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Assessing the Feasibility and Effectiveness of Reverse Circulation in Drilling Operation

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AFFIDAVIT

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Assessing the Feasibility and Effectiveness of Reverse Circulation in Drilling Operation

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Chair of Drilling Engineering

To my family Silvija, Zoran, Elena Una and Irena,
to my Ana
and my friends from Croatia and Leoben.

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I am happy to have my friends and especially Ana around me.

Thanks to my family for always believing in me.

Abstract

Hole cleaning and cement quality improvement are considered some of the challenges facing energy extraction companies, especially for horizontal wells. One of the solutions proposed a decade ago to overcome these issues was Reverse Circulation (RC). Reverse Circulation has been implemented in many industries, and it has been proven to be a promising method with the potential to significantly increase drilling efficiency while reducing total drilling costs. In Reverse Circulation, drilling fluid is pumped from the surface into the annulus, where it then flows to the base of the wellbore. Cuttings from the formation are then transported back to the surface through the inside of the drill string. Despite numerous successful studies published on the utilization of RC for various purposes, there remains a common deficiency in the majority of these works. The limitations of applying this method and the necessary requirements are often inadequately explained. Therefore, the ultimate goal of this thesis is to look into the many uses of RC, including drilling, cementing, and hole-cleaning processes. In addition, it will highlight the unique challenges of RC drilling and point out the significance of comparing this technology against conventional approaches.

The primary focus of this thesis is to explore the benefits and drawbacks of RC drilling, particularly in the context of fluid mechanics, limitations, applicable scenarios, and economic implications. Additionally, the thesis undertakes a comparative analysis of hole cleaning efficiency between Reverse Circulation and conventional circulation by constructing scenario cases using the eDrilling simulator. To conduct a fair comparison between the two methods, two Key Performance Indicators (KPIs) were employed: cuttings profile and cuttings transport rate. The performed case studies revealed that under lower or equivalent pressures, conventional circulation outperformed Reverse Circulation in terms of cuttings transport efficiency. However, with appropriate input adjustments, the best-case scenario for Reverse Circulation matched or even exceeded the performance of conventional circulation, demonstrating that the Reverse Circulation process can be optimized for more effective cuttings removal and wellbore stability.

Zusammenfassung

Die Reinigung von Bohrlöchern und die Verbesserung der Zementqualität gehören zu den Herausforderungen, denen sich Energie unternehmen stellen müssen, insbesondere bei horizontalen Bohrungen. Eine der vor einem Jahrzehnt vorgeschlagenen Lösungen zur Überwindung dieser Probleme war die Reverse Circulation. Reverse Circulation wurde in vielen Branchen eingesetzt und hat sich als vielversprechende Methode erwiesen, die das Potenzial hat, die Bohreffizienz erheblich zu steigern und gleichzeitig die Gesamtbohrkosten zu senken. Bei der Reverse Circulation wird die Bohrspülung von der Oberfläche in den Ringraum gepumpt, von wo aus sie zur Bohrlochsohle fließt. Das Bohrklein aus der Formation wird dann durch das Innere des Bohrgestänges zurück an die Oberfläche transportiert. Trotz zahlreicher erfolgreicher Studien, die über den Einsatz von RC für verschiedene Zwecke veröffentlicht wurden, gibt es in den meisten dieser Arbeiten einen gemeinsamen Mangel. Die Grenzen der Anwendung dieser Methode und die notwendigen Voraussetzungen werden oft nur unzureichend erläutert. Ziel dieser Arbeit ist es daher, die vielfältigen Einsatzmöglichkeiten von RC zu untersuchen, einschließlich der Bohr-, Zementier- und Bohrlochreinigungsverfahren. Darüber hinaus werden die besonderen Herausforderungen des RC-Bohrens hervorgehoben und die Bedeutung des Vergleichs dieser Technologie mit konventionellen Verfahren aufgezeigt.

Das Hauptaugenmerk dieser Arbeit liegt auf der Untersuchung der Vor- und Nachteile des RC-Bohrens, insbesondere im Zusammenhang mit der Strömungsmechanik, den Einschränkungen, den Anwendungsszenarien und den wirtschaftlichen Auswirkungen. Darüber hinaus wird in dieser Arbeit eine vergleichende Analyse der Effizienz der Bohrlochreinigung zwischen Reverse Circulation und konventioneller Zirkulation durchgeführt, indem Szenarien mit dem eDrilling-Simulator erstellt werden. Um einen fairen Vergleich zwischen den beiden Methoden durchzuführen, wurden zwei Key Performance Indicators (KPIs) verwendet: Bohrkleinprofil und Bohrkleintransportrate. Die durchgeführten Fallstudien ergaben, dass die konventionelle Zirkulation bei niedrigeren oder gleichwertigen Drücken hinsichtlich der Effizienz des Bohrkleintransports besser abschneidet als die Reverse Circulation. Mit entsprechenden Anpassungen der Eingaben erreichte oder übertraf die Umkehrzirkulation im besten Fall die Leistung der konventionellen Zirkulation, was zeigt, dass der Umkehrzirkulationsprozess für eine effektivere Bohrkleinentfernung und Bohrlochstabilität optimiert werden kann.

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Chapter 1

1 Introduction

1.1 Overview

The drilling industry can overcome future challenges and sustainably deliver essential natural resources for economic growth and development by utilizing advanced drilling technologies and methods. One recent innovation is Reverse Circulation (RC), which has been extensively researched in recent years and has the potential to significantly enhance drilling innovation and efficiency, resulting in potential overall cost reductions.

RC in context of drilling operation can be defined as a process in which drilling fluid is pumped from the surface into the annulus and then flows downwards to the bottom of the wellbore. Then it returns upwards, carrying cuttings from the formation through the inner part of the drill string up to the surface. RC can increase the efficiency and safety of drilling operations by minimizing borehole erosion and pressure drops across the flow path, particularly in complex operations such as those found in deep-water and deep geothermal drilling [1]. Additional, RC has been implemented in geothermal wells to overcome lost circulation events, which mainly occur during casing cementing. In this case, the cement is pumped directly down the annulus.

Figure 1.1 provides a straightforward visual comparison in terms of flow direction between conventional circulation and Reverse Circulation when used in the process of pumping cement. The direction of the black arrows shows the flow path of the Reverse Circulation when applied to the casing cementing process compared to normal circulation.

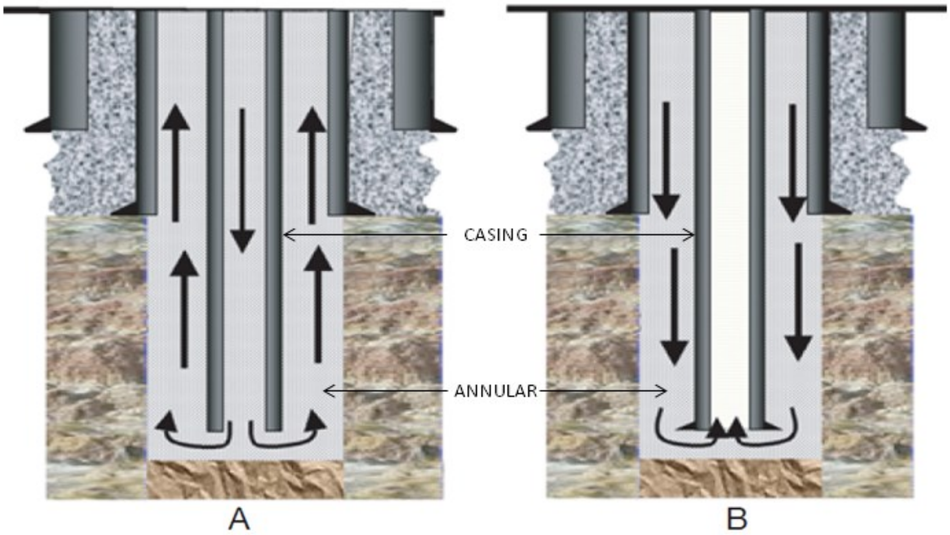


Figure 1. 1 - Flow path of fluids during conventional placement (A) and Reverse Circulation (B) (Adapted from Kuru, Seatter, 2005)

In industry, Reverse Circulation has several applications [2]. Its many uses include drilling, cementing, and hole-cleaning procedures. Drilling using Reverse Circulation is admired for its effectiveness and speed in penetrating diverse geological formations. It is also very effective in mineral exploration and geotechnical drilling. Furthermore, Reverse Circulation technology improves cementing operations by guaranteeing that the cement slurry is accurately put in the wellbore, improving well integrity and long-term production potential. Hole cleaning cannot be forgotten; it effectively eliminates cuttings and debris, eliminates obstructions, minimizes downtime, and encourages cleaner, more ecologically responsible drilling methods. The broad use of Reverse Circulation technology in drilling, cementing, and hole-cleaning procedures highlights its significance in improving safer, more efficient, and environmentally responsible methods in the energy and mining industries.

1.2 Motivation

Reverse Circulation in softer and unconsolidated geological formations provide specific problems in the drilling industry that demand attention and commitment for effective and safe operations. These challenges mostly revolve around borehole instability and potential collapse, which endangers the drilling crew and nature. When pressurized drilling mud is used in RC drilling, there is a greater chance that fluid may leak out via the formation's weak spots, which raises the likelihood of kicks and blowouts [2]. Additionally, when drilling deeper into the earth's crust, the weight of the drilling mud may put undue strain on the drill bit, which might cause irritating delays or, in extreme situations, cause efforts to come to a complete halt [3].

Another factor that must be taken into consideration when employing RC is the associated cost, since it requires specialized equipment that at first glance could seem to be an expensive investment. However, it must be taken into account potential efficiency advantages, such as shorter drilling times, improve cement quality and reduce the likelihood of undesired events, and accept that these increases might result in large cost savings that eventually offset the initial expenditure. Given the significant challenges posed by RC, it is essential that this process to conventional drilling techniques is first understood and compared before tackling the aforementioned problems. Because it paves the way for a thorough analysis of the advantages, drawbacks, and potential solutions related to RC over a wide variety of geological formations and operating scenarios, this endeavor is particularly significant in the field of industrial research. Through exhaustive study and testing, the industry may obtain important insights that will provide the foundation for the development of best practices, cutting-edge machinery, and operational standards aimed at maximizing the potential of RC. These concerted efforts will not only encourage the responsible use of natural resources but will also show unwavering commitment to environmental protection and worker safety [4].

Establishing the course for the future of drilling technology by facing the issues of RC head-on and doing substantial research is important. This can bring safer, more efficient, and ecologically responsible methods.

1.3 Objectives

The main objective of this thesis is to conduct a comprehensive examination, assessment, and analysis of potential areas for advancements and improvements in the Reverse Circulation, with a particular focus on fluid mechanics, limitations, applicable cases, and economic implications. The thesis aims to identify the strengths and weaknesses of the current approach and explore potential avenues for enhancement in order to improve the effectiveness and efficiency of Reverse Circulation. In order to achieve the proposed objective, this thesis focuses on the stepped objectives. These specific objectives are listed below and systematically shown in Figure 1.2.

- Conduct a comprehensive literature review and analysis to develop a baseline understanding of the Reverse Circulation approach and its existing applications, including the advantages and limitations of this drilling method.

- Conduct research on the specific drill-bit materials and technologies used in Reverse Circulation, including their properties, design, and performance.

- Understand the differences in fluid dynamics and removal of cuttings between Reverse Circulation drilling and conventional circulation drilling and cementing.

- Investigate the limitations of Reverse Circulation in different operations, such as cementing, drilling, hole cleaning, etc., and identify potential areas for advancements and improvements through the use of eDrilling software.

- Develop several business cases using eDrilling software to compare the outcome of Reverse Circulation with normal circulation in terms of hole cleaning efficiency, and downhole problem avoidance.

- Investigate the economic effectiveness of Reverse Circulation as a method.

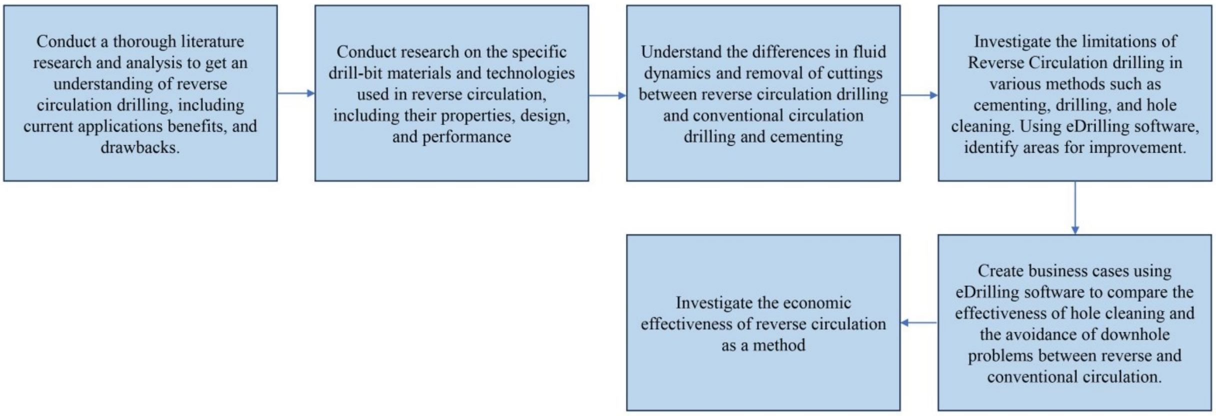


Figure 1. 2 - Stepped objectives of the thesis

1.4 Thesis Structure

The thesis begins with Reverse Circulation methods overview, a full description of the Reverse Circulation strategy, which is backed by a thorough literature review. This first section establishes a good foundation for our investigation. The thesis then compares Reverse Circulation with regular drilling techniques, taking drilling techniques and cementing processes into consideration. The argument also addresses the complexities of hole-cleaning technologies as well as the numerous drill bit varieties utilized in Reverse Circulation drilling.

Following this comparison, the thesis investigates the advantages, limitations, and possible risks of the Reverse Circulation approach. It explains the benefits of this method, such as improved cuttings conveyance, reduced formation damage, positive environmental consequences, and economic considerations. Furthermore, it assesses the obstacles encountered by Reverse Circulation drilling, including technical and practical challenges, formation compatibility issues, fluid management challenges, and safety considerations.

The next section, Introduction to eDrilling simulator describes the simulator, and its critical role in thesis' research approach. It summarizes the program's characteristics and their relevance to our investigation. The thesis also includes a detailed explanation of the setup and settings for the eDrilling, as well as methodology overview and illustrative cases that were utilized to evaluate the efficacy of Reverse Circulation drilling and hole cleaning to conventional circulation. These examples are an important part of our research.

The thesis concludes with an assessment of the economic efficacy of the Reverse Circulation. It makes recommendations for improving the operation of the eDrilling program and maximizing the application of Reverse Circulation in real-world scenarios. It outlines the key findings and contributions of the research.

Chapter 2

2 Reverse Circulation Methods Application Overview

2.1 Chapter Background

This chapter is divided into three main parts. It will begin with a brief overview of Reverse Circulation. Following that, a comprehensive literature review of various applications of RC in drilling will be conducted, with a specific focus on its role in improving the well cementing process, enhancing hole cleaning procedures, and optimizing drilling operations. A significant portion of this chapter is dedicated to a thorough comparison of Reverse Circulation and conventional circulation in drilling. Their performance and efficiency will be carefully examined in critical areas, including cementing, hole cleaning, and the impact on drill bits. The chapter concludes by presenting the advantages and limitations of Reverse Circulation, based on the topics discussed.

2.2 Reverse Circulation Overview

The Reverse Circulation drilling method was first used in Australia in the mid-1970s for the purpose of mining drilling [5]. Reverse Circulation drilling in simple form can be defined as a drilling technique that entails the circulation of clean drilling fluid down the annulus to the bottom of the borehole and subsequently returning the cuttings to the surface via the drill pipe. A schematic representation of Reverse Circulation drilling is shown in Figure 2.1.

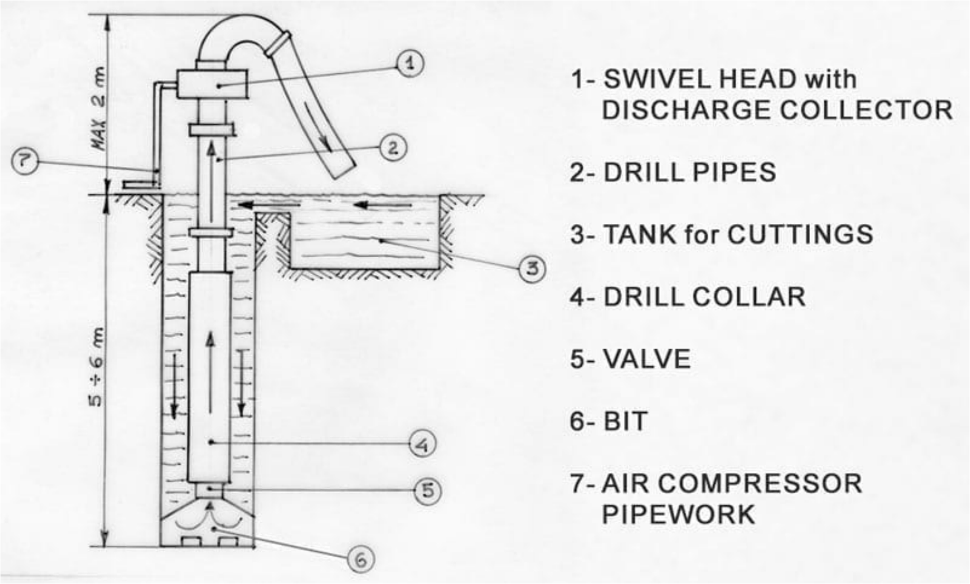


Figure 2. 1 - Reverse Circulation drilling schematic (Taken from: https://www.massenzarigs.com/reverse-circulation-drilling/)

Although the method was initially introduced for mining, over the decades, it has expanded to cover a variety of industries and serve different purposes [7], as follows:

- Reverse Circulation drilling is commonly employed in mineral exploration projects such as gold, copper, and diamond exploration. It is a popular choice in this industry due to its capacity to give efficient geology samples, reduce drilling fluid losses, and increase drilling productivity. According to the Society for Mining, Metallurgy, and Exploration, Reverse Circulation drilling is well suited to large-diameter mineral deposit drilling.

- Reverse Circulation drilling techniques are used in oil and gas drilling operations, particularly in difficult formations. It provides benefits such as enhanced well control, lower drilling fluid losses, and longer equipment lifespan. The International Association of Drilling Contractors recognizes Reverse Circulation drilling's advantages in oil and gas exploration, particularly in high-pressure and high-temperature conditions.

- Geotechnical studies, including soil sampling, groundwater monitoring well installations, and geotechnical testing, rely heavily on Reverse Circulation drilling. It is a valuable tool in geotechnical engineering projects because of its capacity to capture high-quality samples, reduce drilling fluid pollution, and improve drilling efficiency.

2.3 Literature Review on Reverse Circulation Applications in Drilling

2.3.1 RC Application on Drilling Efficiency Improvement

Li Lichang et al. highlighted the significance of choosing between conventional drilling (direct circulation drilling) and Reverse Circulation drilling for successful outcomes. Conventional drilling, as Li Lichang et al. underlined, entails drilling mud down the drill string and returning it to the surface. This technology excels in removing drill cuttings from boreholes effectively, allowing for proper disposal and geological study. Furthermore, it relies on wellbore pressure management to reduce the danger of problems and wellbore collapse during drilling. Furthermore, they illustrate the benefits of Reverse Circulation drilling in dealing with complicated formations. One of its primary advantages is that it reduces formation damage. Drilling fluid is transferred from the annulus to the drill string by reversing the flow direction, considerably minimizing contact with the formation. The preservation of formation integrity makes study and analysis easier [7].

In the context of drilling operations, Zhang et al. said that the choice of drill bits can have a considerable influence on efficiency, costs, and performance [8].

According to Cao et al., typical drill bits include cone-shaped blades composed of hardened steel or tungsten carbide that are ideal for a variety of rock forms. RC drill bits, on the other hand, have a dual-wall construction consisting of an inner tube and an outer casing with strategically positioned perforations for effective cuttings and drilling fluid management. RC drill bits perform well in softer to medium-hard rocks, resulting in higher drilling efficiency and sample recovery rates [9].

Yong et al. also talk about the advantages of implementing a secondary injector device [10], while Cui et al. describe retractable drill bit used in casing while drilling with Reverse Circulation [11].

Unfortunately, as Zhang et al. point out, RC drill bits are more expensive due to their specialized design, which can be justified by aspects such as higher sample recovery, shorter drilling durations, and the ability to collect critical geological data during exploration [8].

2.3.2 RC application on Well Cementing

Conventional cementing procedures, despite their extensive history, have significant limits. Historically, achieving a full and homogenous cement column behind casing threads has proven difficult, frequently resulting in lost circulation during cementing operations. Over time, this inadequate cementation might cause well integrity difficulties. This loss of cement into the formation results in a lower-than-designed top of cement, incomplete cement coverage, poor zonal isolation, and the potential need for costly remediation [12].

In contrast, Hernández et al. recommend Reverse Circulation Cementing (RCC) as a viable approach, particularly in difficult geothermal situations. RCC streamlines the procedure by injecting cement into the annulus between the casing and the wellbore. This eliminates the need for high pressures to increase the cement slurry, resolving concerns about time consumption, cement waste, costly additives, and temperature-related issues associated with traditional cementing [2]. As Hernández et al., Wreden et al. also present a range of similar advantages and considerations of RC in cementing operations [3].

In their study, Kuru and Seatter compared the Reverse Circulation placement approach to the conventional placement technique to see how they affected Equivalent Circulating Density (ECD) during cementing operations. The Reverse Circulation approach includes pumping cement in the opposite direction of the drilling fluid flow, whereas the traditional technique uses the regular circulation pattern. The study aimed to see if Reverse Circulation resulted in reduced ECD values during cementing when compared to the standard approach. The placement was done using radioactive tracers, and fluid markers [13].

Bour, Hodson-Clarke, and Russell described a revolutionary use of the Reverse Circulation Cementing technology in high-pressure, high-temperature (HP-HT) geothermal wells in Australia's Cooper Basin region in their study. The primary goal of this study was to evaluate the efficiency of RCC in such difficult geothermal settings and to compare its performance to standard cementing techniques. The study discovered that using RCC in HP-HT geothermal wells provided numerous significant benefits. It considerably enhanced cement application and bonding, resulting in more stable and dependable zonal isolation. Furthermore, it successfully addressed lost circulation difficulties by guaranteeing a continuous cement column below casing threads. These results were critical for preserving well integrity and avoiding potential environmental and operational issues in geothermal well applications [14].

2.3.3 RC Application on Hole Cleaning Improvement

Kumar et al. offer an unusual approach to cleaning out horizontal wells [15]. The report demonstrates how the buildup of acid-insoluble debris, particularly scale, in injectors and producers reduced well production, necessitating a more effective cleaning process. Kumar et al. overcome this difficulty largely through the installation of the coiled tubing Reverse Circulation technique. A venturi junk basket is used in combination with Reverse Circulation in this procedure. The venturi run detects and removes bigger fill particles from the wellbore, followed by Reverse Circulation to remove smaller particles. The goals include determining the efficiency of Reverse Circulation in cleaning horizontal wells and developing a technique for its use. Kumar et al. give three case studies that demonstrate the results of coiled tubing Reverse Circulation. The key findings and conclusions from these case studies include improved injectivity, effective scale, and particle removal, and the process's applicability to horizontal wells, where circulation was previously difficult due to well losses or low reservoir pressure. Kumar et al. emphasize the coiled tubing Reverse Circulation process's potential future uses in horizontal producers, highlighting its ability to sustain and improve oil output [15].

Mahmoud et al. also describe hole cleaning and drilling fluid sweeps in horizontal wells, with implications in deviated wells as well that provide high drainage areas within the reservoirs [16].

Crabtree, Li, and Luft introduce a new technique to wellbore cleanup employing Reverse Circulation with coiled tubing (CT), ushering in an industry paradigm change. With a focus on hydraulics design, this detailed comparison assesses the merits and limitations of the Reverse Circulation Cement Placement Technique (RCCPT) vs the Conventional Cement Circulation Placement Technique (CCCPT). This study uncovers numerous benefits associated with RCCPT – reduced Equivalent Circulating Densities (ECDs), decreased excess cement usage, and improved safety and environmental management. They uncover it by using a meticulous methodology that analyzes critical hydraulic design considerations and calculates the Equivalent Circulating Pressure (ECP). However, it is important to highlight that using RCCPT necessitates more equipment and a greater grasp of drilling fluid properties. This study acts as a lighthouse for practitioners, underlining the necessity of making a well-tailored decision between RCCPT and CCCPT while taking into account unique wellbore conditions and needs, guaranteeing optimal performance while maintaining safety and environmental integrity [17].

Annular fracturing is gaining popularity, particularly in horizontal wellbores employing CT. Sand jet perforation, well-cleaning, fracturing, and isolation are all part of the operations. The problem comes from proppant buildup as a result of horizontal placement, which has an influence on operating efficiency. To improve well cleaning in horizontal wells, Li et al. proposed a new approach including ideal CT pull-out speed, fluid flow rate, and beginning solids bed height [18]. There are two basic fluid circulation modes – normal and Reverse Circulation. Normal cleaning procedures have limitations, motivating the search for more effective cleaning solutions. The study takes a unique method of well cleaning in horizontal wells, combining Reverse Circulation with CT pull-out. This solution removes the requirement for a wiper trip, resulting in increased efficiency. The hole cleaning procedure was tested using a full-scale flow loop, which revealed the effects of critical factors such as flow rate, beginning solids bed height, and CT eccentricity. Empirical correlations were created to predict appropriate CT pull-out speed, assisting field engineers in the design of well-cleaning procedures. Field examples show how the technology may be used to remove particles from abrasive perforation procedures and proppants following fracture [18].

2.4 A Multifaced Comparison between Reverse Circulation and Conventional Circulation in Drilling Operation

This section will compare the methods of Reverse Circulation (RC) and conventional circulation (CC) in drilling operations. The primary focus will be on four critical aspects – cementing, hole cleaning, drilling efficiency, and drilling bit performance.

2.4.1 Circulation while Drilling

The drilling process depends on the circulation of drilling fluid for a number of important reasons. The effectiveness of normal circulation drilling in eliminating drill cuttings from the borehole is one of its main advantages. The drilling cuttings are transported by the drilling fluid as it moves down the drill string and returns to the surface. This permits their correct disposal or analysis, which is necessary for comprehending the geological formations being drilled and maintaining the borehole clear. Furthermore, sustaining pressure inside the wellbore depends heavily on the flow of drilling fluid. In order to prevent wellbore collapse and regulate the flow of formation fluids, pressure management is essential. It reduces the possibility of unforeseen problems by ensuring the stability of the wellbore during drilling. Reverse Circulation drilling's capacity to adapt to complex formations that can present problems for conventional circulation is one of its most notable benefits. When the flow direction is reversed, the drilling fluid flows from the annulus into the drill string as opposed to directly into the formation. That is shown in as shown in Figure 2.2. With that, the wellbore instability can be reduced since the clean fluid is pumped downwards through the annulus, which facilitates research and analysis [7].

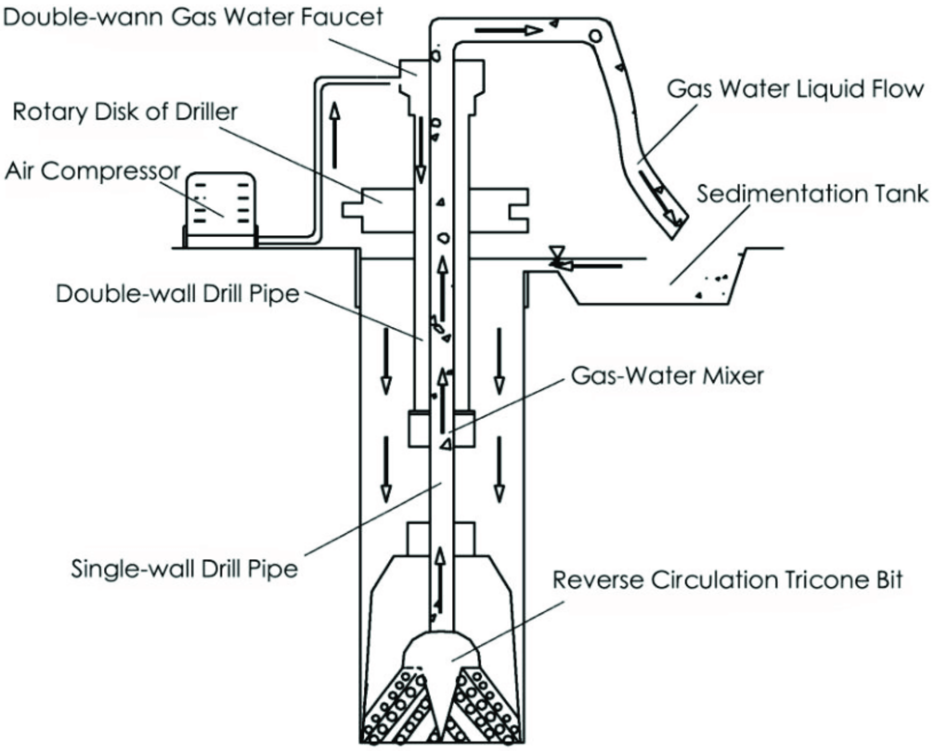


Figure 2. 2 - Reverse Circulation drilling flow (Taken from: Xiumin et al., 2014)

The following is a broad explanation of how the values of the dependent variables may change in each circulation method as explained by Zhu, L.H et al. [20].

1. Rate of Penetration (ROP)

In conventional drilling, increasing the weight-on-bit, rotary speed, or bit type usually results in a higher ROP. These variables have a direct impact on cutting transport efficiency and the bit's ability to penetrate the formation. In conventional drilling weight-on-bit and the rotational speed change the ROP. Increasing the weight-on-bit (WOB) improves drilling efficiency, which has a direct impact on the ROP. The increased force applied to the drill bit, enables more effective cutting and removal resulting in higher ROP, and also makes drilling operations more efficient. Similarly, by increasing the rotational speed of the drill bit, the ROP increases. The additional energy helps the bit to cut through rock formations more quickly, causing for the increase in ROP. [21].

In the case of Reverse Circulation drilling, changes in flow rate have a considerable impact on ROP. If the flow rate is increased, the ROP may increase. This enhancement is the result of improved cuttings conveyance and higher flushing velocity, both of which contribute to faster drilling progress.

2. Drilling Fluid Properties

Changing the drilling fluid's properties, such as density, viscosity, or rheology, can have an effect on the drilling process. Higher-density fluids can aid in wellbore stability and inflow prevention, while certain rheological qualities can improve cuttings transport and hole cleaning [18].

3. Bit Wear and Damage

Changing drilling parameters such as weight-on-bit and rotary speed can affect drill bit wear and damage. Higher weight-on-bit and high rotational rates can hasten bit wear, resulting in shorter bit life and possibly impacting drilling performance.

When the weight applied to the drill bit is increased, the bit erodes faster. This event has the potential to reduce the bit's operating lifespan. The increased WOB places the bit under increased stress and contact forces, resulting in faster wear and a shorter lifetime [22].

4. Sample Recovery

Variables such as flow rate, drilling fluid characteristics, and bit design can all have an impact on sample recovery in Reverse Circulation drilling. Higher flow rates and proper bit designs can improve cutting collection and recovery, resulting in more accurate geological data. When the flow rate is increased, sample recovery improves noticeably. In particular, the recovery rate may increase up to 10% [20]. This improvement is due to the improved capabilities of cuttings collection and flushing efficiency at the increased flow rate. The increased flow rate allows more efficient transport and collection of drill bit rock cuttings, ensuring that a more significant proportion of the underground material reaches the surface. Furthermore, better flushing efficiency minimizes congestion and obstructions, resulting in an overall increase in sample recovery. By leveraging the benefits of increased flow rates, Reverse Circulation drilling operations may significantly improve sample collection accuracy and dependability, enhancing the quality of geological insights generated from these recovered materials [20].

5. Hydraulic Efficiency

Changing the flow rate, nozzle size, or drilling fluid qualities can all have an effect on Reverse Circulation drilling's hydraulic efficiency. These factors can be optimized to increase hole cleaning, reduce fluid losses, and improve overall drilling performance [20].

6. Pressure Drop

The term pressure drop in drilling occurs as drilling mud or fluid passes through the wellbore. In normal circulation drilling, pressure drop occurs as drilling fluid is pumped down the drill string and up through the annulus. Factors like drill string length, flow rate, fluid viscosity, and density influence the pressure drop. Drilling fluids with higher viscosity will create higher pressure drops because of the frictional ressistance. Furthermore, the increase in flow rate increases the fluid velocity which can result in a larger pressure drop. With denser fluids, there is higher weights that also contribute to higher pressure drops. Lastly, the size and length of the drill string affect pressure drop as the longer and narrower drill strings tend to lead to higher pressure drops due to increased friction along their length [12].

Because the flow direction is reversed in Reverse Circulation drilling, the dynamics of pressure drop is different. Transport efficiency of cuttings is a critical component in pressure drop in Reverse Circulation. Cuttings that build up or get stuck in the annulus may cause more resistance and barriers, which could result in a greater pressure drop. Also, higher velocities lead to a larger pressure drop because of increased friction, therefore flow velocity is important [7].

Another parameters which can influence on pressure drop, are the regimes of flow. The two regimes are laminar and turbulent. Laminar Flow is usually found in the annulus during drilling operations. This type of flow is generally desired in the annulus since it does not lead to hole erosion and does not produce excessive pressure drops. This type of flow can be represented by Hagen–Poiseuille Equation:

$$\Delta P = \frac{(128 \cdot \mu \cdot L \cdot Q)}{\pi \cdot r^4} \tag{2.1}$$

where ΔP = Pressure drop, μ = Fluid viscosity, L = Length of the wellbore, Q = Flow rate and r = Radius of the wellbore.

Turbulent Flow is the type of flow regime found inside the drill string during drilling operations. Since high mud velocities are required to achieve turbulent flow, this results in high pressure drops. This type of flow is generally not desired in the annulus due to its tendency to cause excessive hole erosion and high equivalent circulating densities. It can be represented by Darcy-Weisbach Equation:

$$\Delta P = \frac{f \cdot \frac{L}{D} \cdot \rho \cdot V^2}{2} \tag{2.2}$$

where ΔP = Pressure drop, f = Darcy friction factor, L = Length of the wellbore, D = Diameter of the wellbore, ρ = Fluid density and V = Flow velocity.

Estimating pressure drop in Reverse Circulation drilling can be more complex due to the reversed flow direction. One commonly used equation for estimating the pressure drop in Reverse Circulation is:

$$\Delta P = \frac{4 \cdot f \cdot L \cdot \rho \cdot V^2}{d \cdot Re} \tag{2.3}$$

where ΔP = Pressure drop, f = Darcy friction factor, L = Length of the drill string, ρ = Fluid density, V = Flow velocity inside the drill string, d = Inside diameter of the drill string and Re = Reynolds number for flow inside the drill string [23].

7. Bit Performance

Drilling parameters such as bit design, bit type, and flow rate can all have an impact on bit performance in Reverse Circulation drilling. Cutting efficiency and the capacity to handle diverse formation circumstances can be improved with proper bit selection and design [8].

2.4.2 Drill bit Design

The rolling cone-shaped cutters shown in Figure 2.3 used with conventional circulation are typically constructed of hardened steel or tungsten carbide. For effective cutting through varied rock formations, the cutters are set up in a variety of configurations, such as milled teeth or tungsten carbide inserts (TCI).

A drill bit for Reverse Circulation drilling shown in Figure 2.4 is made specifically for this method of drilling. They typically have an inner tube and an outer casing with a dual-wall design. The bit has strategically placed apertures or nozzles that allow drilling fluid and cuttings to move up through the inner tube while guarding against wear on the outer casing [8].

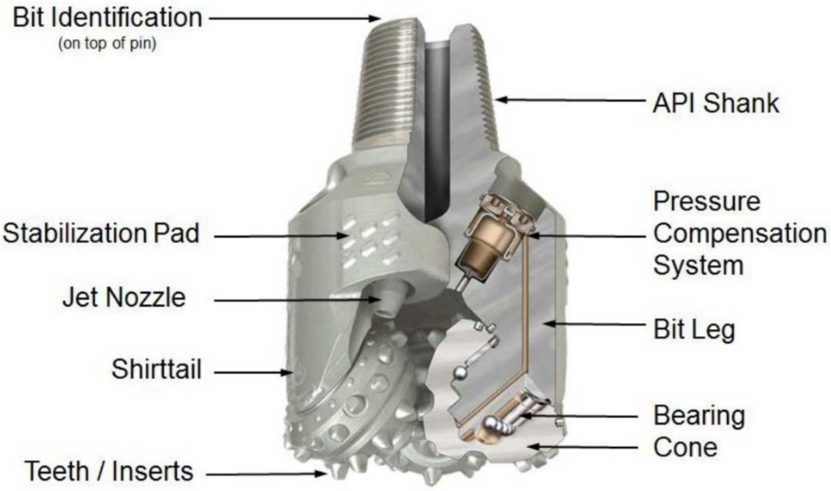


Figure 2. 3 - Tricone bit assembly (Taken from : https://firmtechco.com/pdc-vs-tricone/)

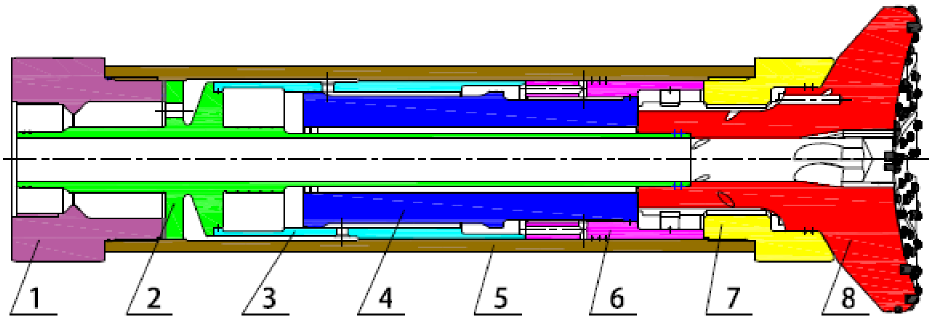


Figure 2. 4 - RC drill bit assembly; 1: upper connection; 2: center tube; 3:inner casing; 4: piston; 5: outer tube; 6: spacer bush; 7: splined hub; and 8: drill bit (Adapted by Zhang et al., 2019)

Conventional circulation drilling bits have the purpose of allowing the downward flow of drilling fluid and the removal of cuttings up the annulus. Nozzles and channels are frequently used on these bits to assist in guiding the mud flow across the cutting surface and clean the cuttings away from the bit teeth. Reverse Circulation bits are designed to conduct drilling fluid down the annulus while preventing cuttings from entering the drill pipe. These bits have specific features such as bypass channels to allow fluid to flow down and keep cuttings from being sucked into the drill pipe [9].

One of the most important drilling bits used in the Reverse Circulation method is a revolutionary percussion drilling tool powered by air – the Reverse Circulation down-the-hole (RC-DTH) air hammer. Schematic of the RC-DTH air hammer drilling system is shown in the Figure 2.5.

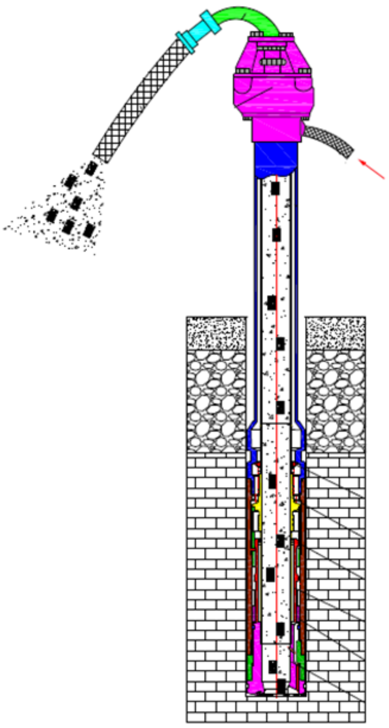


Figure 2. 5 - Schematic of RC-DTH hammer drilling system (Adapted by Zhang et al., 2019)

Due to its benefits over conventional rotary drilling, percussion drilling is a recommended technique for drilling hard rock. It increases penetration rates and cuts down on wasted time brought on by problems like clogged pipes and high bit consumption. Additionally, because the drill bit is in contact with the rock for a shorter period of time, there is a higher immediate weight-on-bit. Straighter holes and cheaper prices per meter are the results of percussion drilling. Due to the frequency of hard rock formations, it is extensively utilized in mining and has expanded to oil and gas drilling [9].

The Reverse Circulation drill bit is an advanced assembly that optimizes sample retrieval efficiency during exploration and hydrocarbon drilling. The drill bit body provides the basic structure. Its design is critical to the overall system's effectiveness.

Flushing nozzles strategically positioned discharge high-speed air streams, pushing cuttings toward the center tube. This not only helps with cooling but also with cuttings removal. Suction nozzles intercept the center passage in addition to the flushing nozzles. They create a low-pressure zone by generating high-speed air streams, allowing for the continual drawing of air and cuttings into the center route. The drill bit, like the cleaning nozzles, has pressure-restoring grooves that regulate the flow of air and cuttings within the drill bit, ensuring effective circulation. The drill bit's working face has strategically positioned tungsten carbide inserts that offer resistance to wear, assuring the drill bit's durability. The central passage, a hollow canal that runs through the core of the drill bit, acts as a path for the upward movement of air and cuttings. Another critical component is the splined sleeve, which adds the structural integrity of the drill bit. The drill bit is attached to the DTH hammer's housing. This casing covers not only the DTH hammer but also the drill bit during the drilling operation, assuring their safety and efficiency. Spacers, semicircle clips, and bushings are utilized to ensure exact spacing and alignment between different sections of the drill bit assembly. The piston is also an important component that transmits impact energy to the drill bit. This energy is critical for the efficient progression of the drilling operation. Lastly, the core tube is an essential component for sample analysis and geological evaluation because it collects core samples or cuttings when they are retrieved throughout the drilling process [9].

When drilling, pressurized air is pumped into the annulus of the dual-wall pipes, causing the RC-DTH hammer to strike the drill bit with high-frequency blows, resulting in Reverse Circulation. A notable feature of this type of drilling is the utilization of both Reverse Circulation drilling and percussion drilling. According to Figure 2.5, compressed air transports drill cuttings in Reverse Circulation, which means that cuttings travel directly from the bottom of the borehole to the surface along the center channel of the drill pipes [8].

Reverse Circulation can eliminate many of the disadvantages of traditional air drilling. A crucial distinction is the ability to drill in broken or shattered strata. With implementing a secondary injector device, a gas injector designed with the gas injecting principle, to the central hole of the Reverse Circulation Bit, RC can be used in broken formation or under leakage formation conditions, caused by injected gas [10].

Another advantage is the minimal air consumption, which allows for large-diameter hole drilling. The continuous return of formation cores to the surface without the need to pause drilling results in higher core recovery rates. The operational environment has been enhanced, and the atmosphere is oil-free, protecting drill personnel and equipment from the dangers of drilling dust. This is due to the fact that the air and rock cuttings discharged from the flexible discharging hose can be directed straight into the cuttings and dust collector unit, which is located far away from the drill site [8].

Casing while Drilling (CwD) is also an advantage that allows the simultaneous installation of casing or pipe while drilling a borehole. The drill bit used in CwD with Reverse Circulation is specially designed to accommodate the casing installation process. It is a retractable drill bit. This drill bit can be expanded or contracted to allow the casing to be installed through it. When the casing is not in use, the drill bit is expanded for drilling operations. When the casing needs to be installed, the drill bit is retracted to a smaller diameter to allow the casing to pass through [11].

Cost factors are also important to consider. Due to their specific design and fabrication, RC drill bits are typically regarded as more expensive than conventional drill bits. However, considerations like better sample recovery rates, shorter drilling times, and the capacity to obtain important geological data during the exploration can justify their cost-effectiveness.

2.4.3 Well Cementing

Conventional cementing methods have been used in the business for a long time, but they are not without limitations and obstacles. The achievement of a complete and homogeneous column of cement behind casing threads has been a substantial challenge. Historically, lost circulation during drilling and cementing operations has caused difficulties, resulting in inadequate cement placement. Because cyclic temperature loading on the well casing throughout its lifetime can generate integrity difficulties, incomplete cementation can lead to well failure. Furthermore, because cement systems are often denser than mud systems, operators have had difficulty successfully cycling cement from the bottom to the top of the well [12].

The weight of the cement, in comparison to drilling mud, is one of the key disadvantages of conventional cementing. The cement imposes a tremendous weight on the casing string as it runs down the casing. Due to the resistance of flow and the pressure difference between the fluids inside the casing and the cement slurry outside, pumping cement up through the annulus from the bottom of the casing can be difficult. These high pressures may cause the cement to be lost into the formation, resulting in an insufficient circular cement column [12].

Reverse Circulation Cementing has evolved as an effective technique in recent years, particularly in difficult geothermal locations. Conventional cementing methods frequently entail pumping cement to the annulus's bottom and then circulating it back up the casing. This method, however, can be time-consuming, resulting in increased cement waste and higher costs due to increased cement usage. Furthermore, pricey additives may be necessary to postpone cement setting. High borehole temperatures and water loss to the formation can also have an impact on traditional cementing, resulting in problems such as early or delayed cement setting, which raises overall well completion costs [3].

Unlike conventional circulation cementing, RCC entails pumping cement downward into the annulus between the casing and the wellbore rather than into the bore of the casing. High pressures are not required to raise the cement slurry up the annulus in RCC. Instead, fluids are pumped into the annular space of the wellbore and returns are obtained from the interior of the cementing casing [12].

This method addresses the difficulties associated with traditional cementing, making RCC a viable choice in some situations (Figure 2.6).

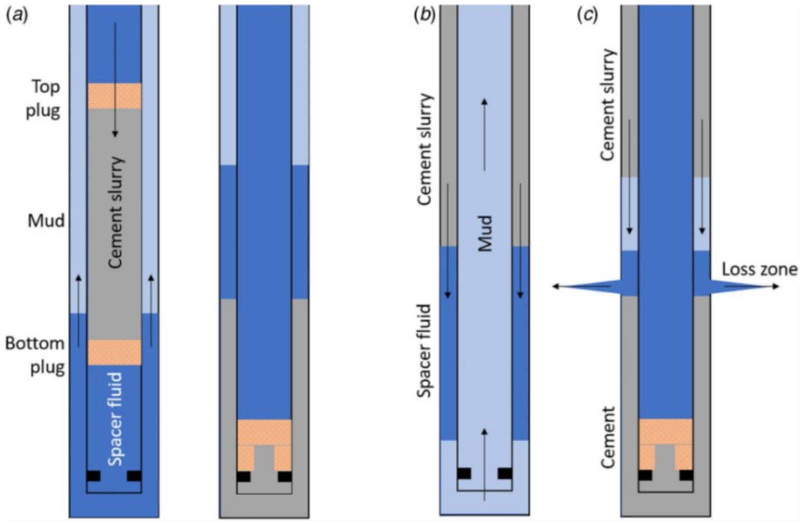


Figure 2. 6 - Conventional a) and Reverse cementing b) (Adapted by Wreden et al., 2014)

This is established by using special equipment. For RCC projects, conventional float equipment is inadequate [2]. RCC-capable flotation equipment must be utilized and is typically ordered specifically. The three most popular forms of RCC float equipment are shown in Figure 2.7. The ability to do a task in a manner like inner-string cementing is provided by

(a) a float and stinger assembly

(b) the pump outvalve assembly can be engaged by landing a ball on the valve and ripping the valve from the float collar to enable Reverse Circulation

(c) a guide shoe can also be employed in specific situations

With (b) and (c), however, surface pressure must be maintained on the casing for the duration of the cement's setting time [2].

Figure 2. 7 - Float equipment in RCC (Adapted by Hernández et al., 2010)

Another important aspect is the two methods for identifying the location of the top of the cement slurry. These methods are radioactive tracers with recording device, and fluid markers. Fluid markers have been preferred since they are less costly and pose no environmental dangers. Logging devices and radioactive tracers are preferred when the top of the cement must be precisely identified [12].

One of the benefits of RCC is that it requires less hydraulic horsepower. Gravity promotes slurry flow in RCC, greatly reducing the hydraulic horsepower required for cement application. The equivalent circulation density of RCC is lower when compared to traditional cementing. RCC can significantly reduce ECDs by not circulating the thicker and more viscous cement slurry back to the surface through the casing [3]. This reduction in ECDs can improve the well's integrity and lessen the danger of complications like lost circulation. That is shown in Figure 2.8.

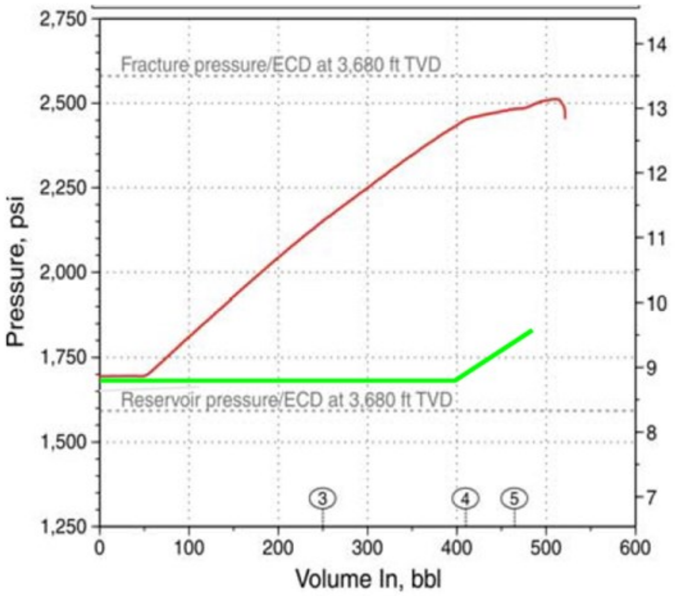


Figure 2. 8 - Fracture pressure (Adapted by Wreden et al., 2014)

RCC provides various benefits in addition to the ones stated. RCC allows for faster slurry thickening and stronger compressive strength development, increasing the overall efficiency of cementing operations. Furthermore, by reducing the volume of cement waste and eliminating the usage of costly additives, RCC can contribute to improved safety and environmental management [3].

While RCC has advantages, it also has drawbacks that must be addressed. These include correct cement placement identification, proper rigging of the essential equipment, rigorous project design, perfect execution of the cementing operation, and the selection of appropriate float equipment. These aspects must be carefully considered to ensure the successful deployment of Reverse Circulation technology in cementing operations [12].

The Reverse Circulation method was also used in geothermal wells in the Cooper Basin Region of Australia where it has also shown numerous advantages over standard cementing methods. Lower circulation pressures, faster compressive strength development, the use of higher-density cement, reduced hydraulic horsepower requirements, enhanced environmental management, shorter thickening time, and total cost reductions are among the advantages. By integrating RCC, operators may greatly improve the efficiency, integrity, and sustainability of cementing operations in geothermal well projects, laying the groundwork for the industry's future growth [14].

2.4.4 Hole Cleaning Efficiency Improvement

Various wellbore cleanout technologies have evolved throughout the years in the oil and gas sector. Among these, the use of coiled tubing for solids removal has become commonplace. However, as the industry wrestled with more complicated wellbore geometries and horizontal wells, problems arose. Notably, solids, such as scales, corrosion products, and other solid particles, tend to settle at the bottom or low side of the wellbore in severely deviated or horizontal wells using the conventional circulation method. Because of this settling, the cleanout procedure may be ineffective in getting the sediments to the top. The Reverse Circulation approach, on the other hand, reverses the flow pattern and increases velocity inside the CT, allowing the fluid to bring particles back to the surface, including those that have accumulated at the bottom of the well [18].

With normal circulation, the approach needs pumping cleanout fluid via the small diameter coiled tubing, and the returns travel through the bigger annulus between the coil and the open hole. This strategy may not be useful in dealing with ECD concerns connected with horizontal wells, especially if the well's pressure is significantly lower than hydrostatic and no returns to the surface are recorded. In the Reverse Circulation process, higher velocity and reduced pressure difference within the coiled tubing allow the fluid to efficiently go back to the surface, together with the solids. This strategy can aid in the management of ECD and is especially effective when there is a possibility of short-circuiting neighboring producers [16].

In Reverse Circulation (see Figure 2.9), clean fluid is pushed down through the annular flow channel outside the CT, returning to the surface via the CT's internal flow channel. This approach has found uses in cementing, drilling, and fill cleaning. Reverse Circulation, like forward circulation, has significant problems, and careful well selection is essential. Notably, the lack of a check valve at the end of the CT complicates well control. A thorough grasp of wellbore hydraulics is required not only for properly removing debris from the wellbore but also to prevent CT collapse. Balancing the necessity for appropriate annulus injection pressure at the surface to maintain circulation, while guaranteeing the structural integrity of the CT, is a major operating problem. Continuous monitoring of injection and return flow rates, as well as annulus injection pressures and the use of pressure relief valves becomes required for CT Reverse Circulation operations. Furthermore, the prospective use of a partly concentric coiled tubing string shows promise for improving CT's collapse resistance, further broadening the bounds of this unique approach [17].

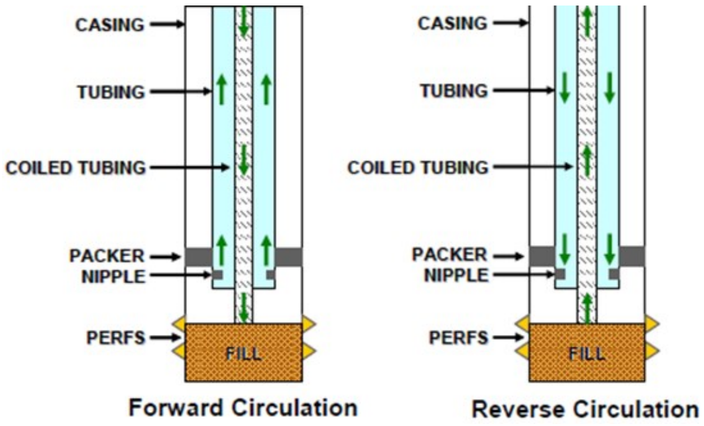


Figure 2. 9 - Normal and Reverse Circulation cleaning with using coiled tubing (Adapted by Crabtree et al., 2007)

As with the losses during well operations, normal circulation through the small diameter coiled tubing and the larger annulus might result in the loss of kill or completion fluid into the formation. This loss might make preserving well integrity difficult. The Reverse Circulation technique efficiently mitigates fluid loss difficulties because it assures that the fluid, together with the solid debris, goes back to the surface, even in fractured reservoir conditions. This reduces the possibility of fluid leakage into the formation [15].

The use of Reverse Circulation for wellbore cleaning can be an important aspect in the industry. It handles difficult cleaning circumstances, especially in horizontal and deviated wells. The key advantages are improved control of ECD and reduced fluid losses, setting it apart from normal circulation.

2.5 Advantages and Limitations of Reverse Circulation

The information acquired from the previously discussed references is used to determine the advantages and limitations of Reverse Circulation based on the author's opinion.

2.5.1 Advantages

- **Effective Geology Sampling**

One of the key advantages of Reverse Circulation drilling is its ability to sample geology accurately. The drilling fluid returns directly to the surface from the drill tool's inner hole, enhancing cuttings carrying capacity and ensuring cleaner, more representative samples. This feature is particularly beneficial when dealing with leaky strata, as it allows for successful geology sampling even in challenging conditions.

- **Enhanced Drilling Efficiency**

Reverse Circulation drilling significantly boosts drilling efficiency, especially in difficult, leaky strata. The suction force created by the drilling fluid around the bit efficiently carries cuttings to the hole's bottom, reducing fragmentation and compaction. This results in higher penetration rates and improved drilling effectiveness. Research published in the Journal of Petroleum Science and Engineering has demonstrated that Reverse Circulation drilling achieves higher drilling rates and lower drilling fluid losses in leaky formations compared to conventional drilling [2].

- **Reduced Drilling Fluid Leaks**

Reverse Circulation drilling minimizes or eliminates drilling fluid leaks, contributing to the preservation of the production zone. It achieves this by reducing annulus pressure loss, thereby protecting the integrity of the production zone and saving a significant amount of drilling fluid material. This reduction in drilling fluid leaks not only offers cost savings but also has environmental benefits [2].

- **Extended Mud Pump Lifespan**

Reverse Circulation drilling extends the lifespan of mud pumps. With its straightforward process of dumping mud into the annulus or using a charge pump, it decreases wear and tear on mud pump equipment. This results in cost savings and greater operational efficiency.

- **Enhanced Well Control Flexibility**

Reverse Circulation drilling provides added flexibility during well control processes by supporting both normal and Reverse Circulation. This flexibility is particularly useful in well control, where it allows for the direct delivery of heavy mud to the well's bottom for well killing. This eliminates the need for subsection circulation and shortens the time required for mud handling. The ability to adapt efficiently to changing well control approaches enhances operational efficiency and overall drilling performance.

2.5.2 Limitations

- **Comprehensive Economic Analysis and Risk Assessment**

Prior to commencing Reverse Circulation drilling operations, meticulous economic analysis and risk assessment are imperative. This involves in-depth financial planning, a thorough evaluation of potential risks, and the implementation of appropriate risk-mitigation strategies. Stringent risk assessments, in compliance with industry standards and safety regulations, using best practices, are essential. By effectively managing these risks, project stakeholders can secure the economic feasibility and success of the drilling project while mitigating potential downsides.

- **Borehole Instability**

Reverse Circulation drilling utilizes compressed air injection into the borehole, creating a high-pressure environment. In certain geological formations, this increased pressure can lead to borehole collapse or deviation. To mitigate this risk and ensure borehole stability, it is crucial to conduct proper geological assessments and possess the necessary technical knowledge [3].

- **Equipment Constraints**

Another limitation is related to equipment. Reverse Circulation drilling requires specialized equipment designed to address the unique challenges of the method. Utilizing drill bits, hammers, and tools specifically tailored for Reverse Circulation activities is essential. Insufficient or defective equipment can lead to operational issues, reduced productivity, and significant downtime.

- **Environmental Impact**

Reverse Circulation drilling, like any drilling method, presents potential environmental risks. These risks encompass factors such as the discharge of compressed air, noise pollution, and the release of drill cuttings. Implementing mitigation measures, including proper waste management, noise reduction strategies, and adherence to environmental regulations, is crucial to minimize the environmental impact associated with Reverse Circulation drilling.

Chapter 3

3 Introduction to eDrilling Simulator

3.1 Chapter Background

This chapter will focus on providing high-level details of one drilling simulator, namely eDrilling. This simulator will be used later for conducting case studies aimed at understanding the advantages and disadvantages of Reverse Circulation when it is implemented in different drilling processes. The chapter begins with a review of drilling simulators, covering their basic features, functions, historical context, and general information. Next, various features and practical applications of the eDrilling simulator will be discussed. Following that, the workflow of a case implementation will be explained, showing the sequential processes involved in its functioning.

3.2 Drilling Simulator Overview

Although "drilling simulators" may appear to be a relatively recent topic, they are not. Early in the 1980s, individuals from the petroleum sector created computer-controlled drilling simulators. A drill string simulator was created and put into use to help drilling engineers during the planning, drilling, and analyzing phases. The "Pascal" is a written simulator that was able to foresee the loads and strains that drill strings and casing strings would experience across the majority of typical drilling operations. Additionally, it was able to display data streams graphically, and the models' accuracy was high enough to be relied upon for actual drilling operations. Computers have proven to be expensive and of limited capability throughout that time. Most hurdles were on the electrical and mechanical side of the whole system. The software and hardware capabilities were limited as well [25].

Endeavor Drilling Simulator is an additional one. It is a cutting-edge simulator that generates realistic drilling scenarios in a virtual setting. Users control a simulated rig, which enables them to improve their drilling techniques. Risk mitigation, cost-effective training, and performance assessment are some effects. It encourages cost-effectiveness, skill development, and safety in the drilling sector [26].

ESIMTech's Drilling and Well Control Simulators, another important drilling simulator operates by creating a virtual drilling environment. It's all about safety, where the user can practice drilling and well control without any real-world risks. This ensures a safer working environment and minimizes accidents. These simulators are like personal trainers, ensuring that the user is fully prepared for the toughest challenges in the drilling industry, from pressure changes to equipment malfunctions [27].

The world's number one Simulator Technology Provider, 3t develop and manufacture with over 1500 simulator the advanced simulation technology solutions that improve safety and efficiency in the oil and gas industry. 3t's simulators integrate with 3t digital's powerful connected cloud-based software and technology modules to create a tailored solution for any workforce [28].

It is crucial to employ these simulators because today's software and technology are comparatively affordable and cutting-edge. The petroleum sector is rapidly automating and going digital. Intelligent designs and integrated real-time digital technologies are used in next-generation drilling rigs. To maximize the asset value, drilling operations and maintenance are optimized to the fullest extent possible [29].

Besides the primary purpose of drilling simulators, they can offer unforeseen additional value. The list below highlights some of these, according to the author's opinion:

1. Drilling operations training plays a significant role in reducing the severity and frequency of blocked pipe occurrences and other wellbore problems. Consequently, it immediately influences the company's revenue.

2. Makes it feasible to simulate situations that, at a specific time, cannot be experienced on a real drilling rig.

3. Providing instruction in a 1:1 drilling setting, improves the efficiency of the rig staff.

4. Real operational ideas are implemented.

5. Increase staff understanding of well-designed systems.

6. Decrease operational risk by modeling it beforehand.

7. Wells can be drilled more quickly and safely.

8. It is simple to upgrade and incorporate new drilling technologies for the simulator.

9. Prediction of wellbore issues and safety concerns during specific operations, or "look ahead simulations".

10. Evaluate simulation findings against actual parameters to automatically spot variations.

One of the top suppliers of drilling and well performance solutions today is eDrilling AS, a Norwegian firm. They work closely with operators, E&P (exploration and production) firms, and a number of service providers everywhere in the world. The major goal is to use a solution with mathematical models developed, tested, and proven over 20 years to help them reduce costs, increase drilling operations' efficiency, and increase safety. The "Life Cycle Drilling Simulation" idea, which combines intricate dynamic drilling models with analysis and 3D (three-dimensional) visualization technologies, underpins all of their currently offered solutions [30].

The ultimate solution combines a decision-assistance system that enables planning, drilling, analyzing, and training with a transient integrated drilling simulator.

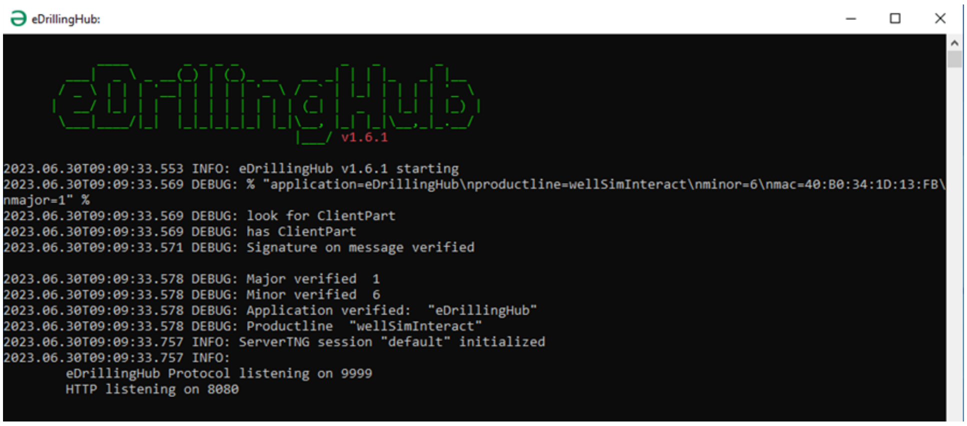
3.3 eDrilling Simulator Capabilities and Applications

The simulator's major goal is to simulate how a well would actually respond to drilling mud, drill string, and drilling rig movements. Additionally, drilling mishaps and wellbore issues such as stuck pipe, leaking BOP, nozzle blockage, losses, etc. need to be presented realistically. The inputs for the simulation will include all necessary variables, such as those impacting the rig, wellbore, drill string, fluids, and geological information. The simulator models, such as the fluid or torque and drag model, are fed by the input. The metrics needed by the driller, such as torque or ROP, are output by these models and are also available in a driller's cabin in real life.

The main uses of the simulator software/products used for this thesis will be to compare the drilling cases using Reverse Circulation and normal circulation. For this eDrillingHub, and OpenView2D are needed. Another „feature“ WellViz3D will also be described.

3.3.1 eDrillingHub

The "eDrillingHub" client must be opened as the initial step in starting the simulator. When opened, it looks as it is shown in Figure 3.1. It serves as the main connection point for all other eDrilling apps, as the word "hub" already denotes. The "Connected" button must always be displayed and in green to indicate that the web interface is successfully connected to the server [30].



```
2023.06.30T09:09:33.553 INFO: eDrillingHub v1.6.1 starting
2023.06.30T09:09:33.569 DEBUG: % "application=eDrillingHub\nproductline=wellSimInteract\nminor=6\nmac=40:B0:34:1D:13:FB\
nmajor=1" %
2023.06.30T09:09:33.569 DEBUG: look for ClientPart
2023.06.30T09:09:33.569 DEBUG: has ClientPart
2023.06.30T09:09:33.571 DEBUG: Signature on message verified

2023.06.30T09:09:33.578 DEBUG: Major verified  1
2023.06.30T09:09:33.578 DEBUG: Minor verified  6
2023.06.30T09:09:33.578 DEBUG: Application verified:  "eDrillingHub"
2023.06.30T09:09:33.578 DEBUG: Productline  "wellSimInteract"
2023.06.30T09:09:33.757 INFO: ServerTNG session "default" initialized
2023.06.30T09:09:33.757 INFO:
        eDrillingHub Protocol listening on 9999
        HTTP listening on 8080
```

Figure 3. 1 - eDrillingHub interface: The central control platform for eDrilling applications, connecting to the online server with system messages displayed in the console window

When a message appears in yellow, the system is alerting the user that a function or variable may not have been provided. Furthermore, the simulation cannot be executed if a critical message in red appears. Additionally, the error type and location are important indicators that are displayed.

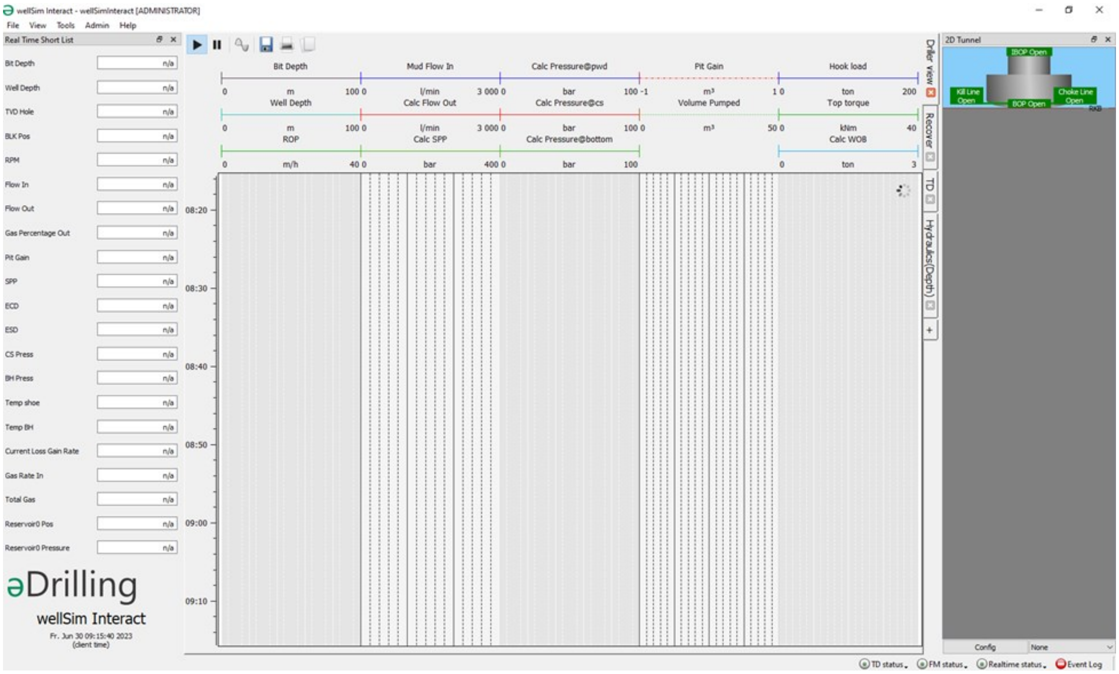
The "eDrillingHub" needs to be restarted every time one of the code files are modified in order to reload the files and check them once again for errors. Any web browser can be used to access the following unified resource locator (URL) after the "eDrillingHub" has been successfully run. The URL is "http://localhost:8080/admin". It will open a window with a web interface listing all of the current "tags" along with their name, type of value,

value, and timestamp. "Calculate.HKITd" is one possible name for such a tag, which in this instance denotes the value of a hook load. Right-clicking on a tag will reveal a menu with additional choices, including the ability to check the tag or enter or define its value. Additionally, this can be carried out while the simulation is running [30].

The system's internal null value is represented by the value "-999.25". It suggests that there isn't any information or value for this parameter, but it doesn't imply that it has a value of 0.

3.3.2 OpenView2D

Next step is to start the "OpenView2D" program after launching the "eDrillingHub" and the webpage. When opened, it looks as shown in Figure 3.2. It serves as a real-time training simulator for a number of effective engineering disciplines [30]. In its most fundamental form, it embodies the ideal engineering solution to deliver trustworthy feedback from the well while responding in real time to dynamic user interaction.



Bit Depth	n/a
Well Depth	n/a
TVD Hole	n/a
BLK Pos	n/a
RPM	n/a
Flow In	n/a
Flow Out	n/a
Gas Percentage Out	n/a
Pit Gain	n/a
SPP	n/a
ECD	n/a
ESD	n/a
CS Press	n/a
BH Press	n/a
Temp shoe	n/a
Temp BH	n/a
Current Loss Gain Rate	n/a
Gas Rate In	n/a
Total Gas	n/a
Reservoir0 Pos	n/a
Reservoir0 Pressure	n/a

Fr. Jun 30 09:15:40 2023
(client time)

Figure 3. 2 - The interface of OpenView2D

Furthermore, there are more advantages of OpenView2D.

1. NPT reduction through better planning and risk management.
2. Simulate actual operational issues to investigate potential solutions.
3. Sharing simulations across several fields and teams is a possibility.
4. Comprehension of appropriate behavior.
5. Downhole improvements offer remedies for drilling-related issues.
6. Interactive user input or control.
7. Possibility of causing problems, kicks, and losses in certain situations.

By selecting "Tag List" within "Admin", all the available tags and their status, as in the web interface, get listed. The four light-emitting diodes (LED) in the bottom right corner are important indicators regarding the status of models, real-time stream, and events [30]. They are listed here:

a) TD (true depth) Status

Turns red if server signals are absent and green if the torque and drag model is running. If the model is taking too long to calculate, a clock is shown. The model can be started, restarted, paused, or stopped simply by clicking on it.

b) Fluid Model

The FM status behaves similarly to the TD status.

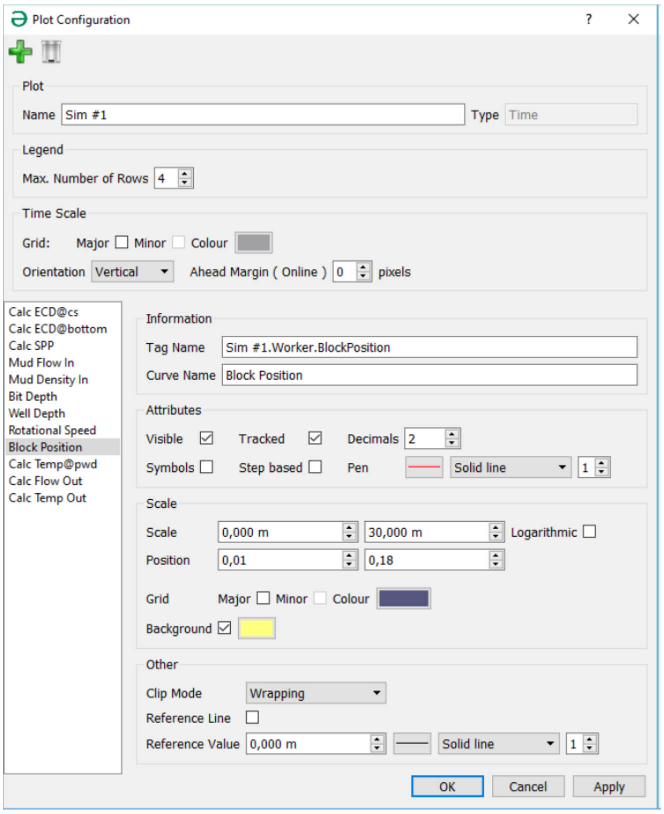
c) Status for Real-time Data

Turns green if it can be received, red otherwise.

d) Event Log

Changes from green to red depending on whether there are any messages in the log or not. Once the icon has been clicked, the messages are listed.

Additionally, a customized layout with depth- or time-based graphs can be shown in the center of the pane, depending on the parameters the driller wants to observe. All plots and the layout can be changed by selecting "Plot Configurator" from the menu. The menu is shown in Figure 3.3. New plots can be added to the layout by selecting the green "plus" icon in the top left corner.



Name: Sim #1 Type: Time
Max. Number of Rows: 4
Grid: Major ☐ Minor ☐ Colour
Orientation: Vertical Ahead Margin (Online) 0 pixels

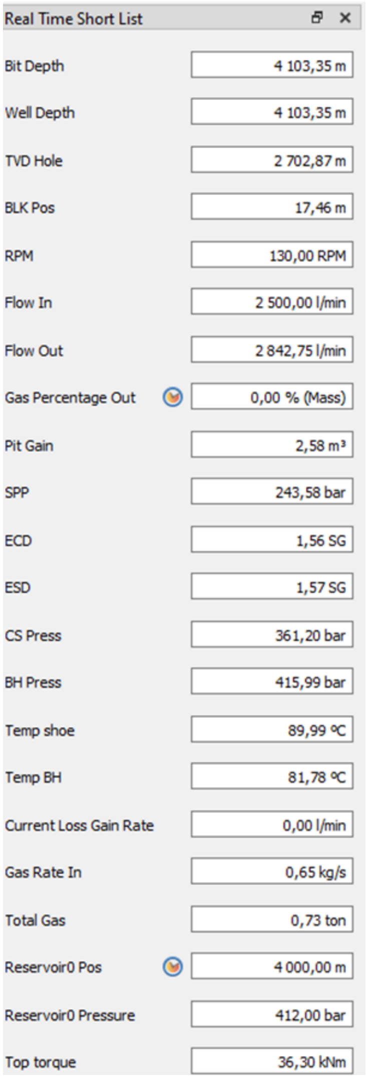
Calc ECD@cs
Calc ECD@bottom
Calc SPP
Mud Flow In
Mud Density In
Bit Depth
Well Depth
Rotational Speed
Block Position
Calc Temp@pwd
Calc Flow Out
Calc Temp Out

Tag Name: Sim #1.Worker.BlockPosition
Curve Name: Block Position
Visible ☑ Tracked ☑ Decimals 2
Symbols ☐ Step based ☐ Pen Solid line 1
Scale: 0,000 m 30,000 m Logarithmic ☐
Position: 0,01 0,18
Grid Major ☐ Minor ☐ Colour
Background ☑
Clip Mode: Wrapping
Reference Line ☐
Reference Value: 0,000 m Solid line 1

Figure 3. 3 - Menu of the plot configuration

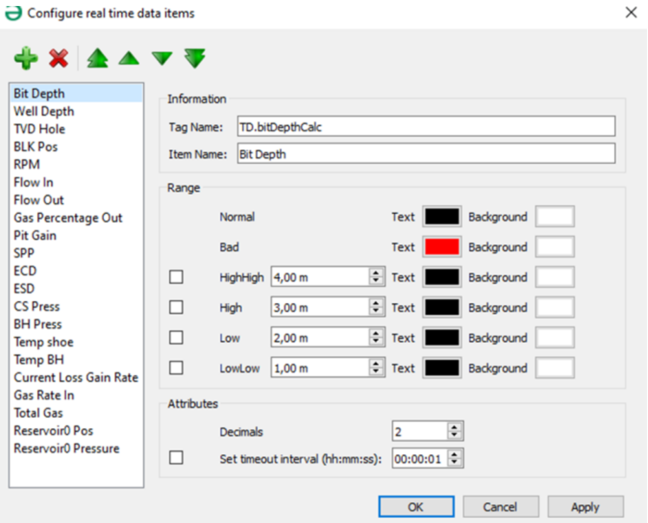
By selecting "Tunnel" under "View" on the "View" menu, a two-dimensional (2D) view of the wellbore configuration will be shown on the right side of the "OpenView2D" window.

"Real Time Short List" can be found under the "Tools" tab. Itis shown in Figure 3.4 and Figure 3.5. You can view and adjust key parameters that you want to keep an eye on during the simulation. You can select boundary values and highlight specific colors, as well. The "taglibrary.xml" and "taglist.xml" files must have the necessary parameters, just like in the "Plot Configurator".


Real Time Short List

Bit Depth	4 103,35 m
Well Depth	4 103,35 m
TVD Hole	2 702,87 m
BLK Pos	17,46 m
RPM	130,00 RPM
Flow In	2 500,00 l/min
Flow Out	2 842,75 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	2,58 m³
SPP	243,58 bar
ECD	1,56 SG
ESD	1,57 SG
CS Press	361,20 bar
BH Press	415,99 bar
Temp shoe	89,99 ºC
Temp BH	81,78 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,65 kg/s
Total Gas	0,73 ton
Reservoir0 Pos	4 000,00 m
Reservoir0 Pressure	412,00 bar
Top torque	36,30 kNm

Figure 3. 4 - Real Time Short List with a list of signals from the well or models


Configure real time data items

Bit Depth
Well Depth
TVD Hole
BLK Pos
RPM
Flow In
Flow Out
Gas Percentage Out
Pit Gain
SPP
ECD
ESD
CS Press
BH Press
Temp shoe
Temp BH
Current Loss Gain Rate
Gas Rate In
Total Gas
Reservoir0 Pos
Reservoir0 Pressure

Information

Tag Name: TD.bitDepthCalc
Item Name: Bit Depth

Range

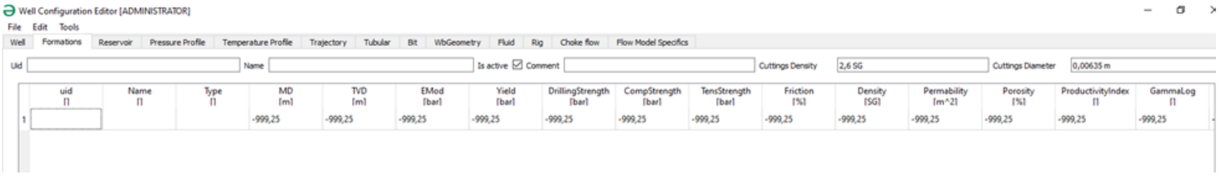
	Normal		Text	■	Background	☐
	Bad		Text	🟥	Background	☐
☐	HighHigh	4,00 m	Text	■	Background	☐
☐	High	3,00 m	Text	■	Background	☐
☐	Low	2,00 m	Text	■	Background	☐
☐	LowLow	1,00 m	Text	■	Background	☐

Attributes

Decimals: 2
☐ Set timeout interval (hh:mm:ss): 00:00:01

Figure 3. 5 - Real Time Short List Configurator

The Well Configuration Editor must be opened after that. It is shown in the Figure 3.6. It is located under the tab Tools. To ensure that the simulation produces its best results, this must be done extremely carefully. The data can be easily copied and pasted from spreadsheet programs. Because setting up a new case to mimic is the most time-consuming and delicate portion of the process, a thorough step-by-step tutorial for each editing step tab is available.



Uid
Name
Is active ☑
Comment
Cuttings Density 2,6 SG
Cuttings Diameter 0,00635 m

	uid []	Name []	Type []	MD [m]	TVD [m]	EMod [bar]	Yield [bar]	DrillingStrength [bar]	CompStrength [bar]	TensStrength [bar]	Friction [%]	Density [SG]	Permability [m^2]	Porosity [%]	ProductivityIndex []	GammaLog []
1				-999,25	-999,25	-999,25	-999,25	-999,25	-999,25	-999,25	-999,25	-999,25	-999,25	-999,25	-999,25	-999,25

Figure 3. 6 - Well Configuration Editor which consists of Well, Formations, Pressure and Temperature Profile, Trajectory, Tubular, Bit, WbGeometry, Fluid, Rig, Choke flow, Flow model Specifications data

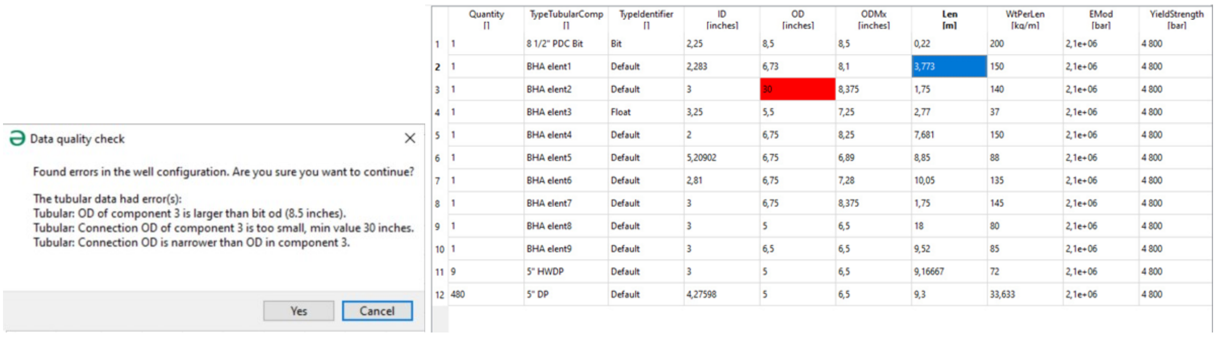
The Tools button Check data quality verifies the data and highlights mistakes when all the necessary information has been entered [30]. It is shown in Figure 3.7. The method additionally suggests a range for the expected value. Up until all of the data is accurate, changes must be made. Prior logical quality tests include the following:

a) The bit's OD (outside diameter) must match the maximum outer diameter.

b) If the substance has a density similar to steel or iron, the weight per length ought to be proportional to the diameter.

c) The tubular parts' ID (inside diameter) must be smaller than their OD.

d) It is necessary to continuously raise the measured depth of the trajectory, pressure, and temperature profile, and formations.



Found errors in the well configuration. Are you sure you want to continue?

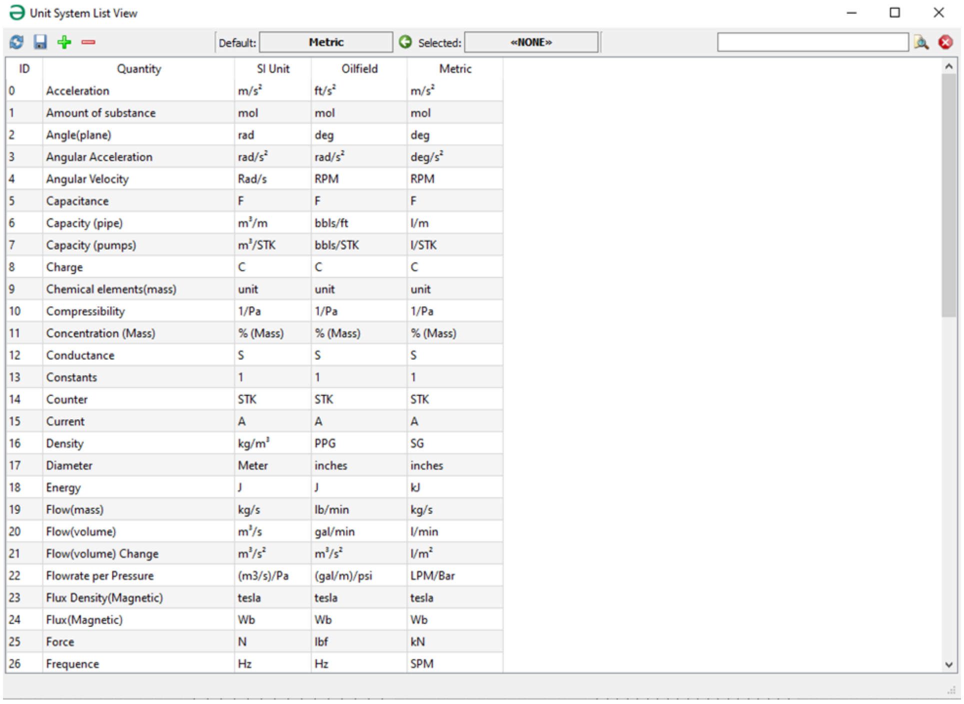
The tubular data had error(s):
Tubular: OD of component 3 is larger than bit od (8.5 inches).
Tubular: Connection OD of component 3 is too small, min value 30 inches.
Tubular: Connection OD is narrower than OD in component 3.

	Quantity []	TypeTubularComp []	TypeIdentifier []	ID [inches]	OD [inches]	ODMx [inches]	**Len [m]**	WtPerLen [kg/m]	EMod [bar]	YieldStrength [bar]
1	1	8 1/2" PDC Bit	Bit	2,25	8,5	8,5	0,22	200	2,1e+06	4 800
2	1	BHA elent1	Default	2,283	6,73	8,1	3,773	150	2,1e+06	4 800
3	1	BHA elent2	Default	3	30	8,375	1,75	140	2,1e+06	4 800
4	1	BHA elent3	Float	3,25	5,5	7,25	2,77	37	2,1e+06	4 800
5	1	BHA elent4	Default	2	6,75	8,25	7,681	150	2,1e+06	4 800
6	1	BHA elent5	Default	5,20902	6,75	6,89	8,85	88	2,1e+06	4 800
7	1	BHA elent6	Default	2,81	6,75	7,28	10,05	135	2,1e+06	4 800
8	1	BHA elent7	Default	3	6,75	8,375	1,75	145	2,1e+06	4 800
9	1	BHA elent8	Default	3	5	6,5	18	80	2,1e+06	4 800
10	1	BHA elent9	Default	3	6,5	6,5	9,52	85	2,1e+06	4 800
11	9	5" HWDP	Default	3	5	6,5	9,16667	72	2,1e+06	4 800
12	480	5" DP	Default	4,27598	5	6,5	9,3	33,633	2,1e+06	4 800

Figure 3. 7 - Data quality check

The current well configuration must always be sent to the server and made active by selecting Send to a server under the Edit option after the data has passed the quality check.

Another honorable mention is the Unit System List View. It is shown in Figure 3.8. This unit system list view gives a thorough overview of all the various unit systems for display and analysis. Users can configure and choose their preferred unit system for viewing drilling data and parameters using the Unit System List View, a user interface element [30].



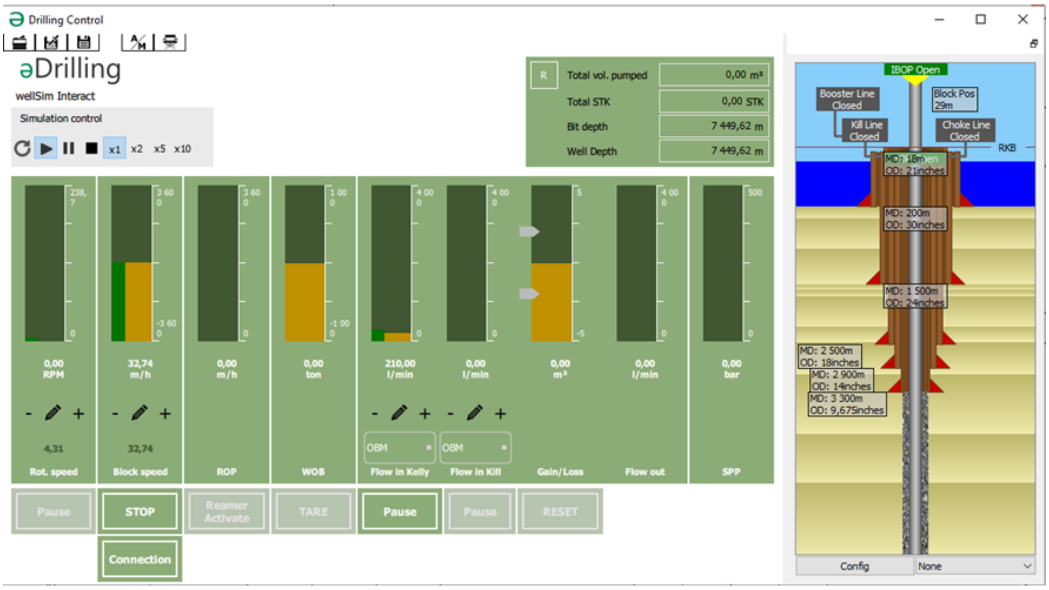
Default: Metric

Selected: «NONE»

ID	Quantity	SI Unit	Oilfield	Metric
0	Acceleration	m/s^2	ft/s^2	m/s^2
1	Amount of substance	mol	mol	mol
2	Angle(plane)	rad	deg	deg
3	Angular Acceleration	rad/s^2	rad/s^2	deg/s^2
4	Angular Velocity	Rad/s	RPM	RPM
5	Capacitance	F	F	F
6	Capacity (pipe)	m^3/m	bbls/ft	l/m
7	Capacity (pumps)	m^3/STK	bbls/STK	l/STK
8	Charge	C	C	C
9	Chemical elements(mass)	unit	unit	unit
10	Compressibility	1/Pa	1/Pa	1/Pa
11	Concentration (Mass)	% (Mass)	% (Mass)	% (Mass)
12	Conductance	S	S	S
13	Constants	1	1	1
14	Counter	STK	STK	STK
15	Current	A	A	A
16	Density	kg/m^3	PPG	SG
17	Diameter	Meter	inches	inches
18	Energy	J	J	kJ
19	Flow(mass)	kg/s	lb/min	kg/s
20	Flow(volume)	m^3/s	gal/min	l/min
21	Flow(volume) Change	m^3/s^2	m^3/s^2	l/m^2
22	Flowrate per Pressure	(m3/s)/Pa	(gal/m)/psi	LPM/Bar
23	Flux Density(Magnetic)	tesla	tesla	tesla
24	Flux(Magnetic)	Wb	Wb	Wb
25	Force	N	lbf	kN
26	Frequence	Hz	Hz	SPM

Figure 3. 8 - Unit System List View

The "Drilling Control" is another crucial tool. It is shown in Figure 3.9. By simply altering the rotating speed, block speed, and pump rate, the entire drilling process can be reproduced and controlled. By manually entering a number, this is accomplished. As a result, the other shown metrics, such as WOB, ROP, or standpipe pressure (SPP), are produced.



Total vol. pumped 0,00 m³
Total STK 0,00 STK
Bit depth 7 449,62 m
Well Depth 7 449,62 m

Figure 3. 9 - Drilling Control used to run and control simulations in wellSim Interact and manipulate input to control the emulation of drilling equipment

The „Simulation control's“ many buttons are used to control the simulation. Either real-time operation or time-lapse stages are possible. The entire simulation can be started over by pressing the quadratic stop icon.

The "Connection" button must be hit if a stand of drill pipes has to be added or removed. The simulator will carry out the entire procedure of adding/removing a stand automatically. Before tapping the button to add a stand, the block position must be lower than the length of one stand. It must be higher in order to remove one.

A detailed description of all relevant drilling parameters in the Drilling control is listed in the following Table 1.

Table 1 - Description of parameters in Drilling control (Adapted by eDrilling manual)

Bit depth	The position of the bit, with RKB (rotary kelly bushing) as reference.
Well depth	In TD and FM (formation marker) this is used to set an initial well depth internally, after this FM uses the highest bit depth input value, and TD uses the highest corrected bit depth value. This value is also used in the 2D and 3D visualization.
Block position	Distance between RKB and traveling block.
Rotational speed	This is the rotational speed of the string at RKB.
SPP	Stand pipe pressure.
Mud density in	The measured density of the fluid pumped into the well. This is measured at the temperature received at Mud temp in.
Mud flow in	This is the flow rate in, measured in volume not strokes.
Mud flow out (net)	This is the normal mud flow rate out (excluding the back pressure pump if this is used).
Mud temp in	Measured temperature of mud going in.
Hook load	Weight on hook, hence excluding the weight on block. If this includes the weight on block, an action must be taken to subtract it. If the server is configured for this, the user only needs to input the block weight in the well configuration. See the rig chapter in well configuration. Contact the eDrilling server administrator for correcting hook load. An explanation on subtracting this can be found in the server user manual.
Tank volume	This is the volume of the active tank(s).
Stroke rate	The stroke rate of the mud pumps.
ROP	Measured rate of penetration.
WOB	Weight on bit.

The internal blowout preventer (IBOP), a blowout preventer (BOP), a booster line, a choke line, and a kill line can all be opened and closed in the 2D tunnel view of the wellbore, which is once more comparable to the OpenView2D window. The tunnel view can be seen in Figure 3.10. If they are open, they are marked green, and if they are closed, they are marked gray. The green line is the dynamic equivalent circulation density, while the red, blue, and green lines show the pore and fracture pressure. This tunnel view can be also configured. That is shown in Figure 3.11.

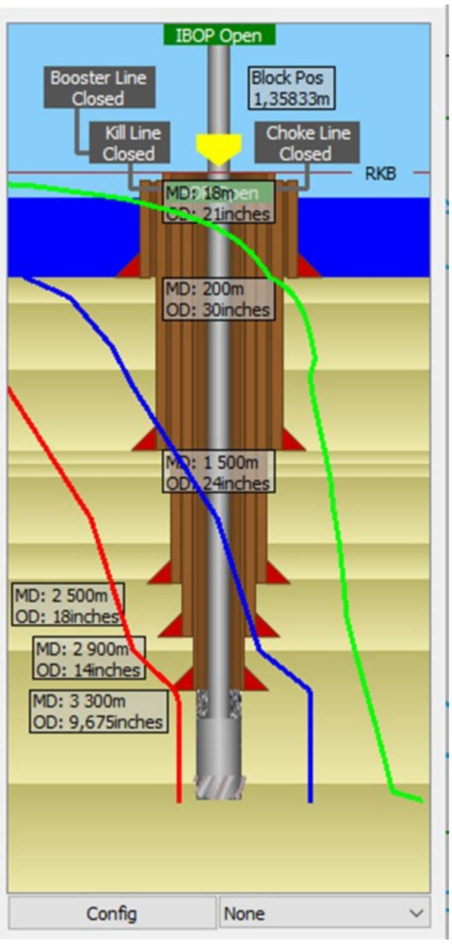
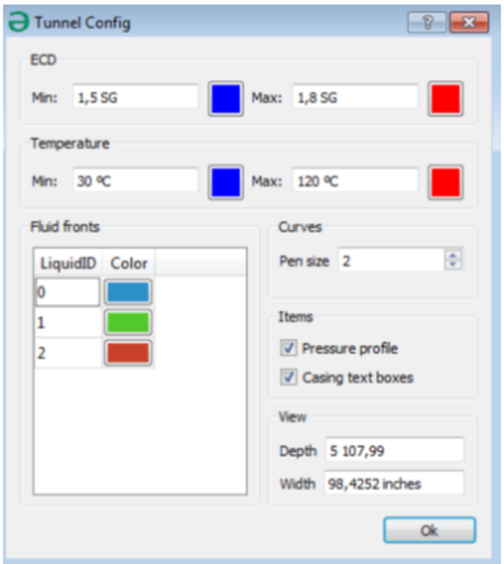


Figure 3. 10 - Tunnel view 2D shows an overview of the visual situation below the rig and the lines which can be closed and opened by clicking on the boxes



ECD

Min: 1,5 SG 🟦 Max: 1,8 SG 🟥

Temperature

Min: 30 °C 🟦 Max: 120 °C 🟥

Fluid fronts

LiquidID	Color
0	🟦
1	🟩
2	🟥

Curves

Pen size 2

Items

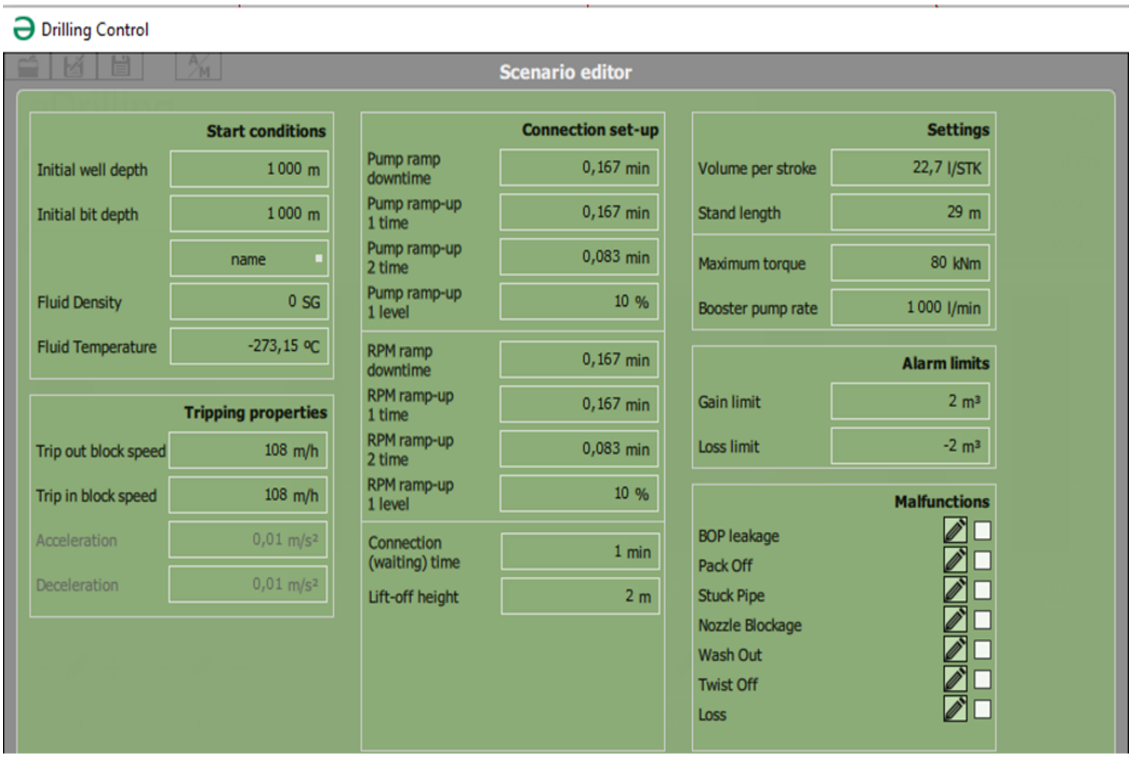
☑ Pressure profile
☑ Casing text boxes

View

Depth 5 107,99
Width 98,4252 inches

Figure 3. 11 - Tunnel configuration where the user can set ECD and Temperature ranges, fluid front colors that indicate the type of fluid at different depths, line thickness for drawing curves, show or hide pressure profiles and casing details, and adjust view depth and width

By selecting the Scenario editor, additional conditions pertaining to the simulation process' responsiveness can be set. The scenario editor is shown in Figure 3.12. A number of pre-defined malfunctions such as BOP leakage, stuck pipe, loss, and others can be actuated before a simulation begins, in addition to various starting conditions such as initial depth, fluid density, and rig parameters.



Drilling Control

Scenario editor

Start conditions

Initial well depth 1 000 m

Initial bit depth 1 000 m

name

Fluid Density 0 SG

Fluid Temperature -273,15 ºC

Tripping properties

Trip out block speed 108 m/h

Trip in block speed 108 m/h

Acceleration 0,01 m/s²

Deceleration 0,01 m/s²

Connection set-up

Pump ramp downtime 0,167 min

Pump ramp-up 1 time 0,167 min

Pump ramp-up 2 time 0,083 min

Pump ramp-up 1 level 10 %

RPM ramp downtime 0,167 min

RPM ramp-up 1 time 0,167 min

RPM ramp-up 2 time 0,083 min

RPM ramp-up 1 level 10 %

Connection (waiting) time 1 min

Lift-off height 2 m

Settings

Volume per stroke 22,7 l/STK

Stand length 29 m

Maximum torque 80 kNm

Booster pump rate 1 000 l/min

Alarm limits

Gain limit 2 m³

Loss limit -2 m³

Malfunctions

BOP leakage ☐

Pack Off ☐

Stuck Pipe ☐

Nozzle Blockage ☐

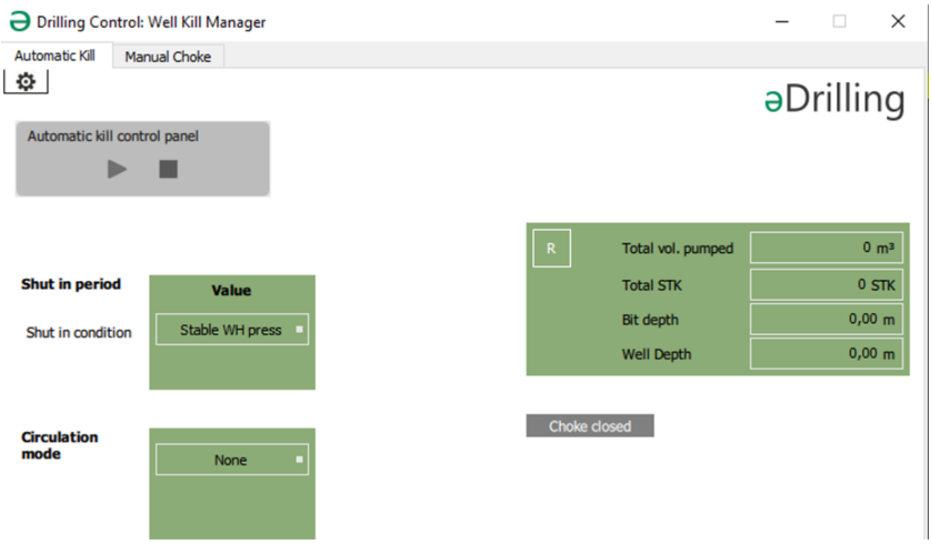
Wash Out ☐

Twist Off ☐

Loss ☐

Figure 3. 12 - Scenario editor where the user sets up parameters for the simulation and for equipment control properties

Also, in Drilling Control an automatic kill procedure can be performed based on what has been defined in the Automatic Kill window. That is shown in Figure 3.13.



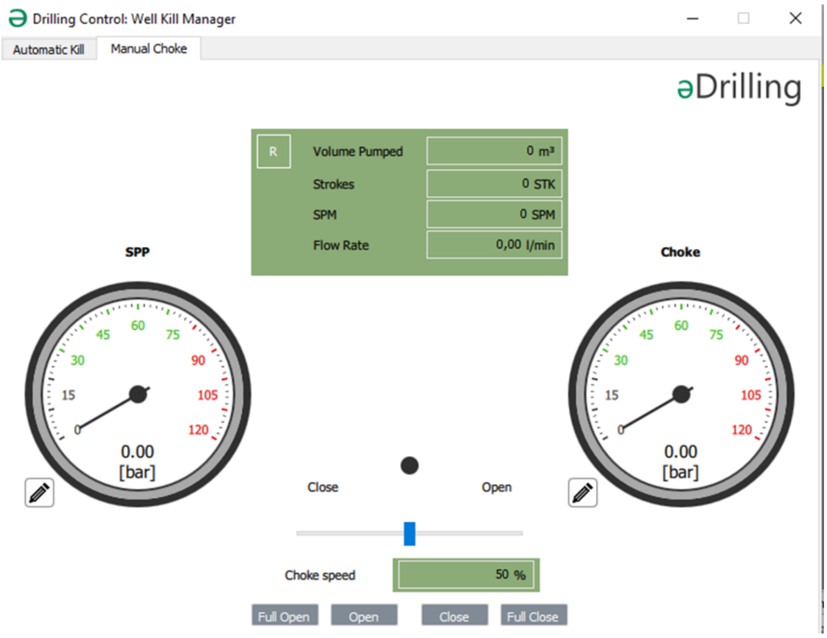
Total vol. pumped 0 m^3
Total STK 0 STK
Bit depth 0,00 m
Well Depth 0,00 m

Shut in period
Shut in condition: Stable WH press

Circulation mode: None

Figure 3. 13 - Automatic kill where the user can define the kill parameters and control and monitor the automatic kill sequence with closing or opening the choke

The automatic kill procedure starts from the current state of the well and completes a full kill procedure automatically by controlling the pumps/pressure and the choke [30]. A manual choke is also present. It is shown in Figure 3.14. In the manual choke panel, there are two gages, one for the stand pipe pressure and one for the choke pressure. The choke opening is adjusted by pressing the Open and Close buttons. The choke speed can be adjusted with the slider below the choke opening indicators.



Volume Pumped 0 m^3
Strokes 0 STK
SPM 0 SPM
Flow Rate 0,00 l/min
Choke speed 50 %

Figure 3. 14 - Manual Choke with two gages. One represents standpipe pressure and the other represents choke pressure. Choke opening is adjusted by pressing the Open and close buttons

3.3.3 WitsML Importer

The WitsML Importer allows the user to browse and download well configurations from a WitsML server. When you start the WitsML Importer, the wells that are available are listed on the left. This list will be updated with the wellbores connected to the well you have chosen. When a wellbore is chosen, the information that is accessible will be added to each of the other lists [30].

When you select the accessible data and choose the Import specified, the Well Configuration Editor will load the specified data. The models won't use it unless a Send to Server button is selected in the menu of the Well Configuration Editor. Since it's likely that the imported data is of low data quality, information should be reviewed and updated before being sent to the server.

3.3.4 WellViz3D

"WellViz3D" is the eDrilling software's final major application. It is shown in Figure 3.15. A virtual wellbore can be created by using this 3D application, complete with formations, trajectories, seismic data, and tools [30] . Giving people a greater grasp of what is happening during the drilling operation is really helpful. It responds in real time and is connected to a variety of simulation data sources, much like all other tools. Other characteristics include – display of all information in context, two flight modes and the potential for free flight.

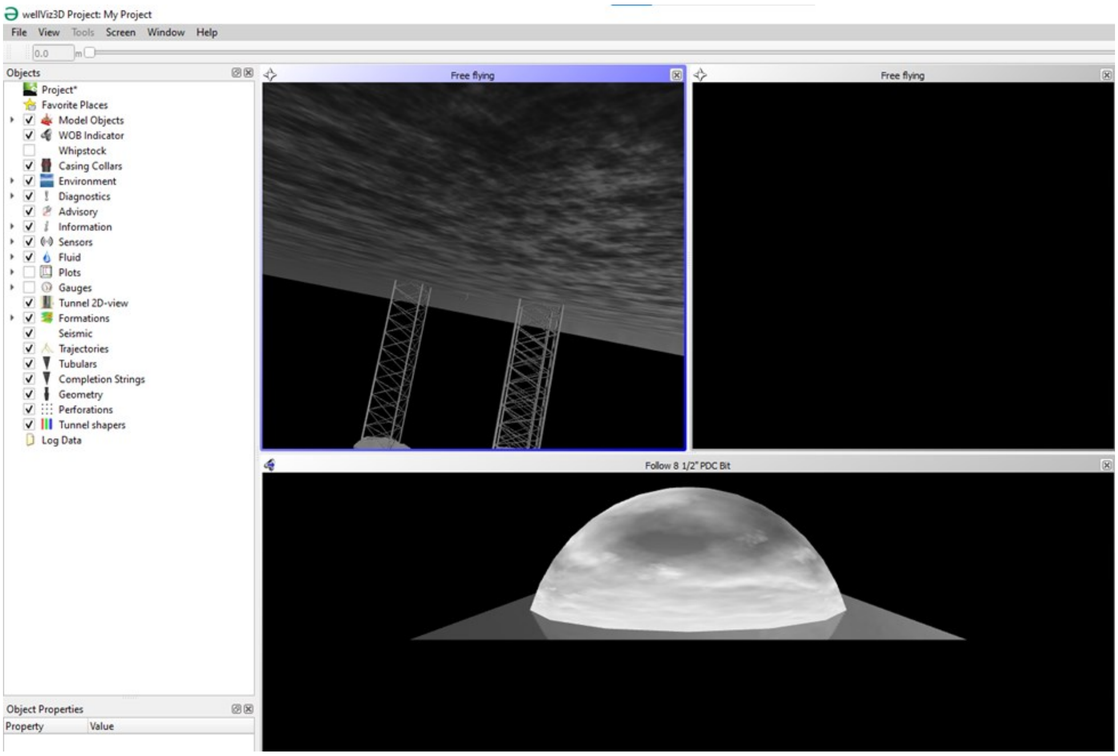


Figure 3. 15 - Interface of WellViz3D with 3D views and several ways to navigate the 3D model of the world and with objects that can be adjusted with user preference

Following any BHA (bottom-hole assembly) component, following the trajectory, displaying information along the BHA or wellbore, visualizing simulated data, and displaying fluid and cuttings flow are all possible. As in the previous phases, the wellbore's 2D tunnel view is once more on the right. The "Objects" section is on the left. You can choose which information and objects to display. To be able to choose a 3D model for each tubular component, the "User Level" under "File" must be changed to "System Administrator". "Admin" was chosen as the password for this user level tier. The central depiction area can be individually tailored. The area can be divided into up to four different windows by clicking "Window" in either a vertical or horizontal direction. The "Flying mode" allows you to follow lone objects as well. The "Selection mode" setting enables you to use the mouse pointer to independently select objects. It is also possible to create the depth-based plots of all the drilling parameters needed along the wellbore [30].

3.4 eDrilling Simulator Workflow

This part will explain the Workflow when the user wants to create a fresh case study in the simulator. The user will be guided through the process in step-by-step directions, ensuring a quick and effective approach. Figure 3.16 depicts a flowchart of how a workflow was implemented in the eDrilling program.

Figure 3. 16 - Workflow of a case implementation

Firstly it is important to launch the eDrillingHUB and connect to the eDrilling's online server. After that, the OpenView2D can be opened and connected to the same server via the file-connect to the server shortcut.

The Well Configuration Editor can be then accessed by selecting the button Tools from the OpenView2d. The main window must be filled with the necessary data before any simulation can be run. The process of the Well Configuration Editor is depicted in the Figure 3.17.

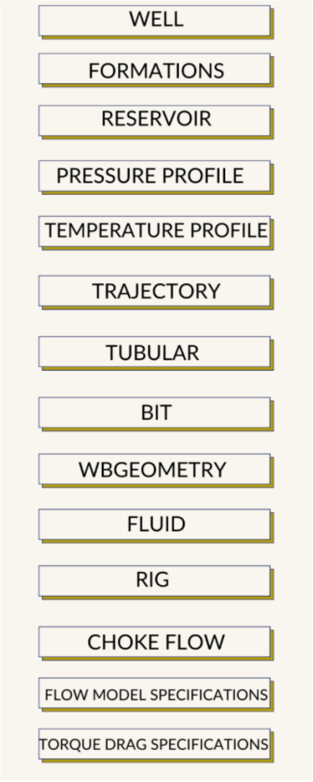


Figure 3. 17 - Well Configuration Editor – Workflow

Additionally, the items are given a thorough description.

a) Well

It is essential to include a full explanation of the well, its wellbore, and work specifications in this section. It is important to note that the information in this tab has no direct influence on the simulation.

b) Formations

This tab is critical for determining and specifying the measured depth (MD) and true vertical depth (TVD) of each of the well's formations. This data is frequently used in the software models for both functional calculations and visualization. Moreover, when the "Type" of the formation is chosen from the dropdown menu, all relevant values, such as yield strength and tensile strength, are automatically filled in.These default values can also be customized to align with user preferences.

c) Reservoir

It is possible to enter reservoir property data here. If no reservoir is found, it is recommended that this field remains unchanged.

d) Pressure Profile

It is necessary to input the pressure data in the unit SG (specific gravity) and to set the column "Collapse Pres" equal to the column "Pore Pres."

e) Temperature Profile

Even in the absence of specified data, the geothermal gradient may be generated by right-clicking a cell in the "Formation Temp" column and selecting "Calculate dynamic profile" from the context menu. Manually adjusting the "StringTemp" and "AnnulusTemp" values to match the "FormationTemp" value completes the simulation.

f) Trajectory

The trajectory data should cover the final target depth and both the actual and anticipated trajectory. After entering the data, you must select "Is active" in the box.

g) Tubular

The full string and the BHA are picked. It is essential that users of the tubular device have access to a selection of pre-defined components under the "Tools" and "Tubular Library" tabs. To enable the simulation to achieve the specified depth, the length of all components should be enough. The OD and ODMax of the bit must be equal.

h) Bit

Each nozzle's diameter or the bit's entire flow area should be categorized.

i) WbGeometry

Every component of the casing must be described, with the exception of the section that must be drilled during the simulation. The program uses the final entry in the table's column "MDBottom" as the open hole section, which continues up to the present well depth. The first element must begin at zero depth and end with a casing ID bigger than the bit OD.

j) Fluid

For the required simulation, the selected mud or fluid is defined. Except for the density and the name of the new fluid, all other input parameters, such as the fluid constituents or the thermal data, are pre-defined by the system and can be used. The density must remain within the suggested mud window's pore and fracture pressure boundaries.

k) Rig

A rig from the tab "Rig Templates" should be selected in order to establish the essential rig requirements, such as "WeightOnBlock," which specifies the weight of the moving block including the top drive, and the Kelly flowline characteristics.

l) Choke Flow

Nothing from the default setup should be changed.

m) Flow Model Specifications

Nothing from the default setup should be changed.

n) Torque Drag Specifications

Nothing from the default setup should be changed.

A detailed sequence of the data implementation into the eDrilling AS software is presented in Figure 3.18.

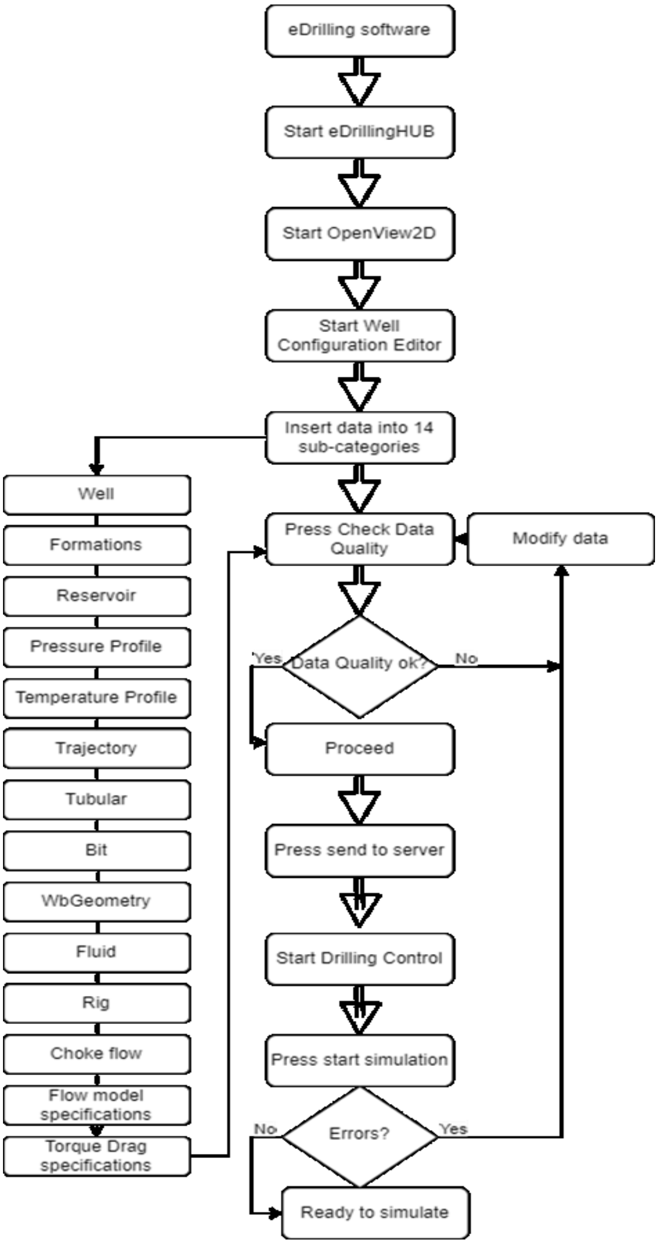


Figure 3. 18 - Sequences of data implementation

After the data has passed the quality check and the simulation has been checked, the plot arrangement of the "OpenView2D" application can be altered through the plot configuration menu. After that, it is necessary to open the Drilling control menu and the input values such as rotational speed, block speed, flow in kill, and flow in kelly must be given values before starting the simulation [30]. If the simulation starts successfully, the distinct programming component of the configuration directory files begins. Each code update must be tested by restarting the complete simulator software. It is a process of trial and error. Repeat this process step by step till the training case simulation works as desired.

Chapter 4

4 Methodology Overview and Illustrative Cases

4.1 Overview

As mentioned in previous chapters, Reverse Circulation has been put into practice in numerous drilling processes to enhance drilling efficiency in terms of time and cost. However, most of the discussed cases do not typically involve a comparison between RC and normal circulation. Therefore, this work aims to conduct a comparative analysis between RC and normal circulation for a specific drilling process using the eDrilling simulator. Firstly, the key performance indicators that are going to be tracked to compare the normal circulation and Reverse Circulation are going to be described. The KPIs that are tracked are pressures, cuttings profile, and Cuttings Transport Rate profile. They provide quantitative measures to analyze the method's efficiency, and performance, contributing to decision-making, and process improvement.

As explained in Chapter 3, the e-drilling simulator was initially developed for typical drilling scenarios, making it challenging to adapt it for studying Reverse Circulation (RC) scenarios involving well cementing and casing while drilling. Consequently, the only process that could be effectively investigated was hole cleaning. Three specific cases were developed using real data to successfully achieve the primary goal of this thesis. For all three cases, normal circulation served as the baseline for comparison.

In each case, the methodology remained consistent as follows: A baseline scenario was created for Reverse Circulation, and it was compared to the normal circulation process using the mentioned KPIs. Then, through a series of iterations involving adjustments to input parameters such as bit nozzle, mud density, hole size, drill pipe diameter, wellbore inclination, and the rotation of drill pipes during circulation, the optimal parameters for Reverse Circulation were defined. These optimized parameters were then used collectively for the RC scenarios which are compared with normal circulation using the same KPIs. The workflow for implementing this methodology is illustrated in Figure 4.1.

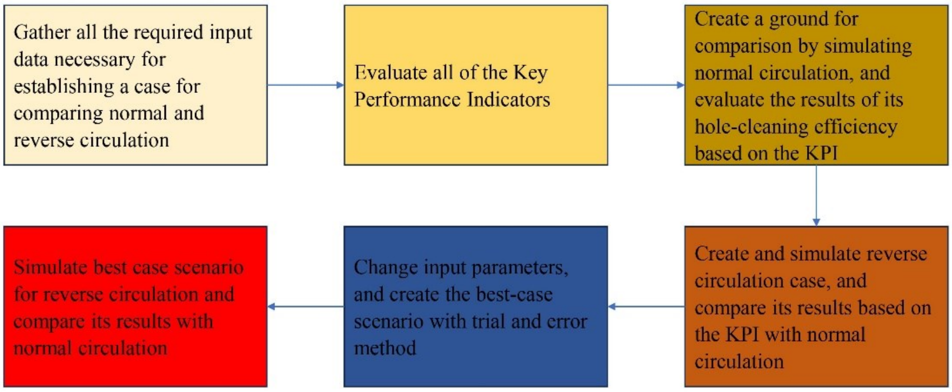


Figure 4. 1 - Workflow of the methodology

4.2 Key Performance Indicators (KPI)

Numerous technical Key Performance Indicators (KPIs) have been developed over the last few decades for monitoring and comparing drilling processes. However, when it comes to the application of Reverse Circulation in drilling, the available KPIs are somewhat limited. Among the KPIs that can be utilized to compare RC with normal circulation are pressure measurements, cuttings profile, and cuttings transport rate profile. To be more precise, the pressures that were tracked because it is essential to ensure safe and efficient operations are the casing pressure, the bottom hole pressure, reservoir pressure, the wellhead pressure, pore pressure, and lastly the fracture pressure and standpipe pressure.

4.2.1 Casing Pressure

Indicates the build-up of gas pressure in the outer walls of a well.Monitoring casing pressure helps to minimize well casing fractures, extends the life of drilling equipment, and, most importantly, avoids blowout [31].

4.2.2 Bottom-hole Pressure

Pressure at the bottom of the hole, equal to the pressure drop in the tubing plus the wellhead pressure. In order to avoid kicks (the uncontrolled injection of formation fluids) and well blowouts, maintaining the right BHP is essential for drilling and well management [31].

4.2.3 Reservoir Pressure

Pressure of the fluid in pores and fractures. Monitoring reservoir pressures is essential for reservoir management, production optimization, and determining recoverable reserves. Understanding how reservoir pressure changes over time enables operators to make better-informed production decisions [31].

4.2.4 Wellhead Pressure

Pressure at the top of the well, at its wellhead. The flow rate of production fluids must be controlled in order to guarantee that wellhead equipment can safely bear the pressure [31].

4.2.5 Pore Pressure

The pressure of fluids in the pore space of rock.To avoid wellbore instability, kicks, or blowouts during drilling, the pore pressure must be known [31].

4.2.6 Fracture Pressure

The magnitude of pore pressure that the rock can withstand before it fails.Knowing the fracture pressure is critical for workover and intervention operations since exceeding the fracture pressure would result in substantial fluid loss and a loss of hydrostatic overbalance [31].

4.2.7 Standpipe Pressure

Total frictional pressure drop in the hydraulic circuit. It is monitored to ensure the proper functioning of the drilling operation. It helps to assess the effectiveness of both methods [31]. Tracking and understanding these pressures, in both normal and Reverse Circulation, is crucial for making decisions throughout drilling, completion, and production activities. Differences in these pressures between the two circulation systems can provide important insights into the operation's efficiency and safety, as well as help improve the well's overall performance.

4.2.8 Cuttings Profile

Comparing the cuttings profiles in normal and Reverse Circulation can give insight into the drilling process's efficiency. Differences in cutting size, or volume might reflect how effective each procedure is. You may determine whether the circulation method is more efficient in terms of cuttings removal and overall drilling efficiency by monitoring the cuttings at the bottom of the well. It can also offer information regarding the stability of the wellbore during drilling. If you see changes in the size, type, or quantity of the cuttings during the simulation, this might indicate changes in formation lithology, hardness, or fluid characteristics. Monitoring it at the well's bottom is vital since here is where the actual drilling takes place and where wellbore stability concerns are most critical. A lower or finer cuttings profile with smaller and more uniform cuttings tends to be preferred because it indicates efficient drilling with minimal bit wear, suggests better wellbore stability, provides more accurate information about formation lithology, and is less likely to clog the drilling fluid system. However, in tougher formations, a higher cuttings profile, defined by bigger or more diversified cuttings, may be acceptable. When drilling through zones with possible hydrocarbon displays, bigger cuttings may indicate the existence of oil or gas [32].

4.2.9 Cuttings Transport Rate

The comparison of cuttings transport rates between normal and Reverse Circulation assists in determining the effectiveness of both systems. It is used to determine which circulation approach removes cuttings from the wellbore more efficiently. Cuttings transport that is efficient lowers the likelihood of wellbore instability and stuck pipe concerns. A well-optimized cuttings transfer rate also helps in preventing excessive bit wear. A greater cuttings transport rate, which implies effective cuttings removal from the wellbore, is frequently preferred. Lower cuttings transport can be preferred when drilling into soft formations because it can assist in preventing excessive fluid loss into the formation. Another case is controlled loss zones, where a lower cuttings transport rate may be required to manage drilling fluids and maintain well control [33]. In the studied cases, a lower cuttings profile and higher cuttings transport rates will be preferred.

4.3 Data Description

Necessary analyses for this case studies performed using historical data belonging to slightly deviated wells drilled in North Africa. As mentioned earlier, the main objective of the three studied cases is to compare the effectiveness of Reverse Circulation in hole cleaning compared to normal circulation.

Table 2, 3, and 4 present information regarding the input parameters employed in simulating the first case. In this scenario, the drilling process began by drilling a 45 ft section, extending from 11,718 ft to 11,763 ft. Subsequently, a simulation of normal circulation was carried out. Afterward, the same 45 ft section was drilled once more, and a Reverse Circulation (RC) simulation was performed.

Table 2 - Case 1 input parameters (Lithology)

Formation Name	**Measured Depth Top (ft)**
QUASAR WEDDINGTON	36
MARVIN DELIGHT	238
DIBONATRIX SANDS	1592
AUGILIAN EMBER	2358
ELARIAN ECHO	2523
GIALONOVA SPECTRUM	2776
JAKHIRA ENIGMA	3331
COSMOLUSH	3674
GIRONYX VEIL	4707
KHEIRON STARFALL	6106
ZELTONIAN DREAM	6204
MEGRAFIC AURORA	7227
KALASHIRO CRYSTAL	8060
SIRTEAN SERENITY	9169
UPPER RACHMANTIA	9415
LOWER RACHMETIS	10678
UPPER MARAGHESIA	11007
AMALIUS RIFT	11068
UPPER GARGALIAN HAV	11794

Table 3 - Case 1 input parameters (BHA)

Component Type	Number of Joints	Length (ft)	OD (in)	Cum Length (ft)
Polycrystalline Diamond Bit	1	1.00	8.5	1.00
Positive Displacement Motor	1	27.64	7	28.64
Float Sub	1	2.95	6.75	31.59
Cross Over	1	2.56	6.5	34.15
Integral Blade Stabilizer	1	6.67	6.19	8.38
Spiral Drill Collar	1	30.79	6.5	71.61
Integral Blade Stabilizer	1	6.67	6.19	8.38
Spiral Drill Collar	13	404.18	6.5	482.46
Hydro-Mechanical Jar	1	15.25	6.313	497.71
Spiral Drill Collar	3	93.02	6.5	590.73
Cross Over	1	3.00	6.5	593.73
Heavy Weight Drill Pipe	15	462.19	5	1 055.92
Bit Nozzles 6*11				

Table 4 - Case 1 input parameters (Drilling Fluid Properties amd Choke Pressure)

Type:	Water
MD Check (ft):	11804
Mud Name:	KLC/Polymer
Density (ppg):	11.5
Viscosity (s/qt):	58
PV(cp):	28
PH:	9.5
KCl (%):	3.1
HGS (%):	4.6
Choke Pressure: 5000 psi	

Table 5, 6 and 7 provide information about the input parameters that were used for simulating the second case. In this case, the drilling process began with drill of 60 ft section, extending from 11,885 ft to 11,945 ft. Subsequently, a simulation of normal circulation was carried out. Afterward, the same 60 ft section was drilled once more, and a Reverse Circulation (RC) simulation was performed.

Table 5 - Case 2 input parameters (Drilling Fluid Properties amd Choke Pressure)

Type:	Water
MD Check (ft):	12 348
Mud Name:	KLC/CaCO3/Polymer
Density (ppg):	9.05
Viscosity (s/qt):	59
PV(cp):	22
PH:	9.5
KCl (%):	3.0
HGS (%):	0.4
Choke Pressure: 5000 psi	

Table 6 - Case 2 input parameters (BHA)

Component Type	Number of Joints	Length (ft)	OD (in)	Cum Length (ft)
Polycrystalline Diamond Bit	1	1.00	6.5	1.00
Bit Sub	1	4.00	4.75	5.00
Drill Collar	1	30.78	4.75	35.78
Integral Blade Stabilizer	1	6.71	4.75	42.49
Drill Collar	1	30.87	4.75	73.36
Integral Blade Stabilizer	1	6.71	4.75	80.07
Drill Collar	16	497.20	4.75	577.27
Hydro-Mechanical Jar	1	16.12	4.75	593.39
Drill Collar	3	93.03	4.75	686.42
Heavy Weight Drill Pipe	9	277.14	3.5	963.56
Bit Nozzles 3*11 and 3*12				

Table 7 - Case 2 input parameters (Lithology)

Formation Name	Measured Depth Top (ft)
QUASAR WEDDINGTON	36
MARVIN DELIGHT	238
DIBONATRIX SANDS	1592
AUGILIAN EMBER	2358
ELARIAN ECHO	2523
GIALONOVA SPECTRUM	2776
JAKHIRA ENIGMA	3331
COSMOLUSH	3674
GIRONYX VEIL	4707
KHEIRON STARFALL	6106
ZELTONIAN DREAM	6204
MEGRAFIC AURORA	7227
KALASHIRO CRYSTAL	8060
SIRTEAN SERENITY	9169
UPPER RACHMANTIA	9415
LOWER RACHMETIS	10678
UPPER MARAGHESIA	11007
AMALIUS RIFT	11068
UPPER GARGALIAN HAV	11797

As for the decisive and last case 3, Table 8, 9 and 10 below provide information about the input parameters that were used for simulating this case. For this case, the process commenced by drilling 62 ft segment, spanning from 11,238 ft to 11,300 ft. Following that, a simulation of the conventional circulation was executed. Then, the identical 45 ft segment was drilled again, and a Reverse Circulation (RC) simulation was conducted.

Table 8 - Case 3 input parameters (Drilling Fluid Properties amd Choke Pressure)

Type:	Water
MD Check (ft):	11310
Mud Name:	PERFORMA
Density (ppg):	12.5
Viscosity (s/qt):	70
PV(cp):	43
PH:	10.8
KCl (%):	0
HGS (%):	12.5
Choke Pressure: 5000 psi	

Table 9 - Case 3 input parameters (Lithology)

Formation Name	**Measured Depth Top (ft)**
QUASAR WEDDINGTON	36
MARVIN DELIGHT	216
DIBONATRIX SANDS	1593
AUGILIAN EMBER	2314
ELARIAN ECHO	2716
GIALONOVA SPECTRUM	3282
JAKHIRA ENIGMA	3282
COSMOLUSH	3641
GIRONYX VEIL	4775
KHEIRON STARFALL	6171
ZELTONIAN DREAM	6289
MEGRAFIC AURORA	7372
KALASHIRO CRYSTAL	8170
SIRTEAN SERENITY	9058
UPPER RACHMANTIA	9312
LOWER RACHMETIS	10716
UPPER MARAGHESIA	11235

Table 10 - Case 3 input parameters (BHA)

Component Type	**Number of Joints**	**Length (ft)**	**OD (in)**	**Cum Length (ft)**
Polycrystalline Diamond Bit	1	1.08	12.25	1.08
Positive Displacement Motor	1	35.89	9.5	36.97
Non-Mag Crossover Sub	1	2.50	9.5	39.47
MWD Tool	1	18.02	9.5	57.49
Pulser Sub	1	12.14	9.5	69.63
Non-Mag Crossover Sub	1	2.30	7.5	71.93
Cross Over	1	2.98	9.5	74.91
Drill Collar	1	30.80	8.25	105.71
Hydraulic Jar	1	15.76	8.25	121.47
Drill Collar	1	29.90	8.25	151.37
Cross Over	1	2.98	8.25	154.35
Heavy Weight Drill Pipe	15	462.23	6.5	616.58
Drill Pipe	15	470.10	5	1 086.68
Heavy Weight Drill Pipe	12	369.91	6.5	1 456.59
Cross Over	1	2.64	6.5	1 459.23
Drill Collar	3	185.59	6.5	1 644.82
Cross Over	1	2.98	6.5	1 647.80
Heavy Weight Drill Pipe	3	92.34	6.5	1 740.14
Bit Nozzles 8*18				

The pressure profile and temperature profile data used for the three studied cases are depicted in Figure 4.2.

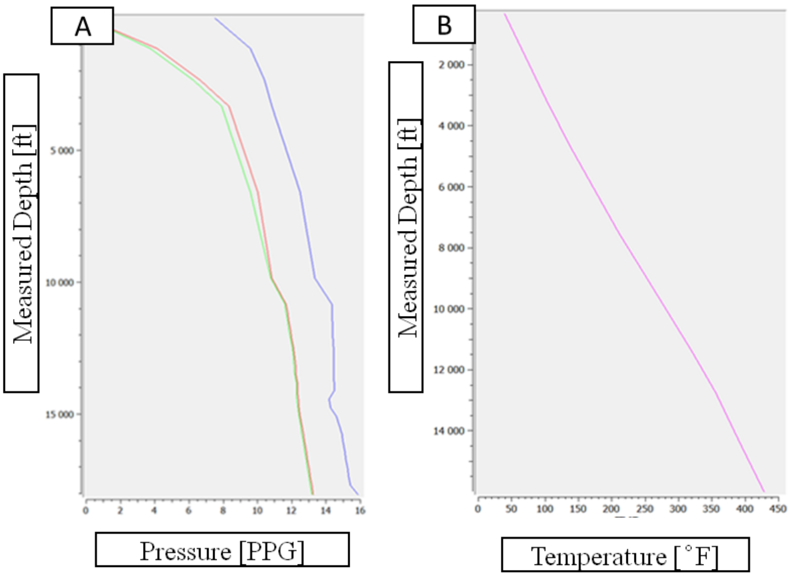


Figure 4. 2 – A: Pressure Profile: The red line presents pore pressure, the blue line fracture pressure, and the green line collapse pressure. B: Temperature Profile: The pink line presents the dynamic profile

4.4 Case Studies

The following cases were built on hole cleaning after drilling a section of the hole. Each case will involve a comparison between normal circulation and Reverse Circulation. In each case, the hole cleaning was first done with normal circulation to create a ground for comparison, and then a Reverse Circulation hole cleaning was done to compare the results of these two methods using KPIs. Reverse Circulation was then adjusted by varying input parameters. The aim was to achieve a best-case scenario for Reverse Circulation when compared to normal circulation, which tries to be equally or more efficient in meeting the defined Key Performance Indicators.

4.4.1 Case #1

A simple well configuration sketch for Case 1 is shown in Figure 4.3. The objective of this case was to compare the effectiveness of Reverse Circulation hole cleaning to normal circulation hole cleaning, with a focus on achieving a high cuttings transport rate, a low cuttings profile at the bottom, and maintaining acceptable well pressures after drilling the section from 11,718 ft (3,571.64 m) to 11,763 ft (3,585.36 m).

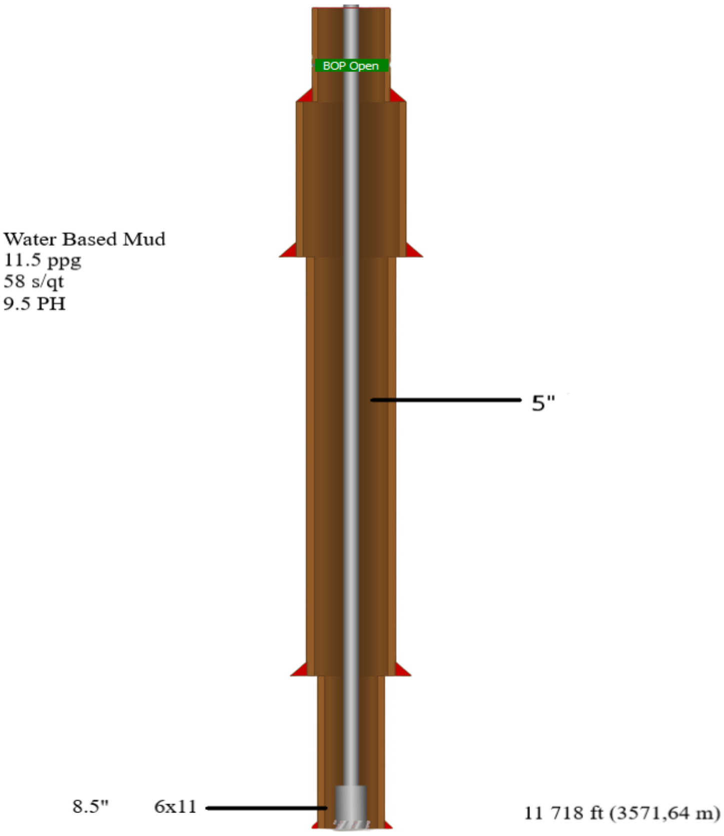
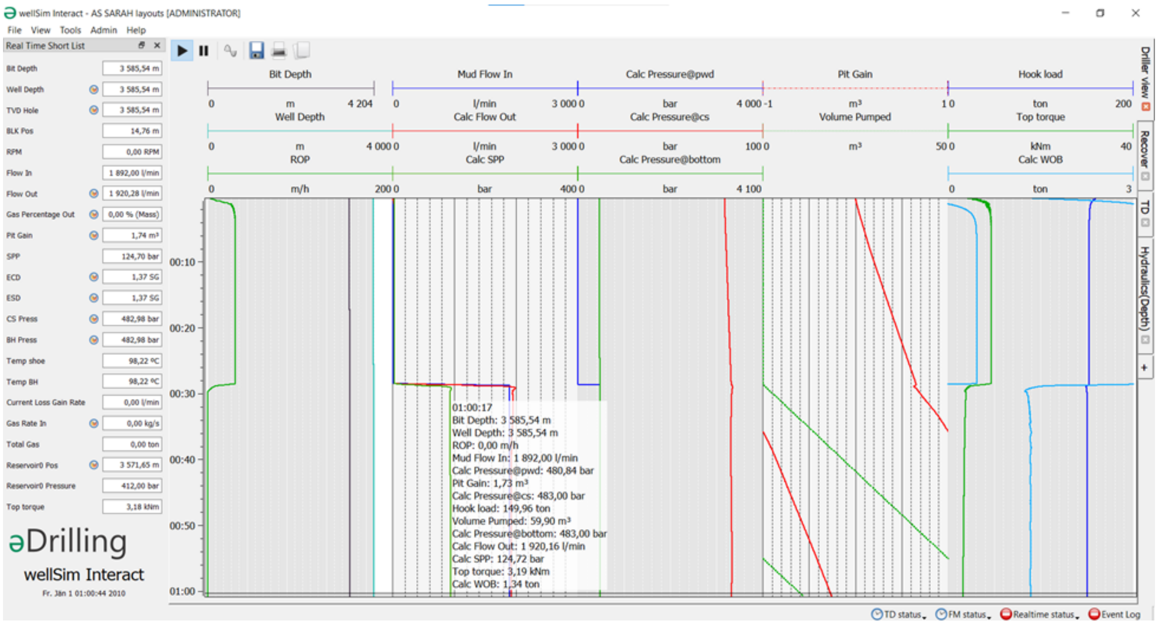


Figure 4. 3 - Case 1 Well Configuration

After drilling 45 ft (13.71 m) with an RPM of 220 and a block speed (ROP) of 30 m/h, drilling was stopped, and cleaning of the cuttings with normal circulation started. A half an hour time was given for an appropriate effect of the cleaning. The inside blowout preventer and blowout preventer were left open and the booster line, kill line, and choke line were closed. After that, the flow in kelly necessary for pumping the mud through the pipes, cleaning the cuttings at the bottom, and returning back through the annulus was put to the value of 1892 l/min.

Figure 4.4, Figure 4.5, Figure 4.6, and Figure 4.7 show the results of normal circulation. Figure 4.4 represents a Drillers View which is a real-time visualization tool that displays critical drilling parameters such as pressures, bit and well depth, rop, mudflow in and out, etc. Figure 4.5 shows a recovery plot following key parameters such as flow in, flow out, wellhead pressure, and SPP. Figure 4.6 shows the true vertical depth of a wellbore. Figure 4.7 shows hydraulics data such as necessary Cuttings transport rate and cuttings transport rates profile at every depth.



Real Time Short List	
Bit Depth	3 585,54 m
Well Depth	3 585,54 m
TVD Hole	3 585,54 m
BLK Pos	14,76 m
RPM	0,00 RPM
Flow In	1 892,00 l/min
Flow Out	1 920,28 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	1,74 m³
SPP	124,70 bar
ECD	1,37 SG
ESD	1,37 SG
CS Press	482,98 bar
BH Press	482,98 bar
Temp shoe	98,22 ºC
Temp BH	98,22 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	3,18 kNm

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wellSim Interact
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01:00:17
Bit Depth: 3 585,54 m
Well Depth: 3 585,54 m
ROP: 0,00 m/h
Mud Flow In: 1 892,00 l/min
Calc Pressure@pwd: 480,84 bar
Pit Gain: 1,73 m³
Calc Pressure@cs: 483,00 bar
Hook load: 149,96 ton
Volume Pumped: 59,90 m³
Calc Pressure@bottom: 483,00 bar
Calc Flow Out: 1 920,16 l/min
Calc SPP: 124,72 bar
Top torque: 3,19 kNm
Calc WOB: 1,34 ton

Figure 4. 4 - Normal circulation Driller view

Real Time Short List	
Bit Depth	3 585,54 m
Well Depth	3 585,54 m
TVD Hole	3 585,54 m
BLK Pos	14,76 m
RPM	0,00 RPM
Flow In	1 892,00 l/min
Flow Out	1 920,28 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	1,74 m³
SPP	124,70 bar
ECD	1,37 SG
ESD	1,37 SG
CS Press	482,98 bar
BH Press	482,98 bar
Temp shoe	98,22 ºC
Temp BH	98,22 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	3,18 kNm

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wellSim Interact
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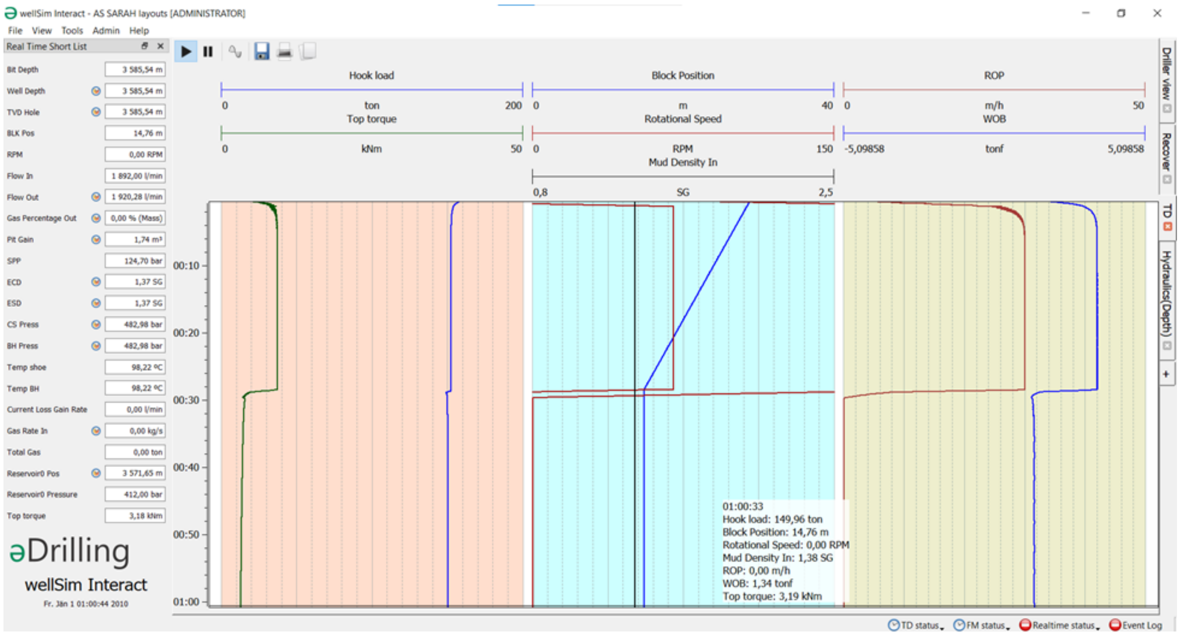
01:00:17
Flow In: 1 892,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 1 920,21 l/min
SPP: 124,72 bar
Well head pressure: 4,37 bar

Figure 4. 5 - Normal circulation Recovery



Bit Depth	3 585,54 m
Well Depth	3 585,54 m
TVD Hole	3 585,54 m
BLK Pos	14,76 m
RPM	0,00 RPM
Flow In	1 892,00 l/min
Flow Out	1 920,28 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	1,74 m³
SPP	124,70 bar
ECD	1,37 SG
ESD	1,37 SG
CS Press	482,98 bar
BH Press	482,98 bar
Temp shoe	98,22 ºC
Temp BH	98,22 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	3,18 kNm

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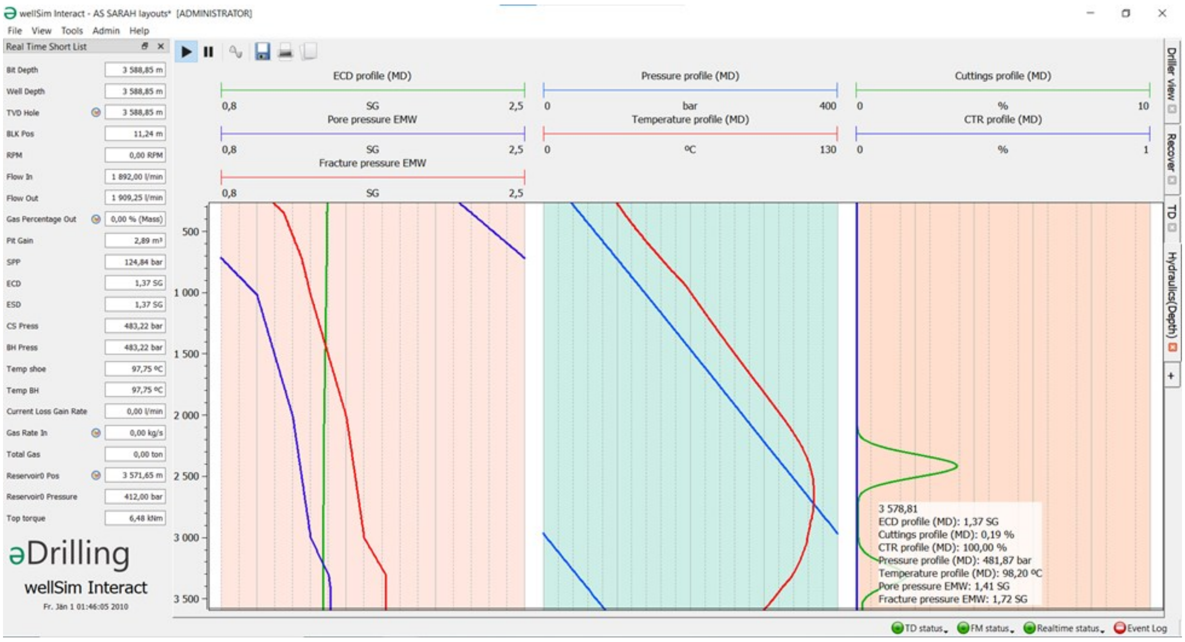
01:00:33
Hook load: 149,96 ton
Block Position: 14,76 m
Rotational Speed: 0,00 RPM
Mud Density In: 1,38 SG
ROP: 0,00 m/h
WOB: 1,34 tonf
Top torque: 3,19 kNm

Figure 4. 6 - Normal circulation True Depth



Bit Depth	3 588,85 m
Well Depth	3 588,85 m
TVD Hole	3 588,85 m
BLK Pos	11,24 m
RPM	0,00 RPM
Flow In	1 892,00 l/min
Flow Out	1 909,25 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	2,89 m³
SPP	124,84 bar
ECD	1,37 SG
ESD	1,37 SG
CS Press	483,22 bar
BH Press	483,22 bar
Temp shoe	97,75 ºC
Temp BH	97,75 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	6,48 kNm

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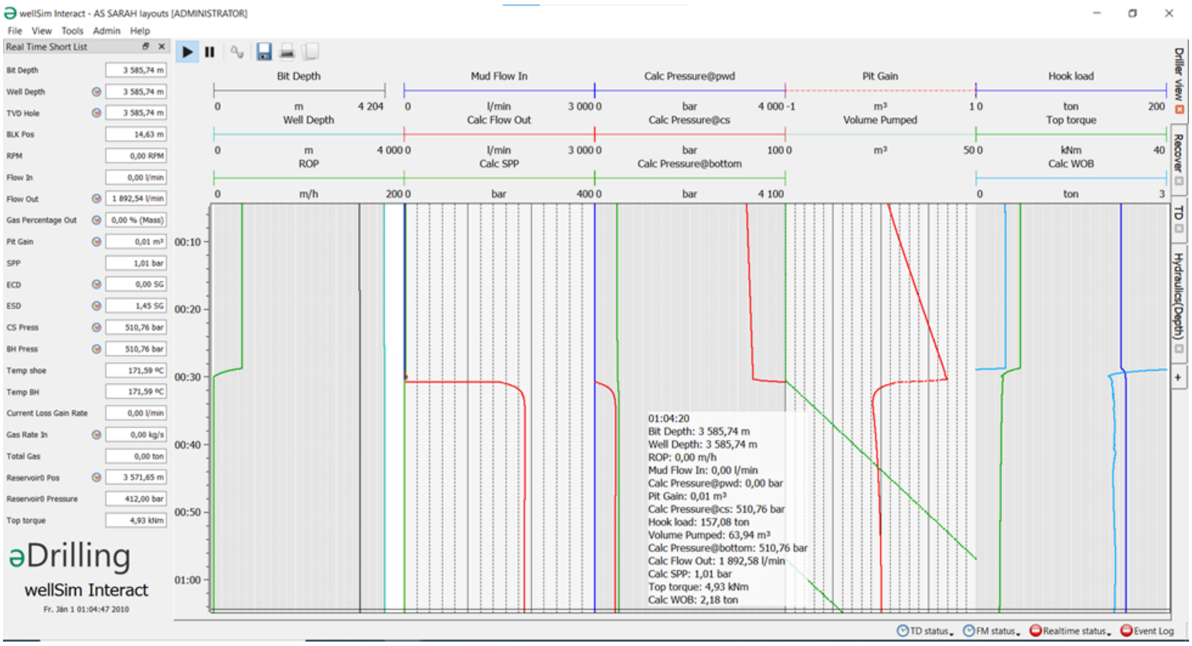
3 578,81
ECD profile (MD): 1,37 SG
Cuttings profile (MD): 0,19 %
CTR profile (MD): 100,00 %
Pressure profile (MD): 481,87 bar
Temperature profile (MD): 98,20 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

Figure 4. 7 - Normal circulation Hydraulics Data

The KPIs mentioned before have shown the expected results for this kind of method and inputs. Casing pressure and bottom hole pressure of 483.22 bar, reservoir pressure of 412 bar, wellhead pressure of 4.27 bar, pore pressure of 1.41 SG, fracture pressure of 1.72 SG, and standpipe pressure of 124.7 bar. Regarding the cuttings, the normal circulation was very effective with a good cuttings transport rates of 100% which means that the process is effectively and completely removing all the cuttings from the wellbore as they are generated at the drill bit and the cuttings profile of 0.19% at the bottom. This suggests that there is a very low concentration of cuttings remained at bottom. This is good since it indicates that the drilling process is efficiently eliminating cuttings as they are formed at the drill bit, reducing excessive cuttings accumulation towards the well's bottom. With this data, the effectiveness of the Reverse Circulation was ready to be compared.

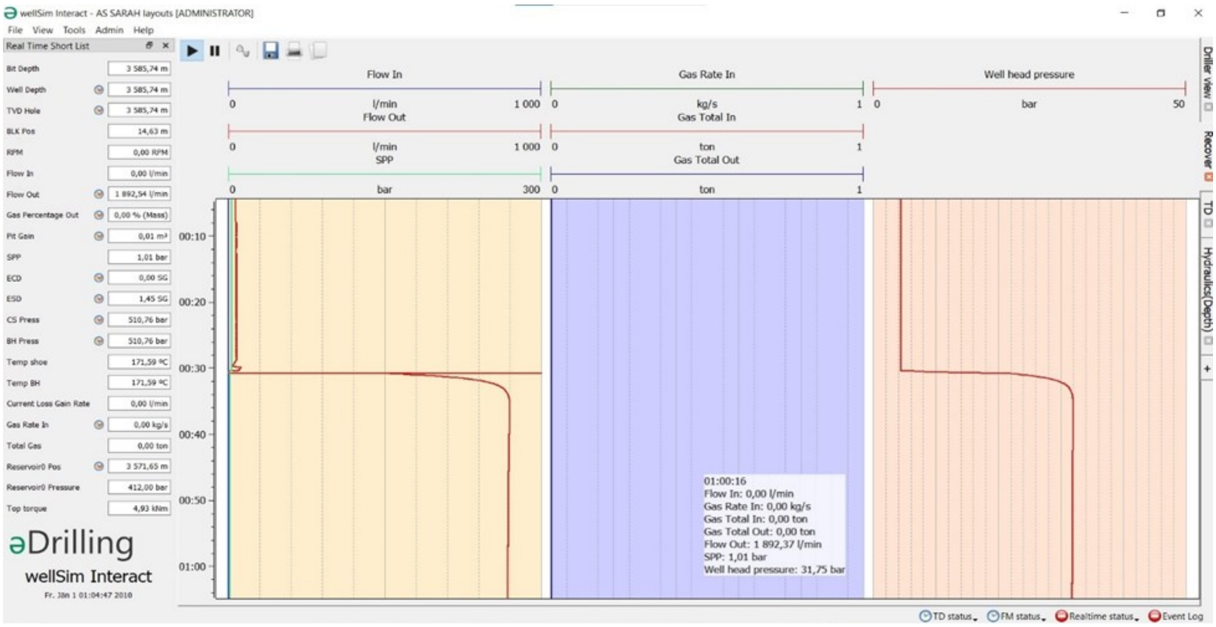
The same procedure followed, with drilling 45 ft (13.71 m) with an RPM of 220 and the block speed (ROP) of 30 m/h. After that, the drilling stopped and once again half an hour time was given for an appropriate effect of the cleaning. The IBOP and BOP were closed and the kill line and choke line were opened as we needed to pump the mud via the kill line, through the annulus, returning it through the pipes, and receiving it at the choke line, for this the choke also needed to be opened and the flow in kill was set up to 1892 l/min. Figure 4.8, Figure 4.9, Figure 4.10, and Figure 4.11 show the results of Reverse Circulation.



Bit Depth: 3 585,74 m
Well Depth: 3 585,74 m
TVD Hole: 3 585,74 m
BLK Pos: 14,63 m
RPM: 0,00 RPM
Flow In: 0,00 l/min
Flow Out: 1 892,54 l/min
Gas Percentage Out: 0,00 % (Mass)
Pit Gain: 0,01 m³
SPP: 1,01 bar
ECD: 0,00 SG
ESD: 1,45 SG
CS Press: 510,76 bar
BH Press: 510,76 bar
Temp shoe: 171,59 ºC
Temp BH: 171,59 ºC
Current Loss Gain Rate: 0,00 l/min
Gas Rate In: 0,00 kg/s
Total Gas: 0,00 ton
Reservoir0 Pos: 3 571,65 m
Reservoir0 Pressure: 412,00 bar
Top torque: 4,93 kNm

01:04:20
Bit Depth: 3 585,74 m
Well Depth: 3 585,74 m
ROP: 0,00 m/h
Mud Flow In: 0,00 l/min
Calc Pressure@pwd: 0,00 bar
Pit Gain: 0,01 m³
Calc Pressure@cs: 510,76 bar
Hook load: 157,08 ton
Volume Pumped: 63,94 m³
Calc Pressure@bottom: 510,76 bar
Calc Flow Out: 1 892,58 l/min
Calc SPP: 1,01 bar
Top torque: 4,93 kNm
Calc WOB: 2,18 ton

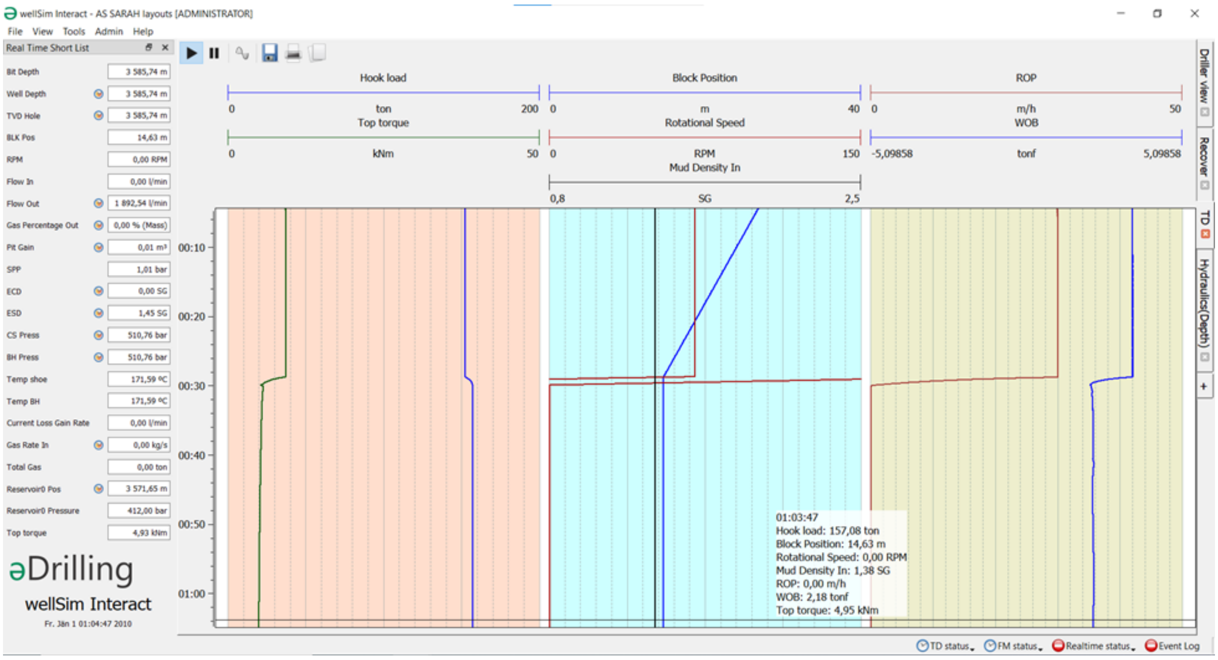
Figure 4. 8 - Reverse Circulation Driller View



Bit Depth	3 585,74 m
Well Depth	3 585,74 m
TVD Hole	3 585,74 m
BLK Pos	14,63 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	1 892,54 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,01 m³
SPP	1,01 bar
ECD	0,00 SG
ESD	1,45 SG
CS Press	510,76 bar
BH Press	510,76 bar
Temp shoe	171,59 ºC
Temp BH	171,59 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	4,93 kNm

01:00:16
Flow In: 0,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 1 892,37 l/min
SPP: 1,01 bar
Well head pressure: 31,75 bar

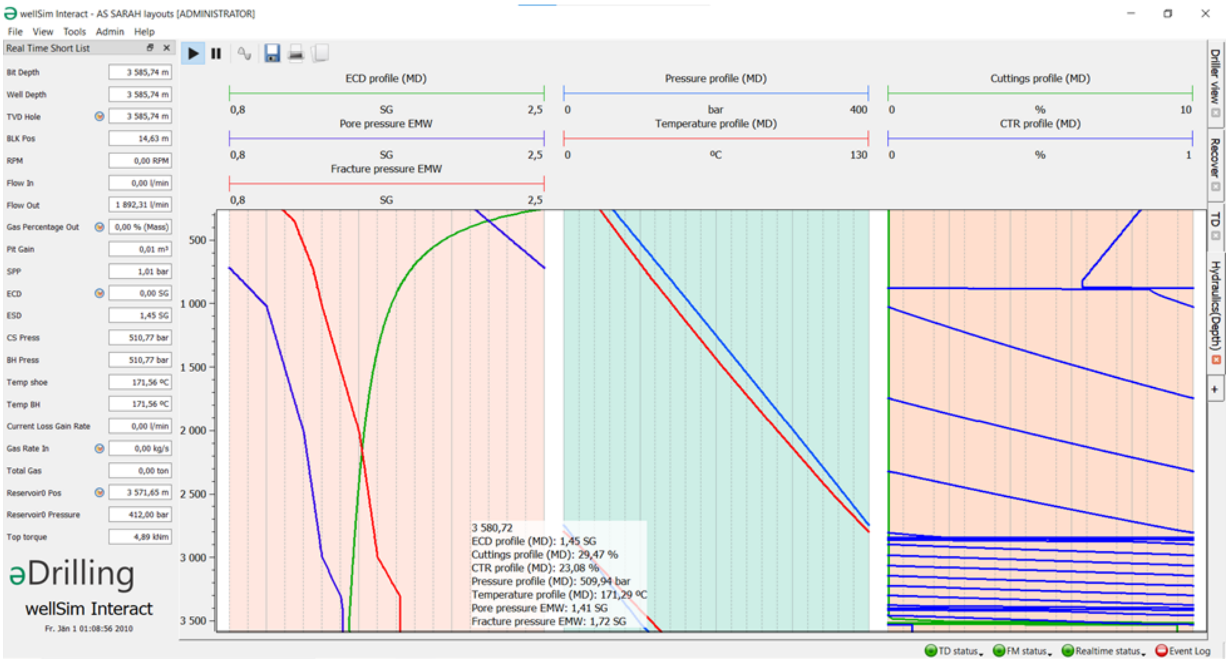
Figure 4. 9 - Reverse Circulation Recovery



Bit Depth	3 585,74 m
Well Depth	3 585,74 m
TVD Hole	3 585,74 m
BLK Pos	14,63 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	1 892,54 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,01 m³
SPP	1,01 bar
ECD	0,00 SG
ESD	1,45 SG
CS Press	510,76 bar
BH Press	510,76 bar
Temp shoe	171,59 ºC
Temp BH	171,59 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	4,93 kNm

01:03:47
Hook load: 157,08 ton
Block Position: 14,63 m
Rotational Speed: 0,00 RPM
Mud Density In: 1,38 SG
ROP: 0,00 m/h
WOB: 2,18 tonf
Top torque: 4,95 kNm

Figure 4. 10 - Reverse Circulation True Depth



Bit Depth	3 585,74 m
Well Depth	3 585,74 m
TVD Hole	3 585,74 m
BLK Pos	14,63 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	1 892,31 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,01 m³
SPP	1,01 bar
ECD	0,00 SG
ESD	1,45 SG
CS Press	510,77 bar
BH Press	510,77 bar
Temp shoe	171,56 ºC
Temp BH	171,56 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	4,89 kNm

3 580,72
ECD profile (MD): 1,45 SG
Cuttings profile (MD): 29,47 %
CTR profile (MD): 23,08 %
Pressure profile (MD): 509,94 bar
Temperature profile (MD): 171,29 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

Figure 4. 11 - Reverse Circulation Hydraulics Data

The results pressures for this case were, casing pressure and bottom hole pressure of 510.76 bar, reservoir pressure of 412 bar, wellhead pressure of 31.75 bar, pore pressure of 1.41 SG, fracture pressure of 1.72 SG, and standpipe pressure of 1.01 bar. This indicates higher pressures which come with differences in the drilling process and hydraulics between these two modes of circulation and with poorer cleaning properties. Regarding the cuttings, the cuttings transport rates was only 23.08% which is considered relatively low. The cuttings profile at the bottom was 29.47% and it suggests that a significant portion of the cuttings generated during drilling is not effectively being transported to the surface and is accumulating at the lower section of the wellbore. With these significantly worse results, it was necessary for further assessment and adjustments to optimize the process. This was done using iterations or simplified trials and errors to achieve the best-case scenario.

Going through multiple iterations in order to optimize the Reverse Circulation procedure was necessary. Firstly a smaller bit nozzle was inputted. Following that, a bigger nozzle, to see how it affected the drilling process compared to the previous nozzle size was experimented with. Rotating the drill pipes while circulating was also an option. The effects of mud density fluctuations, both high and low, on drilling performance were investigated. In addition, the wellbore's inclination was altered to various angles to determine its impact. It was also experimented with the diameter of the drill pipes, increasing and decreasing the diameter to see how it influenced the entire drilling operation. Also, the hole size to see how it affected drilling performance.

With the help of the iterations and the KPIs mentioned above, where the importance was to get lower pressures, higher cuttings transport rate, and lower cuttings profile the best-case scenario for the Reverse Circulation was made. The best-case scenario data (shown in Table 11) is to have a smaller nozzle size, to rotate the pipes while circulating, to have higher density mud, a higher/bigger diameter of the drilling pipes, and a bigger hole size.

Table 11 - Case 1 Best-case scenario data for RC

	Original scenario	**Best-case scenario**
Bit nozzle size	6x11	6x9
Rotating pipes while circulating	NO	YES
Mud density	11.5 ppg	12.5 ppg
The diameter of DP	5”	6”
Hole size	8.5”	10”

The implementation of a smaller nozzle size, such as the 6x9, allowed for more effective mud circulation and less pressure drop, both of which contributed to the overall success of the Reverse Circulation process. Keeping the drill pipes rotating while cycling the mud proved to be quite useful in maximizing the cutting's transport rate. Cuttings were easily carried to the surface thanks to the continual rotation, which prevented them from settling. Using greater density mud was critical in decreasing cuttings settling and improving overall pressure control. The higher density boosted hydraulic lift capability, which aided in cutting clearance. Increasing the diameter of the drill pipes resulted in higher flow rates and lower pressure drop. This modification accommodated the higher mud density and aided in the effective transfer of cuttings. By increasing the hole size, a more spacious conduit for the cuttings to ascend to the surface was constructed, resulting in a smaller cuttings profile and smoother Reverse Circulation [34].

The operation for it was the same as before, drilling 45 ft (13.71 m) with an RPM of 220 and a block speed of (ROP) 30 m/h. After that, the drilling stopped, the IBOP, and BOP were closed and the kill line and choke line were opened as we needed to pump the mud via the kill line, through the annulus, returning it through the pipes, and receiving it at the choke line, for this the choke also needed to be opened and the flow in kill was set up to 1892 l/min.

The results of all the optimization processes can be found in the Appendix at the end of this document. The results pressure after applying the optmimum prameters are: casing pressure and bottom hole pressure of 556.38 bar, reservoir pressure of 412 bar, wellhead pressure of 35.13 bar, pore pressure of 1.29 SG, fracture pressure of 1.59 SG, and standpipe pressure of 1.01 bar. Cuttings transport rate is now 100% and cuttings profile 23.54%. Achieving 100% cuttings transfer vs 23.08% in the standard case is a significant improvement. It means that the changes effectively improved the system for transporting all cuttings to the surface while preventing them from settling and producing clogs. Reducing the cuttings profile to 23.54%, as opposed to 29.54% in the standard case, is another positive outcome. This means that the cuttings are more evenly distributed, minimizing the risk of any issues related to cuttings accumulation.

Regarding the pressures, the formation and pore pressure are reduced which can help prevent formation damage and improve wellbore stability. Higher casing and bottom hole pressures may be favorable in some drilling conditions, particularly where maintaining wellbore stability and preventing fluid influx or well control issues is critical. In this scenario, this might be due to increased mud density and other alterations. Higher wellhead pressure is frequently related to maintaining control and safety during drilling operations [31]. The comparison of the results of normal circulation, standard Reverse Circulation, and best-case RC scenario can be seen in Table 12.

Table 12 - Case 1 Comparison of the results

	Normal circulation	**Reverse Circulation**	**Best-case RC**
Casing pressure	483.22 bar	510.76 bar	556.38 bar
Bottom hole pressure	483.22 bar	510.76 bar	556.38 bar
Reservoir pressure	412 bar	412 bar	412 bar
Wellhead pressure	4.27 bar	31.75 bar	35.13 bar
Pore pressure	1.41 bar	1.41 bar	1.29 bar
Fracture pressure	1.72 bar	1.72 bar	1.59 bar
Standpipe pressure	124.7 bar	1.01 bar	1.01 bar
CTR	100%	23.08%	100%
Cuttings profile	0.19%	29.47%	23.54%

As the data used originated from the same well for all three cases and considering the time required to attain the optimum parameters, it was decided to employ similar optimal parameters for Cases 2 and 3.

4.4.2 Case #2

The goal of case 2 was to compare the effectiveness of Reverse Circulation hole cleaning in comparison to normal circulation after the section was drilled from 11 885 ft (3622.5 m) to 11 945ft (3640.8 m), and to get even better results out of the best-case scenario for RC. A simple well configuration sketch for Case 2 is shown in Figure 4.12.

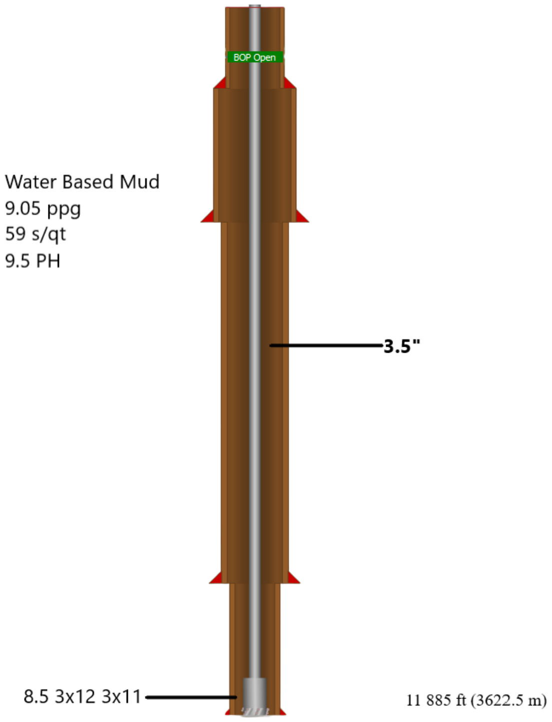


Figure 4. 12 - Case 2 Well Configuration

After drilling 60 ft (18.3 m) with an RPM of 60 and a block speed (ROP) of 30 m/h drilling was stopped, and cleaning of the cuttings with normal circulation started. A half an hour time was given for an appropriate effect of the cleaning. The IBOP and BOP were left open and the booster line, kill line, and choke line were closed. After that, the flow in kelly necessary for pumping the mud through the pipes, cleaning the cuttings at the bottom, and returning back through the annulus was put to the value of 1041 l/min. The graphical presentations of the results of normal circulation can be found in the Appendix.

In this case, the casing pressure and bottom hole pressure were 399 bar, reservoir pressure of 412 bar, wellhead pressure of 3.67 bar, pore pressure of 1.41 SG, fracture pressure of 1.72 SG, and Standpipe pressure of 757.96 bar.

Regarding the cuttings, the normal circulation was very effective with a good cuttings transport rates of 100% which means that the process is effectively and completely removing all the cuttings from the wellbore as they are generated at the drill bit and the cuttings profile of 00 % at the bottom. This suggests that there is a very low to non-concentration of cuttings at bottom hole.

As conducted in previous case, the same procedure followed, with drilling 60 ft (18.3 m) with the RPM of 60 and the block speed (ROP) of 30 m/h. After that, the drilling stopped and once again half an hour time was given for an appropriate effect of the cleaning. The IBOP and BOP were closed and the kill line and choke line were opened as we needed to pump the mud via the kill line, through the annulus, returning it through the pipes, and receiving it at the choke line, for this the choke also needed to be opened and the flow in kill was set up to 1041 l/min. The graphical presentations of the results of Reverse Circulation of this case can be found in the Appendix. The results pressures were as follows: casing pressure and bottom hole pressure of 391 bar, reservoir pressure of 412 bar, wellhead pressure of 10.26 bar, pore pressure of 1.41 SG, fracture pressure of 1.72 SG, and standpipe pressure of 13.14 bar. This indicates higher pressures which come with differences in the drilling process and hydraulics between these two modes of circulation and with poorer cleaning properties. Regarding the cuttings, the cuttings transport rates profile was only 28.65% which is considered relatively low. With these significantly worse results, it was necessary to simulate the best-case scenario as in Case 1. The best-scenario data is shown in Table 13.

Table 13 - Case 2 Best-case scenario data for RC

	Original scenario	**Best-case scenario**
Bit nozzle size	3x12 3x11	6x9
Rotating pipes while circulating	NO	YES
Mud density	9.05 ppg	12.5 ppg
The diameter of DP	3.5”	6”
Hole size	8.5”	10”

The graphical presentations of the simulator results after applying the optimal parameters can be found in the Appendix. The comparison of the results of normal circulation, standard Reverse Circulation, and best-case RC scenario can be seen in Table 14.

Table 14 - Case 2 Comparison of the results

	Normal circulation	Reverse Circulation	Best-case RC
Casing pressure	399 bar	391 bar	315.86 bar
Bottom hole pressure	399 bar	391 bar	395.27 bar
Reservoir pressure	412 bar	412 bar	412 bar
Wellhead pressure	3.67 bar	10.26 bar	9.26 bar
Pore pressure	1.41 bar	1.41 bar	1.41 bar
Fracture pressure	1.72 bar	1.72 bar	1.72 bar
Standpipe pressure	757.96 bar	13.14 bar	14.15 bar
CTR	100%	28.65%	100%
Cuttings profile	0.00%	0.00%	0.00%

Obtaining the results in terms of Cuttings Transport Rate (100%) and a Cuttings Profile (0%) indicates consistent hole cleaning performance. As the pressures are slightly lower while using Reverse Circulation than normal, it can be said that the ideal Reverse Circulation case is better than normal circulation.

4.4.3 Case #3

A basic well configuration diagram for Case 3 is illustrated in Figure 4.13. Case 3 played a significant role in validating the data acquired in the first two cases. The section was drilled from 11,238 ft (3,425 m) to 11,300 ft (3,444 m), followed by the hole cleaning process. The same procedures that were employed in the previous two cases were applied to the third case.

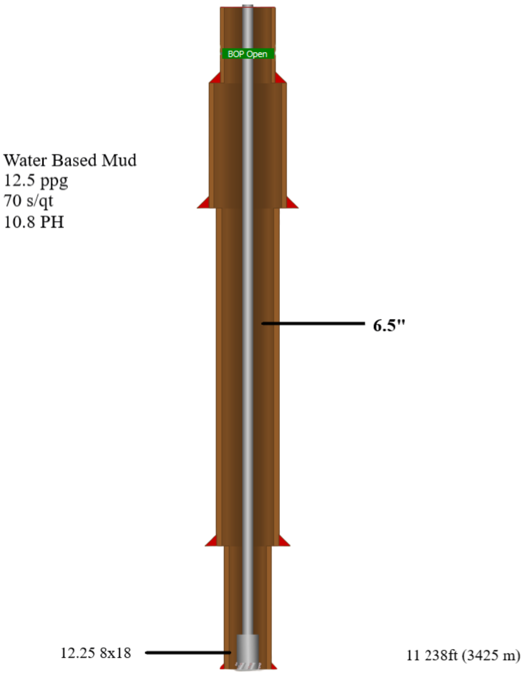


Figure 4. 13 - Case 3 Well Configuration

After drilling 62 ft (18.9 m) with an RPM of 118 and the block speed (ROP) of 30 m/h. The drilling was stopped, and cleaning of the cuttings with normal circulation started. A half an hour time was given for an appropriate effect of the cleaning. The IBOP and BOP were left open and the booster line, kill line, and choke line were closed. After that, the flow in kelly necessary for pumping the mud through the pipes, cleaning the cuttings at the bottom, and returning back through the annulus was put to the value of 2081 l/min. The simulator results for this case can be found in the appendix. The results pressures were as follows: casing pressure and bottom hole pressure of 537.95 bar, reservoir pressure of 412 bar, wellhead pressure of 4.66 bar, pore pressure of 1.41 SG, fracture pressure of 1.72 SG, and standpipe pressure of 168.65 bar.

For cuttings transport rate and cuttings profile, the results are that at the bottom, there is a 100% cuttings transport rate and a 0% cuttings profile. A cutting transport rate of 100% indicates that the drilling mud is efficiently transporting all of the cuttings formed at the bottom. The cuttings profile at the bottom of 0% shows that no cuttings are collecting at this depth. This is a good indicator. At 6053 feet (1845 m), the cuttings transport rate is 100% and the cuttings profile is 2.79%. A cuttings transport rate of 100% at that depth indicates that the drilling fluid is efficiently transporting the cuttings at this level, which is also a great indicator. With a cuttings profile of 2.79%, despite the high transport rate, a tiny fraction of the cuttings created at this level is not efficiently eliminated by the drilling mud.

As as previous, the same procedure followed, with drilling 62 ft (18.9 m) with an RPM of 118 and the block speed of 30 m/h. After that, the drilling stopped and once again half an hour time was given for an appropriate effect of the cleaning. The IBOP and BOP were closed and the kill line and choke line were opened as we needed to pump the mud via the kill line, through the annulus, returning it through the pipes, and receiving it at the choke line, for this the choke also needed to be opened and the flow in kill was set up to 2081 l/min. The graphical presentations of the results of normal circulation can be found in the Appendix.

The recorded pressures for the RC in this case were: casing pressure and bottom hole pressure were both 575.88 bar, reservoir pressure of 412 bar, wellhead pressure of 4.66 bar, pore pressure of 1.41 SG, fracture pressure of 1.72 SG, and standpipe pressure of 72.64 bar. Reverse Circulation appears to increase casing and bottom hole pressures while decreasing standpipe pressure substantially. The critical reservoir, pore, wellhead, and fracture pressure variables are the same for both circulation techniques.

At the bottom, the cuttings transport rate was just 40.44%. This means that eliminating a significant amount of the cutings at the bottom may be challenging. A bottom cuttings profile of 84.80% indicates that a significant amount of the cuttings remain within the wellbore, perhaps posing a danger of hole instability. This is less than ideal and shows that there has been a considerable accumulation of cutings. A cuttings transport rate of 19.75% at 6053 feet (1845 m) is considered poor. A 0% cuttings profile at that depth indicates no accumulation at that time, but the situation might quickly change if drilling circumstances alter. The transport rate in normal circulation was much greater (100%) at both depths, indicating more effective cutting removal than in Reverse Circulation when transport rates were lower. Normal circulation showed low or no accumulation at both depths, whereas Reverse Circulation showed a large buildup at the bottom and no accumulation at the intermediate depth. The ideal scenario was once again implemented, and its data is shown in Table 15.

Table 15 - Case 3 Best-case scenario data for RC

	Original scenario	**Best-case scenario**
Bit nozzle size	8x18	8x9
Rotating pipes while circulating	NO	YES
Mud density	12.5 ppg	15 ppg
The diameter of DP	6.5”	8”
Hole size	12.25”	15”

The graphical presentations of the simulator results after applying the optimal parameters can be found in the Appendix. The result pressures as depicted in the figures located in the appendix, for these practical scenarios are: casing pressure of 570.05 bar, and bottom hole pressure of 672.09 bar, reservoir pressure of 412 bar, wellhead pressure of 69.9 bar, pore pressure of 1.41 SG, fracture pressure of 1.72 SG, and standpipe pressure of 70.38 bar. The casing and bottom hole pressures are higher in the ideal Reverse Circulation scenario compared to normal circulation but lower in the normal Reverse Circulation scenario. This implies that in the ideal Reverse Circulation situation, the drilling process is steadier and more regulated than in the non-ideal condition. In the ideal Reverse Circulation scenario, standpipe pressure is relatively low, suggesting that the drilling fluid in the wellbore is not under excessive pressure. This is comparable to the issue of non-ideal Reverse Circulation. Reservoir pressure, pore pressure, and fracture pressure all stay stable. Contrary to what was expected, wellhead pressure was the highest in an ideal environment. The ideal Reverse Circulation case has acceptable steady pressures, with a higher bottom hole pressure than normal circulation but a lower pressure than the non-ideal Reverse Circulation example. The rise in wellhead pressure in the perfect Reverse Circulation instance might be related to a variety of operational factors.

At the bottom of the well, the cuttings transport rate was 100%. This is ideal, with extremely effective cuttings removal at the bottom. A cuttings profile of 0% indicates that there is no cuttings buildup. Cuttings transport rate was 92.69% at depths of 6053 feet (1845 m) and 6063 feet (1848 m). This number indicates an extremely fast transport rate, and excellent cutting removal. A cuttings profile of 0% at that depth, like the bottom depth, indicates that no cuttings are collecting there. It suggests that the drilling fluid is efficiently transporting all of the cuttings produced at this depth. The comparison of the results of normal circulation, standard Reverse Circulation, and best-case RC scenario can be seen in Table 16.

Table 16 - Case 3 Comparison of the results

	Normal circulation	**Reverse Circulation**	**Best-case RC**
Casing pressure	537.95 bar	575.88 bar	570.05 bar
Bottom hole pressure	537.95 bar	575.88 bar	672.09 bar
Reservoir pressure	412 bar	412 bar	412 bar
Wellhead pressure	4.66 bar	4.66 bar	69.9 bar
Pore pressure	1.41 bar	1.41 bar	1.41 bar
Fracture pressure	1.72 bar	1.72 bar	1.72 bar
Standpipe pressure	168.65 bar	72.64 bar	70.38 bar
CTR	100%	40.44%	100%
Cuttings profile	0.00%	84.80%	0.00%

Compared to the scenarios before, the results indicated a 100% cuttings transit rate and a 0% cuttings profile at the bottom in normal circulation, which is close to the ideal Reverse Circulation situation. However, in normal circulation, the cuttings profile was 2.79% at 6053 ft (1845 m), indicating a minor buildup. The cuttings transport rate in the non-ideal Reverse Circulation scenario was 19.75% at that depth, which was much lower than in the ideal, implying less efficient cuttings removal. Furthermore, there was no cuttings buildup at that depth (0% cuttings profile) in the non-ideal example, which is consistent with the ideal situation. With a 100% cuttings transport rate and a 0% cuttings profile, the perfect Reverse Circulation case stands out for its very effective cuttings removal at both the bottom of the well and other depths.

4.5 Case Study Conclusion

Case 1

- Lower casing and bottom hole pressures were observed in normal circulation while higher casing and bottom hole pressures were observed in Reverse Circulation.
- The normal circulation had an ideal cuttings transport rate (100%) and a low cuttings profile (0.19%) at the bottom, indicating efficient cuttings removal.
- The standard scenario of Reverse Circulation had a lower cuttings transport rate (23.08%) and a higher cuttings profile (29.47%) at the bottom, indicating less effective cuttings removal and buildup difficulties.
- In the best-case scenario for Reverse Circulation, the system was significantly improved, achieving a 100% cuttings transport rate and a lower cuttings profile (23.54%) at the bottom, showing successful optimization of the RC.
- The best-case scenario for Reverse Circulation provided better cuttings transport efficiency compared to the standard Reverse Circulation case and approached the performance of normal circulation.

Case 2

- The pressures were this time similar in both normal and Reverse Circulation standard and best case.
- In the normal circulation scenario, there was an ideal cuttings transport rate (100%) and an extremely low cuttings profile (0%) at the bottom, indicating highly efficient cuttings removal and no cuttings accumulation.
- In the standard Reverse Circulation case, the CTR profile was only 28.65% which is considered relatively low.
- In the best-case scenario for Reverse Circulation, the system was significantly improved, achieving a 100% cuttings transport rate and a 0% cuttings profile, indicating highly efficient cuttings removal.

Case 3

- Except for SPP, there were slightly lower pressures in normal circulation than in both Reverse Circulation cases.
- In normal circulation, there was an ideal cuttings transport rate (100%) and a very low cuttings profile (0%) at the bottom, indicating efficient cuttings removal.
- In the Reverse Circulation standard case there was a lower cuttings transport rate (40.44%) at the bottom and a significant cuttings profile (84.80%), suggesting issues with cuttings removal and accumulation.

- At 6053 feet (1845 m), normal circulation was also much better with the cuttings transport rate at 100% and the cuttings profile of 2.79% than RC standard case with only 19.75% cuttings transport rate.
- As for the best-case scenario for Reverse Circulation, the system was significantly improved, achieving a 100% cuttings transport rate at the bottom and a cuttings transport rate of 92.69% at 6053 feet (1845 m), and a 0% cuttings profile at both depths, indicating highly efficient cuttings removal.

From the data aquired, the pressure profile was slightly lower in standard Reverse Circulation then in normal circulation. That was expected because during normal circulation higher pressure is at the bottom of the wellbore due to the fluid being pumped down the drill string, and the pressure profile in Reverse Circulation has lower pressure at the wellbore bottom as drilling fluid is pumped down the annulus and back up through the inside of the drill string. The much lower pressure profile in the best-case scenario for Reverse Circulation is due to the combination of input factors and modifications made to the drilling system. The changes that contributed to a more efficient drilling system, resulting in a lower pressure profile and reduced pressure drop are:

- Smaller nozzle size that increased fluid velocity
- Rotation of the pipes that prevented cuttings accumulation
- Higher density mud which achieved better cuttings transport
- Larger drill pipe diameter accommodating higher flow rates
- Bigger hole size allowing easier fluid flow

To sum up, the case studies constantly showed that normal circulation outperformed Reverse Circulation in terms of cuttings transport efficiency at lower or equal pressures. However, with appropriate input changes, the best-case scenario for Reverse Circulation matched or even exceeded the performance of normal circulation, demonstrating that the Reverse Circulation process can be optimized for more effective cuttings removal and wellbore stability. These results show the relevance of proper drilling optimization in Reverse Circulation operations.

4.6 Drilling Simulator Limitations and Possible Improvements

The following are the limitations of the eDrilling simulator observed during the establishment of the case studies.

The biggest limitation of the eDrilling simulator was that the Reverse Circulation could only be represented by putting a flow in, opening the kill and choke lines, closing the BOP, and opening the choke in "Drilling control-Well Kill Manager". The problem with this method is that the visualization is not good enough, there is no distinction between normal and Reverse Circulation as the simulator does not provide information about the flow direction or does not distinguish the ECD by colors. The reason for this was that the simulator was not designed for Reverse Circulation but especially for failure cases and worst-case scenarios such as stuck pipe, leaking BOP, pack-off, losses, nozzle blockage, etc.

Another limitation was that the Reverse Circulation cementing case scenario was not possible because the simulator does not provide the capability to input the pump-out float collar, which is a crucial component for simulating Reverse Circulation cementing effectively. The software only offers the input float, which is the conventional float which is not suitable for the Reverse Circulation cementing scenario.

Based on these limitations, the possible improvements based on RC case studies should be to enhance the visualization of Reverse Circulation to clearly distinguish it from normal circulation. This can be achieved by adding arrows or directional indicators that show the flow direction of the mud.

Another improvement is ECD-Based Color Coding where the mud's color is based on its equivalent circulating density. Higher ECD mud could be represented with darker colors, making it visually distinct from lower ECD mud. This would allow users to quickly identify areas of mud mixed with cuttings.

The user interface could also be improved to provide more detailed information. This could include real-time data on flow direction, ECD, and other relevant parameters, helping users better understand the operations.

As for cementing limitation, there should be an ability to input a pump-out float collar, which is crucial for simulating Reverse Circulation cementing effectively. The software should support both conventional floats and specialized pump-out floats.

All of this could be possible with a feedback system within the simulator that allows users to report errors, suggest changes, or request new features.

All in all, eDrilling should implement Reverse Circulation as a viable option for simulating cases.

Chapter 5

5 Conclusion and Future Work

This thesis has provided a thorough analysis of the efficiency and performance of Reverse Circulation drilling in the oil and gas sector when compared with conventional drilling methods. The goal was to analyze RC drilling in various drilling settings in order to acquire insight into its advantages and limitations. The following points summarize the main conclusions of the work presented in this thesis:

1. Reverse Circulation drilling can be a valuable method when dealing with comlex formations because of the reversed flow.

2. . RCC increases the overall efficiency of cementing operations, and reduces the usage of costly additives

3. RC hole cleaning efficiently mitigates fluid loss difficulities in comparison to normal circulation.

4. Furthermore, RC enhances drilling efficiency, and provides well control flexibility. On the other hand, RC can lead to borehole instability, it presents more potential environmental impact, and it utilizes special equipment which is expensive.

5. Through the various eDrilling simulations and cases, where normal and Reverse Circulation were compared, variations in casing and bottom hole pressures became evident, with normal circulation consistently showing lower pressures. Notably, normal circulation showed exceptional efficiency in cuttings removal, maintaining a 100% cuttings transport rate and a minimal 0.19% to 0% cuttings profile at the wellbore's base.

6. As for Reverse Circulation, the standard case showed high cuttings profile 29.47 to 84.80 %, and low cuttings transport rate 23.08-40.44%, and the ideal case showed a 100% cuttings transport rate and a reduced cuttings profile of 0 to 23.54% With that the simulation showed that, with careful parameter optimization, RC drilling can have similar or even better results than normal circulation in terms of cuttings transport and pressure control.

7. It is crucial to note that this study is not thorough and has certain limitations. The reliance on only one simulation tool, which may not reproduce real-world drilling circumstances, is one such constraint. Real field testing and validation are required to evaluate how successful RC actually is.

8. RC can be an innovative approach within the oil and gas industry, in specific cases and input parameters. However, field trials and improvement in the eDrilling simulation tool will be necessary to unlock its full potential. Before making it a choice for the operation in the industry, it is mostly important to conduct a comprehensive economic analysis to evaluate the cost-effectiveness of RC drilling, considering the potential savings in operational costs and reduced downtime.

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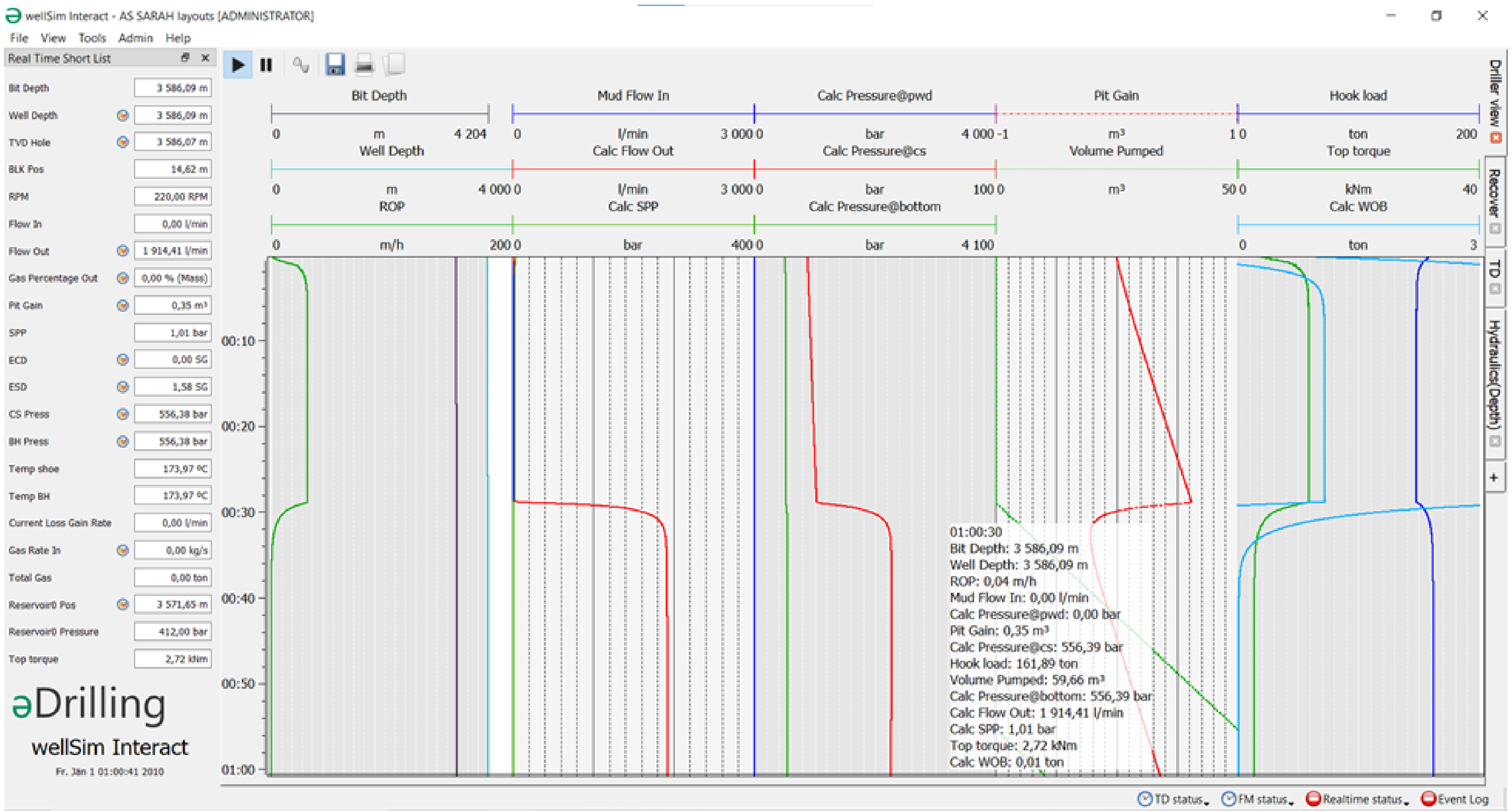
7 Appendix



wellSim Interact - AS SARAH layouts [ADMINISTRATOR]

File View Tools Admin Help

Real Time Short List

Bit Depth: 3 586,09 m
Well Depth: 3 586,09 m
TVD Hole: 3 586,07 m
BLK Pos: 14,62 m
RPM: 220,00 RPM
Flow In: 0,00 l/min
Flow Out: 1 914,41 l/min
Gas Percentage Out: 0,00 % (Mass)
Pit Gain: 0,35 m³
SPP: 1,01 bar
ECD: 0,00 SG
ESD: 1,58 SG
CS Press: 556,38 bar
BH Press: 556,38 bar
Temp shoe: 173,97 ºC
Temp BH: 173,97 ºC
Current Loss Gain Rate: 0,00 l/min
Gas Rate In: 0,00 kg/s
Total Gas: 0,00 ton
Reservoir0 Pos: 3 571,65 m
Reservoir0 Pressure: 412,00 bar
Top torque: 2,72 kNm

01:00:30
Bit Depth: 3 586,09 m
Well Depth: 3 586,09 m
ROP: 0,04 m/h
Mud Flow In: 0,00 l/min
Calc Pressure@pwd: 0,00 bar
Pit Gain: 0,35 m³
Calc Pressure@cs: 556,39 bar
Hook load: 161,89 ton
Volume Pumped: 59,66 m³
Calc Pressure@bottom: 556,39 bar
Calc Flow Out: 1 914,41 l/min
Calc SPP: 1,01 bar
Top torque: 2,72 kNm
Calc WOB: 0,01 ton

Figure 4. 14 - Reverse Circulation Driller View Ideal Scenario

Bit Depth	3 586,09 m
Well Depth	3 586,09 m
TVD Hole	3 586,07 m
BLK Pos	14,62 m
RPM	220,00 RPM
Flow In	0,00 l/min
Flow Out	1 914,41 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,35 m³
SPP	1,01 bar
ECD	0,00 SG
ESD	1,58 SG
CS Press	556,38 bar
BH Press	556,38 bar
Temp shoe	173,97 ºC
Temp BH	173,97 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	2,72 kNm

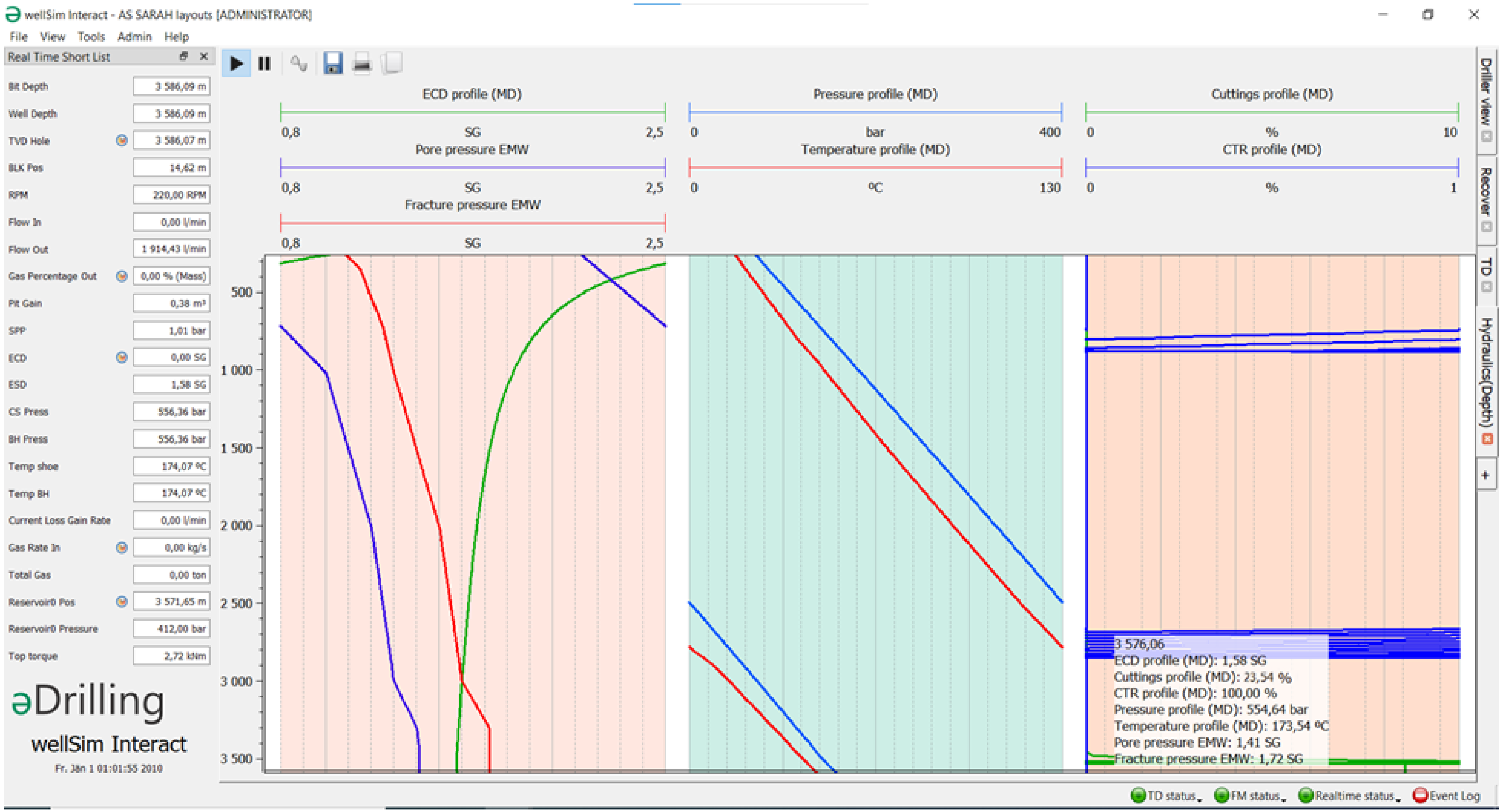
01:00:35
Flow In: 0,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 1 914,41 l/min
SPP: 1,01 bar
Well head pressure: 35,13 bar

Figure 4. 15 - Reverse Circulation Recovery Ideal Scenario

Bit Depth	3 586,09 m
Well Depth	3 586,09 m
TVD Hole	3 586,07 m
BLK Pos	14,62 m
RPM	220,00 RPM
Flow In	0,00 l/min
Flow Out	1 914,41 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,35 m³
SPP	1,01 bar
ECD	0,00 SG
ESD	1,58 SG
CS Press	556,38 bar
BH Press	556,38 bar
Temp shoe	173,97 ºC
Temp BH	173,97 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	2,72 kNm

01:00:30
Hook load: 161,89 ton
Block Position: 14,62 m
Rotational Speed: 220,00 RPM
Mud Density In: 1,50 SG
ROP: 0,04 m/h
WOB: 0,01 tonf
Top torque: 2,72 kNm

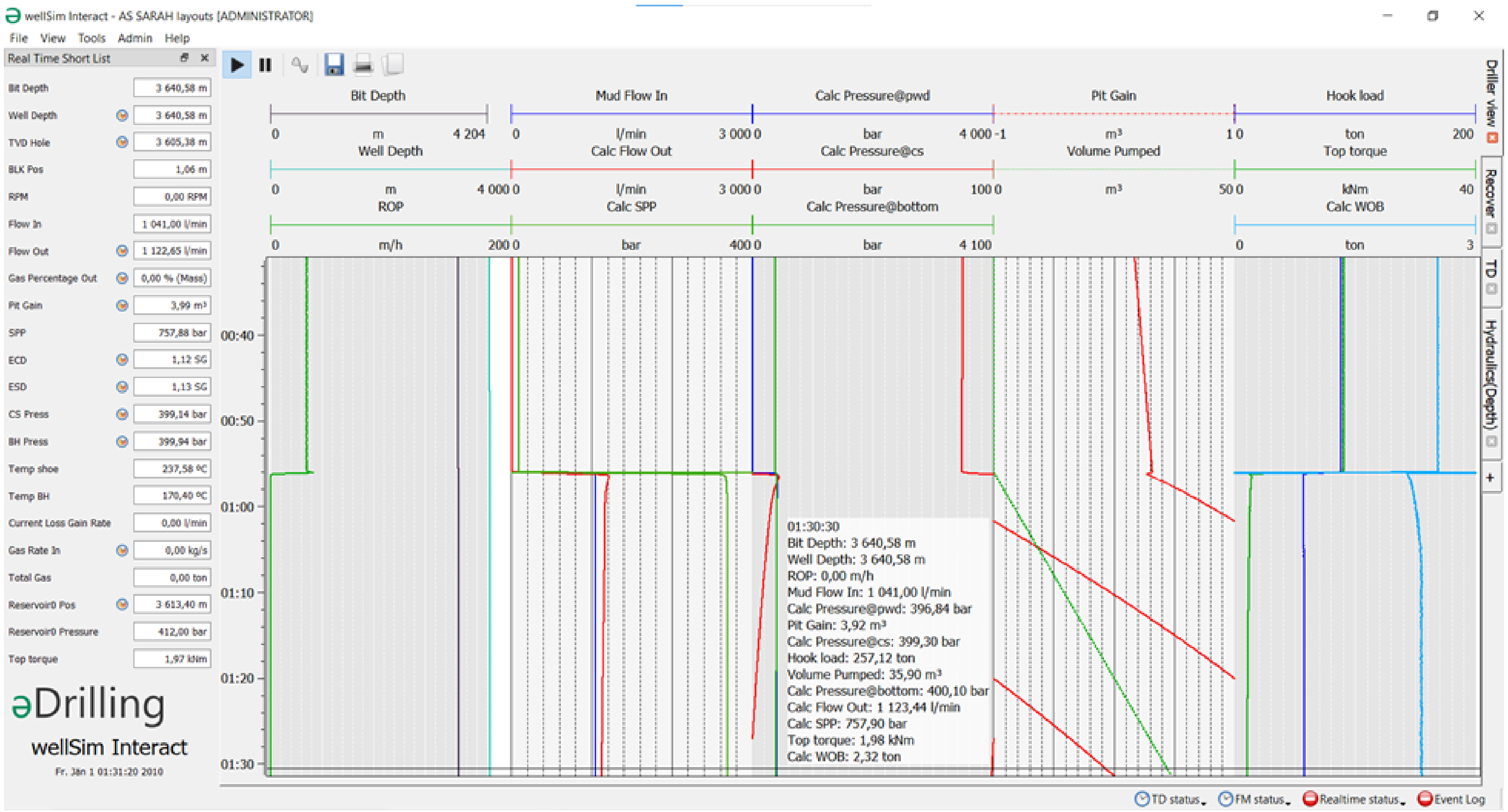
Figure 4. 16 - Reverse Circulation True Depth Ideal Scenario



Bit Depth	3 586,09 m
Well Depth	3 586,09 m
TVD Hole	3 586,07 m
BLK Pos	14,62 m
RPM	220,00 RPM
Flow In	0,00 l/min
Flow Out	1 914,43 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,38 m³
SPP	1,01 bar
ECD	0,00 SG
ESD	1,58 SG
CS Press	556,36 bar
BH Press	556,36 bar
Temp shoe	174,07 ºC
Temp BH	174,07 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 571,65 m
Reservoir0 Pressure	412,00 bar
Top torque	2,72 kNm

3 576,06
ECD profile (MD): 1,58 SG
Cuttings profile (MD): 23,54 %
CTR profile (MD): 100,00 %
Pressure profile (MD): 554,64 bar
Temperature profile (MD): 173,54 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

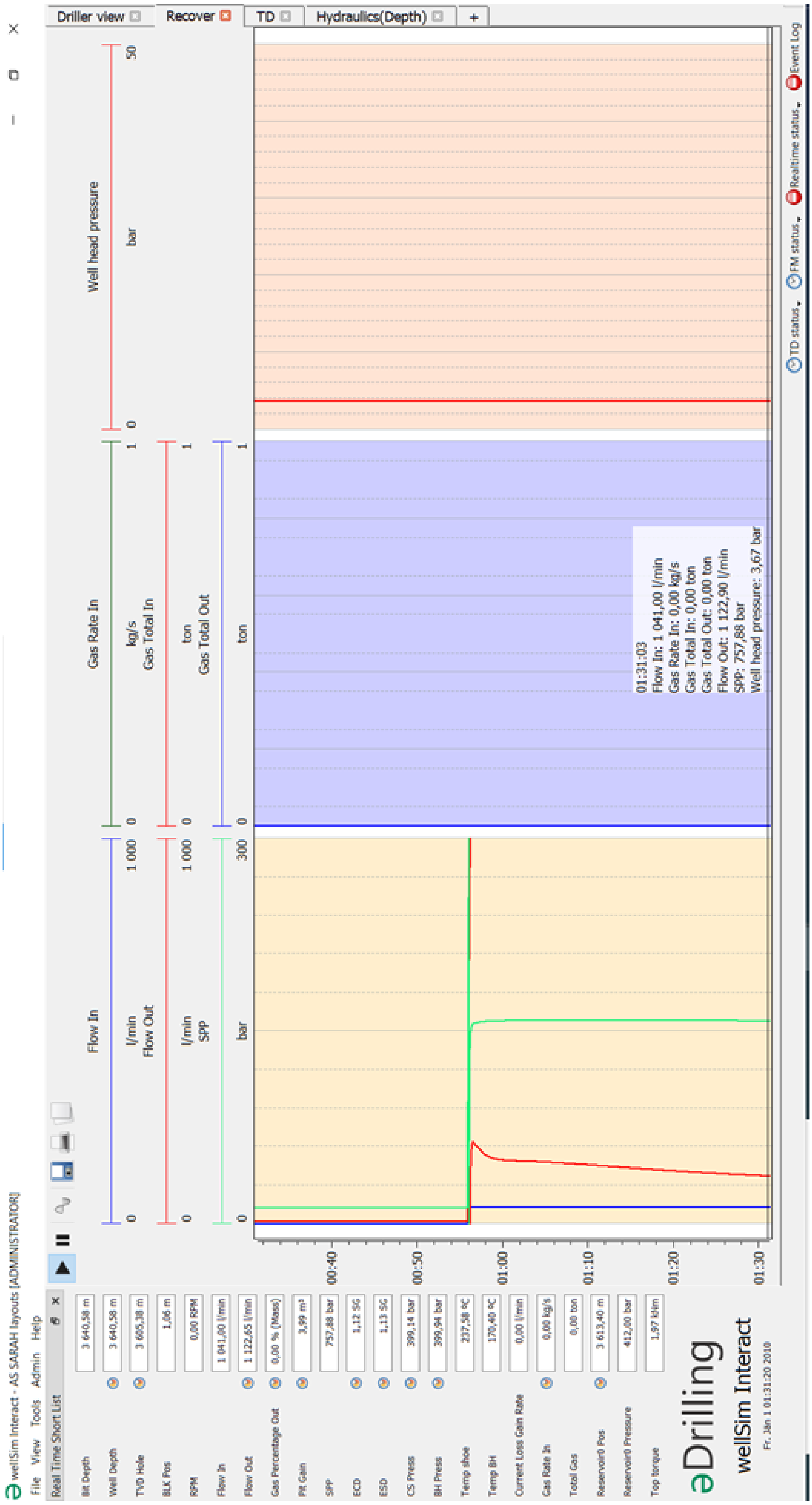
Figure 4. 17 - Reverse Circulation Hydraulics Data Ideal Scenario



Bit Depth: 3 640,58 m
Well Depth: 3 640,58 m
TVD Hole: 3 605,38 m
BLK Pos: 1,06 m
RPM: 0,00 RPM
Flow In: 1 041,00 l/min
Flow Out: 1 122,65 l/min
Gas Percentage Out: 0,00 % (Mass)
Pit Gain: 3,99 m³
SPP: 757,88 bar
ECD: 1,12 SG
ESD: 1,13 SG
CS Press: 399,14 bar
BH Press: 399,94 bar
Temp shoe: 237,58 ºC
Temp BH: 170,40 ºC
Current Loss Gain Rate: 0,00 l/min
Gas Rate In: 0,00 kg/s
Total Gas: 0,00 ton
Reservoir0 Pos: 3 613,40 m
Reservoir0 Pressure: 412,00 bar
Top torque: 1,97 kNm

01:30:30
Bit Depth: 3 640,58 m
Well Depth: 3 640,58 m
ROP: 0,00 m/h
Mud Flow In: 1 041,00 l/min
Calc Pressure@pwd: 396,84 bar
Pit Gain: 3,92 m³
Calc Pressure@cs: 399,30 bar
Hook load: 257,12 ton
Volume Pumped: 35,90 m³
Calc Pressure@bottom: 400,10 bar
Calc Flow Out: 1 123,44 l/min
Calc SPP: 757,90 bar
Top torque: 1,98 kNm
Calc WOB: 2,32 ton

Figure 4. 18 - Normal circulation Driller View Case 2

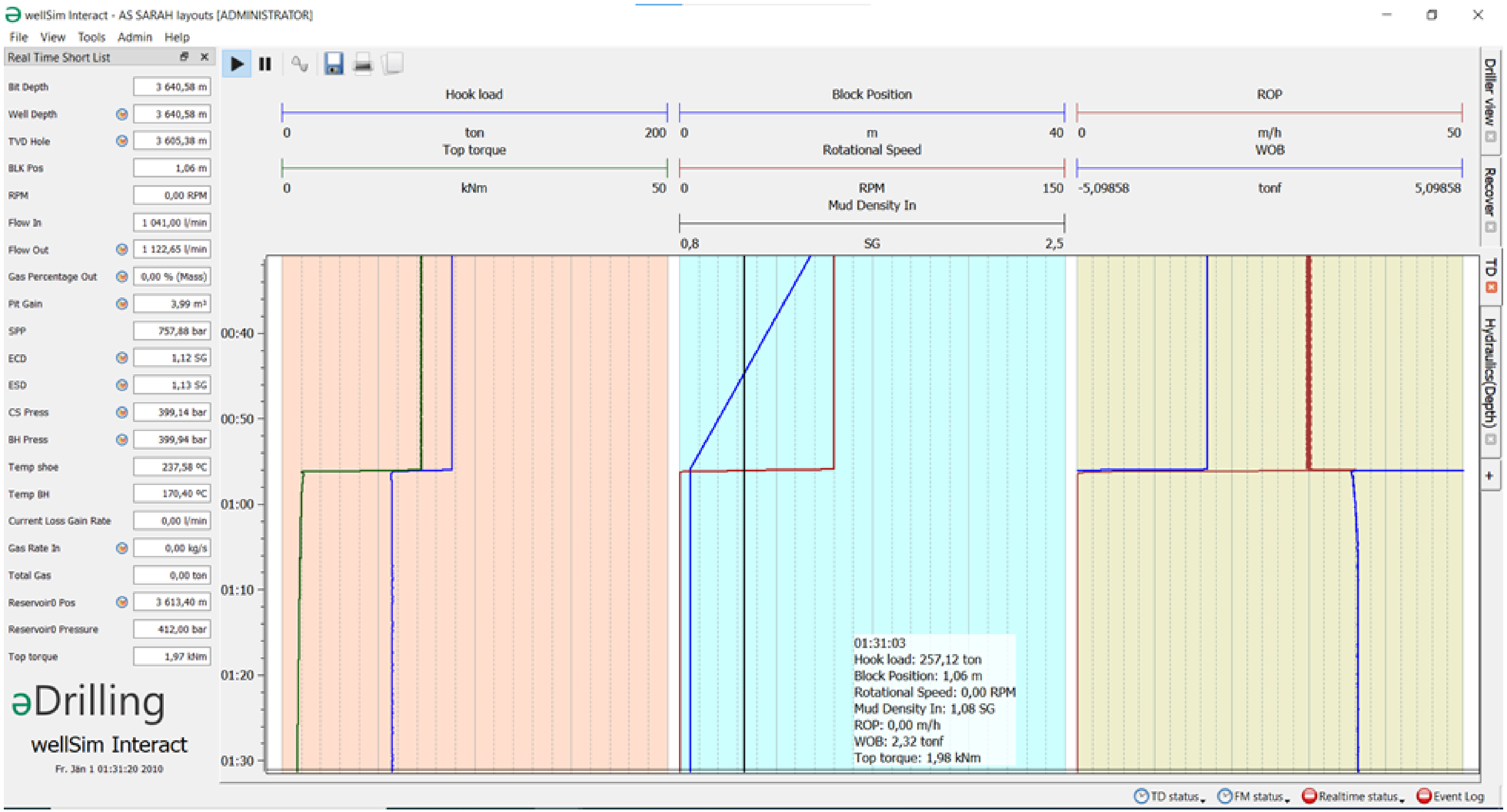


Real Time Short List

Bit Depth	3 640,58 m
Well Depth	3 640,58 m
TVD Hole	3 605,38 m
BLK Pos	1,06 m
RPM	0,00 RPM
Flow In	1 041,00 l/min
Flow Out	1 122,65 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	3,99 m³
SPP	757,88 bar
ECD	1,12 SG
ESD	1,13 SG
CS Press	399,14 bar
BH Press	399,94 bar
Temp shoe	237,58 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	1,97 kNm

01:31:03
Flow In: 1 041,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 1 122,90 l/min
SPP: 757,88 bar
Well head pressure: 3,67 bar

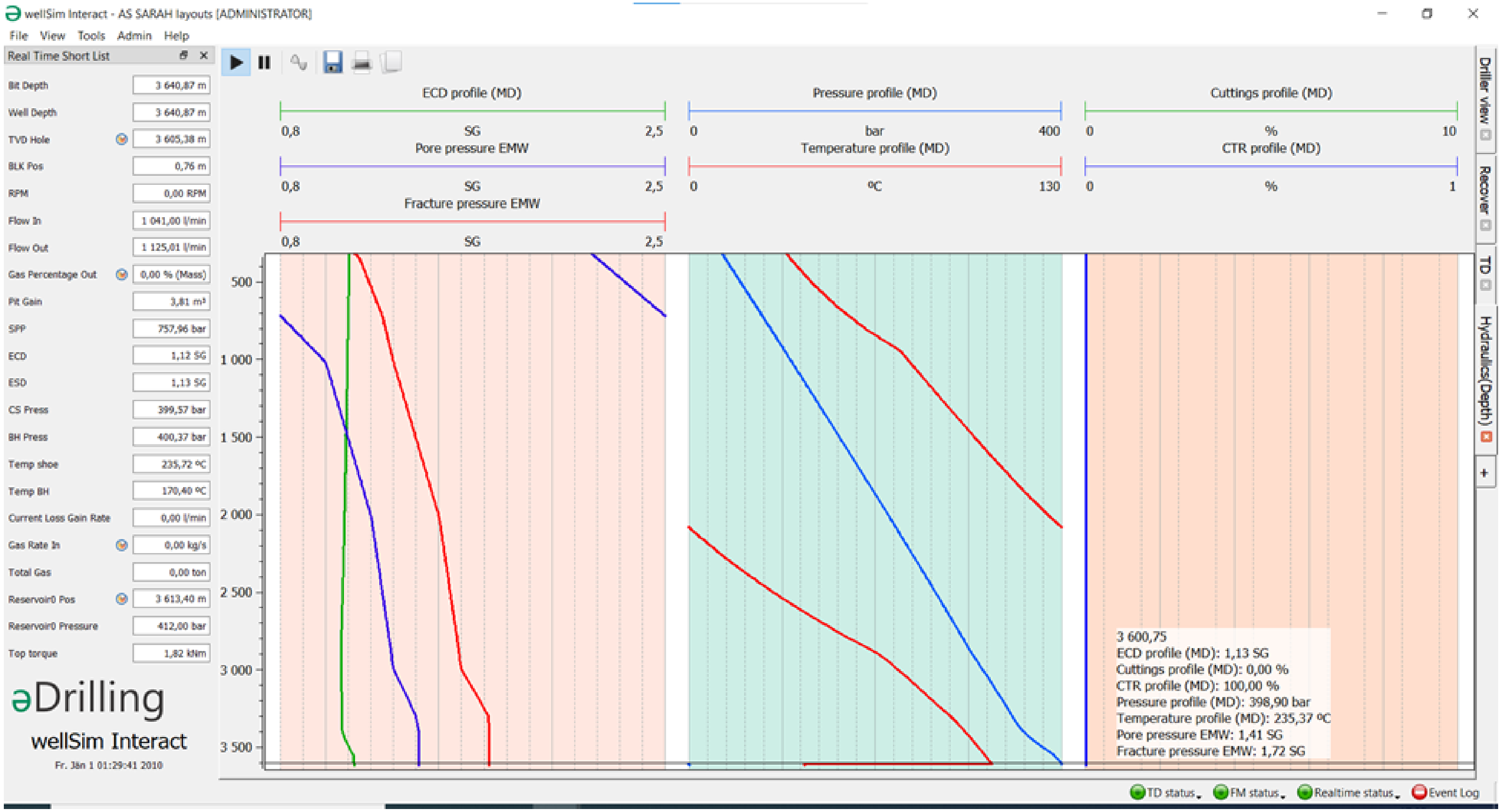
Figure 4. 19 - Normal circulation Recovery Case 2



Bit Depth	3 640,58 m
Well Depth	3 640,58 m
TVD Hole	3 605,38 m
BLK Pos	1,06 m
RPM	0,00 RPM
Flow In	1 041,00 l/min
Flow Out	1 122,65 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	3,99 m³
SPP	757,88 bar
ECD	1,12 SG
ESD	1,13 SG
CS Press	399,14 bar
BH Press	399,94 bar
Temp shoe	237,58 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	1,97 kNm

01:31:03
Hook load: 257,12 ton
Block Position: 1,06 m
Rotational Speed: 0,00 RPM
Mud Density In: 1,08 SG
ROP: 0,00 m/h
WOB: 2,32 tonf
Top torque: 1,98 kNm

Figure 4. 20 - Normal circulation True Depth Case 2



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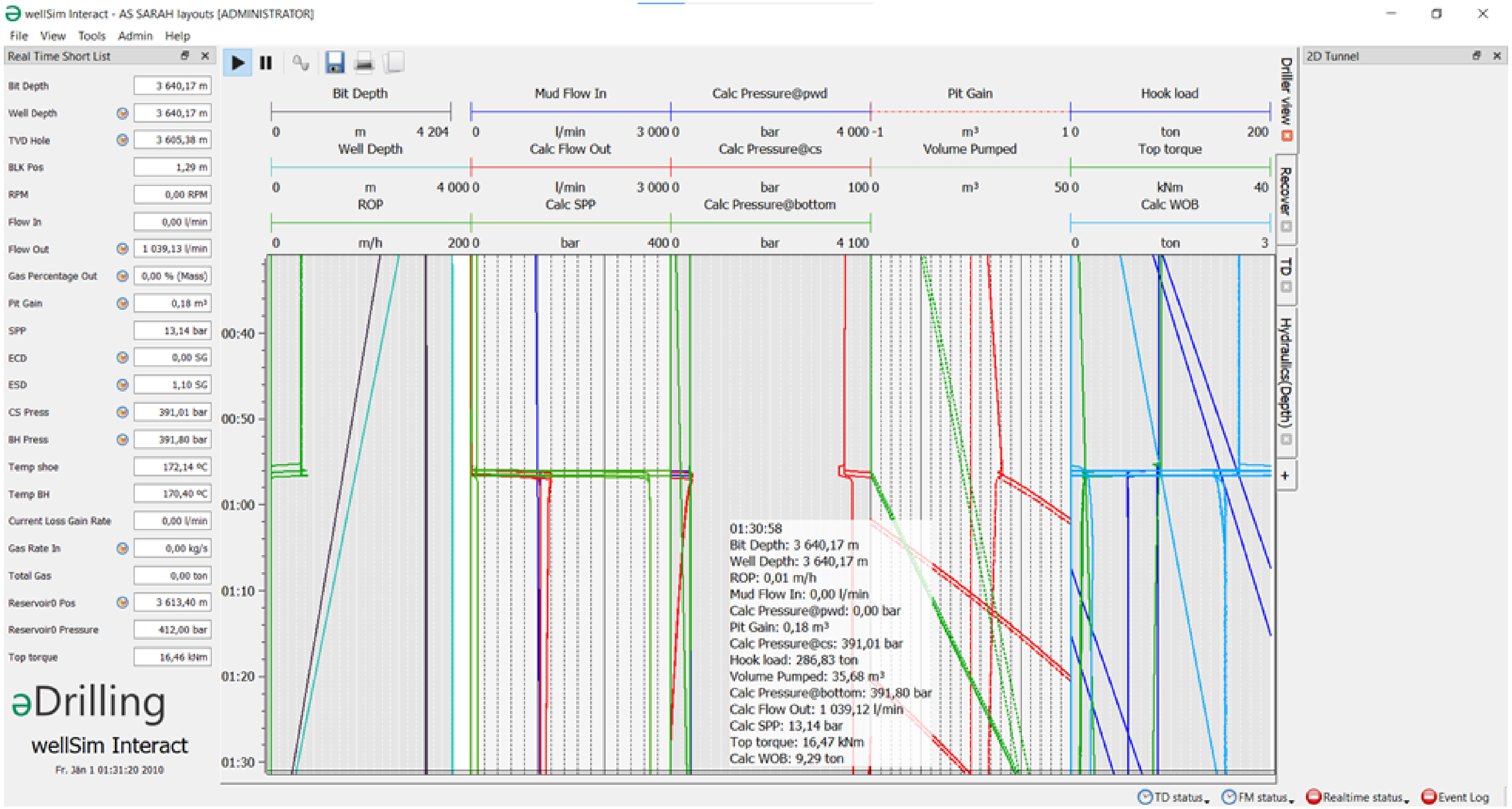
Real Time Short List

Bit Depth	3 640,87 m
Well Depth	3 640,87 m
TVD Hole	3 605,38 m
BLK Pos	0,76 m
RPM	0,00 RPM
Flow In	1 041,00 l/min
Flow Out	1 125,01 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	3,81 m³
SPP	757,96 bar
ECD	1,12 SG
ESD	1,13 SG
CS Press	399,57 bar
BH Press	400,37 bar
Temp shoe	235,72 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	1,82 kNm

3 600,75
ECD profile (MD): 1,13 SG
Cuttings profile (MD): 0,00 %
CTR profile (MD): 100,00 %
Pressure profile (MD): 398,90 bar
Temperature profile (MD): 235,37 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

Figure 4. 21 - Normal circulation Hydraulics Data Case 2



Bit Depth: 3 640,17 m
Well Depth: 3 640,17 m
TVD Hole: 3 605,38 m
BLK Pos: 1,29 m
RPM: 0,00 RPM
Flow In: 0,00 l/min
Flow Out: 1 039,13 l/min
Gas Percentage Out: 0,00 % (Mass)
Pit Gain: 0,18 m³
SPP: 13,14 bar
ECD: 0,00 SG
ESD: 1,10 SG
CS Press: 391,01 bar
BH Press: 391,80 bar
Temp shoe: 172,14 ºC
Temp BH: 170,40 ºC
Current Loss Gain Rate: 0,00 l/min
Gas Rate In: 0,00 kg/s
Total Gas: 0,00 ton
Reservoir0 Pos: 3 613,40 m
Reservoir0 Pressure: 412,00 bar
Top torque: 16,46 kNm

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01:30:58
Bit Depth: 3 640,17 m
Well Depth: 3 640,17 m
ROP: 0,01 m/h
Mud Flow In: 0,00 l/min
Calc Pressure@pwd: 0,00 bar
Pit Gain: 0,18 m³
Calc Pressure@cs: 391,01 bar
Hook load: 286,83 ton
Volume Pumped: 35,68 m³
Calc Pressure@bottom: 391,80 bar
Calc Flow Out: 1 039,12 l/min
Calc SPP: 13,14 bar
Top torque: 16,47 kNm
Calc WOB: 9,29 ton

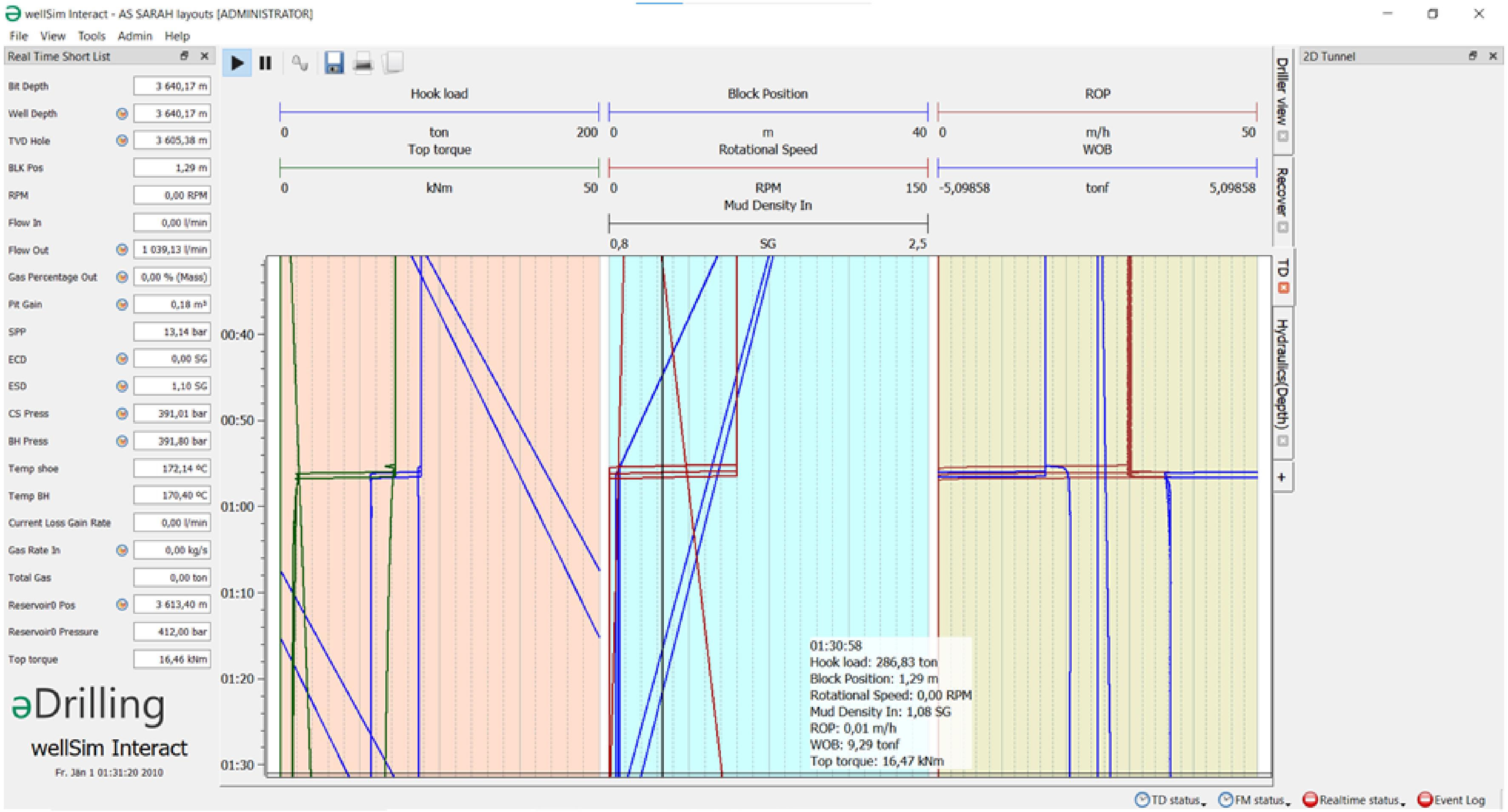
Figure 4. 22 - Reverse Circulation Driller View Case 2

]

Bit Depth	3 640,17 m
Well Depth	3 640,17 m
TVD Hole	3 605,38 m
BLK Pos	1,29 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	1 039,13 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,18 m³
SPP	13,14 bar
ECD	0,00 SG
ESD	1,10 SG
CS Press	391,01 bar
BH Press	391,80 bar
Temp shoe	172,14 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	16,46 kNm

01:30:47
Flow In: 0,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 1 039,11 l/min
SPP: 13,14 bar
Well head pressure: 10,26 bar

Figure 4. 23 - Reverse Circulation Recovery Case 2



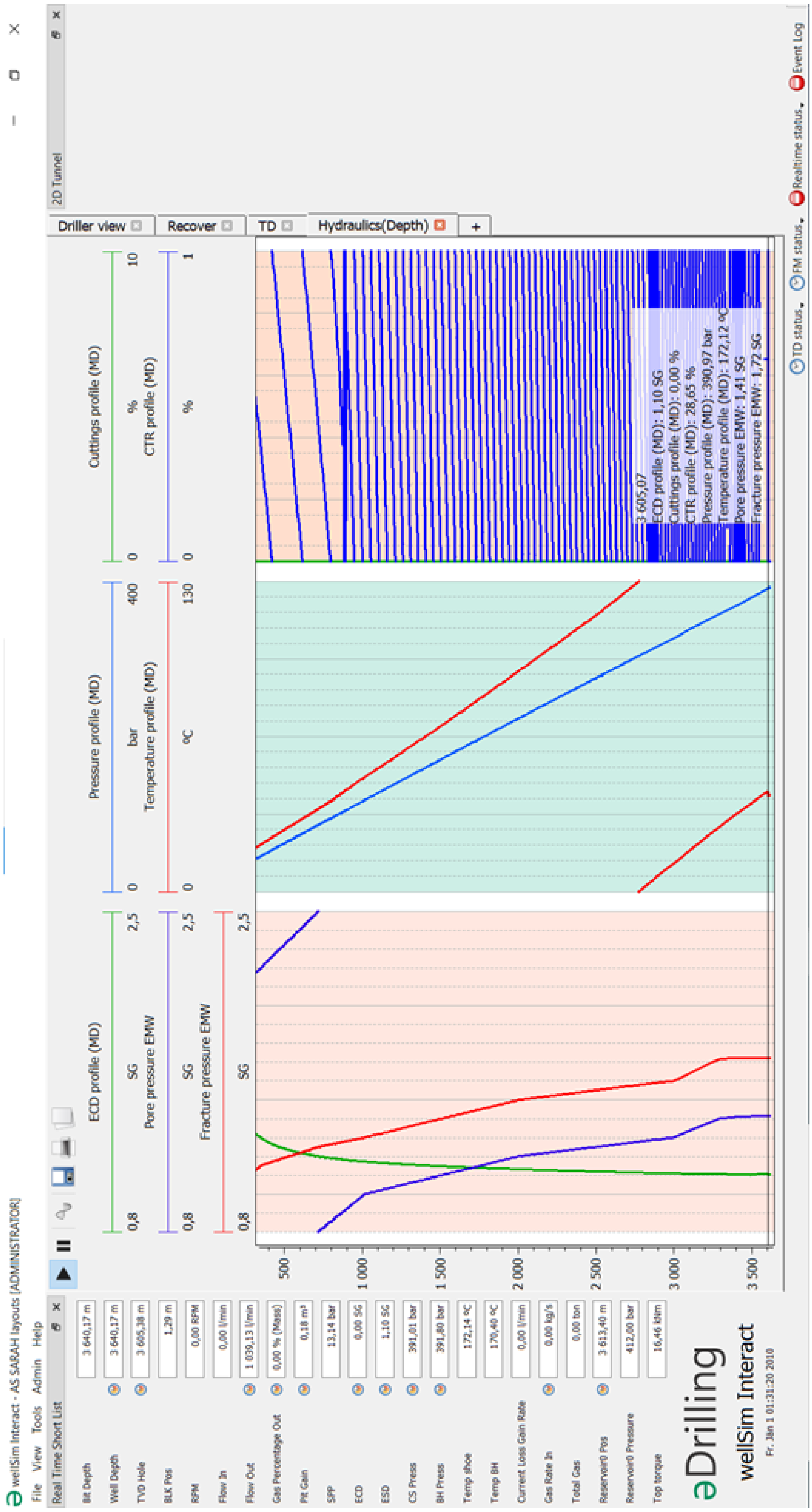
wellSim Interact - AS SARAH layouts [ADMINISTRATOR]

Real Time Short List

Bit Depth	3 640,17 m
Well Depth	3 640,17 m
TVD Hole	3 605,38 m
BLK Pos	1,29 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	1 039,13 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,18 m³
SPP	13,14 bar
ECD	0,00 SG
ESD	1,10 SG
CS Press	391,01 bar
BH Press	391,80 bar
Temp shoe	172,14 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	16,46 kNm

01:30:58
Hook load: 286,83 ton
Block Position: 1,29 m
Rotational Speed: 0,00 RPM
Mud Density In: 1,08 SG
ROP: 0,01 m/h
WOB: 9,29 tonf
Top torque: 16,47 kNm

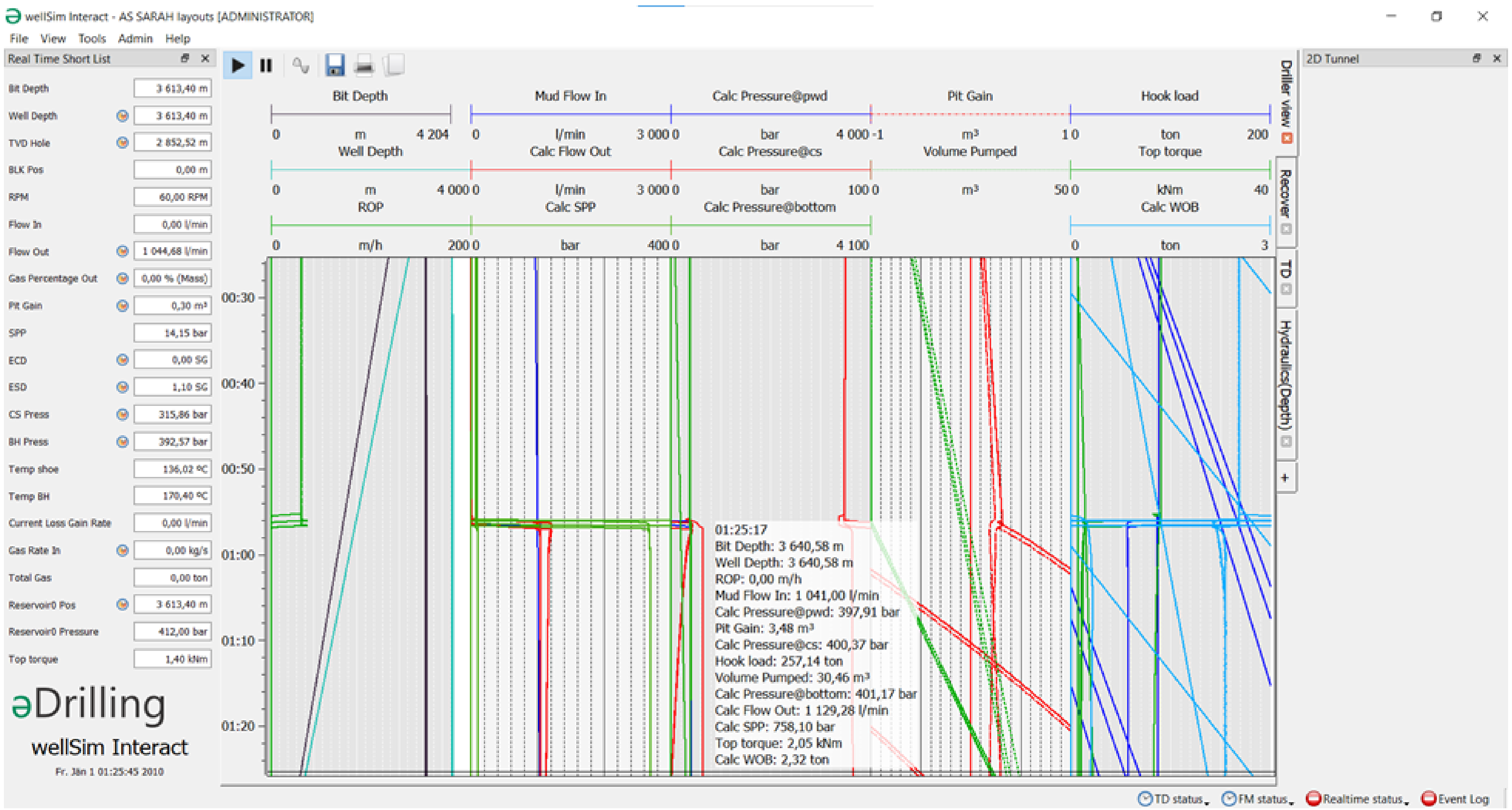
Figure 4. 24 - Reverse Circulation True Depth Case 2



Bit Depth	3 640,17 m
Well Depth	3 640,17 m
TVD Hole	3 605,38 m
BLK Pos	1,29 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	1 039,13 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,18 m³
SPP	13,14 bar
ECD	0,00 SG
ESD	1,10 SG
CS Press	391,01 bar
BH Press	391,80 bar
Temp shoe	172,14 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	16,46 kNm

3 605,07
ECD profile (MD): 1,10 SG
Cuttings profile (MD): 0,00 %
CTR profile (MD): 28,65 %
Pressure profile (MD): 390,97 bar
Temperature profile (MD): 172,12 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

Figure 4. 25 - Reverse Circulation Hydraulics Data Case 2



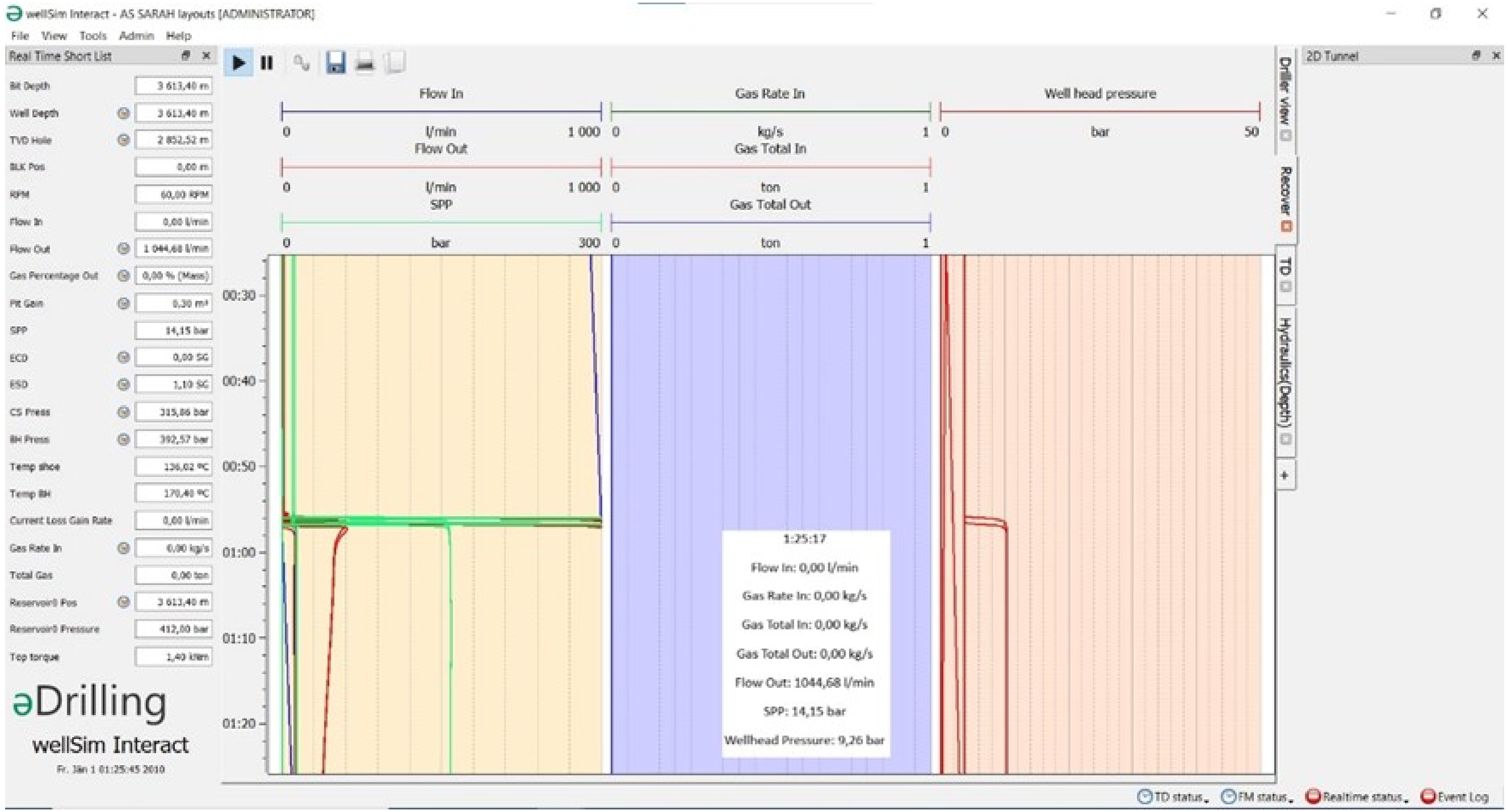
wellSim Interact - AS SARAH layouts [ADMINISTRATOR]

Real Time Short List

Bit Depth	3 613,40 m
Well Depth	3 613,40 m
TVD Hole	2 852,52 m
BLK Pos	0,00 m
RPM	60,00 RPM
Flow In	0,00 l/min
Flow Out	1 044,68 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,30 m³
SPP	14,15 bar
ECD	0,00 SG
ESD	1,10 SG
CS Press	315,86 bar
BH Press	392,57 bar
Temp shoe	136,02 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	1,40 kNm

01:25:17
Bit Depth: 3 640,58 m
Well Depth: 3 640,58 m
ROP: 0,00 m/h
Mud Flow In: 1 041,00 l/min
Calc Pressure@pwd: 397,91 bar
Pit Gain: 3,48 m³
Calc Pressure@cs: 400,37 bar
Hook load: 257,14 ton
Volume Pumped: 30,46 m³
Calc Pressure@bottom: 401,17 bar
Calc Flow Out: 1 129,28 l/min
Calc SPP: 758,10 bar
Top torque: 2,05 kNm
Calc WOB: 2,32 ton

Figure 4. 26 - Reverse Circulation Driller View Ideal Scenario Case 2



Bit Depth	3 613,40 m
Well Depth	3 613,40 m
TVD Hole	2 852,52 m
BLK Pos	0,00 m
RPM	60,00 RPM
Flow In	0,00 l/min
Flow Out	1 044,68 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,30 m³
SPP	14,15 bar
ECD	0,00 SG
ESD	1,10 SG
CS Press	315,86 bar
BH Press	392,57 bar
Temp shoe	136,02 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	1,40 kNm

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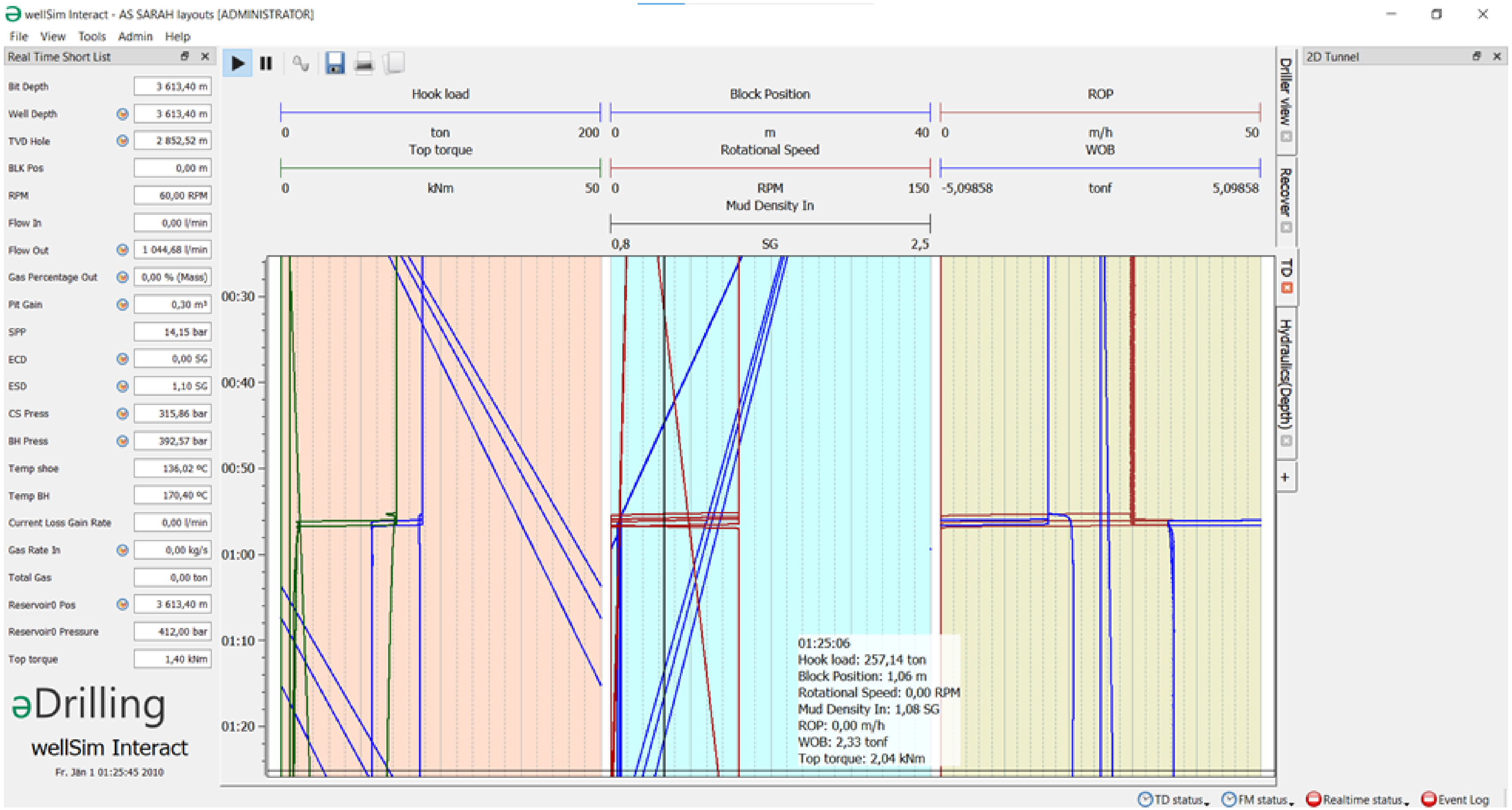
1:25:17
Flow In: 0,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 kg/s
Gas Total Out: 0,00 kg/s
Flow Out: 1044,68 l/min
SPP: 14,15 bar
Wellhead Pressure: 9,26 bar

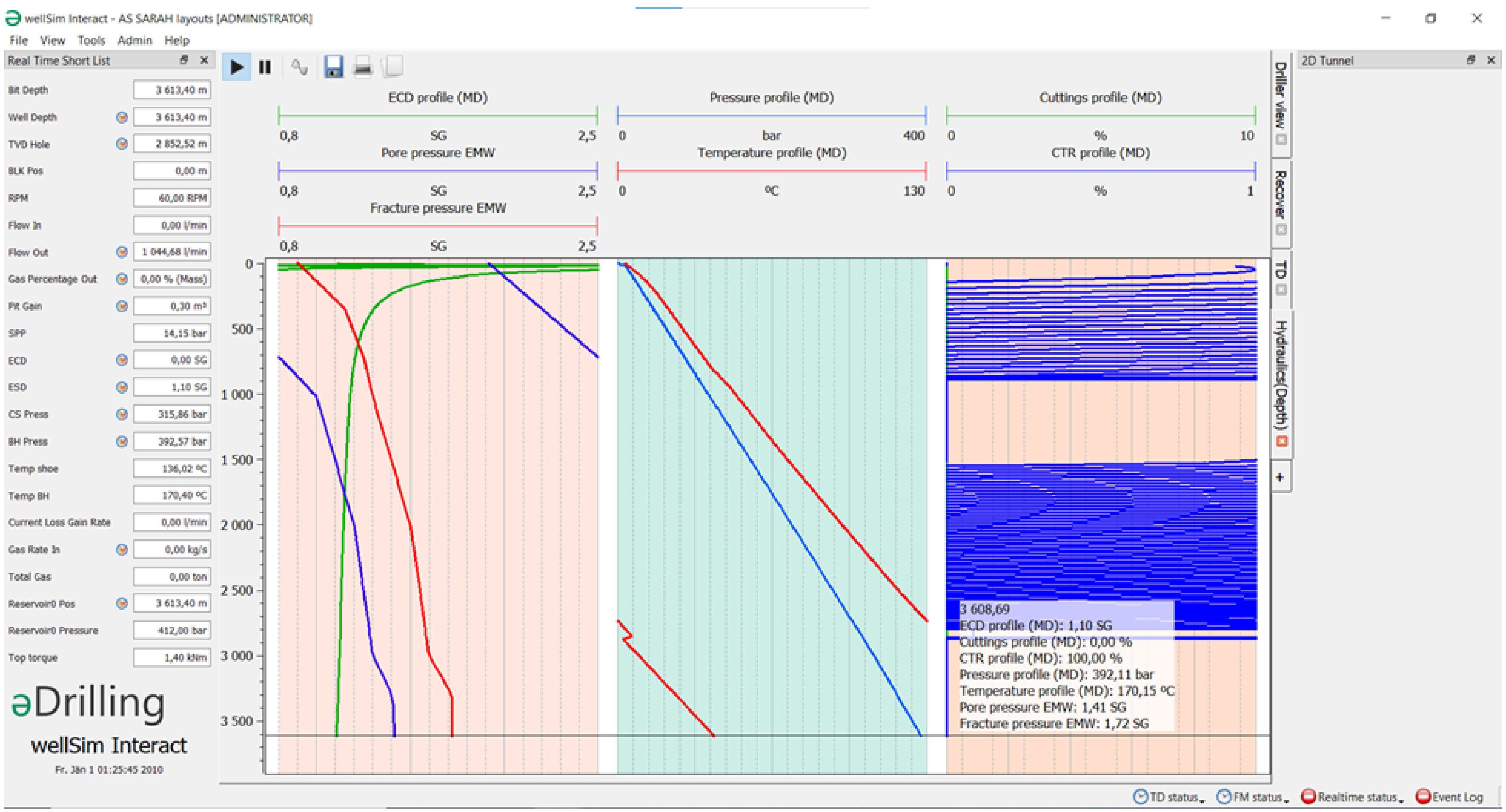
Figure 4. 27 - Reverse Circulation Recovery Ideal Scenario Case 2



Bit Depth	3 613,40 m
Well Depth	3 613,40 m
TVD Hole	2 852,52 m
BLK Pos	0,00 m
RPM	60,00 RPM
Flow In	0,00 l/min
Flow Out	1 044,68 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,30 m³
SPP	14,15 bar
ECD	0,00 SG
ESD	1,10 SG
CS Press	315,86 bar
BH Press	392,57 bar
Temp shoe	136,02 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	1,40 kNm

01:25:06
Hook load: 257,14 ton
Block Position: 1,06 m
Rotational Speed: 0,00 RPM
Mud Density In: 1,08 SG
ROP: 0,00 m/h
WOB: 2,33 tonf
Top torque: 2,04 kNm

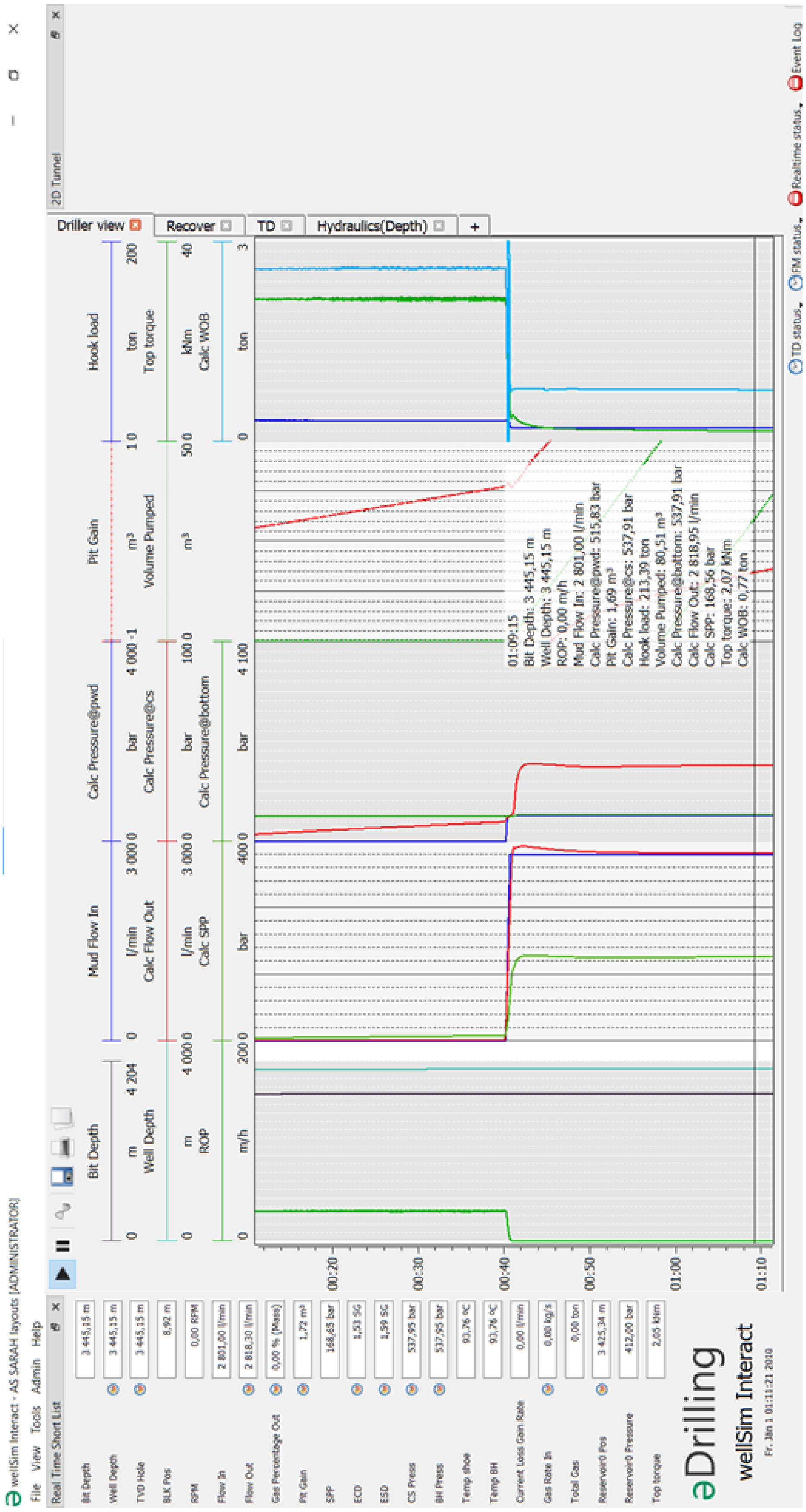
Figure 4. 28 - Reverse Circulation True Depth Ideal Scenario Case 2



Bit Depth	3 613,40 m
Well Depth	3 613,40 m
TVD Hole	2 852,52 m
BLK Pos	0,00 m
RPM	60,00 RPM
Flow In	0,00 l/min
Flow Out	1 044,68 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	0,30 m³
SPP	14,15 bar
ECD	0,00 SG
ESD	1,10 SG
CS Press	315,86 bar
BH Press	392,57 bar
Temp shoe	136,02 ºC
Temp BH	170,40 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 613,40 m
Reservoir0 Pressure	412,00 bar
Top torque	1,40 kNm

3 608,69
ECD profile (MD): 1,10 SG
Cuttings profile (MD): 0,00 %
CTR profile (MD): 100,00 %
Pressure profile (MD): 392,11 bar
Temperature profile (MD): 170,15 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

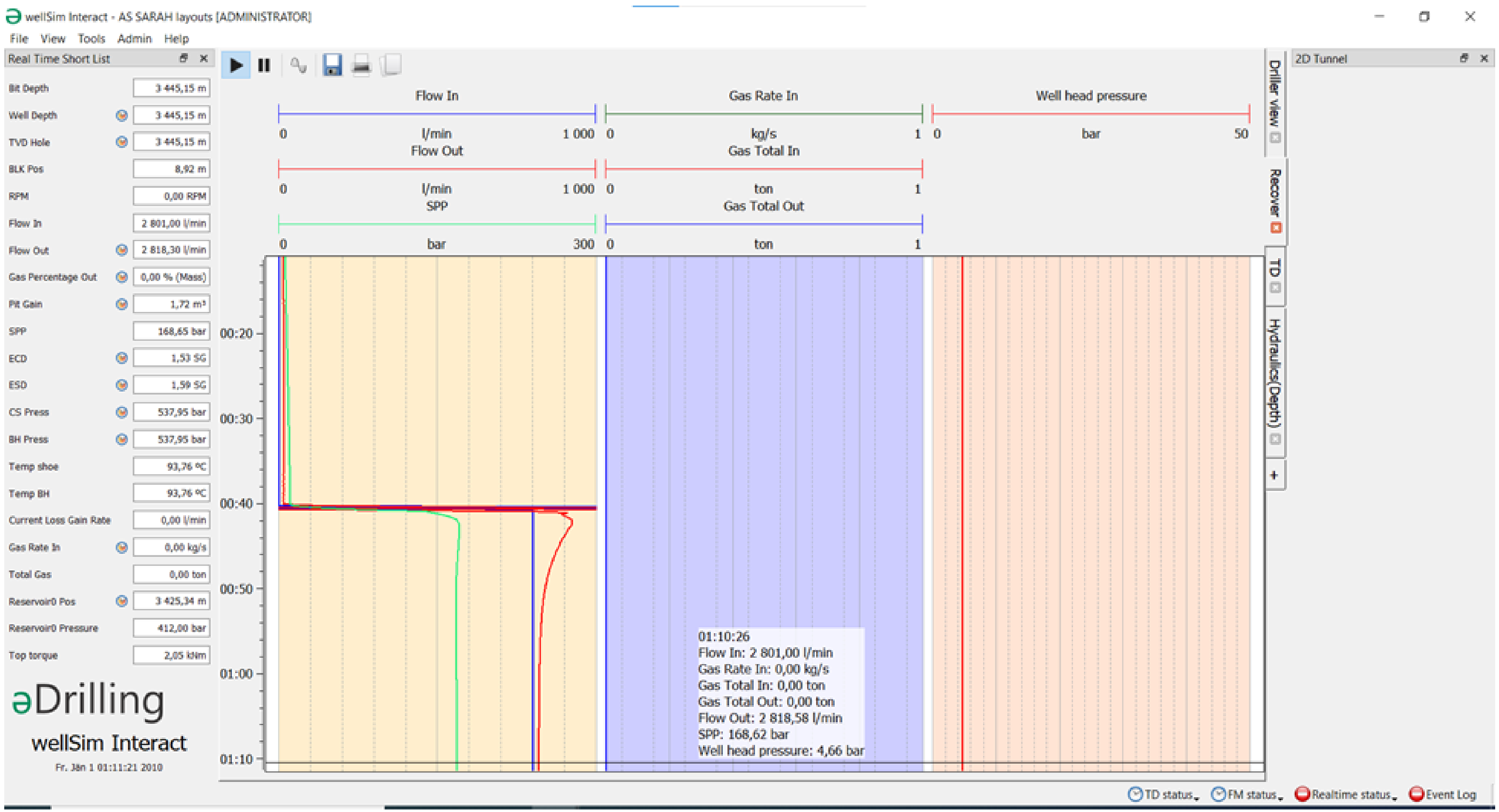
Figure 4. 29 - Reverse Circulation Hydraulics Data Ideal Scenario Case 2



Bit Depth 3 445,15 m
Well Depth 3 445,15 m
TVD Hole 3 445,15 m
BLK Pos 8,92 m
RPM 0,00 RPM
Flow In 2 801,00 l/min
Flow Out 2 818,30 l/min
Gas Percentage Out 0,00 % (Mass)
Pit Gain 1,72 m³
SPP 168,65 bar
ECD 1,53 SG
ESD 1,59 SG
CS Press 537,95 bar
BH Press 537,95 bar
Temp shoe 93,76 ºC
Temp BH 93,76 ºC
Current Loss Gain Rate 0,00 l/min
Gas Rate In 0,00 kg/s
Total Gas 0,00 ton
Reservoir0 Pos 3 425,34 m
Reservoir0 Pressure 412,00 bar
Top torque 2,05 kNm

01:09:15
Bit Depth: 3 445,15 m
Well Depth: 3 445,15 m
ROP: 0,00 m/h
Mud Flow In: 2 801,00 l/min
Calc Pressure@pwd: 515,83 bar
Pit Gain: 1,69 m³
Calc Pressure@cs: 537,91 bar
Hook load: 213,39 ton
Volume Pumped: 80,51 m³
Calc Pressure@bottom: 537,91 bar
Calc Flow Out: 2 818,95 l/min
Calc SPP: 168,56 bar
Top torque: 2,07 kNm
Calc WOB: 0,77 ton

Figure 4. 30 - Normal circulation Driller View Case 3



Bit Depth	3 445,15 m
Well Depth	3 445,15 m
TVD Hole	3 445,15 m
BLK Pos	8,92 m
RPM	0,00 RPM
Flow In	2 801,00 l/min
Flow Out	2 818,30 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	1,72 m³
SPP	168,65 bar
ECD	1,53 SG
ESD	1,59 SG
CS Press	537,95 bar
BH Press	537,95 bar
Temp shoe	93,76 ºC
Temp BH	93,76 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	2,05 kNm

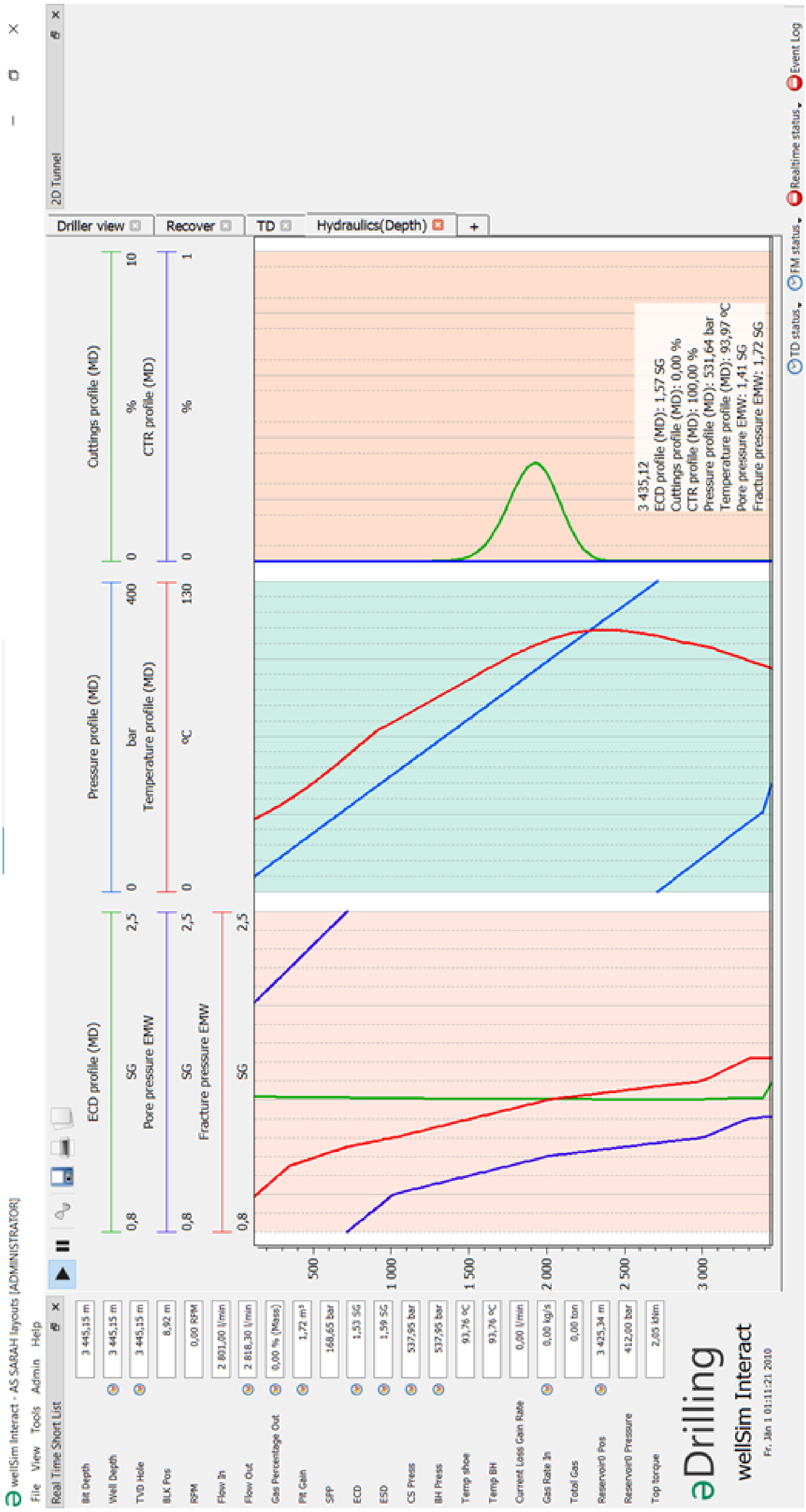
01:10:26
Flow In: 2 801,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 2 818,58 l/min
SPP: 168,62 bar
Well head pressure: 4,66 bar

Figure 4. 31 - Normal circulation Recovery Case 3

Bit Depth	3 445,15 m
Well Depth	3 445,15 m
TVD Hole	3 445,15 m
BLK Pos	8,92 m
RPM	0,00 RPM
Flow In	2 801,00 l/min
Flow Out	2 818,30 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	1,72 m³
SPP	168,65 bar
ECD	1,53 SG
ESD	1,59 SG
CS Press	537,95 bar
BH Press	537,95 bar
Temp shoe	93,76 °C
Temp BH	93,76 °C
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	2,05 kNm

01:10:31
Hook load: 213,39 ton
Block Position: 8,92 m
Rotational Speed: 0,00 RPM
Mud Density In: 1,50 SG
ROP: 0,00 m/h
WOB: 0,77 tonf
Top torque: 2,06 kNm

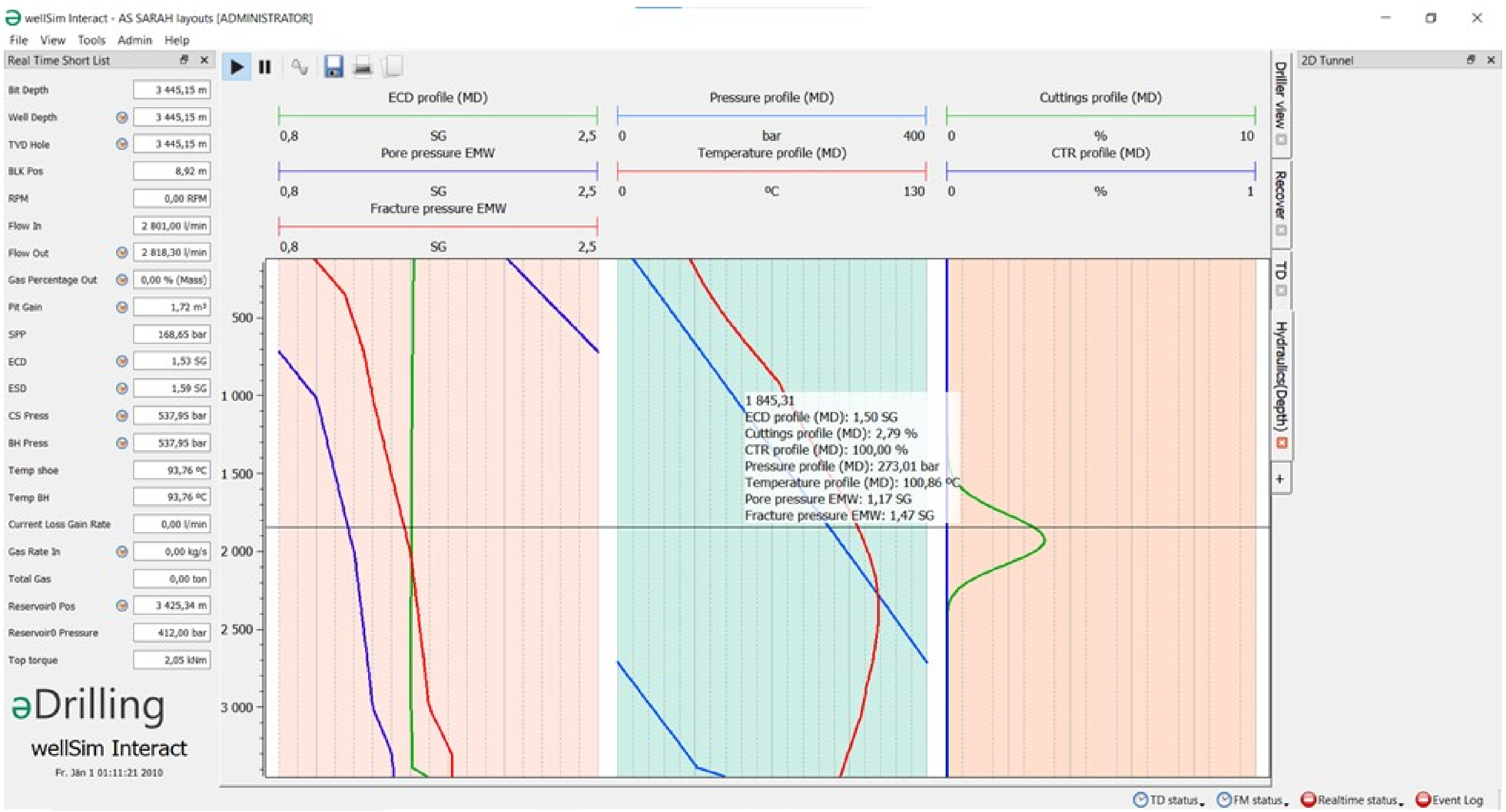
Figure 4. 32 - Normal circulation True Depth Case 3



Bit Depth 3 445,15 m
Well Depth 3 445,15 m
TVD Hole 3 445,15 m
BLK Pos 8,92 m
RPM 0,00 RPM
Flow In 2 801,00 l/min
Flow Out 2 818,30 l/min
Gas Percentage Out 0,00 % (Mass)
Pit Gain 1,72 m³
SPP 168,65 bar
ECD 1,53 SG
ESD 1,59 SG
CS Press 537,95 bar
BH Press 537,95 bar
Temp shoe 93,76 ºC
Temp BH 93,76 ºC
Current Loss Gain Rate 0,00 l/min
Gas Rate In 0,00 kg/s
Total Gas 0,00 ton
Reservoir0 Pos 3 425,34 m
Reservoir0 Pressure 412,00 bar
Top torque 2,05 kNm

3 435,12
ECD profile (MD): 1,57 SG
Cuttings profile (MD): 0,00 %
CTR profile (MD): 100,00 %
Pressure profile (MD): 531,64 bar
Temperature profile (MD): 93,97 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

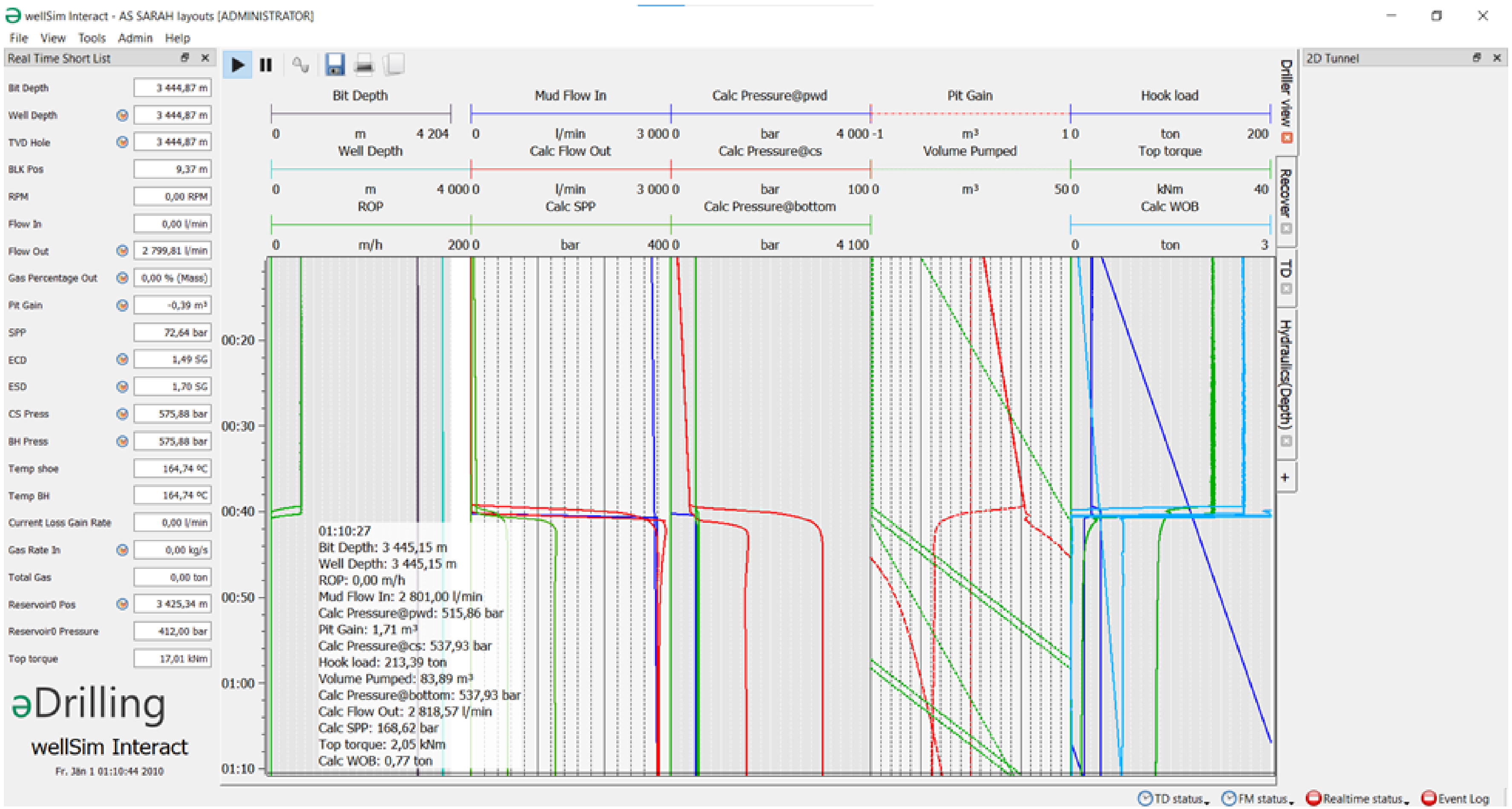
Figure 4. 33 - Normal circulation Hydraulics Data Case 3



Bit Depth 3 445,15 m
Well Depth 3 445,15 m
TVD Hole 3 445,15 m
BLK Pos 8,92 m
RPM 0,00 RPM
Flow In 2 801,00 l/min
Flow Out 2 818,30 l/min
Gas Percentage Out 0,00 % (Mass)
Pit Gain 1,72 m³
SPP 168,65 bar
ECD 1,53 SG
ESD 1,59 SG
CS Press 537,95 bar
BH Press 537,95 bar
Temp shoe 93,76 ºC
Temp BH 93,76 ºC
Current Loss Gain Rate 0,00 l/min
Gas Rate In 0,00 kg/s
Total Gas 0,00 ton
Reservoir0 Pos 3 425,34 m
Reservoir0 Pressure 412,00 bar
Top torque 2,05 kNm

1 845,31
ECD profile (MD): 1,50 SG
Cuttings profile (MD): 2,79 %
CTR profile (MD): 100,00 %
Pressure profile (MD): 273,01 bar
Temperature profile (MD): 100,86 ºC
Pore pressure EMW: 1,17 SG
Fracture pressure EMW: 1,47 SG

Figure 4. 34 - Normal circulation Hydraulics Data at Specific Depth Case 3



Bit Depth	3 444,87 m
Well Depth	3 444,87 m
TVD Hole	3 444,87 m
BLK Pos	9,37 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	2 799,81 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	-0,39 m³
SPP	72,64 bar
ECD	1,49 SG
ESD	1,70 SG
CS Press	575,88 bar
BH Press	575,88 bar
Temp shoe	164,74 ºC
Temp BH	164,74 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	17,01 kNm

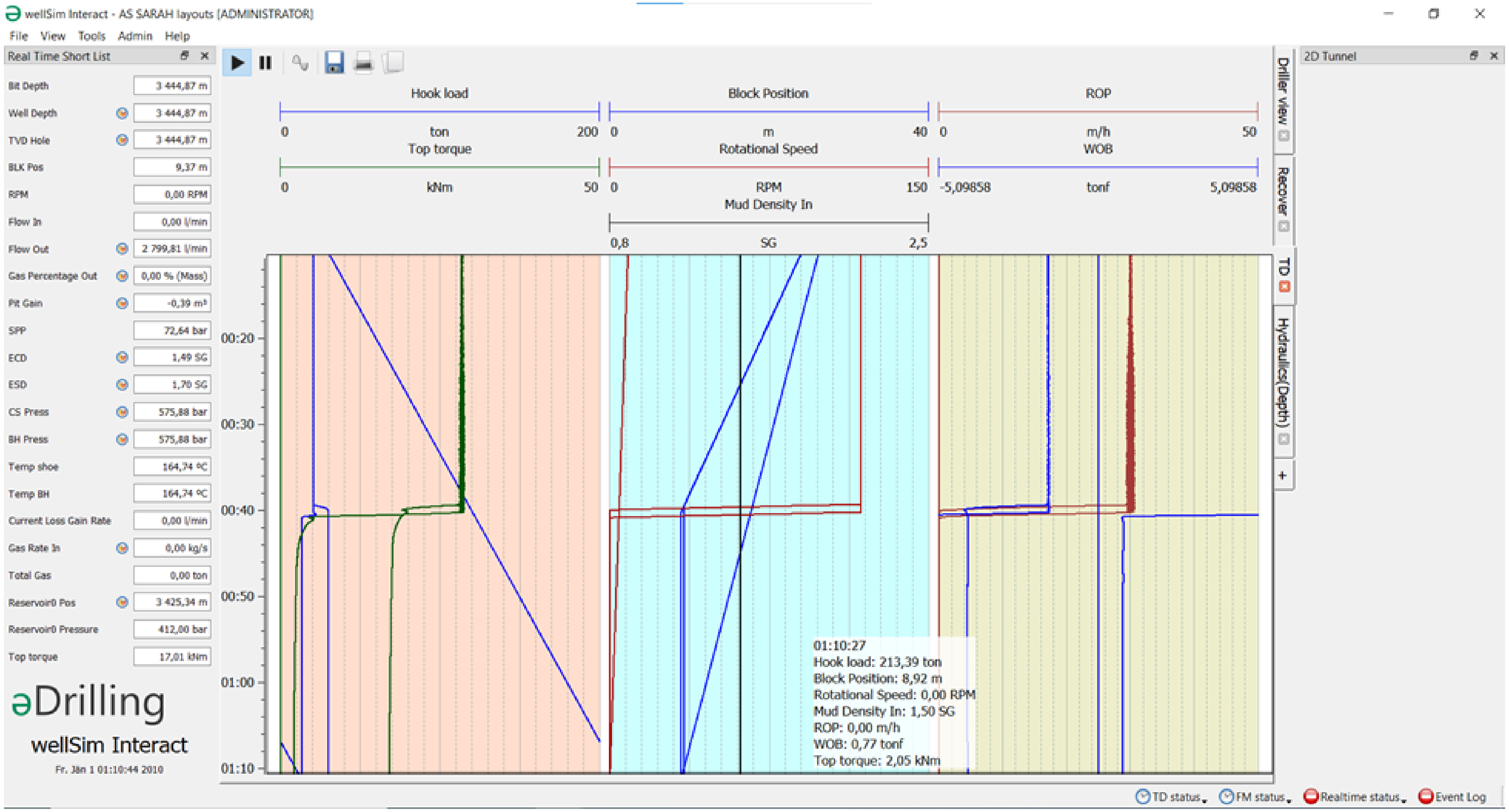
01:10:27
Bit Depth: 3 445,15 m
Well Depth: 3 445,15 m
ROP: 0,00 m/h
Mud Flow In: 2 801,00 l/min
Calc Pressure@pwd: 515,86 bar
Pit Gain: 1,71 m³
Calc Pressure@cs: 537,93 bar
Hook load: 213,39 ton
Volume Pumped: 83,89 m³
Calc Pressure@bottom: 537,93 bar
Calc Flow Out: 2 818,57 l/min
Calc SPP: 168,62 bar
Top torque: 2,05 kNm
Calc WOB: 0,77 ton

Figure 4. 35 - Reverse Circulation Driller View Case 3

Bit Depth: 3 444,87 m
Well Depth: 3 444,87 m
TVD Hole: 3 444,87 m
BLK Pos: 9,37 m
RPM: 0,00 RPM
Flow In: 0,00 l/min
Flow Out: 2 799,81 l/min
Gas Percentage Out: 0,00 % (Mass)
Pit Gain: -0,39 m^3
SPP: 72,64 bar
ECD: 1,49 SG
ESD: 1,70 SG
CS Press: 575,88 bar
BH Press: 575,88 bar
Temp shoe: 164,74 ºC
Temp BH: 164,74 ºC
Current Loss Gain Rate: 0,00 l/min
Gas Rate In: 0,00 kg/s
Total Gas: 0,00 ton
Reservoir0 Pos: 3 425,34 m
Reservoir0 Pressure: 412,00 bar
Top torque: 17,01 kNm

01:10:05
Flow In: 2 801,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 2 818,69 l/min
SPP: 168,60 bar
Well head pressure: 4,66 bar

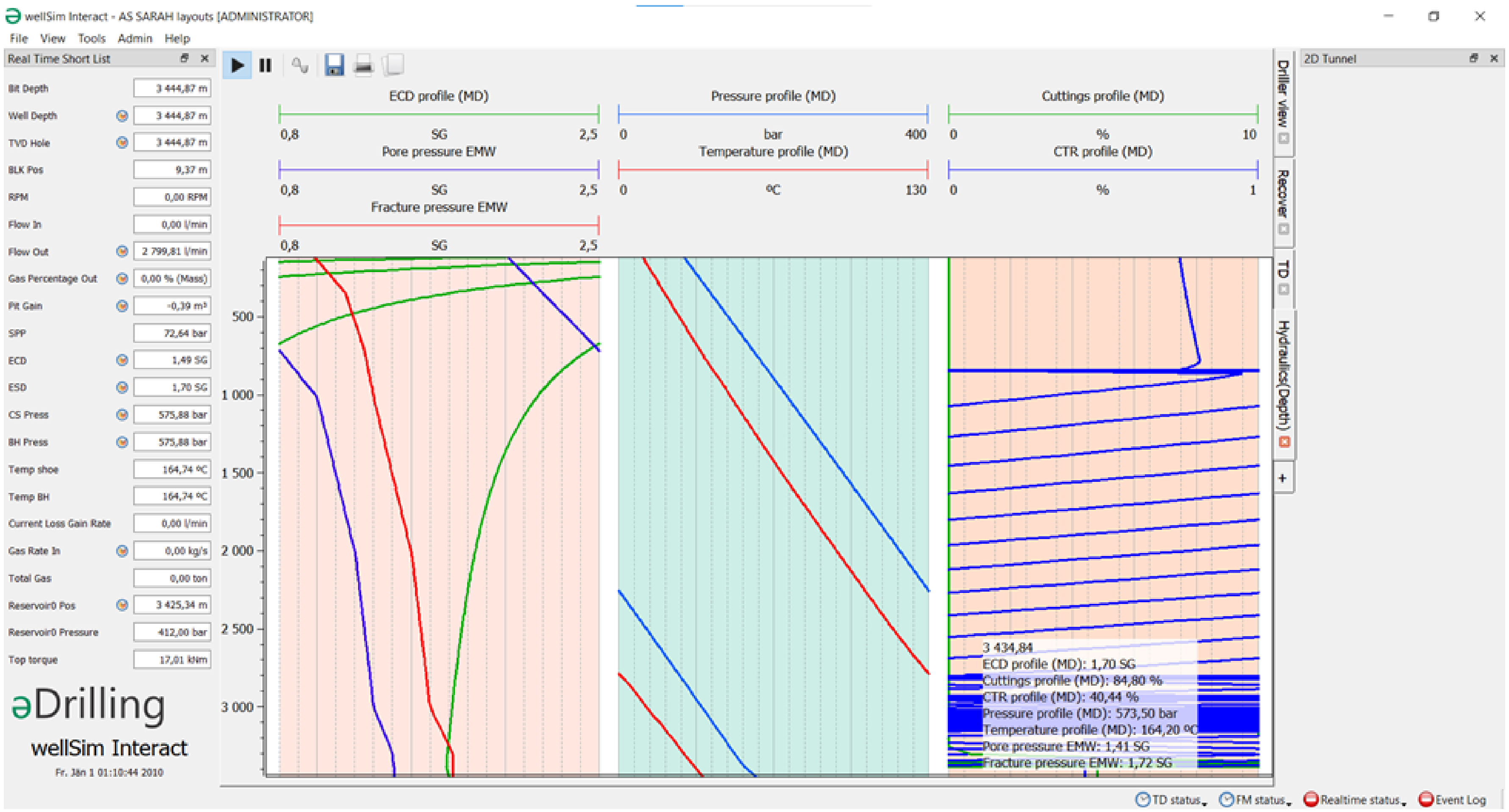
Figure 4. 36 - Reverse Circulation Recovery Case 3



Real Time Short List	
Bit Depth	3 444,87 m
Well Depth	3 444,87 m
TVD Hole	3 444,87 m
BLK Pos	9,37 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	2 799,81 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	-0,39 m³
SPP	72,64 bar
ECD	1,49 SG
ESD	1,70 SG
CS Press	575,88 bar
BH Press	575,88 bar
Temp shoe	164,74 °C
Temp BH	164,74 °C
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	17,01 kNm

01:10:27
Hook load: 213,39 ton
Block Position: 8,92 m
Rotational Speed: 0,00 RPM
Mud Density In: 1,50 SG
ROP: 0,00 m/h
WOB: 0,77 tonf
Top torque: 2,05 kNm

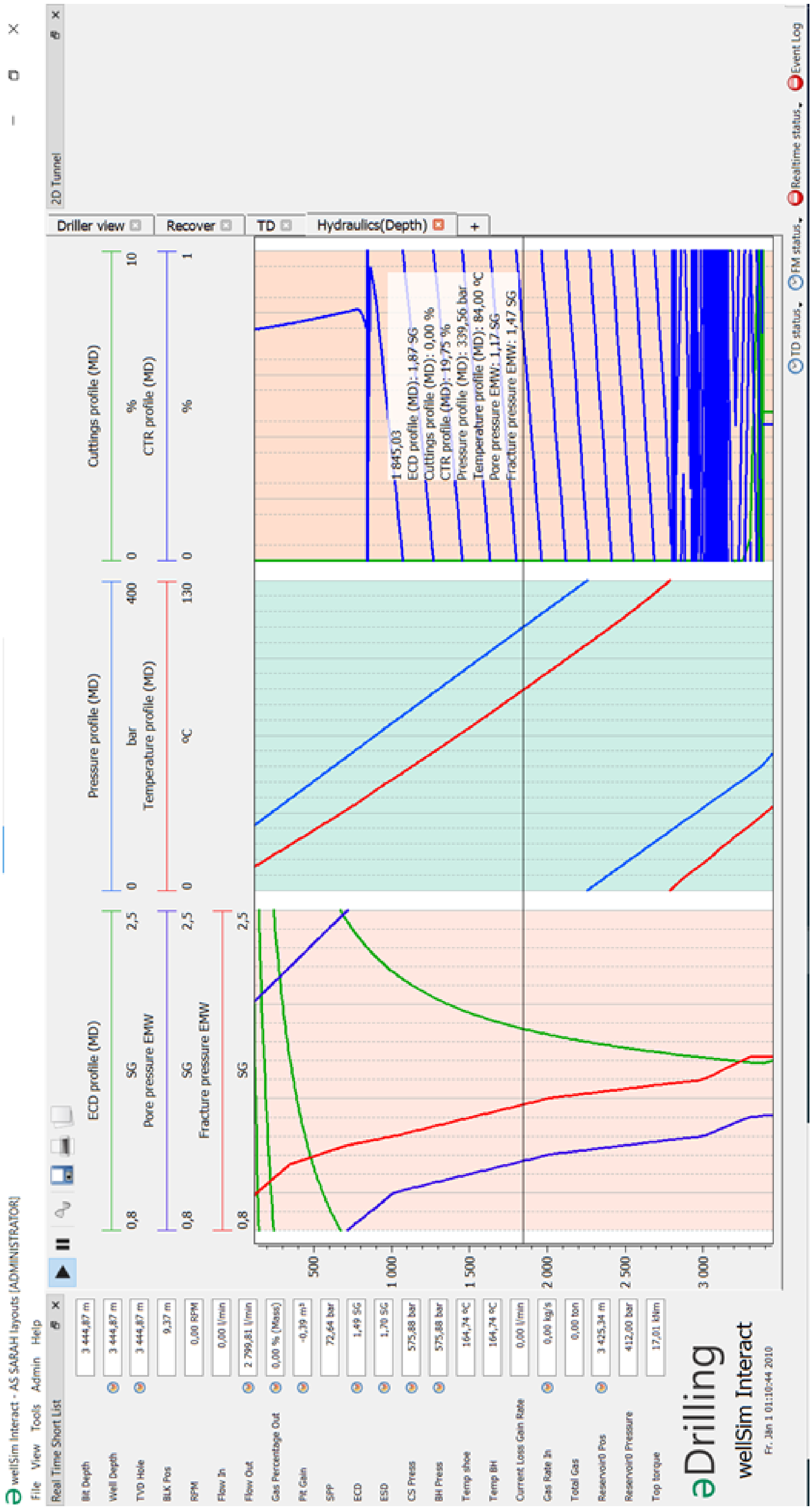
Figure 4. 37 - Reverse Circulation True Depth Case 3



Bit Depth	3 444,87 m
Well Depth	3 444,87 m
TVD Hole	3 444,87 m
BLK Pos	9,37 m
RPM	0,00 RPM
Flow In	0,00 l/min
Flow Out	2 799,81 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	-0,39 m³
SPP	72,64 bar
ECD	1,49 SG
ESD	1,70 SG
CS Press	575,88 bar
BH Press	575,88 bar
Temp shoe	164,74 ºC
Temp BH	164,74 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	17,01 kNm

3 434,84
ECD profile (MD): 1,70 SG
Cuttings profile (MD): 84,80 %
CTR profile (MD): 40,44 %
Pressure profile (MD): 573,50 bar
Temperature profile (MD): 164,20 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

Figure 4. 38 - Reverse Circulation Hydraulics Data Case 3

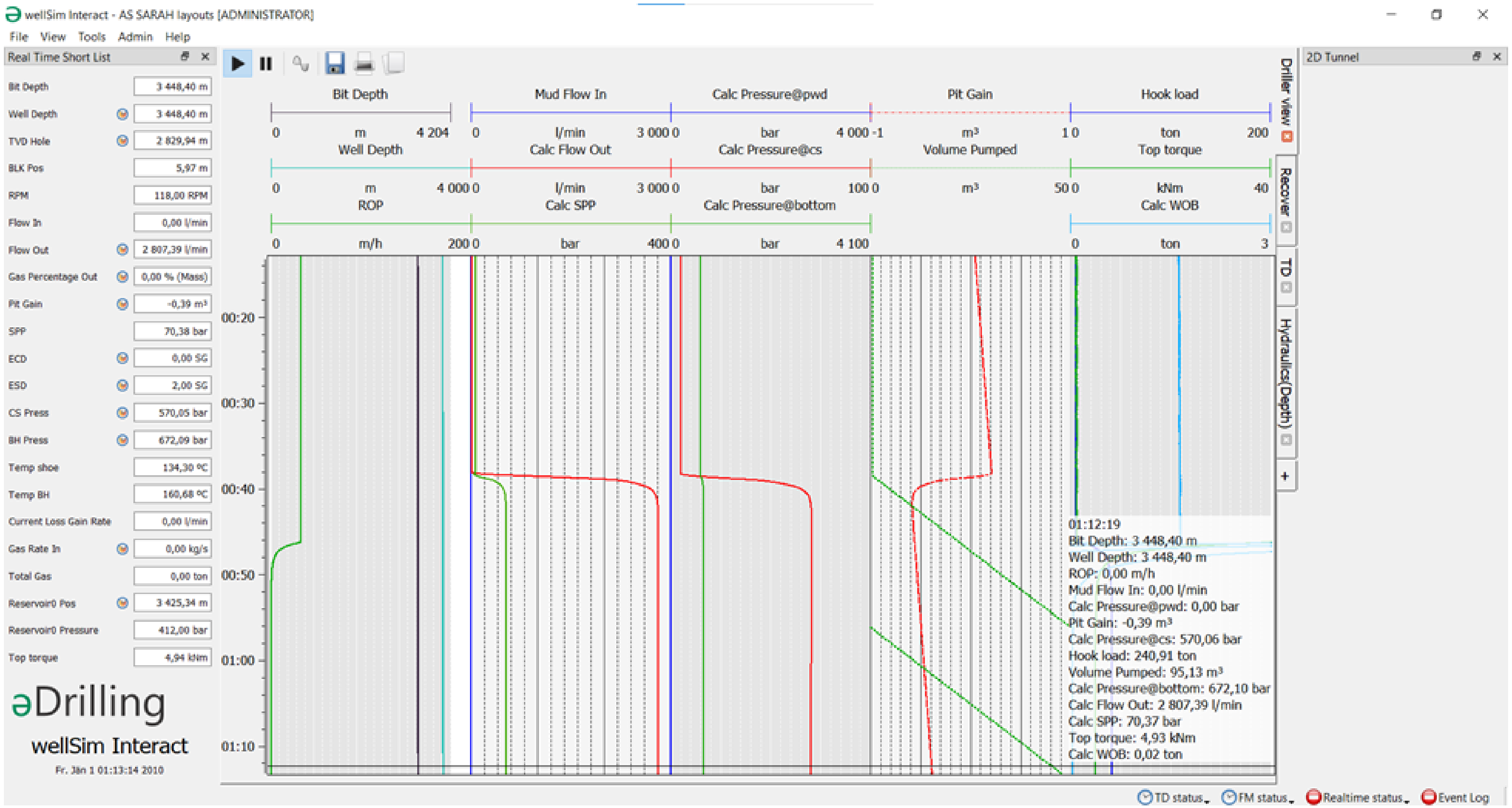


Bit Depth: 3 444,87 m
Well Depth: 3 444,87 m
TVD Hole: 3 444,87 m
BLK Pos: 9,37 m
RPM: 0,00 RPM
Flow In: 0,00 l/min
Flow Out: 2 799,81 l/min
Gas Percentage Out: 0,00 % (Mass)
Pit Gain: -0,39 m³
SPP: 72,64 bar
ECD: 1,49 SG
ESD: 1,70 SG
CS Press: 575,88 bar
BH Press: 575,88 bar
Temp shoe: 164,74 ºC
Temp BH: 164,74 ºC
Current Loss Gain Rate: 0,00 l/min
Gas Rate In: 0,00 kg/s
Total Gas: 0,00 ton
Reservoir0 Pos: 3 425,34 m
Reservoir0 Pressure: 412,00 bar
Top torque: 17,01 kNm

Fr. Jan 1 01:10:44 2010

1 845,03
ECD profile (MD): 1,87 SG
Cuttings profile (MD): 0,00 %
CTR profile (MD): 19,75 %
Pressure profile (MD): 339,56 bar
Temperature profile (MD): 84,00 ºC
Pore pressure EMW: 1,17 SG
Fracture pressure EMW: 1,47 SG

Figure 4. 39 - Reverse Circulation Hydraulics Data at Specific Depth Case 3



Real Time Short List

Bit Depth	3 448,40 m
Well Depth	3 448,40 m
TVD Hole	2 829,94 m
BLK Pos	5,97 m
RPM	118,00 RPM
Flow In	0,00 l/min
Flow Out	2 807,39 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	-0,39 m³
SPP	70,38 bar
ECD	0,00 SG
ESD	2,00 SG
CS Press	570,05 bar
BH Press	672,09 bar
Temp shoe	134,30 ºC
Temp BH	160,68 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	4,94 kNm

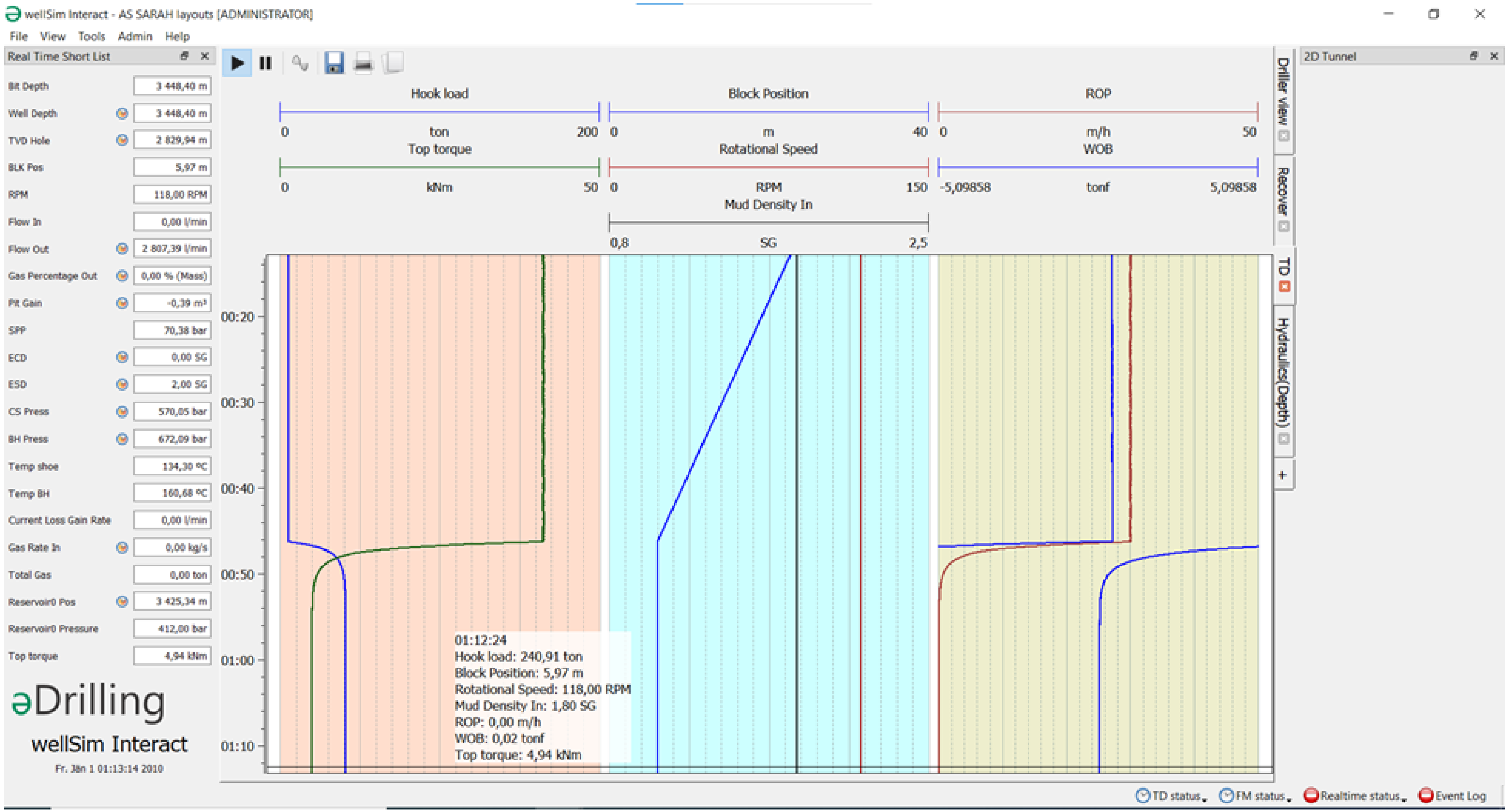
01:12:19
Bit Depth: 3 448,40 m
Well Depth: 3 448,40 m
ROP: 0,00 m/h
Mud Flow In: 0,00 l/min
Calc Pressure@pwd: 0,00 bar
Pit Gain: -0,39 m³
Calc Pressure@cs: 570,06 bar
Hook load: 240,91 ton
Volume Pumped: 95,13 m³
Calc Pressure@bottom: 672,10 bar
Calc Flow Out: 2 807,39 l/min
Calc SPP: 70,37 bar
Top torque: 4,93 kNm
Calc WOB: 0,02 ton

Figure 4. 40 - Reverse Circulation Ideal Scenario Driller View Case 3

Bit Depth	3 448,40 m
Well Depth	3 448,40 m
TVD Hole	2 829,94 m
BLK Pos	5,97 m
RPM	118,00 RPM
Flow In	0,00 l/min
Flow Out	2 807,39 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	-0,39 m³
SPP	70,38 bar
ECD	0,00 SG
ESD	2,00 SG
CS Press	570,05 bar
BH Press	672,09 bar
Temp shoe	134,30 °C
Temp BH	160,68 °C
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	4,94 kNm

01:12:08
Flow In: 0,00 l/min
Gas Rate In: 0,00 kg/s
Gas Total In: 0,00 ton
Gas Total Out: 0,00 ton
Flow Out: 2 807,39 l/min
SPP: 70,37 bar
Well head pressure: 69,90 bar

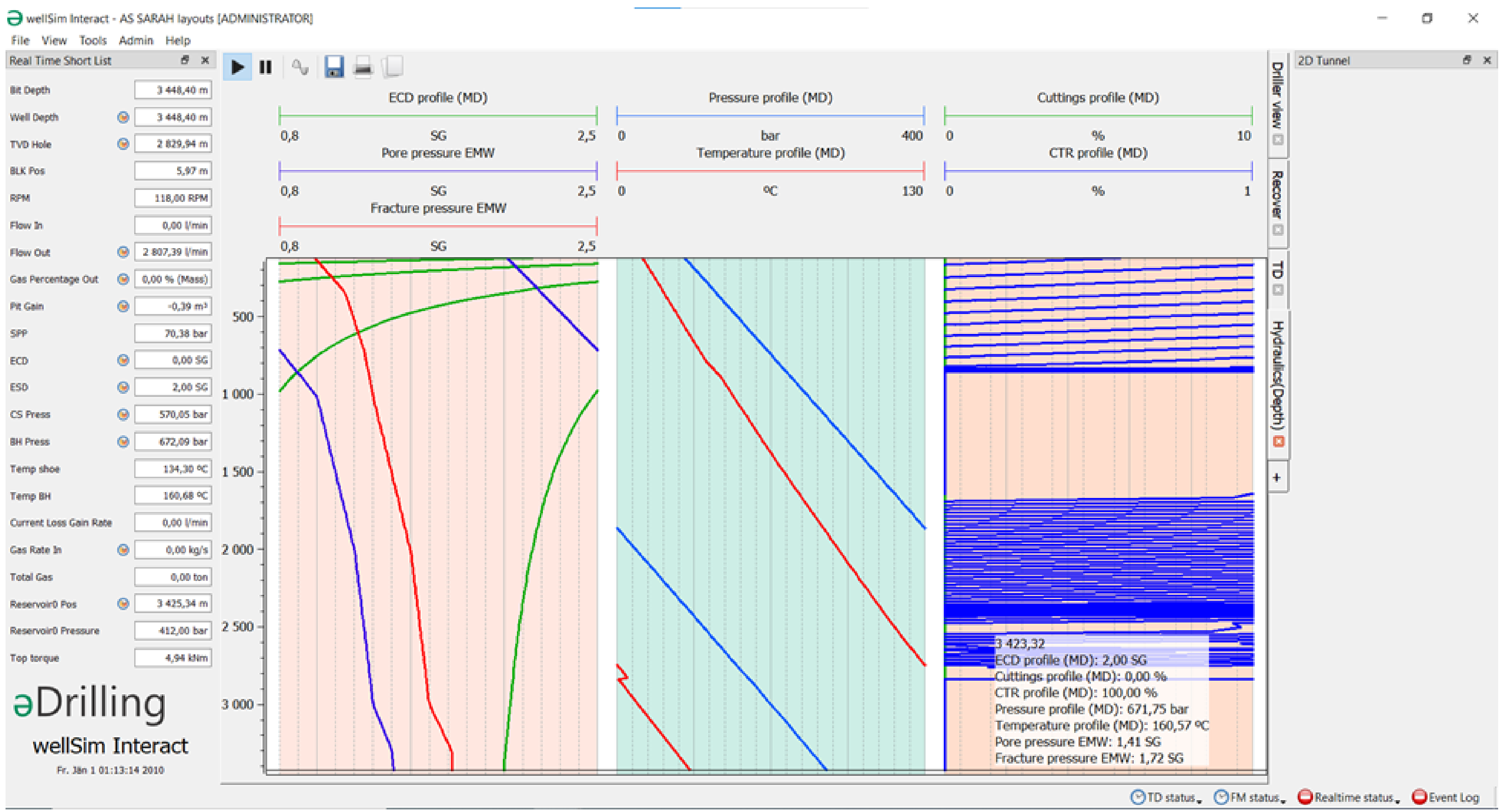
Figure 4. 41 - Reverse Circulation Ideal Scenario Recovery Case 3



Bit Depth	3 448,40 m
Well Depth	3 448,40 m
TVD Hole	2 829,94 m
BLK Pos	5,97 m
RPM	118,00 RPM
Flow In	0,00 l/min
Flow Out	2 807,39 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	-0,39 m³
SPP	70,38 bar
ECD	0,00 SG
ESD	2,00 SG
CS Press	570,05 bar
BH Press	672,09 bar
Temp shoe	134,30 ºC
Temp BH	160,68 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	4,94 kNm

01:12:24
Hook load: 240,91 ton
Block Position: 5,97 m
Rotational Speed: 118,00 RPM
Mud Density In: 1,80 SG
ROP: 0,00 m/h
WOB: 0,02 tonf
Top torque: 4,94 kNm

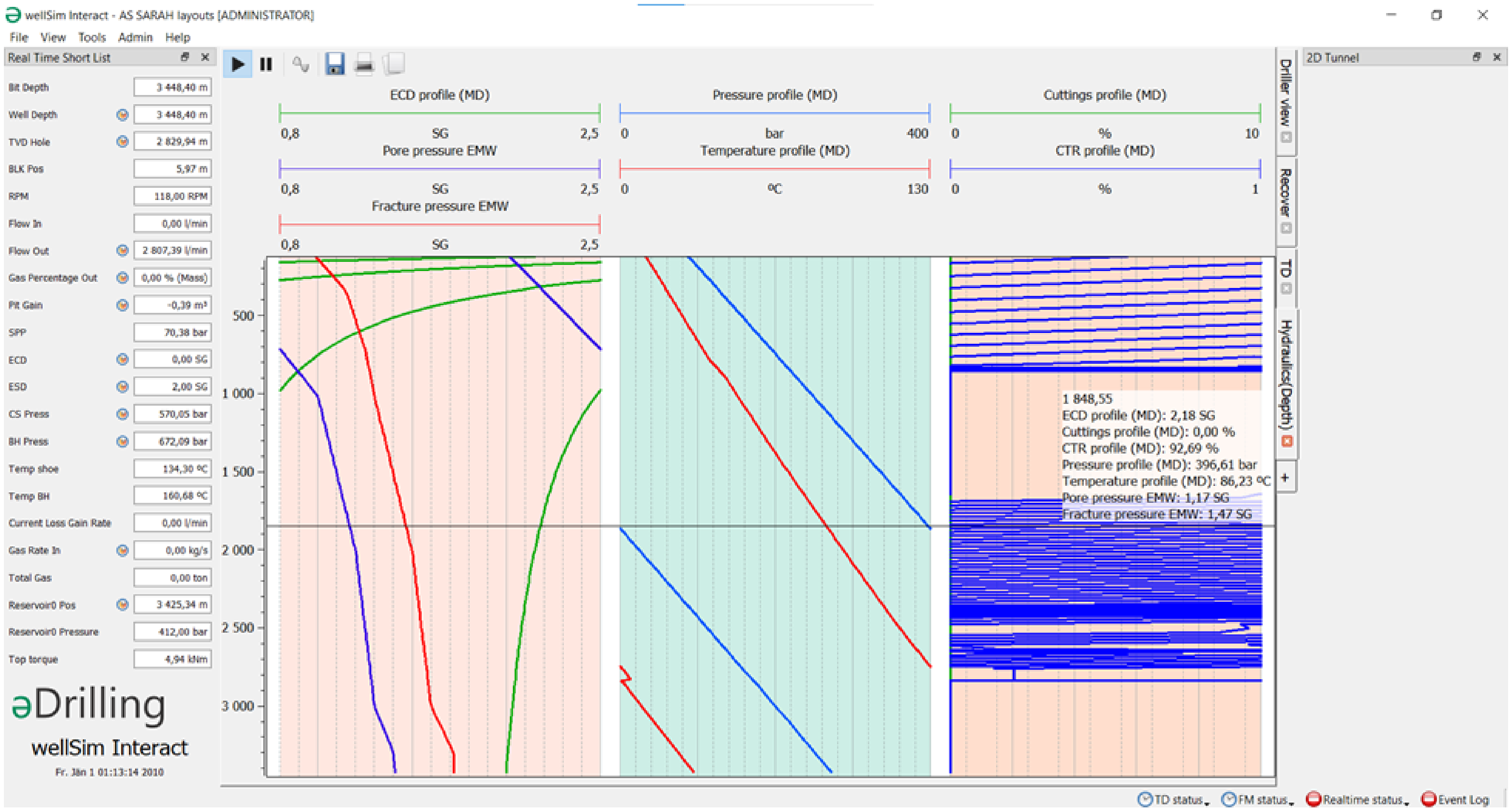
Figure 4. 42 - Reverse Circulation Ideal Scenario Hydraulics Data Case 3



Bit Depth	3 448,40 m
Well Depth	3 448,40 m
TVD Hole	2 829,94 m
BLK Pos	5,97 m
RPM	118,00 RPM
Flow In	0,00 l/min
Flow Out	2 807,39 l/min
Gas Percentage Out	0,00 % (Mass)
Pit Gain	-0,39 m³
SPP	70,38 bar
ECD	0,00 SG
ESD	2,00 SG
CS Press	570,05 bar
BH Press	672,09 bar
Temp shoe	134,30 ºC
Temp BH	160,68 ºC
Current Loss Gain Rate	0,00 l/min
Gas Rate In	0,00 kg/s
Total Gas	0,00 ton
Reservoir0 Pos	3 425,34 m
Reservoir0 Pressure	412,00 bar
Top torque	4,94 kNm

3 423,32
ECD profile (MD): 2,00 SG
Cuttings profile (MD): 0,00 %
CTR profile (MD): 100,00 %
Pressure profile (MD): 671,75 bar
Temperature profile (MD): 160,57 ºC
Pore pressure EMW: 1,41 SG
Fracture pressure EMW: 1,72 SG

Figure 4. 43 - Reverse Circulation Ideal Scenario Hydraulics Data Case 3



Bit Depth 3 448,40 m
Well Depth 3 448,40 m
TVD Hole 2 829,94 m
BLK Pos 5,97 m
RPM 118,00 RPM
Flow In 0,00 l/min
Flow Out 2 807,39 l/min
Gas Percentage Out 0,00 % (Mass)
Pit Gain -0,39 m³
SPP 70,38 bar
ECD 0,00 SG
ESD 2,00 SG
CS Press 570,05 bar
BH Press 672,09 bar
Temp shoe 134,30 ºC
Temp BH 160,68 ºC
Current Loss Gain Rate 0,00 l/min
Gas Rate In 0,00 kg/s
Total Gas 0,00 ton
Reservoir0 Pos 3 425,34 m
Reservoir0 Pressure 412,00 bar
Top torque 4,94 kNm

1 848,55
ECD profile (MD): 2,18 SG
Cuttings profile (MD): 0,00 %
CTR profile (MD): 92,69 %
Pressure profile (MD): 396,61 bar
Temperature profile (MD): 86,23 ºC
Pore pressure EMW: 1,17 SG
Fracture pressure EMW: 1,47 SG

Figure 4. 44 - Reverse Circulation Ideal Scenario Hydraulics Data at Specific Depth Case 3

8 List of Figures

Chapter 1 Figures

Chapter 2 Figures

Chapter 3 Figures

Chapter 4 Figures

9 List of Tables

10 Nomenclature

ΔP	Pressure drop	[Pa]
SPP	Standpipe Pressure	[Pa]
μ	Fluid viscosity	[Pa·s]
ρ	Fluid density	[kg/m^3]
L	Length of the wellbore	[m]
D	Diameter of the wellbore	[m]
r	Radius of the wellbore	[m]
Q	Flow rate	[m^3/s]
d	Inside diameter of the drill string	[m]
Re	Reynolds number for flow inside the drill string	[]
f	Darcy friction factor	[]

11 Abbreviations

RC - Reverse Circulation

RCC - Reverse Circulation Cementing

ECD - Equivalent Circulating Density

HP-HT - High- pressure High-temperature

CT - Coiled tubing

RCCPT - Reverse Circulation Cement Placement Technique

CCCPT - Conventional Circulation Cement Placing Technique

ECDs - Equivalent Circulating Densities

ECP - Equivalent Circulating Pressure

CC - Conventional Circulation

ROP - Rate of penetration

WOB - Weight on bit

TCI - Tungsten Carbide Inserts

RC - DTH-Reverse Circulation down-the-hole

CwD - Casing while Drilling

E & P - Exploration and production

3D - Three- Dimensional

URL - Unified resource locator

LED - Light -Light-emitting diode

TD - True depth

2D - Two-Dimensional

OD - Outside diameter

ID - Inside diameter

SPP - Standpipe pressure

RKB - Rotary Kelly Bushing

FM – Formation marker

IBOP - internal blowout preventer

BOP - blowout preventer

BHA - Bottom-hole assembly

MD - Measured depth

TVD - True vertical depth

SG - Specific gravity

ODMax - Maximum outside diameter

KPI - Key performance indicators

CTR - Cutting transport rate

BHP - Bottom-hole pressure

CUM - Cumulative

PV - Pressure Volume

PH - Potential of Hydrogen

KCL - Potassium chloride

HGS - Mercury (II) sulfide

F - Fahrenheit

PPG - pounds per gallon