Chair of Drilling and Completion Engineering

Master's Thesis

Risk assessment of drilling process with Managed Pressure Drilling and Wired Drill Pipe technologies application

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AFFIDAVIT

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Chair of Drilling and Completion Engineering

I dedicate this work to my mother

for her boundless sacrifices for my future.

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Abstract

The consumption of oil and gas worldwide continues to experience a dramatic increase. However, the era of "easy" resource extraction has already ended, and the production of oil and gas has become a more complex process. Petroleum engineers are searching for the most efficient methods to enhance existing technologies. Nonetheless, the high complexity of such projects results in increased costs and implementation risks.

Managed Pressure Drilling (MPD) is an advanced drilling technique that enables precise control of the wellbore pressure profile during drilling operations. The advantages of applying MPD can significantly enhance well control issues and minimize many risks associated with drilling. Real-time downhole data measurements are a crucial component for improving MPD, enabling engineers to monitor wellbore pressure and adjust drilling parameters in real-time. The most promising technology that provides such capabilities today is Wired Drill Pipe (WDP) technology providing power and data supply from surface to downhole, implemented by an Austrian technology company.

One of the most demonstrative aspects of the mutual application of MPD and this new downhole power and data transmission technology is the ability to prevent and mitigate kick incidents, which can lead to disastrous consequences such as a blowout without proper management. These two technologies are capable of reducing risks related to kick and blowout events, but the primary research interest is dedicated to examining the extent of their joint effectiveness in comparison with separate applications.

To achieve this research objective, the overall advantages of the technologies and their safety barriers against kick incidents are examined in comparison with conventional and alternative practices. For quantitative estimation, the Probabilistic Risk Assessment (PRA) is conducted. The obtained results for collaborative application show that the probability of experiencing kicks and blowouts decreased by 23 and 97 times respectively. The synergetic effect, represented by the estimation of general benefits and quantitative risk assessment performed in this study, demonstrates the essential improvement in the safety and efficiency of the drilling process, justifying additional expenditures associated with the joint MPD and the downhole power and data technology utilization.

Zusammenfassung

Der weltweite Verbrauch von Öl und Gas steigt weiterhin dramatisch an. Die Ära der "einfachen" Ressourcengewinnung ist jedoch bereits vorbei, und die Förderung von Öl und Gas ist zu einem komplexeren Prozess geworden. Erdölingenieure sind auf der Suche nach den effizientesten Methoden zur Verbesserung der bestehenden Technologien. Die hohe Komplexität solcher Projekte führt jedoch zu erhöhten Kosten und Umsetzungsrisiken.

Managed Pressure Drilling (MPD) ist eine fortschrittliche Bohrtechnik, die eine präzise Steuerung des Druckprofils im Bohrloch während des Bohrvorgangs ermöglicht. Die Vorteile der Anwendung von MPD können die Bohrlochkontrolle erheblich verbessern und viele mit dem Bohren verbundene Risiken minimieren. Echtzeitmessungen von Bohrlochdaten sind eine entscheidende Komponente für die Verbesserung von MPD, da sie es den Ingenieuren ermöglichen, den Bohrlochdruck zu überwachen und die Bohrparameter in Echtzeit anzupassen. Die vielversprechendste Technologie, die solche Möglichkeiten bietet, ist die von einem österreichischen Technologieunternehmen eingeführte Wired Drill Pipe -Technologie, die die Energie- und Datenversorgung von der Oberfläche bis zum Bohrloch gewährleistet.

Einer der anschaulichsten Aspekte der gemeinsamen Anwendung von MPD und dieser neuen Technologie für die Energie- und Datenübertragung im Bohrloch ist die Fähigkeit, Kick-Ereignisse zu verhindern und zu entschärfen, die ohne angemessenes Management zu katastrophalen Folgen wie einem Blowout führen können. Diese beiden Technologien sind in der Lage, die Risiken im Zusammenhang mit Kick- und Blowout-Ereignissen zu verringern, aber das primäre Forschungsinteresse gilt der Untersuchung des Ausmaßes ihrer gemeinsamen Wirksamkeit im Vergleich zu getrennten Anwendungen. Um dieses Forschungsziel zu erreichen, werden die Gesamtvorteile der Technologien und ihre Sicherheitsbarrieren gegen Kick-Ereignisse im Vergleich zu herkömmlichen und alternativen Praktiken untersucht. Zur quantitativen Abschätzung wird die probabilistische Risikobewertung (PRA) durchgeführt. Die Ergebnisse für die gemeinsame Anwendung zeigen, dass die Wahrscheinlichkeit von Kicks und Blowouts um das 23- bzw. 97-fache gesunken ist. Der Synergieeffekt, der durch die Schätzung des allgemeinen Nutzens und die in dieser Studie durchgeführte quantitative Risikobewertung dargestellt wird, zeigt die wesentliche Verbesserung der Sicherheit und Effizienz des Bohrprozesses und rechtfertigt die zusätzlichen Ausgaben im Zusammenhang mit der gemeinsamen MPD und der Nutzung der Energie- und Datentechnik im Bohrloch.

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Chapter 1

Introduction

1.1 Background

Drilling of wells is one of the most expensive and risky parts of the oil and gas production process. The preparation and execution stages should include precise risk management for achieving safe drilling process, otherwise there could be not only time or cost overruns, but also irreparable consequences for human resources or environment.

Based on risks exist while the operations, different strategies for risk reduction can be implemented into the projects. The fundamental method for improving any technical operations and drilling process, in particular, is the application of advanced techniques and approaches that can prevent and mitigate undesirable events. However, there is no guarantee of fully eliminating all risks, some of them may still occur due to numerous factors that influence the safety of drilling operations.

The most well-known technique for improving of well control procedures is Managed Pressure Drilling (MPD). The benefits of this technology have already been appreciated by the world's drilling companies showing incremental interest and demand on the market.

The primary focus for enhancing the Managed Pressure Drilling technique is to automate the process by gathering real-time data. It can be implemented through Wired Drill Pipes (WDP), which are promising telemetry channels that provide high-speed interaction between the surface and the formation. The application of this telemetry system provides the possibility to use not only bottomhole sensors for precise drilling parameters monitoring, but also along-string measurements (ASM). In the result, the data provide great insight into the hole conditions along the drill string and at the bottom hole assembly (BHA) (Nygård et al., 2021). The initial instance of implementing combination of MPD and WDP in the field was in the Nagar-1 well, which is an exploratory well located in block M16 in the Andaman Sea. With the high-speed wired drill pipe telemetry, the hydraulic model used in the MPD system could be calibrated against downhole measurements every 2 seconds, which ensures highly accurate downhole pressure estimates during drilling (Fredericks et al., 2008).

Nowadays, the most powerful Wired Drill Pipe system implemented by an Austrian company is capable of transmitting information at a speed of 200,000 b/sec and providing 300W power to downhole equipment. The combination of Managed Pressure Drilling (MPD) and advanced WDP technology has the potential to significantly improve drilling performance and efficiency.

1.2 Objectives

Separate application of these two modern technologies has certain advantages in comparison with conventional methods which can be used instead of them. Theoretical joint implementation of MPD with the most advanced WDP can give precise monitoring and analysis of drilling parameters and powerful prevention and mitigation safety barrier system as result.

At the same time, both of these technologies impose additional expenditures for the projects. It's evident that the cost of projects will increase significantly. We need to maintain a balance between our expenditures, profits, and risks.

The primary objective of the research is to assess the reasonability of integrating Managed Pressure Drilling (MPD) technology with the most powerful Wired Drill Pipe (WDP) telemetry in the context of minimizing risks associated with kick and blowout events, considering them as the most serious and potentially dangerous incidents that can occur during drilling process.

This evaluation will take into consideration general theoretical predictive and mitigating capabilities of technologies in addressing influx problems with further consequences and quantitative risk assessment of joint technologies application. The Probabilistic Risk Assessment (PRA) will be accomplished for three scenarios:

- **Scenario 1**: Managing kick events for conventional drilling;
- **Scenario 2**: Managing kick events using MPD;
- **Scenario 3**: Managing kick events using the combination of MPD and advanced WDP;

Therefore, the main question for research: "Can the use of risk assessment techniques demonstrate that the combination of these technologies is superior to each technology used independently?"

Chapter 2

Kick incident

Kick is any undesirable process of formation fluid entering the wellbore, whether gas, oil, water or a mixture of these, during the drilling process. Gas blowouts are universally recognized as one of the most dangerous phenomena that can occur during drilling operations. The behavior of gas as it expands during the drilling process is subject to fundamental physical principles that govern gas behavior. These principles depend on parameters such as pressure, temperature, gas composition, gas flow rate, and well geometry. However, this does not mean that gas expansion can be easily predicted for every well configuration and geological condition.

Early kick detection (EKD) is one of the key areas for improving well control. The earlier, more accurate, and reliable the recognition of a kick can be, the safer the drilling process becomes. The Bureau of Safety and Environmental Enforcement's (BSEE) analysis of incidents involving loss of well control concluded that 50% of these incidents could have been prevented or mitigated through the use of EKD.

A prime example in this context is the Macondo field, where 11 lives were lost and billions of dollars in economic and environmental damage were incurred due to inadequate interpretation of early warning signs indicating unwanted fluid flow into the wellbore (Fraser et al., 2014).

2.1 Kick causes

The main cause of a kick is primarily insufficient bottomhole pressure, which is lower than the formation pressure, resulting in the inflow of fluids as a consequence. Prerequisites for this circumstance can be divided into several groups:

1) Insufficient weight of drilling fluid:

- Abnormal pressure zones - during drilling, so-called abnormal formation pressure zones that have not been identified in advance may be encountered. These formations are typically tight reservoirs, i.e., clays or salts, with impermeable rock confining them on all sides. Drilling these formations requires heavier drilling fluids, but if the abnormal pressure zone is encountered suddenly, it may result in kick.

- Drilling mud design failure - insufficient mud weight, can exist as a separate problem relating to improper selection of drilling fluid density, chemical composition or rheological properties, which can lead to incidents, and the kick in particular.
- Loss Circulation - while drilling in naturally fractured formations, there is a possibility of encountering complete loss or lost circulation. This can lead to insufficient mud volume in the well and, consequently, a kick.
- Gas-cut mud - when drilling gas-bearing zones, especially gas caps, the gas carried by the cuttings gets released from the cuttings and mixes with the drilling mud, causing it to become lighter. This phenomenon is sometimes visible as a "gas bubble" on the surface. Consequently, this situation can lead to an insufficient mud weight in the well, thereby increasing the likelihood of a kick.
- Inadequate filling of the hole during tripping operations can happen in the moment of pulling out the drill string from the well. This reduction in hydraulic column level is a result of the volume being removed, which was previously occupied by the drill pipe's wall thickness and the Bottom Hole Assembly (BHA). Consequently, if the level of drilling fluid filling in the well is not properly controlled, it can lead to a kick

2) Drill string movements:

- Swab effect - the high speed of pulling out the drill string and the small clearance between the drill string and the wellbore wall can create a swabbing effect expressed in low-pressure zone below the drill string, which can lead to the kick.
- Surge effect - due to rapidly running the drill string into the hole, the formation may experience fracturing leading to mud loss. When mud loss becomes excessive, quick control might not be feasible, potentially replacing the issue with another problem, such as a kick.

3) Well integrity failures

- Casing or cementing failure – any incidents such as casing collapse or bad cementing can result in losing wellbore isolation and creating the pathway of fluids migration into the well.

The analysis of kicks and blowouts occurred in a Middle Eastern field showed that mostly kick occurred due to loss circulation (20,5%), insufficient mud weight (23,9%) and gas cut mud (20,5%) (Ashena et al., 2023).

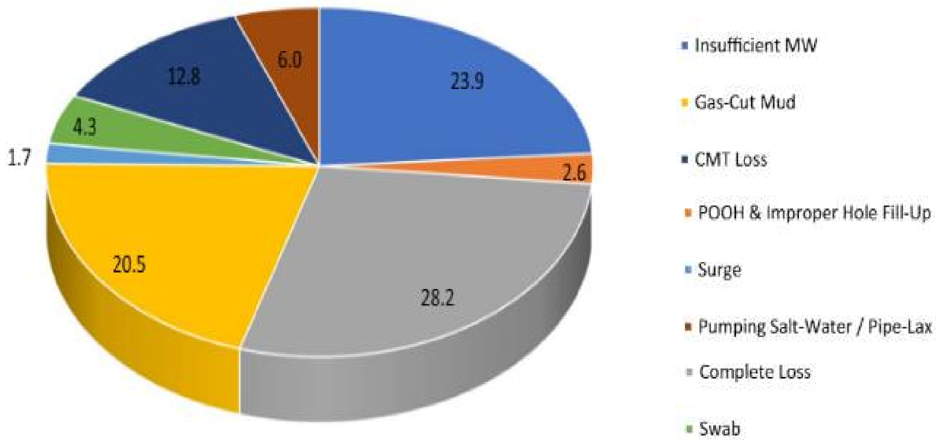

Figure 1 - Middle Eastern field kick causes (Ashena et al., 2023)

2.2 Safety kick parameters

2.2.1 Kick tolerance

Kick tolerance is the maximum influx volume that can be invaded into the well and safely stopped and circulated out without damaging the casing shoe which is typically the weakest point in the open hole. In most cases, the simplest calculation methods are used to calculate the maximum allowable kick volume by making the following assumptions:

- Kick is assumed to be a homogeneous single bubble flow;
- In the moment of the well shut in, the kick is located at the bottomhole;
- The effects of gas migration, dispersion, solubility, compressibility and downhole temperature are ignored.

The simplest calculations involve finding the Maximum Allowable Annulus Surface Pressure (MAASP). Subsequently, the maximum allowable height of the kick column in the open hole is determined. The kick volume at the top of the open hole is then calculated based on this height, and the volume is subsequently recalculated relative to the bottomhole using Boyle-Marriott's law. Therefore, the kick volume should not surpass the derived maximum allowable value. According to the Well Control Manual provided by a British company, it is generally accepted that a notification should be made to the drilling supervisor if the maximum allowable volume is less than 50 barrels. If the maximum allowable volume is less than 25 barrels for offshore wells or 10 barrels for onshore wells, drilling can proceed only with the approval of the city's drilling manager.

2.2.2 KPI kick parameters

There are two key performance indicators (KPI) that require special attention and consistent monitoring:

- Kick Detection Volume: How much volume of influx can be obtained before it is positively identified?
- Kick Response Time: How much time elapses after positive identification of the influx before well control procedures stop its progress?

Both of these indicators should be considered safety KPIs because they measure parameters that directly integrate process capability and personnel operational effectiveness as it relates to fluid flow into the well.

2.3 Kick detection

2.3.1 Detection indicators

One of the main kick indicators is the control of flow in and flow out amount of drilling fluid pumped into the wellbore. In the presence of kick into the well, the drilling fluid flow out rate obtained after circulation will exceed the flow in rate. Nevertheless, there are a number of other kick signs, usually they categorized into primary and secondary kick indicators.

Table 1 – Kick warning signs (Huque et al., 2020)

Primary warning signs	Secondary warning signs
Flow out rate increases	Drilling break (change of ROP)
Pit volume increases	Pump pressure decreases
Flowing well with mud pump off	Cut mud weight decreases
Sudden downhole pressure change (PWD)	Drill string weight decreases

2.3.2 Conventional kick detection systems limitations

While listed kick indicators and corresponding systems for their detection can be highly reliable, their response time is not very fast to avoid loss of well control. There is a lag between kick initiation and kick detection for conventional systems.

The work presented by Olamigoke & James (2022) demonstrates that gas kick detection under deep offshore conditions is primarily influenced by lagged parameters. Firstly, the safe drilling operating window narrows. Secondly, bottom-up circulation can take up to 4 hours in ultra-deep conditions, resulting in indicators not being noticed for a prolonged period. Thirdly, the oil-based systems used for such conditions have much higher solubility than water-based systems. This implies that the gas will remain dissolved until much lower pressures are encountered. Fourthly, measurements can be affected by currents or waves. Fifthly, the choke and kill lines of subsea wells can become blocked by hydrates generated due to the low temperatures and high-pressure conditions.

2.3.3 Early kick detection developments in conventional drilling

As it was already mentioned, early kick detection is one of the main directions for well control improvements today in the drilling industry. The kick detection fault tree analysis presented by Brakel at al. (2015) concluded that there are two main directions for the kick detection improvements: the application of "best sensors" and the integration of "smart alarms" with the potential incremental improvement equal 16,9% and 9,1% respectively.

The real-time data has sufficient advantages for improving kick detection while drilling. The work shown by Mao & Zhang (2019) represents the application of real-time trends analysis based on the divergence of moving average (DMA) for three kick indicators variations: ROP, flow rate and mud pit volume. The received automated alarm system was tested on statistics of 15 wells and showed that average detection time before actual recorded time was 8,5 minutes.

One of the problems which also remains in the kick detection algorithms is "false alarms" which can be caused by transient periods, such as pump stopping and staring. It means that, the kick should be not only accurately and reliably detected, but also normal situations should be correctly recognized.

In the work of Lafond et al. (2019) the new flow modeling integrated in kick detection software was suggested. The comparison between measured and predicted flow conditions for the kick detection process showed much better software efficiency while reducing the false alarm rate in comparison with current flow computations used in the industry (see Figure 2). The main difference in the models that pump efficiency for new model is not taken as constant parameter. Therefore, kick can be detected accurately and with false alarm rate below 5%.

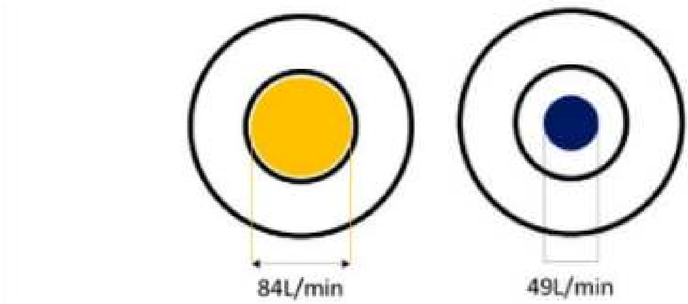

Figure 2 – The kick detection of current and new models (Lafond et al.,2019)

One of the ways for the kick detection process was also suggested by the real-time sensor calibration suggested by Pournazari et al. (2015). The idea of this methodology based on continuous calibration of surface sensors accuracy. For instance, the checking that sensor data has not drifted past a set threshold due to the accumulation of cuttings in return line. If there is a deviation between calibrated signals, the process of recalibration will be done. In the result, the system architecture consisting of sensor calibration and event detection modules (see Figure 3) tested on 5 datasets showed not only decreasing of time necessary for kick detection in comparison with crew detection, but also dramatic false alarms eliminating by 50%.

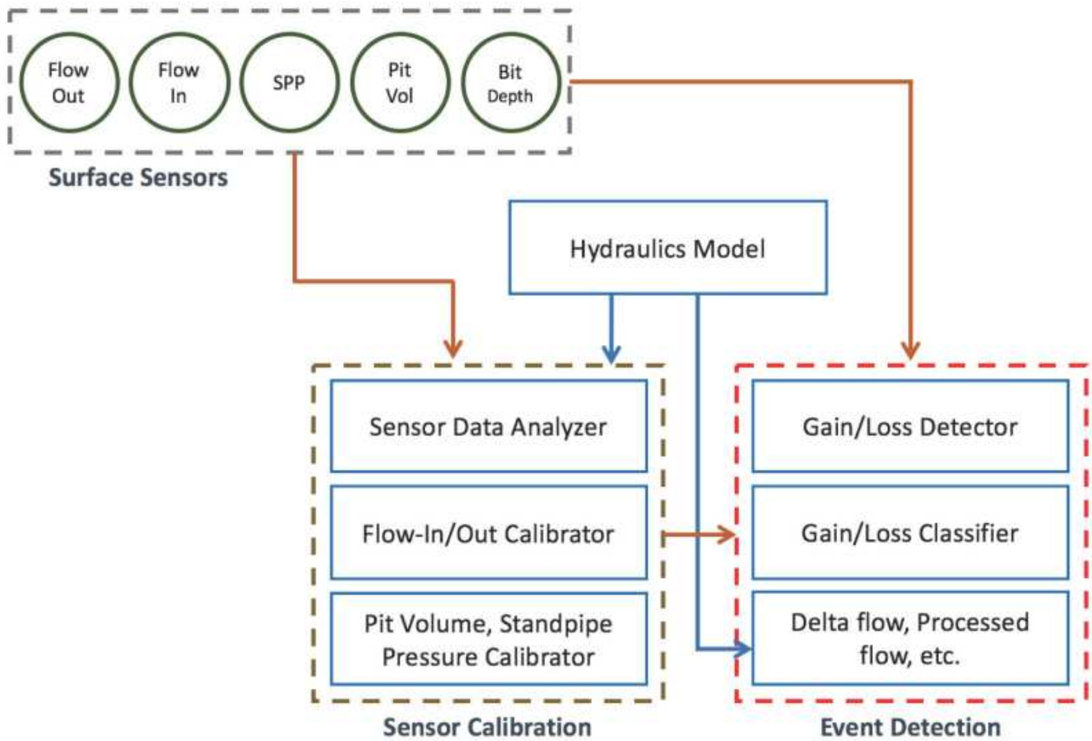

Figure 3 - System architecture of methodology (Pournazari et al. 2015)

Chapter 3

Managed Pressure Drilling

According to the International Association of Drilling Contractors (IADC), MPD is "an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore." It's achieving by application of "backpressure" for controlling BHP in static conditions. It means that in comparison with conventional drilling, where BHP is achieved by mud weight (MW) and annular frictional pressure, the BHP for MPD will include also additional control parameter such as "backpressure".

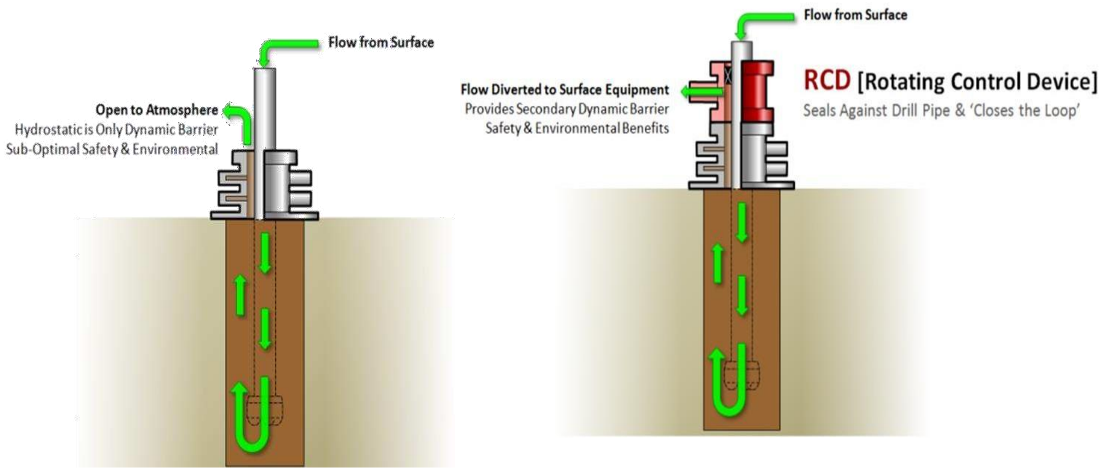

Figure 4 - The comparison between conventional drilling and MPD

3.1 MPD variations

3.1.1 Constant Bottom-Hole Pressure (CBHP)

This variation of MPD is also known as "ECD Management". It's used commonly for narrow drilling windows or for unknown pressure environment conditions. In case when there is no circulating and the circulating annulus friction pressure additive is not present, the bottomhole pressure may be at balance or slightly less than the pore pressure of the formation being drilled. Influx of formation fluids is prevented by the application of backpressure on the annulus.

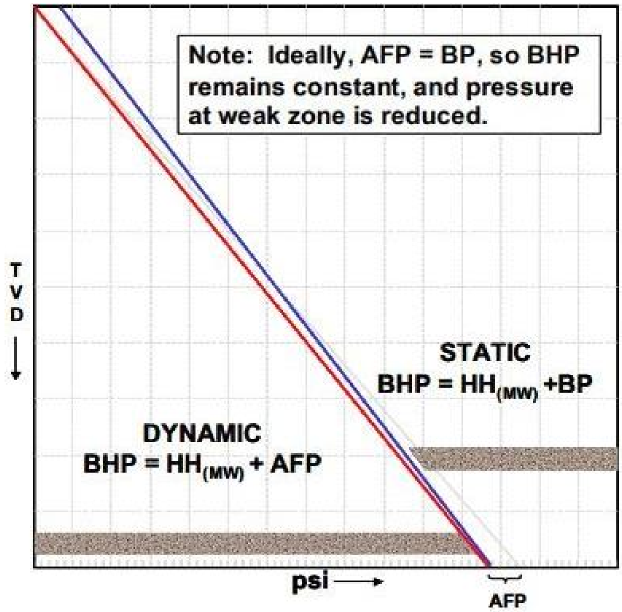

Figure 5 - Constant Bottom Hole Pressure (CBHP) (Hannegan et al., 2006)

3.1.2 Pressurized Mud Cap Drilling (PMCD)

This technique gives the possibility to mitigate extreme losses while drilling highly depleted zones with large natural fractures or voids. In case of the minor losses, Lost Circulation Material (LCM) can be used, but it's not applicable for severe losses and PMCD technique should be used, providing higher ROP and lower cost in such loss zones (Kuehn, 2015).

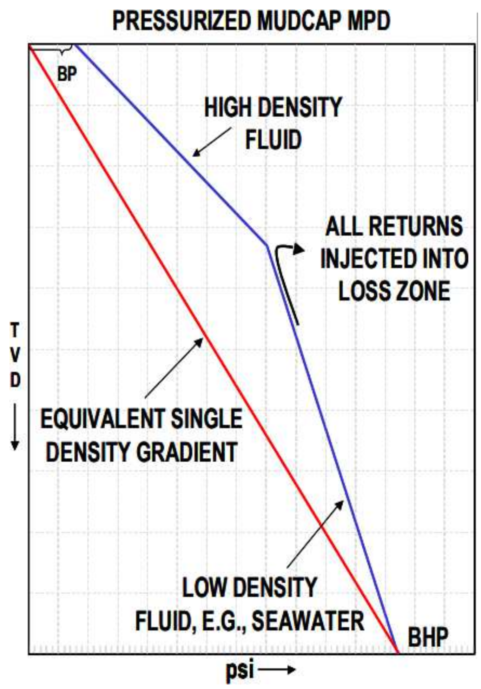

Figure 6 - Pressurized Mud-Cap Drilling (PMCD) (Hannegan et al., 2006)

The technique maintains a column of heavy fluid on top of zones where there are severe losses. The Light Annular Mud (LAM) is pumped down the annulus and works as a primary barrier for avoiding the kick. Sacrificial fluid (SAC) for example, sea water is pumped down the string and into the large voids while drilling continues until the voids and fractures will be cased off.

3.1.3 Dual Gradient Drilling (DGD)

The primary application direction for Dual Gradient Drilling is offshore drilling. One of the primary implementations of this technique involves filling the top of the riser with riser fluid while the remaining part of the riser and well is filled with drilling fluid. This is achieved through the use of a separate mud return line. As a result, the pressure profile becomes much more flexible for narrow offshore drilling windows, enabling the drilling of longer sections in comparison with conventional single gradient drilling (Cohen et al., 2015).

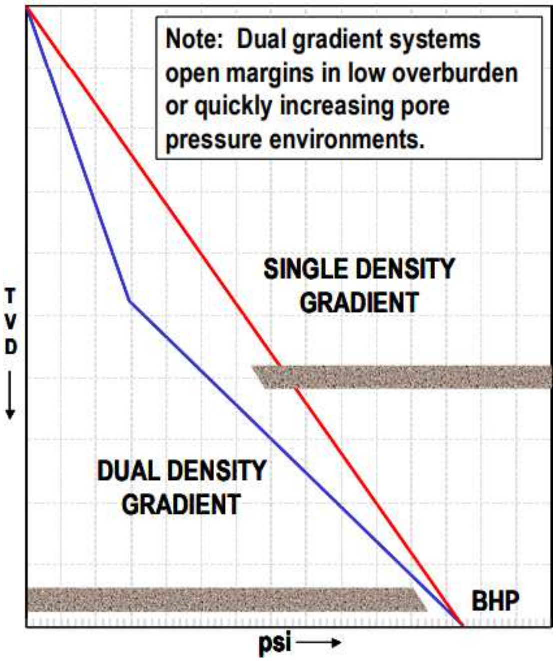

Figure 7 - Dual Gradient Drilling (DGD) (Hannegan et al., 2006)

3.1.4 Returns Flow Control (RFC)

This type of MPD systems doesn't control annular pressure profile but it gives crucial HSE aspects regarding the drilling process. It's accomplished by diverting annulus returns from the rig floor to prevent the presence of toxic gases such as H2S there. Finally, the workplace for drilling crew is becoming safer in comparison with open to atmosphere conventional drilling conditions.

3.2 MPD equipment

A simple MPD system is equipped with several key components, including rotating control device (RCD), a MPD choke manifold, flowmeter and backpressure pump as shown below (see Figure 8).

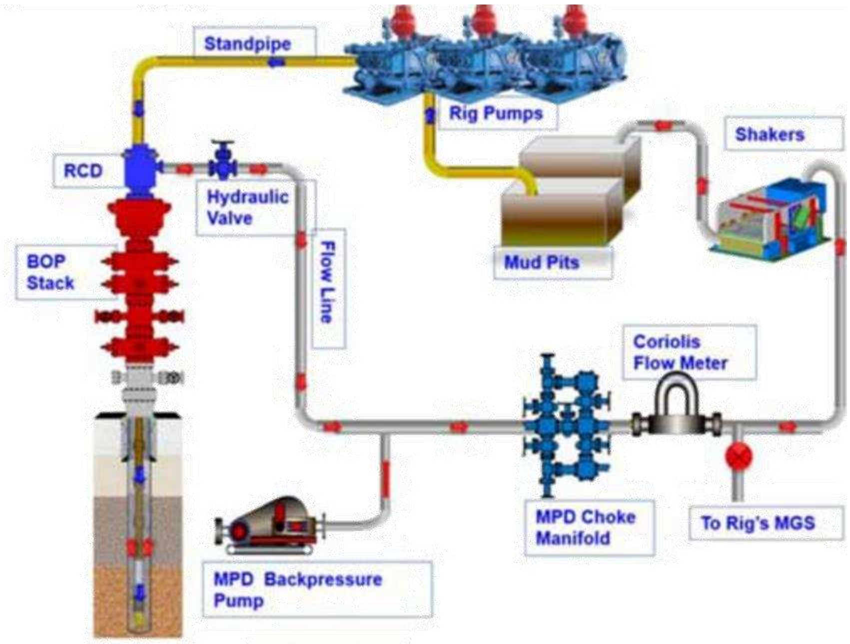

Figure 8 - Simple MPD system (Hoe et al., 2018)

- Rotating control device (RCD) or rotating control head - is used to divert flow away from the rig floor creating closed pressure system. In the case of MPD application, the standard blowout preventer is complemented by RCD locating on the top of BOP. The pressure range for RCD between 500 – 5000 psi, the maximum rotation speed for the bearing equals 200 rpm (Vargas, 2006).
- MPD choke manifold – functions as pressure regulator while MPD system. The adjusting of choke opening provides desired downhole pressure. MPD choke manifold can be equipped with either automatic or manual controls. In the case of a manual choke, the designated rig personnel have the ability to manually regulate the backpressure using a hydraulic control panel or a software application. On the other hand, an automatic choke is governed by electronic monitoring equipment, providing the speed and accuracy needed to properly adjust the back pressure and uphold the desired bottomhole pressure.
- Back pressure pump (BPP) – is used in cases when MPD choke is not able to provide required backpressure. For instance, it can be caused by decreasing of the mud flow.
- Flowmeter - is utilized to accurately measure the flow rate achieved after circulation at the surface. Coriolis flowmeters are commonly employed for this purpose. This flowmeter will be discussed in the work later.

3.3 MPD kick detection

3.3.1 Coriolis flowmeter

The most common flow meter for MPD systems is Coriolis mass flow meter. In comparison with other flow meters, Coriolis mass flow meter offers low measurement uncertainty, high repeatability, and is less affected by temperature and pressure changes.

In this meter unit, the liquid flows through a U-shaped tube that vibrates angularly. Coriolis forces cause the tube to deform and add an additional vibration component to the existing oscillation. As a result, certain parts of the tube experience a phase shift or twist. The received phase shift measured by sensors is proportional to the mass flow rate.

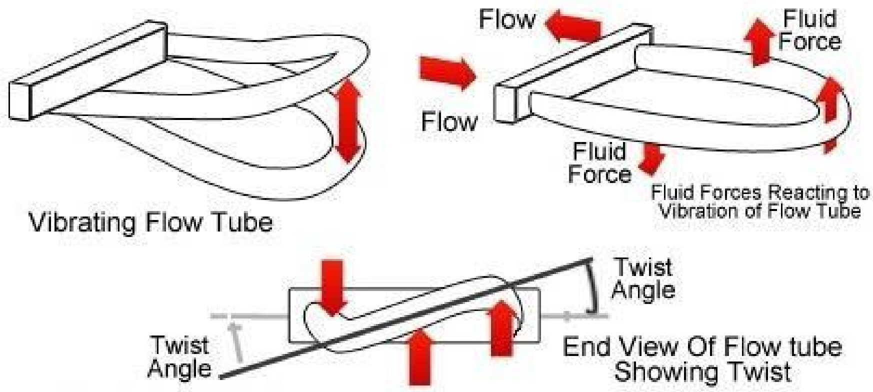

Figure 9 - The principle of Coriolis flowmeter

Nevertheless, the application of the Coriolis flow meter unit has some shortcomings which should be considering while performance:

- The work of Shumakov et al. (2014) highlights one of the main shortcomings of the Coriolis mass flow meter expressed in low accuracy in measuring two-phase flow, especially in case of slug flow (when there is rapid succession of liquid and gas slugs). This problem involves a deep examination of improving the Coriolis meter from a signal processing perspective by transitioning from analog signals to digital signals. By utilizing amplitude control, this shift in signal processing can result in achieving a density error of mostly within +/-1% and a mass flow error within +/- 2% (Yeung et al., 2005).
- For optimal accuracy, it is recommended to use the Coriolis mass flow meter in the upper part of its flow range. When used at lower flow rates, the accuracy of the meter can deteriorate significantly, potentially resulting in inaccuracies of 2% or worse, compared to the typical accuracy of 0,1% (Nas, 2011).
- In practical application was mention, that if the Coriolis meter is situated downstream of the surface chokes in an MPD system, differential pressure through the chokes can

result in entrained gas or gas bubbles. It leads to additional vibrations of tubes in meter unit. This is especially likely to occur when applying SBP at moderate or high-pressure levels, and when mud returns have a high temperature, contain oil-based mud, or when there are low mud flow rates, or a combination of these conditions. The reducing of pressure drop effect in this case was mitigated by Globe Valve installed downstream of the flow meter (Emam et al., 2018).

Efforts to improve Coriolis flow meters are ongoing, encompassing both signal processing and design. For example, the use of a 4-tube measurement unit instead of a 2-tube unit has been shown to significantly reduce the incidence of inaccurate data (Nuber et al., 2012).

Coriolis flow meters are widely used in the oil and gas industry and especially in managed pressure drilling (MPD) systems due to their high level of accuracy. However, it's important to take into account their sensitivity to two-phase flow, as this can be a crucial factor in achieving precise flow measurements.

3.3.2 Early kick detection through Automated MPD

A successful operation in managed pressure drilling relies heavily on automated control systems. The most important control variables for MPD system are flow rate of mud, bottomhole pressure and surface backpressure. The control system continuously measures the return flow and compares it to an ideal condition, enabling it to detect any deviations quickly.

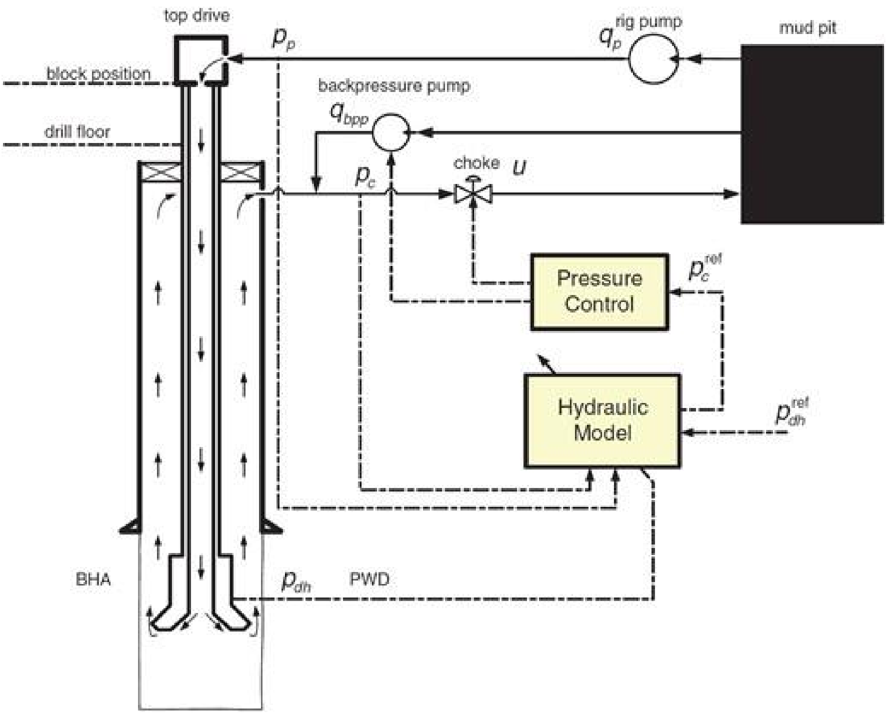

Figure 10 - Automated MPD (ArnØ et al., 2020)

The control system of automated MPD includes two main parts: a hydraulic model and a control algorithm. The function of the hydraulic model is to calculate and predict downhole pressure based on receiving measurements. The function of the control algorithm is to properly maintain the choke manifold for achieving necessary bottomhole pressure.

To design pressure control systems for Managed Pressure Drilling (MPD), it is crucial to have precise hydraulic system modeling. However, achieving accurate modeling of drilling systems requires the use of highly intricate models involving parameterized, nonlinear, nonconservative hyperbolic Partial Differential Equations (PDEs) along with nonlinear and implicit boundary conditions (Olamigoke & James, 2022). One of the most representative realization of advanced real-time hydraulic model shown by Bjørkevoll et al. (2010) demonstrates the deviation of constant bottomhole pressure + 2,5 bars, in narrow margin window of 7 bars.

At the same time, the study by Kaasa et al. (2012) suggests that high-accuracy prediction of bottomhole pressure can be achieved without using complicated hydraulic models by simplifying the model and neglecting unnecessary amounts of uncertainty and complex calculations, which can still be difficult to manually calibrate even by experts due to the model's high complexity.

The improvement of such control systems can be achieved through the design of controller algorithms. A major amount of industrial control loops is linear. However, nonlinear model-predictive control (NMPC) systems can show much better performance than Proportional-Integral-Derivative (PID) controllers (Godhavn et al., 2011).

The estimation of unknown states and unmeasured parameters included in observers of control systems is another direction for improvements. The most well-known method for these reasons is the Kalman filter (KF). For instance, the application of Unscented Kalman Filter (UKF) for the estimation of the kick magnitude using surface measurements in Habib et. al. (2021). This suggestion was tested on filed data from MPD operations in western Canada. As a result, the application of the Unscented Kalman Filter (UKF) provided the possibility to detect the kick 20 seconds earlier than it can be accomplished by Coriolis flowmeter.

Another powerful tool for early kick detection is the micro-flux control systems. When used in conjunction with MPD, it saved 15 days of rig time for two wells in the Shakal field. The system rapidly identifies influx and automatically circulates it, limiting the volume of influx contributed from the well to typically less than 5 barrels (Santamaría et al., 2016).

It is clear that automated MPD can be a valuable tool for early kick detection (EKD), enabling high-resolution detection and minimizing the inflow time and volume of kicks that enter the wellbore. Nevertheless, the most promising direction for improving Automated MPD system highlighted in majority of works is the application of downhole measurements which can improve as hydraulic models as well as control algorithms in control systems. High-quality and reliable downhole data is the key tool for achieving a fully automated process, not only for drilling procedures in general but also for early kick detection possibilities. This point will be discussed in further detail later in this work.

3.4 MPD kick response

The IADC makes a statement in the definition of MPD that "Any influx incidental to the operation will be safely contained using an appropriate process”.

The initial kick response for MPD unit can be split in two categories: non-circulating and circulating often named as dynamic. The choice of kick response methods depends on several factors. One of the main important is the presence of the accurate flow measurement equipment. Nevertheless, the equipment used in MPD system related to backpressure capabilities provides alternatives to the typical shutting of the well giving the huge options to have safe well control process.

3.4.1 Non-circulating kick responses

Non-circulating responses include the conventional shut-in procedure and different variations of pump shut down. The conventional shut-in procedure can be used when accurate flow metering is not available. This method is achieving by pump shut down and closing the choke as soon as practical.

Another non-circulating response is Modified MPD pump shut down. The process based on following a schedule for incremental pump shut down until pumps are off and then maintaining the casing pressure required for compensating Annular Pressure Losses for two minutes. It gives the opportunity to check the precalculated casing pressure for stopping formation flow. If necessary, the choke or back pressure pump can be used to impose the required casing pressure.

3.4.2 Circulating kick responses

This type of kick response is named as circulating due the fact that mud circulation is not halted during them. The main aim of such methods is to increase BHP. This can be achieved by increasing choke pressure or pump rate. The most effective among these two increasing the choke pressure, achieved by maintaining the same pump rate, but changing the choke opening position. Then the flow out rate drops to around 110% of the flow in rate, and smaller choke adjustments are used to match flow in and flow out rates.

3.4.3 Comparison of kick responses

The deep learning of these alternative initial responses to kick during MPD by Davoudi et al. (2010) showed that a circulating response with rapid increasing of the choke pressure is the safest process in comparison with others due to the lowest pressure at shoe and addled gain until influx is stopped. Generally, circulating responses are much safer due to the absence of bottomhole fluctuations and risks associated with fracturing weak zones. Accurate flow metering is essential for their application. These initial responses can yield efficient results with the application of automated systems.

Non-circulating responses generally increase the size of BHP fluctuations due to the need to shut down the pump. One advantage of well shut-in responses to kicks is that they completely stop flow at the surface, which eliminates the need for accurate flow metering to evaluate whether the formation flow has stopped.

Non-circulating responses can be used for precautionary reasons, but in cases where a weak zone is located above the kick zone and there is low kick tolerance, their application is unsafe and can lead to fracturing of the weak zone.

The work of Davoudi et al. (2010) also proposed an algorithm for selecting the kick response, highlighting the main logic in the choice between the discussed methods.

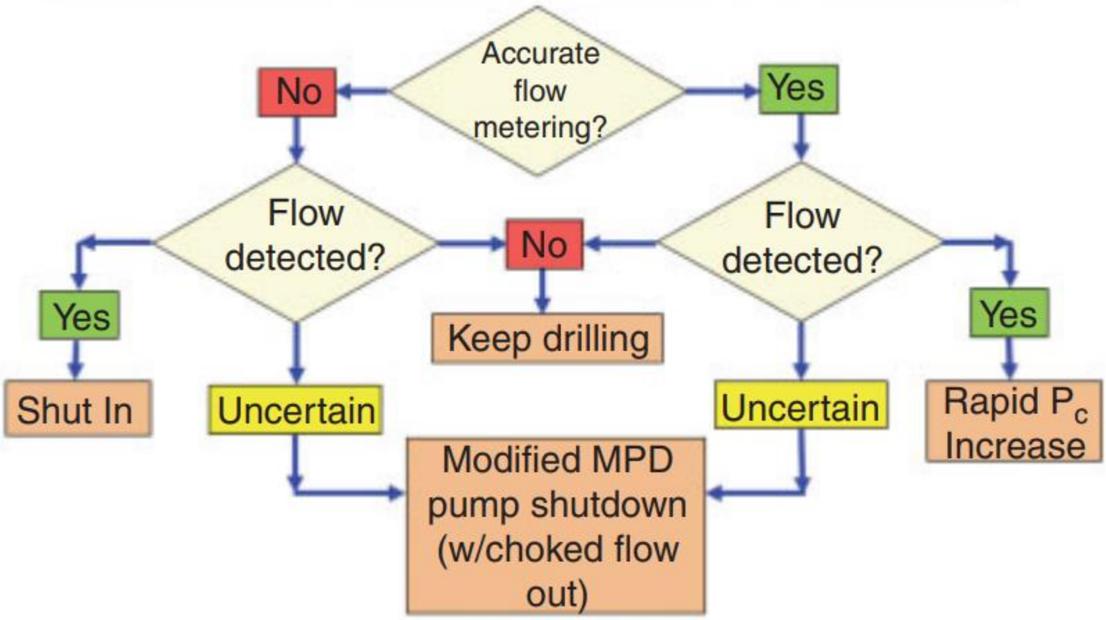

Figure 11 – The kick response selection algorithm by Davoudi et al. (2010)

Chapter 4

Downhole measurements while drilling

Conventionally, operational personnel or automatic control systems rely only on surface measurements. It's quite obvious that correct interpretation of developing downhole events using surface measurements is impacted by many circumstances. The work of Veeningen et al. (2012) highlighted the most crucial factors which should be taken into account if surface measurements are used:

- Equipment issues – the proper functioning of measurement equipment, for instance, it can be shortcomings of Coriolis flowmeter discussed in previous chapter.
- Mechanical factors - for instance, hydrates formation or some lines plugging.
- Execution factors - for instance, not correct lining up of surface lines or tanks.
- Environmental conditions – offshore drilling rely some additional movements of all equipment caused by heave, roll or pitch.
- Physical behavior factors – even the application of sophisticated hydraulic models can't give the full representation of downhole condition changes.

When there is a gas influx, it causes a decrease in pressure in the annulus, which is influenced by the contrast between the mud and gas/fluid density. However, detecting this slight pressure drop with conventional annular pressure measurement can be difficult because the equivalent circulating density (ECD) is calculated at the surface. Therefore, even small pressure variations downhole may not be discernible as changes in downhole pressure (Sehsah et al., 2017).

Downhole measurements can provide more accurate and reliable information about the wellbore conditions, such as the pressure and fluid flow rates, which are essential for detecting and monitoring the onset of kicks.

4.1 MWD/LWD measurements

The utilization of Measurement While Drilling (MWD) and Logging While Drilling (LWD) tools has increasingly become integral in ensuring safety during the drilling process. These technologies play a crucial role for monitoring and controlling drilling operations, resulting in safety measures improving.

4.1.1 LWD measurements

LWD tools are responsible for providing petrophysical data. Kick detection can be accomplished by monitoring three key measurements affected by borehole fluids (Olamigoke & James, 2022):

- Bulk density – declining;
- Electrical resistivity – increasing;
- Acoustic velocity – compressional wave velocity will increase.

One example of acoustic LWD measurements tools is Ultrasonic Caliper offered by Elahifar et al. (2014), which detects the kick in real-time drilling application by monitoring the speed of sound in the drilling fluid. The design of this tool also allows for kick detection through annular pressure and temperature monitoring.

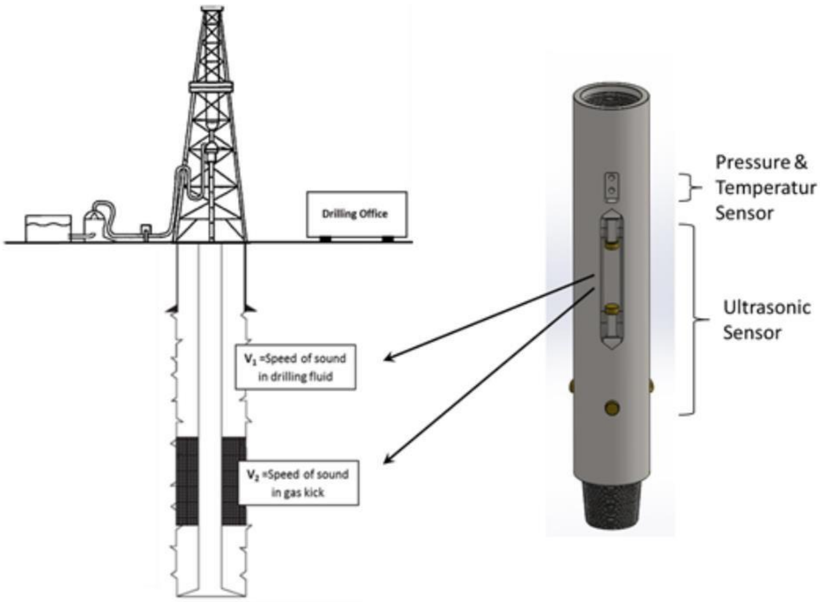

Figure 12 - Ultrasonic Caliper (Elahifar et al., 2014)

Sonic methods can easily detect early gas kick, but there is the limitation that most of the sonic kick detection methods are based on water-based mud only and can't reliably detect the kick in oil-based mud conditions. Also, as shown by Jianhong et al. (2015) measurement accuracy decreases when the drilling fluid density and the annular gas injection rate are increased.

4.1.2 MWD measurements

Measurements While Drilling (MWD) tools provide downhole measurements such as annular pressure, which is among the most crucial for early kick detection, downhole temperature, RPM, downhole TOB, WOB, downhole vibrations and some directional parameters such as azimuth or inclination.

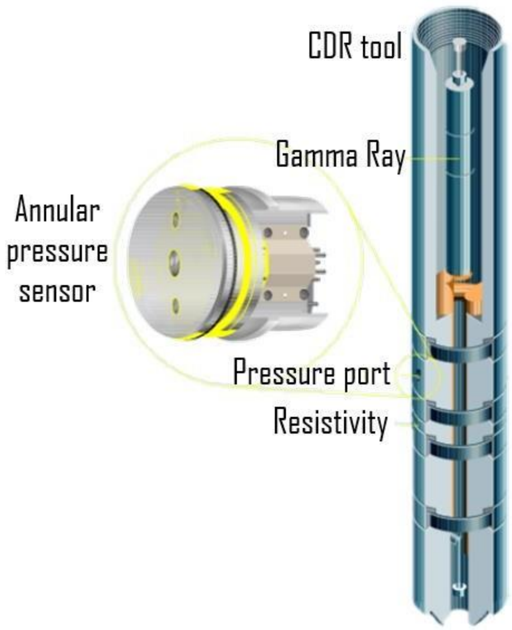

Figure 13 - APWD included in CDR tool (Aldred et al., 1998)

One of the examples of an annular pressure sensor is presented in the figure 13. Annular Pressure While Drilling (APWD) measurements in the Compensated Dual Resistivity (CDR) tool are accomplished by resistor-based bellows gauges. These tools are used with a mud pulse telemetry system, which means that if the pumps are off, the real-time connection between the surface and downhole is not available. Nevertheless, the tools are able to record measured information and transmit it when circulation is recovered.

4.2 Telemetry channels

The telemetry channel is integral part of communication between downhole and surface carrying information between them. The channel signal transmitting capacity expressed in bits per second (bps) is one of the main parameters describing the efficiency of telemetry system. Mud pulse telemetry (MPT) is the main commonly acknowledged real-time data transmission technology in the drilling field. At the same time, one really prospective telemetry systems named as Wired Drill Pipe (WDP) is becoming more and more used in the industry showing some advantages which cannot be performed by MPT. Other possible telemetry systems are electromagnetic telemetry and acoustic telemetry, but as they are used only in special cases, they will not be touched upon in this work due to their rare application.

4.2.1 Mud Pulse Telemetry (MPT)

Telemetry systems are equipped with transmitter and receiver. In MPT, the technologies for transmitter and receiver differ depending on whether information is being uplinked or downlinked. In up-linking, a mud-pulser in the BHA generates pressure fluctuations, which are detected by sensors and signal processing modules at the surface. If there is a need to send the signal in the opposite direction, periodic changes of mud flow rate or RPM can provide it.

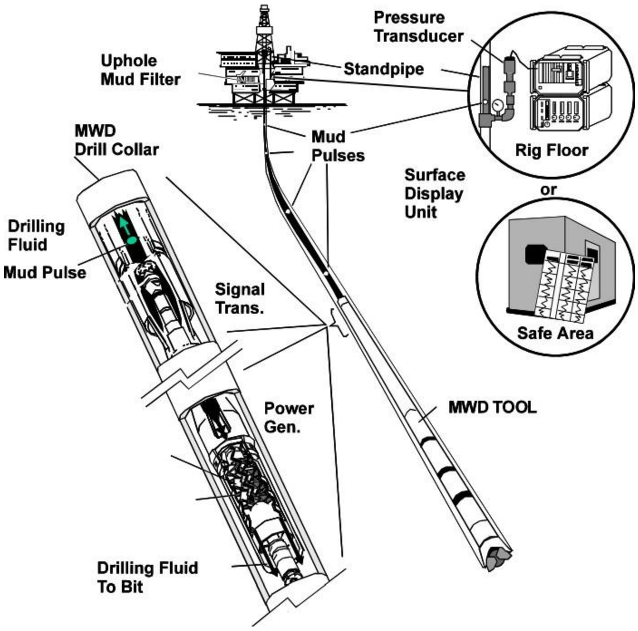

Figure 14 - Mud Pulse Telemetry communication (Macpherson et al., 2007)

4.2.1.1 Positive Mud Pulse Telemetry

This type of MPT system is based on transient restriction of the mud flow going through the tool using hydraulic poppet valve. As a result, the positive pulse is generated by increasing the pressure in the standpipe, which is then detected at the surface. Data transmission includes several series of such positive pulses.

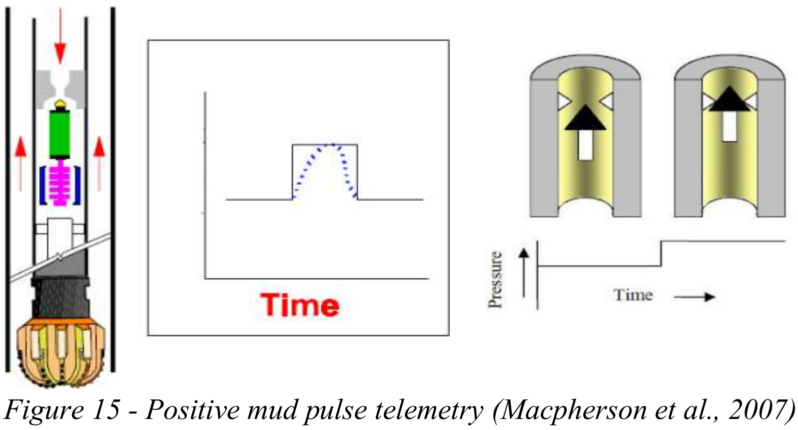

Figure 15 - Positive mud pulse telemetry (Macpherson et al., 2007)

4.2.1.2 Negative Mud Pulse Telemetry

Negative MPT employs a controlled valve to temporarily release mud from the tool's interior into the annulus. This action induces a pressure reduction, manifesting as a negative pulse or pressure wave that propagates back to the surface and gets detected at the standpipe.

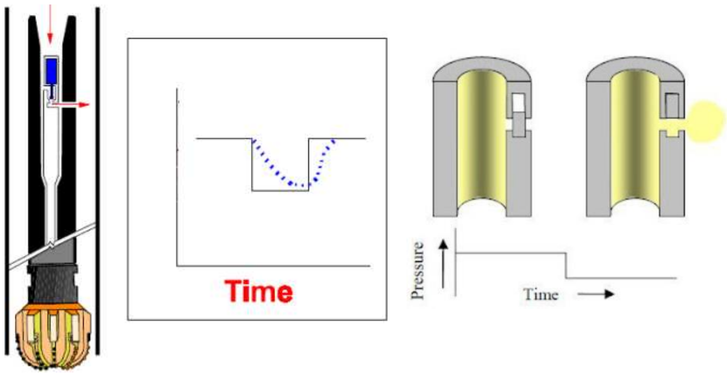

Figure 16 - Negative mud pulse telemetry (Macpherson et al., 2007)

4.2.1.3 Continuous Mud Pulse Telemetry

Continuous wave telemetry employs a rotary valve, often referred to as a "mud siren," featuring a slotted rotor and stator configuration. This arrangement regulates the flow of mud, generating a modulating positive pressure wave. This wave then travels to the surface and is detected at the standpipe. One of the discs remains stationary, while the other is driven by a motor. The consistent motor speed induces a regular and uninterrupted pressure variation, essentially creating a standing wave. This wave is used for the data transmitting.

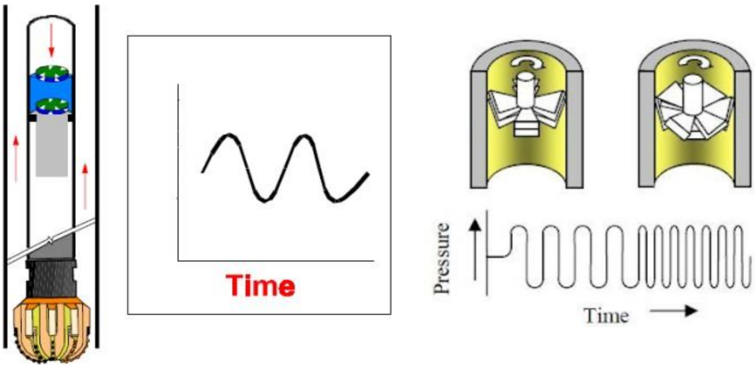

Figure 17 - Continuous MPT (Macpherson et al., 2007)

4.2.1.4 Disadvantages of MPT system

The MPT system is a mature technology that has been in use for several decades, and it is considered to be the most widely used form of downhole telemetry. However, some shortcomings of such communication between downhole and surface cannot provide the necessary confidence in reliable application for projects that require real-time data as crucial indicators for a safe drilling process.

- Signal Attenuation and Dispersion – this is one of the disadvantages this technology. It significantly limits its application in deep wells. Changes in mud density and compressibility, influenced by the raise of solids or gas in the mud content, lead to mud pulse velocity decrease. If the pulser strength is 200 psi at the tool and the pulser is located at 20,000 feet, the received signal at surface in water-based mud will equal 30 psi, in oil-based mud the signal received at the surface is even smaller - 10 psi for this depth (see Figure 18).

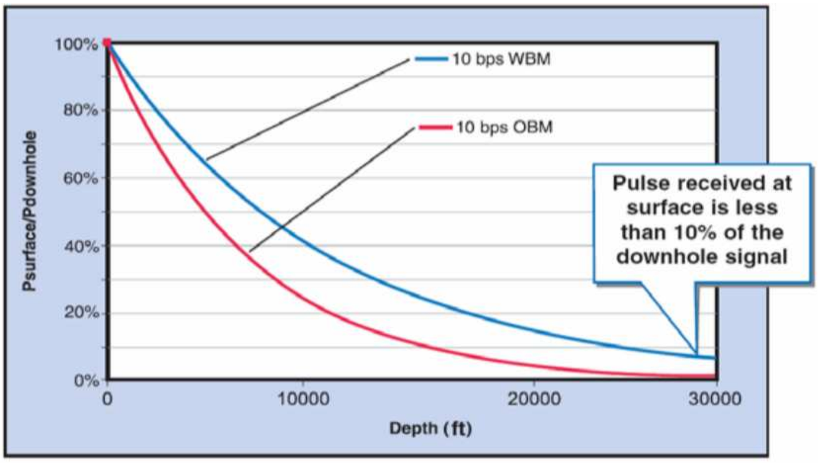

Figure 18 - Mud Pulse Telemetry Attenuation (Macpherson et al., 2007)

- Limited amount of transmission data rate – this disadvantage is a consequence of the first one: lower frequency components are subject to less attenuation than higher frequencies. Therefore, the maximum available data transmission rate for mud pulse telemetry is currently limited to around 20 bits per second (bps). However, ongoing efforts are being made to develop techniques for data compression, signal encoding, and decoding that can increase the effective data rate. For instance, by combining a physical data transmission link with a rate of 4 bps with data compression, effective data rates of up to 33 bps can be achieved. Despite these advancements, these signal processing techniques have not yet been widely integrated in the MPT systems (Mwachaka et al., 2018).
- MPT is highly affected by downhole sources of noise such as bit vibrations or drilling motor stalling, which can introduce interference into the signal transmission. This problem is being attempted to be solved by the utilization of signal filters. For instance, Jianhui et al. (2007) considering the pump noise as the main source of the noise during the transmission process of the signal suggested the application of FIR low-pass filter for these reasons. Nevertheless, it implies huge extra efforts for reliable and proper communication. Systems requires regular maintenance and calibration to ensure accurate data transmission, which can be costly and time-consuming.

- In MPT, data is only collected at the BHA and not along the string. The absence of measurements along the string makes it challenging for wellsite personnel to understand the reasons behind the well behavior. For example, in situations where low weight on bit is observed.
- Not working without mud circulation – it's critical aspect of the application such telemetry system in the case of kick incidents. This type of telemetry is not available when accurate and immediate downhole measurements are required.

4.2.2 Wired Drill Pipe telemetry (WDP)

Nowadays, advanced MWD and LWD units included in BHA are able to provide large amount of information about downhole conditions, generating a huge amount of data. However, the limitations imposed by conventional mud pulse telemetry systems don't give the opportunity to take these advantages. The Wired Drill Pipe telemetry is an alternative that able to significantly enhance real-time downhole measurements while drilling.

One of the most well-known wired drill pipe telemetry system today is able to transmit 57,600 bits per second, providing significant communication efficiency in comparison with conventional MPT systems.

The wired drill pipe incudes armored coaxial cable encapsulated in the pressure-sealed conduit, and low-loss inductive coils are embedded within double-shouldered connections for each tubular joint. As a result, the transmitting of signals achieving by electromagnetic induction.

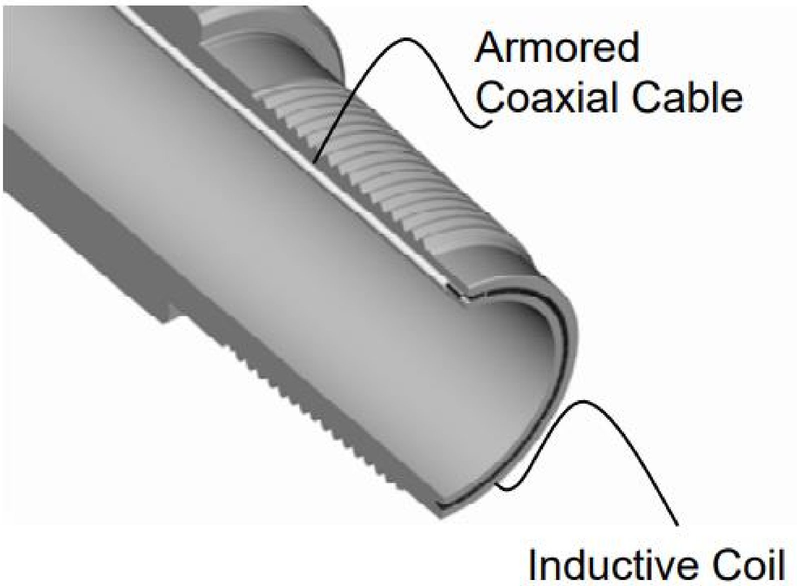

Figure 19 – Wired drill pipe double-shouldered joint

4.2.2.1 Identification of Safe Drill Margin by WDP

The identification of a safe drill margin is a crucial activity in drilling operations. It provides an understanding of the necessary drilling fluid density, pressure control of drilled sections and wellbore configuration. The failure of proper drilling operating window can result in essential drilling incidents including the kick. The pore pressure in case of kick incidents is the main parameter which should be properly predicted. Instead of using typical pre-drilled formation pressure prediction methods like seismic waves from surface or while drilling methods like d-exponent which have very poor prediction accuracy (Ma et al., 2018), real-time pore pressure measuring tools can be used.

The experience of different variations of LWD formation pressure testing tools or Formation Pressure Testing While Drilling tools (FPTWD) (see Figure 20) application showed their efficiency not only for testing procedures necessary for further completion and production phases, but also for giving much safer drilling process with proper pore pressure prediction trends with correct mud weight optimization and ECD management.

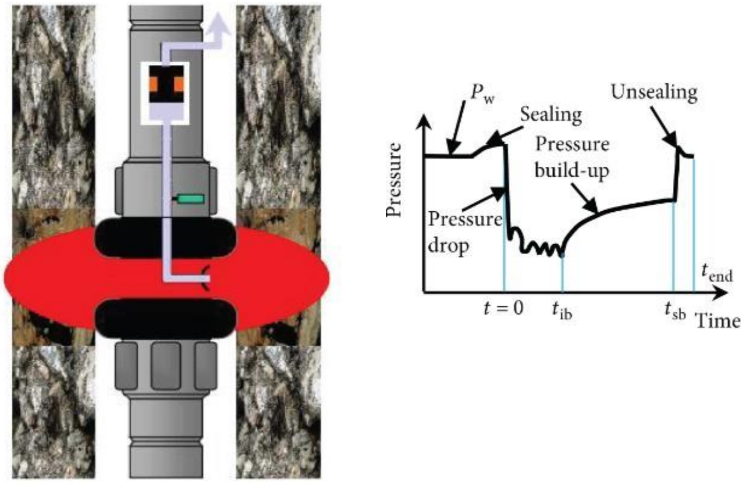

Figure 20 - Drilling Formation Tester (DFT) (Ma et al., 2018)

The work of Edwards et al. (2013) showed that LWD formation testing with the utilization of Wired Drill Pipe telemetry instead of Mud Pulse telemetry is able to eliminate huge amount of Non-Productive Time. The average time saved for 53 tests was 10 minutes per test.

4.2.2.2 Early kick detection and well control by WDP

The high signal transmission rate of WDP and downhole measurements allow to use early kick detection. The presence of influx into wellbore can be instantly noticed and necessary kick responses measures will be taken when the volume of influx is limited in size.

Along String Measurements (ASM) which can be located along whole drill string allow to accurately determine the kick position into wellbore, dramatically enhancing well control procedures.

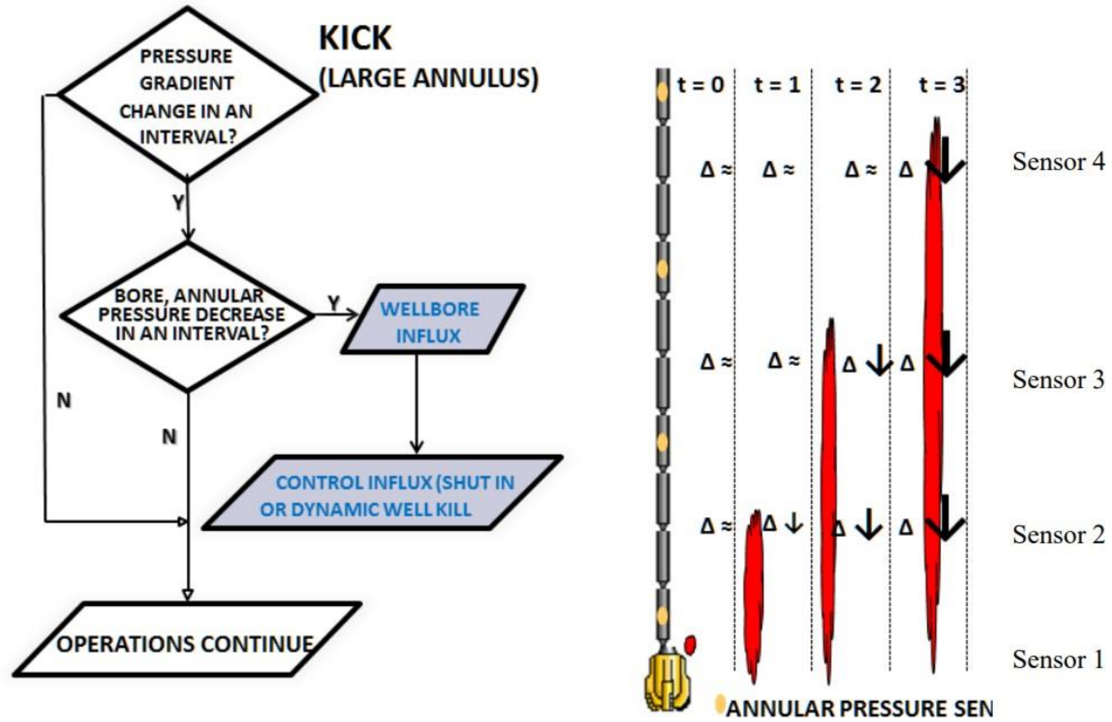

Figure 21 - Early Kick Detection with WDP and ASM (Veeningen, 2011)

Figure 21 represents the kick detection which can be provided by Along-String Measurements (ASM). At the initial conditions (t=0), the influx remains below the pressure sensors, keeping pressure gradients unchanged. As drilling progresses, formation pressure exceeds hydrostatic pressure, allowing formation fluids to enter the wellbore (t=1). The nearest sensor to the bit (Sensor 1) records the first pressure reduction. As influx reaches the next sensor (Sensor 2), the gradient reduces between the two deepest sensors close to the bit, while upper gradients remain constant. At t=2 and t=3, passing Sensor 3 and Sensor 4, the gradients (ΔP) in these sections also decrease. Importantly, the overall gradient $\Delta P_{1\text{-}3}$ from t_1 to t_3 decreases, offering wellsite personnel and software systems an extra method to detect a wellbore influx (Veeningen, 2011).

Chapter 5

Joint application of MPD and advanced WDP

The combined application of Managed Pressure Drilling and Wired Drill Pipe telemetry provides significant advantages not available with traditional drilling and telemetry methods.

WDP is not dependent on fluid, allowing downhole measurements to be obtained in places where it was not previously possible, including areas where traditional telemetry methods are not available and during intervals when pumps are not running. Moreover, high quality data from MWD/LWD tools located in BHA or ASM subs, will be achieved in real time manner.

These technologies provide powerful tools for preventive and mitigating kick incidents, as demonstrated by examples of their separate application and the performance achieved as a result of their implementation. Currently, there are 122 wells worldwide drilled using Wired Drill Pipe (WDP) systems, while only 11 wells have been drilled with underbalanced operations (UBO) or MPD application (Pixton et al., 2014).

5.1 Combined application of MPD and WDP experience

5.1.1 Case #1

The world's first well drilled with MPD and WDP is the Nagar-1 exploratory well, positioned in Block M16 within the Andaman Sea at water depth 400 meters. Seismic findings from this site revealed the presence of shallow gas-bearing sands, which hold potential as reservoirs for production at depths ranging from 260 to 400 meters below the seafloor. To ascertain the existence of hydrocarbons, an exploratory drilling operation was undertaken. At the same time, a challenge emerged as there were no wells within a 100-kilometer radius to serve as references, so the proper pressure conditions for drilling were unexamined and unknown.

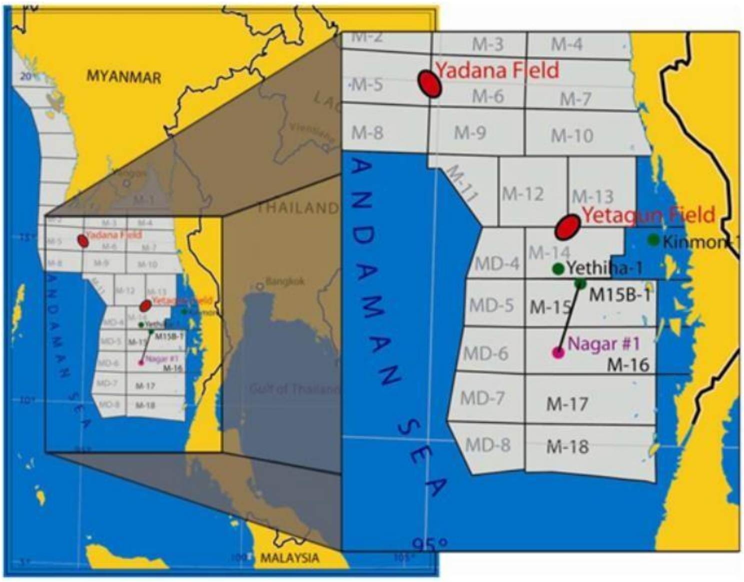

Figure 22 - Map illustrating location of Nagar-1 in block M-16 (Fredericks et al., 2008)

In addition to the lack of precise data concerning pressure conditions, the drilling of shallow gas-bearing sands implies additional challenges related to well control, because limited timeframe exists for detecting and responding to gas releases before the kick reaches the riser. The initial estimates during the planning phase indicated that within a matter of minutes, the inflow would reach the riser, and should this occur, it could lead to the destruction of the shoe before circulation operations take place.

It was determined that following the well shut-in, the rig's manual control system lacked the necessary precision to manage well pressure, particularly when dealing with estimated fluctuations within the range of 150 to 200 psi from the intended value. Ideally, the pressure should not have fluctuated more than +/- 50 psi during drilling. Otherwise, the loss of well control would lead to disaster consequences following by shoe destruction.

That's why for the well Nagar-1 the company decided to use MPD with combination of WDP including PWD measurements. The precise control of bottomhole pressure was implemented by Dynamic Annular Pressure Control (DAPC) system. It consists of a real-time hydraulic model, an automated manifold, an automated backpressure pump and Coriolis flow meter, a programmable control system and a data network (see Figure 23).

The PWD sensor was able to detect pressure change equals 1 psi. The time necessary for transmitting these measurements from PWD to DAPC system was 2-4 seconds. It gave the real-time hydraulic model with very precise downhole conditions vision.

In the result, the drilling of the well Nagar-1 was accomplished with the lowest possible level of risk reduction through proper planning and utilization automated MPD system including real-time pressure measurements given by WDP telemetry system. The downhole pressure fluctuations were +/-15 psi and +/- 45 psi during drilling and connections respectively.

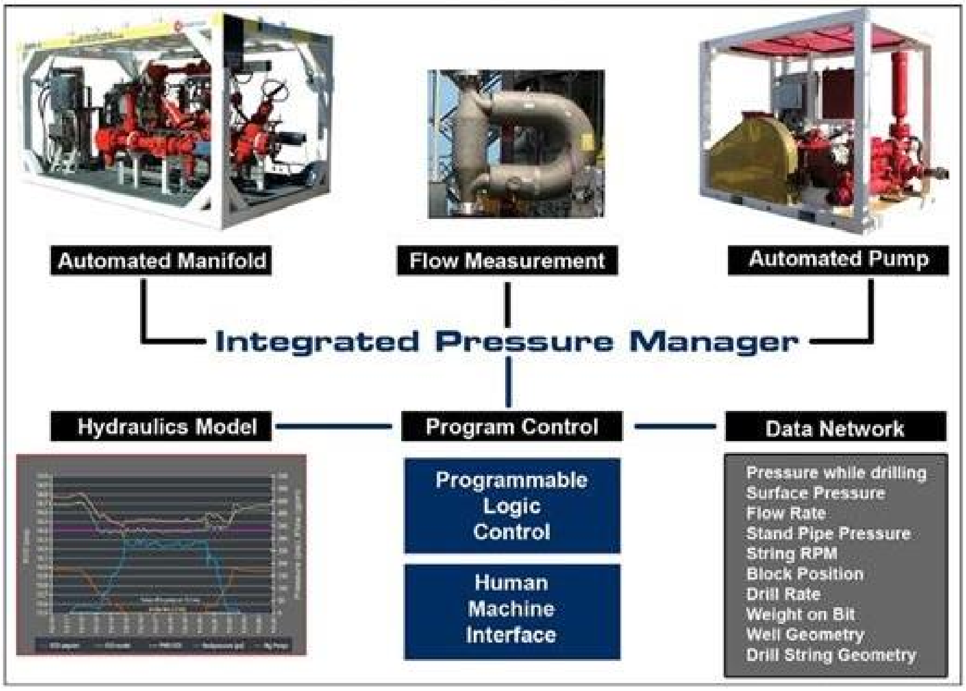

Figure 23 - DAPC system elements used for drilling Nagar – 1 well (Fredericks et al., 2008)

5.1.2 Case #2

The field in which the combined application was utilized had a highly complex geological structure, including salts and faults oriented in different directions. The production of hydrocarbons from a specific interval in the reservoir resulted in a dramatic drop in the pressure profile, creating an ultra-depleted zone (see Figure 24).

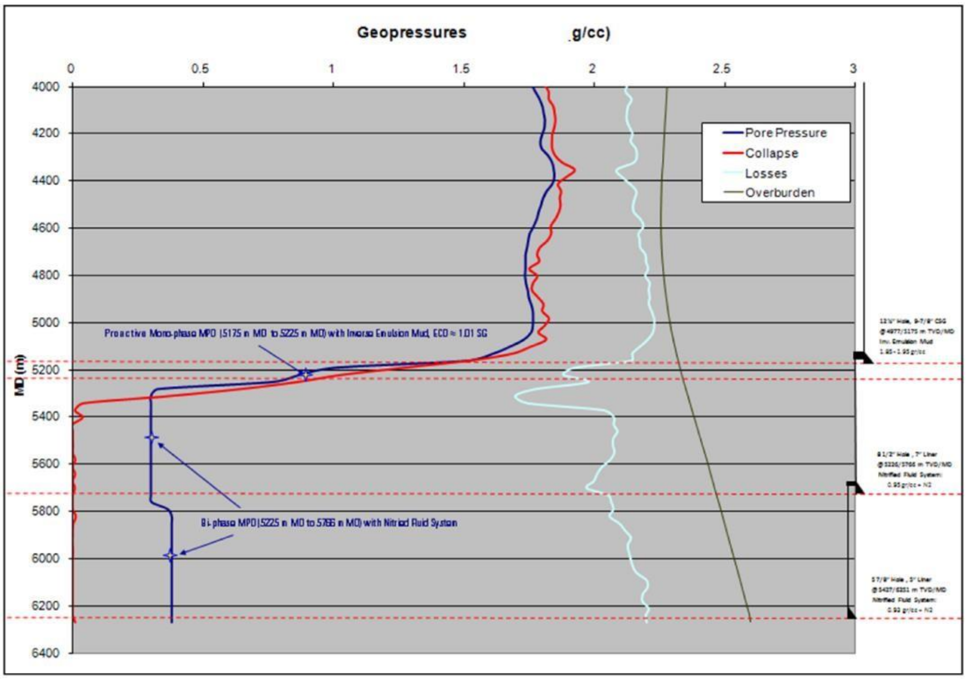

Figure 24 - Pressure profile of the well drilled in ultra-depleted zone (Rasmus et al., 2013)

The encountered depleted zone during drilling necessitated the use of lighter mud weights. The application of such drilling muds increases the operational risks due to potential kick incidents in upper sections and loss circulation incidents in lower sections.

The solution for this situation was found by employing the multi-phase Managed Pressure Drilling (MPD) technique. The interval from 5120 to 5200 meters (measured depth, MD) was drilled using single-phase MPD with 350 psi backpressure to prevent influxes. For the section from 5200 meters (MD) to total depth (TD), multi-phase MPD with direct nitrogen injection was utilized to prevent loss circulation events when passing through the depleted zone.

Real-time downhole measurements while drilling played a crucial role in making informed decisions for the successful execution of these operations. The application of conventional Mud Pulse Telemetry (MPT) system under such conditions was not feasible. The presence of nitrogen injection increases fluid compressibility, leading to signal transmission deterioration. The solution of this problem is the application of Wired Drill Pipe (WDP) telemetry system. As a result, the drilling process was completed with 1-second signal transmission between annular while drilling measurements (APWD) and the surface.

5.2 Advanced WDP application

The collection of data from downhole measurement tools at the bottom and along the string requires not only bi-directional commination which was achieved by implementation of Wired Drill Pipe telemetry systems instead of MPT systems, but also a reliable power source. Available technologies do not fulfill such requirements. WDP telemetry systems are limited to 57,600 bits per second signal transmission rate and use batteries integrated into BHA as the primary power source for downhole devices.

The advanced WDP provided by an Austrian technology company is a drill string with an integrated power cable that simultaneously provides high-speed data telemetry (200,000 bps) and a powerful power supply network (300W). These parameters provide a reliable and ultra-high-speed communication channel giving the possibility for implementation of any high-quality and real-time measurements while drilling at the bottom and along the string.

For this purpose, company also offers its own sensors capable of measuring not only the annular pressure, as one of the main tools for detection of the kick in the annulus, but also many other parameters that significantly increase the certainty of the conditions in the wellbore. The sensors can work at temperatures up to 175 °C. Taking into account current interests of the industry to geothermal energy. where well are drilled in high temperature conditions, the sensors are met possible temperature environments.

5.2.1 Technology readiness level

The full-scale drilling operations using this advanced WDP on the NORCE/Ull platform in Norway were conducted. The technology was successfully applied and met all test criteria under real field conditions using standard tubing procedures and equipment.

The successful testing of the technology was based on a series of individual tests to analyze the properties and elements of the system in detail:

- Fatigue failure test of NC50 joints

The fatigue failure test was performed with constant bending stress (150 MPa, 200 MPa, 250 MPa). Two of the four drill pipes were equipped with company's sensors, for which no failures were observed. The most important result obtained from the study is that the integrated cable was energized during the test and no failures were observed for the transmission of electricity.

Figure 25 - Test bench for fatigue failure of joints

- Testing the conduit for dogleg severity

The testing of the conduit in dogleg situations was carried out together with tensioning and rotation. The tested dogleg severity of 30°/30 meters, together with 250 rpm, shows the high potential of the technology for directional and horizontal drilling.

Figure 26 - Test bench for conduit bending

- Double Shoulder Main Sealing Test

The testing of double-shoulder main sealing was carried out with pressure up to 1400 bar. It was verified that sealing can hold this pressure. There wasn't damage related to internal parts or seals.

Figure 27 - High pressure double-shoulder main sealing test bench

- The conduit test with downhole devices

Downhole tools can be tested with the real electrical interface and drill string length before going into the work on the field. As a result, there is ability to replicate the entire data chain from downhole devices to the surface system with the entire IT infrastructure.

Figure 28 - 8 km conduit test bench

5.2.2 Advanced WDP benefits

This advanced WDP technology offers a number of benefits that not only greatly increase the efficiency of the drilling process, but also significantly reduce the risks inherent in the process associated with a conventional wired telemetry's systems.

- Reduction of risks associated with malfunctions of system elements

The presence of any additional equipment increases the overall risks associated with the operation. In the case of this advanced WDP, it does not need such elements as: batteries, turbines (to create electricity), pulse generators, intermediate repeaters, which in turn eliminates the risks associated with their failure. Moreover, the failure of any of these elements will cause the entire system to stop working because of the interconnection between them. For example, signal repeaters in wired drill pipes are installed every 500 meters, a defect in the operation of one of them will lead to the failure of the entire system.

- Eliminated need for wireline logging

The signal transmission capabilities of this WDP enable real-time logging of the borehole with similarly high and equivalent resolution to wireline logging, making the need for wireline logging irrelevant when using this WDP technology. As a result, the risks associated with cable logging, such as cable breakage or tool stuck in the borehole, are eliminated.

- Reduced BHA length

A significant advantage of WDP provided by an Austrian company over available WDP telemetry systems, that if batteries or turbines are excluded, is the reduced BHA length.

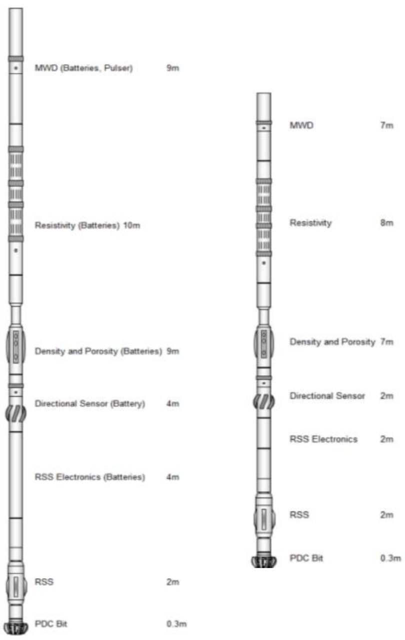

Figure 29 - The comparison of BHA lengths for advanced WDP (right) and typical WDP (left)

The reduction in BHA length of approximately 26% for every 10 meters achieved with advanced WDP brings the measurement devices closer to the bit. As a result, the shortest possible measurement distance is achieved, resulting in better control of drilling parameters and reduced risks associated with deviations from acceptable values.

Closeness of measurements to the bit is of special importance when performing complex directional trajectories. Accurate determination of the current position and inclination angle allows for making quick decisions on necessary adjustments to achieve high-precision positioning of the equipment inside the well. In light of the above, expanding the capabilities of rotary steerable systems (RSS) can be considered as one of the promising areas of further technology integration, also possessing instantaneous interaction between equipment elements downhole and control systems on the surface.

- Overall drilling safety

Given the ability to place sensors anywhere in the drill string due to the availability of a robust electrical power supply and possible real-time measurements close to the bit, the overall safety optimization of the entire drilling process is evident. Any drilling-related incidents can be detected by personnel in a timely manner, preventing the escalation of them.

- Economic advantages

Considering also the choice between simple Wireline drill string and advanced WDP, there are two also very substantial economic benefits. Firstly, the advanced WDP technology requires less time to connect the pipe compared to conventional wired drill pipe. Secondly, the initial investment cost of a project using advanced WDP is lower due to the ability to place a powerline kit on a conventional drill pipe, while conventional wireline drill pipes are manufactured to order, hence the price of manufacturing affects the cost of implementation.

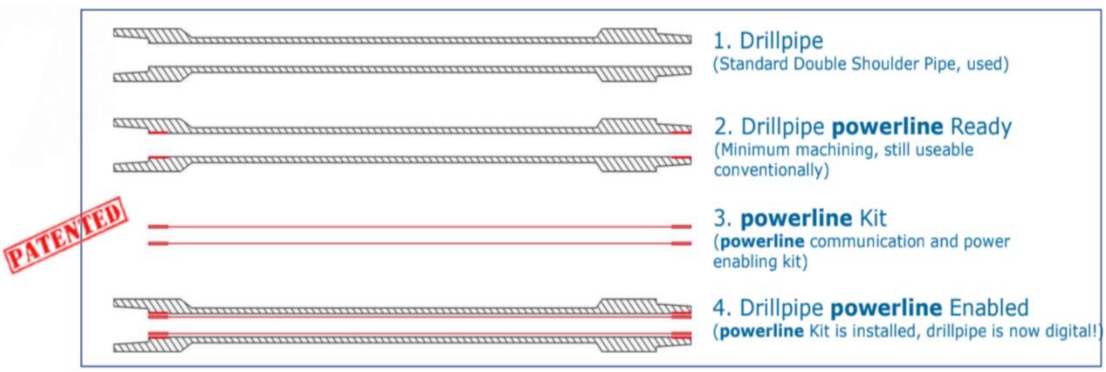

Figure 30 - Powerline kit installation in drill pipe (advanced WDP)

Chapter 6

Risk assessment

6.1 Problem statement

The most severe consequence of kick incidents is blowout. The impact which can be caused by a blowout has catastrophic outcomes for health, safety and environment issues. Due to this fact, the proper risk management of drilling operations including risk assessment and risk reduction processes has essential importance.

The suggested joint application of MPD and advanced WDP theoretically presents evident prevention and mitigation capabilities, dramatically decreasing of risks related to kick and blowout incidents. Nevertheless, any additional expenditures in the projects should be thoroughly explained for implementation. The solutions should be as reasonably efficient as possible to achieve.

6.2 Methodology

To ascertain the potential risk reduction capabilities through the combined application of MPD and advanced WDP technology, Probabilistic Risk Assessment (PRA) models have been implemented for three scenarios:

- **Scenario 1**: Managing kick events for conventional drilling;
- **Scenario 2**: Managing kick events using MPD;
- **Scenario 3**: Managing kick events using the combination of MPD and advanced WDP;

The models are founded upon bow-tie diagrams corresponding to each scenario, and they are implemented through Bayesian networks to conduct a comprehensive forward and backward analysis of the most pivotal events that could culminate in kick and blowout incidents.

The Managed Pressure Drilling technique is included in the fault tree of the bow-tie diagram and solely represents the preventive possibilities of this technique. Conversely, the advanced WDP is incorporated into the event tree of the bow-tie diagram, exclusively depicting the mitigative measures achievable for enhancing kick detection compared to conventional drilling. The reciprocal consideration of the preventive and mitigative potentials of both technologies was omitted.

The blowout incident is regarded as a consequence of the kick incident in cases where kicks go undetected, and there is a failure in the closure of the Blowout Preventer for shut-in operations. As previously mentioned, dynamic kick response methods are not encompassed in the models.

The critical factor that profoundly influences the overall safety of the kick management process is the timely detection of kicks. The mere probabilities of measurement equipment failure and operator oversight in recognizing kick indicators cannot accurately define the efficacy of kick indicator functionality. A time delay exists between the initiation of influx flow into the wellbore and the getting of surface measurement equipment readings indicating the kick. The more intensive the kick, the higher the kick invasion rate into the well. Consequently, even a detected kick can potentially result in a blowout, as influx volume within the well may already exceed the kick tolerance. This work is specifically focused on cases where a high kick intensity is assumed, and any delays between kick detection and kick initiation can lead to a blowout.

6.2.1 Construction of models

6.2.1.1 Bow-tie diagram

The bow-tie (BT) model is recognized as one of the most effective graphical methodologies for depicting a comprehensive accident scenario, encompassing the initiation from accident causation and culminating in the subsequent outcomes. Bow-tie analysis are commonly used as a platform for quantitative and qualitative risk assessment approaches (Yu et al., 2017).

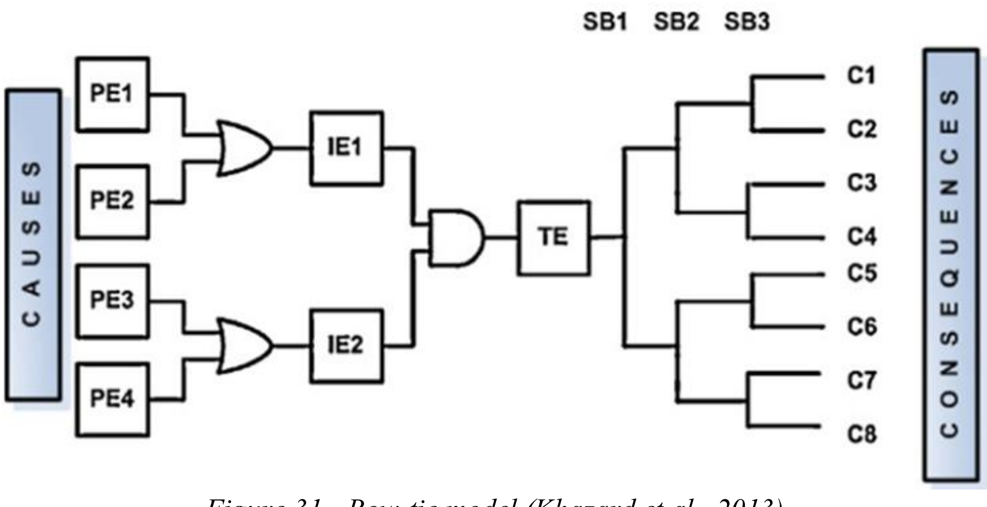

Figure 31 - Bow-tie model (Khazard et al., 2013)

The bow-tie diagram is constructed for a single top event that is under examination. On the left side of this event, there is a fault tree (FT) diagram comprising primary causes that lead to the top event. On the right side, an event tree (ET) diagram presents potential outcomes that could occur if the top event were to happen. The bow-tie diagram includes different components such as primary or basic events (PEi), intermediate events (IEi), top event (TE), safety barriers (SBi), and accident consequences (Ci) (Khazard et al., 2013).

6.2.1.2 Bayesian network

Bayesian inference, a form of statistical method. In simple terms, the Bayesian inference based on updating beliefs about a hypothesis after evidences collecting. It means that if more evidences are observed, the degree of belief in hypothesis will be higher (Maurya et al., 2013).

$$P(H|E) = \frac{P(E|H) * P(H)}{P(E)} \quad (1)$$

P(H) - prior probability of the hypothesis

P(E) is the occurring evidence E probability together all mutually exclusive cases of hypothesis

P(H|E) is the posterior probability, conditional probability of H with given evidence E

P (E|H) is the likelihood function of H with fixed E

Visually, each Bayesian Network (BN) can be depicted using a Directed Acyclic Graph (DAG), encompassing two fundamental components: nodes and edges. Nodes stand for specific variables, while edges, represented by arrow symbols, establish directional connections between these nodes, signifying their relationships (Lu et al., 2022).

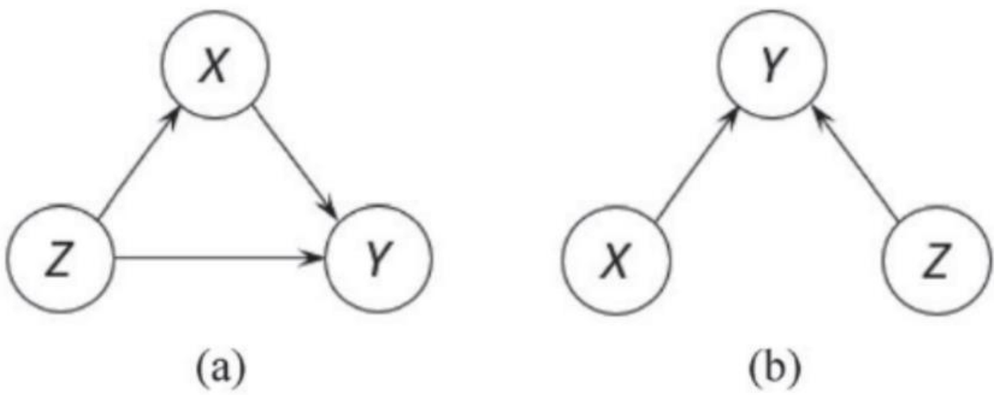

Figure 32 - DAGs with two edges and three nodes (Lu et al., 2022)

6.2.1.3 Converting BT into BN

The converting algorithm from BT to BN includes FT mapping and ET mapping (Khakzad et al., 2013). The proper algorithm of converting fault trees into Bayesian networks is explained by work Bobbio et al. (2001). Each element of the fault tree is transformed into the corresponding node of the Bayesian network. There is no difference for connections between nodes in the Bayesian network and those in the fault tree diagram. The logical gates 'OR' and 'AND' are represented by Conditional Probability Tables (CPTs). The figure illustrates how this implementation works and the differences between them.

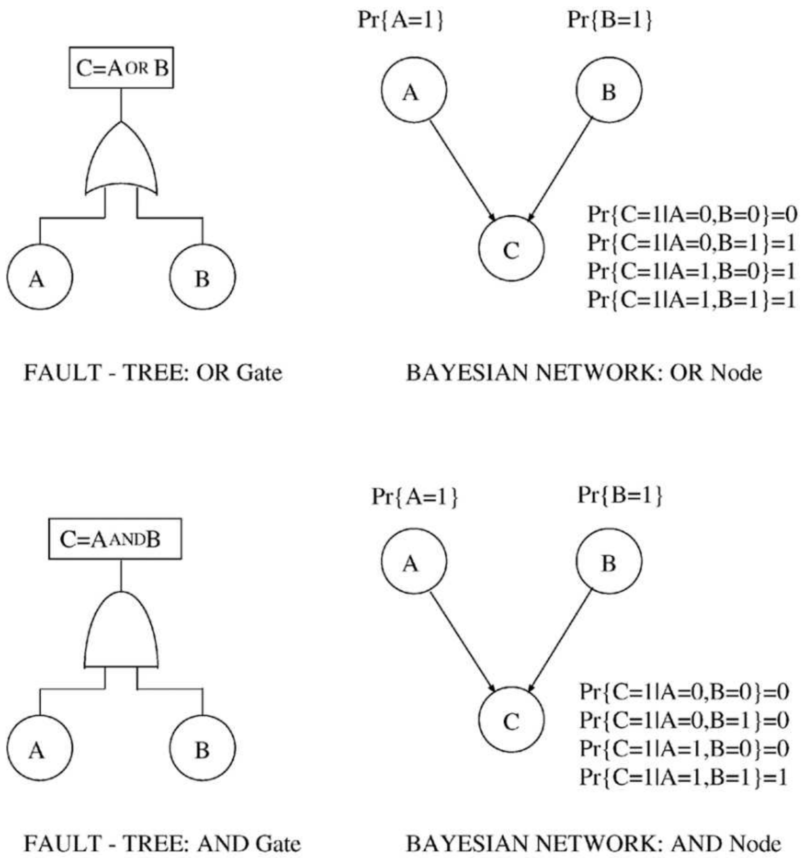

Figure 33 - 'OR' and 'AND' gate in FT and BN representation

The algorithm of converting evet trees into Bayesian network is explained by Bearfield & Marsh (2005). Safety barriers included in ET is transforming into corresponding barrier nodes of BN having two states – failure or success. The connection between safety barrier nodes and consequence node which has a state for each of the consequences in the event tree can be accomplished by two types of arcs – consequence and causal arcs. With the reason to simplify the model, both types of arcs and be eliminated depend on different scenarios. In simple words, if there is no influence of the previous safety barrier to next one, the causal arc connection can be eliminated and if the consequences don't refer to any outcome of barrier, the cosequnce arc connection can be eliminated.

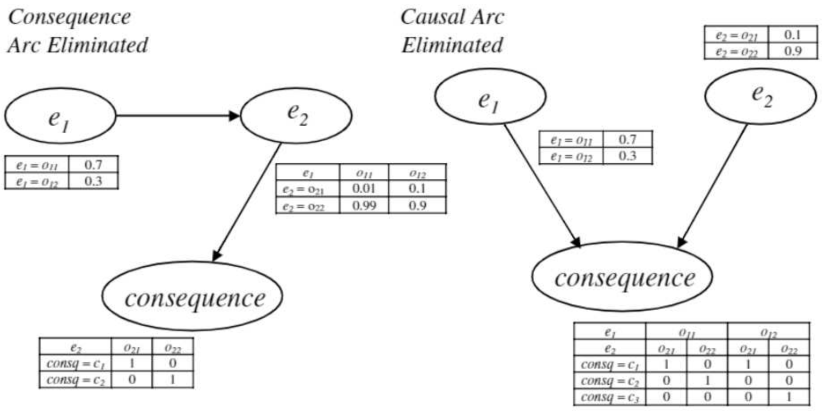

Figure 34 - Two types of arc elimination (Bearfield & Marsh, 2005)

6.2.2 Time parameter based on fuzzy possibility

The time parameter discussed earlier is estimated in this work based on expert judgement. The rating of expert judgement can be conducted in linguistic terms. These linguistic terms represent the possibility of kick indicators to detect kick in time without exceeding kick tolerance, assuming a high kick intensity and the need for the smallest possible kick volume to invade into the wellbore. In other words, the expert should estimate the efficacy of each kick indicator.

Table 2 - Fuzzy scale for linguistic terms

Linguistic term	Fuzzy Scale
Very Low	(0,0,0.1,0.2)
Low	(0.1,0.25,0.25,0.4)
Medium	(0.3,0.5,0.5,0.7)
High	(0.6,0.75,0.75,0.9)
Very High	(0.8,0.9,1,1)

The Similarity Aggregation Method (SAM) presented in the work of Lavasani et al. (2015) is used for the base of expert judgement calculation. The proper sequent of methodology presented below:

1) Opinion of experts $E_k (k = 1,2, \dots, M)$ expressed by trapezoidal fuzzy number sets:

$$E_a = (a_1, a_2, a_3, a_4), E_b = (b_1, b_2, b_3, b_4)$$

2) Calculation of agreement S degree between experts:

$$S_{ab} = 1 - 1/4 \sum_{i=1}^{4} |a_i - b_i| \quad (2)$$

3) Calculation of average agreement (AA) degree:

$$AA_a = \frac{1}{M-1}\sum_{a \neq b}^{M} S_{ab} \tag{3}$$

4) Calculation of relative agreement (RA) degree:

$$RA_a = \frac{AA_a}{\sum_{k=1}^{M} AA_k} \tag{4}$$

5) Calculation of expert's consensus coefficient (CC) degree:

$$CC_a = \beta \cdot w_a + (1-\beta) \cdot RA_a \tag{5}$$

Where $\beta \in [0,1]$ – is a relaxation factor of SAM method

w_a- weight factor of expert based on classification

Table 3 - Expert weighting scores classification

Parameter	**Range**	**Score**
Service time	≥ 30 years	4
	20-29	3
	10-19	2
	≤ 10 years	1
Educational level	PhD	4
	Master	3
	Bachelor	2
	School level	1
Age	≥ 50 years	4
	35-49	3
	20-34	2
	≤ 20 years	1
Assessment target understanding	Well	4
	Medium	3
	Hardly	2
	No	1

6) Calculation of aggregated result of expert's judgements (AG):

$$AG = CC_a \times E_a + CC_b \times E_b + \cdots + CC_M \times E_M \tag{6}$$

7) Defuzzifying of trapezoidal fuzzy number AG = (x_1, x_2, x_3, x_4) to a crisp number:

$$\text{Possibility} = \frac{1}{3}\,\frac{(x_4 + x_3)^2 - x_4 x_3 \; - (x_1 + x_2)^2 + x_1 x_2}{(x_4 + x_3 - x_1 - x_2)} \tag{7}$$

Chapter 7

Results and Discussions

7.1 Results

7.1.1 Fault and event trees

The event tree for all three scenarios has the same structure (see Figure 34). There is a Top event – Kick, and there are two main safety barriers to prevent the blowout incident – Kick Detection subsystem and BOP subsystem. As it was already mentioned, the difference in models is achieving through preventive and mitigating properties of the suggested technologies. MPD preventive possibilities are implemented in the Kick fault tree for scenarios 2 and 3. The advanced WDP possibilities are implemented in the Kick detection fault tree for the 3rd one.

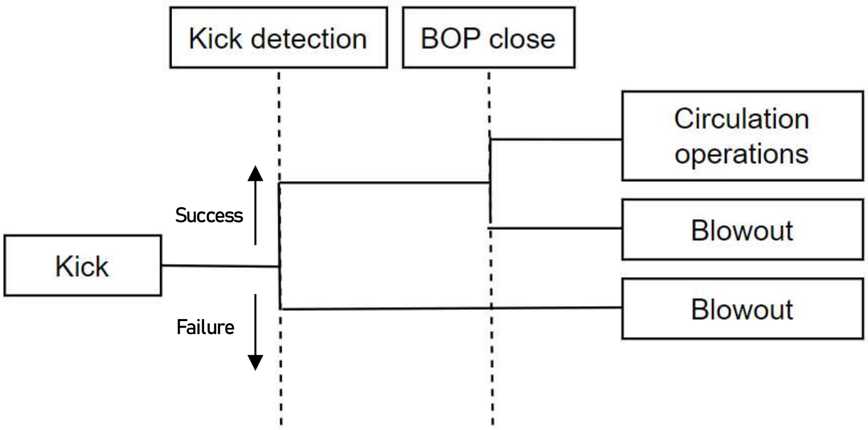

Figure 35 - Event tree for all scenarios

7.1.1.1 Kick fault tree

Scenario 1: The kick fault tree for conventional drilling includes two main intermediate elements leading to initiating of the kick – BHP is lower than formation pressure or Well integrity failure. The BHP in this case controlled only by drilling mud.

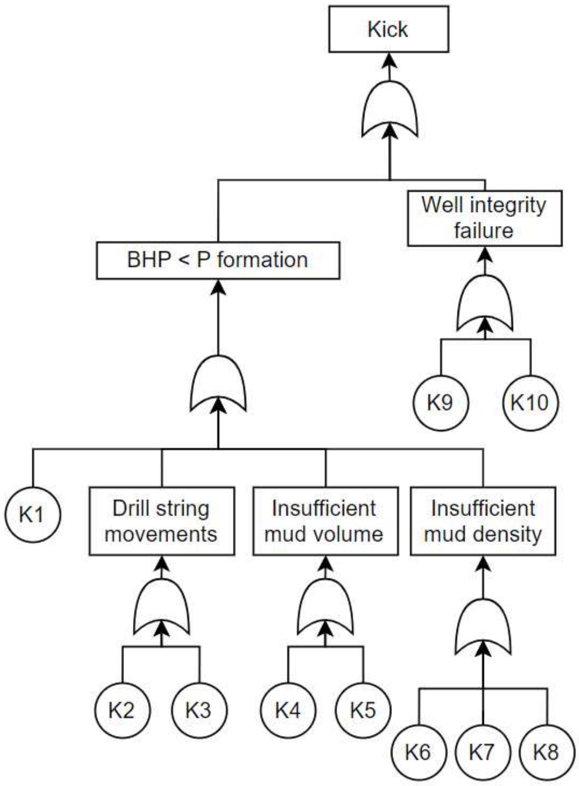

Figure 36 - Kick fault tree (scenario 1)

Table 4 - Kick basic events (Khakzad et al., 2013; Abimbola et al., 2014)

Index	Basic event	Probability
K1	Abnormal pressure zone	1,50E-01
K2	Swabbing	5,40E-02
K3	Surge	5,40E-02
K4	Inadequate filling of hole	2,00E-03
K5	Loss circulation	1,00E-02
K6	Gas cut mud	7,00E-03
K7	Unpredicted temperature effect	2,50E-03
K8	Operator failure in mud mixing	3,00E-02
K9	Bad cement	1,00E-03
K10	Casing failure	6,40E-04

Scenario 2 & 3: The use of MPD technique gives the additional pressure control through backpressure application. In term of fault tree diagram, this means that even if BHP is lower than formation pressure, the kick will not initiate because backpressure can be employed. Therefore, the kick for the 2nd and 3rd scenarios occurs in case of Well Control Loss, which happens due to insufficient BHP and MPD failure, and Well Integrity failure which remains an external factor.

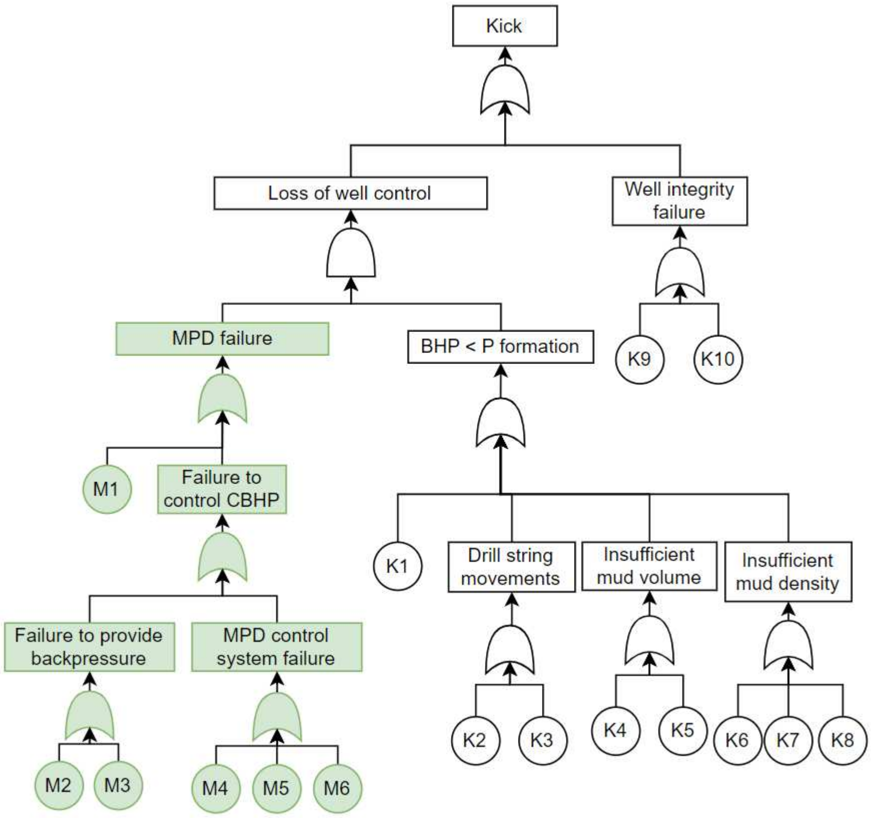

Figure 37 - Kick fault tree (scenario 2 & 3)

Table 5 - MPD system failure basic events (Khakzad et al., 2013; Abimbola et al., 2014)

Index	Basic event	Probability
M1	RCD failure	6,70E-03
M2	Adjustable choke in MPD manifold failure	2,50E-02
M3	Backpressure pump failure	4,30E-03
M4	Controller failure in MPD control system	2,52E-04
M5	Hydraulic model failure	1,00E-03
M6	Coriolis flow meter failure	1,10E-04

7.1.1.2 Kick detection fault tree

Scenario 1 & 2: The kick detection process based on surface measurements, including primary and secondary indicators. The application of downhole measurements is not included in these scenarios. The efficacy of each indicator is estimated based on time parameter discussed in the previous chapter.

Scenario 3: Downhole measurements are included in the kick detection fault tree as primary indicator. The efficacy of this indicator is assumed to be 100%.

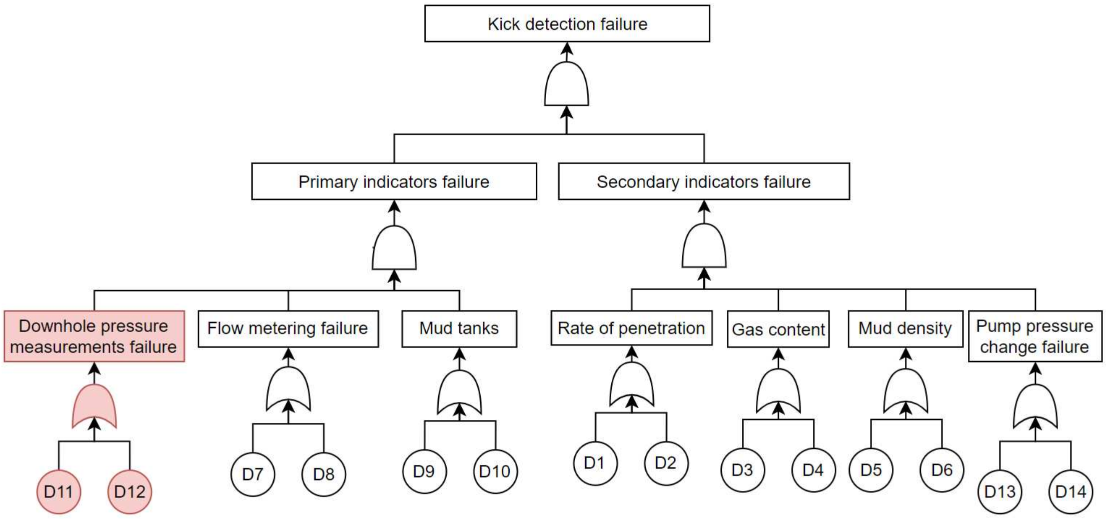

Figure 38 - Kick detection fault tree (scenario 1 & 2 – except red symbols / scenario 3 - all)

Table 6 - Kick detection basic events (Khakzad et al., 2013; Abimbola et al., 2014)

Index	Basic event	Probability
D1	Displacement sensor failure	2,00E-04
D2	Operator failure to notice change in penetration rate	5,00E-02
D3	Failure of gas detector	2,00E-04
D4	Failure of operator to notice gas	5,00E-02
D5	Failure of density meter	2,00E-04
D6	Failure of operator to notice density changes	5,00E-03
D7	Failure of flow meter	1,10E-04
D8	Failure of operator to notice flow change	5,00E-03
D9	Failure of tank level indicator (float system)	1,40E-04
D10	Operator failure to notice tank level changes	1,00E-01
D11	Failure of downhole pressure sensor	1,10E-04
D12	Failure of operator to notice downhole pressure change	1,00E-01
D13	Failure of pump pressure sensor	1,65E-02
D14	Failure of operator to notice pump pressure change	1,00E-01

Table 7 - Expert judgement in linguistic terms about possibility to detect kick in time

Kick indicator	**Expert 1** (w = 0,375)	**Expert 2** (w = 0,250)	**Expert 3** (w = 0,375)
Mud tanks	M	VH	H
Flow metering	M	VH	H
Rate of penetration	L	H	M
Gas content	H	H	L
Mud density	L	VH	L
Pump pressure	M	VH	L

Table 8 - Expert judgement in crisp numbers about possibility to detect kick in time

Kick indicator	Aggregated expert decision				Possibility
Mud tanks	0,555	0,708	0,737	0,860	0,713
Flow metering	0,555	0,708	0,737	0,860	0,713
Rate of penetration	0,316	0,484	0,484	0,653	0,484
Gas content	0,444	0,594	0,594	0,744	0,594
Mud density	0,256	0,395	0,418	0,534	0,399
Pump pressure	0,361	0,517	0,543	0,673	0,522

7.1.1.3 BOP fault tree

The blowout preventer fault tree also has the same structure for each scenario (see Figure 38). There are two main intermediate components – BOP stack failure or BOP communication system failure.

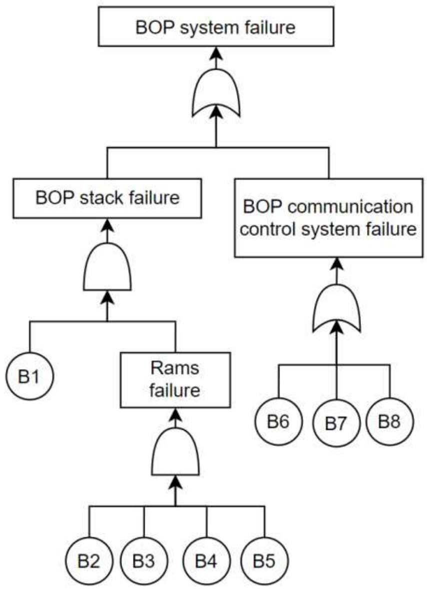

Figure 39 - BOP fault tree

Table 9 - BOP basic events (Khakzad et al., 2013; Abimbola et al., 2014)

Index	Basic event	Probability
B1	Annular preventer failure	2,60E-04
B2	Upper pipe ram failure	2,50E-05
B3	Middle pipe ram failure	2,50E-05
B4	Lower pipe ram failure	2,50E-05
B5	Blind shear ram failure	1,00E-05
B6	Hydraulic unit failure	1,00E-05
B7	Power supply failure	5,00E-04
B8	Operator failure to close BOP	2,00E-03

7.1.2 Comparison of scenarios

Based on fault tree and event tree diagrams, three Bayesian networks were created. The probable causes of having kick are named as:

- **Consequence C1** – Circulation operations, it means that kick happened and all safety barriers successfully fulfilled their functions. The kick was detected and BOP was closed for further circulation operations. Considering added time parameter to kick detection efficacy, the kick tolerance will not be exceeded at the moment of starting circulation operations.
- **Consequence C2** – Blowout due to BOP malfunction, it means that kick happened and was identified by kick detection indicators, but blowout preventer didn't fulfill its function.
- **Consequence C3** – Blowout due to non-detected kick, it means that kick was not detected, and even if it was detected, it was too late for safe management of the kick.

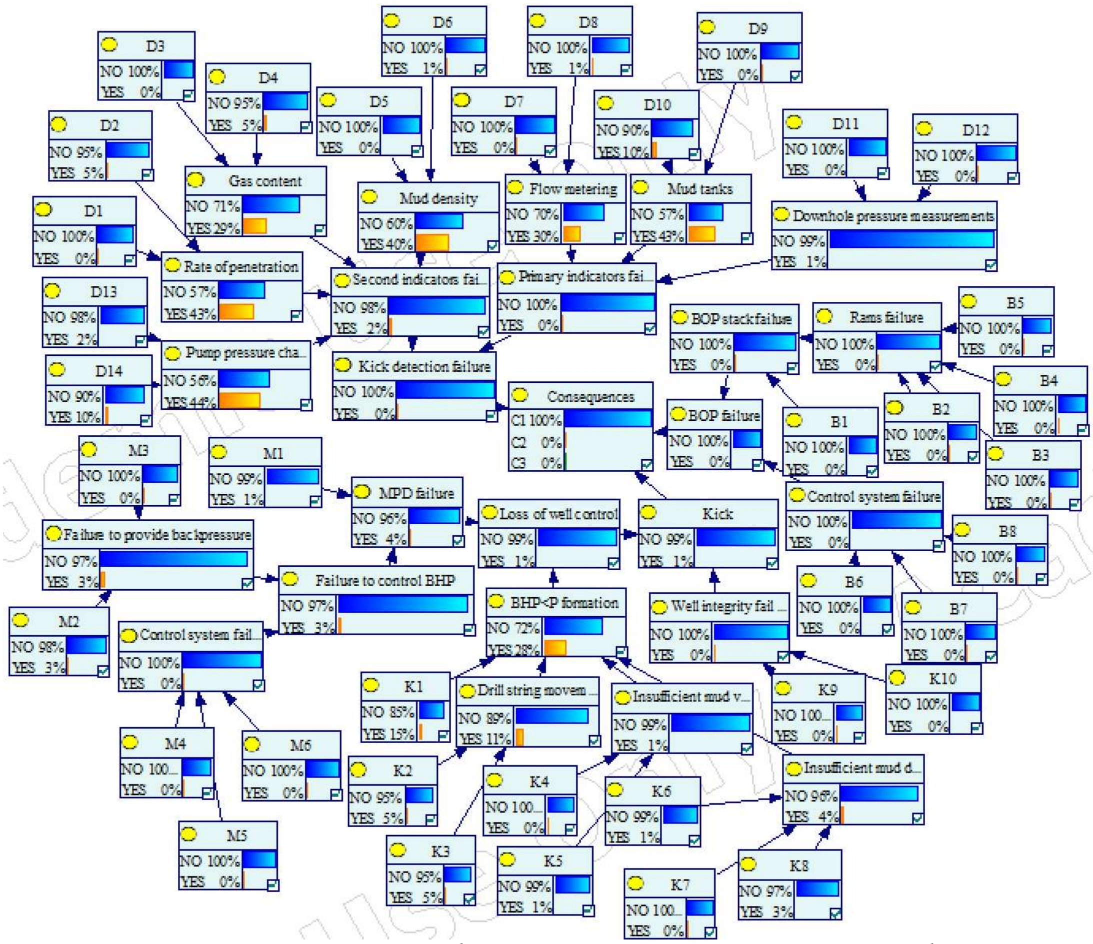

Figure 40 - Bayesian network for 3rd scenario (the difference with 1st and 2nd scenarios explained in fault tree construction chapters)

To compare all scenarios, the probabilities of a kick and the resulting consequences C2 and C3, which summarize the blowout event, were taken into consideration. Based on this data, conclusions were drawn regarding the application reasonability of the technologies.

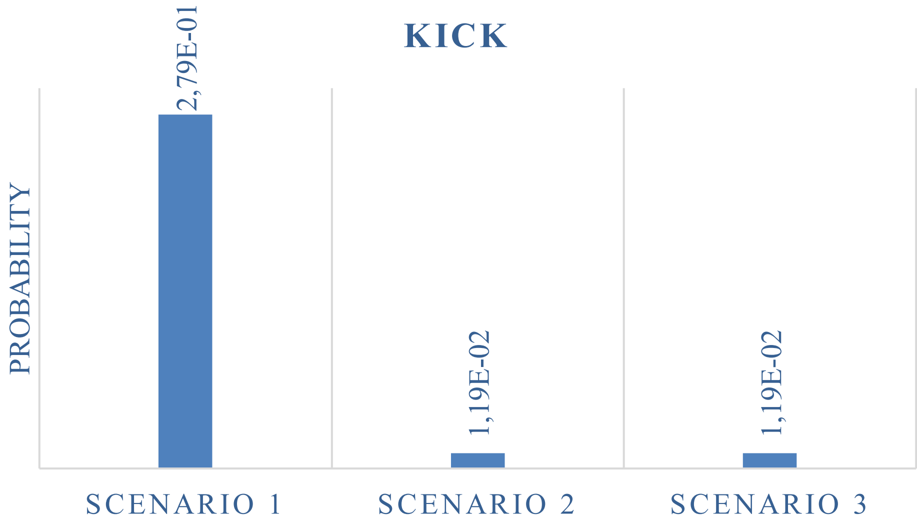

Figure 41 - Probabilities of kick for all scenarios

From the figure 40, it's evident that MPD technology used in 2nd and 3rd scenarios dramatically decreased the risk associated with kick incident. The probability of having a kick is 23 times less than for the conventional drilling without advanced pressure control application.

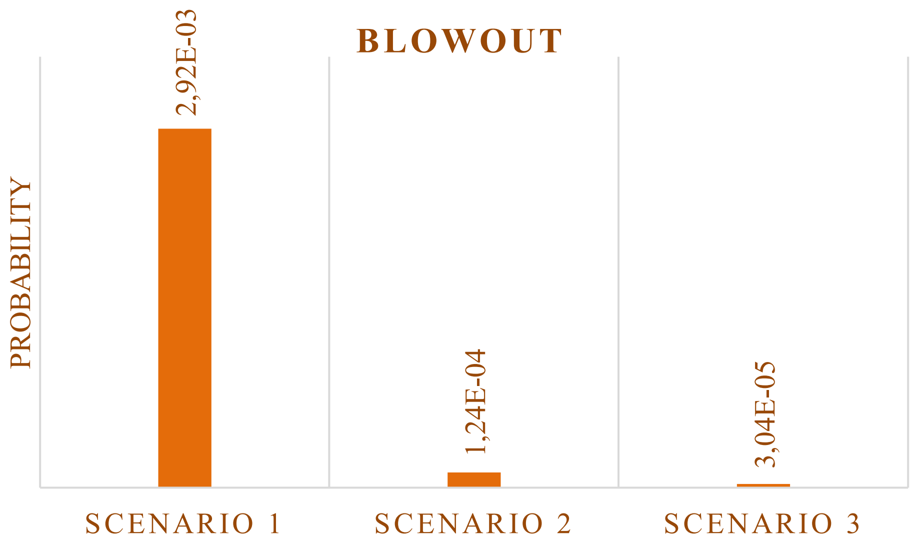

Figure 42 - Probabilities of blowout for all scenarios

The probability of a blowout differs between the 2nd to 3rd scenarios due to real-time downhole pressure measurements and instantaneous kick detection capabilities, decreasing by 4 times. Scenario 3 can significantly improve the safety of the drilling process due to handing hazardous consequence like blowout in a real-time manner. Overall, the blowout probability with combined MPD and advanced WDP utilization is reduced by 97 times in comparison with conventional drilling process.

7.1.3 Basic elements estimation

After developing the models and finding the probability of top event, the significance of basic events can be evaluated. This provides an understanding of which basic events have the most crucial impact on the top event. The kick fault tree was estimated for 2nd and 3rd scenario.

The basic events that lead to the kick were analyzed by Risk Reduction Worth technique. This technique gives the ratio of top event (TEi) probability to the probability of top event given that the basic event (BEi) is optimized, so the probability of this event is assumed to be zero.

$$RRW = \frac{P(TE)}{P(TE|P(BEi) = 0)} \quad (8)$$

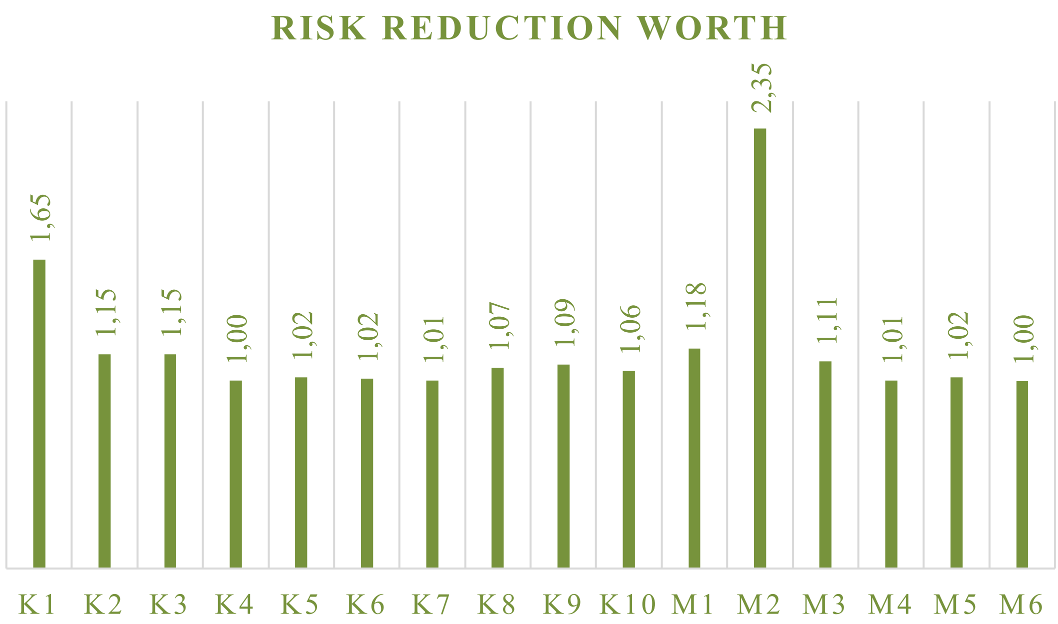

Figure 43 - Risk reduction worth of basic events leading to kick

Concerning the risk reduction worth analysis several conclusions can be drawn about the kick causes and the basic within the MPD system leading to kick incidents:

- The optimization of basic event K1 (abnormal pressure zone) can significantly reduce the kick probability. It should be noted that advanced WDP preventive possibilities were not considered in the models, but there is a huge potential to optimize such parameter by real-time downhole measurements. Especially the prevention of abnormal pressure zones can be achieved with Automated MPD systems. The experience of joint application of PWD and automated MPD system approved this state.
- The most impactful basic event leading to MPD system failure is M2 (adjustable MPD choke). The optimization of this element in system can provide reduction of kick probability by 2,35 times.

- Properly managing the drill string speed during movements that could cause swab or surge events can also noticeably reduce the risks associated with kick incidents. Overall optimization of these parameters together can decrease the kick probability by 30%.

7.2 Discussions and limitations

It should be emphasized that this study considered only MPD preventive and advanced WDP mitigating possibilities for handling kick incidents. Moreover, the advanced WDP was estimated solely in terms of real-time Pressure While Drilling measurements, but the overall benefits of this system are much broader. As the result, the probabilities of kick and blowout incidents are likely even lower than presented. For instance, as it was shown in Risk Reduction Worth analysis the most crucial parameter influencing on kick initiation is encountering abnormal pressure zone. High quality real-time MWD/LWD/PWD measurements provided by advanced WDP can significantly optimize this event. The mitigating capabilities of MPD are also not included in the study due to the exclusion of circulation operations in calculations, but advantages of MPD system related to safe kick response and circulation can also reduce operational risks and non-productive time essentially.

Overall, the achieved results don’t capture whole system advantages and can’t be used as accurate probabilities values for kick and blowout incidents due to certain simplifications in the models. However, the implemented Probabilistic Risk Assessment provides general trends that support the initial expectations about the efficiency of mutual MPD and advanced WDP application, giving additional and quantitative argument about safe and reliable system obtained by technologies combination.

Chapter 8

Conclusion

8.1 Summary

The individual application of Managed Pressure Drilling technique has essential preventive and mitigating tools related to the kick and blowout incidents. The utilization of automated MPD, which includes advanced hydraulic models and predictive control systems for early kick detection and kick circulation provides a powerful tool for identification and management the kick as soon as possible. However, the utilization solely surface measurements may not give complete confidence in the accuracy of the results. Surface measurements, such as those obtained from flow meters or pressure sensors on surface cannot capture the entirely of the complexities and dynamics of downhole conditions. Especially, these limitations expressed in delay between events initiating and the reception of readings change at the surface, which could significantly increase risks, particularly in cases of encountering high kick intensity situations.

Downhole measurements greatly reduce the risks related to any drilling problems and the kick and blowout results particularly. Nevertheless, it is important to consider current capabilities and limitations of telemetry transmission channels. The MPT has limitations in transmitting downhole data at adequate rates and providing real-time data quality. It can only transmit data during fluid flow, leaving the downhole environment unknown during pump shutdowns, reduced flow rates, or severe lost circulation events. Furthermore, MPT can only provide data from near the bit. The implementation of WDP has superior advantages in comparison with conventional telemetry channels. From the perspective of early kick detection, WDP technologies offer significant potential by providing real-time borehole data. These data can contribute to the advancement of Managed Pressure Drilling automation, including the calibration of hydraulic models and estimators used in control systems.

The joint application of MPD and WDP has been observed in only four instances globally. These instances were associated with a limitation on drilling margin, averaging around 50 psi, due to challenging geological conditions that posed high risks of kicks. The combination of MPD and WDP demonstrated excellent results by maintaining the planned bottom hole pressure (BHP) during drilling and connection procedures. The transmission of signals from downhole tools to the surface took less than 2-4 seconds.

The most advanced WDP technology has list of benefits which can enhance the combination of MPD and Wired Drill Pipe telemetry system to new level of mutual MPD and WDP utilization, providing reliable power supply for downhole measurement equipment and huge signal transmission rate.

The obtained probabilities of the kick and blowout incidents can be considered as very promising potential providing much lower risks and justified additional expenditures for technologies combination. In comparison with conventional drilling, 23 times decreased the kick probability and 97 times decreased the blowout probability with application of MPD and advanced WDP provide safe drilling process practically eliminated from probable undesirable causes for health, safety and environment issues. The comparison of 2nd and 3rd scenarios has essential presentation of the cumulative synergetic effect of technologies application decreasing the probability of blowout incident by 4 times with adding advanced WDP to Managed Pressure Drilling technique. Moreover, the non-productive time (NPT) which can exist without such technologies can be also essentially decreased.

Considering the trends in the modern drilling industry towards increasingly complex conditions, whether involving ultranarrow operational drilling windows or ultra-depleted reservoirs, the combined utilization of Managed Pressure Drilling and advanced Wired Drill Pipe (WDP) technology has the potential to become a fundamental approach for addressing such challenges, providing by synergetic effect not only great safety preventive and mitigating barriers against kick and blowout incidents, but the new safety and efficiency reference of the drilling process.

8.2 Future Work

Probabilistic Risk Assessment has been implemented in this work with certain assumptions made to simplify the evaluation process. The primary focus of further research should be directed towards capturing the entire combination of elements, rather than considering only selective safety measures that can be achieved.

Another area for research could involve a more detailed examination of NPT and economic aspects, which can be significantly optimized through mutual utilization. Offshore drilling is quite illustrative instance in this case. Only at the cost of renting a semi-submersible drilling platform of $500,000 per day, it is obvious that even one day of non-productive time can significantly increase the rationality of investments in these technologies. The real field cases can be used for this estimation.

The others drilling problems and incidents should be considered for creating overall demonstration of MPD and advanced WDP capabilities. Kick and blowout accidents are fundamental drilling issues that reflect the overall safety of the drilling process. At the same, other drilling problem risks, which can also be significantly reduced, can provide a more complex evaluation of technology implementation.

Finally, the work should be shift from static to dynamic risk assessment. The time parameter estimated by experts alone can't provide the proper understanding of interactions between such parameters as kick intensity, kick detection volume and kick response time. Further Quantitative Risk Assessment should combine the modeling of kick into the wellbore and simultaneous risk estimation.

As it was already mentioned, the benefits offered by these technologies can give absolutely new level of drilling safety and efficiency. The theoretical overview and Probabilistic risk assessment presented in this work are only first steps related to examination this broad and interesting topic.

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Abbreviations

MPD	Managed Pressure Drilling
WDP	Wired Drill Pipe
EKD	Early Kick Detection
BHA	Bottom Hole Assembly
ASM	Along-string measurement
APWD	Annular While Drilling Measurements
PRA	Probabilistic Risk Assessment
MAASP	Maximum Allowable Annulus Surface Pressure
KPI	Key Performance Indicator
IADC	International Association of Drilling Contractors
MW	Mud Weight
ECD	Equivalent Circulating Density
CBHP	Constant Bottom-Hole Pressure
PMCD	Pressurized Mud-Cap Drilling
LAM	Light Annular Mud
SAC	Sacrificial fluid
DGD	Dual Gradient Drilling
RFC	Returns Flow Control
HSE	Health, Safety & Environment
RCD	Rotating Control Device
BPP	Backpressure Pump
NMPC	Nonlinear Model-Predictive Control
PID	Proportional-Integral-Derivative
BHP	Bottom Hole Pressure
PWD	Pressure While Drilling
MWD	Measurements While Drilling

LWD	Logging While Drilling
APWD	Annular Pressure While Drilling
MPT	Mud Pulse Telemetry
FPTWD	Formation Pressure Testing While Drilling
UBO	Underbalance Operations
DAPC	Dynamic Annular Pressure Control
RSS	Rotary Steerable Systems
BT	Bow-Tie diagram
BN	Bayesian Network
FT	Fault Tree
ET	Event Tree
TE	Top Event
BE	Basic Event
SAM	Similarity Aggregation Method
CDR	Compensated Dual Resistivity
KF	Kalman Filter
UKF	Unscented Kalman Filter
DFT	Drilling Formation Tester
CPT	Conditional Probability Table
RPM	Revolutions per minute
TOB	Torque on Bit
WOB	Weight on Bit
TD	Total Depth
MD	Measured Depth