OD = 13.375	12.347	3768.00
2	Open Hole	12.250	19000.00

Pressure drop across motor				
Q (gpm)	600	700	800	950
DP (psi)	600	700	800	950

Work strings (from top to down)

#	Description	OD (in)	ID (in)	Len. (ft)	W/Tool joint	TJOD (in)	TJID (in)	Joint Len. (ft)	TJLen. (ft)
1	DP Premium	5.500	4.778	17947.00	Yes	6.938	3.000	29.00	2.00
2	HWDP	5.500	3.313	750.00	Yes	7.250	3.500	29.00	2.00
3	DC	8.000	2.813	65.00	No	0.000	0.000	0.00	0.00
4	WF Dailey Hyd	8.000	3.000	18.00	No	0.000	0.000	0.00	0.00
5	AVS	8.000	2.360	14.00	No	7.250	3.500	29.00	2.00
6	DC	8.000	2.813	155.00	No	0.000	0.000	0.00	0.00
7	Stabiliser	8.000	2.810	5.00	No	0.000	0.000	0.00	0.00
8	MWD	8.000	2.500	25.00	No	8.625	2.500	0.00	0.00
9	Stabiliser	8.000	2.810	4.00	No	0.000	0.000	0.00	0.00
10	RSS	8.250	2.000	15.00	No	12.250	0.000	0.00	0.00
11	Bit	12.000	1.035	2.00	No	0.000	0.000	0.00	0.00

Circulation sub: Location: 18000.00 (ft) Downward port: Wide open

Sideway port	No. of Nozzle	1	1	1	1	TFA (in2)
	nozzle ID (1/32in)	8	8	10	10	0.252

Nozzle discharge coefficient: .95

Bit information:				
No. of nozzle	6			TFA (in2)
Nozzle ID (1/32in)	15			1.035

Mud properties

MW (ppg)	Rheology model	PV (cP)	YP (lbf/100ft2)	GS (lbf/100ft2)	n (-)	K (lbf-s^n/100ft2)
12.00	Bingham plastic	22	13.0	10.0	n/a	n/a

Total flow rate: 800 (gpm)

Output table and graph

1	Auto-fill tool is located at	18000.00	(ft)
2	Total flow rate	800	(gpm)
3	Sideway port nozzle TFA	0.252	(in2)
4	Downward port	Wide open	
5	Bit nozzle TFA	1.035	(in2)
6	Pump pressure	4647	(psi)
7	Bottom hole pressure (BHP)	12019	(psi)
8	Bottom hole ECD	12.17	(ppg)
9	Flow split - sideway (%)	34	(%)
10	Flow split - downward (%)	66	(%)
11	Flow rate - sideway	270	(gpm)
12	Flow rate - downward	530	(gpm)
13	Pressure drop - sideway port	1273	(psi)
14	Pressure drop - downward port	0	(psi)
15	Pressure drop - bit	289	(psi)

Figure 3.13: Illustration of the software used for the AVOS system [50]

3.2. DAV MX circulation tool

Churchill Drilling Tools have regional offices in Aberdeen, Houston, and the United Arab Emirates. They have a number of local distributors around the world. They are a drilling tool specialist delivering innovative solutions to the industry, with mainly downhole tools which are activated by pumping darts from the surface. The company has been ISO 9001 registered by the DNV since 2009, and in Figure 3.14 the application highlights until 2016.

The DAV MX^{TM} Circsub is a class-leading downhole circulation bypass tool that delivers significantly improved performance across drilling, completions, and plugging and abandoning (P&A) operations. This is activated by many different darts for improving a broad assortment of applications, involving hole cleaning, displacements, and regaining circulation [51].

Churchill delivers many different tools and has several solutions, such as the following:

Float and fill

- Top Jet
- DICV MAX

- DURA DRILL FLOAT
- SELF-FILLING FLOAT
- SELF-FILLING FLOAT TRIGGER

Speciality tools

- Pressure test sub MX
- Mud_shear sub
- Drift catcher
- Hyper HoleSaver

Circulation tools

- **DAV MX circsub**

There are additionally many types of darts, which are presented in the following chapter.

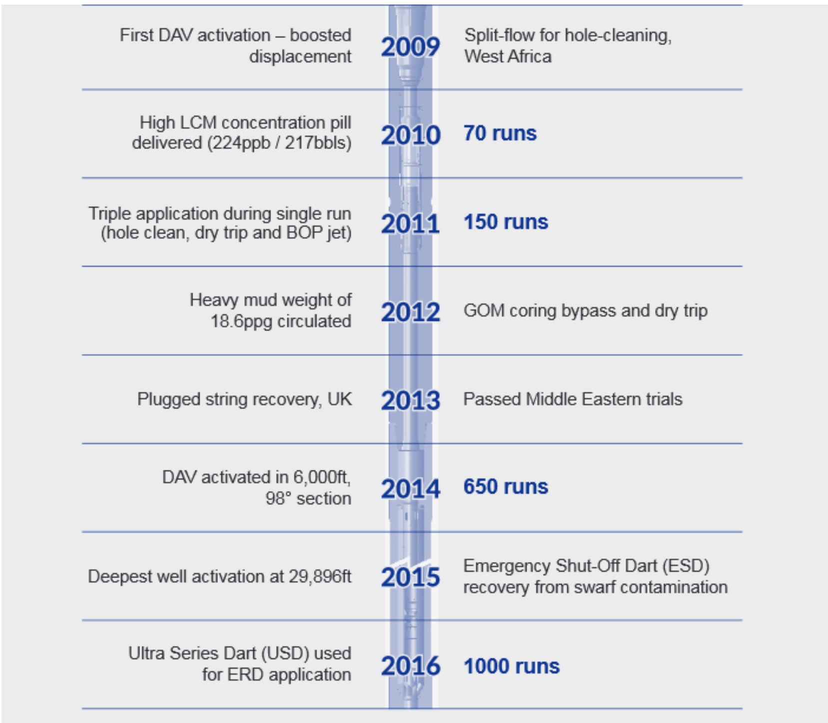


Figure 3.14: Application highlights for the DAV MX Tool [51]

3.2.1. DAV MX

The DAV is a multi-cycle circulating sub with a simple design which brings rapid, reliable deployment. The activation and control of the tool have been patterned by MX Smart Darts, with features such as hold open, latch and seal, high-speed activation, soft shearing, and emergency shut-off. The Circsub is harmonised with a majority of the Churchill products, and has the most ideal benefit when run in conjunction with the HyPR HoleSaver to create the ultimate contingency recovery system. The DAV MX covers deep water, high angle, and high pressure, high temperature (HPHT) without any pre-configuration or service required. The activators and darts have a large variety of openings and closings, which are simple to use, and the tool is highly reliable [52].

The tool involves the use of a 7 ft long valve sub with side ports, as well as a standard catcher sub which is 12–13 ft long. The number of ports is reliant on the model that is delivered. The spring-loaded piston is normally shut.

Applications

- Displacements
- Curing losses
- Reverse circulating
- Hole cleaning
- Self-filling dry tripping
- BOP or wellhead jetting
- Mechanical bypass
- Swab and surge relief
- Regaining circulation

Table 3.4: Features and benefits of the DAV MX Tool [51]

Fast activating (darts travel up to 1000 ft/min)
Versatile – provides split-flow, full bypass, and soft shear dependant on dart choice (over 20 application types in drilling, completion or P&A)
Innovative and simple design gives robust sub with high reliability
Requires no service hand and no need for configuration prior to use
Largely immune to variations in angle, temperature, differential pressure, mud type, and mud weight
Only downhole repairable circus on the market

3.2.1.1. Cycling sequence

1. Simple dart choice

- Well-labelled cartons make selecting the application dart a simple process

2. Rapid activation
- Drop dart and pump into place.

3. Clear opening confirmation
- At the surface, a clear pressure drop confirms bypass activation.

4. Application stability
- Unique lock open, latch, and seal features ensure valve position and complete fluid isolation integrity at all angle for the entire bypass cycle.

5. Faster, safer tripping
- Lock-open additionally provides the option of tripping out dry to self-fill when tripping in.

6. Rapid and efficient closing
- The universal closing dart rapidly shears the selected activating dart into the catcher in order to close the tools. This is confirmed by a pressure increase shown at the surface. Darts are stored in a highly efficient catcher sub with negligible pressure loss.

7. Unlock backup closing
- Not only does the DAV MX push the envelope further, but it additionally provides a backup closing system. Should the valve become damaged by any unexpected events, users can deploy the emergency shut-off dart and save a trip.

3.2.1.2. Darts

The DAV MX circulation tool has five different standards in darts, as illustrated in Figure 3.15. The darts are described in the following [52].

1. Standard diverter dart (SDD)

The standard diverter dart offers 100% bypass, latch and seal, and nose-lock open features. It is ideal for LCM spotting and dry tripping. It is not recommended to RIH with a standard diverter dart if there is a float or blockage below due to the risk of hydrostatic pressure-locking.

2. Split flow dart (SFD)

The split-flow dart provides flow to bit (10–15%), with a nose-lock open feature. It is used for self-filling and hole cleaning.

3. Alternative diverter dart (ADA)

The alternative diverter dart offers 100% bypass, with pump to keep open. It is ideal for non-return and non u-tube.

4. Ultra-series dart (USD)

The ultra-series dart offers high-speed activation (400 gpm) and low shear closing pressure. It is ideal for ERD and fragile formations.

5. Universal closing dart (UCD)

The tool can be closed by pumping the UCD in the valve. A static pressure of approximate 2000 psi shears it out, and both darts go down into the catcher below.

The UCD sequence:

A. Flush through 1xstring volume of clean mud at maximum flow rate to ensure the valve is free from any debris (for example, Swarf, LCM, coarse additives).
B. Insert the UCD nose down into the drill string and re-connect the top-drive.
C. The UCD must be pumped all the way into place to ensure the valve is flushed clean for the dart's arrival. There is no maximum flow rate for pumping the UCD.
D. Closure of the tool results in a higher flowing pressure. At lower pump-in flowrates, the shear is seen as expected; however, at high flowrates, the shear may not be seen.

6. Emergency shut-off dart (ESD)

The ESD sequence:

A. If upper seal washing is suspected, stop or at least slow pumping to minimise the wash damage to the tool.
B. Unwrap and drop the ESD the correct way around
C. Pump the ESD all the way into place at a medium flowrate.
D. The ESD has a soft nozzle in it which further increases the pressure on landing, and after landing, the extra pressure gradually reduces as the soft nozzle washes away to nothing.

Using EOB that it is designed to only be used in no flow or minimal or low-flow situations where the smart darts cannot and will not seat and activate the tool. Note that after EOB has been activated, it will not shear out and the tool will not close. For using the EOB, the following simple instructions must be followed:

1. Drop the ball.
2. Wait for it to land.
3. Cycle pressure to max possible repeatedly until it flows.

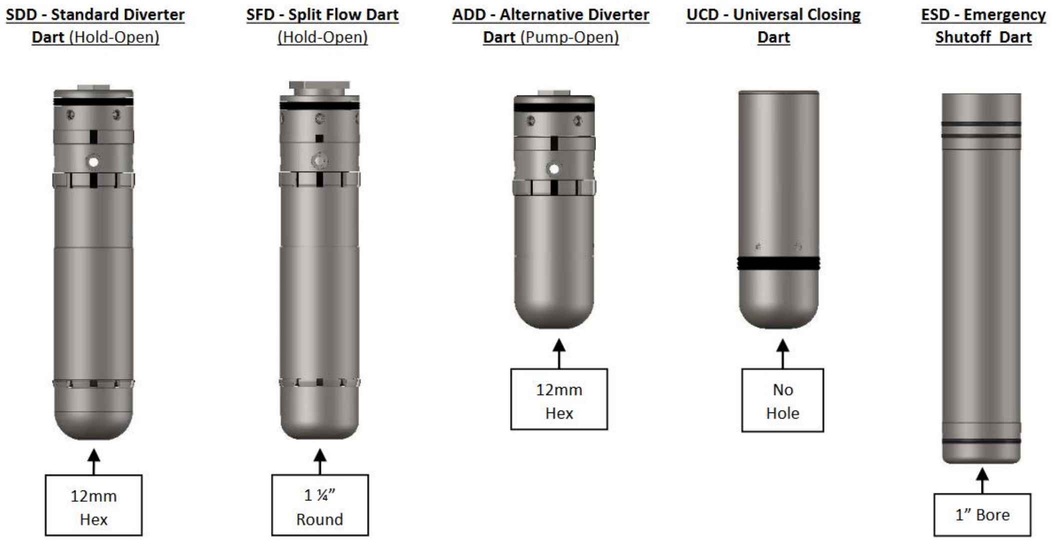


Figure 3.15: Dart identification [52]

3.2.1.3. Tool specification

The size of the tool varies, as it is customized to the drill string. The tool size determines the number of ports and the type of darts used, which is illustrated in Table 3.5.

Table 3.5: Tool and dart specifications [52]

Nominal Sizes	Conns.	Ports	Port TFA (sq in)	Drift ID (in)	Dart OD (in)
9 ½"	7 ⅝ Reg.	4 or 6	0.44 - 4.71	2.64	2.69
8 ¼"	6 ⅝ Reg.	4 or 5	0.44 - 3.93	2.64	2.69
6 ¾"	NC 50	2, 3 or 4	0.44 - 3.14	2.14	2.25
4 ¾"	NC 38	2	0.44 - 1.57	1.89	2.00

3.2.1.4. Operating procedure

When the tool is sent offshore, there is a crate, and it should be filled with a kit of standard darts, which is sealed in its own packaging, with each dart unmistakably marked as to what it contains.

Each tool has a different type of colour:

- NC38 is associated with GOLD DAV dart cartons

- NC50 is associated with BLUE DAV DART cartons
- 6 5/8” Reg and 7 5/8 Reg are associated with GREEN DAV dart cartons

It is crucial to ensure that the correct sized dart and ball are in use.

A standard Churchill DAV MC kit contains the following:

Table 3.6: A standard Churchill DAV MC kit

4 x Standard diverter darts	6 x universal closing dart
2 x splitflow dart	1 x emergency opening ball
2 x alternative diverter darts	1 x emergency shut-off dart

Before using the tool, it is compulsory to follow these directions:

- The catcher sub must be positioned below the valve
- The drill string above both subs should ideally have at least the minimal drift (ref. Table 3.7)
- Do not remover any nozzles on the sub
- Connections must not exceed the make-up torque (ref. Table 3.8)

Table 3.7: Drift requirements for each tool size [52]

DRIFT	Tool Size			
	NC38 (3 ½” IF)	NC50 (4 ½” IF)	6 5/8” Regular	7 5/8” Regular
Minimum	2.00"	2.25"	2.70"	
Recommended	2 1/16"	2 5/16"	2 3/4"	

Table 3.8: M/U torque for each tool size [52]

	Tool Size			
	NC38 (3 ½” IF)	NC50 (4 ½” IF)	6 5/8” Regular	7 5/8” Regular
TORQUE (k-ft-lbs)	10-11	28-30	47-51	80-85

After cycling, there is limited access below the catcher sub as it does not allow any wireline access through it, and it may be advantageous to position the catcher as low as possible in the drill string.

When pumping darts into the drill string, each type of dart has its own specific range of flowrate to ensure that it suitably assembles and does not blow through on docking the valve, as seen in Table 3.9. The limit differential pressure on the valve seals as the dart docks, and the tool instantly opens at 1,500 psi and further, may damage the seals as it opens [52].

Table 3.9: Pumping rate to initially place the dart [52]

SIZE OF TOOL	FLOW RATE (GPM) FOR PUMPING DART INTO PLACE (STEP 4)		
	SDDMX HOLD OPEN	SFDMX SPLIT FLOW	ADDMX PUMP-OPEN
NC38	50-225	150-250	50-225
NC50	80-250		80-250
6 5/8 " REG.	100-300	180-300	100-300
7 5/8 " REG.			

The darts have to be pumped into place at the precise flow rate and pressure to decrease the chance of a malfunction, as shown in Table 3.10. When the correct dart is selected, it is important to ensure that there are no issues or conflicts with any of the subsequent sections of the procedures before the dart is dropped into place. If there is an insufficient flowrate to pump the dart into place, applying the single-shot emergency opening ball is the only possible solution.

Table 3.10: Selection of dart based on borehole instability issue [52]

OPENING DART APPLICATIONS	SDDMX (Hold-Open)	SFDMX (Split-Flow)	ADDMX (Pump-Open)	EOB (Emergency Opening Ball)
LOSSES	✓	✗	Specific Applications (1)	✗
BOP / WELLHEAD JETTING	✓	✓	Specific Applications (1)	✗
DRY TRIPPING - OUT	✓	✓	✗	✗
RIH/ SELF FILLING	✗	✓	✗	✗
POOR AV	✓	✓	Specific Applications (1)	✗
HOLE CLEANING w/ BHA COOLING	✗	✓	✗	✗
SWAB/SURGE RELIEF	✗	✓	✗	✗
REVERSE CIRCULATING	✗	✓ (2)	✗	✗
PACKED-OFF/VERY LOW FLOW	✗	✗	✗	✓ (3)

Consideration when deciding the correct dart:

1. Specific applications: The ADD has all but been replace by the SDD. The ADD can be beneficial when utilised in some circumstances as the valve can close when the pumps are off, however, a good full closing float can prevent this through pressure locking below.
2. It is best if fully cosing float is present below, as this prevents any reversing force on valve

3. Once EOB has been activated. It is not reversible as it cannot be sheared through into the catcher.

When diverting the flow, one can use a higher flow rate to improve hole cleaning. To avoid damaging the ports, the flow rate as described in Table 3.11 should be followed. It is important that there is equal flow through all ports, and the operator should be informed that the flowrate should be decreased if there an extensive time period of large mud solids content is anticipated.

Table 3.11: Maximum flow rates based on mud weight [52]

MUD WEIGHT	Very Heavy >14.0ppg	Heavy 14.0 - 11.0ppg	Medium 11.0-8.3ppg	Light < 8.3ppg / no solids
MAXIMUM FLOW RATE RANGE PER PORT	200 - 240 gpm	240 - 260 gpm	260 - 280 gpm	280 - 325 gpm

When the different darts are run in the tool, there is a one per cent chance that the tool will not shut correctly. The most common reason for this is the presence of debris or swarf in the mud. This can stop the piston from fully returning, or worse, damage the seal and clog the piston. In these cases, the ESD can be utilised. This is a sleeve which can isolate the upper seal area, preventing any further wash-out damage to the tool and channelling all the flow to the bit. After the ESD has been activated, the valve cannot be reopened.

It is recommended to pull out of the hole with the tool immediately after pumping LCM. However, there is a stabiliser, or the bits packed-off the well will SWAB.

When the job is completed, the valves can be re-used, but the dependability progressively reduces the additional times they are cycled. They additionally must be pressure tested when they come back to the surface.

The darts cannot be re-used; as mentioned, it is necessary to open and use a new dart that is sealed in the carton. [52]

3.2.2. HyPR HoleSaver™

The HyPR™ Hole Saver™ is a system of hydraulic pipe recovery that can make releasing stuck pipes faster, simpler, and more secure. One has to only drop the dart and start pumping to activate the dart. With no setup or personnel required, and using no explosives, it can provide a low-cost solution to downhole problems [53].

Dissimilar to conventional processes, the HyPR HoleSaver is a pre-positioned sub or subs inside the BHA. The device can be turned on by readily using the HyPR™ Smart Dart. With no moving parts, the HyPR™ Sub lies hidden in the string. When activated with the HyPR™

Smart Dart, the flow of mud is redirected, creating a high-velocity radial jet of fluid to erode and cut the sub in only a few hours.

As illustrated in Figure 3.16, the dart cuts through the drill string and cuts more than 91% of the pin cut area in 2.5 hrs. [53].

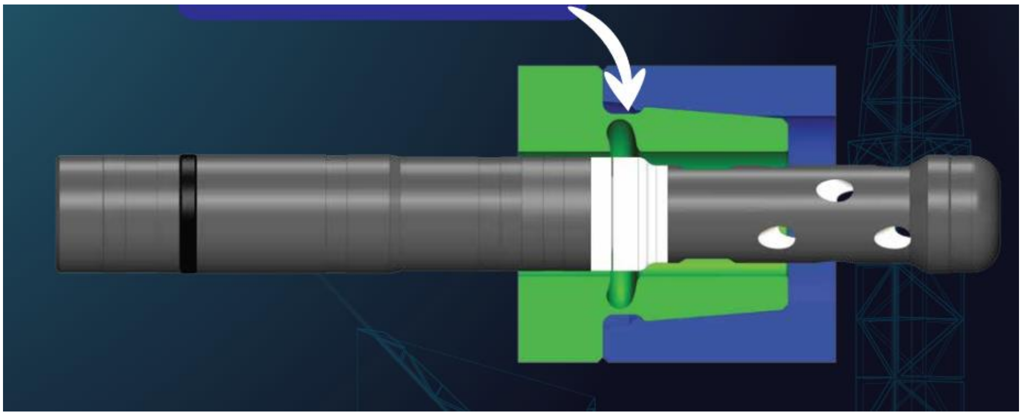


Figure 3.16: Illustration of the cutting tool [53]

The tool cuts around 91%, where it is calculated that the torque should be able to complete the cut. In a seven-inch liner, it is calculated that it takes around 2.5 hours until the connection is gone. As seen in Figure 3.17, it nearly cuts in the hole way, and there are several small indications of torque evidence in the picture.

Figure 3.17: Illustration of the cut and drag pipe [53]

3.3. Well Commander

M-I SWACO has a ball-activated drilling circulating valve. The Well Commander is a ball-activated drilling circulating valve that is placed above the BHA. It additionally has the ability to be run in a wellbore clean-up string to boost annular velocity and attain turbulent flow for improved cutting removal. It additionally provides an alternate circulating path in troublesome zones, for example, LCM plugging the BHA or damaging the connected tools. The ports of circulation open and are subsequently closed by dropping a ball and applying pressure, with limited opening and closing cycles of the capacity of the ball catcher installed in the tool. Figure 3.18 presents a picture of the Well Commander [54].

Figure 3.18: The Well Commander valve [54]

The Well Commander is ball-activated and can be activated several times. The ball is a single size to open and close the tool and has a second size to isolate if that is required. When the tool is open, the majority of the flow exits through the ports, and a minor amount of the flow goes through the tool to cool down the BHA; if not, a shut-off ball is dropped. [54].

Features:

- Generous flow
- Through via multiple ports
- Ball catcher has 18-ball capacity
- Ports open and close using same size ball
- Available in 5, 7, 8¼, and 9 ½ inches of outside diameter (OD)
- No internal tool connections
- Tool activation mechanism locks into open or closed position and is isolated from wellbore fluid
- Ball catcher permits smaller ball or limited wireline access through the tool, including after a ball has been dropped
- Optional shut-off ball prevents coarse LCM from entering sensitive BHA
- Easy spotting of LCM while drilling
- Cuttings beds removal, enhanced hole cleaning, and efficient fluid displacement by boosting AV in conjunction with pipe rotation.

3.3.1. Operation

The Well Commander valve is RIH or ROOH with the ports locked open or closed. The ports in the tool are inactive until it is placed in the well and activated by dropping a ball and pressuring it to turn the circulating port. The ball catcher is the only limitation of how many times the ports can be open and closed, and the capacity of the ball catcher is 18 balls and 9 cycles. To prevent fluid flow or solids deposition at the top of the BHA, a shut-off ball can be dropped, which additionally is collected in the ball catcher assembly, as seen in Figure 3.19, number 4. It encapsulates the balls to one side of the inside diameter to facilitate placing other ball drop tools below it, ensuring that the smaller activation balls can pass through. M-I SWACO has made a technology that allows the same size ball to open and close the tool to eliminate the risk of dropping the wrong ball. [54].

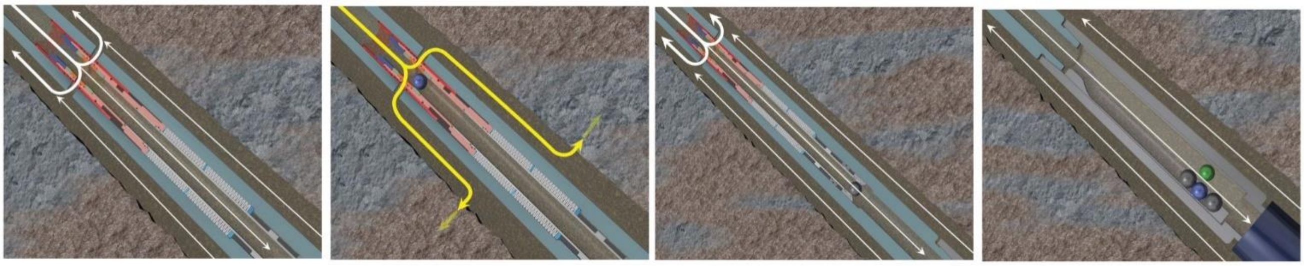


Figure 3.19: (1) Activating valve; (2) Spotting LCM; (3) Boosting annular velocity; (4) Dropping smaller ball past ball catcher [54]

To open and close the Well Commander, it is necessary to start recording the flow rate and pressure through the string before activating the tool. Then, all pumping has to be stopped before dropping the correct size for opening or closing the ball. Choosing the right balls is discussed in Chapter 3.3.2. When the ball is dropped, it is important that the pumps do not exceed the maximum circulation rate and pressure for pumping the ball. When the ball hits the tool, there should be a pressure build-up. Then, it is important to not bleed off but to continue lowly applying pressure until the hold pressure has been reached, which should be held for 30 seconds. After this, it is important to slowly increase the pressure to the recommended shear value, once more holding for thirty seconds. Then, there should be a drop in pressure. The waiting time allows the tool internals to cycle to the next position. After this, the pressure can be permitted to bleed off before resuming the operation. [54].

3.3.2. Tool Ball details

The Well Commander has four different borehole operating sizes, 5”, 7”, 8 ¼” and 9 ½”. For the 8 ¼” and 9 ½” strings the same ball size can be utilised. The various operating sizes have a ball for either opening or closing the tool with different operating pressures. Table 3.12 shows the recommended circulating rates, pressure circulating hours and time below rotary table when circulating the balls [54]. The parameters should not exceed ± 25% of guidelines to avoid failure.

Table 3.12: Guidelines to operate the tool [54]

Recommended Max Circulating Rates / Pressures / Circulating Hours / Time below Rotary Table								
Tool OD	Open Position	Closed Position	Pumping Balls			Operating Pressure (Shear)	Circulating	Time below Rotary Table
	USgpm (Lpm)	USgpm (Lpm)	USgpm (Lpm)		Psi (Bar)	Psi (Bar)	Hours	Hours
5.00”	840 (3180)	672 (2545)	84 (318)	Or	1000 (69)	2400 (165)	250	300
7.00”	1050 (3976)	840 (3180)	126 (477)	Or	1000 (69)	2000 (138)		
8.1/4” / 9.1/2”	1680 (6362)	1344 (5089)	126 (477)	Or	800 (55)	1600 (110)		

3.4. Jetstream RFID-activated drilling circulation sub

Weatherford released in 2015 the Jetstream radio-frequency identification (RFID) circulation sub. The Jetstream RFID circulation sub gives the operator the ability to manage a sequence of tools at various places along the drill string and remotely activate the valves a limitless number of times in a single trip to reach higher flow rates and cleaner wellbores. It additionally gives an open path to high flow rates, and the full through-bore is beneficial when running several tools instead of the conventional subs where the ball seat creates a major restriction. The Jetstream has a large flow area and reduction in ID, as illustrated in Figure 3.20 [55].

Weatherford specialists programme several RFID tags at the surface, which enables on-demand deployment of the tags during the operation. When the operator desires activation of the sub, an RFID tag is dropped from the surface and communicates commands to the sub as it flows past the tool. Upon receipt of the RFID signal, a hydraulic pump driven by battery with an electric motor moves a sleeve into one of three positions: open, closed, or split flow.

As drillers have more difficult wellbores, the capability to drop an RFID tag from the surface and circulate it through the sub enables the opening and closing of downhole tools multiple times, which offers more operational flexibility and saves rig time. RFID tags offer limitless activation of circulating valves for high-volume pumping of mud and LCM. The RFID eliminates bulky balls, seats, darts, and pins for activation and gives the drill string ID at full bore. The RFID connects communication to tandem, can adjust the total flow area, and retrieve and display data using memory logging [56].

Figure 3.20: The Jetstream RFID [57]

While cleaning the wellbore, the Jetstream sub raises annular velocity to deliver a turbulent flow that boosts waste removal to enhance drilling efficiency. This additionally makes the tool useful for other purposes such as fishing and milling. Full through-bore, high-velocity performance helps relieve drilling hazards by eliminating restrictions that decrease flow rates causing poor hole cleaning and cutting-bed build-up. The dependable performance of the Jetstream circulation sub allows the driller to find LCM on demand through the process. If the LCM spotting is not efficient and accurate, the driller can, in the worst case, be forced to abandon the well because of fluid loss [55].

This gives more downhole control and predictable operations. The RFID technology gives full command over the sub, activations, and results [56].

3.4.1. Operation

The RFID tag is lowered into the drill string from the surface and circulated to the sub, where it communicates commands with a signal which is received from the tool with a built-in antenna. The tool is driven by a battery-powered electric motor which runs the hydraulic pump. The hydraulic pump moves the valve into the desired position: closed, mid, or open. In Figure 3.21, the ports are closed, and the diverter is open. This allows unrestricted, full through-bore flow during drilling and no change from conventional drilling [56].

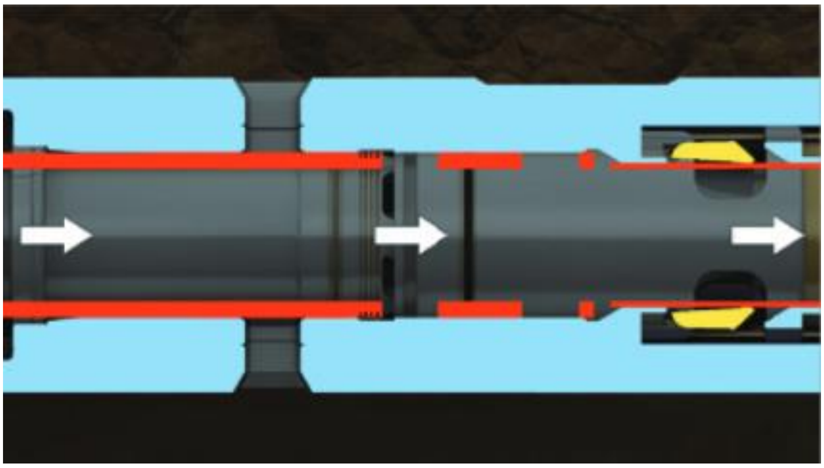


Figure 3.21: Illustration of a closed position [55]

In Figure 3.22, the ports are open, and the diverter is open. This gives the opportunity to simultaneously divert a customisable percentage of the flow through the wellbore, while it boosts annular velocity in the annulus, which enables the cleaning out of cuttings while drilling [56].

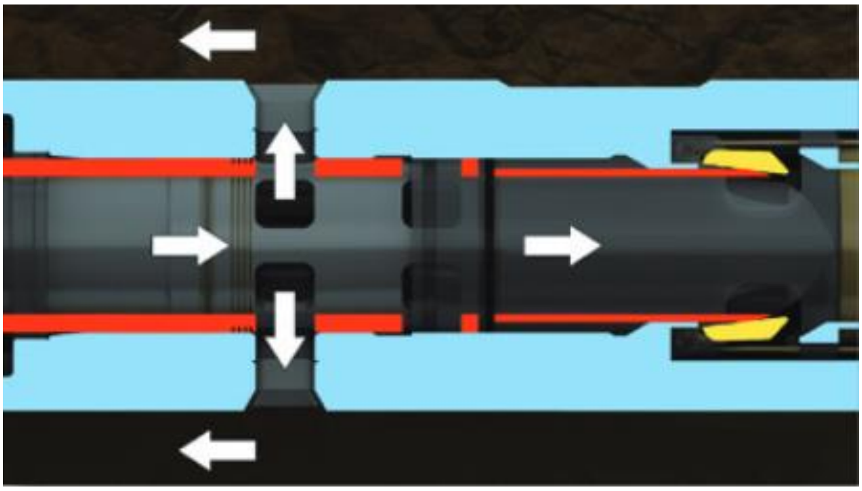


Figure 3.22: Illustration of a mid-/splitflow position [55]

In Figure 3.23, the ports are open, and the diverter is closed. This redirects the drilling fluid into the annulus and back to the surface with high-velocity, with turbulent annular flow for efficient wellbore cleaning [56].

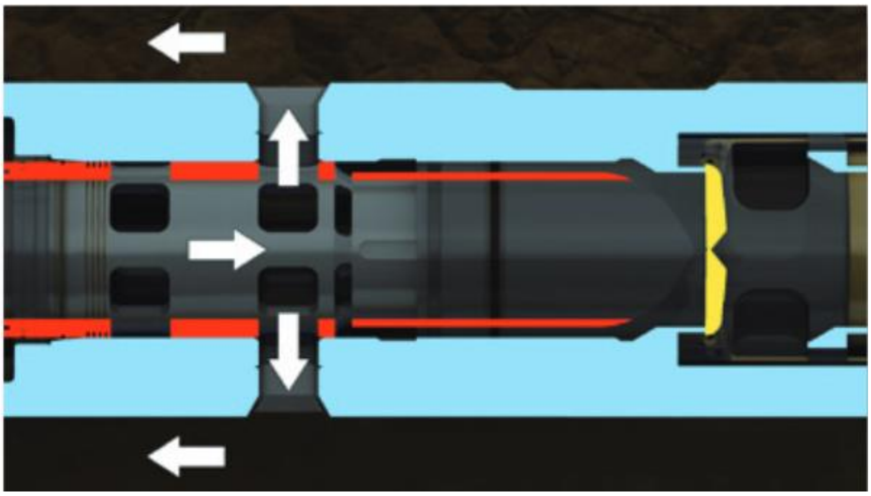


Figure 3.23: Illustration of an open position [55]

The Jetstream RFID with full-bore performance has a broad range of functions [55]:

Bottom Hole Assembly

Improved hole cleaning and cuttings removal by boosting circulation rates, regularly controlled by a mud motor, turbine, or any other component. It permits using several tools with selective activation.

Wellbores clean up strings

Enhanced cutting extraction by boosting annular velocity and turbulent flow together with different cleaning tools.

Drilling assemblies

Exchange of information among the drill pipe and annulus to place LCM at the necessary locations without subjecting the pills to other components beneath the tool.

Deepwater riser less drilling

The Jetstream does not have to be tripped to the surface, saving trips and rig time.

Underbalanced and managed pressure drilling

Enables the quick identification in extended-reach or horizontal wells of kill-weight fluid prior to pulling out of the hole.

Fishing and milling

Superior hole cleaning performance and limitless activation make the tool useful for fishing and milling.

3.4.2. Design

The Jetstream sub is activated by the RFID. The RFID is installed with downhole sensors and monitors tool performance with a memory that can be used in various tools. This data can be transmitted and downloaded by Waterford’s i-Rabbit® close-proximity communication device. This data provides time, temperature, drillpipe pressure, hydraulic micro-pump pressure, and battery capacity. Data are automatically transformed and shown on a vertical strip chart. In Figure 3.24, an illustration of the panel for the Jetstream RFID sub shows how simple it is.

Figure 3.24: The panel for the tool [56]

It has been documented that the Jetstream sub has a median of 750 hours in the middle of service intervals to improve efficiency. A standard override can be provided to override the RFID for improved reliability. There is additional backup communication through a pressure cycling sequence.

In Table 3.13, an overview of the circulating sub size, tool OD, ID, flow ports, maximum flow rate, and other important information is provided. [56]

Table 3.13: An overview of the sub sizes [56]

Circulating Sub Size (in./*mm*)	Tool OD (in./*mm*)	Tool ID (in./*mm*)	Tool ID Flow Area (in.^{2}/*mm*^{2})	Number of Flow Ports	Port Flow Area (in.^{2}/*mm*^{2})	Maximum Flow Rate (gal/min, *m*^{3}*/min*)	Temperature Rating (°F/*°C*)	Hydrostatic Rating (psi/*MPa*)	Differential Pressure Rating (psi/*MPa*)	Torsional Rating (ft-lbf/*N•m*)	Tensile Rating (lbf/*N*)	Length (in./*mm*)	Tool Joint[a]
5.25 *133.3*	5.25 *133.3*	1.932 *49.1*	2.95 *19.0*	4	3.45 *22.2*	840 *3.18*				28,185 *38,214*	729.7 *3,245.87*	148.2 *3,764.30*	XT39
7.00 *177.8*	7.00 *177.8*						302 *150*	25,000 *172.30*	10,000 *68.95*	66,911 *90,719*	960.7 *4,173.41*		XT54
8.25 *209.5*	8.25 *209.5*	2.875 *73.0*	6.50 *41.9*	6	7.67 *49.4*	1,260 *4.77*				93,880 *127,284*	1,988.0 *8,887.55*	163.3 *4,147.82*	6-5/8 API Reg
9.50 *241.3*	9.50 *241.3*									131,170 *177,843*	2,455.0 *10,920.38*		7-5/8 API Reg

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4. Discussion

As mentioned in the introduction, NORSOK and other regulations have created standards for companies to develop innovative solutions that meet the desired functional requirements in the Norwegian offshore industry. Hole cleaning is considered one of the major expenses in drilling, which is why services companies could benefit from exploring new techniques to avoid undesired interference while drilling. Several companies are starting to use new technology emerging in the industry, such as the circulating tools described in this thesis, to help optimise downhole operations. Based on the circulation tools presented in Chapter 3, this chapter highlights the advantages and disadvantages of the tools, as well as a comparative discussion.

4.1. Activation

The four different circulating tools have different methods of activation, which will be presented in the sections below.

The AVOS is installed with electronic sensors, which are activated with a simple sequence of RPM followed by a pump on-and-off cycle pulsated from the rig. AVOS has its own system that is called downlinking and can turn the pumps on and off as requested to place the AVOS tools in the corresponding position as desired. The pattern to activate this can be programmed before tripping down the tool.

With the DART MX, pumping darts into the drill string, each type of dart has its own specific range of flow rate to ensure that it suitably assembles and does not blow through on docking the valve. The darts cannot be re-used; it is necessary to open and use a new dart that is sealed in the carton. The darts must be pumped into place at the precise flow rate and pressure to decrease the chance of a malfunction. When the different darts are run in the tool, there is a one percent chance that the tool will not shut correctly. The most common reason for this is the presence of debris or swarf in the mud.

To open and close the Well Commander, it is necessary to start recording the flow rate and pressure through the string before activating the tool. Then, all pumping must be stopped before dropping the correct size for opening or closing the ball. When the ball is dropped, it is important that the pumps do not exceed the maximum circulation rate and pressure for pumping the ball. When the ball hits the tool, there should be a pressure build-up. Subsequently, it is important to not bleed off but to continue slowly applying pressure until the hold pressure has been reached, which should be held for 30 seconds. After this, it is important to slowly increase the pressure to the recommended shear value, once more holding for 30 seconds. Then, there should be a drop in pressure. The waiting time allows the tool internals to cycle to the next position. Finally, the pressure can be permitted to bleed off before resuming the operation. The Well Commander tool uses the same size operating ball to open and close the ports. Ball catcher and other smaller balls can go through.

The Jetstream RFID circulation sub gives the operator the ability to manage a sequence of tools at various places along the drill string and remotely activate the valves a limitless number of times. When the operator desires activation of the sub, an RFID tag is dropped from the surface and communicates commands to the sub as it flows past the tool. This excludes the need for flow-restricting mechanical activation components in the BHA for through-bore performance.

The DAV MX and the well Commander has big similarities in activation, since they both uses ball and darts to activate different operability. This can be problematic in horizontal wells where the ball or the dart quickly can get stuck in the string. The Jetstream drop a tag through the drill string and uses RFID for activation and has a much higher reliability. The AVOS can be activated without any flow restricting in the drill string and have a much higher activation time since it does not have to wait until the “activation” mechanism reach the tool.

4.2. Operability

Both the AVOS and the Jetstream have three identical operability modes

- *Splitflow*, where a ratio of the flow is being pumped down in the drill string while a percentage of the drilling fluid bypasses in the annulus reducing pressure losses and allowing flow increase.
- In *through-bore mode* the flow goes directly through the wellbore.
- *Bypass mode*, which involves all the valves are closed and the TFA opens up for maximum flowrate to the annulus for the highest annular velocity at the lowest surface pressure.

The DAV MX circulating tool has multiple different darts with several modes. The standard diverter dart offers 100% bypass. The split-flow dart provides flow to bit (10–15%), and the rest goes to annulus. The alternative diverter dart also offers 100% bypass but has a pump to keep open. It is ideal for non-return and non u-tube. The ultra-series dart offers high-speed activation (400 gpm) and low shear closing pressure. It is ideal for ERD and fragile formations.

The Well Commander has only one operating mode, which can be activated several times. When the tool is open, most of the flow exits through the ports, and a minor amount of the flow goes through the tool to cool down the BHA; if not, a shut-off ball is dropped.

The Jetstream RFID circulation sub and AVS have a large total flow area and no reduction in ID after actuation, which enables wireline operations or other equipment to pass the circulation tool. This is a great advantage as other operations can be run while the tool is installed. For the DAV MC and the Well Commander only the use of smaller balls in the drill string will make activation of other equipment possible as these will enter through the circulation tool.

All four tools have nozzles installed to transport fluid into the annulus. The AVS, the Well commander and the Jetstream all have four nozzles, while the DAV MX usually has four nozzles, but number of ports is reliant on the model used. The largest advantage of the AVS nozzles is the radial position of 15 degrees with respect to the drill string position, while the other tools have flow perpendicular to the drill string. This results in a higher annular velocity, which plays a key role for transporting cuttings and controlling concentration levels.

One of the advantages with the Jetstream RFID circulation sub and AVS is that the operator can change the percentage of fluid released into the annulus, while for the DAV MX and the Well Commander this is pre-set. Adjustment in the fluid transport and the flow directed in the annulus will make maximum optimisation while drilling easier, as formation properties will vary throughout the drilling process.

4.3. Collection and Transmission of Data

The two most critical factors in the drilling process are drill string and formation challenges. The best approach to minimize the risk of these problems occurring is to monitor in real time using high technology software. Real-time drilling optimisation help drillers to detect the source of the problems and initiate counteractive measures as soon as possible. The software should enable quick and easy comparison of pressure and flow rate and show limitations in order for tool to be calibrated with offset well information for higher accuracy.

All AVOS tools are electronic with sensors and power packs. The software analyses the drilling hydraulics data given from the AVOS system in the drill string. It calculates the flow split between sideways nozzles and downward ports, and the overall hydraulics of different flow paths. The software can be installed on a computer or a tablet of any kind. It gives access to all the functions and data from the tools, as well as the settings from the operator's commands.

The Jetstream stores the data in the tool's internal memory and automatically converts into a vertical strip chart, which enables the operator to validate tool performance after the operation is finished. Compare to the AVOS this system does provide the same level of detailed data from the operation. For the DAV MX and the Well Commander no software has been developed.

4.4. Failure

All circulation tools carry a risk, in particular once activated, the tool may not close properly. However, the tools function mechanically and can occasionally be affected by the arrangement of other equipment in the well. Likewise, foreign objects or chemicals in the fluids, through design or by accident, can additionally sometimes cause problems. These are likely to cause internal damage, which can subsequently lead to failure to close properly, washout, or damage to the tool beyond repair. Most problems with closing are initially caused by not opening the tool properly.

In the case of activation there is a less chance of failure using the AVS and the Jetstream since they are not dependent on dropping a ball or dart to activate. If they do not activate it would not cause any problems in the well since the ID is equal to the drill string and the drilling will just operate as normal without the tools.

Collecting data from the well gives more control over the well conditions and the data given can help to avoid failure by implementing corrective measures. AVS and the AVOS tools are the only one who has this function and is a highly advantage.

The Well Commander has only one type of operation mode, and the ball or dart sequence is not complicated. Its only function is on and off, which means it has less ways to failure, while the DAV MX has several types of darts that can only be used one time and the wrong type of dart can accidently be dropped if the operator is not careful. If there is a problem with the Well Commander, one can simply drop another opening or closing ball, or maintain the pumping rate and rotate the drill string to attempt to get the ball on seat.

4.5. Additional features

Two of the tools have manufactured supplements to the circulation tool, which functions in collaboration with other tools that can be mounted on the drill string. In the event of a stuck pipe situation Churchill and Intelligent Drilling Tools have engineered two different tools to disconnect the BHA in case of stuck pipe. This additional technology provided by these two tools are a great advantage.

The Churchill has constructed a HyPR Hole Saver which is activated by a drop dart. The HyPR hole saver is pre-positioned inside the BHA and lies “hidden” in the string. When activated it uses the mud creating a high velocity radial jet to erode and the dart cuts almost through the drill string in 2.5 hrs. The last piece is cut due to torque in the drill string.

Intelligent Drilling Tools has presented a function of the AVD that is compatible with and performs the same functions as the AVS, but the main difference is that it has a unique BHA detach module that is fully integrated allowing the operator to separate the drill string from the BHA if it becomes stuck. AVD has integrated sensors that measure pressure, accelerometers, and MEMS gyro to establish if it is stuck. This requires no balls, darts, or any other surface deployed system. A pre-defined Morse code is sent to the rig by moving the drill string up to full tension and then back to compression.

Intelligent Drilling Tools have also engineered the AVT, which is run in combination with the AVS in a so-called tandem. It has the full bypass position and is intended for use in conjunction with AVS in the BHA; there is no option to have full closure as in the AVS. AVT is run in the drill string ideally at the base of a built-up section, but this is up to the situation and where it is most strategic to put it. The operator can have a maximum rate and move the cuttings the fastest route. This is ideal for ERD type wells where sections of the hole are cleaned in turn to ensure maximum cutting removal in the least amount of time.

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5. Conclusion

This thesis has investigated four different drilling circulation tools showing the potential of improvement in the process of hole cleaning. The key to unlocking the full potential of drilling operations consist of two components; the ability to adjust operations for unanticipated challenges and the ability to complete the job in as few trips as possible. The key factors for optimisation of hole cleaning is a result of thorough well planning, impeccable drilling fluid properties, and ideal drilling conditions.

The continuation of this research should involve in-depth testing of all four tools in the same environment, analysis of the results implemented with the findings in this thesis. In the future, the main focus should be on developing tools at lower cost and energy, reducing the impact of well loss and stuck pipe as well as creating new technology for increased control during the operation.

5.1. Activation

One of the most important factors in the function of the circulation tool is the activation. Slow activation can create severe problems in the well, making the activation a crucial step in the process. Since the only tool that can be directly operated from the drill floor have the fastest activation and the smallest risk for contamination during activation mode, AVOS has the preferred activation. The remaining tools depend on dropping balls or a tag to activate, which is more time consuming and create a higher risk of well complications. It also has unlimited activations with improves efficiency and uptime by eliminate unnecessary tripping.

5.2. Operability

The AVS and The Jetstream has the unique functionality of changing the flow rate to the annulus, and furthermore have the same ID as the drill string. They have the same operation modes and can easily be changed into the preferred mode. In more complex wells the AVS and the Jetstream are to be preferred in terms of operation modes. With the new technology from the AVS, where the nozzles have 15 degrees angle, this tool has a further advantage in regard to the flow in the annulus.

5.3. Collection and Transmission of Data

The Jetstream and the AVOS are the only tools with software, which brings them a step ahead of the others. As the AVOS can gather more specific data that provides more information about the well, this is the preferred tool in terms of collection and transmission of data.

5.4. Failure

The fact that the AVS is activated without using a ball or dart reduces possible blockage and human errors and eliminates the risk of balls left in the well. In case of failure to activate the tool, this will not cause problems in the well because the ID of the tool is equal to the ID of the drill string. The AVS is also the greatest for collecting data, which reduces the risk of failure in future wells. Even though the Well Commander is less likely to fail in operation since it only has one operation mode, the AVS is still favoured as the activation and software exceed the more complicated operation modes.

5.5. Additional Features

As mentions, only the AVS and the DAV MX have additional supplement tools that give a severe advantage in the case of the drill string getting stuck. The advantage with the AVD is that it is reconnectable after disconnecting, while the HyPR HoleSaver destroys the drill string. In addition, the AVS has a tandem tool, the AVT, which provides more flow further up in the annulus. Based on this, the conclusion is that the AVS is more qualified combined with the supplementing tools.

5.6. Final Conclusion

Based on the work carried out in this thesis, I have come to the conclusion that the AVS circulation tool by Independent Drilling Tools is the preferred tool out of the four tools presented. The AVOS exceeds the other tools in terms of activation, operability, collection and transmission of data and additional supplements. This is also the only tool with the ability for future development and can potentially be a crucial part of optimising the drilling operation, helping reduce risk of stuck pipe and loss of circulation.

5.7. Recommendation for Future Work

In terms of making it the ideal tool, the goal is to adapt tools to work on a wired drill pipe. This means that the activation would be instant regardless of well depth or inclination. The tool would be controlled via a laptop at the surface, and the driller could activate the tool to clean the well whenever desired via the wired drill pipe network. Sensors are placed in the BHA and the drill string to record downhole data transmitted to the operator, making it possible to adjust the drilling parameters. Today, only a few sensors are integrated in the BHA, which makes it problematic to get complete overview of drill string and to find the source of complication.

High-resolution measurements are made possible by WDP, as it facilitates the placement of multiple sensors in the BHA. Several sensors enable along-string measurements and thus improves the control, enhancing the downhole environment understanding. Several of the big operators such as ConocoPhillips and VårEnergi, have applied this technology in recent times. Equinor currently does not employing WDP. An assembly with multiple sensors distributed within would provide easier prediction through improved data feedback. This would improve real-time decision-making as it allows for monitoring higher up in the system.

A higher level of automated control can be achieved through the increased detail of the information captured during drilling, in turn improving the reliability of each downhole component. The current hindrance to the industry is the cost of the technique, however as this technology can serve to minimize loss of circulation and stuck pipe, it will be beneficial to employ in the future.

As wells continue to increase in complexity and difficulty, there is no doubt that lost circulation and stuck pipe will remain major causes of concern. It has already been proven that utilizing high technology in complex wells can reduce the number of stuck pipe incidents. Applying technology in the attempt to improve wellbore clean up, lost circulation and disconnecting the BHA should be an area of focus in the effort to reach improved drilling optimisation.

When discussing the effect of different tools and techniques it is difficult to come up with conclusive answers, due to the fact that several factors will influence the hole cleaning, and some of the tools have additional functionalities. In order to make a conclusive judgement on what is the optimal tool, the conclusion should be based on comparative case studies.

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