Chair of Drilling and Completion Engineering

Master's Thesis

RHEOBOT – The Conceptual Design of an Autonomous Mud Testing Robot

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Der Wille zum Sinn,
Ist des Lebens Beginn.
Die Freiheit als Verständnis,
Verstößt der Sicherheiten Bedrängnis.

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Abstract

Drilling fluid properties are critical for drilling operations. The drilling mud acts as the primary well barrier and is an essential parameter for drilling efficiency. It is crucial to maintain the optimum settings in order to ensure safe and efficient drilling operations.

Two main parameters, rheology and density, are commonly evaluated manually at the rig site. The testing frequency relies on specific operator requirements but is currently not sufficient enough to properly support real-time decisions. Steadily evolving technological applications allow the operator to drill more complex wells, such as high-pressure and high-temperature, or extended reach wells. Together, with the increasing use of Managed Pressure Drilling systems to facilitate drilling of narrow mud windows, these operations especially require a higher frequency and transmission of drilling fluid measurements.

The commonly used field-testing devices to measure the drilling fluid parameters were designed decades ago and did not keep up with the technological development of other drilling equipment. The manually testing procedures are error-prone, have low measurement frequencies, and thus cannot support the real-time decisions at the rig or remote operating centers.

The drilling industry aims to develop higher degrees of automation regarding the handling of equipment and substances. The automation of drilling fluid measurements with high measurement frequencies can detect anomalies early enough to counteract and therefore reduce the non-productive time as well as the risk of any unwanted events. To provide consistent high-performance drilling operations and to perform the critical step-change to a fully automated drilling rig, a reliable autonomous drilling fluid measurement system is of great significance.

This thesis presents the state of the art of drilling mud testing systems and develops a conceptual design of an autonomous mud testing robot, which increases the frequency of mud testing and provides a more detailed picture of the mud behavior during the drilling operations.

Zusammenfassung

Die Eigenschaften des Bohrschlammes sind für Bohrvorgänge von entscheidender Bedeutung. Der Bohrschlamm fungiert als primäre Bohrlochbarriere und ist ein wesentlicher Einflussfaktor für die Bohrleistung. Es ist wichtig, die optimalen Parameter beizubehalten, um einen sicheren und effizienten Bohrvorgang zu gewährleisten.

Zwei Hauptparameter, Rheologie und Dichte, werden üblicherweise manuell am Bohrplatz gemessen. Die Testhäufigkeit hängt von den spezifischen Anforderungen des Betreibers ab, diese reichen jedoch derzeit nicht aus, um Echtzeitentscheidungen ordnungsgemäß zu unterstützen. Die sich ständig weiterentwickelnden technologischen Anwendungen ermöglichen es dem Operator komplexere Bohrlöcher, wie Hochdruck- und Hochtemperaturbohrlöcher oder Bohrlöcher mit erhöhter Reichweite, zu bohren. Zusammen mit dem zunehmenden Einsatz von Managed Pressure Driling-Systemen, um enge Bohrschlammfenster zu bohren, erfordern diese Prozesse insbesondere eine höhere Frequenz und Übertragung von Bohrflüssigkeitsmessungen.

Die häufig verwendeten Feldtestgeräte zur Messung der Bohrflüssigkeitsparameter wurden vor Jahrzehnten entwickelt und konnten mit der technologischen Entwicklung anderer Bohrgeräte nicht Schritt halten. Die manuellen Testverfahren sind fehleranfällig, haben niedrige Messfrequenzen und können daher die Echtzeitentscheidungen am Bohrturm oder in entfernten Kontrollzentren nicht unterstützen.

Die Bohrindustrie strebt einen höheren Automatisierungsgrad beim Umgang mit Geräten und Substanzen an. Durch die Automatisierung von Bohrflüssigkeitsmessungen mit hohen Messfrequenzen können Anomalien früh genug erkannt werden, um die unproduktive Zeit sowie das Risiko unerwünschter Ereignisse zu reduzieren. Ein zuverlässiges autonomes Bohrflüssigkeitsmesssystem ist von großer Bedeutung, um konsistente Hochleistungsbohrvorgänge zu ermöglichen und den kritischen Schrittwechsel zu einem vollautomatischen Bohrturm durchzuführen.

Diese Arbeit präsentiert den Stand der Technik von Bohrschlammprüfsystemen und entwickelt ein Konzept für einen autonomen Bohrschlammtestroboter, der die Häufigkeit von Bohrschlammmesungen erhöht und ein detaillierteres Bild des Bohrschlammverhaltens während der Bohrvorgänge liefert.

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Contents

Chapter 1 Introduction

The modern oil and gas industry explores towards more challenging hydrocarbon prospects. The downhole pressure margins to reach the reservoirs become very narrow and further include high complex wellbore trajectories. To enable the successful and safe exploitation of these resources, it is imperative implementing innovative technologies.

The wellbore construction process utilizes highly advanced applications to fulfill the demands to maintain well integrity. However, the drilling fluid is the primary wellbore barrier to assure well integrity during drilling operations, and the precise monitoring of the two most influencing parameters, density and rheology, is mandatory. The standard testing method relies on manual measurements, and the current routine testing frequency is prone to provide data up to twenty-four hours old. The newly introduced drilling fluid additives such as polymers, weighting material, surfactants, or viscosifiers create further challenges to evaluate the mud properties.

The currently ongoing development of automated testing equipment is the next essential step to enhance safe and efficient drilling operations further. There are many associated tasks and demands to these testing instruments such as precision, reliability, harsh environments, high pressure and high-temperature testing subjects, accessibility of data in real-time, and cost-efficiency. However, the benefits outweigh the effort, and the successful development efforts of the drilling industry clearly prove that.

The automation of the drilling fluid testing process enables real-time hydraulic optimization, accurate predictions of the downhole conditions, reduction in rig site staffing and associated human exposure, reduction in measurement inaccuracy, and thus reduces the overall risk and costs of drilling operations.

1.1 Objective and Scope of Work

This thesis presents a concept for an automated drilling fluid measurement system. The main goal and attributes of the testing equipment include the continuous measurement capability, real-time data availability, and overall modularity of the system. The basis of the design of the incorporated instruments arises from state-of-the-art technologies applied throughout different industries.

The main objectives of this thesis encompass:

- An intensive literature review to enable a holistic picture of automation development throughout the drilling industry
- The theoretical fundamentals of drilling fluid properties and functions
- A cross-industry market analysis to determine available systems and devices
- The concept of an automated modular drilling fluid measurement system, as a profound basis for future research and experimental studies

1.2 Literature Research and Historical Evolution

This section provides the results of the literature review in chronological order. The research starts with the beginning of the investigation of drilling fluids and the associated measurement techniques. This analytical approach is mandatory to enable a holistic overview and unite knowledge about the drilling fluids testing development. Therefore, it is clear why the manual determination processes are firmly accepted and what challenges the establishment of automated technologies confronts the drilling industry.

The central part of this research relies on technical papers from the Society of Petroleum Engineers (SPE), the International Association of Drilling Contractors (IADC), the American Association of Drilling Engineers (AADE), the American Society of Mechanical Engineers (ASME), the American Petroleum Institute (API), and the Society of Petrophysicists and Well Log Analysts (SPWLA). Further, it includes information from petroleum engineering books, journal articles such as the Drilling Contractor or the Offshore Engineer, and discussion points from colleagues working in the drilling industry. This literature research incorporates the most recent development efforts of automation in the drilling industry, focusing on the continuous monitoring of drilling fluids. However, the research and development departments of the drilling industry publish new studies about automation technology frequently, and thus, not mentioned research efforts are still precious but were not in time for the deadline of this thesis.

1.2.1 Inception of Drilling Fluid Investigation

"As a matter of fact, it is one of the most complicated, technical, important, and interesting subjects in connection with rotary drilling." was stated by Hallan Marsh and refers to the drilling mud. Continuing the research of Eugene Bingham (Bingham 1917, 1922), who described the laws of plastic flow together with a laboratory measurement tool, the technical paper of Marsh was one of the starting points to evaluate the drilling fluids in a theoretically and practical way by characterizing and defining the associated properties and treatments. Marsh describes the most significant mud properties as follows: specific gravity, mechanical analysis, and consistency. Further, he introduces the Funnel Viscosimeter as the standard measurement tool for viscosity in the field, which is still the primary tool for the manual measurements today. (Marsh 1931)

The research about the flow behavior of drilling fluids started at the beginning of the twentieth century with Herrick as one of the first to describe the flow characteristics of drilling muds through a pipe. The presented equations and methods derive on the concept that drilling muds are not liquids, but plastic solids. Further, Herrick (1932) already emphasizes on the effect of pressure on the viscosity of the drilling fluid and introduces a pressure viscosimeter for testing purposes. (Herrick 1932)

In 1937, Jones initially presented the essential field-testing equipment. He describes the apparatus and associated procedures to evaluate the weight, viscosity, sand content, yield point, and static performance of the drilling mud. The research work delineates the following related instruments, respectively: the mud-weight balance, the Marsh funnel device, an elutriation method, the torsion shearometer, and the static-performance tester. The central concept behind all these measurement tools is that they are durable, reasonably accurate, and simple to operate. (Jones 1937)

Several research applications (Evans and Reid 1936; Beck et al. 1947; Rogers 1948) continued the studies of Bingham and the properties and behavior of drilling fluids so that Bingham's law of plastic flow became the leading theory used to describe the non-turbulent flow behavior of most drilling muds. The efficient control of drilling fluids requires sound knowledge about the associated properties, and the related testing methods must be reliable and accurate for the application in the field. Due to the empirical nature of the initial used conventional viscosity test methods, Savins and Roper invented the direct-indicating viscometer, commercially also known as Model 34 Fann V-G meter. This instrument enables us to determine the flow properties from torque readings at fixed rotor speeds and to calculate the plastic viscosity and the yield point with two simple equations (see subsection 2.3.2). The primary intention of this practical viscometer was the reduction in time and complexity, the simplicity of the applied equations, the attainment of data under nearly equilibrium conditions, the improvement to measure gel strengths, and the easy and reliable usage in the field. (Savins and Roper 1954)

In 1984, Rogers et al. presented a coiled-pipe viscometer with the advantage over the traditional rotational viscometer to be able to test crosslinked fracturing fluids. Further, this coiled-pipe viscometer gives an optimistic estimate of proppant transport and delivers the same results as the classical viscometer for non-crosslinked Non-Newtonian fluids. (Rogers et al. 1984)

In 1985, a set of standards and guidelines (see section 3.1) published by the American Petroleum Institute combined the research efforts about drilling fluids and the related testing equipment. These standards specify the manual testing techniques as the recommended practices for the field and laboratory within the drilling industry. However, the late 80s also define the time when the drilling industry started investigating the automation of drilling fluids testing.

Due to the conservative approaches of the industry, the expensive field testing, and the preference to conduct the confirmed manual tests, the implementation of new automation technology was slow and created a research gap between the theoretical possibilities and the practical application. Therefore, the research development parts into two categories: the hydraulic and rheological models and the automation of drilling fluid measurement applications.

1.2.2 Hydraulic and Rheological Models

The newly available data provided from rig sensors enabled the invention of primary hydraulic models to predict and enhance the performance of the drilling operations. The first computer-based drilling engineering programs only considered a single aspect of the wellbore construction progress. Therefore, Swanson et al. introduce an integrated procedure, called the Wellbore Fluids Model, which realistically combines all interacting processes of the drilling fluid during drilling operations. For example, hydraulic pressures, cutting transports, and changes due to temperature and pressure are simulated and evaluated. Thus, the presented model can simultaneously provide a solid basis for engineering decisions. The model predictions were compared against real field measurements and enable a simulation to illustrate the different drilling interactions. This simulator already includes changes in pressure, density, drilling fluid density, drilling fluid viscosity, drilling fluid velocity, and cuttings accumulations while drilling. (Swanson et al. 1991)

The research work of Growcock et al. details what happens inside the mud during the execution of an electrical stability test (see subsection 3.2.12). It is imperative to measure the electrical stability of the drilling fluid continuously to achieve good drilling performances with oil-based muds. Further, this paper describes how the different drilling mud compositions can affect the electrical stability measurement trends and how these trends help obtain the emulsion stability and the oil wettability of the drilling fluid. (Growcock et al. 1994)

The drilling performance initially relied on trial and error or repetitive calculations by combining several computer programs. The different variables of the drill string configuration, the nozzle diameters, the rig capabilities, the system pressure distribution, and the mud properties are required to determine the optimum drilling fluid flow-rate to enable the highest possible rate of penetration. The research of Swanson et al. transforms the routine drilling engineering tasks into a hydraulics and hole cleaning application. The input for this system uses the different variables for hydraulics optimization identified in several studies (Millheim 1983; Reza and Alcocer 1986; Monti et al. 1987). Further, it combines them with the financial and physical limits by applying the following calculations: circulating pressure losses, bit hydraulics, and minimum flow rates for cutting removal. This presented application combines the drilling hydraulics optimization from previous approaches and introduces a graphical interface to illustrate the multi-parameter optimization model to the engineer in the field. (Swanson et al. 1994)

The exact knowledge of the pressure drop within the hydraulic circuit is vital for all drilling operations. The development of the Herschel & Bulkley rheological model (see subsection 2.3.2) sets the start point for the research of the drilling fluid flow behavior. Based on this, the research about the influence of temperature and pressure effects on the drilling fluid was subject to many studies (Annis 1967; Ferry 1980; Baranthol et al. 1995; Maglione et al. 1996). The high temperature and pressures can affect the rheological parameters of the drilling fluid in the following way: physically, electrochemically, and chemically. However, since already small differences in the drilling mud composition can result in an alternate rheological behavior, it is challenging to state a general guideline for the drilling mud behavior.

Based on the wellbore fluids simulator (Swanson et al. 1991), the research of Swanson et al. introduces a system for early kick detection (EKD). This EKD system uses real-time analysis of the mud logging data to compare the mudflow and standpipe pressure values from a dynamic wellbore model. Therefore, this kick detection visualizes the deviations between the measurements and the predictions from the idealized model. Further, this research already emphasizes that future work must include real-time automation applications and the benefits of visualizing trends to react faster to occurring well control issues. (Swanson et al. 1997)

Especially for high temperature and high pressure (HPHT) wells, it is imperative to have good knowledge about the effects of pressure and temperature on the mud system. The work of Rommetveit et al. (1997) presents the practical implementations for the pressure and temperature dependency of the rheological parameters and describes the associated calculations. It outlines the transformation of reliable HPHT hydraulic models into an advanced pressure and temperature simulator. These simulated predictions require an accurate understanding of the temperature and pressure profile of the wellbore and precise knowledge of the density, viscosity, and gel strength of the active drilling fluid. (Rommetveit and Bjorkevoll 1997)

The ongoing progress of new drilling challenges, economic realities, and environmental concerns drives advancements in drilling fluids technology. At the beginning of the twenty-first century, the drilling industry introduced several new technologies, such as real-time downhole pressure measurements, powerful but inexpensive computers, and reliable viscometers with wide temperature and pressure limits, to properly analyze and optimize drilling fluid hydraulics. Together with these improvements, Zamora and Roy present the main reasons to re-evaluate the drilling fluid rheology and hydrodynamics critically. They emphasize that most unscheduled drilling trouble events are related to hydraulics, and that fuzzy logic and real-time automated modeling are the most promising upcoming technologies to improve further the drilling fluid optimization and the performance of the overall wellbore construction. (Zamora and Roy 2000)

The rheological models, such as the Bingham Plastic, the Herschel-Bulkley, the power law, and the yield power law, represent the flow behavior of a drilling fluid. The relationship between the particular rheological model and the friction pressure loss calculations for drilling operations is the subject to the research work of Subramanian. He presents an experimental study to determine the frictional pressure drop for five different drilling fluids in a pipe and annular flow. Another experimental study was conducted by Herzhaft et al. to determine the influence of temperature and pressure effects on the drilling fluid rheology. The mathematical laws can describe the temperature and pressure subjection of the drilling fluid rheology, and the comparison with field data simulations demonstrate the prediction of the downhole values. (Subramanian and Azar 2000; Herzhaft et al. 2001)

In 2002, Zamora and Power emphasize the need to update the drilling fluid rheology guidelines to keep up with evolving drilling technologies and to close the gap between theoretical and practical solutions regarding advanced drilling hydraulics, enabled by computer applications. Further, the research work introduces the so-called unified rheological model to support the argument. This drilling fluid model is based on the commonly used Herschel-Bulkley flow equation and aims to correspond to the industry practices in a closer and more practical way. However, due to the complexity of the different drilling fluids used throughout the industry, it is challenging to develop a consistent practice for all operations, and a general guideline to address complex wells as well as conventional wells is hardly possible. (Zamora and Power 2002)

Laurenco et al. present an empirical study of the rheological behavior of foam flowing horizontally in pipes under elevated pressures and temperatures. The paper indicates a primary effect of the quality and texture of the foam on the rheology and only a secondary effect of pressure and temperature. (Loureno et al. 2004)

The traditional hydraulics optimization methodology starts by determining the optimized flow rate based on the rheology parameters of the drilling fluid. This flow rate needs to be inside the physical limits of the wellbore and also maximize a specific optimization criterion. The research work of Guarneri et al. presents that this hydraulic optimization process improves by considering mud rheology as an outcome value rather than an input. Based on the drilling hydraulics constraints, the paper from Guarneri et al. presents two hydraulic windows with the flow rate and pressure limitations as the boundaries. Temperature and pressure affected changes for downhole mud density and rheology additionally define these boundaries. The hydraulic windows illustrate the concept of the software behind the hydraulic optimization process. Primarily this software evaluates the Herschel-Bulkley rheological parameters and the required flow rate regarding the defined optimization criteria. (Guarneri et al. 2005)

In extension to the antecedent paper of Zamora and Power, Zamora et al. present additional equations to the prior invented unified rheological model to address further important hydraulic issues. The primary objective of this research is still to provide an easy to use hydraulic model besides the high-end hydraulics software applications, in the perspective of the engineers at the rig site, who use this technology in the field. The results of a comparison of this improved unified rheological model with a laboratory flow loop and large-scale yard test results were favorable. (Zamora and Power 2002; Zamora et al. 2005)

In 2005, Gravdal et al. presented a new methodology to update the critical parameters of a wellbore flow model by integrating real-time measurements and the associated uncertainties. This estimation technique development derives from the traditional Kalman Filter method. It enables a combination of the hydraulic model with real-time measurements to gain enhanced knowledge about the behavior of the wellbore. This understanding is imperative for the reliable use of automated managed pressure drilling systems and additionally provides an enhancement in the ability to act in terms of wellbore problems. (Gravdal et al. 2005)

The increased well complexity, the extensive use of high pressure and high-temperature sensitive drilling fluids, and the demand to develop a holistic wellbore engineering approach were the reasons why the industry methods for drilling fluid hydraulics have deviated from the American Petroleum Industry (API) Recommended Practice 13D. Further, the theoretical research work has parted away from the field practices by introducing highly advanced hydraulics software applications. To close this widening gap and to revise the API standard, an extended workgroup modernized it. They introduced it as a practical reference and a training guide for both office engineers and well site operational staff. Bern et al. present the main focus and the associated workflow, and the introduced updated API standard offers an ideal fundamental concept for drilling fluid design and optimization. (Bern et al. 2006)

Most managed pressure drilling (MPD) systems rely mainly on the hydraulic model, which operates as the control element. Therefore, several studies (Iversen et al., 2006) analyze the challenges and possibilities of the different MPD choke control systems, including assessing the two principal methodologies for an automatic choke control: the linear PID controller and the nonlinear Model Predictive Controller. In 2008, Iversen et al. presented an integrated drilling control system, based on previous laboratory tests, on an offshore platform in the North Sea. This system continuously optimizes the operational parameters by using calibrated dynamic process models. However, the drilling fluid input consisted only of the density and the temperature, measured at the pits. (Iversen et al. 2006b; Iversen et al. 2008)

The previously described flow model is presented in detail by Petersen et al. The model is part of new technologies to meet the challenges of the more advanced well designs, drilling conditions, and reliable real-time decision support. The main objection of such hydraulic flow models are the correct involvement of all essential parameters, the possible critical events (Petersen et al. 1998; Petersen et al. 2001), and to compute the results fast enough for real-time decisions. The research work of Petersen et al. describes the assumptions, the architecture, and the solution methods for such an advanced hydraulic flow model and presents results of field applications. (Petersen et al. 2008)

Based on drilling operations in the North Sea, a methodology was further developed by Lohne et al. to calibrate the real-time computer models. This technique led to more precise estimations of the wellbore and drill-string status and thus can enhance the performance of real-time decision support systems. Integrating and visualizing the accumulated real-time and historical data can fill the technological capability gap and thus further enhance the drilling performance and the well productivity and enable a fully digital oilfield. The development needs not only the integration of data but must combine it with the existing applications and monitoring systems. That can be achieved by improved workflows and computing power and by adopting soft computing methods, such as neural networks, probabilistic reasoning, and fuzzy logic. (Lohne et al. 2008; Holdaway 2010)

The digital oilfield is described by Holdaway as follows: “The digital oilfield is a strategy for improving a specific area of an oil company’s business by deploying people, technology, and knowledge effectively.” Further, he emphasizes that this step will transform how people work, and the main ingredient will be qualitative, secure, and timely access to data. To overcome this technology gap, Holdaway defines three essential categories: data management, data extraction, transformation and loading, and data cleansing. (Holdaway 2010)

The fluid flow and the pressure response describe roughly the overall wellbore hydraulics and are an essential element of real-time drilling monitoring. The real-time monitoring and the related analysis of the drilling fluid combined with hybrid algorithms can recognize variations in expected behaviors, and thus preventive actions can be taken. This monitoring of these critical parameters is currently mainly based manually and inconsistent. The drilling fluid monitoring needs to be automated to remove the inaccuracy and inconsistency in the data gathering process. The research work of Zoellner et al. presents a methodology and a case study by comparing the fluid flow with the pump pressure and other drilling rig sensors. This concept defines four problem groups to establish a common basis for discussion: the change of pump efficiency, tubular flow path, annular flow path, and material balance. The changes in the drilling fluid volume or mass can result from fluid influx from the formation, drilling fluid losses, or formation contaminants. These problems can be detected and prevented by monitoring density and rheology. (Zoellner et al. 2011)

It is imperative to re-examine many traditional techniques for drilling operations prior to their application at high temperature and high-pressure (HPHT) wells. The research of Shrivastav et al. emphasizes the dynamic impact of high temperature and high-pressure effects on the drilling fluid properties and introduces an integrated methodology for this behavior. Further, it presents the thermal disintegration of several mud types, how to extend the temperature limits of the drilling fluids, and describes the associated kick prevention, kick detection, and well control measures. (Shrivastav 2012)

Several automated drilling applications already replace manually conducted drilling operations. Further, the drilling automation provides smart safeguards, safety triggers, and has the final goal of complete or semi-automated drilling rigs. The development of the related analysis software shows the limitations of the currently used measurement sensors. Every new drilling automation technology relies on a physical model of the drilling process, including mechanical, hydraulic, and heat transfer models. The research of Cayeux et al. analyses the necessary measurements, by comparing them with the model requirements, to develop drilling automation further. Four types of information can describe the relationship between the rig sensors and the physical models: the equation domain, the structural information, the operational information, and the boundary conditions. For automated drilling fluid measurements and control the structural and operational data is crucial. The current measurement limitations for drilling mud data are the frequency and operator error. The analysis shows that for this drilling process, new real-time sensor systems and the right placement are imperative for the drilling process automation. (Cayeux et al. 2013)

Complex drilling operations require sophisticated applications. Automatic systems can improve the overall performance and safety during the wellbore construction phase. The use of real-time mechanical and hydraulic mathematical models for drilling operations support these automated drilling processes. The advantages of implementing high-fidelity models are: to fill data gaps of sensors, to add redundancy, to improve the wellbore status knowledge, and to perform predictions. However, the associated challenges are adequate calibration, reliable sensor data, and to know when the model assumptions are incorrect. Common issues of sensor measurements are the inaccuracy of centered noise, poorly calibrated sensor systems, and synchronization of real-time measurements. (Bjørkevoll et al. 2015)

Further, the generally used rig sensor system was not initially invented based on automation and mathematical models. For implementation into physical models, the measurements should correspond to the physical boundaries of the modeled system. Those exact measurements are rarely available and are often estimated using other sensor data. For example, the evaluation of the return flow rate is not direct, although it is a critical parameter for influx and loss detection. The research work of Bjørkevoll et al. shows these limitations of mathematical models and discusses the limitations. The results clearly outline that drilling automation development also requires advancements of the related models to enable more reliable and user-friendly applications. (Bjørkevoll et al. 2015)

A full mud test typically includes the mud balance, Fann 35 viscometer, API filter press, and High-pressure high-temperature filter press to evaluate the drilling mud properties. The testing frequency at the rig site is 10 – 15 minutes for mud density, Marsh funnel viscosity, and solids content, but only twice a day for the full mud test. The density of the drilling mud controls the formation pressure, and the plastic viscosity and yield point are the characteristic properties to evaluate hole cleaning. The rheology values of the drilling fluid are mandatory to specify the hole cleaning efficiency, pressure losses, equivalent circulating densities, and the fluid flow profile. The research of Elkatatny introduces a novel model to predict drilling fluid rheological properties. An artificial neural network created the mathematical model. The input variables are the density, viscosity, and the solids content, and the result is a set of empirical correlations that predict the rheological properties of the drilling mud. This technique can support drilling decisions and help to monitor and control drilling fluid measurements. (Elkatatny 2016)

The measurement uncertainties in the drilling process make it mandatory to implement several safety factors to reduce the operational risks to a minimum. However, this safety margin method is ineffective and represents additional operating costs. The safety margins of the equivalent circulating density (ECD) management and the hole cleaning reflect the outcoming of inaccurate drilling fluid measurements. Jamison et al. emphasizes on the conventional sources of measurement errors at the rig site and presents how an automated real-time density and rheology measurement can positively affect the ECD safety margins and thus reduce the casing-to-casing time effectively. The approach uses the application described in Dotson et al. to evaluate the density and viscosity of the circulating drilling mud. The results show two main advantages: the automated system can more closely track the changing pressure deltas, and the capability to identify trends is significantly simplified. Additionally, this research implements analytics to reduce measurement uncertainties further. (Dotson et al. 2017; Jamison et al. 2019)

1.2.3 Automated Drilling Fluid Management

The idea to automate the drilling operations started in the mid-nineteenth century when Robert Beart (1845) granted a patent for the rotary rig with continuous circulation. The main motives to mechanize and automate drilling applications are to reduce the headcount on the rig floor, enable operations in harsh environments, reduce the overall rig weight and areal size, to increase the efficiency and thus reduce the operating costs. Mechanization, semi-automation, and local automation are the three divisions of the related technological developments. This evolution process starts with the substitution of human power by mechanical power. In the next step, the automation of a particular operation takes place, which an operator supervises and partly controls. (Beart 1845a, 1845b; Carter 1961; Brantly 1971; Eustes 2007)

The final goal is then the fully automated application, which does not need any intervention, and the operator only needs to start up the machine. Most automation inventions are related to the rig floor as this is the most dangerous place and thus has the highest risk potential. The most significant drilling operation improvements are the top drive, the iron roughneck, and the automated racking system. However, to accomplish the goal of an entirely automatic drilling rig, all the applications at the well site need to be automated and combined. (Carter 1961; Brantly 1971; Eustes 2007)

The start of the automated testing of drilling fluids began with Zamora et al. defining five main factors for the selection of drilling fluid measurement tools: accuracy, usability, time constraints, operating environment, and investment and operating costs. The frequent testing of the drilling fluid parameters is necessary due to the high complexity of the drilling mud. Further, this paper presents three testing devices. First, it describes the automatic shearometer, a tool that gives a picture of the shear strength and solids distribution of a statically aged column of drilling fluid. Second, the paper outlines the dynamic filtration tester, which can define the dynamic filtration characteristics of drilling mud at high pressures and high temperatures. Third, it presents the filter-cake penetrometer, a device to evaluate static and dynamic filter cake and identify possible filtration problems. (Zamora et al. 1990)

The functionality of the drilling fluid testing equipment is fundamental for save and economical drilling operations and the accuracy and reliability of the measurement data. Therefore, Geraghty and Motley introduced the criteria and procedures for calibration and function testing of the drilling mud testing instruments used in the field. This quality assurance program establishes out of two main definitions. The first one is the calibration, which defines the testing and associated adjustment of the entire operating range of the testing equipment. The manufacturer generally states this in the technical specifications of the device. The second characterization is the invented concept of function testing, which specifies if a particular instrument performs within the predefined limits at the specific environment. Further, this paper outlines five leading design criteria for this quality assurance program: practicality, sensibility, precision, usefulness, and responsiveness. Besides the industry standards (see section 3.1) for testing equipment, this research illustrated the reduction in equipment failure rate and the appropriate standardization of calibration and related training. (Geraghty and Motley 1992)

The solids removal equipment usually removes the main fraction of the drill cuttings from the drilling mud. However, the remaining portion of the drilled solids, such as low gravity solids, still affect the functional properties of the drilling fluid. The measured density and the volume of the solids fraction provide the basis to calculate the initial measurement of these solid fractions. The measurement instruments to determine these parameters are the mud balance and the mud retort, respectively. Due to accuracy limitations, assumptions, and operator errors, the concept of measuring solids in drilling fluids by applying x-ray fluorescence (XRF) replaced the mud retort. Houwen et al. introduced this new methodology and implemented an algorithm that utilizes the barium fluorescence, backscattering intensity, and fluid density to predict the solids concentration. Research estimations describe the XRF technology about ten times more precise than the conventional mud retort technique. (Houwen et al. 1993)

In the nineties, Mureh et al. presented a joint industry project, which describes the invention of an integrated automated mud system and the related potential benefits. The project implemented installing a test system at an offshore rig, and the paper further displays the design criteria for such equipment, the communication network, and the overall benefits. (Mureh et al. 1994)

The ongoing development of the X-ray spectrometry technology (XRF) presented by Davison et al. showed promising outcomes. The XRF was initially only available for water-based mud tests, but the continuous improvements enabled the technology to measure the concentrations of solid phases, liquid phases, and some ions. (Davison et al. 1996)

Each newly invented drilling technology for any drilling operation has the goal to optimize the performance to drill a wellbore. These technologies derive from two main intentions: enhance operational safety and reduce the costs as low as practically possible. Since rotary drilling started in 1901 with the well at Spindletop, many novel technologies improved the overall drilling performance. In the late nineties, Reinhold and Close evaluated the development of the driller's role in the wellbore construction process and present that the industry moves toward computer-based instrumentations and operations and automation. (Reinhold and Close 1997)

This research clearly shows the trend that by utilizing more advanced technologies, also the exceptionally trained staff is required. Further, Reinhold and Close explain the progress of automation within the drilling industry shows three phases: the fully manual phase, the fully supervised automated phase, and the minimally supervised automatic phase. The future task will be to integrate all the specialized operations into one remotely controlled automated system. The applications show that with automation, the overall safety enhances, as well as the operational costs decline. (Reinhold and Close 1997)

The drilling of extended reach wells introduced new hole cleaning problems to the industry, since the cuttings accumulation develops higher torque, pressure losses, and increases the risk for stuck pipe incidents. An enhanced understanding of the wellbore cleaning process and status can lead to improved overall drilling performance. The work of Naegel et al. establishes the cuttings flow meter (CFM), which is an instrument to measure the cuttings flow at the shale shakers outlet continuously. This measurement enables the comparison between the drilled hole volume and the volume of the returned cuttings at the surface, which further directs to the cuttings accumulation in the hole and the associate increase in hole friction. Therefore, the mud rheology and the circulating rate can be adjusted to keep the circling pressures at a minimum. This research shows that the drilling fluid rheology values and the flow rate are the main parameters for efficient hole cleaning, and in conclusion it presents, that the circulating pressure both at the surface and downhole are the limiting factors. Since the flow rate of the cuttings is relatively low compared to the mudflow rate, the continuous measurement must be done directly at the mud treatment units to be accurate enough. (Naegel et al. 1998)

For the determination of drilling fluid parameters, the usage of the Herschel and Bulkley model from 1926 is possible. Maglione et al. present a method which records the pump rates and the relative standpipe pressures during flow tests at fixed drilling depths. Therefore, the in-situ Herschel and Bulkley parameters of the circulating drilling fluid can be determined. The next step is to compare the obtained results with laboratory measurements made with a Fann VG 35 viscometer. The paper concludes that the rheological parameters of oil-based muds are mainly dependent on temperature and shear rate. (Maglione et al. 2000)

Further, the paper describes a contrary behavior of the equivalent viscosities for shear rates below and above 30 seconds^{-1}. However, the results of the suggested method show proper alignment with the laboratory measurements with only minimal errors from the practically used rheological models (e.g. Bingham, Ostwald and de Waele, and Herschley and Bulkley). The standpipe pressure monitoring enables determining the variations of the rheological parameters versus the pressure and the temperature and checking the integrity of the hydraulic circuit from the drilling process. (Maglione et al. 2000)

The driller's role modifies with changing responsibility from the basic drilling mechanics to a real-time drilling supervisor. Havrevold and Hytten emphasize this and describe one of the first real-time applications called Analysis-While-Drilling (AWD). At the beginning of the twenty-first century, a project under the name Drilltronics started, which is presented by Rommetveit et al. This work picks up the real-time approach and specifies an innovative system for drilling automation and simulation. This system combines all available rig sensor data. It includes the following elements: a modeling software, continuously calibrated real-time drilling data models, real-time drilling process diagnosis, an integrated drilling simulator, and automated critical sub-operations. (Hytten et al. 1991; Reinhold and Close 1997; Rommetveit et al. 2004; Dash 2019a)

This Drilltronics project emerges from several research programs conducted at the Rogaland Research since the 1980s and further improves the Integrated Drilling System (IDS) project, performed from 1990 – 1994. The Drillltronics project consists of different modules, including tasks such as hole cleaning, downhole pressure, tripping, torque and drag, stick-slip prevention, and bit load. This project was successfully tested at the Ullrigg testing facilities of the Rogaland Research and marks the primary step to combine all drilling sensor data, including the outlook for integrated automation in the future. (Rommetveit et al. 2004)

In 2006, Iversen et al. described the testing of the application of integrated monitoring and control systems for drilling operations. The results show that this technology is highly dependent on the parameters of the hydraulic model and the drilling mechanics. Therefore, a vital element of this methodology is to update the measurements of these parameters continuously. (Iversen et al. 2006a)

To properly design the required drilling mud for optimum drilling fluid performance, it is mandatory to know if the produced solids are cuttings or cavings. Initially, the only method was to anticipate the performance of the solids control equipment as no measurement instruments to control the quantity and particle size distribution (PSD) was available. A method for a real-time continuous PSD measurement is presented by Omland et al., which uses image analysis to provide this information. Further, this paper presents a technique to characterize cuttings and provides data about the mineralogical properties of the formation by implementing a Raman spectroscopy. This research shows the potential of automated measurement applications to improve drilling performance by continuous drilling fluid monitoring. Implementing this new technology, the effects of the particle size distribution on sag, formation damage, and rheology changes can be discovered early and thus prevented by optimizing the drilling fluid. (Omland et al. 2007)

To drill wells in high-pressure and high-temperature (HPHT) reservoirs in the North Sea, Syltoy et al. developed and presented an advanced managed pressure drilling (MPD) system. This application includes, amongst other things, a real-time dynamic flow model, with continuously updated pressure setpoints for the choke system, and a continuous circulation system. Typically high-pressure and high-temperature wells show high variations in the bottom-hole pressure due to but not limited by changes in mud weight, viscosity, and cuttings load. To safely drill the well, the dynamic flow model manipulates the choke and compensates for the related downhole temperature and pressure changes. The limitations for the hydraulic model are the computing power, the accuracy and speed of the rig sensors, and the calibration of all the associated instruments. For this MPD system, a mass flowmeter with a bypass was used, but only with a monitoring purpose and no direct control to the overall system. However, these mass flowmeters can provide high-quality data, and further automation and related reduction of manual operations is the future goal for MPD systems. For this specific well, as presented by Syltoy et al., an annulus pressure while drilling sub was used to measure the downhole annulus pressure in real-time. The research shows, by comparing this measurement with the advanced hydraulic model, that the mud rheology input can account for an offset of around eight to ten bar. (Syltoy et al. 2008)

To further remotely control the drilling process and strengthen the ability to react to changes, it is imperative to measure several essential drilling parameters automatically. The work of Saasen et al. describes the design of the combination of instruments to measure the density, the viscosity, the fluid loss, the electric stability, the particle content, and size distribution, and chemical properties such as the pH value and the H2S concentration, automatically and continuously. Further, this paper presents the results of a full-size yard test at the Ability Test Centre and the outcomes of individually tested single components at different rig sites. (Saasen et al. 2008)

The general categories of the automated drilling process are the following: automatic pipe handling, automated drilling operations, such as drilling on bottom, reaming and tripping, automated mud sampling and analysis, and automated managed pressure drilling. All these technologies further develop the overall automatic drilling process, but it is mandatory to notice that the interfaces between them must be consistent. Strøm et al. present a good overview and review of existing automated drilling applications and related field tests and the challenges of the future drilling scenario. Further, this research points out that there are many different sub-systems currently being developed, but not a specific solution to tie them together. (Strom 2008)

Most of the standard drilling activities traditionally implement manual operations. However, there is significant economic potential to automate these tasks by reducing drilling time, increasing regularity, and improving performance. The work of Godhavn discusses control requirements for drilling operations and presents some field experiences. The paper emphasizes that repeatability is one of the most crucial measurement characteristics because most drilling processes operate below the technical limit. The control of the drilling process is mainly performed based on surface data since the knowledge of the downhole condition is limited and indirect. A partly or fully automation is necessary to see a significant step-change within the drilling operations. The main reasons for automatic control are health, safety, and environmental improvements, reduced costs, and enhanced efficiency. (Godhavn 2009)

Godhavn separates the term automated drilling into the following subcategories: robotics, instrumentation, and control methodology. A fully automated robotic system can deliver significant efficiency developments and reduce the number of people on the drill floor. The rig machines must be controlled by a computer, which can entirely automatically connect and coordinate the control of mud pumps, draw works, and pipe handling robots. The general average for non-productive time is 20-25%. This inefficiency is mainly related to wellbore instabilities and well control issues. In addition, a significant fraction of the non-productive time is due to the reliability of the instrumentation and equipment, such as mud pumps, sensors, and communication. (Godhavn 2009)

The primary control mechanism is a feedback control system, using the sensor measurement as a feedback signal for the supervised output and compares it with a reference signal. Further, the system creates an error signal based on this comparison, filtered by a controller unit to generate the system's control input. The most widely used industrial controllers are based on the simple linear proportional and derivative (PID) systems and the model predictive control (MPC) systems. (Godhavn 2009)

Two of the major factors to integrating an automatic system are standardization and modularization. The management system should be the same for all data sets and updated with a high frequency. The synchronization with the onshore crew should be via standardized protocols. Redundant measurements and fault detection algorithms can enhance the robustness of the systems. The utilization of an automated real-time measurement system improves the accuracy of the hydraulic model. (Gravdal et al. 2005; Iversen et al. 2008; Lohne et al. 2008; Godhavn 2009)

At the turn of the millennium, drilling automation was rapidly developing within several diverse organizations of the drilling industry. Together with these independent developments, the related jargon evolved and created misunderstanding and confusion in some areas. Thorogood et al. pointed out that it is imperative to define and agree on basic terms regarding drilling automation to avoid unnecessary misinterpretation, to create a research basis everybody understands, and to assure that the progress towards automation leads to efficient and safe operations. Further, this research classifies the critical categories of automation and presents related drilling technologies. (Thorogood et al. 2009)

The initial advancements split into three groups: specialized controls integrated on the rig or the drill string, models for better understanding and enhanced performance, and visualization techniques. Several research approaches (Sheridan 2002; Hui-min Huang 2004; H. Huang et al. 2005) defined the degree of automation. In 2009, Thorogood et al. outline the automation levels for the drilling industry including the operator. To the time of this research, most of the applied drilling technologies fall into category 0, where a human operator executes the action or determines a setpoint, and some are between levels 2 and 3, for which the system supports the operator with suggestions. (Eustes 2007; Thorogood et al. 2009)

For drilling operations in depleted reservoirs, Managed Pressure Drilling (MPD) is becoming the technology of choice. To ensure safe and efficient drilling performances, the control of the particle size distribution (PSD) is imperative. The initially used instruments are the granulometer, which monitors the trend of the PSD, the laser light scattering method, or the wet sieve analysis. However, all these measurement techniques require sampling of the drilling fluid and thus contain the issues due to sampling accuracy and sample preparation. (Ronaes et al. 2009)

The Focused Beam Reflectance Measurement (FBRM) fills the gap of suitable equipment for real-time PSD measurement. The research of Ronaes et al. presents this technology, shows results of trial and field tests, and the comparison against the commonly used laser diffraction analysis. The given FBRM system demonstrates to be beneficial for solids control management and procedures to maintain the particle size distribution. Further, it is an "off-the-shelf" tool because it requires no mechanical modifications or software format changes. (Ronaes et al. 2009)

The use of the gathered data during drilling operations is mainly for planning, documenting, and post-analysis. However, the data quality is good enough to optimize drilling operations in real-time and utilize it to support real-time decisions. The different systems need to inter-operate. Also, there are standards for exchanging drilling-related information, but no standard defines the communication for drilling control. The research of Ornaes shows the different standardization systems and requirements to face the data integration of the automated drilling technology, together with the related levels of autonomy and automation. This study defines the basis of the AutoConRig project, which focuses on such autonomous drilling machine communication standards. (Ornas 2010)

There is a high risk to fracture the formation during the pump start-up for several drilling operations. The industry developed a semi-automated mud pump management to reduce the risk of breaking the formation while circulating or ramping up the mud pumps. The three included areas of these management systems are pump start-up management, maximum pump rate limits, and automatic pump shutdown procedures for abnormal situations. Significantly as the wellbore conditions are continuously altering the related safeguards and restrictions to operate, the mud pumps must be updated accordingly. Cayeux et al. present the needed methodology to implement the functions mentioned earlier to a mud pump management system. The primary necessity is to have reliable data about the downhole conditions and a trustworthy hydraulic model that supplies the decision making process with real-time estimations. This continuous knowledge about the well status includes the following points: temperature of the drilling fluid conduit, cuttings ratio in the annulus, local densities in the annulus, barite sag effect, liquid level inside the drill string, drilling mud gelling time, and the friction coefficients inside the annulus. The research work of Cayeux et al. presents such an advanced mud pump management system and highlights the observations of field applications and virtual tests. (Cayeux et al. 2010)

Due to the limitations of the manually drilling fluid measurement frequencies, which can be up to 24 hours old, Broussard et al. started researching automatic routines for fluid property tests. Based on their field trials, they executed a comparative analysis of automated and traditional measurements. Further, the technical paper presents the strengths and limitations, the integration and presentation possibilities, and the overall lessons learned for automated density and rheology measurements. The field trials utilized an oscillating u-tube for density measurements and a Couette viscometer for the rheological parameters. Further, Broussard et al. emphasize the importance of the cleaning process and the differences between testing water-based and oil-based drilling fluids. (Broussard et al. 2010)

The research work of Miller et al. analyses the required design criteria of the different instruments and suggest an automated drilling fluid measurement package, using the "Tuning Fork" technology to obtain density and viscosity data. This instrument combination has been under development for eight years, including extensive laboratory testing and several field trials in the North Sea. (Miller et al. 2011)

To automate a process is not a new idea in general, but it took some time until the drilling industry integrated it into the daily operations. In general, an automated application enables more efficient, safer, and repeatable processes. The following four levels describe the degree of automation of a system: a fully manual operation, a remotely operated or partly automated system, an automated system, and a fully-automated real-time measurement-based system. The research of Kvame et al. presents the development of the automated drilling mud mixing systems. This paper shows that automated drilling processes increase in importance throughout the industry and emphasizes that the development of automated drilling fluid systems enhance the safety, quality, and efficiency of the mixing procedure. The outlined results show an increase of 80-95% regarding exposure to dust, noise, and heavy lifts and improved efficiency of 30-60% by applying an automated mud mixing system for daily mud mixing operations. (Kvame et al. 2011)

Further, this research work describes the four central systems involved in the mud mixing process: the bulk system, the mud mixing system, the liquid additive system, and the low-pressure mud mixing circulation system. The main limitation within automated mud mixing systems is to determine the degree of automation the user required. Also, the operator must consider the limiting factors of the additionally needed space and installation of equipment, as well as the user knowledge and skepticism about the new systems and interfaces. (Kvame et al. 2011)

However, to reach the last level of automation, the challenge is to develop a reliable computer model that converts real-time measurement data into a recipe for the mud mixing system to maintain optimum drilling fluid parameters throughout the entire drilling operations. For this model, density and viscosity are the most relevant parameters. Still, it also has to integrate pH-value, electric stability, salinity, oil/gas ratio, H_2S concentration, particle size distribution, and the fluid loss to generate a more accurate recipe. The industry must develop surface-based, as well as downhole measurements to deliver these parameters in real-time. (Kvame et al. 2011)

When drilling through permeable formations, the drilling fluid density column and dynamic pressure losses mainly establish an overbalanced pressure that causes a drilling mud loss into the rock formation. The development of a filter cake on the wellbore wall is imperative to prevent critical losses of the drilling fluid. The creation time and the filter cake thickness generally depends on specialized chemical additives and solids particles that the drilling mud contains. During drilling operations, the drilling fluid typically experiences the following three stages of filtrations: spurt loss, static filtration, and dynamic filtration. The first phase describes the initial fluid loss into the formation until a competent filter cake establishes. At the same time, as the filter cake continuously develops, the filtration rate reduces with time. This filtration is the so-called static filtration and occurs during operation periods without circulation, such as open-hole completion, tripping, or making connections. The manually operated static filter press determines the associated measurement. Contrary, the dynamic filtration appears while drilling fluid moves perpendicular to the filter cake and filtrate flow. This crossflow restricts the filter cake development by erosion. The research of van der Zwaag et al. analyses the dynamic loss mechanisms and presents the results of a field experiment in the North Sea, where high seepage losses occurred. (van der Zwaag et al. 2012)

Automation combines control systems and information technology to minimize the physical and intellectual tasks of human operators. In contrast, mechanization assists the operator by replacing the applied human force with mechanical power. Thus, automation describes the next step: the goal is to increase the overall economic and operational performance of a process while performing it as safe as possible. The research work of Breyholz and Nikolaou describes the different management modes for automation of drilling processes and the related applied systems such as envelope protection, closing the loop, multilevel control structures, feedback control, and supervisory control. Further, it outlines how the role of the driller changes if applying highly automated drilling operation systems. The main limitation is that the driller must be able to take control of the operation if the system fails. Thus, as an automated environment becomes the norm, the overall manual skills of the drillers will decline as the applications decline. The primary bottleneck of any automated drilling system is the diagnostic system, which must deliver reliable and high-quality measurement data to detect all unwanted borehole conditions. (Breyholtz and Nikolaou 2012)

The drilling industry steadily develops new technologies to automate the drilling processes further and thus achieve higher performances and safety standards. One of the primary automation motives is to reduce human error. However, several research studies outline that automation not necessarily reduces human error but creates a different class of error. Depending on the level of automation and autonomy, the most critical error source is mode confusion. Hereby, the operator expects the technical system to behave differently from the expectation and leads to inappropriate use of the system. For example, if the driller displaces the wellbore to a higher mud weight and expects the automated Equivalent Circulating Density (ECD) to supply a low flow rate, not to fracture the formation, but did not update the system with the new mud properties. (Skitka et al. 1999; Bredereke and Lankenau 2002; Iversen et al. 2012)

The research of Iversen et al. analyses the different modes and levels of automated drilling support systems. Further, the study outlines the various influences these systems have on performance and human error. The results of this research clearly show that a well-functioning communication system, a solid knowledge about the system, and the behavior of the system is imperative to reduce the overall error frequency. (Iversen et al. 2012)

The drilling industry recognizes the advantages of automating vital elements of the drilling process. In 2012, Stock et al. and Ronaes et al. review the possibilities of sensors, which can perform real-time monitoring of critical drilling fluid parameters. Therefore, the existing sensor technologies used in other industries and those requiring further development are discussed by this research work. (Ronaes et al. 2012; Stock et al. 2012)

The research of Stock et al. is a continuation of Saasen et al. and further describes the possible instrumentation, which can utilize automated drilling fluid measurements. This technical paper also emphasizes that the ongoing development of managed pressure drilling requires and drives the trend for automatic mud testing units as most MPD systems use a hydraulic model to calculate the required setpoint for the choke pressure. Additionally, this research executed a field trial to evaluate the control capabilities from an onshore drilling center of these operations. This test showed that the drilling fluid analysis must be obtained on-site, and thus an automatic system is the only solution to reduce human activities at the drilling rig. (Saasen et al. 2008; Gunnerod et al. 2009; Godhavn et al. 2011; Stock et al. 2012)

The three main petrophysical data acquisition areas are wireline, Logging While Drilling (LWD), and mudlogging. The research approach by Loermans et al. developed the field of Advanced Mud Logging (AML). This well site technique includes the monitoring of all drilling-related parameters, the acquisition and processing of cutting images, and direct cutting measurements, such as grain density, porosity, spectral Gamma Ray (GR), Nuclear Magnetic Resonance (NMR), X-ray Diffraction (XRD), and X-ray Fluorescence. (Loermans et al. 2012)

This scientific investigation points out the different cuttings measurements and that the main limitation is within the sample preparation and not with the analysis itself. Further, this research shows that for most drilling activities, sensors are commercially available, but no system which combines all the measurement data into information that can support the real-time decision-making process. The presented Advanced Mud Logging unit does not replace wireline or LWD logging but provides a “first aid” for the overall formation evaluation procedure. Further, it shows that technology is available to implement the measurements from laboratories into modular, portable, and well site suited systems. (Loermans et al. 2012)

In 2013, Carlsen presents the standard drilling fluid measurement and calculation practices and how the drilling fluid density and frictional parameters can be collected more accurately and autonomous using differential pressure transducers placed between the rig pumps and the connection to the drill string. This research emphasizes that the update of the traditional mud check is necessary to assure well integrity for today’s challenging drilling operations. (Carlsen et al. 2013)

By automatically controlling the drilling process and reducing human engagement at the rig site to a minimum, the industry wants to enhance the performance and quality, improve safety aspects, and proactively manage associated risks. Several drivers and enablers pushed the commitment of the industry to develop drilling automation. Still, with some barriers, on the other hand, the current state shows a wide variety of automation levels for the different drilling domain segments. (Macpherson et al. 2013)

The evolution automation of drilling operations started with the mechanization of specific applications, to current semi-automated systems, where the operator supervises the machine and leads to fully autonomous services in the future. However, besides all the different tools and equipment changing to automated functions, one of the most important enablers for drilling automation is the collaboration for an open digital communication environment.

Due to the enhanced use of sensors to monitor downhole and surface operations, the available data and information about the rig and wellbore state increases and will even further maximize in the future. However, this large volume of data is mainly used for planning and post-analysis but would have an even more significant benefit if used for real-time decisions. The open connectivity unified architecture standard (OPC UA) and the wellsite information transfer standard markup language (WITSML) are the two mainly used communication protocols. They enable reliable transfers from the process level to the remote software systems, respectively. (Macpherson et al. 2013)

In terms of the process level regarding the instrumentation measurements, the drilling industry has two critical sensor drawbacks. The first problem is that several sensors are inadequate to control a process in real-time which they are measuring. And the second issue is that there are insufficient measurement techniques to provide an overall picture of all drilling operations at the rig. The harsh oilfield environment, together with the chemically active, corrosive, rheologically complex, and solids-ladened drilling mud, create a lot of difficulties even for quality sensors. (Macpherson et al. 2013)

The most critical and essential measurements regarding drilling fluids are density, rheology, and temperature. Few new instruments already deliver information about drilling fluid properties automatically, but mainly it is still done manually. The primary barriers for the development and integration of automated drilling fluid measurement systems are economic constraints, calibration and maintenance requirements, reliability, and accuracy. The lessons learned of automation development from other industries show four major threads: interoperability, remote control, measurement instrumentation, and integration. Besides that, the human factor is an essential component in automation technology. (Macpherson et al. 2013)

The human operator must, regardless of the vicinity, always maintain full situational awareness and be able to take over the control of the drilling operations in unwanted situations. Therefore, every drilling automation development effort should put the human in a central role, and the invention must differentiate between what humans do best and what machines do best.

The research work of Macpherson et al. presents these enablers and barriers regarding drilling automation, states the involved notable initiatives, and shows an outlook for the development combined with an associated business model. It is imperative to optimize each step of the drilling operation due to the high associated costs. The research work of Magalhães et al. presents a large scale automated flow loop plant, including commercial and built-in property sensors, to evaluate the measurement results. The results show that accurate online sensors are available and propose the next step for drilling automation. (Macpherson et al. 2013; Magalhaes et al. 2014)

In 2015, Abrahamsen et al. presented the results of the world's first implementation of an automated drilling control system on a North Sea rig. This deployment includes advanced wellbore numerical modeling with closed-loop control of the drilling system. Through provided safeguards, optimization of manual operations, and automation of repetitive tasks, this automated system saves 10% rig time per well. The research work clearly indicates how automation of drilling processes can reduce invisible lost time and enhance overall rig safety. (Abrahamsen et al. 2015)

The impact of time and temperature on the drilling fluid properties has a significant role in time-saving regarding the pump start-up procedures. However, the study of Abrahamsen et al. also displays that automation generates the following new risk elements: logic errors in the control system, reduced responding time due to over trust in the system, as well as bad sensor data, and insufficient calibration can lead to wrong decisions of the system. (Abrahamsen et al. 2015)

It is imperative to control and maintain the particle size distribution of circulation and wellbore strengthening materials, to avoid suffering from critical mud loss events. The research of van Oort et al. investigates three different particle size analyzers for their utility for automated drilling fluid analysis. The two main aspects of these applications are to evaluate the degradation of the particle size distribution under shear force influence and the effects on the drilling mud properties of the emulsion droplet size distribution of invert mud systems. (van Oort et al. 2016)

This examination includes novel data analyses and a comparative study to rank the particle size analyzers according to accuracy, user-friendliness, automation potential, and real-time monitoring capability. The results clearly show that automated, in-line measurement devices for particle size distribution analysis are available and can support the real-time decision-making process. (van Oort et al. 2016)

The research of Vajargah et al. picks up the Instrumented Standpipe method, together with their previous technique, to continuously measure downhole rheology with wired drill pipe, and presents an automated measuring method based on the pipe viscometer approach. The design includes a Coriolis flowmeter at the inlet to measure drilling fluid density, temperature, and flow rate. Two pipes with different diameters and differential pressure measurement devices deliver the required rheology parameters for the hydraulic model. The presented results for four different drilling muds show good accordance with the standard rotational viscometer measurements. With this new technology, any occurring changes in drilling fluid properties are visible within minutes, and the rig personnel can take the appropriate actions immediately. This development indicates a step-change enhancement for real-time mud monitoring. (Carlsen et al. 2013; Vajargah and van Oort 2015; Vajargah et al. 2016)

The traditional mud check (see section 3.2) as already described is error-prone and not suitable to support real-time decisions for drilling operations. Spelta et al. present two cases where the conventional mud monitoring failed to recognize the drilling fluid changes in time, and non-productive time was the result. This research work displays two real-time monitoring devices. The first application uses the tuning fork approach to evaluate density and viscosity. The second method describes the Focused Beam Reflection Monitoring operational principle, which can measure the particle size distribution continuously. This technique is especially helpful in determining the performance of the shaker screens. (Miller et al. 2011; Ronaes et al. 2012; Spelta et al. 2017)

The research from Dotson et al. apprehends the prototype introduced by Broussard et al. The new design eliminates the issues regarding measurement errors due to entrained air and the clogging of screens by solids. The presented density rheology unit (DRU) continuously receives by an own fluid supply system the drilling fluid directly from the flowline or tank. (Broussard et al. 2010; Dotson et al. 2017)

The fluid system works with a pump and two filter units, which function alternately as a siphoning filter to prevent solids build-up and provides intermittent backwashing of the lines. The densitometer and the viscosimeter both operate in a batch sampling mode and deliver drilling fluid property data every 1 to 5 minutes and every 10 to 60 minutes, respectively. The measurement instrumentations are periodically washed with a cleaning fluid to prevent any build-up of solids inside. The field trial results of the density rheology unit outlined by Dotson et al. show good accordance with API procedures for both measurement devices. (Dotson et al. 2017)

The typical drilling mud outflow is gravity-based from the wellbore, through a diverter system, via the flowline to the solids control equipment. The return flow rate is conventionally measured by a flow paddle sensor, which provides a percentage of the total outflow. Other common technologies to measure the mud outflow realy on pump strokes or sound speed timing. The mutual problem is that non of these existing sensors actually determines the true volumetric flow. The most advanced application is the Coriolis flow meter, which evaluates the return mass flow rate in real-time. However, a Coriolis flow meter is expensive and error-prone due to cuttings accumulation.

The work of Hong and van Kuilenburg introduces an active mud line pumping system. This application comprises Telsa pumps that transfer solids laden drilling mud from the diverter system directly to a trip tank with a weight sensor. This novel technology provides faster recognition of a wellbore kick, and the additional trip tank weight indicator facilitates a real-time density evaluation. The executed field test shows promising results for the kick detection, the density data collection, and since the mudflow is not gravity-based, the rig design is more efficient. (Hong and van Kuilenburg 2018)

The work of Lambie and Sampaio continues the investigations of Hong and van Kuilenburg and presents a newly invented active return flowline sensor. The so-called Active Control Volumetric Flowrate (VFR) Meter operates on the mass continuity principle and can deliver the return flow rate in real-time. Additionally, this system can provide real-time density measurement data with instrumentation using sound principles. The main components of the Active Control VFR Meter are a progressive cavity pump and a velocity tank. The results from the small scale yard test are accurate and capable of detecting influx or fluid loss within seconds. (Hong and van Kuilenburg 2018; Lambie and Sampaio 2019)

The research work of Blue et al. describes an advanced mud logging system comprising a kick-detection system, drilling fluid flow back monitoring, and software for trip monitoring and mud accounting. This application utilizes a high-end advanced flowmeter and a sophisticated software model to enable a safer control of the overall drilling process. The drilling industry introduces several kick-detection systems over the past few decades. Still, the accuracy and reliability of the surface measurement sensors limit the capability of precise and timely detection. (Blue et al. 2019)

The flow paddle is the most widely used measurement instrument to determine the return flow rate. Some more advanced sensors use radar or sonar to measure this parameter, but higher flow rates and the harsh oilfield environment lead to incorrect measurements. The high-end measurement technique implements a combination of two flow meters: A magnetic flowmeter to evaluate the flow of water-based drilling fluids, and a Coriolis system to cover other fluid types. However, the Coriolis flowmeter is rather expensive and has some drawbacks regarding rig modifications.

The results of the well control research by Blue et al. show that unreliable data is the origin of non-productive time for many drilling rig processes. Still, the majority of drilling rigs use outdated surface sensors. Development efforts show that the required technologies are available but need to be accepted by the industry to be commercially successful. (Blue et al. 2019)

The ongoing development of drilling automation relies on proper surface measurements and thus needs standards according to the automated measurement equipment. Several studies (Saasen et al. 2008; Broussard et al. 2010; Ronaes et al. 2012; Stock et al. 2012; Magalhaes et al. 2014) use the common API standards measurement techniques and try to mechanical automate them. The shared limitation of these approaches lies within the temperature control, equipment cleaning, and the calibration of the instrumentation.

The research of Gul et al. presents the most recent deployment of a real-time drilling mud measurement device, which is a refinement of the pipe viscometer approach illustrated by Vajargah et al. This measurement apparatus determines drilling mud density, rheology profiles, friction factors, critical Reynolds number, water-cut, and temperature automatically and in real-time. The results from the preliminary field trial show accurate, reliable, and high-quality data, they are in good comparison with the traditional measurement standards but can be delivered 25 times more frequently. (Vajargah et al. 2016; Gul et al. 2019)

The industry introduced several different automatic measurement techniques to evaluate drilling fluid properties. The research work of Taugbøl et al. presents the most recent development to automatically analyze the most critical drilling fluid parameters, density and rheology, in real-time. The approach implements a horizontal and a vertical pipe rheometer measurement to determine the drilling mud density and the frictional pressure drop. These two measurements, together with adjusted fluid velocities, are the basis for the rheology profile of the drilling mud. (Omland et al. 2007; Saasen et al. 2008; Taugbøl et al. 2019)

The presented automatic measurement device shows accurate and reliable data during the field tests conducted at offshore operations in the North Sea. The favorable outcomes of this field experience demonstrate that the automatic measurement of density and rheology in real-time enables a reduction of operating costs, an enhanced drilling performance, and increased safety at the rig. (Taugbøl et al. 2019)

1.2.4 Research Summary

The literature research above presents the historical evolution of the essential technologies regarding measuring and evaluating drilling fluid parameters. This investigation highlights that applications invented during the twentieth century still determine the measurement regulations of today's operations. Further, this research indicates an increase in newly arising technology since the implementation of easily accessible computational power and the industry's favor to implement software models more likely than hardware applications, due to associated costs.

The experiences from this literature research outline that the regulations and standards are the main drivers to push advances and changes in the oil and gas industry. Thus, new automated systems, such as the RHEOBOT, will be at least encouraged by the authorities. The ideal way forward is to implement and intrinsically test new applications in the laboratory and the field to assure and prove the reliability and change the existing regulations accordingly to enable an appropriate basis for future development.

The first chapter outlines the literature research results and presents a holistic picture of automation development throughout the drilling industry. The subsequent Figure 1 and **Figure 2** illustrate the most significant technology milestones focusing on drilling fluid automation of the petroleum industry history. This graphical summary covers the technological achievements from 1845 to 2020 in chronological order. The caption of **Figure 1** and **Figure 2** does not include the used references to assure good readability of the graphics.

The following list highlights the utilized reference sources for **Figure 1** and **Figure 2**: Brantly (1971), Carter (1961), Eustes (2007), Doe (2000), Lynch and Rowland (2005), Lambert and Franks (1984), aoghs.org (2006), Campbell (1891), National Driller (2020), Society of Petroleum Engineers (2020), Mau and Edmundson (2015), Moore (2020), Bingham (1917, 1922), Barret (2011), Dickson (2020), Marsh (1931), Jones (1937), KBS Tricone Drill Bits & Drilling Products (2013), Savins and Roper (1954), International Association of Drilling Contractors (2015), U.S. Department of Energy (2014), Rogers et al. (1984), Zamora et al. (1990), Swanson et al. (1991), Houwen et al. (1993), Growcock et al. (1994), Mureh et al. (1994), Naegel et al. (1998), Maglione et al. (2000), Rommetveit et al. (2004), Omland et al. (2007), Syltoy et al. (2008), Broussard et al. (2010), Cayeux et al. (2010), Geehan and Zamora (2010), Miller et al. (2011), Kvame et al. (2011), Ronaes et al. (2012), Magalhaes et al. (2014), Vajargah and van Oort (2015), Elkatatny (2016), Vajargah et al. (2016), van Oort et al. (2016), Dotson et al. (2017), Hong and van Kuilenburg (2018), Taugbøl et al. (2019), Gul et al. (2019), Lambie and Sampaio (2019), Alsabaa et al. (2020).

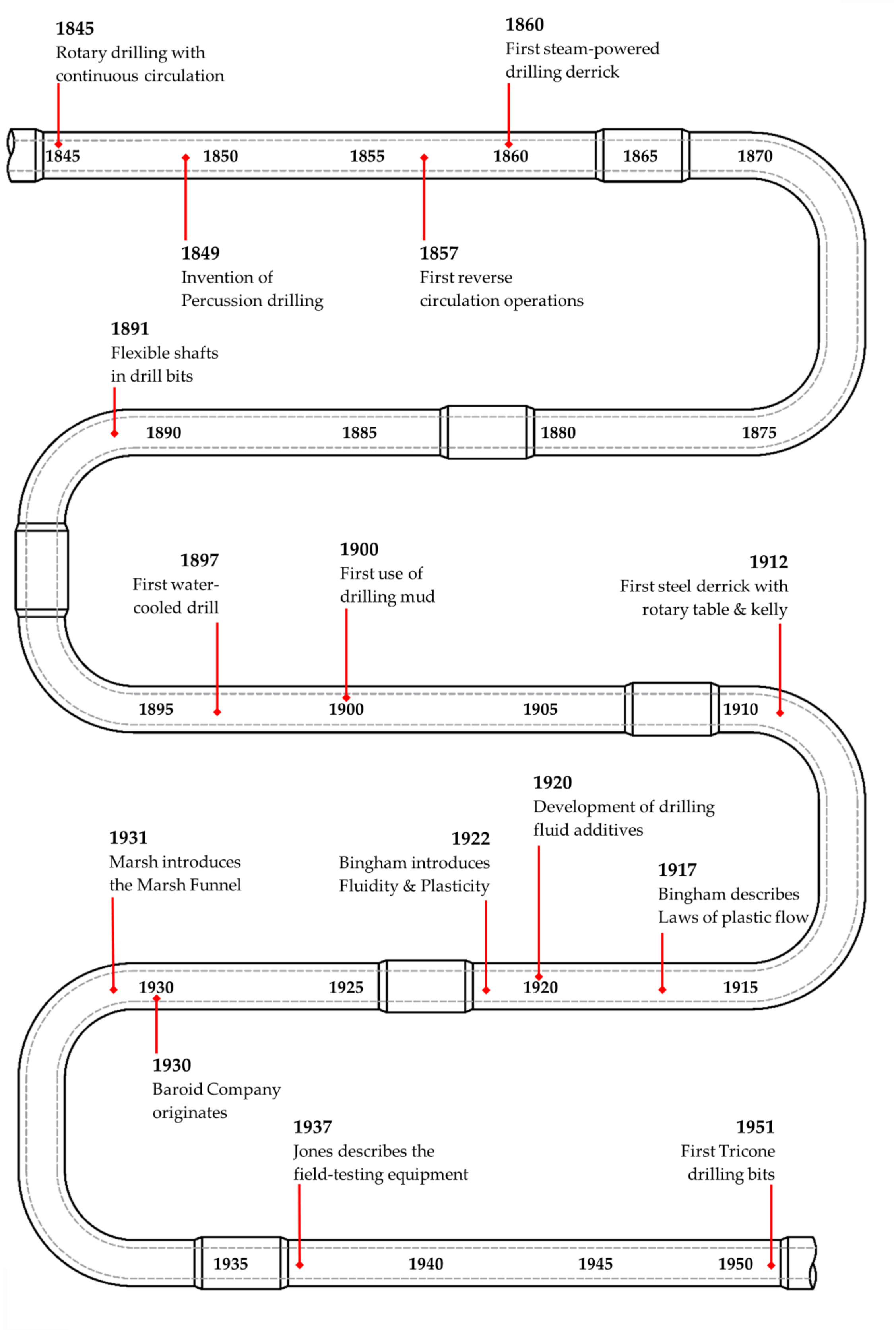

Figure 1: Historical overview of drilling fluids from 1845 – 1950

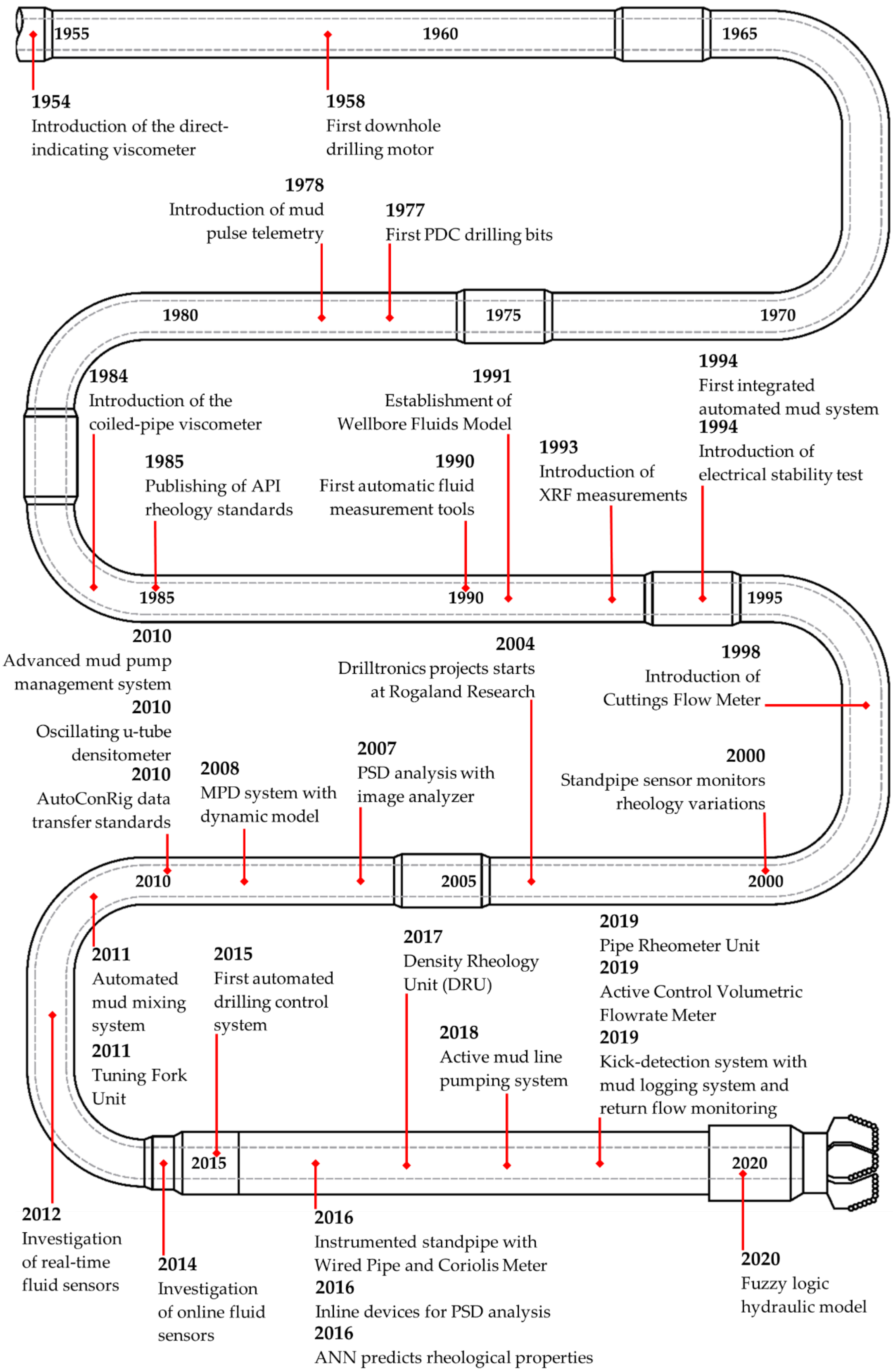

Figure 2: Historical overview of drilling fluids from 1950 – 2020

Chapter 2 Drilling Fluid Fundamentals

This chapter outlines the fundamental theory of drilling fluids in today's petroleum drilling industry. The objective is to provide an overview of the fluid composition and the essential components of the solids control equipment. Further, this chapter addresses the purposes of the drilling fluid within the overall drilling process.

The first drilling fluid was solely water-based and meant for the removal of cuttings. According to Carter and Brantly**,** this happened already 3000 BC in Egypt and during the Chou dynasty (1122 – 250 BC) in China, for shallow borings between twenty to hundred feet deep. The technological drilling innovations of the nineteenth century continued to use water-based drilling fluid. Within the 1920s, the first additives came into use, and thus the drilling fluid served to control the formation pressure. With the recognition of fluid loss and the related filter cake build-up, the drilling fluid composition included several more additives. (Carter 1961; Brantly 1971)

As already mentioned in section 1.2 and described in more detail in section 3.2, the industry developed simple tests to evaluate the drilling fluid properties. The three objectives to control formation pressure, transport cuttings, and to manage fluid loss control, are still the most critical drilling fluid purposes, along with the separation of drilled solids. During drilling operations, the drilling fluid serves as the primary well barrier. Thus, a reliable and close monitoring of the related properties is a crucial factor for safe and efficient operations.

2.1 Functions of drilling fluids

The more challenging drilling operations steadily expand the tasks of the drilling mud. Chapter 1 shows the historical advancement of drilling fluids and describes the associated testing development. Today used high-technical drilling fluids deliver various functions and can face many challenges from the modern drilling industry. **Error! Reference source not found.** shows the main objectives of drilling muds.

The primary operational purposes of a drilling fluid require continuous monitoring and maintenance by the fluid specialist. However, the drilling fluid serves several purposes, and the mud must provide all these tasks to drill the well successfully. This section presents the essential drilling fluid purposes and describes the relative importance of each function related to the consequences of their failure.

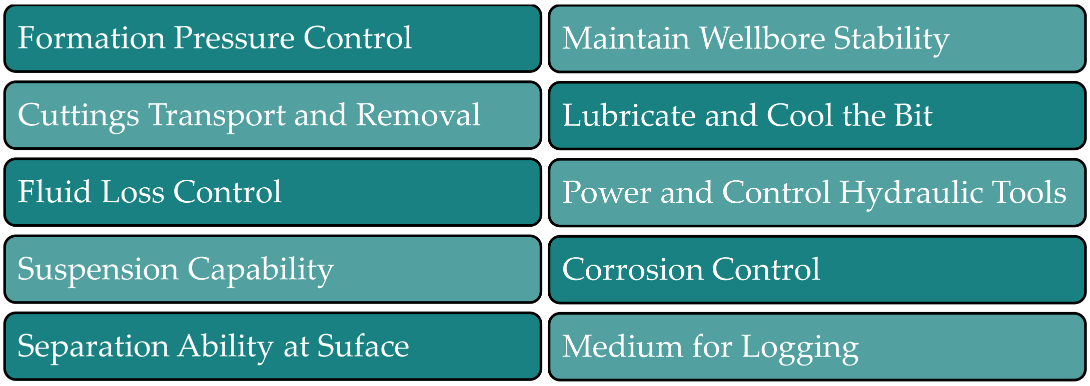

Figure 3: Overview of drilling fluid functions (derived from Caenn et al. 2017)

2.1.1 Formation pressure control

The most critical aim of drillings muds is to guard the borehole against the undesired influx of subsurface fluids. During all drilling operations, the drilling fluid column inside the wellbore serves as the primary well barrier. The loss or insufficient performance of this barrier can lead to several hazardous events, affecting health, safety, and the environment. Therefore, strict standards (*NORSOK D-010:2013* 2013; *ISO 16530-1:2017* 2017) regulate this drilling fluid function. These regulations specify the following criteria for drilling fluids: function, design selection, initial test and verification, use, monitoring, and failure modes.

The subsurface formations establish a surrounding pressure, which acts on the borehole during drilling operations. This pressure refers to formation pressure or pore pressure. The drilling fluid column must supply at least the same hydrostatic pressure to avoid an inflow of formation fluids. The height of the drilling fluid column and the mud density specifies this hydrostatic pressure, with the assumption that the fluid is homogeneous and incompressible. The equation (1) shows the downhole fluid pressure:

$$p = \rho \cdot g \cdot h \tag{1}$$

Where p represents the pressure, ρ the fluid density, g the gravitational constant, and h the height of the fluid column.

Additionally, the implementation of the frictional pressure losses arising in the annulus and inside the drill string is imperative to manage the wellbore pressure during circulation precisely. The equivalent circulating density (ECD) is the total, annular pressure gradient term during circulation. It consists of two components: the hydrostatic pressure of the drilling fluid column and the hydrodynamic pressure losses due to circulation. Equation (2) shows the common expression of the equivalent circulating density.

$$\rho_{ECD} = \rho_{Mud} + \frac{\Delta p_{FL}}{g \cdot h} \tag{2}$$

Hereby, ρ_{ECD} is the equivalent circulating density, ρ_{Mud} is the density of the drilling fluid, Δp_L is the sum of annular frictional pressure losses, g is the gravitational constant, and h the height of the fluid column.

The determination of the proper drilling mud density is imperative to safely and efficiently drill a well. Besides the above mentioned frictional pressure losses in the annulus, the following effects influence the mud density selection: annular width variation, swab and surge incidents, cuttings loading, rotation of the drill string, downhole conditions. The bottom hole pressure (BHP) implements all theses effects and represents the sum, together with the hydrostatic pressure, the equivalent circulating density component, and possibly applied back pressure.

The control of the formation pressure thus strongly consists of the maintenance of the desired drilling fluid density. The proper fluid management must account that the mud weight is large enough to avoid an influx from the formation, as well as that it does not exceed the fracture pressure gradient. The fracture pressure gradient is the point at which the rock starts to yield, and the formation breaks down. If the equivalent circulating density surpasses this fracture gradient, the drilling fluid flows into the fractures. This loss of mud expresses in a decrease of the total, annular fluid volume, and a reduced cuttings transport or the loss of well control are the possible consequences.

The so-called mud weight window (**Figure 4**) illustrates the relationship of the pore pressure gradient and the fracture pressure gradient and shows the specific operating window for drilling operations. This pressure gradient graph strongly affects the mud weight selection.

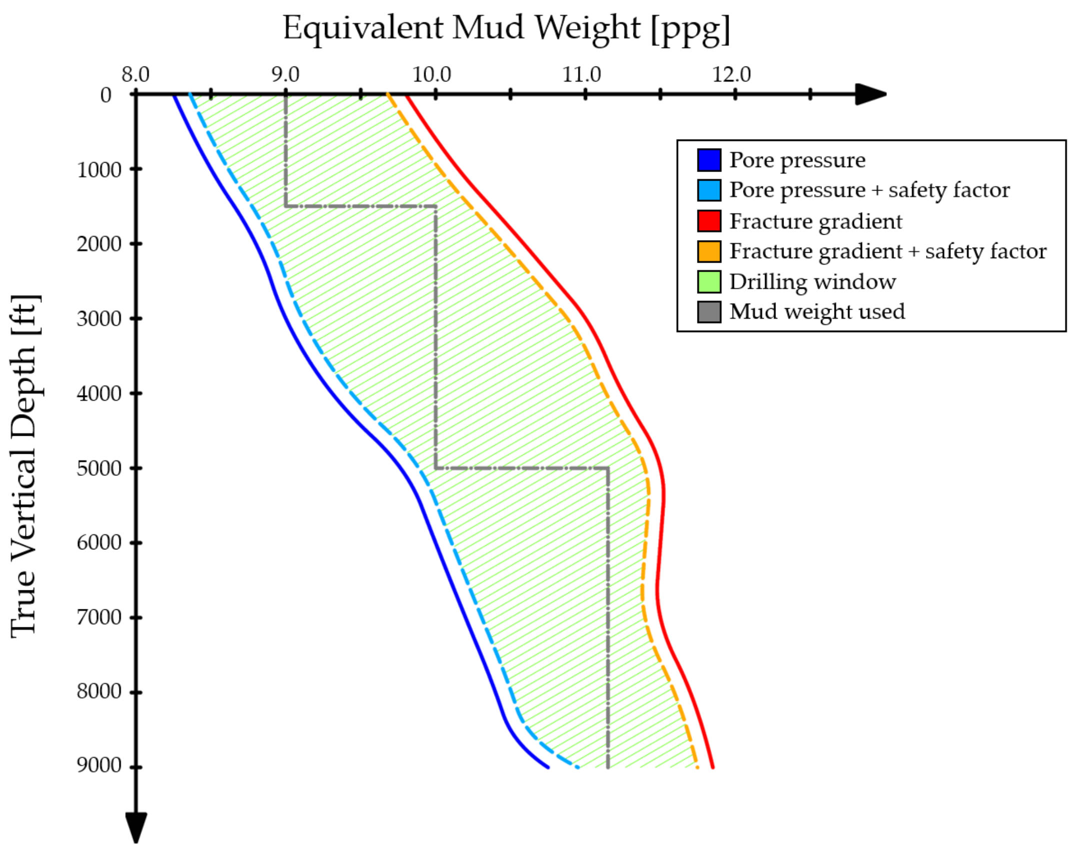

Figure 4: Example of a mud weight window

2.1.2 Cuttings transport and removal

The transportation and removal of the accumulating cuttings is the historically initial purpose of circulating mud during drilling operations. Without the extraction of the cuttings, the bit becomes hard to remove or stuck. The drilling fluid property that generally carries the cuttings is the viscosity. Thus, the control and maintenance of the desired viscosity are crucial to drilling activities. The drilling industry pushes the limits regarding well geometry and length with every new wellbore, and therefore, the cuttings removal is more critical and challenging than ever.

The required viscosity for efficient hole cleaning is not a rule of thumb, applicable for all wells. The hole cleaning efficiency of the circulating drilling mud depends on the following aspects: borehole size and inclination, fluid rheology, the geometry of the excavated particles, flow rate, and drill pipe rotation and eccentricity. All of these factors are subject to the planning phase. However, the two main parameters to enable control of the cuttings transport are the mud rheology and the flow rate. (Adari et al. 2000)

The immediate removal of the rock cuttings after the bit excavates them from the formation is imperative for high performance. If the drilling fluid is not sufficient to deliver this task, the drill bit further crushes the cuttings into smaller debris. The result is a more difficult separation of these fine particles and enhanced degradation of the overall drilling fluid. The density and the viscosity of the drilling mud are the two decisive parameters to enable this instant removal.

In a static fluid column, rock particles fall through the fluid due to their higher density and gravity. The resulting downwards velocity, known as settling velocity or slip velocity, depends on three factors: the difference between the rock and the fluid densities, the shape and size of the rock particles, and the drilling mud viscosity. The annular flow velocity must exceed the set velocity to ensure the efficient transportation of the cuttings. The difference between the drilling fluid velocity and the slip velocity specifies the rate at which the cuttings travel upwards. The viscosity strongly influences the lifting capability of the drilling mud. The density maintains the natural buoyancy of the rock particles, and therefore, a denser drilling fluid provides more elevation.

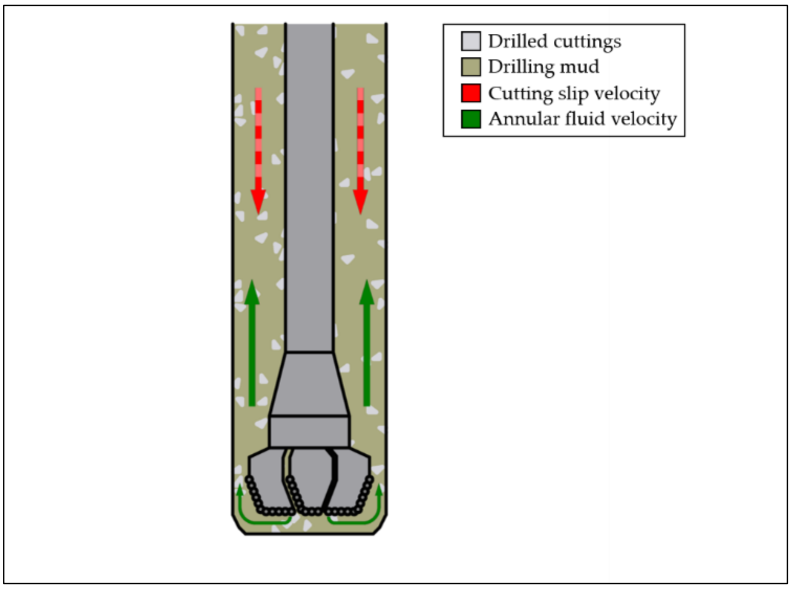

Figure 5: Schematic of a wellbore with the drill bit. The figure shows the annular and the cutting slip velocity.

Without proper hole cleaning, the excavated cuttings accumulate in the borehole. This insufficient removal of the cuttings can cause several severe unwanted events during drilling. They can be but are not limited to a reduced rate of penetration, excessive equivalent circulating density, increased bit wear, poor cuttings separation, tight hole, high torque, stuck pipe, and lost circulation. It is not uncommon for this to further result in the loss of the entire wellbore.

2.1.3 Fluid loss control

The drilling fluid column inside the borehole is the primary well barrier during drilling operations and provides a hydrostatic pressure to guard the wellbore against an influx of formation fluids. However, during this so-called overpressure drilling, a part of the drilling mud invades the permeable formations. The drilling fluid penetrates the formations, and the suspended solids inside the mud stick at the borehole wall and plug the throats of the pores. Whit time, the drilling mud creates a so-called filter cake, which hinders the suspended particles from penetrating into the formation.

The required time to establish an efficient filter cake is crucial for drilling operations. The permeability of the filter cake determines the flow rate at which the drilling fluid filtrate flows into the formation. The drilling mud design must aim for a thin filter cake with low permeability, to minimize the filtrate invasion. A high permeability causes a thick filter cake, which results in a reduction of the wellbore diameter and several drilling problems. Significantly, the control of the filtrate invasion is essential when drilling productive formations. The worst-case scenario is too much drilling mud filtrate invading and damaging the production zone and resulting in an unproductive well.

2.1.4 Suspension capability of weighting material

During some drilling activities, the operations require interrupting the continuous circulation of drilling mud due to several reasons. The pause time can last from minutes to several consecutive hours. The drilling mud must keep the weight materials and drilled cuttings in suspension to avoid them to settle back at the bottom and cause a pack off of the annulus.

The thixotropic properties define the capability of the drilling mud to constitute a gel structure if the fluid motion stops. The ideal design of the drilling mud sets the gel strength to be just high enough to suspend the weight materials and drilled cuttings during the time the circulation ceases. An excessively high gel strength has two significant detriments. First, it reduces the time for the segregation of the associated gas and the separation of the drilled cuttings at the surface. Second, a pressure peak higher than the fracture pressure can arise when ramping up the mud pumps to restore the drilling mud circulation. The timely recovery of the mobile state of the drilling fluid enhances the performance of the overall drilling process.

2.1.5 Separation ability at the surface

Additionally, to the cuttings transport and gel strength capabilities of the drilling mud mentioned above, the fluid must provide an efficient separation at the solids control equipment. The partition includes the drilled solids as well as the entrained gases inside the drilling fluid. In contrast to sections 2.1.2 and 2.1.4, the viscosity and the gel strength of the mud should be as low as possible to enable an efficient separation. An inadequate segregation ability leads to more prolonged treatment and residual times of the drilling mud at the solids control equipment. That can result in higher costs due to higher total mud volumes and reduced rate of penetration. Therefore, the optimum drilling mud is a compromise that meets all of the conflicting properties to enable the best performance.

2.1.6 Maintain wellbore stability

The mud weight window (**Figure 4**) determines the operating window for each well individually. The drilling operator sets casings to secure the wellbore and adjust the drilling mud for the new section. During all drilling activities, the drilling fluid must provide a stable borehole and maintain the wellbore stability for the uncased sections. The wellbore stability regarding drilling fluids divides into two main groups. First, an interaction between the subsurface substances and the drilling fluid can cause physicochemical stability issues. And secondly, the rheological properties and the movement of the drilling mud define the mechanical stability category. The loss of wellbore stability can result in various unwanted events but, in the worst case, in the loss of the wellbore and drilling equipment.

2.1.7 Lubricate and cool the drill bit

During drilling operations, the bit teeth rotate against the rock at high rotations per minute and with an enormous amount of pressure. Together with the drill pipe turning against the casing and wellbore wall, this creates enhanced friction and high temperatures. The purpose of the drilling mud is to dissipate the heat and reduce the friction. Insufficient cooling and lubrication can fail the bit or other bottom hole assembly equipment due to overheating. The result is damaged equipment and an extra trip to replace it. The absorption of the heat by the drilling fluid can affect and alter the rheological properties.

2.1.8 Power and control hydraulic tools

The mud motor, positioned above the drill bit, allows the bit to turn while the rest of the drill string is stationary. Together with the so-called bent sub, located near the bit, this enables to build an angle in the desired direction. The drilling mud powers the helical steel rotor inside a rubber body.

Passive tools for directional drilling do not need constant two-way communication with the surface. The mud pulse technology incorporates downhole tools with a valve that sends a signal with the drilling mud as a medium to the surface. This technology enables taking measurements and various electric logs while drilling.

2.1.9 Additional functions

The drilling mud also provides the following objectives during the wellbore construction process: control corrosion, prevent hydration of sensitive formations, serves as a medium for formation evaluation and logging, provides buoyancy for the drill string and casing.

All of the mentioned drilling mud functions are critical for the drilling process, and failure can have serious consequences. However, the rheological properties of the fluid influence all of the required objectives, and thus the monitoring and maintenance of them is most crucial for drilling operations.

2.2 Drilling Fluid Composition

The term “drilling fluid” also often refers to as drilling mud or slurry and is a generic term for many different fluid types within the oil and gas industry. The usage of drilling fluids is critical for the entire well construction process, from drilling to completion, as well as during workover operations.

The drilling mud is a heterogeneous composition of discrete chemical additives in a base fluid. Every well is unique, and so is the drilling fluid configuration. The drilling mud formula must meet safety as well as performance aspects. The advancing drilling technology enables the industry to drill more complex wells, and together with that, the complexity of drilling fluid formulas increases to meet more and more demands. However, the following three drilling mud types are the foundation for all the drilling fluid compositions implemented nowadays.

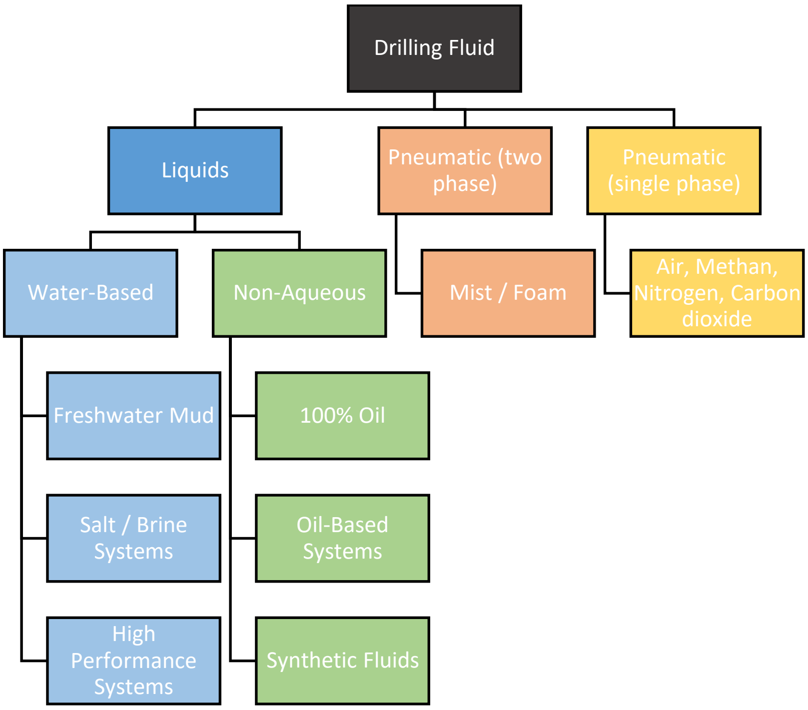

Figure 6: Overview of drilling fluid systems (derived from ASME 2011; Caenn et al. 2017)

2.2.1 Water-based muds (WBM)

These drilling fluid systems use water as the continuous phase. Further, these muds can include various dissolvable and insolvable substances. These additives can be salts, polymers, surfactants, barite, or clay.

2.2.2 Oil-based muds (OBM)

These drilling fluids employ oil, such as diesel or mineral oil, as the continuous phase. All oil-based muds must contain water-emulsifying agents to keep the residual water suspended as microscopic droplets. The different oil-based drilling fluids can also encompass weighting substances, viscosifiers, and suspending agents. The main advantages of oil-based muds are the penetration rate, the lubricity, as well as the thermal and wellbore stability. However, these drilling mud systems are more expensive than water-based drilling fluids and underly stricter standards concerning discharge and recycling.

2.2.3 Gaseous or foam-based muds

This drilling mud consists of gas bubbles which are surrounded by a film of water. Air or other gases create this foam, and substances, such as polymers or bentonite, are mandatory to stabilize the foam.

2.2.4 Measurement Influence

The measurement techniques must consider the different drilling fluid types within the design and calculations. Certain chemical additives require special treatment and handling to ensure safe and secure working conditions. Further, the various ingredients have diverse attributes, and thus, an alteration in the measurement accuracy is possible. Most of the components of a drilling mud affect electrical stability (ES) trends (Growcock et al. 1994). In general, an increase in oil concentration, emulsifier, or barite exhibits an increment in electrical stability. In contrast, an increase of hematite, water, or calcium chloride in the drilling mud leads to a decrease in electrical stability.

2.3 Drilling fluid properties

The essential and decisive characteristics of the drilling mud are the density, the viscosity, and the gel strength of the fluid.

The drilling fluid is present and crucial for the operations beginning from the spud to the final completion of the wellbore. The costs of the drilling mud take a considerable fraction of whole well construction costs. The complexity of the drilling fluid properties and the associated solids control equipment can drive the expenses significantly. Therefore, the wrong design of the drilling mud or deficiency within the maintenance of the fluid properties during the operations can cause various costly complications and especially hazardous well control events.

The drilling fluid design emerges from the complicated three-way relationship between the drilling mud, the drilled solids, and the solids control equipment. The fluid properties are accountable for the hole cleaning capability of the mud, and thus, they indirectly affect the shape and size of the drilled solids. Further, the solids control equipment must efficiently treat the drilling fluid and adequately separate the solids, to maintain the properties and reduce the degradation of the drilling fluid. This example shows the dynamic and intricate connection, where any change to one category affects the other two, and they, in return, can influence the first one. It is imperative to monitor and optimize the drilling fluid properties continuously. The knowledge about how the drilled cuttings or failure within the solids control equipment can alter the drilling mud properties is thus crucial for the overall drilling operation.

2.3.1 Density

The density constitutes per definition of mass per volume unit. The expression of equation (3) shows the mathematical description of the density. The drilling industry expresses it in pounds per gallon (ppg), kilograms per cubic meter ($\mathrm{kg/m^3}$), or as specific gravity (sg), and also refers to it as mud weight.

$$\rho = \frac{m}{V} \tag{3}$$

Here ρ is the density, m the mass, and V the volume.

The fluid density appears within the drilling industry in two definitions: the equivalent static density and the equivalent circulating density. The first expression refers to the hydrostatic pressure resulting from the drilling mud column and the embarked gases, fluids, and solids. The second phrase describes the density for a circulating well, and because of the arising annular frictional pressure losses, the pressure for this density is higher. Section 2.1 describes the equivalent circulating density and the related objectives and limits in detail.

It is essential to include both the static and the dynamic density into the drilling mud design not to fall below or exceed any formation pressure limits. Three main contributors affect the drilling mud density: pressure, temperature, and suspended solids. Generally, low temperatures increase, and higher temperatures decrease the drilling fluid density. The generalized impact of pressure is as it rises, it compresses the mud, thus reduces the volume and enhances the density. The magnitude of these two impacts depends strongly on the composition of the drilling fluid. The suspended drilled cuttings are commonly denser than the drilling mud and thus increase the effective density.

The detailed design of the drilling fluid includes the proper calculation of the arising effects on the mud during drilling operations. However, the continuous monitoring of the inflow and outflow of the drilling mud density is mandatory because nearly all drilling activities connect to the mud weight design, and failure can lead to severe consequences.

2.3.2 Rheology

The term rheology defines the part of physical sciences that analyses the deformational behavior of matter and flow, especially fluids and gases. The study of rheology includes elasticity and fluid mechanics. The empirical determination of the relationship between stresses and the associated rates of strain is a significant task of rheology studies. A wide range of different industries, for example, the pharmaceutical, food, construction, or petroleum, have to apply the subject of rheology for their products. Particularly for the drilling industry, the effect on the drilling mud viscosity from dispersed small solids is of great technical importance.

The precise design of the rheology parameters of the drilling fluid is critical during drilling activities. The drilling mud rheology strongly affects the pressure losses during circulation and therefore influences the calculation of the frictional pressure losses and the flow regime inside the drill pipe and the wellbore annulus. It is imperative to include the rheology effects into the determination of the equivalent circulating density and for hydraulic optimization. Further, it plays a significant role in the assessment of wellbore cleaning performance and the estimation of the occurring pressures during swab and surge incidents.

An accurate hydraulic calculation must account for the temperatures and pressure affecting the drilling mud rheology downhole. Already moderate differences in temperature can alter the rheological parameters of the drilling fluid and can limit the use of surface measurements without an adequate hydraulic computational model. An overall, more precise knowledge about the rheological behavior of the drilling fluid enables safer and more efficient drilling operations. Therefore, the reliable and continuous monitoring to detect changes within the drilling mud rheological parameters is imperative for secure drilling processes.

The characterization of the drilling fluid develops from the measurement of the viscosity. The viscosity of a fluid defines as the resistance of a material against deformation or flow. The drilling industry uses centipoise (cP) for the unit of viscosity, which equals millipascal second (mPa s). The rheological behavior of a drilling mud divides it into two general categories: Newtonian fluids, which show a constant viscosity at changing shear rates, and non-Newtonian fluids, which demonstrate various viscosity behaviors with changing shear rates.

Newtonian fluids exhibit a directly proportional relationship, as shown in **Figure 7**, between the shear stress and the shear rate. This definition indicates that the liquid is continuously flowing, regardless of the forces acting upon it. The viscosity of a Newtonian fluid thus only depends on the prevailing pressure and temperature. Equation (4) expresses this interpretation in mathematical terms.

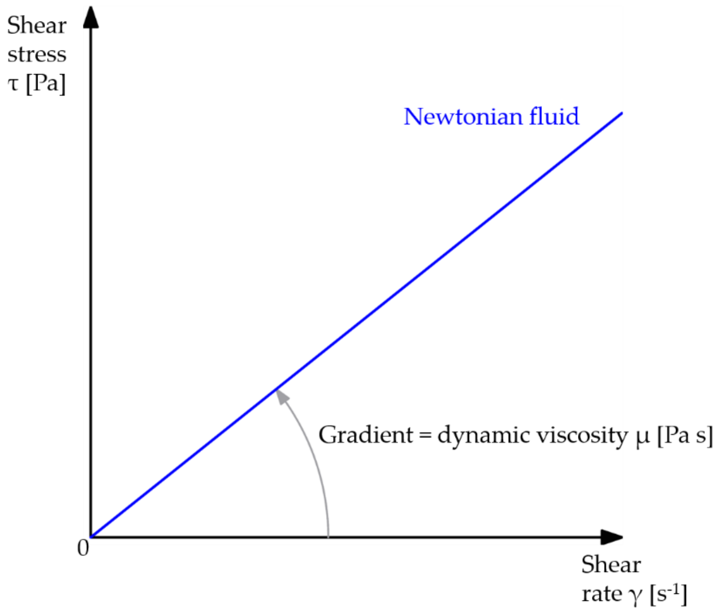

Figure 7: Rheology diagram for a Newtonian fluid (derived from Caenn et al. 2017)

$$\mu = \frac{\tau}{\gamma} \tag{4}$$

Here μ is the viscosity, τ is the shear stress, and γ is the shear rate.

The suspended solids inside the drilling mud affect the fluid in such a way that the Newtonian law of flow does not account anymore. For a non-Newtonian fluid, the shear stress and rate relationship are nonlinear. **Figure 8** illustrates a rheological diagram that visualizes the different flow behavior of liquids. The main behavioral categories for shear dependent fluids are plastic, viscoplastic, pseudoplastic, and dilatant. Some fluids further have a time-dependent viscosity. **Figure 9** displays this thixotropic and rheopectic behavior in shear stress versus time diagram.

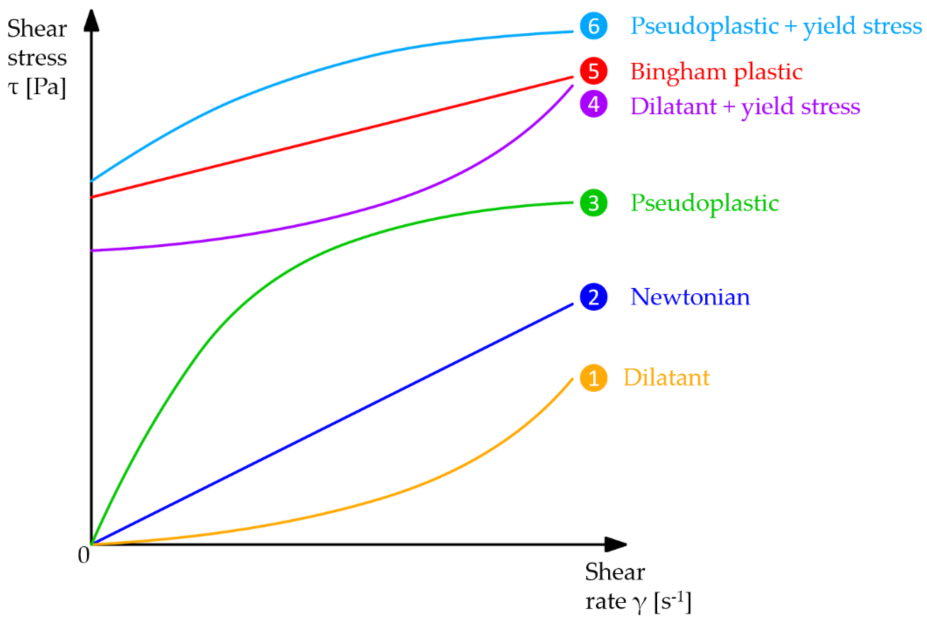

Figure 8: Rheogram for different types of rheological fluid behavior (derived from Sikorski 2002; Caenn et al. 2017)

The diagram in **Figure 8** shows the following types of fluid behavior:

- Dilatant: The viscosity and the volume of these fluids increase with shear rate. This effect refers to shear thickening, and the fluid suspension contains high concentrations of fine deflocculated solids.
- Pseudoplastic: The viscosity decreases with higher shear rates, which classifies as shear thinning behavior. These fluids often have polymers in solution, and their re-alignment or release of solvents cause this behavioral effect.
- Viscoplastic: These fluids require initial yield stress to start flowing and afterward follow a Newtonian like behavior.

Thixotropy liquids exhibit a rheogram curve similar to the pseudoplastic behavior. But they are also time-dependent, which means that the fluid thins out with time even at constant shear rates. If a step change in shear rate applies to this type of fluid, it requires a finite time to obtain the equilibrium viscosity. Typical examples are pastes, creams, gels, and paraffin oil. The rheopectic fluids show a shear thickening behavior in the rheological diagram analogous to dilatant fluids. With steady shear rates, these fluids develop an increment in their viscosity with time. Gypsum paste or lubricants are classical types of liquids with a rheopectic flow behavior.

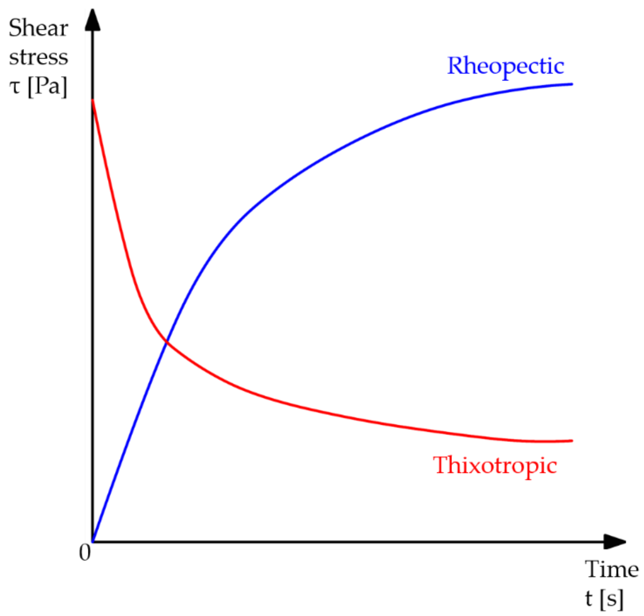

Figure 9: Shear stress versus time diagram for thixotropic and rheopectic fluids (derived from Monicard 1982)

Concluding from above, the composition of the drilling mud has a strong influence on the rheological behavior. The most common rheological models in the drilling industry to describe the drilling fluid behavior are the Bingham Plastic, the Power Law, and the Herschel-Bulkley.

Bingham plastic fluids require initial finite yield stress before shearing starts, and they begin to flow. Afterward, theses liquids exhibit a linear relationship between shear stress and shear rate. Typical examples that show this kind of behavior are: ketchup, toothpaste, greases, clay suspensions, and drilling mud. The drilling fluids which act most accordingly to the Bingham plastic model are those with a high solids content. The mathematical definition (Equation (5)) for these drilling muds consists of the yield point (YP), which is the required shear stress to commence the flow, and the plastic viscosity (PV), which indicates the necessary supplementary shear stress to increase the shear rate by one unit. The blue graph in **Figure 10** illustrates the rheogram for a typical Bingham plastic fluid.

$$\tau = YP + PV \cdot \gamma \tag{5}$$

In this equation, τ is the shear stress, YP is the yield point, PV is the plastic viscosity, and γ is the shear rate.

The effective viscosity of a Bingham plastic fluid enables the expression of the capability of this fluid to resist flow. Equation (6) indicates the apparent viscosity (μ_{eff}) for a specific shear stress.

$$\mu_{eff} = \frac{\tau}{\gamma} = \frac{YP}{\gamma} + PV \tag{6}$$

Here μ_{eff} is the effective viscosity, τ is the shear stress, γ is the shear rate, YP is the yield point, and PV is the plastic viscosity.

Typical behavior of Bingham plastic fluids is the shear thinning effect, which most of the drilling fluids in the industry experience. This effect indicates that the viscosity of the mud decreases as the shear rate increases. **Figure 10** visualizes this behavior by displaying the reduction of the apparent viscosities from $\mu_{eff,1}$ to $\mu_{eff,2}$, together with the shear increment from γ_1 to γ_2.

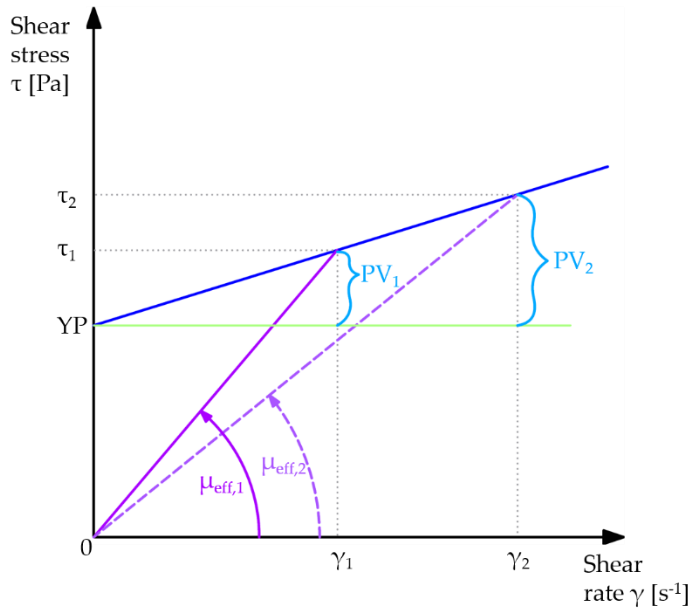

Figure 10: Rheological diagram for a Bingham plastic model (derived from Caenn et al. 2017)

The shear thinning response of the Bingham plastic liquids is a desired characteristic for drilling muds. The high shear rates inside the drill pipe result in a comparatively low viscosity, which lowers the pump pressure. On the other hand, the low shear rates prevalent inside the annulus increase the effective viscosity and thus enhances the cuttings transport performance of the drilling fluid.

The drilling industry implements the Bingham plastic model as the standard model due to the reason that the yield point and the plastic viscosity are reliable indicators to evaluate the conditions of the drilling mud properties. The yield point signifies the tendency of the fluid components to build up a shear resistance. Further, the yield point expresses the capability of drilling mud to transport the drilled cuttings in the annulus. Accordingly, the higher the yield point, the better, the better is the lifting capability of the mud. The monitoring of the plastic viscosity of the drilling fluid leads to the determination of shape, size, and concentration of the suspended solids in the mud. The Bingham plastic model characterizes the drilling fluid most properly in the shear rate range from 300 to 600 rotations per minute (RPM). Therefore, the model is not suitable for the interpretation of the drilling fluid behavior related to pressure loss evaluations, and thus the implementation of other models for the lower shear rates is important.

The Power Law model characterizes a so-called pseudoplastic behavior as it exhibits a nonlinear relationship between the shear stress and rate. Hereby the liquid becomes continuously less viscous as the shear rate increases due to the breaking of the intermolecular bonds. This model enables a more precise definition of the actual behavior of the drilling mud and also allows a higher detailed characterization at low shear rates. Besides drilling fluids, this behavior is also typical for polymer and rubber solutions. Equation (7) illustrates the mathematical definition of the relationship between shear rate and shear stress of the Power Law model, with τ as the shear stress, γ as the shear rate, K_p as the fluid consistency index, and n_p as the flow behavior index.

$$\tau = K_p \cdot \gamma^{n_p} \tag{7}$$

Equation (7) further indicates that if the shear rate equals one, the fluid consistency index equals the shear stress for any value of the flow behavior index. This indication shows a strong relation to the drilling fluid viscosity at low shear rates and that an increment from the fluid consistency index leads to an enhanced lifting ability of drilled solids of the drilling fluid. The flow behavior index displays how the drilling fluid viscosity diverges from a Newtonian fluid behavior at rising shear rates. The smaller the value of the flow behavior index is, the greater is the shear thinning effect of the drilling mud.

The modified Power Law or Herschel-Bulkley model combines the two characterization methods of the Bingham plastic model and the Power Law model to enable a more precise determination of the drilling fluid behavior at very low shear rates. To do so the Herschel-Bulkley model implements the necessary yield stress to initiate the flow, as Equation (8) expresses.

$$\tau = \tau_0 + K \cdot \gamma^n \tag{8}$$

Here τ is the shear stress, τ_0 is the yield stress, K is the consistency factor, γ is the shear rate, and n is the flow behavior index.

The parameters of the consistency factor and the yield stress have the same functionality as the terms of the Bingham plastic model regarding the indications of the drilling fluid behavior. Still, the numerical value is not the same.

The drilling industry applies the Herschel-Bulkley model because the majority of drilling muds behave accordingly to this characterization. Further, the implemented yield stress is crucial for various hydraulic determinations. With the incorporation of the Bingham plastic and the Power Law model, the Herschel-Bulkley also covers multiple special cases. Further, the American Petroleum Institute (API) suggests the use of the modified Power Law model as it is most suitable for water- and non-aqueous-based drilling muds and consistently delivers precise simulations.

The kinematic viscosity delivers the relationship between the dynamic viscosity and the density of a substance. Advanced fluid mechanics apply this concept for their hydraulic calculations. Equation (9) shows the expression of the kinematic viscosity, which has the unit square meter per second ($m^2 s^{-1}$).

$$\nu = \frac{\mu}{\rho} \tag{9}$$

In this equation, ν is the kinematic viscosity, μ is the dynamic viscosity, and ρ is the density.

2.4 Circulation system

The drilling rig incorporates a variety of different instruments that together form the circulation system. The continuous circulation of the previously described drilling mud is mandatory to establish the primary well barrier and that the drilling fluid can accomplish the required functions. **Figure 11** shows an example of a rotary table drilling rig with the associated circulation system, and below this section describes the integrated pieces of equipment and processes.

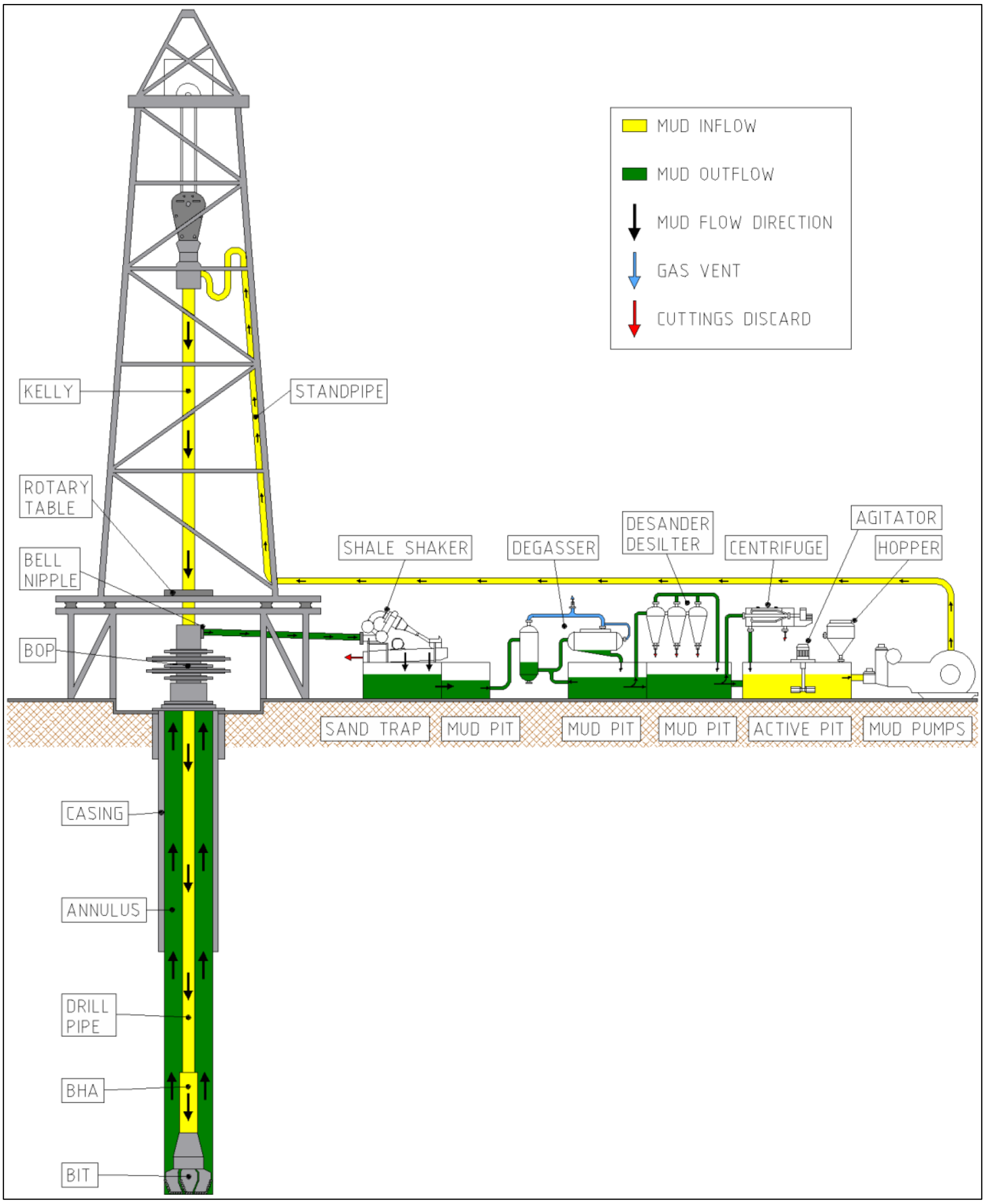

Figure 11: Drilling Fluid Circulation System

The start of the circulation path from the drilling mud is the big mud pumps, which deliver the required pressure to push the drilling fluid down the drill string, through the bit, and upwards the annulus. **Figure 11** shows the typical setup of the drilling fluid circulation system for a drilling rig with a rotary table.

The drilling fluid flows up through the standpipe and the rotary hose and then downwards through the kelly or top drive system. The drilling mud exhibits shear and temperature effects as it travels through the drill string and bottom-hole assembly to the drill bit at high velocity and pressure. The mud passes through the nozzles of the drill bit and creates a high-velocity jet, which impacts on the formation. This passage, through the drill bit nozzles, generates a substantial pressure loss, which can be more than half of the provided mud pump pressure.

The downhole conditions degrade the drilling fluid, it is dehydrated and loaded with formation solids, so-called cuttings. This formation material can be inert or reactive substances or also liquids or gases from the subsurface section. These subsurface materials continuously interact with the mud during the drilling process and can create significant changes in the drilling fluid properties. In the worst cases, this can lead to lower rates of penetration, several wellbore stability problems, and severe drilling risks.

The remaining pressure forces the mud to return up through the annulus. The capability of the drilling fluid to transport the cuttings depends on the flow velocity and the viscosity and density. The flow velocity must exceed the settling speed of the solids in the drilling fluid to carry them to the surface.

At the surface, the drilling mud streams from the bell nipple, through the flowline to the solids control equipment. The costs of the drilling mud are a considerable amount of the total drilling costs. Therefore, the operator wants to reuse as much of the fluid as possible prior to its recycling and discharge. The solids control system enables the separation of the drilled cuttings and the associated gas. The principle of the equipment, as shown in **Figure 12** and **Figure 13**, is the continuous maintenance of the drilling fluid, starting by removing the larger solids before the smaller ones.

The drilling mud spreads from the possum belly to the shale shakers, which are the first devices to remove the unwanted solids from the slurry. These shakers are the essential solids control equipment and consist of metal screens and counterweights attached to a motor, which causes the screens to vibrate. The drilling mud flows across the screens, thereby the particles stay on top, and the shakers discard them into a waste pit. The drilling fluid passes through the shaker screens into a compartmentalized tank, the so-called sand trap, or settling pit.

The sand trap tank allows the particles inside the drilling fluid to settle. This tank has no agitators, and the outlet is located at the top of the tank to provide maximum settling time. The bottom of this tank has a slope from back to front with a large drainage valve to discard the contents. However, the modern shale shakers operate so efficiently that the use of sand traps gets obsolete. After the sand trap, the drilling mud flows into a series of pits or section of pits, by an overflow transfer system. The total volume of the mud system varies between the different rig sizes and can range from 25 barrels to 2000 barrels and more.

During drilling of gas-bearing formations, the drilling fluid may transport gas to the surface. A portion of the associated gas dissolves at the shale shakers, but it is imperative to excrete the remaining gas by special degassing equipment. Afterward, the use of desanders and desilters between the different tanks enable the filtration of the smaller particles. These separation apparatuses use centrifugal forces created by hydroclones, which are simple mechanical devices without any moving parts, to remove the very small grains. The last option of the solids control equipment is a centrifuge, a device that can remove particles of sizes between six to ten micrometers.

At the end of the solids control process, the drilling mud arrives at the suction pit. From there, the mud pumps feed it back downhole to repeat the circuit. At the suction tank, the mud engineer adds required additives to the drilling mud, as well as replenishes the continuous phase and adjusts the mud weight. The mud hopper is a venturi device to add dry materials into the drilling fluid. Further, a so-called pill pit or slugging pit enables to mix and prepare small quantities of special drilling mud. It is imperative to monitor the drilling fluid, to maintain the desired mud properties. The mud engineer takes fluid samples at several measurement points (**Figure 14**) and tests them immediately. Section 3.1 thoroughly describes the commonly applied field tests.

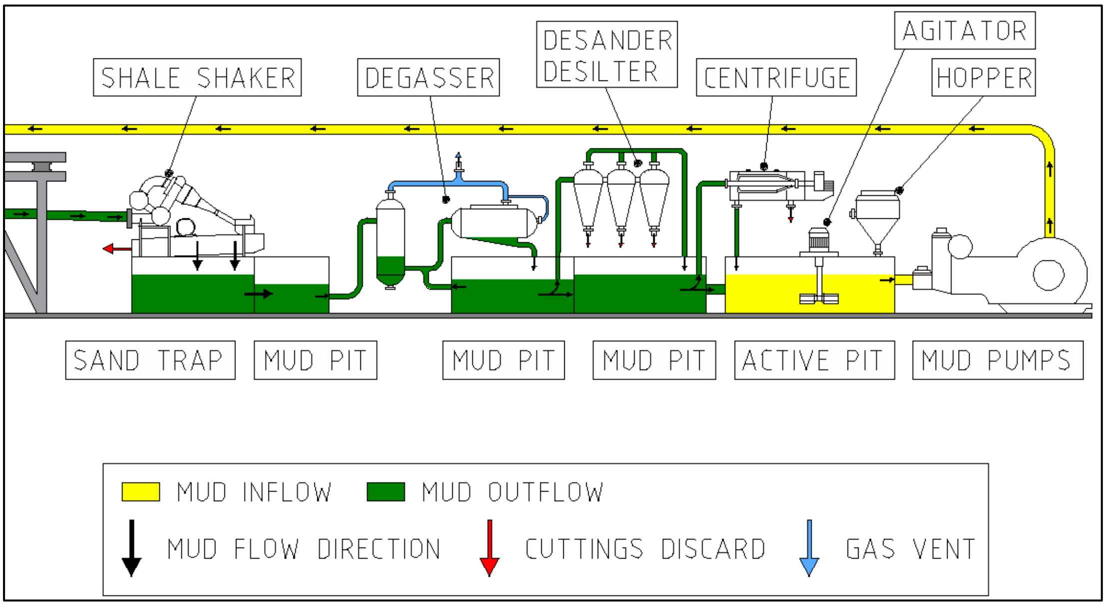

Figure 12: Sectional view of typical solids control equipment

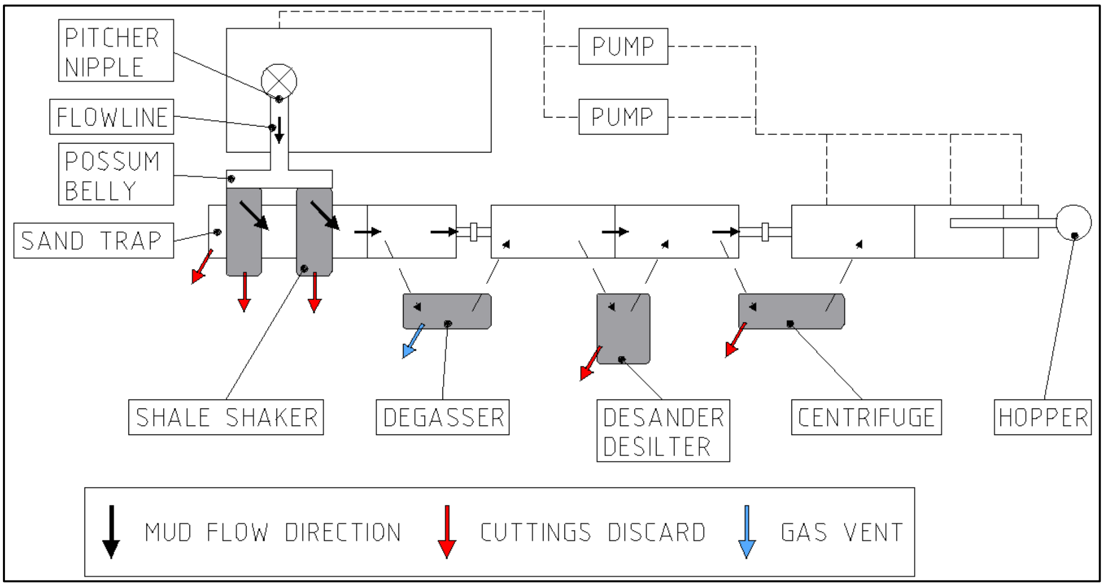

Figure 13: Layout of typical solids control equipment (derived from Philips 2011)

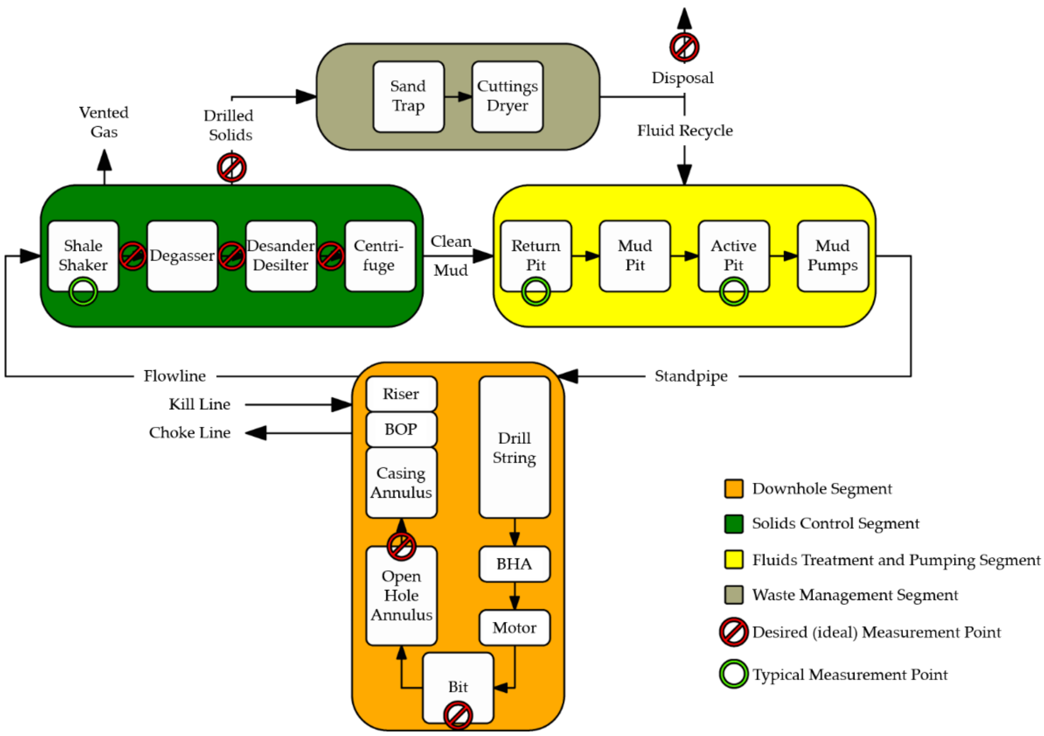

Figure 14: Drilling fluids system with typical and desired measurement points (derived from Geehan and Zamora 2010)

Chapter 3 Market Analysis

This chapter gives a short introduction to the industry standards regarding the testing and the treatment equipment of drilling fluids. The second section discusses the common field testing methods and applications. The main part of this chapter outlines and compares the existing automated mud management systems and their integration principles. The purpose of this chapter is to address the advantages and disadvantages and providing an overview of these applications.

3.1 Industry Standards

An industrial standard provides and organizes specifications, qualifications, and norms for a commonly used technical operation. These standardizations treat the following main types of criteria: a unit system for measurements, a set of definitions according to the industry, a group of requirements for specific equipment or material, and guidelines for operational methods or procedures. Private, corporate, or governmental associations typically develop these technical standards. The petroleum industry implements standards mainly from two leading standardization organizations: the International Organization for Standardization (ISO) and the American Petroleum Institute (API).

The International Organization for Standardization implements 165 national member associations (ISO 2020) and serves as a network to exchange knowledge and expertise on every technical field to develop relevant international standards. The member corporation of the United States is the American National Standards Institute (ANSI), which assigns and guides standardization developers for each specific industry. The American Petroleum Institute is a member and authorized standards developer of the American National Standards Institute (www.ansi.org 2020). For over ninety years, the American Petroleum Institute leads the progress of establishing standards regarding operations and equipment for the petroleum, natural gas, and petrochemical industries. The common objectives of these standardization organizations are to create a safety level and establish interchangeable equipment globally across the industry.

The most important standards for drilling fluid design and treatment are the following:

- **ISO 10414-1:2008 Petroleum and natural gas industries – Field testing of drilling fluids – Part 1: Water-based fluids**

  In 2001 the International Organization for Standardization published the first version of this standard, with a revision in 2008 and periodical reviews since then. The ISO 10414-1:2008 specifies the standard testing methods to evaluate the parameters of water-based drilling muds. In addition to the procedures, this standard also provides the necessary calibration processes of the equipment. The test procedures include the determination of the following fluid characteristics: density, viscosity and gel strength, filtration, oil, water, and solids concentration, sand content, methylene blue capacity, pH, alkalinity and lime content, chloride content, resistivity, and total hardness. Further, the document includes various additional chemical analyses. (*ISO 10414-1:2008* 2008)

- **ISO 10414-2:2011 Petroleum and natural gas industries – Field testing of drilling fluids – Part 2: Oil-based fluids**

  The International Organization for Standardization revised the initial ISO 10414-2 standard from 2002 in 2011 and reviewed it twice since then. The ISO 10414-2:2011 standard covers the similar testing procedures as the ISO 10414-1:2008 but for the determination of oil-based drilling muds. In addition to the fluid characteristics, this standard defines the methods for the following typical measurements of chloride and calcium concentrations, electrical stability, calcium chloride and sodium chloride concentrations, weighting material concentrations and sag, drilling fluid activity, and aniline point. (*ISO 10414-2:2011* 2011)

- **ISO 10416:2008 Petroleum and natural gas industries – Drilling fluids – Laboratory testing**

  In 2002 the International Organization for Standardization published the guideline ISO 10416:2002. The current version ISO 10416:2008 is the revision from 2008 and includes the periodical reviews. This standard defines the laboratory testing procedures for all drilling fluid types. The methods implement the testing of the fluid materials as well as the fluid properties regarding their chemical, physical, and performance measurements. However, the ISO 10416:2008 does not serve as an operational manual for the maintenance and control of the drilling mud parameters. (*ISO 10416:2008* 2008)

- **ISO 13500:2008 Petroleum and natural gas industries – Drilling fluid materials – Specifications and tests**

  The International Organization for Standardization issued the initial ISO 13500 standard in 1998, followed by two revisions, the first in 2006 and the second in 2008. The reviewed and current version ISO 13500:2008 has a technical corrigendum from 2009 regarding a calculation and a technical amendment from 2010 to cover the drilling fluid product Barite 4,1. The ISO 13500:2008 specifies the necessary physical parameters and the associated test methods for manufactured drilling fluid materials, for example, barite, different types of bentonite, haematite, several kinds of cellulose, and Xanthan gum. (*ISO 13500:2008* 2008)

- **ISO 13501:2011 Petroleum and natural gas industries – Drilling fluids – Processing equipment evaluation**

  The initial ISO 13501 standard was from 2005. The revision from 2011 has periodical reviews every five years and remains the current version. The ISO 13501:2011 standard outlines a set of methods to evaluate, control, and adapt the solids control equipment performance. However, this document does not serve as a market research guide to compare individual solids control equipment components. (*ISO 13501:2011* 2011)

- **API SPEC 13A Drilling Fluids Materials**

  The American Petroleum Institute published the first API 13A standard in 1981 and revised it nineteen times to the currently valid version API SPEC 13A from October 2019. This document is in close conjunction with the ISO 13500 standard and establishes a guideline for the required parameters of drilling fluid materials, which are available from multiple sources. The manufacturers, distributors, and end-users are the main practitioner of this standard. (*API SPEC 13A* 2019)

- **API RP 13B-1 Field Testing Water-based Drilling Fluids**

  This document originates from January 1990 and has had nine revisions so far. This standard provides recommended test procedures to evaluate the fluid characteristics of water-based drilling muds, similar to the ISO 10414-1:2008 standard. (*API RP 13B-1* 2019)

- **API RP 13B-2 Recommended Practice for Field Testing of Oil-based Drilling Fluids**

  The American Petroleum Institute issued the original API RP 13B2 in June 1990 and revised it eight times for today's valid version API RP 13B-2 of April 2014. This standardization document is in adjacent affiliation to the ISO 10414-2:2012 and describes the measurement practices to determine the attributes of oil-based drilling muds. (*API RP 13B-2* 2014)

- **API RP 13C Recommended Practice on Drilling Fluids Processing Systems Evaluation**

  The initial basis for this standard is the API 13E, which designates the shale shaker screen cloths. The sixth revision of this guideline in October 2014 is the currently most recent document. This standard defines, similar to the ISO 10416:2008, the required procedures to assess and change the performance of the solids control equipment. (*API RP 13C* 2014)

- **API RP 13D Rheology and Hydraulics of Oil-well Drilling Fluids**

  The primary API RP 13D-1995 guideline originates from June 1995 and combines the before used API BUL 13D standardization bulletins from 1985. The fourth revision is the seventh edition of the currently valid API RP 13D. This recommended practice aims to implement a common basic knowledge about the drilling fluid hydraulics and rheology for all types of wellbore complexities throughout the drilling industry. The objective of this guideline is to provide easy to use equations for spreadsheet analyses. The API RP 13D includes the wellsite measurements, monitoring, and treatments, as well as the laboratory test methods regarding rheology determinations. The target users of this standard are engineers in the office and on the drilling rig. (*API RP 13D* 2017)

In addition to the above-listed standards, also the NORSOK standards and the guidelines from The UK Oil and Gas Industry Association are mentionable. However, the application of the standardization documents issued by these organizations is mainly limited nationally. Further, most of the published guidelines arise from the standards of the International Organization for Standardization and the American Petroleum Institute and only contain a few regional mandatory additions. Even if there are not many differences between the ISO and the API standardization documents, both have a world-wide reputation and serve as the basis for several national regulatory guidelines.

The reason that two organizations provide standards for drilling fluids and the associated testing procedures and equipment emerges from the historic inception and the focus of the oil industry in the United States of America. The American Petroleum Institute was the primary institution to standardize the operations within the petroleum industry. The worldwide recognition of the International Organization of Standardization provides the demand for ISO standards. Therefore, the International Organization of Standardization uses the American Petroleum Industry standards as a foundation and converts them into ISO-formatted documents.

The significant descriptions of the suggested testing methods, the associated formulas, the testing environment, and the utilized units do not deviate between the standards of the two organizations. It appears as if the two organizations take turns auditing each other for the standards. For example, the API RP 13B-1 from 1997 serves as the basis for the ISO 10414-1:2001 standard, which in turn, the API RP 13B-1 from 2003 adopts and adds some modification. Figure 15 illustrates the equivalents of ISO and API standards for drilling fluids and summarizes the area of application in the description. The majority of the standards are equivalent, and only the API Recommended Practice 13D, which describes the rheology and hydraulics for drilling fluids, does not have a counterpart of ISO.

Description	ISO	API
WBM Field Testing	10414-1	RP 13B-1
OBM Field Testing	10414-2	RP 13 B-2
Laboratory Testing	10416	RP 13I
Fluid Materials	13500	Spec 13A
Processing Systems	13501	RP 13C
Rheology & Hydraulics	-	RP 13D

Figure 15: Overview of ISO and API standards equivalents

The American Petroleum Institute (API) published in 1985, as mentioned above, a collection of standards to describe the rheology of drilling fluids. The primary tasks of the drilling fluid rheology contribute to the cuttings transport and fluid loss control. Since the drilling operation technology evolved, the drilling fluid composition became more complicated, but the associated standards did not change accordingly. Due to environmental and operational considerations, the classical bentonite-based muds have changed to polymer-based drilling fluids. Thus, the mechanisms for fluid loss control and viscosity development changed respectively. The work of Clark analyses the previous API standards and emphasizes that ongoing changes within the used drilling fluids have to be adapted continuously. Supplementary, the research of Zamora and Power further highlights the priority to revise the standards frequently, and thus, close the gap between theoretical and practical drilling fluid solutions. (Clark 1995; Zamora and Power 2002)

The ongoing development of drilling automation relies on proper surface measurements and thus needs standards according to the automated measurement equipment. The API Standards 13B-1 and 13B-2 contain the procedures for drilling mud analysis at the rig site. The presented methods are time-consuming, labor-intensive, and error-prone due to high human involvement. Besides the mentioned standards regarding the testing procedures for drilling fluids, automated measurement equipment also needs a common basis for the transfer of the associated data. (Gul et al. 2019)

The Drilling Systems Automation Roadmap (DSA-R) is an initiative to accelerate the adoption of automation systems for the drilling industry and thus enhance the related development of such. The work of de Wardt et al. defines the advantages of subjects that directly benefit from a standardization of the drilling automation operations. The improvements are a higher return on investments, the reduction of extensive inventories, the interchangeability of equipment, the wellsite communication, the shared practical expertise, and, most important, the increased safety and security. The Drilling System Automation Roadmap team specifies 33 standards issued by the International Society of Automation (ISA) as relevant for the adaption of automation in the drilling industry. As a communication protocol between machines, the DSA-R initiative recommends the Open Platform Communication Unified Architecture (OPC UA) as protocol standard. However, the OPC UA protocol is not a suitable solution for all demands of automated drilling equipment. The incorporation of a standardized data transfer protocol is crucial to enable interchangeability and interoperability for automated drilling equipment. (de Wardt et al. 2015)

The API and ISO standards do not have crucial differences regarding the composition, the testing procedures, and the associated equipment of drilling fluids. The choice to test according to API or ISO underlies national and company regulations. However, these standards for the manual field tests impair the development and implementation of new automation equipment for measuring drilling fluid parameters. The invented technologies for automation either try to mechanize the manual testing operations or adjust the new measurement techniques to fulfill the standards for manual testing. The historical emerged units should not influence the monitoring of drilling fluid property trends. Therefore, it is imperative to establish a unique set of standards for automated drilling fluid measurement equipment, to enhance the development further.

3.2 Field-Testing Procedures and Instruments

The functions discussed in section 2.1 emphasize the critical role of drilling muds during drilling operations. The precise capability to monitor, control, maintain, and change the designed drilling fluid properties is significant for safe and efficient drilling activities. The drilling mud directly connects or indirectly contributes to most of the unwanted events for drilling operations, as section 2.1 describes. The sections 2.2 and 2.3 summarize the complex behaviors and connections of the drilling fluid components. The required substances for the drilling fluid design interact among themselves and with the subsurface solids and fluids. The alteration due to time, temperature, pressure, and shear rate additionally impact the drilling fluid parameters. Thus, it is very complicated to predict the downhole condition of the drilling mud precisely.

The standard field tests to evaluate the drilling fluid properties are manual measurements at surface conditions. These manual field testing processes are the result of the historical development and the demands of the harsh wellsite environment to be able to deliver quick results with simple apparatuses. The measurement outcome of these tests reflects the downhole status of the drilling mud only partially, and it requires sufficient experience to correlate the test results to determine useful indications of the downhole drilling fluid behavior. The drilling industry widely accepts these standard field tests as the main procedure to evaluate the drilling fluid properties and to monitor possible changes within the parameters. However, the limitations of these testing procedures are significant, and the decisions based on occurring fluid alterations are only reactive and thus are not sufficient for automated drilling operations.

The ensemble of these standard field tests also refers to as mud check. Table 1 and Table 2 show the basic drilling fluid examination results and the associated equipment for water-based and oil-based muds, respectively. The mud engineer is responsible for the condition of the drilling fluid, and thus, he conducts the mud check to monitor and maintain the planned mud design. The normal drilling operations include two mud engineers, which cover the twelve-hour day and night shifts alternately. The intervals for the mud analysis depend on the type of the drilling fluid, the subsurface solids and fluids, and the drilling activity.

The mud engineer performs the field tests at regular intervals to detect changes within the drilling fluid and hydraulic trends. During all drilling operations with circulation, the interval for the density analysis is fifteen minutes. The common industry practice to execute the full mud check with all points from Table 1 or Table 2 is two times per shift. This testing interval creates a gap for the drilling fluid analysis, and the necessary decisions for the mud maintenance rely on data that is more than twenty-four hours old. Another drawback of the standard field test is that they are very human error-prone and thus influence the accuracy and reliability of the drilling fluid measurements.

This section provides an overview of the common field procedures to test drilling fluids and describes the associated methods and tools.

	Property	Equipment
1	Density	Mud balance
2	Funnel viscosity	Marsh funnel
3	Plastic viscosity	Rotational viscometer
4	Yield point	Rotational viscometer
5	10-second gel strength	Rotational viscometer
6	10-minute gel strength	Rotational viscometer
7	30-minute gel strength	Rotational viscometer
8	Water percentage	Retort
9	Oil percentage	Retort
10	Solids percentage	Retort
11	Filtrate	Filter press (LPTP)
12	High-pressure / high-temperature filtrate	Filter press (HPHT)
13	Filter cake thickness	Ruler
14	Phenolphthalein Endpoint for Filtrate (Pf)	Burette
15	Methyl Orange Endpoint for Filterate (Mf)	Burette
16	Phenolphthalein Endpoint for Mud (Pm)	Burette
17	Chloride concentration (salinity)	Burette
18	pH	pH meter
19	Calcium and magnesium concentration (hardness)	Burette
20	Methylene blue capacity	Burette & filter paper
21	Sand content	Sand tube

Table 1: Results for field tests of water-based drilling fluids (derived from Philips 2011)

	Property	Equipment
1	Density	Mud balance
2	Funnel viscosity	Marsh funnel
3	Plastic viscosity	Rotational viscometer
4	Yield point	Rotational viscometer
5	10-second gel strength	Rotational viscometer
6	10-minute gel stnregth	Rotational viscometer
7	30-minute gel strength	Rotational viscometer
8	Water percentage	Retort
9	Oil percentage	Retort
10	Solids percentage	Retort
11	High-pressure / high-temperature filtrate	Filter press (HPHT)
12	Alkalinity of whole-drilling-fluid	Burette
13	Electric stability	ES-meter
14	Lime, salinity, and solids concentration	Calculator

Table 2: Results for field tests of oil-based drilling fluids (derived from Philips 2011)

3.2.1 Density

The first analysis of the mud check is the measurement of the drilling fluid density. Chapter 2 describes the importance of this mud property and outlines the possible related hazards to poor maintenance of the mud weight.

The principle of density analysis is to measure the density of a given liquid volume. The industry standards (*ISO 10414-1:2008* 2008; *ISO 10414-2:2011* 2011) admit each measurement device with an accuracy of 0,01 grams per cubic centimeter., which converts to 0,083 pounds per gallon. The measurement instrument used in the drilling industry is the so-called mud balance (**Figure 16**).

The assembly of the mud balance consists of a cup with a lid, the base support with a graduated arm, a beam, a counterweight, a level-bubble, and a weighted rider. The holding cup contains the drilling fluid, and the sliding-weight rider balances the beam along a graduated scale to determine the mud weight. The level-bubble enables accurate balancing. The pressurized mud balance is a more advanced tool, which reduces the negative effect of entrained gas by pressurizing the holding cup. The regular calibration of the mud balance with freshwater is imperative to assure precise measurements.

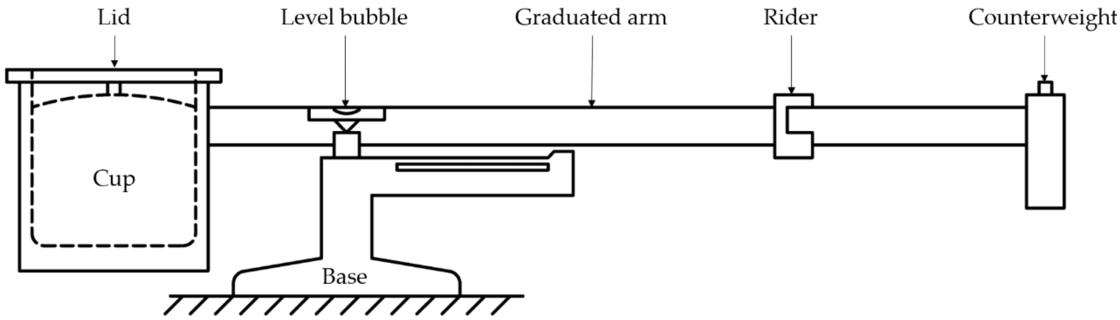

Figure 16: Schematic of a mud balance

3.2.2 Funnel viscosity

The viscosity describes parts of the flow properties of drilling muds and is a crucial parameter for drilling fluid functions. The mud engineer monitors the viscosity regularly with the so-called Marsh funnel and a viscosity cup (**Figure 17**).

The very simple design of these measurement tools makes them nearly indestructible and easy to operate. The instruments include a funnel cone with a meshed screen and a capacity of 1500 milliliters and a graduated cup with at least 946 milliliters (1 quart) of volume. (Marsh 1931)

The test procedure is to fill the Marsh funnel with the drilling mud sample while covering the orifice with a finger. Subsequently, the mud engineer allows the flow and measures the time until the drilling fluid reaches the one quart mark of the viscosity cup. The measurement result also refers to funnel viscosity and has the unit seconds per quart. The medium to calibrate the instrument is freshwater.

The simplicity in design and the easy and quick measurement process of this field test enable regular determinations of the funnel viscosity. This analysis provides only a one-point measurement, and thus, does not give any information about why the viscosity is high or low. On the other hand, measurements at short intervals of the funnel viscosity enable to indicate changes in the mud properties. These alterations within the mud properties can be crucial to the drilling operations. Therefore, the execution of further tests with a rotational viscometer to analyze the viscosity are mandatory.

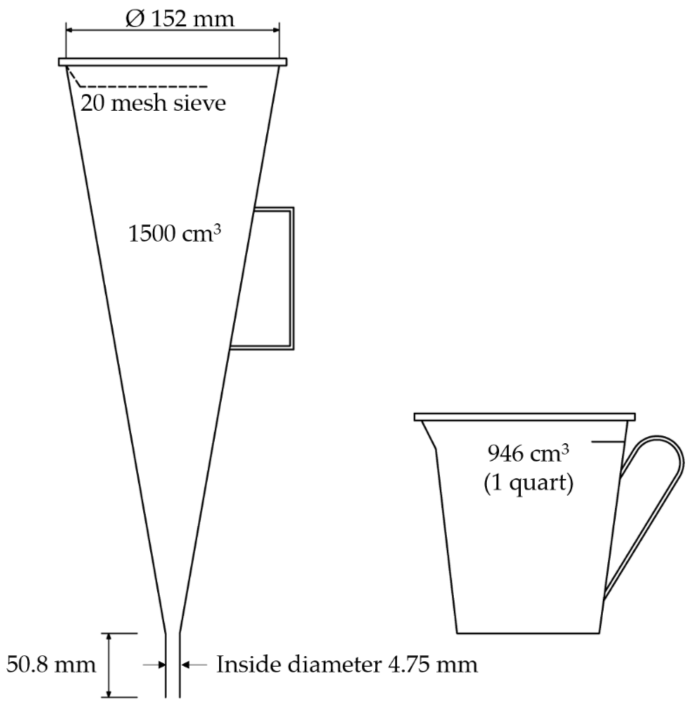

Figure 17: Schematic of a Marsh funnel and viscosity cup (derived from Marsh 1931)

3.2.3 Rheology

Section 2.3.2 presents the important contributions of the rheology as a property of the drilling fluid to the ongoing drilling operations and the possible associated consequence for poor maintenance of the rheology parameters. Further, it outlines the prominent rheological models and mathematical descriptions. These models are important for the implementation of the hydraulic calculations in a circulating well.

The common measurement device to evaluate the rheology behavior as part of the full mud check and to establish the rheological models is the direct-indicating rotational viscometer. **Figure 18** shows the typical setup of a rotational viscometer used in the drilling industry. The results of this analysis enable the calculation of the plastic viscosity, the yield point, the apparent viscosity, the consistency index, and the flow behavior index. Further, the determination of the gel strength at specific times is part of this field test.

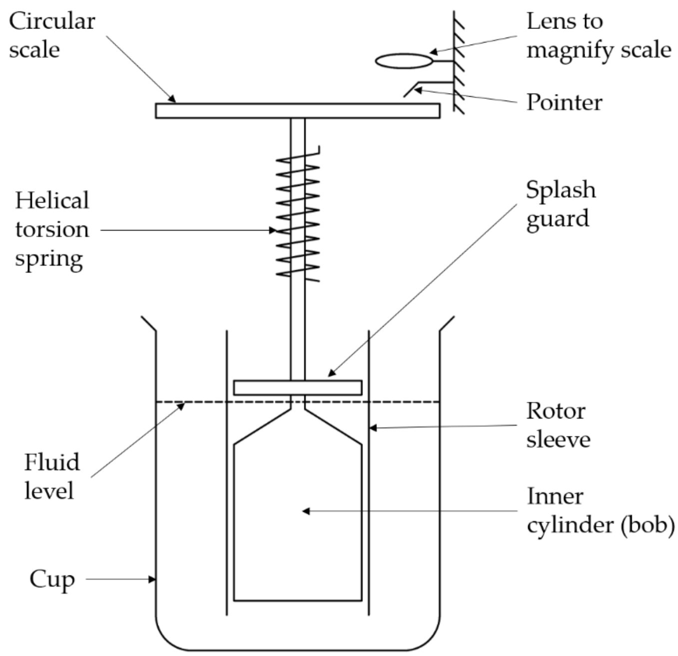

Figure 18: Schematic of a rotational viscometer (derived from Lam and Jefferis 2014)

The rotational viscometers are the standard measurement instruments in the drilling industry for many years. The geometry design also refers to as R-1 rotor, B-1 bob. And S-1 spring. The mandatory speeds for these machines to rotate at are 300 and 600 rotations per minute. Some viscometers have up to twelve preset speeds or run at any individual speeds. The assembly includes an electric motor, an outer cylinder or rotor, an inner cylinder or bob, a helical torsion spring, a dial with a circular scale, and a pointer. There are various models on the market from different manufacturers, but they all work with the same principle.

The cup contains the drilling fluid and the rotor sleeve together with the bob immerse into it so that the drilling mud occupies the annular space in between. The constant rotation of the sleeve shears the drilling mud between the rotor sleeve and the bob at a steady rate. The drilling fluid experience a viscous drag, which applies a torque on the inner cylinder. The helical torsion spring restricts the rotation of the bob, and the dial on the top displays the displacement. The dial reading is a direct measurement for the shear stress in pounds per hundred square feet, due to the designed dimensions of the rotor sleeve, the bob, and the helical torsion spring.

The plastic viscosity in the unit of centipoise is the difference between the dial reading at 600 and 300 rotations per minute (rpm). The calculation of the yield point in pounds per hundred square feet subtracts the previously evaluated plastic viscosity from the 300 rpm dial reading. The maximum dial reading at 3 rpm after a rotation break of 10 seconds, 10 minutes, and 30 minutes, provides the 10 seconds, 10 minutes, and 30 minutes gel strength, respectively.

3.2.4 Retort analysis

The various drilling muds contain several different additive components and additionally incorporate fluids and solids from the subsurface formations. The proper maintenance of the drilling fluid requires measuring the percentage of the water, oil, and solids within the mud. This standard field testing process uses a retort, which comes in three sizes: 10 milliliters, 20 milliliters, and 50 milliliters. (*ISO 10414-1:2008* 2008)

Figure 19 shows the schematic diagram of a 10-milliliters retort with the associated components. The assembly includes a heating element in a jacket, a sample cell with a lid, a discharge tube with steel wool inside, an aluminum condenser, and a graduated glass cylinder. The principle of this device is to provide a separation of the different phases and to measure the related water, oil, and solid volumes within the drilling fluid sample.

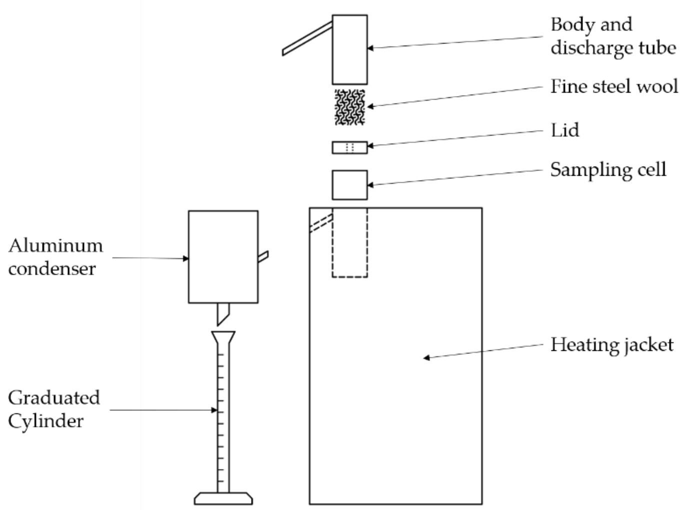

Figure 19: Exploded view schematic of a 10 milliliters retort (derived from Fann Instrument Company 2020g)

In order to determine the fraction of each component, the retort heats a known volume of the drilling fluid inside the cell. The liquid drilling mud constituents vaporize, and the discharge tube carries them to the condenser. The aluminum condenser removes the heat and allows the steam to liquefy. The glass graduate cylinder collects the different fluid types, and the liquid volumes enable direct measurement of the oil and water phases. The combined volume of suspended and dissolved solids is the difference between the total sample drilling mud volume and the received liquid volume in the cylinder. Further calculations enable the determination of the relative fractions of the low gravity solids and the weighting material. The knowledge about the composition and concentration of the apparent solids is essential for the precise viscosity and filtration control of drilling fluids.

The drilling mud analysis with the retort is very error-prone. Some of the possible mistakes are a wrong sample volume, entrained gas, a too-short test duration, a plugged discharge tube, an incorrect amount of fine steel wool, a false meniscus reading, a temperature difference in the drilling mud between the weighting measurement and the retort analysis, and a wet graduated cylinder. Only experience and practice avoids and mitigates these pitfalls, and it is imperative to repeat the test for every unexpected result from the retort analysis.

3.2.5 Filtrate

The filtration behavior and the ability to build a filter cake of the drilling fluid is a crucial characteristic, and thus, it is fundamental to monitor and maintain this function. The quantities and types of solids dispersed in the drilling mud, and their chemical and physical interactions directly affect the filtration. The prevailing pressure and temperature strongly influence these interactions and in the following the filtration behavior. Therefore, the filtration analysis includes tests at low and high pressures and temperatures.

The use of a filter press (**Figure 20**) and a graduated cylinder enable the evaluation of the filtrate. The assembly consists of a cylindrical drilling fluid cell with a cap, a pressure gauge and regulator, a T-screw, several neoprene gaskets, a 60-mesh screen, filter paper, the support frame, and a graduated cylinder.

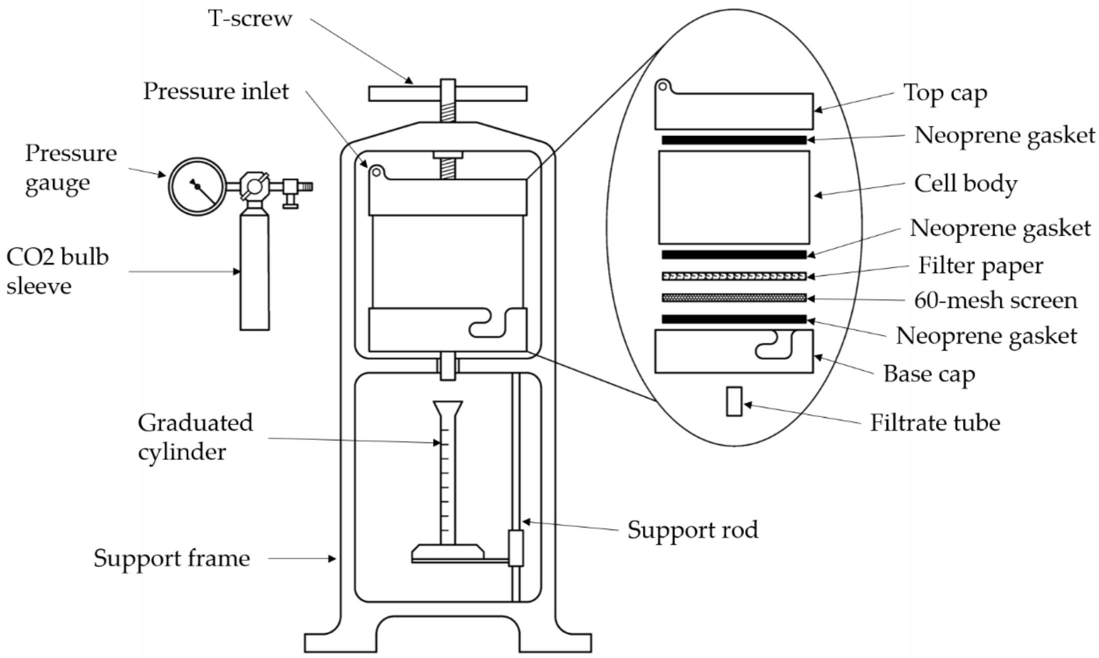

Figure 20: Schematic of a filter press with detail of test cell

The test procedure starts by filling the drilling fluid sample into the cell and placing it inside the support frame. The T-screw locks the cell in place and closes it airtight. A pressure of one hundred pounds per square inch (psi) forces the liquid through the filter paper and the 60-mesh screen. The graduated cylinder collects the filtrate and enables to evaluate the filtrate volume after thirty minutes. This filtrate serves as the test subject in the analysis, which section 3.2.7 describes. The next step is to release the pressure, remove the cell from the frame, and carefully disassemble it. A gentle water stream washes the resulting filter cake on the filter paper and enables measuring the cake thickness and the appearance of the filter cake.

3.2.6 pH

The term "pH" describes the negative logarithm of the activity of the hydrogen ion within aqueous solutions. The pH of a drilling fluid influence the interactions with clay formations, the effectiveness of additives, and the solubility of several components, as the pH controls the acidic and sulfide corrosion processes.

The ISO 10414-1 and API 13B-1 standards suggest using a glass electrode pH meter for the analysis. Still, for quick field measurements of simple water-based drilling fluids, it is also possible to determine the pH with pH strips. (*ISO 10414-1:2008* 2008; *API RP 13B-1* 2019)

3.2.7 Alkalinity

The power of a drilling fluid to neutralize acids refers to alkalinity. For the analysis of the drilling mud alkalinity, either the whole mud or the filtrate serves as a test subject. The alkalinity of a drilling mud influences the additives, especially deflocculants. Alkalinity resulting from hydroxyl ions is favorable, while the one arising from carbonates is not beneficial for the drilling fluid.

The standard procedure for this field test analyses the filtrate or the mud by titration with an indicator solution. The required volume in milliliters to reach the related endpoint is the result of this analysis. The phenolphthalein endpoint (Pf and Pm) indicates a pH of more than 8.3, and the methyl orange endpoint (Mf) prevails at a pH of 4.2. The resulting indicator volumes provide the necessary input to estimate the concentrations of hydroxyl and carbonates, as well as to evaluate the lime content.

3.2.8 Chlorides

Salt plays an essential role as a severe contaminant within all different types of drilling muds. Therefore, the accurate monitoring of salt concentration is important. The titration of the mud filtrate includes potassium chloride as an indicator and silver chloride to titrate the solution to the endpoint. This analysis measures the chloride ion concentration of the drilling mud but does not evaluate the type of the present salt.

3.2.9 Hardness

The presence of magnesium and calcium ions in water establish the hardness in the drilling fluids. Typical drilling muds rarely contain any magnesium, but calcium is a serious component in fresh water-based muds. The hardness test also refers to calcium test and measures the calcium concentration in the drilling mud filtrate. The result of this analysis provides the total hardness of the filtrate in the unit of milligrams calcium per liter.

3.2.10 Methylene blue test

The execution of the methylene blue test determines the amount of reactive clay in the drilling mud. Further, this standard field test enables an estimation of the total cation exchange capacity of the drilled cuttings.

The testing procedure starts by treating the drilling mud sample with hydrogen peroxide, sulfuric acid, and distilled water. After gently boiling it for ten minutes and cooling it down again, the dropwise addition of one-milliliter methylene blue to the liquid sample starts. The field test continues by swirling the mixture for thirty seconds and placing a drop on a special filter paper (**Figure 21**). The analysis repeats these steps until a light blue halo surrounds a dark blue circle on the filter paper. After a pause of two minutes, the mud engineer tests the same liquid sample. If an endpoint appears again after two minutes, the analysis is complete.

The volume of the methylene blue solution serves as the input to calculate the methylene blue capacity, as shown in equation (10).

$$MBT = \frac{V_{mb}}{V_{df}} \tag{10}$$

Where MBT is the methylene blue capacity, V_{mb} is the methylene blue solution volume, and V_{df} is the drilling fluid sample volume.

Equation XXX shows the determination of the bentonite equivalent in kilograms per cubic meter, with the assumption that bentonite has a cation exchange capacity of 70 meq per 100 grams.

$$BE = \frac{14{,}25 \cdot MBT}{V_{df}} \tag{11}$$

Where BE is the bentonite equivalent, MBT is the methylene blue capacity, and V_{df} is the drilling fluid sample volume.

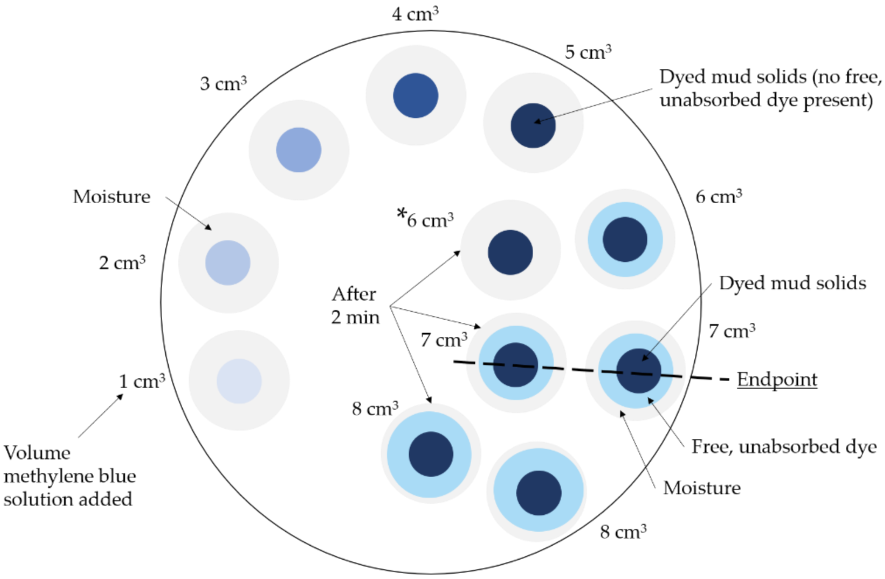

Figure 21: Spot test for the endpoint of the methylene blue titration test. (*After two minutes the filter paper absorbs the free dye detected immediately after adding the sixth cm³ and indicates that the endpoint has not quite been reached.)

3.2.11 Sand content

The last test of the mud check determines the volume fraction of solid particles with a diameter larger than 74 micrometers and refers to the sand content test. This standard field test includes a sand tube, a sieve with a 200-mesh screen, and a funnel.

The test procedure starts with mixing a known drilling mud volume and water volume in the tube. Then the mixture flows through the sieve. A squirt bottle and a funnel wash back the collected sand into the tube. The bottom of the tube marks the sand content between 0.25 and 10 percent. This test is a quick and straightforward analysis but with high importance because a drilling fluid with high sand content damages the rig pumps.

3.2.12 Electrical Stability

This test is only part of the mud check for oil-based drilling fluids (see Table 2). The parameter of electrical stability (ES) defines the emulsion stability and oil-wetting capability of an oil-based drilling fluid.

The testing principle immerses a pair of parallel electrodes and applies a voltage-ramped, sinusoidal electrical signal across them. The arising current stays low until it reaches a certain threshold specific for each fluid. The related threshold voltage defines the electrical stability of an oil-based drilling fluid. The unit for this parameter is peak volts, and the testing temperature should be 120 degrees Fahrenheit or 48.9 degrees Celsius.

The interpretation of a single electrical stability test is not accurate due to the strong and complex influence of chemical additives and shear history on the electrical stability magnitude. Therefore, electrical stability trends are the foundation of any decisions regarding drilling fluid treatments.

3.3 Drilling Fluid Management Systems

This section provides an overview of the most significant contributors in terms of companies developing and distributing drilling fluid measurement systems. The objective is to present existing relevant drilling mud management systems that already enable automated fluid analyses and contribute to the overall automation development of the drilling industry.

The following company listing is alphabetically ordered, unbiased, and does not reflect any market share situation. Due to the Coronavirus outbreak and associated lockdowns at the beginning of this thesis, this market research and all stated technical facts rely mainly on publically available information such as websites, product data sheets, journal articles, and scientific papers.

AMC Drilling Optimization

AMC Drilling Optimization (AMC) is part of the IMDEX Group, a traditional mining technology company that offers solutions for the entire mining value chain to enable successful and cost-effective operations. AMC provides an extensive selection of quality drilling fluids, as well as special equipment for drilling operations. The drilling fluids testing instruments range from the classical mud balance, Marsh funnel, and sand tube, to more sophisticated solids removal and automated fluid testing units, as well as a cloud-based information hub.

The IMDEX MUD AID (Automated In-field Diagnosis) is a field testing unit to optimize the fluid management with remote monitoring via the IMDEXHUB-IQ, a cloud-based data exchange program. The IMDEX MUD AID tests drilling fluids according to API standard using a live sample mode and providing the data in real-time. The most significant advantages establish from the portable and lightweight design, as it only consists of two forty-three kilograms and thirty kilograms Pelican cases, together with the fast installation and setup time of only thirty minutes. The testing capabilities include rheology, density, temperature, pH, chlorides, potassium, and calcium evaluation. The testing frequency ranges from thirty minutes to twelve hours. (AMC Drilling Optimisation 2019a, 2019b)

Baroid

Baroid is a brand of Halliburton and provides solids control equipment, separation and handling technology, solutions for reservoir and drilling fluid systems, special fluid additives, and operational services to the oil and gas industry. As part of the drilling fluids product line, Baroid also offers real-time and automation services. The Baroid Engineering Services face the technical challenges of the more and more complex wellbores with a drilling fluids graphics software to model the hydraulic downhole behavior and conditions. Further, they provide advanced monitoring solutions and related comprehensive optimization techniques. (Halliburton 2020)

The name of the Baroid automation product line is BaraLogix. The combination of experienced personnel and advanced technologies enables to improve the overall drilling performance. The Drilling Fluids Graphics Real-Time (DFG-RT) software facilitates the monitoring of drilling mud and operational parameters. The program integrates real-time data from downhole tools and fluid personnel to provide accurate, traceable, and trending analysis of the downhole fluid behavior. (Halliburton 2020)

The central part of the automation services is the Baralogix Density and Rheology Unit (DRU) that enables real-time density and rheology measurements and has the ATEX and Zone 1 certifications. The DRU stands at the rig site next to the mud tanks and reports density and rheology measurements every minute and every fifteen minutes, respectively. Further, this analytical instrument incorporates a fluid delivery system with a self-generating nitrogen purge function. The density measurement process utilizes a density sensor that applies the patented pulse excitation method (Umfer 2014). The execution of a cleaning cycle with nitrogen is mandatory to prevent any particles from settling inside the density measurement system. The recommended flushing frequency is once after every fifty sample measurements, which is approximately one cleaning run per hour of operation. The DRU characterizes the rheology of the drilling fluid in an automated batch sampling mode analysis with a rheology meter. The results of several field applications of the DRU prove the system to be adequate for the use at the rig site and to deliver accurate data improving the overall drilling performance. (Halliburton 2012, 2017, 2019, 2020)

Core Laboratories

In 1936 Core laboratories started to evaluate cores from oil wells. Today, the company specializes in reservoir description and production enhancement. The testing equipment from Core laboratories is not primarily for drilling fluids, but to characterize the flow of fracturing fluids. However, the company offers a friction flow loop, a lubricity evaluation monitor, a mixing unit with a shear loop and pipe rheology system, and an oil fluoroscope for drilled cuttings. The use of this equipment to evaluate drilling mud is also possible, and thus, the technology can improve the automation development of the drilling industry. (Core Laboratories 2020a, 2020b, 2020c, 2020d, 2020e)

Fann Instrument Company

One of the most famous companies when it comes to drilling fluids testing is the Fann Instrument Company (Fann). Since 1939 Fann provides quality testing analysis equipment for the petroleum industry. Fann designs and manufactures the equipment to evaluate the chemical and physical properties of drilling fluids. In total, this company offers 118 different measurement devices, which cover the analyses as required in the ISO 10414 and API 13B standards, as well as several other fluid tests. (Fann Instrument Company 2020d)

The Fann Instrument Company specializes in the field testing equipment for oil well drilling fluids. The design of the instruments meets the regulations and requirements of the associated API and ISO standards. The operation principle of the majority of the tools is manual, and a small fraction operates partly automatic. The automated devices provide the testing of compressive strength, permeability, viscosity, temperature, filtrate, and Fann offers propriety software to connect these instruments. However, these systems only automate the testing process and still require a human operator for the setup. (Fann Instrument Company 2020a, 2020b, 2020c, 2020e, 2020f)

Geolog

Geolog International (Geolog) provides laboratory services, data management solutions, reservoir and source rock evaluation technology, and drilling solutions, to the oil and gas industry, since 1982. The drilling solutions product line of Geolog includes seven service packages to reduce the non-productive time and enhance safe and efficient operations. (Geolog 2020b)

The DrillClean monitors cuttings removal efficiency and real-time cavings detection while drilling. The GeoPressure software combines offset well data with real-time monitoring from a Wellsite Information Transfer Standard Markup Language (WITSML) data feed to simulate a pore pressure and fracture gradient model in real-time. The DrillBest is a drilling optimization reporting software tool that identifies non-productive time by utilizing independent and high-quality data. The DrillVibe offers a continuous determination of drillstring vibrations, without a logging-while-drilling tool. The software displays and analyses drilling parameters from surface measurements and suggest changes to minimize the string vibrations. The BitLife service package evaluates the cuttings character together with surface drilling measurements to estimate the bit performance and wear. Geolog's GeoMPD is a solution to extract mud gas during managed pressure and underbalanced drilling activities by implementing a degassing system. (Geolog 2020a, 2020c, 2020d, 2020e, 2020f, 2020g, 2020h)

The KickAlarm service enables real-time early kick and mud loss detection. The service package incorporates electromagnetic and Coriolis flowmeters to monitor the in- and out-flow together with the temperature and density of the drilling fluid. The service modifies the rig with the installation of the Coriolis flowmeter at the flow-line, without critical areal restrictions, and enables the detection of flow fluctuations as low as ten liters per minute. The flowmeter sensor is compatible with water- and oil-based muds and delivers measurement data every five seconds. (Geolog 2020i)

Intelligent Mud Solutions

Since the beginning of Intelligent Mud Solutions (IMS) in 2010, this relatively young company entirely and successfully focusses on the automation of the drilling fluid analysis process. Jektevika AS, Equinor Technology Ventures, and the NAVIC group own the majority of IMS. The results of the intensive and detailed research and development effort are currently two unmatched products, the onshore and offshore RheoSense system. Both units autonomously measure and analyze the drilling fluid properties, with additional features to the respective areas of application. (IMS - Intelligent Mud Solutions 2020a)

The onshore RheoSense unit is a compact and easily transportable container that contains the automatic drilling fluid measurement system. This design offers modular installation options to measure the drilling mud in- and out-flow. Access to the measurement data is available locally and remote for implementation in any logging software, enabling real-time analysis and visualization. (IMS - Intelligent Mud Solutions 2020b)

The offshore RheoSense unit is the pendant to the previously described onshore system. It utilizes the same analysis apparatus as a portable skid based design, which allows the installation in more confined spaces. The extended version of the offshore RheoSense unit includes two units. The inflow measurement unit draws the mud samples from the suction pit, and the outflow analysis unit takes the samples directly after the shakers from the return line. (IMS - Intelligent Mud Solutions 2020b)

The RheoSense unit measures and monitors the temperature, density, rheological properties, and gel strengths of drilling fluids. A gravity feed supplies the drilling mud to the progressive cavity pump of the RheoSense unit, which further runs through a cycle of predetermined varying flow rates. The implemented Coriolis device quality controls the output flow of the pump. Two pipe rheometers with different lengths and diameters, together with two mounted pressure sensors, enable the highly accurate determination of the pressure differentials. The unique IMS propriety software analyses and interprets the raw measurement data within seconds. The integrated human-machine interface screen shows the raw data in real-time and the evaluated mud properties within a three seconds update interval. This data is also available for the driller and a remote operation center in real-time. The innovative design of the RheoSense unit enables long operating times without maintenance, and the supervision and calibration happen remotely from the IMS head office. (IMS - Intelligent Mud Solutions 2020b)

The RheoSense unit is the result of comprehensive research and ambition to enhance the automation of drilling operations. IMS aspires to improve the drilling mud properties measurement process further and combine it with automated mud mixing applications, to contribute to the overall goal for fully automated drilling rigs. The development progress of IMS shows the precise design and application concepts to implement the drilling industry needs into a compact and easy to use automation unit. (IMS - Intelligent Mud Solutions 2020b)

M-I Swaco

M-I Swaco is an American company, founded in 1939, and part of Schlumberger since 2010. The company supplies individually engineered drilling fluid systems, production technology solutions, waste management solutions, fluid additives, solids control and cuttings management instruments, and a suite to monitor and simulate drilling fluids. The main objective of M-I Swaco is to enhance the overall drilling performance while maintaining wellbore integrity and achieve a zero emissions footprint. (Schlumberger 2020c)

The drilling fluids simulation of M-I Swaco contains four crucial engineering packages to enhance the drilling efficiency: the Virtual Hydraulics, the PressPro RT, the Optibridge, and the Mudware. The first one model the drilling hydraulics by simulating the downhole conditions. The simulation depends on predicting and monitoring the temperature, the equivalent static and circulating densities, as well as the hole cleaning and tripping operational profiles. The second software measures the downhole performance in real-time by implementing data from pressure-while-drilling (PWD) instruments. Thirdly, the Optibride is a bridging agent selection software that can accurately and rapidly choose the optimal fluid formulation for fluid loss control pills. The software selects the optimum particle size distribution to prevent subsurface damage and pack a formation efficiently. Mudware is the fourth software package of the M-I Swaco hydraulic optimization suite and provides free calculation tools for the most common drilling hydraulic problems. All of the four software packages strongly rely on monitoring and measurement data, and this provides the automated rheometer from M-I Swaco, the RheoProfiler. (Schlumberger 2020b, 2020d, 2020e, 2020g)

The RheoProfiler is a semiautomated measurement system to determine the density and rheological parameters of all drilling fluid types. A vital advantage of this equipment is the compact and mobile design, with a total weight of only 37.6 kilograms. The objective of the RheoProfiler is to solve common industry problems, such as timely and repetitive mud measurement tasks, improve the drilling automation development, and provide accurate real-time data. The aluminum housing contains a rheometer, a densitometer, and a touchscreen interface. The RheoProfiler shows the measurement results directly on display, and via the Wellsite Information Transfer Specification (WITS) data output also enables viewing the data remotely. (Schlumberger 2020a, 2020f)

OFI Testing Equipment Incorporated

The OFI Testing Equipment (OFITE) company provides drilling fluids, wellbore cement, core analysis services, and mud testing instruments for the oil and gas industry since 1982. The tools cover the complete line of drilling fluid testing and fulfill the applicable API and ISO specifications. The OFITE drilling muds testing instrument product line incorporates classic rotational viscometers, retorts, mud balances, and filter presses, and further the so-called OFITE Automated System (OASys). (OFI Testing Equipment 2020a, 2020b)

The OASys implements three new OFITE products, the Mud Watcher, the OLR Series 1000 OnLine Rheometer, and the Mud Aid from IMDEX, to enable real-time measurement and monitoring of drilling mud properties. The Mud Aid uses the same measurement technique as the IMDEX MUD AID but implements a more robust looking body. **Figure 22** shows the full setup of the OASys in the field, where it is outside of Zone 1 and adjacent to the mud pits. (OFI Testing Equipment 2020a, 2020c, 2020d)

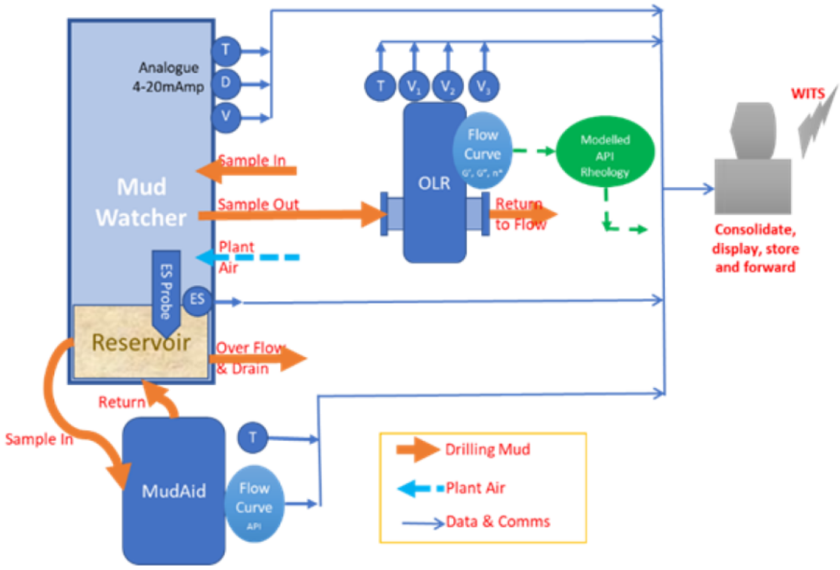

Figure 22: Setup of the OFI Automated System (Kamal et al., 2020)

The OnLine Rheometer (OLR) continuously determines and reports the rheological properties of drilling fluids. The measurement principle of the OLR implements the oscillatory flow mode technique, which holds the fluid sample between two plates, that move at very small amplitudes and different frequencies, to describe the drilling fluid uniquely. This characterization approach uses the small cyclic deformations of the liquid to measure the storage and loss moduli of the sample. Therefore, the OLR enables to report the elastic and viscous parameters of the drilling mud, without destroying the microstructure by the applied flow. While this measurement provides data of the near-linear rheological behavior, the Couette cell from the Mud Aid delivers the non-linear behavior. Thus, these two instruments complement each other. (OFI Testing Equipment 2020e)

The third component of the OASys is the Mud Watcher. This unit functions as the primary subsystem and manages the drilling fluid sample distribution. The entry point of the system is a standard one-inch connection downstream from the shakers. Typically, the suction pit reflects the annular drilling mud most accurately regarding hole cleaning and equivalent circulating density calculations. The drilling fluid samples stream continuously into the internal reservoir of the Mud Watcher, which measures the temperature, the relative viscosity, and the density of the mud. The OnLine Rheometer receives the outflow from the Mud Watcher analysis and returns the drilling fluid to the initial mud pit. The Mud Aid draws the required drilling fluid sample from the internal Mud Watcher reservoir and returns it there after the measurements. The Mud Watcher also implements an automated emulsion stability meter at the enclosed tank. (Kamal et al. 2020; OFI Testing Equipment 2020c, 2020d, 2020e)

A data aggregator collects the data from all three OASys subsystems and transfers it via a standard Well Information Transfer Standard (WITS) interface to the rig data information system. The system enables to monitor the drilling fluid data and real-time calculated hole cleaning and equivalent circulating density values on the rig and also remotely. Miller presents the field results of the Mud Watcher as a stand-alone unit, and the same does the case study from AMC about the Mud Aid field implementation. The work of Kamal et al. describes the pilot field study of the combined OFITE Automated System, in which the system monitored over eighteen well and two hundred thousand drilled feet during a six-month continuous deployment. This extended field pilot proves the OASys to be able to accurately determine drilling fluid properties in real-time without any human intervention. Further, this system is capable of withstanding the harsh and regularly changing rig site conditions. (Miller et al. 2011; AMC Drilling Optimisation 2019a; Kamal et al. 2020; OFI Testing Equipment 2020a)

Other Industries

Several other industries offer measurement devices to evaluate fluid parameters, including products for the food and beverage, chemical, electronics, environmental, material science, paper, and pharmaceutical industry. These analyzing instruments incorporate rotary, vibrating, capillary, flow, Krebs, Mooney, and Ubbelohde viscometers., operating in a semi- or fully-automatic mode. However, the area of application is mainly the laboratory, and the fluid test samples are not complex heterogeneous drilling muds.

Summary

The company listing above describes the main contributors of drilling fluid testing apparatuses and the latest technology of automatic monitoring instruments. Table 3 illustrates the different companies with the relevant automated measurement systems and the belonging measurement property types and frequencies.

The BaraLogix Density and Rheology Unit from Baroid and the Rheoprofiler from MI Swaco represent a compact measurement device that determines the rheology and density of any drilling fluid and provides easy setup. The design and measurement technique of these two systems appears to be similar, and the analysis frequency sufficient enough to supplement the rest of their automated fluid monitoring product lines. However, these two systems do not deliver real-time data, both require automated cleaning runs between the measurements, and the interoperability is questionable. (Halliburton 2020; Schlumberger 2020a, 2020f)

The presented fluid monitoring systems of Core Laboratories are primarily for completion and hydraulic fracturing fluids. The measurement technique is similar to the IMS Rheosense unit, but no information or case studies to implement the device for drilling fluids are available. The automated rheometers of the Fann Instrument Company only automate the process of evaluating the rheology parameters to increase the efficiency of the traditional mud check. However, the analysis still requires manual input of the drilling fluid sample. The introduced KickAlarm system from Geolog does not deliver rheology measurements and thus appears inappropriate for Table 3. However, this monitoring system provides continuous real-time data of the mud in- and outflow and contributes to the overall drilling fluid monitoring. (Fann Instrument Company 2020e, 2020f; Core Laboratories 2020c; Geolog 2020i)

The two systems establishing drilling fluid measurements and providing data in real-time are the Rheosense of IMS and the OFITE Automated System (OASys). The main difference is that the Rheosense contains all measurement techniques in one unit, and the OASys incorporates three pieces of equipment. The additional Mud Aid is equivalent to the presented IMDEX MUD AID as it determines the conventional rotational viscometer shear stress values. Still, the case study of the OFITE system outlines higher measurement frequencies. The online rheometer of the OASys provides extra information about the viscoelastic properties. (Kamal et al. 2020; IMS - Intelligent Mud Solutions 2020b)

The higher number of integrated instruments in the OASys tends to be more error-prone and redundant. An advantage of this system is the included emulsion stability meter. Still, the Rheosense also enables the operator to add measurements such as the determination of gel strength as an automated batch sampling mode. The IMS Rheosense offers a system available for onshore and offshore drilling operations, which utilizes the pipe rheometer technology to determine the density and rheology. (Kamal et al. 2020; IMS - Intelligent Mud Solutions 2020b)

Company	Product	Measurement	Frequency
AMC Mud Optimization	IMDEX MUD AID	Rheology, Density, Temperature, Ions	30 mins – 12 hrs
Baroid – Halliburton	BaraLogix Density and Rheology Unit	Density	1 min
		Rheology	15 min
Core Laboratories	PR-100	Rheology (Completion & fracturing fluids)	N/A
Fann Instrument Company	RheoVADR Rheometer	Rheology	Semi-automated
	iX77 Rheometer	Rheology	Semi-automated
Geolog	KickAlarm	Mass flow, Volume flow, Density, Temperature	Real-time
Intelligent Mud Solutions	Rheosense	Rheology, Density, Temperature	1 sec (raw data), 3 sec (interpreted)
M-I Swaco – Schlumberger	RheoProfiler	Density, Rheology	N/A
OFI Testing Equipment	Mud Aid	Rheology, Density, Temperature, Ions	15 mins
	OnLine Rheometer	Rheology, Temperature	3 mins
	Mud Watcher	Viscosity, Density, Temperature	Real-time
		Emulsion Stability	5 mins

Table 3 Summary and comparison of market analysis (derived from AMC Drilling Optimisation 2019a, 2019b; Kamal et al. 2020; IMS - Intelligent Mud Solutions 2020b; Halliburton 2020; Fann Instrument Company 2020e, 2020f; Core Laboratories 2020c; Geolog 2020i; Schlumberger 2020a, 2020f)

3.4 Real-Time Mud Monitoring Sensors

Besides the previous section, this section describes only fluid sensing systems relevant to any existing or future drilling mud monitoring applications. The method of enumeration and data gathering is identical as before. There is a large variety of drilling rig sensor providers. However, the below-listed companies have the focus on density and viscosity measurements and thus are not primary purely drilling-related.

Anton Paar GmbH

A one-person machine repair workshop and excellent reputation form the inception of the Anton Paar Group in 1922. Today the Anton Paar GmbH is part of the Anton Paar Group, which the Santner Foundation owns. The Anton Paar GmbH evolves, manufactures, and distributes precise laboratory equipment and process measurement instruments. The products cover all relevant industries worldwide, and the focuses especially are density, carbon dioxide concentration, and rheology measurements. (Anton Paar 2020a)

Anton Paar provides solutions throughout the entire petroleum industry production steps, covering up-, mid-, and downstream operations. Besides the various highly accurate rotational rheometers and density meters for laboratory midstream and downstream analyses, the company offers three products especially relevant for drilling operations: the RheolabQC, the L-Dens 7000 series, and the L-Vis 510 and 520 Ex. (Anton Paar 2020b, 2020c, 2020d)

The RheolabQC is a highly advanced rotational rheometer, which determines single-point viscosities but also full rheological fluid behaviors, and categorizes as a semi-automatic device. An immense contribution to the automation efforts of the drilling industry but have so far been relatively unnoticed by the industry are the Anton Paar inline process sensors. The L-Dens 7000 series utilizes inline density sensors with the highest accuracy, robust design, and easy integration options. The sensors employ oscillating u-tube technology as a measurement principle, and a high-performance transmitter enables real-time data availability. Further, the L-Dens 7000 sensors do not obligate any maintenance and are also accessible as an explosion-proof version. (Anton Paar 2020b, 2020d)

The second process sensor type contains the L-Vis 510 and L-Vis 520 Ex a inline viscometer and an explosion-proof inline viscosimeter, respectively. The placement of these sensors is directly in the product flow, and pressure drops, as well as flow velocity changes, do not affect the measurement results. Possible installation points are a stirred tank, the mainline, or a bypass line. The analog outputs and the digital out- and inputs, together with standard computer networks, enable real-time data communication. The measurement principle utilizes the dynamic fluid pressure method and enables the analysis of inhomogeneous and heterogeneous fluid types. (Anton Paar 2020c)

Rheonics

The company Rheonics combines experts from the university and global companies to provide state of the art fluid process sensors to the industrial automation and process industry. The product portfolio of Rheonics implements density and viscosity measurement tools able to monitor fluids in challenging environments for a variety of industries. For the oil and gas industry, Rheonics provides sensors for three application areas: pressure-volume-temperature (PVT) studies, mud weight monitoring, and downhole measurements. (rheonics 2020a)

The Rheonics DVM is a high-pressure high-temperature simultaneous density and viscosity measurement device to improve PVT analyses. The DVM sensor operates directly at the process stream and utilizes a torsional tuning fork resonator to enable highly accurate measurement results. The device is available in an explosion-proof version, and the monitoring accuracy does not suffer from vibrations or flow rate changes. (Dash 2019a; rheonics 2020b)

The SRD sensor from Rheonics is a three-in-one in-line measurement instrument to evaluate the density, viscosity, and temperature of any fluid. The installation of the SRD device is possible at pipes and tanks in a variety of mounting modes such as threaded, flanged, or clamped. The sensing principle applies an immersed torsional resonator, which measures the damping of the fluid. The proprietary algorithm of Rheonics calculates the viscosity and density, with accuracies of one percent and 0.001 grams per cubic centimeter, respectively. (Dash 2018; rheonics 2020c)

Downhole measurement equipment faces four primary challenges: withstand bottom hole vibrations, operate at high-pressures and high-temperatures, deliver high-quality results, and provide reliability with low redundancy. Rheonics presents a technology package including the DV sensor and electronics to enable density and viscosity measurements in logging-while-drilling, measurement-while-drilling, and wireline tools. The DV sensor uses a patented torsional balanced resonator operational principle to provide the real-time density and viscosity measurements in less than two seconds. No case studies of the implementation of a DV sensor during drilling operations are available during the elaboration of this thesis. (Dash 2019b)

Roxar

As part of the Emerson Electric Company, Roxar provides products and solutions for the oil and gas industry. The Roxar technology covers flow metering, corrosion monitoring, downhole monitoring, and production and reservoir management software packages. (Emerson US 2020a)

The downhole monitoring equipment from Roxar provides a variety of transmitters, transducers, and data loggers for the determination and collection of bottom hole pressure and temperature measurements. The Roxar 2600 MVG Multiphase Flow Meter (MPFM) is an inline sensor combining electrical impedance measurements, single high energy gamma for phase fraction determination, and venturi and cross-correlation for velocity evaluation to characterize the multiphase and wet gas fluid flow. (Emerson US 2020b)

Sofraser

Since 1972 the french company Sofraser specializes in viscometry. They deliver in line, at-line, in tank, and on line solutions to provide process viscometry to many diverse industries. For the oil and gas industry, Sofraser offers a variety of on and in line viscometer products. The majority of the instruments severe in the area of refineries and petrochemical applications, but they also provide a downhole viscometer, the so-called Sofeat. (sofraser 2020a)

The Sofeat enables to measure density and viscosity at high pressure and high temperature during drilling operations. Measurement-while-drilling and logging-while-drilling tools accommodate the compact and robust sensor to facilitate in-situ measurements. Unfortunately, to the date of this thesis, no case studies of the Sofeat sensor were available. (sofraser 2020b)

Summary

The above-listed products describe sensors to measure the viscosity and density of liquids. The primary focus of the associated companies lies within the food and beverage, the pharmaceutical, and the coatings industry. Still, they transform their expertise about testing instruments onto the petroleum industry. Table 4 visualizes the summary of the described sensors and presents the essential data.

The described RheoLabQC from Anton Paar is similar to the automated rheometers (RheoVADR and iX77) from the Fann Instrument Company. The measurement methodology requires manual sample preparation and provides automation of the predefined analysis procedure. The publically available information does not state accordance with the API and ISO standards for drilling fluids, and thus explains the rare mention in the petroleum industry. (Fann Instrument Company 2020e, 2020f; Anton Paar 2020d)

The significant advantages of the inline process density meter from Anton Paar (L-Dens 7000 series) are the easy installation and that the device requires no maintenance as there are no consumable parts. The downsides are that the oscillating u-tube technology could be error-prone for the complex drilling fluids, that the installation within an open flow line affects the measurement results, and most importantly, that the device restricts the flowrate with 100 to 500 liters per hour, what converts to 0.44 to 2.2 gallons per minute. The L-Vis 510 and 520 Ex inline viscometers from Anton Paar have similar disadvantages as the narrow aperture necessary for the measurement technique appears to be error-prone for particles to plug it. The publically available information does not provide a range for the recommended flow rate, and the installation of this device in an open flow line is also questionable. Therefore, the possible areas of application would be to evaluate the viscosity within stirred tanks or bypass lines. (Anton Paar 2020b, 2020c)

Different from the Anton Paar devices, Rheonics distributes the SRD sensor that overcomes some measurement drawbacks and enables monitoring of the density and viscosity after the choke manifold, before and after the shale shakers, and before the mud pumps. The other two sensor types from Rheonics, the DVM and the DV, claim to measure density and viscosity in real-time at the surface and downhole, respectively.

However, the DVM appears to be primarily for PVT analysis, and the device operates in a batch sampling mode, which makes the stated measurement frequency questionable. (Dash 2018, 2019a; rheonics 2020b, 2020c)

The DV sensor from Rheonics and the Sofeat sensor from Sofraser promise similar results as they both declare operationality within downhole tools such as measurement-while-drilling devices. The DV sensor utilizes a torsional resonator, which is the same measurement technique as the DVM sensor from Rheonics uses. This methodology requires to immerse the sensor in the drilling fluid and makes it questionable how this measurement operates downhole. Further, it is not clear if the applied magnetic field affects the other downhole tools. The described Sofeat sensor from Sofraser differs within the measurement technique as it is a vibrating device driven by an electrical current. It is also not clear how the installation of the apparatus within the bottom-hole-assembly takes place as it appears that the senors also requires immersion in the drilling fluid. Both companies do not present any field application and case studies which specify the behavior of the sensor during drilling operations. However, the general concept of these sensors is promising for future applications. (Ochoa et al. 2014; Dash 2019b; sofraser 2020b)

The presented Roxar 2600 MPFM is not capable of determining the density and viscosity of a drilling fluid. This inline process device accurately characterizes the flow behavior of liquids, and the production optimization together with well testing are the usual areas of application. However, the technique is reliable, and the apparatus could serve as a counterpart to Coriolis flowmeters. (Emerson US 2020b)

Company	Product	Measurement	Frequency
Anton Paar	RheoLabQC	Rheology	Semi-automated
	L-dens 7000	Density	N/A
	L-Vis 510 & 520 Ex	Rheology	N/A
Rheonics	DVM	Density, Viscosity, Temperature	< 2 sec
	DV	Density, Viscosity	< 2 sec
	SRD	Density, Viscosity	Real-time
Roxar	Roxar 2600 MPFM	Flow Regime	Real-time
Sofraser	Sofeat	Density, Viscosity	Real-time

Table 4 Summary of real-time mud monitoring sensors (derived from Dash 2018, 2019a, 2019b; sofraser 2020b; Anton Paar 2020b, 2020c, 2020d; Emerson US 2020b; rheonics 2020b, 2020c

3.5 Drilling Fluid Mathematical Models

The implementation of hydraulic models to simulate and visualize the behavior of drilling fluids is imperative in the planning phase as well as in real-time during the drilling operations. There is a multitude of mathematical hydraulic models that differ in complexity, area of application, and required computing power.

The research contributions of Swanson, Rommetveit and Bjorkevoll (Swanson et al. 1991; Rommetveit and Bjorkevoll 1997; Swanson et al. 1997) mark the inception of mathematical drilling mud models, which implement the newly available data from rig sensors to predict and simulate the fluid behavior in the wellbore. The advanced technical possibilities arising at the beginning of the twenty-first century enabled more precise hydraulic models (Zamora and Roy 2000). Further, the ongoing research (Herzhaft et al. 2001; Zamora et al. 2005) shows the focus to implement the pressure and temperature influence on the drilling fluid rheology into the models and to apply it with managed-pressure drilling operations (Gravdal et al. 2005; Syltoy et al. 2008).

The successful continuous development of hydraulic models contains the establishment of advanced flow models (Petersen et al. 2008), the utilization of new data filter methodologies (Lohne et al. 2008), and the implementation of real-time and historical data by artificial intelligence (Holdaway 2010; Bjørkevoll et al. 2015; Elkatatny 2016). The more effective computing power enables the processing of the sensor data, as well as to fill the gaps between sensor measurements.

The petroleum industry creates an enormous amount of data within each step of the overall value chain. Furthermore, every produced data affects and helps to optimize related exploration, reservoir engineering, drilling, and production operations. The utilization of artificial intelligence (AI) supports to manage the big databases with implementing a learning manner to establish the relationships between input and output data. The artificial intelligence categorizes into five primary techniques: artificial neural networks (ANN), support vector machines (SVM), fuzzy interference systems, neuro-fuzzy, and ensemble models. (Agwu et al. 2018; Nagy and Hajrizi 2018; Barbosa et al. 2019)

Various research studies develop artificial intelligence techniques for reservoir and production applications (Lim and Kim 2004; Elkatatny et al. 2018) and also implement artificial intelligence to optimize drilling operations in real-time (Elkatatny et al. 2017; Elkatatny and Mahmoud 2017; Kamel et al. 2018). The work of Alsabaa et al. presents a model that uses artificial intelligence to solve the problems associated with manual mud testing and provides predictions of the drilling fluid's rheological properties in higher frequency. The prediction model uses the adaptive neuro-fuzzy interference system (ANIFS) technique to predict the plastic viscosity, yield point, flow behavior indices, viscometer readings at 300 and 600 rotations per minute, and apparent viscosity of the drilling fluid. The real-time prediction only needs two inputs as training data, the mud weight, and the Marsh funnel viscosity. (Alsabaa et al. 2020)

This approach from Alsabaa et al. shows another option to overcome the bottleneck of the timely manual mud check and the most recent advancements in the automation of hydraulic models. On the other hand, the possible development to combine such models with automated mud management systems enables further reliability of the real-time drilling fluid monitoring. (Alsabaa et al. 2020)

3.6 Automatic Mud Treatment Systems

The process to mix a new mud for the next section, to prepare a mud pill, or to include additional additives to the active mud system to maintain the desired mud parameters is already a semi-automatic application at most drilling rigs. The mud engineer analyses the drilling fluid measurement data and takes the required actions via a computer to open or close individual valves for liquid supplements or initiate the supply of an additive with the hopper system.

The continuous development of automated drilling mud measurement systems (Section 3.3), together with the improvement in hydraulic models (Section 3.5), enables to automate the drilling mud treatment process further. The main limitations of a fully autonomous mud mixing system are the precise drilling fluid measurement data, the reliable computer model which delivers the required treatment supplements, and the actions in case of failure (Kvame et al. 2011). A failure within such an autonomous mud mixing process still requires an operator at the rig, and thus, no significant advancement compared to a semi-automatic system. Besides the real-time density and rheology data, the computer model determining the required additives needs additional continuous measurement data such as pH, particle size distribution, and electrical stability.

The possibility to apply automated mud mixing to new drilling techniques such as managed pressure drilling (Gunnerod et al. 2009; Godhavn et al. 2011) and the improvement in efficiency and reduction of associated costs (Nafikov and Glomstad 2013) drives the development of automated treatment systems.

The pilot project DEMO2000 from 2017 contains mud and cuttings monitoring units, a wellbore hydraulic model, and a drilling fluid mixing control system. The executing collaboration includes the companies Huisman, SINTEF Petroleum, Statoil (now Equinor), Cybernetic Drilling Technologies, and Intelligent Mud Solutions. This project shows the combination of state-of-the-art technology to enable a mud management system that enhances managed pressure drilling operations. The hydraulic model receives the measurement data from the monitoring system and defines a density and viscosity setpoint for the mud mixing control unit. The results of this pilot project clearly show the existing possibilities to enhance accuracy and reliability as well as reduce risk and costs by implementing an automated drilling fluid monitoring and mixing system to drilling operations. (El Boubsi et al. 2017)

3.7 Analysis Inference and Recap

The central part of this chapter and the primary objective is the presentation and analysis of the available automated drilling fluid testing systems. Section 3.3 covers this market research. Additionally, in the beginning, section 3.2 describes the traditional manual field tests, and section 3.1 outlines the associated standards for drilling fluid measurements. The chapter ends with the information about density and viscosity sensors from other industries, hydraulic models, and mud treatment systems to enable a comprehensive impression of the drilling fluid measurement process.

The described standards from the American Petroleum Institute (API) and the International Organization of Standardization (ISO) emerged historically and exclusively define the procedures for the manual testing of drilling fluids and their composition. The aspect that these standards are not entirely appropriate for automated monitoring equipment impairs the related development. The inclusion of both standardization organizations for fluid testing is redundant, and the merger of the two definitely would ease and clarify the standardization process. Furthermore, new or updated standards for automated drilling fluids monitoring equipment are necessary.

The market analysis of the drilling fluid monitoring systems shows that the major drilling fluid service companies (Baroid, M-I Swaco) provide an apparatus to complete their product line. Implementing this equipment into a fully automated drilling rig would not be possible, and the data availability is sufficient for current operations but not in real-time. The technology development of OFITE and IMS show promising results to upgrade existing and future drilling rigs with automated mud monitoring systems.

The described viscosity and density sensors display the effort of companies originally from other industries to provide accurate measurement sensors for the drilling industry. The significant drawback of this research is the absence of confirmatory field tests to validate these sensors to be able to withstand the harsh drilling rig environment and providing reliable measurements of the complex drilling fluids.

The sections about the mathematical hydraulic models (Section 3.5) and the automatic mud treatment systems (Section 3.6) serve as an introduction to the topics. The development of computer power, together with the lower experimental costs, drives the development of hydraulic models. The described research activity shows the implementation of artificial intelligence and fuzzy logic to simulate drilling fluid behavior. Still, these models can only serve as an addition to the physical testing of the drilling mud. The introduced achievements to further automize the drilling fluid mixing and treatment process informs about the current development and emphasize the drive of the drilling industry to develop a fully autonomous drilling rig.

The upcoming challenges for developing new and available automated mud monitoring systems are the combination and interoperability with existing field-proven automated drilling rig equipment, and the expansion of the equipment to cover all measurements which the traditional mud check includes.

Chapter 4 RHEOBOT Concept

This chapter provides, based on the research parts of Chapter 1 and Chapter 3, the conceptual approach to design an automated drilling fluid testing system. The first part describes the associated concept process, with the essential included steps. The next sections present the summary of this development progress in the form of a concept map and the generated conceptual ideas resulting from it. The closure of this chapter outlines the final RHEOBOT concept.

Therefore, this chapter obtains the objective of the thesis to present the concept of an automated modular drilling fluid measurement system. This concept design, together with the preceding research, serves as a profound basis for future research and associated experimental studies.

4.1 Conceptual Process

This section presents the approach and the progress of developing the RHEOBOT concept. Figure 23 visualizes the structure of the conceptual process and displays the included progress steps with the essential results and statements.

The initial impetus of this thesis comes from the drawbacks of the still commonly conducted manual drilling fluid tests. The incorporated problems define the first step of the conceptual design approach. The main issues are the low mud check frequency, the poor quality of the manual testing accuracy and reliability, and the human exposure to hazards. These problems further lead to the disadvantages of late operational decisions and are a limiting factor for critical applications such as managed pressure drilling and dual gradient drilling.

The second progress step is the execution of intensive scientific research, and the first chapter covers it in detail. This analysis part enables a holistic picture of automation development throughout the entire drilling industry. The historical study shows how the drilling industry implemented different drilling fluid measurements. One of the key findings is that many advanced automation possibilities and theories exist, but the conservative industry impairs the implementation dramatically. The research shows that the drawbacks of drilling fluid monitoring are often a limiting factor for critical operations. Furthermore, the scientific investigation reveals a substantial increase in new inventions with the improvements in computational systems and the related performance.

The universal market analysis completes the overall research bundle and defines the third step of the conceptual design process. Chapter 3 covers this research part in detail. The first part emphasizes the demand for the update or implementation of a new standard for automated equipment regarding the testing of drilling fluids. The central sections show that most existing monitoring systems and sensors work sufficiently, but need improvements to support real-time decisions. The closure of Chapter 3 shows the advanced development of recent hydraulic models, which arises from the lower costs for research and pilot tests, compared to the implementation of equipment.

The next process phase of the conceptual approach executes the evaluation of the design criteria for the RHEOBOT system, and section 4.2 presents it in detail. The first part introduces the recently implemented collaboration to define an automation roadmap for the drilling industry. The key findings of the associated guidelines, relevant for the conceptual approach, are the demand for interoperability of data transfer protocols, the sensor and instrumentation needs, and the ternary relationship between human engagement, automation level, and remote control. The second part of section 4.2 presents the elaboration of the design criteria as it covers the principal sensor quality requirements, the property specific demands, and the rig integration.

The concept map is the final result of the sixth process step but already starts during the preceding phases, as every relevant research point marks a concept bubble at the map. At this stage, the conceptual approach also integrates several discussions and brainstorming sessions with colleagues from the industry into the previous findings. This process step serves to collect, structure, and connect the wealth of information. The concept map identifies hidden connections, the most significant influencers, and highlights the essential criteria for elaborating concept ideas.

As already mentioned, the process step number seven is the elaboration and formulation of concept theories. This phase favors a creative and outside the box thinking to overcome the conservative approach of the industry and to create numerous possible visions. The ideas described in section 4.4 cover a more realistic and practical approach, a probable technique if the required technology is functioning and available, and a concept vision to set the bar for future inventions.

The final process phase for this thesis of the conceptual process is defining the concept decision for the RHEOBOT system. This progress step compares and examines the different generated conceptual ideas to determine the system that can realize the objectives of the thesis.

The process actions nine and ten illustrated in Figure 23 show the general approach to connect the conceptual design with the prototype to complete the development of the system. These steps serve as a guideline, mark the upcoming tasks, and are the subject for future research work.

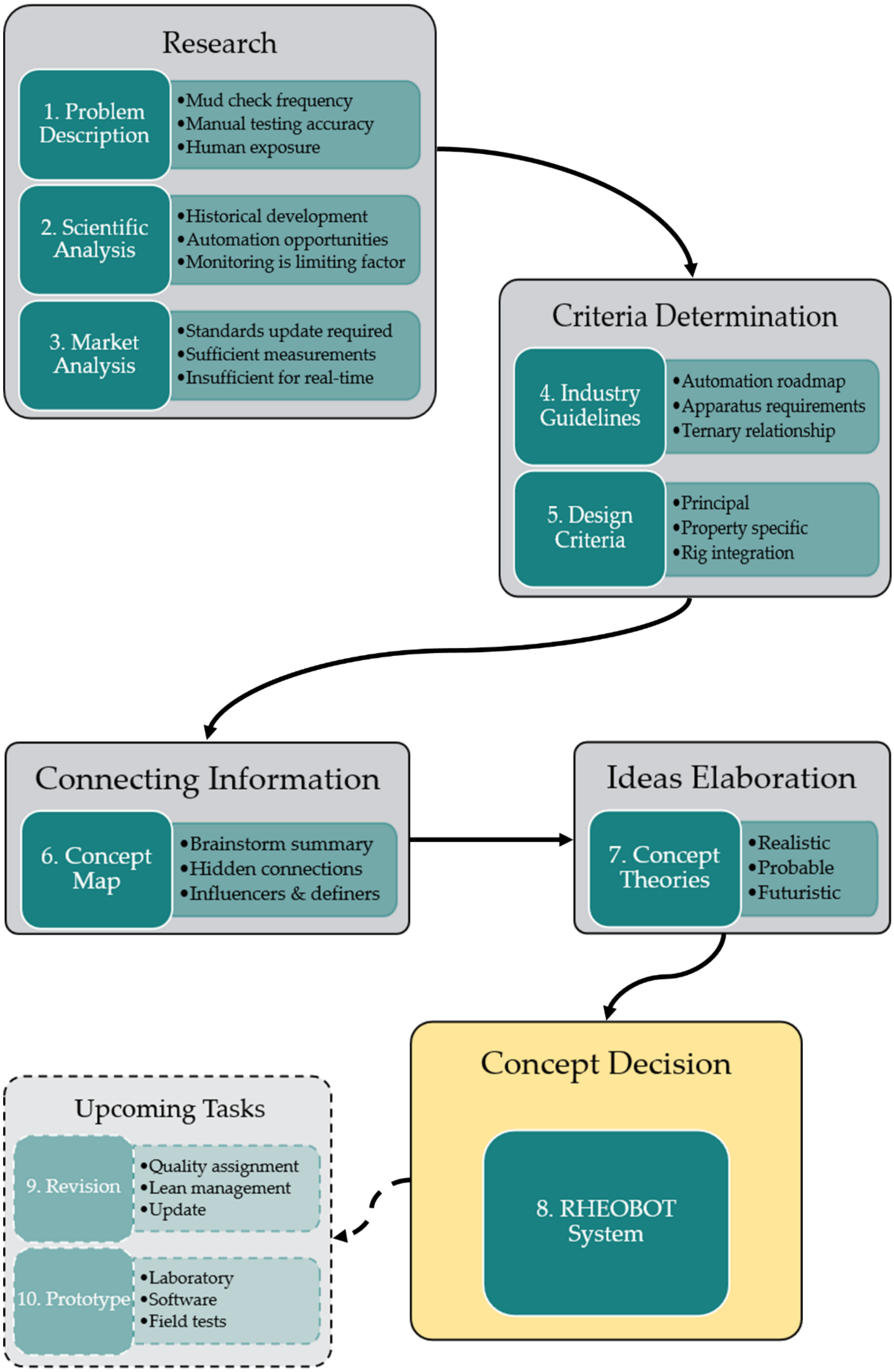

Figure 23: Overview of the conceptual design process

4.2 Determination of Design Criteria

This section outlines the specific design criteria mandatory for the RHEOBOT system to implement. The determination process operates with four categories: the adaption of automation guidelines evaluated by the drilling industry, the principal design criteria, the measurement specific criteria, and the rig integration criteria.

Figure 24 provides an overview of the individual design benchmarks. The subsequent sections describe the elaboration and the reason behind these criteria in more detail.

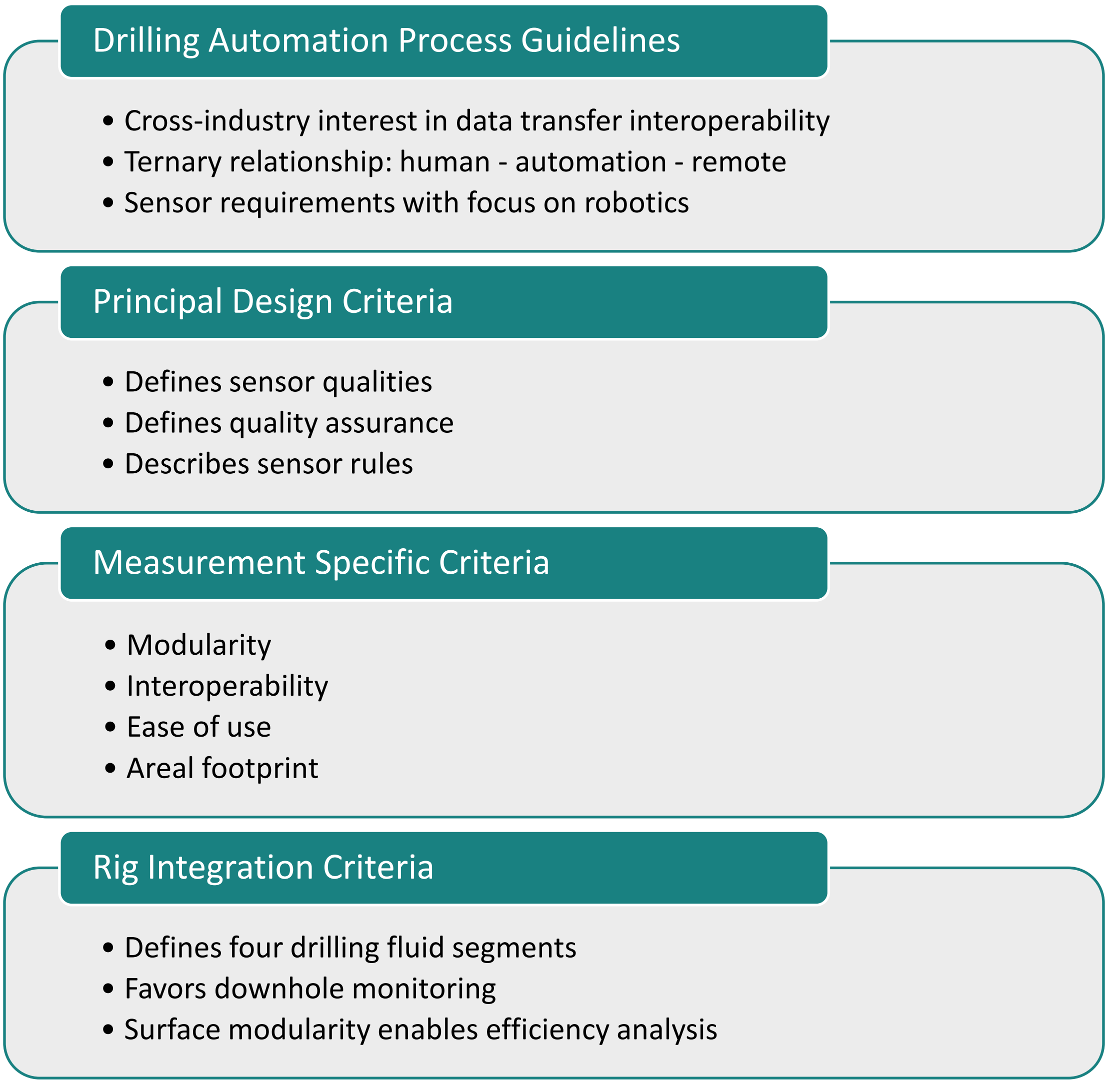

Figure 24: Overview of the determined significant design criteria

4.2.1 Drilling Automation Process Guidelines

The inception of this thesis to evaluate an automated drilling fluid measurement system arises from the general initiative of the drilling industry to automate the drilling operations and create a fully autonomous drilling rig. The first step of the design criteria determination examines the industry committees enhancing drilling automation development.

This part of the conceptual procedure is essential to combine the results from the research about the automation of drilling fluid monitoring with the current view and drive of the drilling industry regarding automation in general. The adaption of the industry guidelines, emerging from these committees, helps to understand the numerous connections between the different components of automated equipment. Further, this process step enhances the understanding of the current limitations and reduces repetitive research to avoid redundancy.

The following multi-faceted committees currently lead the development efforts of the upstream oil and gas industry to industrialize the drilling operations through advancements in drilling process automation:

- Society of Petroleum Engineers Drilling System Automation Technical Section (SPE DSATS)
- International Association of Drilling Contractors Advanced Rig Technology Committee (IADC ART)
- Operators Group on Data Quality (OGDQ)
- Norwegian Global Center of Expertise (GCE) Node
- Norwegian Research Conglomerate (NORCE) (previously International Research Institute of Stavanger IRIS)
- University of Texas Rig Automation & Performance Improvement in Drilling (RAPID)Program

In June 2013, the industry formed the cross-expertise committee Drilling System Automation Roadmap (DSA-R), as an initiative to roadmap the adoption of advancements in drilling systems automation. This workgroup combines experts from the committees, as mentioned earlier, defines the necessary steps to achieve the vision of drilling automation, and presents the current state and the way forward in the DSA-R report. (Geehan and Zamora 2010; de Wardt et al. 2015; de Wardt 2020a, 2020b)

This controlled technology roadmap defines a standard automation language, suitable interface and communication protocols, the implementation of a systems architecture, the sensors and instrumentation needs, the machines and equipment capabilities, and the guidance to common control systems. Further, the DSA-R report provides sections about modeling and simulation, human systems integration, standards and certifications, and contingency management to navigate the drilling automation efforts. (Geehan and Zamora 2010; de Wardt 2020b)

The conceptual design approach of this thesis uses the shared goals from the drilling industry stated in the DSA-R report, as the fundamental principals. Further, parts of the concept goals of the RHEOBOT system arise from the design-aid framework illustrated in **Figure 25**, **Figure 26**, **Figure 27**, and **Figure 28**. The work of Zamora and Hildebrand introduces this ternary chart, which generally describes physical systems with three components, to evaluate individual automation aspirations and implements it to the drilling automation roadmap. The ternary diagram specifies three primary drilling automation components: rig site manpower, automated rig equipment, and remote connectivity (see **Figure 25** and **Figure 26**). This relationship approach is opposite to the commonly used binary attempt, which describes levels of automation regarding the computer and human interfaces. (Zamora and Hildebrand 2013)

With the emergence of the DSA-R committee, Zamora and Geehan presented an update of the previously introduced ternary chart to guide the efforts of drilling automation development. The research divides the drilling domain into six sub-segments and determines the current and possible future state of development (see **Figure 27**). Besides the individual advantages of each automation component, the most success comes with the right balance between all three of them. Looking at the current state, the sub-segments with the highest level of human workforce engagement and low remote monitoring are the solids control and the fluids treatment and pumping (see **Figure 28**). The research emphasizes that the workforce level for all drilling operations commutes between 15 and 30%. (Zamora and Geehan 2013)

It is imperative for future developments, whether the automated instruments or the remote operability takes the central function and related responsibility. The current drilling automation efforts (see Chapter 1 and Chapter 3) clearly show a tendency towards automated equipment. This trend suggests that the industry prefers high-cost investments to develop robotics and shows concerns to related communication reliability. Therefore, the approach for the concept of this thesis focusses on the use of automatic devices.

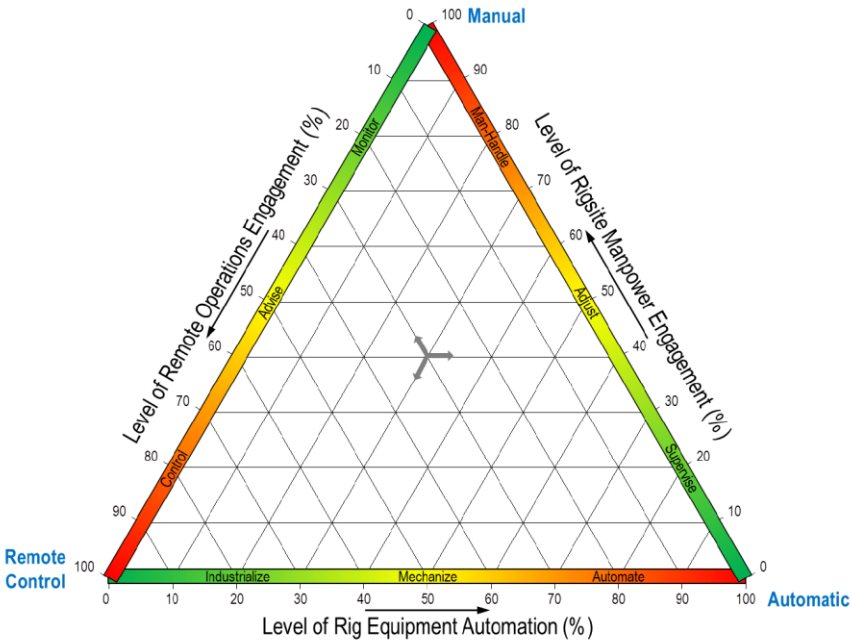

Figure 25: Framework for drilling systems automation ternary design chart. (Zamora and Hildebrand 2013)

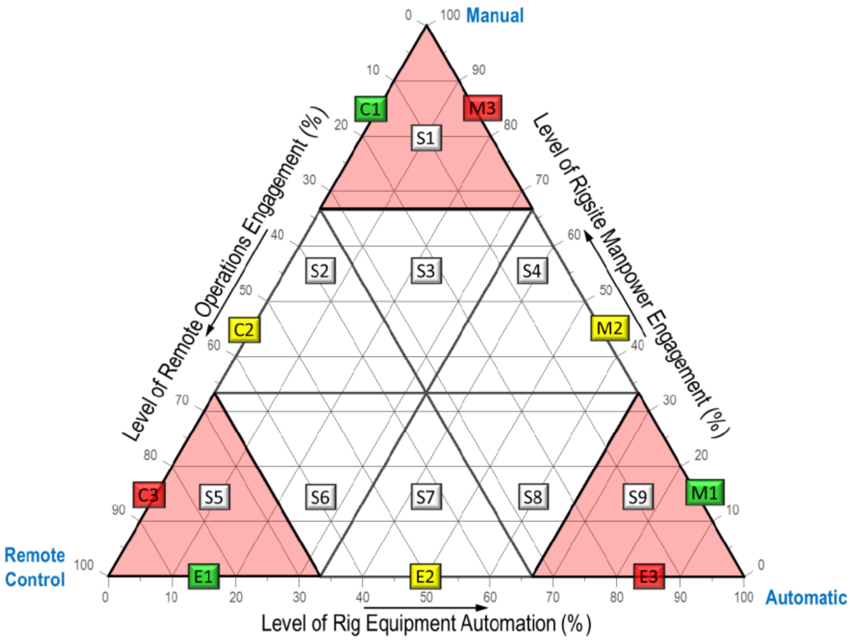

Figure 26: Drilling systems automation ternary chart subdivided into nine taxonomy segments and nine binary segments. (Zamora and Hildebrand 2013)

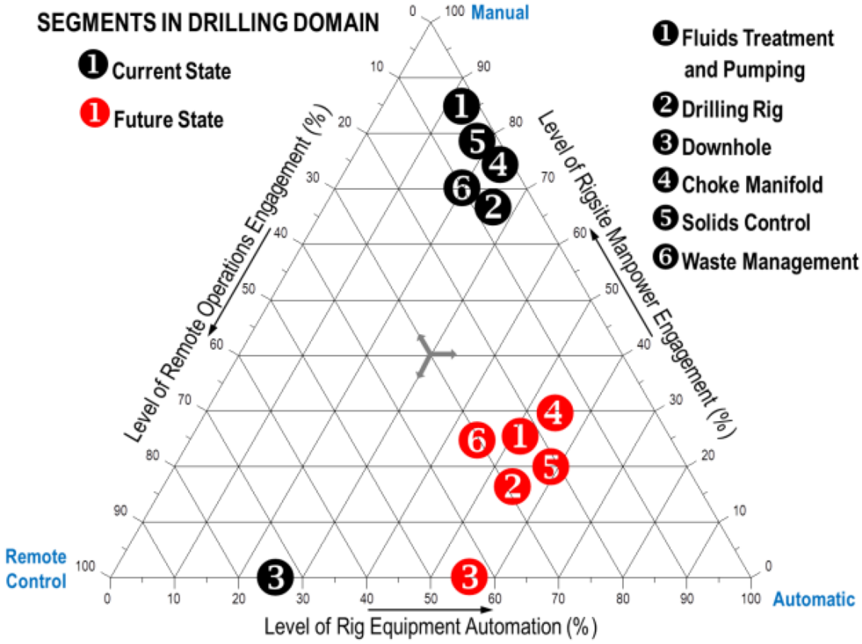

Figure 27: Current and Future States for the six drilling domain segments. (Zamora and Geehan 2013)

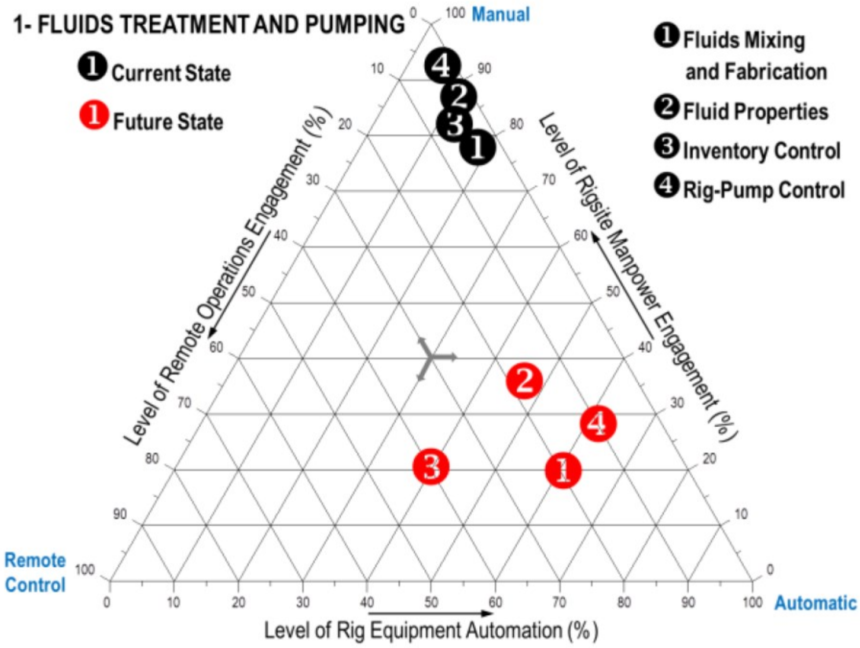

Figure 28: Current and Future States for fluids treatment and pumping systems. (Zamora and Geehan 2013)

4.2.2 Principal Design Criteria

This section specifies the summary of the quality and design aspects demanded by the drilling industry (see Chapter 1). Further, it provides the design criteria, which were the nucleus during the brainstorming part of this thesis conceptual design, and define the decisive principle criteria of the RHEOBOT concept.

The characteristically high aversion against risk and the conservative thinking of the drilling industry leads to a restricted adoption of new technological applications and changes within trusted operational processes. The acceptance of new equipment prescribes several criteria. The following five leading design criteria are mandatory for implementation to provide continuous quality assurance of the automated system:

- Practicality
- Sensibility
- Precision
- Usefulness
- Responsiveness

Further, it is imperative to provide reliable calibration and function testing for a measurement device to enable ongoing accuracy. The functionality of the drilling fluid testing equipment is fundamental for save and economical drilling operations and the accuracy and reliability of the measurement data. (Geraghty and Motley 1992; de Wardt 2020b)

Further demanded requirements are that the measurement results are available in field units and comparable to manual testing procedures, and the accuracy at least equal to manual determinations. The equipment should be explosion-proof to operate within zone 1, and the readings must be repeatable, stable, and reliable. The constructional design of the instruments must withstand the harsh environment, enable measurement of all drilling fluid types, and provide easy operations, maintenance, and calibration. Cost and accommodation constraints at the rig site drive the criteria for the equipment to be operated by the rig crew other than special services crews. The new technology must deliver data in a high frequency of less than a minute and provide it via a standard transfer protocol, to enable real-time decisions and conform with state-of-the-art drilling applications. (Miller et al. 2011; de Wardt 2020b)

The main requirement targets for automated equipment categorizes into four general groups: the certification of the entire device, the operability, the communication ability, and the performance of the implemented sensor. To enable secure and failure-safe automated operations, the users must understand how the instrument derives a measurement and how it affects the automated process. Table 5 shows the related rules which a sensor system must provide to the operator. To assure a certain measurement standard, the sensors within an automated process must fulfill particular qualities (Table 6). (de Wardt 2020b)

The described five quality assurance aspects, together with the rules and qualities for sensors, serve as the principal design criteria within the conceptual design approach.

	Rule	Description
1	Completeness	The system must provide sufficient information that the user can evaluate the full state of the system.
2	Logic Determination	The information must be clear to enable the user to choose the correct sensor as a function of the system state.
3	Proximity	The sensor must assess the measurement as closely and directly to the required parameter as possible. The proximity categorizes in descending order four types: direct, transposed, derived, and estimated.
4	Accuracy	The equipment must provide sufficient information to enable the assessment of the accuracy of the sensor.
5	Conversion	The system must enable to change the measurement if required, or provide another sensor if it is physically not possible.
6	Criticality	The system must assure the redundancy of critical measurements.
7	Availability	The sensor measurement must fulfill the requirements of the most demanding process it serves. The availability defines the probability of a sensor to fail versus the duration of the interruption. The defining terms of applications, from the most to least critical, are closed-loop control, supervisory control, diagnostics, and archival.

Table 5 Rules for sensors of automated equipment (de Wardt 2020b)

	Quality	Description
1	Precision	This quality defines the reproducibility and repeatability of the digital data output at the end of the measurement.
2	Accuracy	The accuracy specifies how close the measured data is, compared to the real value.
3	Latency	The latency types of a sensor are fixed, variable, or non-deterministic and define the time delay between the measurement point and when the operator uses the data.
4	Calibration	The quality of calibration defines through the calibration interval, the examination place, and the required method.
5	Validity	The system must enable to detect of invalid measurements of a sensor and provide the related diagnostic methods.

Table 6 Quality requirements of sensors for automated equipment (de Wardt 2020b)

4.2.3 Drilling Fluid Measurement Criteria

This section defines the criteria for the measurement instruments of the concept approach regarding the required properties in more detail.

The traditional full mud check includes several manual field measurements, as Section 3.2 explains. To find a solution that automates all of them with just one piece of equipment that takes only one measure is not realistic or possible. Therefore, the measurement criteria of the RHEOBOT system incorporates the demands, criticality, and significance of each measurement to find the optimum sensor technique. This benchmark is in accordance with the results of the literature research (Chapter 1) and the principal design criteria (Section 4.2.2).

The operating principle of the investigated equipment serves as another distinguishing feature within the concept approach. The design criteria of proximity (Table 5) suggest inline devices over offline measurement tools. However, the favored benchmark for operability, maintenance, calibration, replacement, and the associated ease of use promotes offline instruments. The conceptual approach of the RHEOBOT considers the criteria of operability more significant to guarantee problem-free drilling activities in case of failure of the measurement equipment. The perception additionally analyses the combination of inline and offline instruments to accomplish a high quality regarding criticality and redundancy.

The concept approach uses the modularity and criticality principle categorizing the complete RHEOBOT system into several measurement packages. The idea of this approach is to make a selection available to the operator regarding the demands of the related drilling operation. Each device should be able to function for itself and also be applicable for integration into the entire RHEOBOT system. The drilling fluid measurements classified during the research (Chapter 1 and Chapter 3) according to their importance after evaluation within the conceptual approach, include the flowrate, the density, the viscosity, the electrical stability, the fluid loss, the liquid and solid fraction, H_2S concentration, pH, and the particle size distribution.

The RHEOBOT concept adopts the design demands as mentioned-above from the industry to assure accordance with the roadmap of the DSA-R committee. However, the chosen measurement instruments for the RHEOBOT concept additionally implement the following decisive criteria:

- Modularity
- Interoperability
- Ease of use
- Areal footprint

These supplementary design criteria do not function as a recommendation for implementation into the DSA-R roadmap. The primary objective is to enable a more precise evaluation of the numerous options of available sensors and possible measurement techniques (see Chapter 1 and Chapter 3).

4.2.4 Rig Integration Criteria

This section presents the criteria that serve as the basis for the conceptual approach evaluating which measurements apply best, at which point at the rig. The determination of this rig integration criteria emerges in a strong connection from the principal design criteria (section 4.2.2) and the drilling fluid measurement criteria (section 4.2.3).

The conceptual approach categorizes the drilling fluids system, with the guidance of the research of Geehan and Zamora, into four segments: downhole, solids control, fluids treatment and pumping, and waste management (**Figure 29**). The total drilling fluid system is an open domain with a not constant mass of material, due to the emerging and separated drilled cuttings, and an alternating liquid composition, because of formation fluids entering and drilling fluids infiltrating the surrounding formations. During drilling operations, approximately fifty percent of the total drilling mud volume resides in the downhole segment, ten percent in the solids control segment, and forty percent in the fluid treatment and pumping segment. The typical average residence time for the drilling fluid is fifteen to sixty minutes within the solids control segment and approximately two to five hours in the entire downhole part. (Geehan and Zamora 2010)

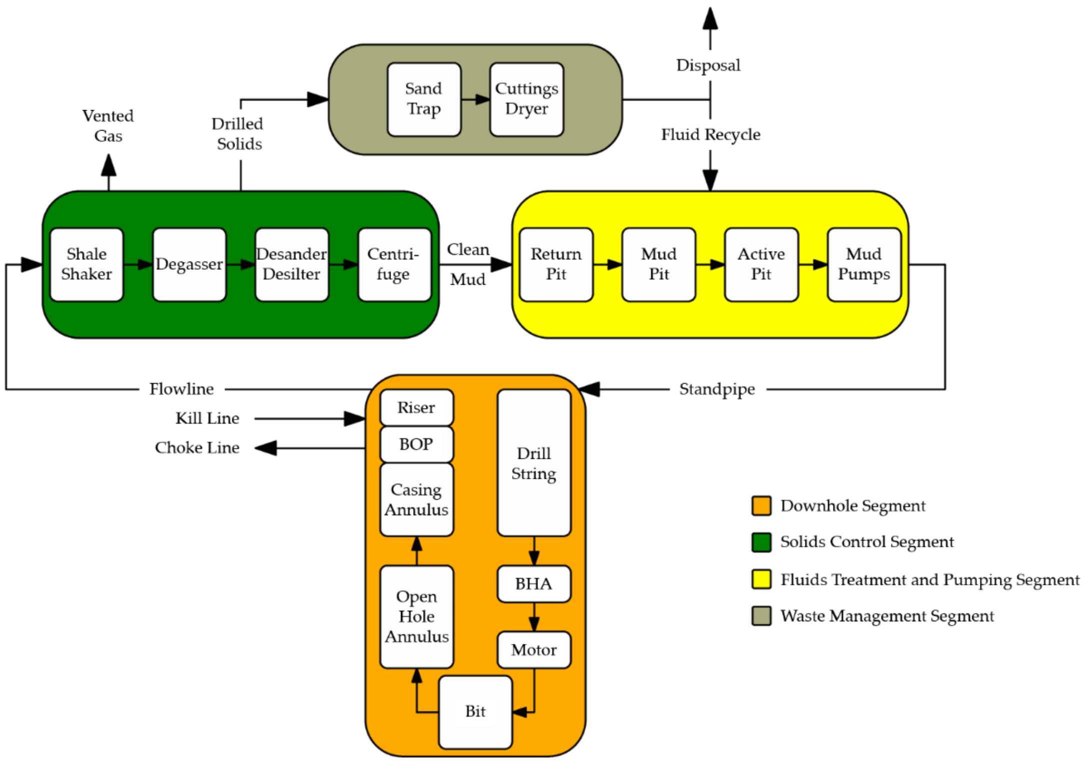

Figure 29: Drilling fluids system with the four categories and the associated equipment inside the individual drilling fluid segments. (derived from Geehan and Zamora 2010)

Section 2.4 describes the individual pieces of equipment of the four drilling fluid segments in more detail, and **Figure 14** shows the standard points for taking the fluid samples for the mud check. The typical measurement points emerged historically, to reduce the exposure of the human operator, and to avoid the drilled solids altering the analysis. The conceptual approach of the RHEOBOT system includes the criteria to evaluate the possibilities of downhole measurements. Further, the rig integration concept combines with the modularity concept to also enable measures between the individual surface equipment to monitor their performance.

The above elaboration summarizes with the following rig integration criteria and integration focus areas for the conceptual approach:

- Definition of four drilling fluid segments
- Focus on achieving downhole monitoring
- Emphasize on surface modularity

The criteria to divide the drilling mud conduit and the definition of the four segments of the drilling fluid system shall enable the evaluation of special equipment individually designed for the respective category. The benchmark to focus on downhole monitoring serves as an emphasis to achieve the ultimate goal to enable the most accurate determination of in-situ drilling fluid properties. The current lack of real-time downhole knowledge impairs the simulation models, and thus improvement is essential. The third rig integration criterion picks up the modularity principle from the previous section with the intention to highlight the opportunity monitoring between the different pieces of equipment. This method enables a performance analysis of the individual instruments, thus serves as a useful combination for monitoring the automated equipment and provides a continuous quality assignment.

4.3 Concept Map

The concluding part of the RHEOBOT concept elaboration combines the results of the literature and market research (Chapter 1 and Chapter 3) with the industry guidelines for drilling automation (Section 4.2.1), the developed design criteria (Sections 4.2.2, 4.2.3, and 4.2.4), and the results of several brainstorming sessions. The conceptual approach of this thesis utilizes a mind map or concept map (Figure 30) to structure this accumulated wealth of information and connect the ideas to the central concept and the initial problem description.

Figure 30 shows the mind map from the conceptual design elaboration. The red figure indicates the initial limitation, and the green circle illustrates the proposed solution. This solution further separates into blue bubbles, which indicate a component of the entire system. The individual component bubbles connect through cross-links and linking words to establish a meaningful relationship. The yellow figures symbolize the criteria decisive for the overall conceptual design.

This step is an essential part of the conceptual approach as it brings together all aspects influencing the development of the RHEOBOT system. The elaborated concept map supports identifying the incorporated connections and is the essential basis for the subsequently presented ideas and theories for the RHEOBOT concept.

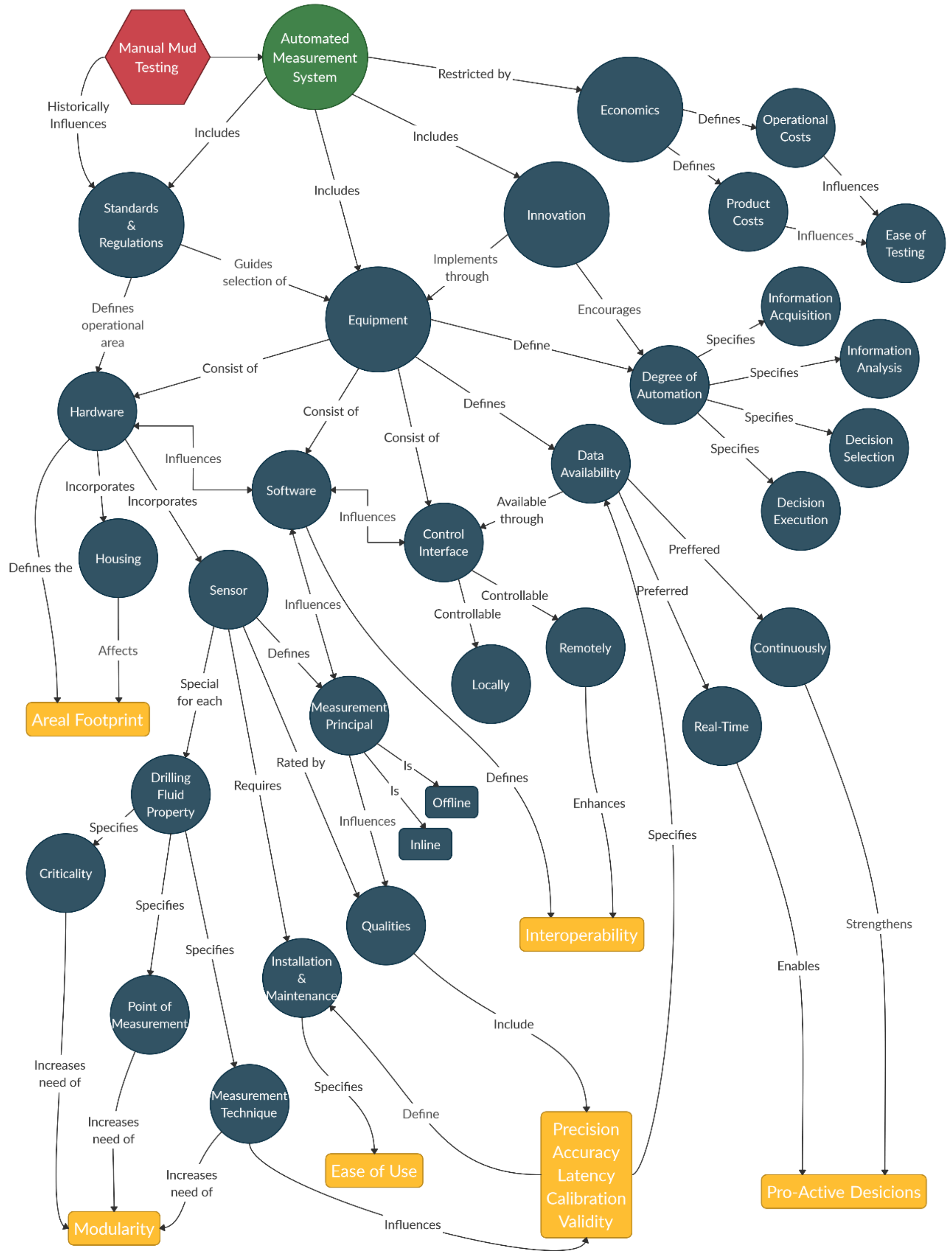

Figure 30: Concept map of the RHEOBOT approach

4.4 Generated Conceptual Ideas

This section is the seventh step of the conceptual design process and describes the three primary concept theories. These hypotheses emerge from the learnings of the research parts and the design criteria. However, it is important to mention that the subsequently described concepts are ideas with the intention to bring the most significant benefits for an automated drilling rig. The below-presented theories do not follow the norm as they do not primarily implement the aspects of cost constraints and technical limitations.

This methodology to develop various conceptual ideas without thinking of boundaries is essential for a design concept to step out of the conventional borders. **Figure 31** illustrates the three conceptual hypotheses within the previously presented ternary chart. The dashed faded area around the number placement symbolizes the probability area of the position. Number one marks the first idea's position and suggests 30% human engagement, 20% remote control, and 50% automation level. The second and third concept theories propose a ternary relationship of 20 – 40 – 40 and 5 – 5 – 90, respectively.

The subsequent sections describe the three concept ideas in more detail and explain the driving ideas behind it.

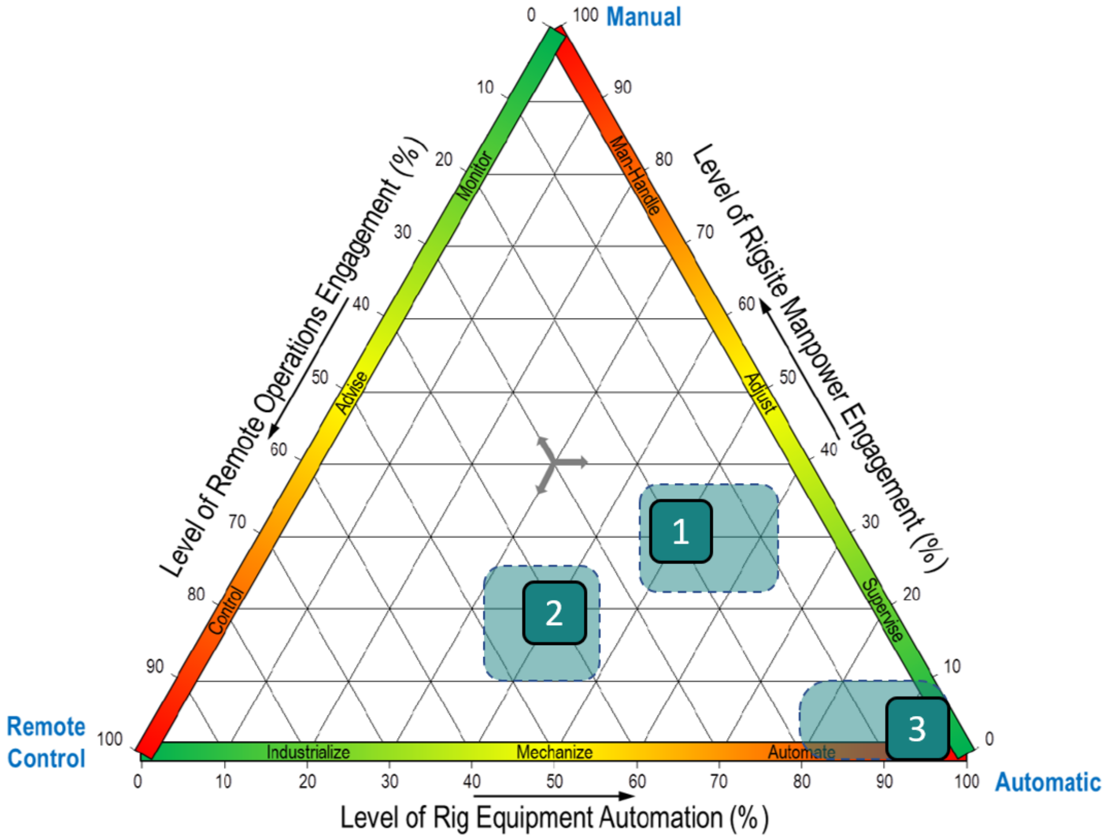

Figure 31: Position of the three concept ideas in the ternary design chart. (adapted from Zamora and Hildebrand 2013)

4.4.1 Realistic – Automated modular surface monitors

The first theory from the conceptual approach consists of surface measurement applications. The current state of available measurement techniques and sensors and the ease of testing these applications clearly give the preference to automated measurement equipment at the surface. The results of the research, together with the outcome of the concept design approach, specify the flowrate, density, and viscosity measurements of the drilling fluid as most significant for the overall drilling process. Furthermore, the concept integrates devices to measure the electrical stability, the fluid loss, the liquid and solid concentration, the cuttings quantity, and the particle size distribution.

The first device within the modular surface concept is the Coriolis flow meter. This instrument overcomes the problematic issues of the classic flow paddle, the magnetic flowmeter, and the pit volume totalizer. This theoretical system facilitates two Coriolis flow meters, one inline between the suction tank and the mud pumps and the second one at the return line. This setup enables to evaluate the drilling fluid entering the well and monitoring the returning flow together with metering the cumulative mass of cuttings. The implementation of these two sensors provide real-time data and helps to solve drilling problems such as quantifying hole-cleaning efficiency, early kick detection, or monitoring the circulating bottoms-up. (Reitsma 2010; Vikram A. Kolhe and Ravindra L. Edlabadkar 2016)

The next piece of equipment implemented within this concept option is the pipe rheometer. The measurement principle measures the differential pressure on a vertical and a horizontal pipe segment. The vertical section serves to determine the density and the frictional pressure drop of the drilling fluid, and the horizontal part delivers further data about the frictional pressure drop. The instrument incorporates a pump that supplies the pipe rheometer with adjustable fluid flow. The combination of the differential pressure measurements with the information about the mud velocity enables to evaluate the rheology and density profile of the drilling fluid. The offline operational method of this device allows for the installation of one instrument to monitor the inflow parameters at the suction pit, and a second instrument is tracking the return properties after the shale shakers. (Taugbøl et al. 2019; IMS - Intelligent Mud Solutions 2020b)

The automated electrical stability meter, the automated fluid loss system, and the liquid particle analyzer together make up the second package of the concept option. All three measurement devices operate with a bypass sampling system directly after the shale shakers or the shaker pit. The automated electrical stability meter utilizes the same operating principle as the manual type explained in section 3.2.12 and uses a batch mode sampling. The design of the automated fluid loss system emerges from the conventional high-temperature high-pressure fluid loss cell but operates autonomously and delivers fluid loss properties in discrete real-time intervals. This apparatus also functions with a batch sampling mode, and the incorporated automated backflushing ability enables repetitive measurements according to API standards. The liquid particle analyzer operates in a batch sampling mode, and the system supplies the device with constant volumes of drilling fluid samples. This instrument utilizes a full-frame photo imaging measurement principle to evaluate the solids within the drilling mud. (T. Allen 1965;

Growcock et al. 1994; T. Allen 1997; Cerni and Seler 2005; Growcock et al. 2007; Saasen et al. 2008)

The next package of the first concept idea includes the cuttings flow meter and the mud solids monitor. The cuttings flow meter operates directly after the shale shakers and weighs the drilled cuttings in a tray. The implementation of this device at each shale shaker enables the determination of the total weight of returned solids. The shale shakers comprise the mud solids monitor, the second apparatus in this package. This device is a field-proven technique and utilizes x-ray fluorescence to determine the concentration of solid and liquid phases. (Houwen et al. 1993; Davison et al. 1996; Naegel et al. 1998; Saasen et al. 2008)

4.4.2 Probable – Full downhole wellbore knowledge

The emerging successful industry efforts of developing data transmission through the drill string serves as the starting point of the second concept option. The idea of transmitting power and data through the drill string originates from 2008, but the related costs hindered the development. Recently the drilling industry introduced several products such as the Powerline Drill String (PDS), the Powered Wired Drill Pipe (DualLink), or the Smart Wired Pipe to enhance the drilling performance. This technology clearly exceeds the classical mud-pulse telemetry, provides a continuous power supply to the downhole equipment, enables high-speed bi-directional data transfer, and implements measurements along the drill string in real-time. (Prammer 2008; Macpherson et al. 2019; Pipeline Oil & Gas Magazine 2020; Silvester et al. 2020; TDE Group 2020; Reelwell AS 2020)

The intention of this concept option incorporates the downhole measurement sensors presented in section 3.4 into the wired drill pipe technology. The measurement devices within the wired drill pipe would additionally implement the downhole density and viscosity sensors. Therefore, the system can evaluate the fluid properties along the drill string, similar to the first concept option.

The advantages of this technology to enable real-time data of the drilling fluid state in the downhole segment clearly correspond with most of the principal design criteria. The concept assimilates inline measurements, no additional footprint in exposed zones at the surface, the identification of downhole alterations enable pro-active decisions at the surface, and the open data transfer of the wired pipe technologies facilitates interoperability. This design enables determining the rheological behavior of the drilling fluid inside the wellbore but does not cover the surface measurement and the entire fluid properties defined with the traditional mud check. Also, this technology can not provide measurement redundancy in case of events that lead to the failure of the equipment. In this case, the associated hydraulic model again relies on the manual surface measurements.

The limited field applications to test and evaluate the downhole sensor technologies lead to yet insufficient knowledge regarding the required maintenance, the endurance of the downhole measurement devices, and their sensor qualities. Further, it is hard to realize this concept in a future laboratory prototype, and many assumptions are necessary to represent the downhole conditions precisely.

4.4.3 Futuristic – Immersed nanoparticle sensors

The third concept idea derives from the vision of how to implement the most innovation in the RHEOBOT system and also how to enable real-time fluid data from the whole circulation conduit. The scientific research shows the successful advancements in the automation of drilling operations and automated fluid measurements in other industries. This concept option implements the identification of exponential improvements in technological capabilities, as described by Moore's Law. (G. E. Moore 1998; Wu et al. 2012)

This concept option differs from the primary aim of the thesis to identify existing measurement instruments but to think about what the continuous technology development enables to offer in thirty years. The concept option includes nanoparticle sensors immersed within the drilling fluid. The intention is that these sensors can measure the desired fluid properties by communicating with each other (**Figure 32**), similar to radio-frequency identification (RFID) transponders. The recent research work of Vryzas et al. shows the approach of implementing smart drilling fluids by using custom-made iron oxide magnetic nanoparticles. The employed particles enable to alter the rheological properties of the drilling fluid, and the scientific paper presents promising results. However, this method of smart drilling fluid does not solve the issues of drilling mud measurements. (Wu et al. 2012; Grinrod et al. 2013; Vryzas et al. 2017)

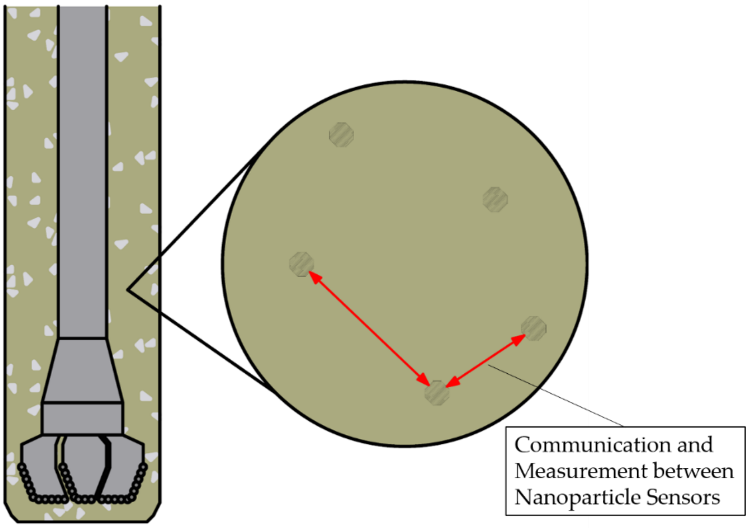

Figure 32: Graphical illustration of nanoparticle sensors for third RHEOBOT idea

The opportunities of the proposed in-situ fluid analysis include the knowledge about the drilling fluid state in every section of the circulation path and the reduction of mechanical equipment prone to failure and maintenance. The constraints of this concept rely on the unknown interaction of the nanoparticles with the drilled solids, the associated changes in the solids control equipment, and the availability of the required technology. However, the thesis presents this option with the intention to answer the question: "Wouldn't it be ridiculous if we did not have this?". (Mui 2017)

4.5 RHEOBOT Concept Decision

This section defines the last step of the presented design process and describes the final concept for the RHEOBOT system. The decision arises and combines the findings of the research parts, the evaluated design requirements of the criteria determination phases, and the theories of the generated concept ideas.

The beginning of the concept elaboration shows a strong desire to implement innovation within the RHEOBOT system, by implementing or inventing undiscovered measurement techniques. However, to fulfill the thesis objective and enable a profound foundation for future research projects with rational and practical aspects, the emphasis of the concept approach shifts more to evaluate possible measurement system combinations.

The first part of the RHEOBOT system includes the surface measurement and the associated devices shown in Table 7. Hereby, the main focus relies on the first three measurement properties because they have the highest criticality regarding drilling operations. Still, the remaining measurements are essential but serve as additional modular options to add to the overall system.

	Measurement	Device
1	Flowrate	Coriolis Flowmeter
2	Density	Pipe Rheometer
3	Viscosity	Pipe Rheometer
4	Electrical Stability	Automated Electrical Stability Meter
5	Fluid Loss	Automated Fluid Loss System
6	Solids Analysis	InFlow Particle Analyzer
7	Cuttings Quantity	Cuttings Flow Meter
8	Solid and Liquid Concentration	Mud Solids Monitor

Table 7 Surface measurement components and the associated monitoring devices of the RHEOBOT system concept

Coriolis Flowmeter

The Coriolis flowmeter consists of a pair of parallel vibrating pipes, a driver unit, and two sensors. The mass flow rate of the drilling fluid flowing through the two parallel tubes deflects them. In the middle between the two pipes, an electromechanical drive unit utilizes the vibrations onto each tube. The particles within the drilling fluid exhibit the same vibrations and result in an induced motion of the particles orthogonal to the direction of flow. This particle motion produces a Coriolis force that deflects the parallel tubes. Suitable sensors measure the deflection and determine the mass flow of the drilling fluid. (Morris and Langari Reza 2020)

The Coriolis flowmeters provide direct and in-line measurements of the mass flow rate with accuracies as high as 0.05% for liquids at flow rates from 5 grams per minute to 350 tonnes per hour. (Crabtree 2020) Further, the mass flow measurement is independent of temperature, pressure, viscosity, conductivity, and density of the drilling fluid. The most significant advantages of Coriolis mass flowmeters are the precise delivery of flow data in real-time and low maintenance. Together with the existing experience of field applications, these benefits clearly outweigh the disadvantage of relatively high costs. Therefore, the Coriolis flowmeter is the choice for the RHEOBOT system to monitor the drilling fluid flowing in and out. The integration of the devices in the rig system is between the bell nipple and the shale shakers to measure the outflow and before the mud pumps to evaluate the inflow, as Figure 40 shows. (Baker 2016; Crabtree 2020; Morris and Langari Reza 2020)

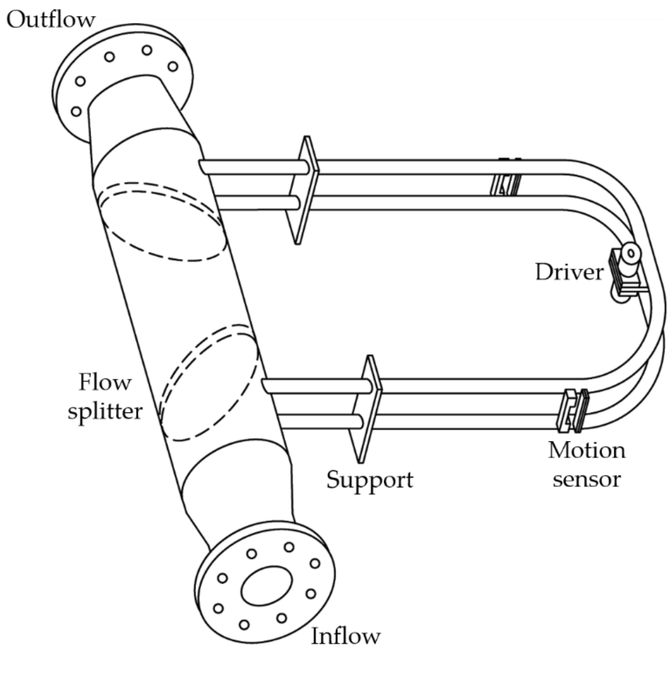

Figure 33: Schematic of Coriolis flowmeter (derived from Anklin et al. 2006)

Pipe Rheometer

The monitoring instrument of choice to observe the drilling fluid's density and rheology is a pipe rheometer. This device uses the method of capillary viscometry as it measures the flow resistance of the drilling fluid through a calibrated channel. The term “capillary” arises from the geometry of the pipes, which have a large length-to-radius ratio. The measurement principle measures the differential pressure on a vertical and a horizontal pipe segment. The vertical section serves to determine the density and the frictional pressure drop of the drilling fluid, and the horizontal part delivers further data about the frictional pressure drop. The instrument incorporates a pump that supplies the pipe rheometer with adjustable fluid flow. The combination of the differential pressure measurements with the information about the mud velocity enables to evaluate the rheology and density profile of the drilling fluid. The offline operational method of this device allows for the installation of one instrument to monitor the inflow parameters at the suction pit, and a second instrument is tracking the return properties after the shale shakers. (Marin et al. 2012; Vicente 2012; Malkin and Isayev 2017; Taugbøl et al. 2019)

The geometrical constraints of pipe rheometers emerge from the length-to-radius ratio and have a negative impact on the areal footprint. Additional drawbacks are the requirement of high accuracy of the circular holes and that the measurement is not direct but needs a bypass line. The significant advantages of the pipe rheometer are the continuous real-time measurements and the possibility to test all kinds of complex drilling fluids. Further, the apparatus incorporates a simple setup with only the pump as a moving part, and therefore, the device requires very few maintenances. (Marin et al. 2012; Malkin and Isayev 2017; IMS - Intelligent Mud Solutions 2020b)

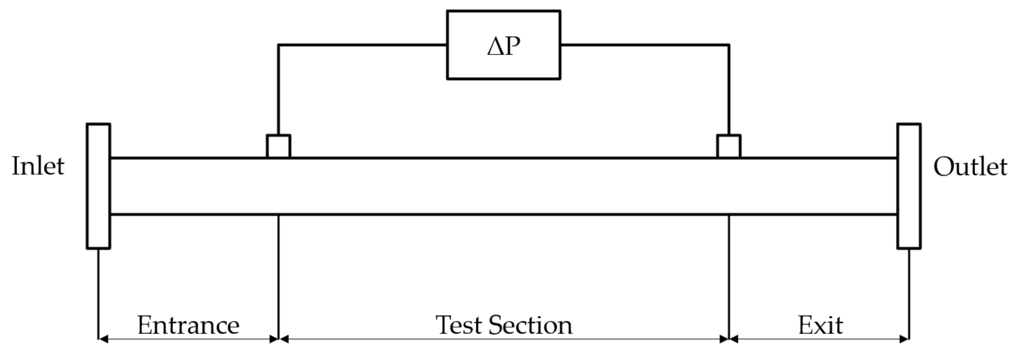

Figure 34: Schematic of pipe rheometer principle (derived from Taugbøl et al. 2019)

Automated Electrical Stability Meter

The automated electrical stability meter measurement principle determines the dielectric breakdown voltage of the invert emulsion fluid between two electrodes. This methodology is similar to the standard electrical stability meter described in subsection 3.2.12, and the design of the automated apparatus also emerges from this standard device. The automatic electrical stability meter consists of an electronic control module, a valve control box, actuated valves, and a probe assembly with a cell and two electrodes 1.5 millimeters apart. This device operates in a batch mode sampling to reduce data error. A by-pass system placed after the shale shakers supplies the automatic electrical stability meter with the drilling fluid samples. Before and after each measurement, the incorporated wiper cleanse the probe assembly automatically. The electronic control module transfers the recorded breakdown voltage to the drilling rig data center in real-time. (Growcock et al. 1994; Growcock et al. 2007)

The influence of the drilling fluid flow rate onto the breakdown voltage readings forces using a by-pass system and a batch mode sampling for the automated electrical stability meter. However, the apparatus enables continuous electrical stability measurements in real-time and is an excellent advantage over the standard electrical stability meter. The simple setup of the device minimizes the associated costs, and the operator can define the testing frequency.

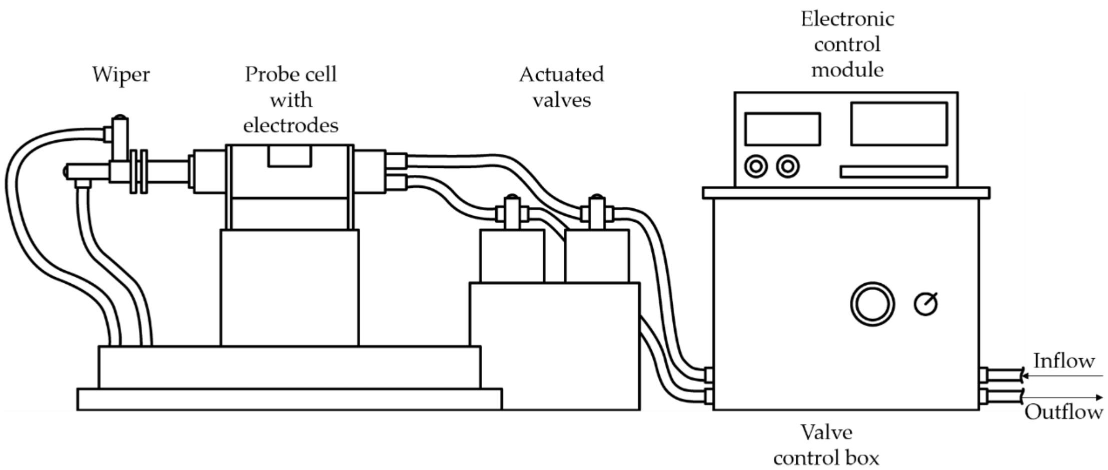

Figure 35: Schematic of automated electrical stability meter (derived from Growcock et al. 2007)

Automated Fluid Loss System

The Automated Fluid Loss System (AFLS) utilizes the same measurement principle as the conventional fluid loss cell (subsection 3.2.5). Still, it determines the fluid loss properties of water- and oil-based drilling fluids autonomously in real-time intervals. The AFLS has the equivalent temperature and pressure ratings as the HPHT fluid loss cell up to 120 degrees Celsius and 35 bar. The AFLS utilizes a metal sheet with very narrow slots to enable repetitive testing without human interventions, instead of the standard HPHT filter paper. The width of the slot perforations can range from two microns to twenty microns and depends on the composition of the drilling fluid. (Tehrani and Cameron 2008)

The apparatus implements a self-cleaning mechanism incorporating backflushing, sonication, and nitrogen purging. The device executes the cleaning process several times between the measurements to ensure the metal filter's original conditions for each testing. The individual metal filters enable upwards of 100 testing cycles before a replacement is necessary. An implemented automatic calibration check analyses the filter performances and calibrates the newly installed filters with a known calibration liquid volume. An incorporated optical vision sensor evaluates the total fluid loss volume. The utilized sensor determines the boundaries between the receiving container and the drilling fluid interface. This sensor further enables the detection of the different liquid interface and thus allows to identify the separation of water from oil. (Tehrani and Cameron 2008)

The same by-pass system as for the automated electrical stability meter supplies the drilling fluid batch samples to the AFLS and ensures a smooth process. The use of the Automated Fluid Loss System can drastically reduce manual working hours. The AFLS only requires a human operator to change the metal filter if necessary. The operator defines the testing frequency, and the AFLS provides the data about the fluid loss properties in real-time continuously. The clear advantages of implementing this apparatus are the significant reduction of human exposure, the limited areal footprint, and the close agreement with API recommendations.

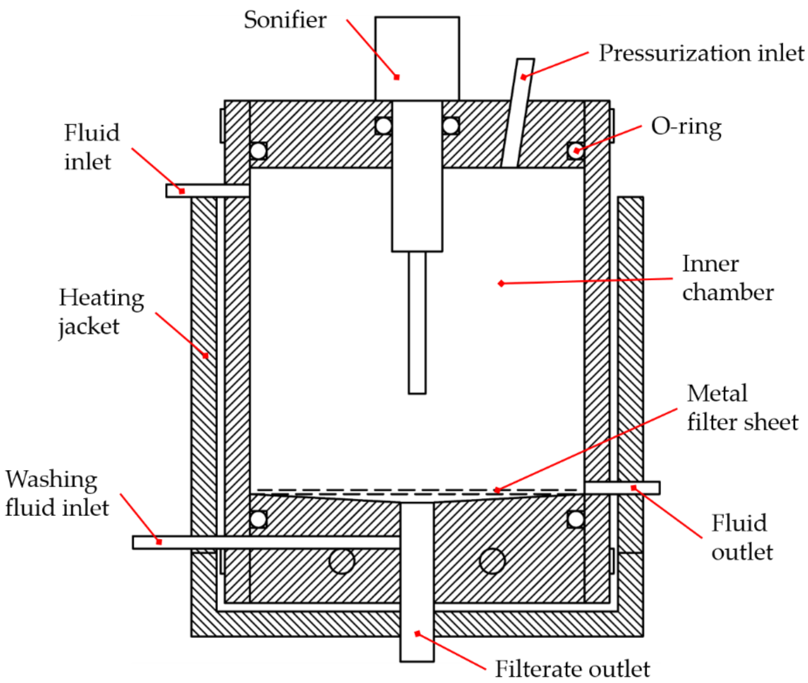

Figure 36: Schematic of the automated fluid loss cell (derived from Tehrani and Cameron 2008)

InFlow Particle Analyzer

The InFlow Particle Analyzer (IPA) incorporates a process connection, a backlight source, a vision system, a network connector, and power supply units. The apparatus determines the particle size distribution with a full-frame photo imaging system. This measurement principle includes three steps: image capture, image processing, and image analysis. The charge-coupled-device camera captures the digital images of the flowing particles. The associated software executes the processing and analysis of every particle picture, which also includes noise filtering. The operator can define the software according to the used drilling mud system. The lower limit for the particle size the LPA can detect is 0.7 micron, and the utilized lens defines the upper limit, which can be up to 20,000 microns. The by-pass system after the shale shakers supplying the automated electrical stability meter and the Automated Fluid Loss System incorporates the IPA device. (Allen 1999a, 1999b; van Oort et al. 2016; J.M. Canty 2020a, 2020b)

This system's most significant limitation is that it requires an expert operator to change the lens or the software according to the drilling mud system in use. However, this system is the most direct way to evaluate the particle size distribution and provides the highest accuracy compared to the other available methods. This apparatus's essential benefits are the continuous real-time availability of the drilling fluids' particle size distribution and the easy integration into the drilling rig system.

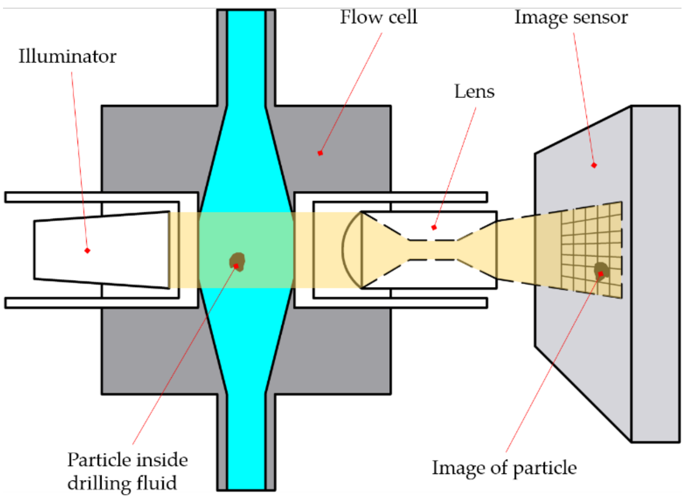

Figure 37: Schematic of automated liquid particle analyzer (derived from J.M. Canty 2020b)

Cuttings Flow Meter

The Cuttings Flow Meter (CFM) provides automatic and continuous measurement and analysis of the weight and volume of cuttings reaching the surface. The CFM unit, located at the end of each shale shaker, incorporates a tray-shaped gutter and a protected enclosure that houses the control mechanisms and sensors. The weighting tray catches the drilled solids as they fall off the shale shaker screens. The incorporated strain gauges determine the accumulated cuttings' weight. The operator predefines a period after which the tray swings down, with a pneumatically controlled device, and discharges the drilled cuttings. The Cuttings Flow Meter continuously measures the cuttings' weight and volume and transfers the data digitally to the drilling rig acquisition system in real-time. The associated software compares it with theoretical data to enable early detection of hole cleaning and wellbore stability problems. (Naegel et al. 1998; Schlumberger 2020h, 2020i)

The CFM provides reliable, accurate, and real-time analysis of the hole cleaning effectiveness and the wellbore stability, which significantly reduces risk and can mitigate severe drilling problems, such as stuck pipe or cuttings bed. Furthermore, this apparatus enables a reduction of the non-productive time and does not interfere with access to the shale shakers. Combined with real-time rheology monitoring, the Cuttings Flow Meter provides a solution to further gain a holistic knowledge of the entire drilling fluids circulation system.

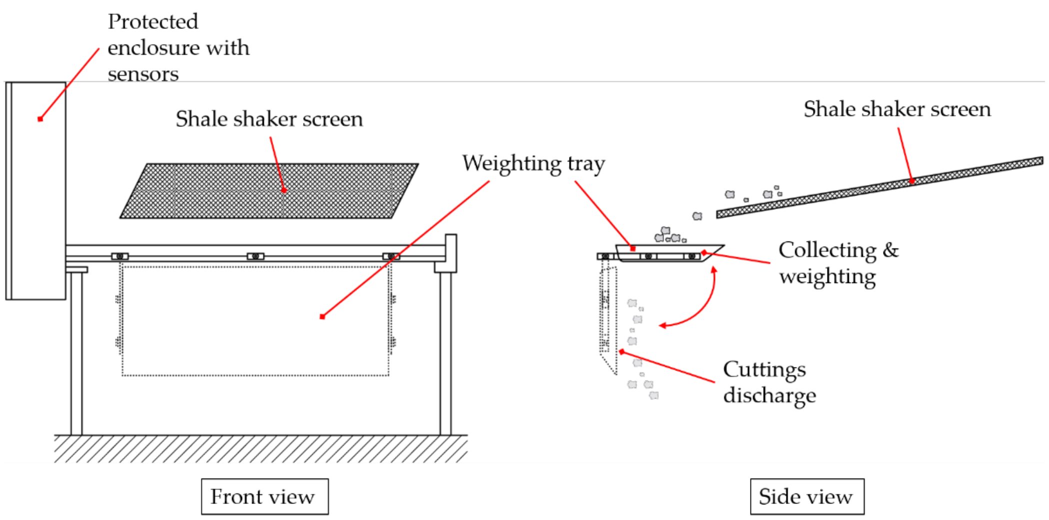

Figure 38: Schematic of Cuttings Flow Meter (derived from Naegel et al. 1998)

Mud Solids Monitor

The Mud Solids Monitor (MSM) utilizes the x-ray fluorescence method to determine the concentrations of solid and liquid phases of the drilling fluid. The apparatus consists of a protective housing, a test chamber, a sampling mechanism slide, and an x-ray fluorescence spectrometer. The MSM device measures the intensity of the fluorescence and scatter. This technique enables the prediction of high- and low-gravity solids within the drilling mud. The x-ray fluorescence measurement technique is about ten times more precise than the conventional API retort method presented in subsection 3.2.4. The MSM unit operates in a batch sampling mode and uses the same by-pass system as the electrical stability meter and the Automated Fluid Loss System to draw the drilling fluid samples. The apparatus transfers the monitoring data to the drilling rig acquisition system in real-time. (Houwen et al. 1993; Saasen et al. 2008; Stock et al. 2013)

The Mud Solids Monitors provides a direct measurement to evaluate the low- and high-gravity solids within the drilling mud. The conventional solids control equipment can not effectively remove these fine dispersed particles. These drilled solids affect the drilling mud's functional properties, and precise monitoring is essential to provide additional treatment if necessary. The main advantages of this technique are the high accuracy and the continuous automatic measurement principle. Recently developed x-ray fluorescence units even eliminate the radioactive-source and replace it with a 500-eV source. The application of the MSM reduces human exposure and analysis errors. The constant determination enables pro-active decisions for the treatment of the mud, and thus, can reduce the non-productive time.

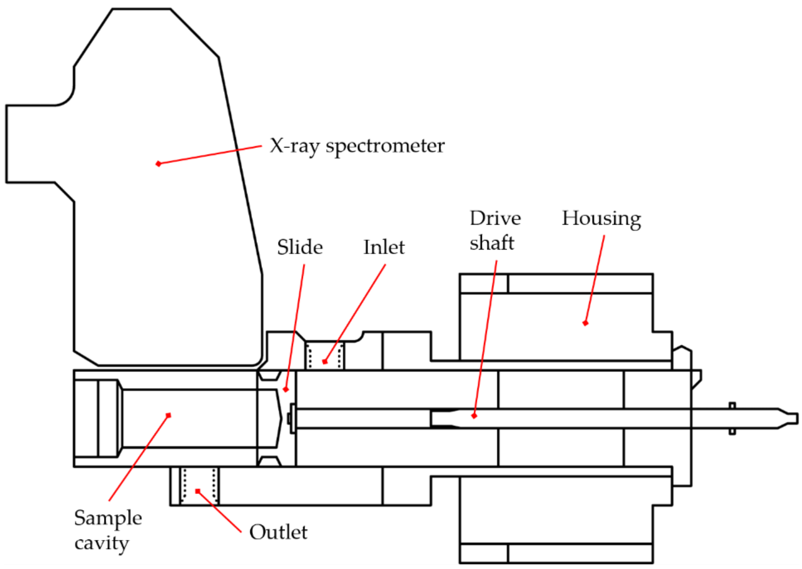

Figure 39: Schematic of Mud Solids Monitor test chamber (derived from Stock et al. 2013)

The RHEOBOT system implements the measurement applications described above due to the proven automation capabilities and the advantages in modularity. This conceptual design enables the operator to select the required measurement apparatuses matched to the complexity, criticality, and interoperability of the individual well construction operation. This ability is in substantial accordance with the demand of the industry to have a general field-proven system that allows implementation into all levels of drilling activities, from low tier factory onshore drilling to highly automated ultradeep offshore drilling operations. Figure 40 shows the drilling rig's schematic ground plan with the solids control equipment, including the placement of the RHEOBOT concept components.

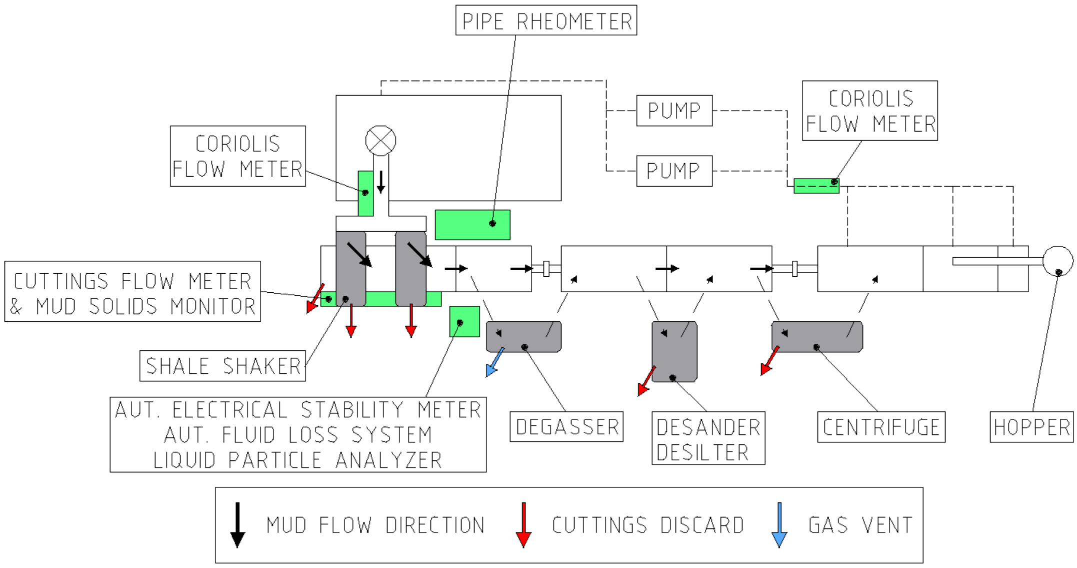

Figure 40: Integration of the components of the first RHEOBOT concept idea

The implementation of the subsequently described concept parts, including the downhole sensor technique and the quality assurance method, distribute as another addition to the central part of the RHEOBOT system – the Coriolis flowmeter and the pipe rheometer. Therefore, these two parts complete the general idea of the overall RHEOBOT concept, are just concisely disclosed, and primarily serve as a guideline for future work.

The second part of the RHEOBOT concept is the intention to implement also aspects of downhole sensors, as described in section 4.4.2. The field application of wired drill pipe technologies increases across the industry due to the many associated advantages. The currently applied downhole sensors implemented in these applications evaluate the pressure, temperature, and vibrations along the drillstring. The idea is to apply the principle of the pipe rheometer to the well itself by using the flow rate provided by the Coriolis flowmeter and the differential pressure data from the wired drill string measurements. This implementation into the concept is only possible if the specific drilling operation uses a wired drill pipe. However, possible future laboratory prototypes can simulate the wired drill pipe, including the pressure measurements, enabling the RHEOBOT system to evaluate the fluid properties within the unite circulating drilling mud conduit. (Maglione et al. 1996; Pipeline Oil & Gas Magazine 2020)

The third system component of the RHEOBOT concept enforces the implementation of a continuous-improvement technique. The associated functionality is to evaluate the task objectives and demands of the holistic RHEOBOT system in accordance with the entire rig system and related automated equipment frequently. The advancing automation of drilling operations with the associated development of new technologies also implements new challenges for the existing equipment and procedures. Utilizing a quality assignment approach, such as Six Sigma, Lean Management, or Measurement System Analysis, helps identify the possible future drawbacks of the above-described surface monitoring systems. Furthermore, this third component of the RHEOBOT system supports implementing newly developed monitoring techniques quickly and maintains the state-of-the-art attitude of the RHEOBOT system.

The primary elements of the RHEOBOT concept are the above-described surface measurement systems. The main instruments are the Coriolis flowmeter and the pipe rheometer to enable a real-time monitoring of the density and the rheological properties of the drilling mud. The additional presented surface measurements represent possible extensions to create a more precise knowledge of the entire drilling fluid conduit and the associated drilled solids. In the same way, the second element of the RHEOBOT concept functions as a supplement to the overall system, enhancing the understanding of the downhole conditions. The third element emphasizes that the RHEOBOT concept is not a reflection of available techniques but strives to maintain the highest quality with ongoing future research work. The subsequent **Figure 41** illustrates and summarizes the main achievements and claims of the RHEOBOT concept system.

Modularity

The RHEOBOT concept incorporates full modularity to enable a monitoring system fit for every condition and operators needs.

Sensor qualities

The RHEOBOT concept incorporates field-proven apparatuses to implement sensors that accomplish the sensor quality criteria.

Ease of use

The RHEOBOT concept implements instruments with minimal installation and maintenance requirements.

Interoperability

The RHEOBOT concept emphasizes the need for universal data transfer standards and a common monitoring system enabling quick integrations into existing rig systems and remote control.

Areal footprint

The RHEOBOT concept combines the different monitoring techniques within shared by-pass and sampling lines reducing the necessary surface area.

Pro-active decision making

The RHEOBOT concept utilizes a holistic approach to cover all aspects of the various drilling fluid segments facilitating a real-time knowledge of the entire drilling mud conduit, to support precise decisions and to mitigate severe drilling problems.

Figure 41: Summary of the primary RHEOBOT achievements and claims

Chapter 5 Conclusion and Outlook

The associated problems and limitations arising from the manual testing of the drilling fluid are significant. The traditional mud check delivers the drilling mud properties only at a specific time, as it is only a spot check. This operational principle of outdated manual analysis is inconsistent because the modern drilling fluid compositions are not homogeneous but constantly changing systems due to continuous treatments, losses, and subsurface alterations.

The drilling fluid remains the primary barrier during drilling operations, and thus it is the most significant component assuring well integrity. The drilling industry defines the explicit aim to automize the drilling activities fully. Therefore, appropriate systems to guarantee the desired drilling fluid parameters are of crucial importance to enable sufficient monitoring of the primary well barrier for autonomous drilling. The automation roadmaps defined by cross-industry collaborations show promising results as various available automatic applications prove.

The automation of the individual drilling operations is perhaps the most game-changing opportunity to enhance operational safety, quality, and performance in an economical way. The mechanization and subsequent automation of drilling processes enable the execution of activities and operations for high complex wellbore constructions, which are not possible with traditional methods. The challenging drilling operations and the increasing complexity of drilling fluid systems do not enable the application of one solution that fits all.

The RHEOBOT system emphasizes on the design principle of modularity and interoperability to enable automated drilling fluid solutions for all individual drilling operations. This conceptual design functions as the basis for future research evaluating automated drilling mud systems and laboratory prototype applications. Further, this thesis presents the necessary guidelines and design criteria for the automation of drilling instruments and describes the approach for the associated concept development.

The thesis accomplishes a holistic interpretation of the state-of-the-art drilling automation development process. Supplementary, this research presents the most significant contributors regarding drilling fluid testing and the associated essential products. The described theoretical fundamentals about drilling fluids and the related solids control equipment provide the necessary understanding of the entire circulation process and emphasize the need to improve the monitoring capabilities. The last chapter of this thesis synoptically describes the distinctive approach of developing a concept for a drilling automation system.

The elaborated RHEOBOT concept combines the recent development efforts and presents a fit for use methodology to monitor drilling fluid parameters in real-time. However, to analytical evaluate the entire system's operability, it is necessary to build a laboratory prototype with the associated flow loop. The first step for future research work is to design and establish a laboratory flow loop that simulates the entire drilling fluid conduit. The ensuing procedure is then to implement the automated measurement apparatuses of the RHEOBOT system progressively. Assuming successful laboratory applications, the associated process steps for future research require implementing software receiving and analyzing the monitoring data. The execution of a field test decisively proves the automated monitoring capability of the RHEOBOT system and defines the final step for a future research project.

The concept design of the RHEOBOT system serves as a further step towards the fully autonomous drilling rig and encourages the implementation of new technologies. The next steps are to create the RHEOBOT prototype, establish a testing environment for the system, and define a connecting software. This approach significantly supports the effort of the drilling industry to develop a drilling rig where a computer receives, connects, coordinates and executes the control of the entire system.

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Acronyms & Abbreviations

AADE	American Association of Drilling Engineers
AFLS	Automated Fluid Loss System
AI	Artificial Intelligence
AMC	AMC Drilling Optimization
AML	Advanced Mud Logging
ANIFS	Adaptive Neuro-Fuzzy Interference System
ANN	Artificial Neural Networks
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
AWD	Analysis-While-Drilling
BHP	Bottomhole Pressure
CFM	Cuttings Flow Meter
CFM	Cuttings Flow Meter
cP	Centipoise
DFG-RT	Drilling Fluids Graphics Real-Time
DRU	Density and Rheology Unit
DSA-R	Drilling Systems Automation Roadmap
ECD	Equivalent Circulating Density
EKD	Early Kick Detection
ES	Electrical Stability
FBRM	Focused Beam Reflectance Measurement
GCE	Norwegian Global Center of Expertise
GR	Gamma Ray
HPHT	High-Pressure High-Temperature
IADC	International Association of Drilling Contractors
IADC ART	International Association of Drilling Contractors Advanced Rig Technology Committee
IDS	Integrated Drilling System
IMS	Intelligent Mud Solutions
IPA	InFlow Particle Analyzer

IRIS	International Research Institute of Stavanger
ISA	International Society of Automation
ISO	International Organization for Standardization
LWD	Logging-While-Drilling
mPa	Millipascal
MPC	Model Predictive Control
MPD	Managed Pressure Drilling
MSM	Mud Solids Monitor
MWD	Measurement-While-Drilling
NMR	Nuclear Magnetic Resonance
NORCE	Norwegian Research Conglomerate
NORSOK	Norsk Sokkels Konkurranseposisjon
OASys	OFITE Automated System
OBM	Oil-Based Muds
OFITE	OFI Testing Equipment
OGDQ	Operators Group on Data Quality
OLR	OnLine Rheometer
OPC UA	Open Connectivity Unified Architecture Standard
PDS	Powerline Drill String
PID	Proportional-Integral-Derivative
ppg	Pounds Per Gallon
PSD	Particle Size Distribution
psi	Pounds Per Square Inch
PV	Plastic Viscosity
PVT	Pressure-Volume-Temperature
PWD	Pressure-While-Drilling
RAPID	University of Texas Rig Automation & Performance Improvement in Drilling
RFID	Radio-Frequency Identification
RPM	Rotations Per Minute
sg	Specific Gravity
SPE	Society of Petroleum Engineers

SPE DSATS	Society of Petroleum Engineers Drilling System Automation Technical Section
SPWLA	Society of Petrophysicists and Well Log Analysts
SVM	Support Vector Machines
UK	United Kingdom
VFR	Volumetric Flowrate
WBM	Water-Based Muds
WITS	Wellsite Information Transfer Specification
WITSML	Wellsite Information Transfer Standard Markup Language
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
YP	Yield Point

Symbols

BE	Bentonite equivalent	$[kg/m^3]$
K	Consistency factor	$[Pa \cdot s]$
ρ	Density	$[kg/m^3]$
ρ_{Mud}	Drilling fluid density	$[kg/m^3]$
V_{df}	Drilling fluid sample volume	$[ml]$
μ	Dynamic viscosity	$[Pa \cdot s]$
μ_{eff}	Effective viscosity	$[Pa \cdot s]$
ρ_{ECD}	Equivalent circulating density	$[kg/m^3]$
n_p	Flow behavior index	[ ]
n	Flow behavior index	[ ]
K_p	Flow consistency index	$[Pa \cdot s]$
g	Gravitational constant	$[m/s^2]$
h	Height of fluid column	$[m]$
ν	Kinematic viscosity	$[m^2/s]$
m	Mass	$[kg]$
MBT	Methylene blue capacity	[ ]
V_{mb}	Methylene blue solution volume	$[ml]$
PV	Plastic viscosity	$[Pa \cdot s]$
p	Pressure	$[Pa]$
γ	Shear rate	$[s^{-1}]$
τ	Shear stress	$[Pa]$
Δp_L	Sum of annular frictional pressure losses	$[Pa]$
t	Time	$[s]$
V	Volume	$[m^3]$
YP	Yield point	$[Pa]$
τ_0	Yield stress	$[Pa]$

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