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ABSTRACT

The focus on permanent Plug and Abandonment (P&A) has increased the last few years, due to aging infrastructure of many of the fields on the Norwegian Continental Shelf (NCS). Permanent P&A introduces significant expenses with no financial returns for the license holders, the state, and the Norwegian tax payers who contribute with 78% of the total costs of P&A. The dominant part of the P&A time is associated with cutting and pulling casing to be able to establish a cross-sectional barrier. To avoid the time-consuming operations of pulling casing out of barite and other settled solids in annulus, an investigation of barite as an annular barrier would be beneficial. The purpose of this thesis is to investigate barite settlement as an opportunity for the industry, and not a challenge. The thesis will highlight factors that are essential for considering barite as a permanent barrier material. To do so, a literature study on P&A and barite in general was conducted, and an experimental part was initiated.

The potential financial savings are enormous if utilization of barite as a permanent barrier material is feasible. To potentially utilize settled barite as a permanent barrier material, a method to identify the settled barite behind the casing must be established. After identification of settled barite, field verification of the barrier must be conducted. In this thesis methods for further investigation regarding identification and verifications procedures are described, to serve as a start point for further investigation. Adding to this, some preliminary laboratory testing has been initiated in to create some set point values for further research. The main experimental set-up consists of a 3.5 meter long pipe. In this pipe, a self-made barite plug is going to be pressure tested, with the aim of publishing the results to spike further interest for investigation on the subject.

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NOMENCLATURE

BFC	Blast Furnace Slag
BOP	Blow out Preventer
BS	Back Scatter
CBL	Cement Bond Log
DHSV	Downhole Safety Valve
GOM	Gulf of Mexico
HSE	Health Safety & Environment
HTHP	High Pressure High Temperature
NCS	Norwegian Continental Shelf
OBM	Oil Based Mud
OPC	Original Portland Cement
P&A	Plug and Abandonment
PV	Plastic Viscosity
PWA	Permanent Well Abandonment
PWC	Perforate Wash and Cement
T	Transmission
TOC	Top of Cement
TSI	Turbiscan Stability Index
UCA	Ultrasonic Cement Analyzers
VDL	Variable Density Logs
WBAC	Well Barrier Acceptance Criteria
WBE	Well Barrier Element
WBEAT	Well Barrier Element Acceptance Table
WBM	Water Based Mud
WBS	Well Barrier Schematic
XG	Xanthan Gum
XMT	Christmas Three

CHAPTER 1

INTRODUCTION

1.1 Permanent vs. temporary plug and abandonment

As of February 2019, there are 6450 wells drilled on the NCS. These wells are a combination of exploration and development wells, and wells that are already plugged and abandoned (Oljedirektoratet, 2019). 2880 of these wells have been permanently plugged and abandoned (Khalifeh, 2016). At some point in time, many of these development wells will reach the end of their lifetime, and need to be plugged or re-completed.

When a well has higher operating expenses than operating income, it is time to re-evaluate the situation, and often decommissioning of the well is a solution. Decommissioning is a general term for all activities and processes which include removing something from active status. Decommission of a well is often referred to as plug and abandonment (P&A) in the petroleum business. In this case P&A includes all the tasks and actions taken to isolate and protect the environment and surroundings from a source of potential inflow (Khalifeh, 2019a). Requirements for isolation of formations, fluids and pressures are the same for all types of abandonment. However, choice of plugging materials and techniques may differ depending on abandonment time, and ability to re-enter the well, or continue operations after temporary abandonment (NORSOK, 2013). Well abandonment activities covered by NORSOK D-010 can be grouped as following:

- Suspension of well activities
- Temporary well abandonment
- Permanent well abandonment

Suspension is a well status, where all well activities are suspended while well control equipment is left in place. A well can for example be put into suspension status under construction or intervention. Some examples that can cause suspension could be bad weather, waiting for equipment, and skidding the rig to do workover on another well.

Temporary abandoned is a status where a well is abandoned and the control equipment is removed. The intension being safe re-entry of the well at after some time, or permanent abandonment of the well in the future. Usually the well is in this state when waiting on a workover or waiting on field development etc. The status begins as soon as the main reservoir is fully isolated from the wellbore and may last a few days to a couple of years (Khalifeh, 2019a).

Temporary well abandonment with well monitoring means that both primary and secondary barriers are monitored and routinely tested. Monitoring and testing of well barrier elements (WBE) should be done according to existing standards. Different regulatory authorities have their own requirements when it comes to maximum abandonment period for such wells. Subsea wells where it is not possible to monitor barriers, can be categorized as temporary well abandonment without well monitoring.

Permanent abandonment is defined as a well status where the well is not planned to be used or re-entered again in the future. The well shall be abandoned with an eternal perspective, taking into consideration any chemical or geological processes that can affect the abandoned well. In the North Sea, there are well defined legislation and practices regarding how permanent P&A should be conducted. These legislations and practices are defined in the NORSOK standards. Different countries have different regulations when it comes to permanent well abandonment (PWA). One example of this could be regulations regarding the length of the plug. In different parts of the world, regulatory bodies have defined procedures and responsibilities for PWA. Despite differences in standards around the world, the intention off all permanent abandonment operations is to achieve the following (Campbell and Smith, 2013):

- Isolate and protect all freshwater zones
- Isolate all potential future commercial zones
- Prevent leaks from or into the well
- Cut pipe to an acceptable level below seabed and remove all surface equipment

1.2 Time consumption and cost of permanent plugging activities

Well abandonment is nothing new to the industry, but the factor that is changing, is the total amount of wells that are currently shut in, suspended or reaching the end of their economic life. The decision to permanently plug and abandon a well is based primarily on economics. When production incomes are less then operating costs, permanent plugging is often the solution. Even in cases where there are considerable reserves left in the reservoir, plugging is often the best solution for the operators, if the cost to extract these resources left is more than the projected income of the well. The cost of PWA operations wary depending on how complex the plugging operation is. In the UK abandonment from a fixed platform can cost around 2 million USD, while abandonment from a semisubmersible or dynamic position drilling unit can be 10 million USD or more (Campbell and Smith, 2013).

With regards to global offshore markets, the two dominating areas when it comes to well abandonment activities are the Gulf of Mexico (GOM) and the North Sea. The reason being that both fields have several aging wells. Both areas are well established and mature producing fields with aging infrastructure. Since the first discovery on the NCS in 1966, there are drilled 6450 wells as of February 2019 (Oljedirektoratet, 2019). Of these wells, 1713 are exploration wells while 4737 are development wells. The development wells could be either an injection, observation or production well, and the distribution among them (as of February 2019) is listed below

(Oljedirektoratet, 2019):

- 747 injection wells
- 523 observation wells
- 3467 production wells

More than thousands of these wells will within the next couple of years be candidates for PWA. The awaiting costs tied to P&A are tremendous, and the Norwegian government is obliged to finance 78% of the operational costs. P&A introduces significant expenses with no financial returns, this is one of the main reasons why historically there was less focus on P&A than producing new wells. The industry is facing its busiest period ever in relation to abandonment work, with drilling activity adding thousands of wells to the P&A list, the volume of permanent abandonment work will only continue to grow.

At the Norwegian Petroleum Directorate fact pages, there are no concrete statistics available on the exact number of wells which will be permanently plugged and abandoned the next couple of years. In the North Sea, an estimation of approximately 2000 wells are planned to be permanently plugged and abandoned in the upcoming decade (Vrålstad et al., 2019). In a presentation held by Martin Straume on the annual Plug and Abandonment Forum in 2014, an estimate of 3000 wells was made to be able to calculate time consumption and cost of permanent P&A (Straume, 2014).

Table 1. 1 P&A Statistics (Straume, 2014)

Time per well	35 days
One rig will P&A 10 wells per year	350 days
15 rigs will P&A	150 wells each year
Time to permanently plug 3000 wells	20 years
New development wells in this period (avg. 144 wells per year)	2880 wells
Time to P&A 2880 wells at this speed	19,2 years
Conclusion: 15 rigs will do full time P&A for	**40 years**

The time spent on permanent P&A is somewhere between 20 and 60 days, depending on how complex the operation is. Based on Straume's statistics presented in Table 1.1 above, it will take 15 rigs permanently plugging for 40 years to plug the wells on the NCS. The yearly cost per rig is estimated to be 1460 million NOK, then it could easily be calculated that the cost of 15 rigs during 40 years of P&A would be 876 billion NOK, and as mentioned before 78% of these costs are payed by the Norwegian tax payers (Straume, 2014).

The need and potential for new time and cost effective methods within this part of the industry is enormous. The industry needs new innovative ideas for time and cost efficient methods for plugging activities. To reduce the cost of abandonment operations, operators and regulators must strive to improve how P&A operations are preformed, and the service companies strive to develop new tools and techniques to increase efficiency without compromising safety. The enormous potential for technology development is a big motivation for the technology investigated in this thesis.

1.3 Well integrity

An essential aspect of P&A is to ensure well integrity after abandonment. NORSOK D-010 defines well integrity as the "application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well" (NORSOK, 2013). When plugging a well, there are different requirements depending on the situation of the well. If the potential source of inflow contains hydrocarbons, the requirement to maintain well integrity is to place two qualified independent well barriers. For non-hydrocarbon inflow potentials, there shall be at least one well barrier between source of inflow and surface (NORSOK D-010 2013). Barriers are defined as any physical elements placed to prevent, reduce or control undesired events and accidents, which in our case is leakage of fluids.

The well needs to be equipped with sufficient well barriers to prevent unwanted flow. There is always a risk of a barrier failure, this considered the well should always be equipped with two independent well barriers, also referred to as a primary and secondary barrier. Under each life stage of the well, primary and secondary barriers may vary. Figure 1.1 illustrates the two-barrier philosophy of a well throughout its lifecycle. Table 1.2 presents examples of the barrier systems of the different stages shown in Figure 1.1 (Khalifeh, 2019a).

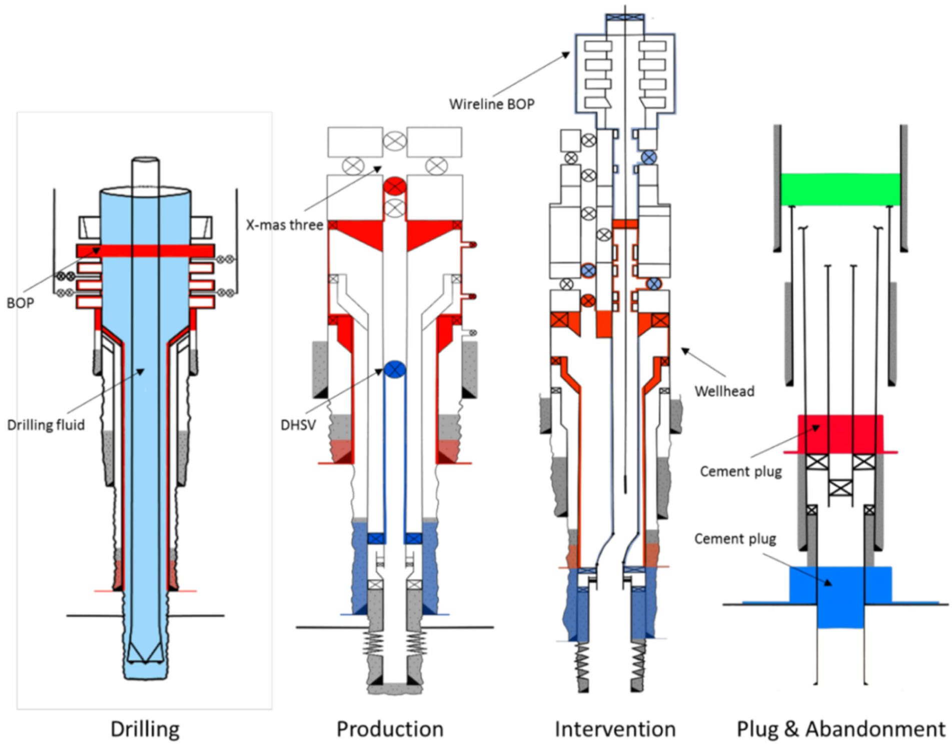

Figure 1. 1 Illustration of the two-barrier philosophy throughout a well's lifecycle (Khalifeh, 2019a)

Table 1. 2 Examples of barrier systems through throughout a well's lifecycle (Khalifeh, 2019a)

Stage of well	**Primary barrier**	**Secondary barrier**
Drilling	Overbalanced mud with filter cake	Casing cement, casing, wellhead and blow out preventer (BOP)
Production	Casing cement, casing, packer, tubing and downhole safety valve(DHSV)	Casing cement, casing, wellhead, tubing hanger, and Christmas tree (XMT)
Intervention	Casing cement, casing deep-set plug and overbalanced mud	Casing cement, casing, wellhead BOP
Plug & Abandonment	Casing cement, casing and cement plug	Casing cement, casing and cement plug

The primary barrier is the first envelope of elements that prevents flow from a potential source, and the secondary barrier is a back-up in case of failure of the primary barrier. In well barrier schematics (WBS), the primary barrier is often represented by a blue color, while the secondary barrier is represented by a red color.

1.3.1 Barrier envelope

Further in this chapter, the focus will be on well integrity during permanent P&A operations. In context of well integrity, a well barrier may be described as an envelope consisting of several impermeable objects, also referred to as well barrier elements (WBE). The WBE together prevent uncontrolled fluid flow from hydrocarbon- or non-hydrocarbon sources. Permanent well barriers shall extend across the full cross section of the well, including all annuli and the barrier should seal both vertically and horizontally as is illustrated in Figure 1.2 below (NORSOK D-010 2013).

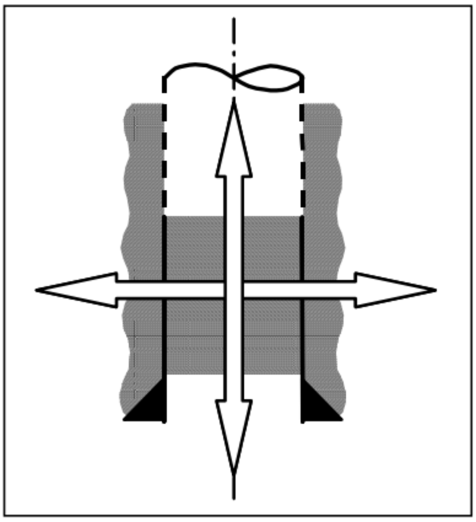

Figure 1. 2 Well barrier criteria *(NORSOK, 2013)*

The barrier envelope needs to extend from formation to formation as shown in Figure 1.2, hence a steel tubular is not acceptable as a permanent barrier, unless it is supported by cement or another plugging material both outside and inside. The well barrier material properties inside and outside the casing should fulfill the following requirements (NORSOK, 2013):

- Impermeable
- Long term integrity
- Non-shrinking
- Ductile, able to withstand the mechanical loads by environment
- Resistance to different chemicals or substances
- Wetting, to ensure bonding to steel and formation

1.3.2 Barrier elements

The elements that builds up a barrier envelope are often referred to as barrier elements. A well barrier element cannot alone block unwanted flow, but can in combination with other WBEs form a barrier envelope. Table 1.2 lists a few WBEs in both primary and secondary barriers, these are listed below (Khalifeh, 2019a):

- Formation
- Casing cement (or other potential material)

- Casing
- Sealing abandonment plug

All these elements must seal tolerably, and if just one of these elements fails the whole barrier envelope is breached, and the well may leak. The formation that is going to be a part of the barrier envelope needs to be impermeable, and be of adequate strength to hold all future pressures it may be exposed to. The plug depth is determined by impermeability and strength of the formation, and the quality of the primary cementation outside the casing. The tubing and the casing which also are a part of the barrier envelope, needs to have clean surfaces and be water wet to ensure good bonding.

1.4 Permanent plug and abandonment operations

The basics of a P&A operation will wary for wells on land and offshore wells, furthermore the details of the P&A operations may differ significantly depending on the actual status of the well and which type of well it is. A simplified approach for PWA is described is described as follows: The first step is always to remove the completion or production string/s. The second step is to set the necessary plugs and cement barriers at specified depths across the producing and water bearing zones to act as permanent barriers (Campbell and Smith, 2013). The regulations in the North Sea requires two independent barriers over the reservoir section, a primary and a secondary barrier as illustrated in Figure 1.3 (Vrålstad et al., 2019). Any fluid bearing formation in the overburden, like for example hydrocarbon bearing zones, or high pressure zones, should also be isolated with two independent barriers. In addition to this, an open- hole to surface plug is placed, this is often referred to as the environmental plug in the industry. This environmental plug is illustrated as a green barrier in Figure 1.3, which is installed below the seabed. The surface plugs main purpose is to prevent any residual fluid contamination to the seabed.

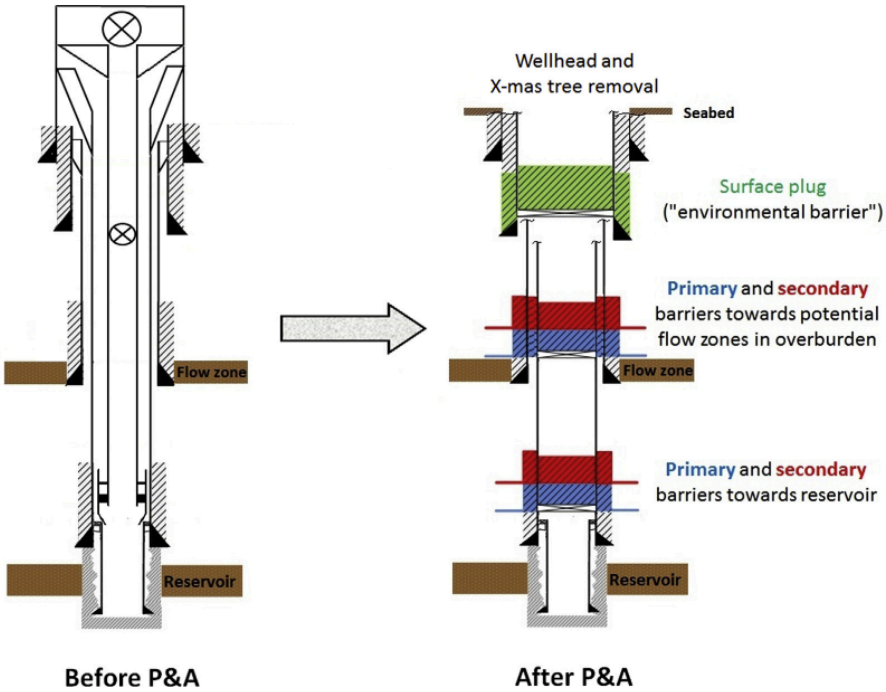

Figure 1. 3 Offshore production well before and after P&A (Vrålstad et al., 2019)

Finally, after all barriers are put in place, the conductor and wellhead can be removed. Operators are obliged to leave the abandoned well in a condition that protects both the downhole and surface environment with eternity perspective. A solid plan is the key to any successful operation. Thorough planning is especially important for PWA activities being that there is no financial gain from the operation, and the result of the operation is planned to hold for eternity.

Oil & Gas UK described the aim of P&A operations as "restoring the cap rock", and to achieve this aim, the wellbore must be sealed off from rock to rock as earlier described. If logs show that the annular cement is not good enough to be a part of the barrier envelope, a new annular barrier needs to be established. This is often the most time consuming, and thus costly part of the P&A process. There are several methods for establishing annulus barriers, and descriptions of the main methods are given below.

1.4.1 Section milling

Figure 1.4 shows an annulus with good quality annular cement to the right, where the cement provides zonal isolation. However, if the annular cement does not provide zonal isolation, the solution is often to remove the casing and cement by section milling. The result of this solution is illustrated to the left in Figure 1.4.

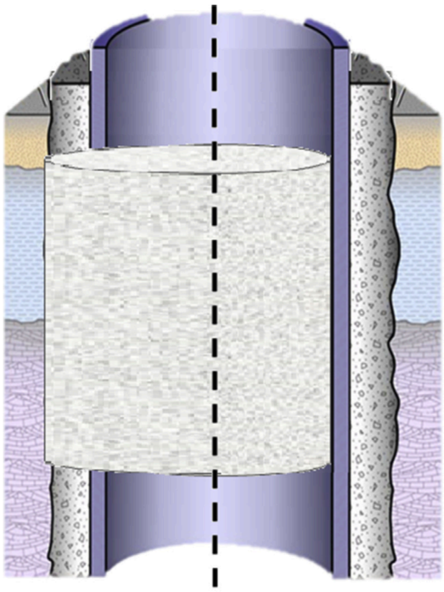

Figure 1. 4 Section milling and good cement(Vrålstad et al., 2019)

To be able to cut through the casing and casing cement, special milling blades and cutters are manufactured. Section milling is a very time consuming operation, and therfore also expensive. The longer the milling interval, the costlier the operation. When milling, various size metal cuttings are created, this is also referred to as swarf. Swarf introduces several operational challenges, such as swarf accumulation in the BOP, which can lead to damage of the well control equipment and cause potential well integrity issues if the BOP breaks down (Vrålstad et al., 2019). Another shortcoming is that the tool can get stuck when pulling out of hole, and swarf at surface can introduce health, safety and environment (HSE) issues.

1.4.2 Perforate-wash-cement

When the annulus is un-cemented or partly filled with poor cement, the perforate-wash-cement (PWC) method is often the solution to establish an annular barrier. The method consists of perforating the casing to get access to the annular space, followed by washing and cleaning the annulus. The annulus is washed to clean out mud, debris, settled barite or poor cement. Lastly, the annulus is filled with new cement. This method can be very time efficient and thus cost effective. PWC is routinely used by operators on the NCS during permanent P&A, and the method has also been successfully used in the Middle East (Ansari et al., 2016).

1.5 Different types of permanent Barrier Materials

There are several different plugging materials used in the industry today; Portland cement being the most common. Cement satisfies the essential criteria of permanent plugging materials and is an inexpensive material, though it does not withstand high temperatures or corrosive environments (Khalifeh et al., 2013). Shortcomings regarding the Portland Cements properties such as durability, drives researchers to investigate alternative plugging materials. A description of Portland cement and other emerging types of alternative plugging materials will be given in the following sections. As the aim of this thesis is to investigate a new alternative annular barrier material, a list of already existing materials is given in this chapter for comparison. All the materials described in this subchapter should fulfill the main requirements for permanent barrier materials described in subchapter 1.3.1.

1.5.1 Portland cement

Ordinary Portland Cement (OPC) is by far the most important cementing material in terms of quantity produced. OPC is produced by pulverizing clinker, which is the burned material that exits the rotary kiln in a cement plant. The main components of the cement clinker are hydraulic calcium silicates, calcium aluminates and calcium aluminoferrites (Nelson and Guillot, 2006). OPC is an example of a hydraulic cement, that means that the cement set and develop compressive strengths when in contact with water. Chemical reactions between the compounds in the cement and water starts the first phase of hardening which is the reactive period; a gel layer on the mineral surfaces is made and it prevents further reaction. This creates a dormant period, where it is possible to pump the cement (Nelson and Guillot, 2006). After a while the mentioned gel starts to form and strengthen rapidly, and the development of strength is uniform within the cement volume. When the cement is set, it has low permeability an is almost insoluble in water, which are essential properties for a plugging material.

Portland cements are manufactured to meet certain chemical and physical standards, and as deeper and more advanced wells were drilled, the OPC developed. The best-known classification system for oil well application are the API or ISO classes, which include A, B C, D, E, F, G, and H cement class (Nelson and Guillot, 2006).

Portland cement systems are designed to perform at temperatures ranging from below freezing point in permafrost zones to as high temperature as 350°C. The cement systems are designed to hold pressures up to 200 MPa, which are conditions often found in deep wells. Additives are chemicals and materials that modify and adjust the behavior of the cement system, ideally allowing successful cement placement in a range of different conditions like: high temperatures and pressures, corrosive fluids and weak and porous formations. As of today, there are hundreds of additives available, and they can be divided into eight major categories as mentioned below (Nelson and Guillot, 2006):

1. Accelerators: reduce setting time of cement system
2. Retarders: delay setting time of cement system
3. Extenders: lower the density of cement system
4. Weighting agents: increase the density of cement system
5. Dispersants: reduce viscosity of cement system
6. Fluid loss control agents: control leakage of a cement system to formation
7. Lost circulation control agents: control loss of cement slurry to weak or vugular formations
8. Specialty additives: miscellaneous additives such as antifoam agents, fibers, and flexible particles

1.5.2 Blast Furnace Slag

Blast Furnace slag (BFS) is a by-product from production of iron through a blast furnace. The BFS appears over the molten iron that is formed at the bottom of the furnace, and it is derived from the iron ore, the combustion residue of the coke, the limestone and the other materials that must be added in the blast furnace process, see for example (Saasen et al., 1994).

BFS can be used as a hydraulic-binder material by itself, but has also been used as an additive to Portland cement systems. In the early 1990s a method developed the Mud-to-Cement system. The concept consisted of a water-based drilling fluid that was converted to a cement by using hydraulic blast furnace slag (Cowan et al., 1992). The BFS was used as both weight- and fluid loss material, and when cementing was to be performed the concentration of BFS was increased. The Mud-to-Cement system based on adding BFS was successful in several onshore fields in Texas, and the technique seemed to be promising for offshore operations as well (Daulton et al., 1995). After some years, this method was abandoned and rarely used because of frequent crack developments in the cured slag cement (Moranville-Regourd and Kamali-Bernard, 2019).

1.5.3 Bentonite

Sodium bentonite has for a long time been identified as a material with excellent plugging capability due its capacity to hydrate, swell and its extremely low permeability (Englehardt et al., 2001). The material has been used to successfully plug and abandon over 500 wells across the USA, and numerous wells in Australia (Clark and Salsbury, 2003). Research presented by Towler et al., 2016, shows that the concentrated bentonite would restore itself if cracks in the material occurred (Towler et al., 2016).

1.5.4 Low melting point alloys

Low melting point alloys have been tested for removing sustained casing pressures. Low melting point alloys including bismuth as an ingredient have also been suggested as a plugging material (Carragher and Fulks, 2018). Due to bismuths expansion during solidification, this method ensures proper bonding between the casing metal and the bismuth plug. The bismuth plug was successfully set in the Norwegian sector of the North Sea (Carragher and Fulks, 2018).

1.5.5 Thermosetting polymers

Thermosetting polymers are fluids with no particles, which has the ability to solidify upon curing. The result material after this process is an impermeable plug. Thermosetting polymers are often referred to as resins in the industry. The curing process is temperature driven, and occurs at a temperature which is defined before setting of the plug. By additives both viscosity and density of the fluid can be premeditated to suit a wide range of applications (Vrålstad et al., 2019). Resins have been used as a plugging material both in the GOM and the North Sea. Laboratory tests have shown a loss of strength of resins in H_2S and crude oil environments (Beharie et al., 2015).

1.5.6 Unconsolidated sand slurries

An alternative plugging material that can be used, is a Bingham-plastic unconsolidated material with high solids concentration. This type of plug does not shrink, and cannot fracture cause the plugs ability to reshape when its exposed to forces which exceeds the materials shear strength. Unconsolidated sand slurries are also impermeable and have a low porosity, the permeability should theoretically be less than 0.01 mDarcy. This is achieved with choosing sand particles with a wide size particle distribution. The large particles alone would make a permeable matrix. The void volume within the large particles is filled with smaller particles. The volume in-between these smaller particles are again filled with even smaller particles and so on, down to micron-sized particles. In this way, one can achieve an almost impermeable matrix. The purpose of sand slurries as plugging material is to fill he well with a deformable, low porosity and impermeable material. Unconsolidated sand slurries were first used for temporary abandonment, but have later also been used for permanent P&A (Saasen et al., 2011). When investigating barite further in this thesis, we may expect that unconsolidated barite particles may have some of the same properties as mentioned above for unconsolidated sand slurries. However, settled barite also have the ability to solidify after settlement, which is not a property of the unconsolidated sand slurries.

1.6 Rules and regulations for qualification of barrier materials

As the industry develops and more complex situations arise, several permanent plugging materials have been developed as good substitutes for Portland cement. Usage of new plugging materials may result in less time-consuming permanent P&A operations but also ensure better performance and accordingly avoid costly remediation operations. To avoid failure of materials, and thus costly remediation operations, it is necessary to evaluate the functional requirements, operating conditions and qualifications procedures for any newly developed permanent plugging material (Khalifeh, 2019a).

To be able to qualify the well barrier, some specific requirements called Well Barrier Acceptance Criteria (WBAC) needs to be fulfilled. WBAC are technical and operational requirements and guidelines of the well barrier. The main functional characteristics of permanent barrier are mentioned earlier, and repeated below (NORSOK, 2013):

- Impermeable
- Long term durability at downhole conditions
- Non – shrinking
- Ductile or non-brittle
- Resistance to downhole fluids and gasses
- Good bonding to casing and formation

To be able to evaluate if a material fulfills the requirements mentioned above, both laboratory measurements and test can must conducted, as well as testing in the field. Some of these qualification methods are mentioned and briefly discussed further in this chapter. Even though there are seven different main criteria, some of these are overlapping each other. One of the criteria involves long term durability of the plugging material. To be able to achieve this, the material needs to be designed in such a way that it can withstand harsh downhole environments, which is a point by itself in the list above. Further in this subchapter some laboratory methods to investigate the properties of a material are explained, as background information for further testing of a new plugging material. Subchapter 1.7 further describes the field testing and verification of the well barrier materials.

1.6.1 Sealing capability

The purpose of a permanent barrier is to prevent unwanted flow, and the sealability of the plugging material is therefore of big importance. The sealability of a material is a function of the materials permeability. Ideally a good sealing material would have a very low permeability and almost be impermeable. The seal entry pressure is the capillary pressure at which fluid leaks into the pore space of the material, therefore the measure of the capillary pressure could give an indication on the sealing capability of the material. Capillary pressure could be measured in a laboratory by one of the following methods mentioned below (Khalifeh, 2019a):

- Mercury porosimetry
- Porous-plate method
- Centrifuge method

In the field, the sealing capability of the plug is determined by pressure testing the set plug. This method is further described in subchapter 1.7.

1.6.2 Bonding capability

Permanent plugging materials must have sufficient bonding properties with both formation and steel tubulars. Shear load and tensile load can cause bond strength failure, which also called debonding. These loads to the barrier material can be caused by thermal cycling, hydraulic forces, volume changes of material, tectonic tresses or a combination of the stresses mentioned (Khalifeh, 2019a). Shrinkage of plugging material or thermal expansion of casing when plugging material is placed inside the casing, may result in tensile failure of bonding.

Shear bond strength defines the bond that mechanically supports the pipe in hole, and can be found by measuring the force applied to move the pipe inside a sealing material. *Tensile bond strength* is the force which acts perpendicularly on the contact surface. *Hydraulic bond* is defined as the bond between two surfaces, which helps to prevent fluid flow between the two surfaces in contact (Khalifeh, 2019a). Shear, tensile and hydraulic bond strength are examined individually in laboratories and studied to be able to say something about the bonding material properties of different plugging materials.

1.6.3 Durability

A permanent plugging material must preferably keep its initial quality, this is referred to as durability. To examine a materials durability, aging tests could be carried out in laboratories. The tests could be carried out with placing a sample of plugging material in fluids which are similar or identical to the wellbore fluid which the material is going to be exposed to, and then study the samples properties after a given time in this fluid.

1.7 Well barrier verification

Permanent well abandonment is done for an eternal perspective, therefore its essential to verify the quality of the barriers set in place. The standards for well integrity also address this topic, different testing procedures for verifying the barriers are often identified (NORSOK, 2013). The verification process of the barrier may differ from one barrier to another.

In the beginning and planning stage of a permanent P&A operation, evaluating the well configuration is important. Depths and specifications of formations which are sources of inflow must be identified and familiarized. Based on the number of potential reservoirs, one can decide the number of plugs and where to place them. The depth interval of the plug must also be examined, the formation which is going to be a part of the barrier needs to have acceptable properties like appropriate strength, be impermeable and show no sign of fractures and faulting. The casing annulus must be logged to verify sufficient length of acceptable cement to the barrier envelope. It is desirable to execute the permanent plugging operations as efficiently as possible, but not compromising the long term well integrity. The most cost efficient form of permanent P&A is when it is possible to use the existing casing strings and primary casing cement as WBE. The cost of the barrier in that case, would only be the cost of placing the plug inside the casing.

To evaluate the possibility mentioned above, the top of cement (TOC) behind the casing string should be located, making it possible to find the sufficient length of the cemented interval behind the casing. If the interval is long enough for placing a barrier, and located in a place where the formation has acceptable WBE criteria, the quality of the primary cement must be assessed. This is done using various logs which include temperature surveys, acoustic logs, cement bond logs (CBL) and variable density logs (VDL) (Benge). Logs of the primary cement operations can be used, but often new logs are run before the P&A operation. Data like slurry rate, density, pressures, returns and volumes pumped recorded in real time gives a better understanding of the cement job execution, and the data can be analyzed and used to check the quality of primary cement (Khalifeh, 2019a). The reading of the CBL and VDL logs is dependent on calibration factors and personal interpretation, and hence the conclusions may differ depending on who interpreted the results of the logging. The downhole condition is another factor affecting the logs measurements, cause these tools are designed for an ideal case where the tool is centralized in a wellbore of uniform size. These weaknesses have inspired service companies over the world to develop and evaluate alternative logging tools and methods for cement job evaluation, including acoustic tools, temperature logging, noise logging, resistivity logs, oxygen activation logs, X-Ray measurements, Gamma-Gamma density measurements, Neutron-Neutron logging, and fiber-optic measurements. However, few of the alternative methods mentioned above are used for cement evaluation at this point of time (Khalifeh et al., 2017). The next step in the process after identifying good cement, is to prepare for a cement plug by retrieving tubing and setting a foundation for the plug. The foundation could be a mechanical plug as shown to the left in Figure 1.5, or a viscous pill pumped in place as illustrated to the right in Figure 1.5 (Khalifeh, 2019a).

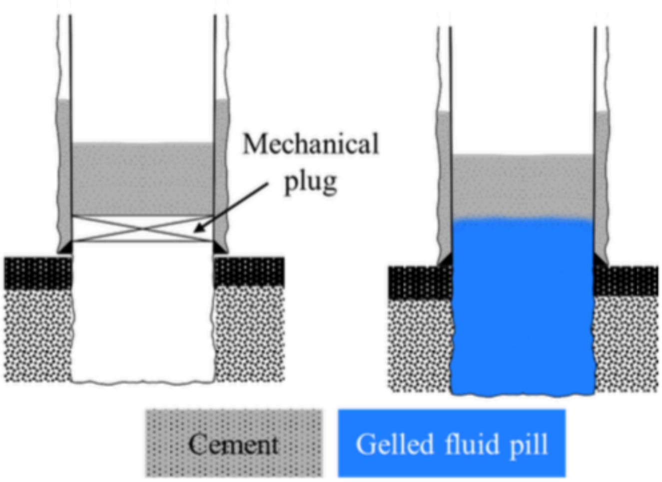

Figure 1. 5 Cement plug on foundation (Khalifeh, 2019a)

If the logs indicate poor or non-existing annular cement, other solutions need to be applied. One need to access the annular space behind the casing and establish a new formation to formation barrier. The option is often section milling or PWC, these procedures are described under subchapter 1.4.1 and 1.4.2. Both after milling and PWC the position and sealing capability of the final barrier envelope must be tested and evaluated after completion.

To verify the depth and sealability of a set plug, the cement is dressed of and TOC is identified by tagging. Cement plugs placed on mechanical barriers don't need to be tagged, because TOC can easily be calculated from the volume of pumped cement. The verification of the plugs sealing capability is done by either pressure testing, or weight testing. When you have a mechanical foundation to your cement plug, the mechanical plug is usually tested and if it passes the pressure test the cement plug installed on top is not tested once more. However, if your mechanical barrier fails the pressure test, the cement plug is tested as well (Khalifeh, 2019a).

There are two types of pressure tests that can be conducted to verify the sealing capacity of a plug, a positive and a negative pressure test. A pressure test is done by applying a given pressure above the estimated leak of pressure, and monitoring the pressure as illustrated in Figure 1.6 a. It is considered a good test if the pressure does not leak of to the surroundings. When applying pressure to the plug, one must be careful to not exceed the burst strength of the casing, to avoid any damage of the casing. A negative pressure test is also referred to as a leak of test or a drawdown test. During a leak of test, the well pressure is dropped, and the pressure build-up is recorded, a key parameter here is that the pressure underneath the plug must be higher than the pressure above the plug as illustrated in Figure 1.6 b. The test is considered successful if there is no pressure build-up recorded (Khalifeh, 2019a).

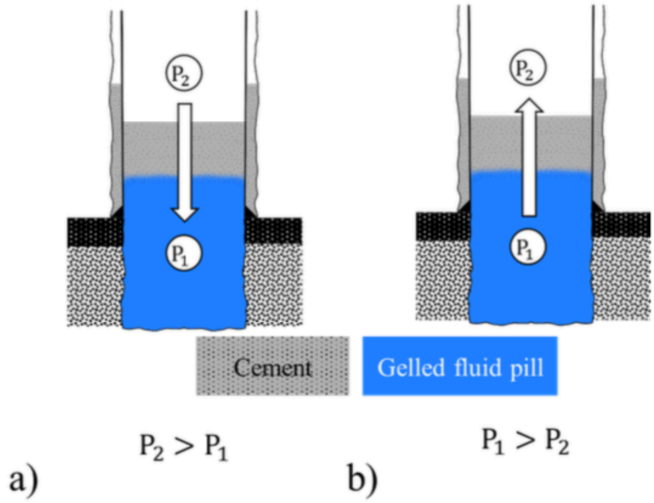

Figure 1. 6 Pressure testing of installed plug inside casing(Khalifeh, 2019a)

1.8 The Objectives

Permanent plug and abandonment of wells is a topic within the drilling industry which has gotten more focus the last few years, because large number of wells on the NCS are approaching the end of their lifetime. Permanent abandonment of wells introduces significant investments with no financial return, and is a massive expense for the license holders, the State, and the Norwegian taxpayers which contribute with 78% of the total cost of plug and abandonment activities. A reduction in P&A cost would therefore be beneficial for the people in the company that is operating, but also for the other stakeholders and contributors.

To be able to reduce the cost of permanent plug and abandonment operations, existing technology needs to be optimized and new time and cost effective methods needs to be developed. As of today, significant amount of permanent plug and abandonment operation time is used for cut-and-pull operations, or milling operations due to inability to pull cut casing. These operations are very time consuming, and therefore also costly. Barite settlement behind casing is a factor causing complications under pulling operations (Saasen, 2018). The barite and other solids settled behind the casing holds the casing back with enormous forces, and makes pulling operations time consuming and thus costly. If settled barite mixed with other solids behind the casing could function as a part of the barrier envelope in permanent P&A, valuable time could be saved. This will be based on the pre-condition that any other cement jobs on outer casings are already approved for use as a barrier, and that the settled solids are at a depth where formation strength and permeability satisfies the requirements for barriers against the identified reservoirs. To be able to verify settled barite as a permanent barrier material, loads of parameters needs to be studied and examined.

This thesis will introduce an approach on how to work towards a goal of utilizing settled barite in the annulus as a permanent barrier material. The thesis describes some theory about barite and laboratory work investigating barite. In the thesis, some experiments are initiated to develop a start point for further laboratory testing and investigation. In collaboration between the University of Stavanger and Equinor, a set up for pressure testing of barite is manufactured, with the aim of inspiring other students to conduct further testing on the topic based on the set point values obtained within this thesis. Ultimately, the objective of this thesis is to help the industry investigate barite settlement as an opportunity, and not a challenge.

CHAPTER 2

BARITE AND SETTLEMENT MECHANISMS

2.1 What is Barite

Barite is a mineral composed of barium sulfate ($BaSO_4$). The name barite comes from the Greek word “barys” which is translated to heavy, a precise name considering barite’s high specific gravity of 4.5. The high specific gravity makes the mineral suitable for a wide range of industrial, medical and manufacturing uses. Barite is one of the few nonmetallic minerals with a specific gravity of four or higher, this combined with properties like low Mohs hardness (2.5 to 3.5) and three directions of right-angle cleavage, makes it easy to identify the mineral. $BaSO_4$ is virtually insoluble in water. Barite quality vary from mine to mine. The mineral may not be 100 per cent pure, and it often contains other substances and impurities such as heavy metals. The barite imported to Norway today, is not 100% pure, and has a specific gravity of 4.15.

Figure 2. 1 Barite minerals from UiS laboratories

Barite frequently occur as concertation and void filling crystals in sediments and sedimentary rocks. Large accumulations of barites are often found at the soil- bedrock contact where carbonate rock units like dolomites or limestones have been heavily weathered. Barite is also found as concretions in sand and sandstone, these concretions grow as barite crystallizes in the spaces between the sand grains. When barite crystalize like this its often called “barite roses”, and they can incorporate large number of sand grains. Barite is used as a pigment in paints, as a weighted filler for paper, cloth and rubber, but the most mined barite is used as a weighting agent in drilling muds. The mineral is extracted by mining, and Morocco is the main source of barite for Norway’s petroleum industry (King, 2019).

2.2 Drilling fluids and barite

In petroleum industry, drilling fluids are used for several purposes like removing drill cuttings and lubricating and cooling the bit and drill string while drilling. Another functionality of the drilling fluids is to provide enough hydrostatic pressure to control the formation pressure, for this purpose weighting agents like barite are added. Drilling fluids may be divided into three main groups conferring to the continued phase that is used while drilling: gaseous, water-based (WB) or oil-based (OB) drilling fluids. Gaseous drilling fluids are rarely used for offshore operations; therefore, the focus will be on WB and OB fluids. WB fluids have a saline water solution as a base, while OB fluids have a hydrocarbon base (American Society of Mechanical Engineers. Shale Shaker, 2005).

Oil based fluids are often favored due to their good technical performance. A disadvantage of the oil based fluids is that the OBM is costlier than the WBM. Another disadvantage of the oil-based fluid is that there are stricter requirements for treatment of drilling waste. The main technical advantages of oil-based drilling fluids can be summarized to
(American Society of Mechanical Engineers. Shale Shaker, 2005):

- Can be used in water sensitive formations like shale and clay
- Better lubrication and thereby increases the rate of penetration
- Prevents bit balling in clay
- Perform better in high pressure high temperature (HPHT) conditions

Additives are added to the drilling fluids to enhance their performances, the most commonly used additives include viscosity control, alkalinity and pH control, contaminant removal, lubrication additives, shale stabilization additives and density control additives (Bourgoyne et al., 1986). Density agents will be discussed in the following, with an emphasis on barite as a density agent.

To maintain well control under drilling, the density of the drilling fluid plays an important part. The density of a fluid can be controlled by using by adding additives like (Pettersen, 2007): bentonite, barite, ilmenite, hematite, magnetite, siderite, dolomite, calcite, manganese tetra oxide and salts. Because of barites high density, virtual insolubility in water and low toxicity, the mineral is often chosen as the main weighting material. The most important environmental differences between barite and other density additives, are associated with differences in production, metal discharging potential and transportation. Barite is traded globally and imported to Norway, while other density additives do not need to be imported, as there are naturally occurring in Norway. An example of this could be that Norway has its own source of ilmenite in Sokndal. Even though barite needs to be imported, it is the main density additive used.

2.2.1 Requirements for barite quality

Barite is used as a weight material, and is often preferred over the other additives because of its high density, insolubility in water and low toxicity. Barite as a weight material consists of approximately 90 per cent $BaSO_4$ and other materials, the composition of the barite varies depending on various barite deposits. Novatech describes analysis of barite samples which have showed to hold various mineral components such as (Gass, 1995):

- Siderite ($FeCo_3$)
- Feldspar ($NaAlSi_3O_8$)
- Quartz (SiO_2)
- Calcite ($CaCO_3$)
- Dolomite ($CaMg(CO_3)_2$)

When barite occurs in sedimentary form, the content of heavy metals is normally lower than in intrusive deposits. Chemical analyses are important to examine the heavy-metal content between the various barite deposits used. Norwegians government requirements for barite were first presented in the 92:03 guidelines from the Norwegian Pollution Control Authority (SFT – now the NEA). Here it was specified that barite intended for use in the drilling industry must have the lowest possible content of heavy metals. The operators must document procedures for quality control of barite. The technical requirements for barite quality, given in API standards are (Gass, 1995):

Density:	min 4,20 g/cm^3
Soluble metals, about:	max 250 ppm
Residual wet screened, 75 µm	max 3.0%
Particles <6 µm	max 30%

Norwegian Oil and Gas recommended guidelines for barite quality – 046 recommends and concludes with letting operators choose barite with the lowest possible heavy-metal content, and instruct the operators to run quality control on the mineral. Information from the suppliers show that heavy-metal values are generally low, and heavy-metal levels in barite have not demonstrated toxic effects in fauna through discharge to the sea (Gass, 1995).

2.3 Challenges induced by barite

Barite settlement can be described as the phenomenon in which barite particles settle due to the impact of gravitational forces applied on the particles suspended in the fluid (Movahedi et al., 2018). Use of barite as a weighing material in drilling fluids causes several challenges in the lifecycle of a well, from the drilling phase of the well to the wells final stage. Another problem that has plagued the industry for years is barite scaling. This chapter gives a short introduction to the challenges introduced by settled barite and barite scales.

2.3.1 During drilling

As mentioned earlier, drilling fluids are used for several purposes like hole cleaning, lubrication and cooling of the drill bit, stabilization of the wellbore and bottom hole pressure control. Stability of the mud is therefore essential for a successful drilling operation. Settlement of barite particles causes density variations in the cross section of the wellbore, which generates pressure imbalance. When barite settles, it starts to slide due to inclinations. This phenomenon is known as barite sagging. Barite sagging is a serious problem of drilling muds in deviated wells, especially at inclinations above 30° (Skalle et al., 1997). The term "barite sag" is used for convenience because barite is the most common weight material. However, sag can occur with any solid, inert weighting agent including barite, hematite, ilmenite etc. Sag causes a decrease in drilling fluid density for fluids close to the surface, while the fluids closer to the bottom experiences increased density. This is known as non-linear hydrostatic pressure gradient. Although inclination is one of the main parameters for barite sagging, experimental and operational studies have shown that the most sagging occurs during circulation, especially at laminar flow regimes (Hanson et al., 1990). Problems continue despite the general agreement on the causes of sagging, and the best practices for its mitigation. Failure to execute a sag management program could lead to several serious drilling complications including (Scott et al., 2004):

- Lost circulation
- Well control difficulties
- Poor cement jobs
- Stuck pipe, casing and logging tools

2.3.2 Barite scaling

Scale deposits are one of the most common and troublesome problems in both production and injection wells. The scales are precipitated as a consequence of change in the systems temperature and pressure, and due to mixing of incompatible waters. Seawater, which often have a high content of sulfates, is injected into reservoirs which need pressure maintenance. The formation waters often have high barium content, and mixing seawater with formation water often lead to barium sulfate ($BaSO_4$) depositions. If this happens near the wellbore, it will have a significant impact on the production. Barite scale could also form when producing from different zones, if one of the zones have fluid containing sulfates and the other zone has a high barium concentration. In both the cases described, large amounts of barite scale can occur (Kan and Tomson, 2012). Barite scales have plagued the industry for a long time, the scales interfere with fluid flow, enhance corrosion, may lead to equipment replacement and causes production losses, and large economical losses for the operators.

2.3.3 During P&A

Equinor conducted a study investigating which process during P&A operations was the most time-consuming one, and the results can be seen in the circle diagram represented in Figure 2.2 (obtained from (Mortensen, 2016)). Visibly the dominant part of P&A time is dealing with the casing.

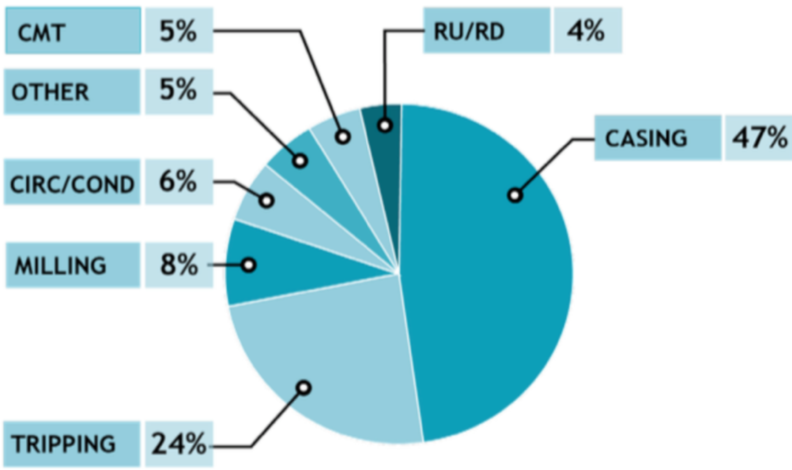

Figure 2. 2 Time consumption during P&A operations (Mortensen, 2016)

The casing part of the chart includes cutting and pulling of casing. This is done to either get access to the annular space behind the casing, or to pull the casing to the surface. Behind the casing, there is often settled and compacted barite. The settled barite is there due to a drilling fluid column which has been static over several years, and gravity has separated the barite particles into a sediment phase. When preforming cut-and-pull operations during well abandonment or slot recovery, casing is often stuck due to the sediments behind the casing holding the casing back with enormous forces. The sediment phase consisting of settled barite behind the casing can cause problems both under intervention and abandonments operations (Kleppan et al., 2016) (Joppe et al., 2017). An example of this has been observed In the North sea, where an operator had to make nearly 40 cuts, and used over 70 days to cut and pull 3000 meter of production casing from one well (Desai et al., 2013).

One of the explanations why the settled barite holds back the casing could be the friction and/or the bonding between the sediments and the casing. Another reason, and probably the most significant one, could be that the casing collars are stuck in the annular sediment like illustrated in Figure 2.3 (Saasen, 2018).

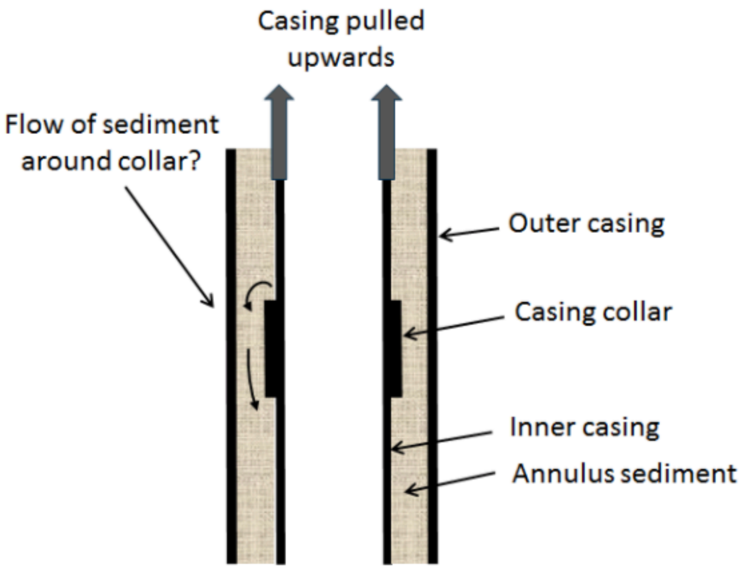

Figure 2. 3 Illustration of possible cause of stuck casing during casing pulling operations (Saasen, 2018)

If the annulus sediment is compacted and hard as a solid, then the casing collars may be stuck in the annulus sediment. However, if the annular sediment behaves like an unconsolidated slurry, then it would be easier to pull the casing upwards. Hence, the consistency and rheological properties of the annular sediment determines how easy it is to pull the casing (Saasen, 2018).

2.4 Barite settlement mechanisms

Barite sag is a complex phenomenon, and to be able to understand the phenomena better a review of the kinetics of barite sag is considered essential. In order to get a good understanding of the barite settlement process this subchapter will include a brief overview of the study that has been done to understand barite settlement in pipes under static and under dynamic conditions. The effect of fluid density on settling mechanism is also discussed.

2.4.1 Hindered and boycott settling kinetics

The settling phenomenon was first introduced by Boycott (1920), his observations of blood corpuscles in narrow tubes lead to the first illustrations of settings in vertical and inclined tubes. Boycotts experiments showed that the sedimentation rate of the particle is a function of tubing inclination (Boycott, 1920). Later other studies conducted by (Hanson et al., 1990) (Bern et al., 1996) (Bern et al., 1998), suggested that the trend was the same when studying barite sag in drilling fluids. The kinetics reported by Boycott are illustrated and compared in Figure 2.4 (Zamora, 2009). In both cases particles that are denser than the suspending fluid settle vertically due to gravitational forces, at a speed of v_0 indicated on the illustration with a bold arrow.

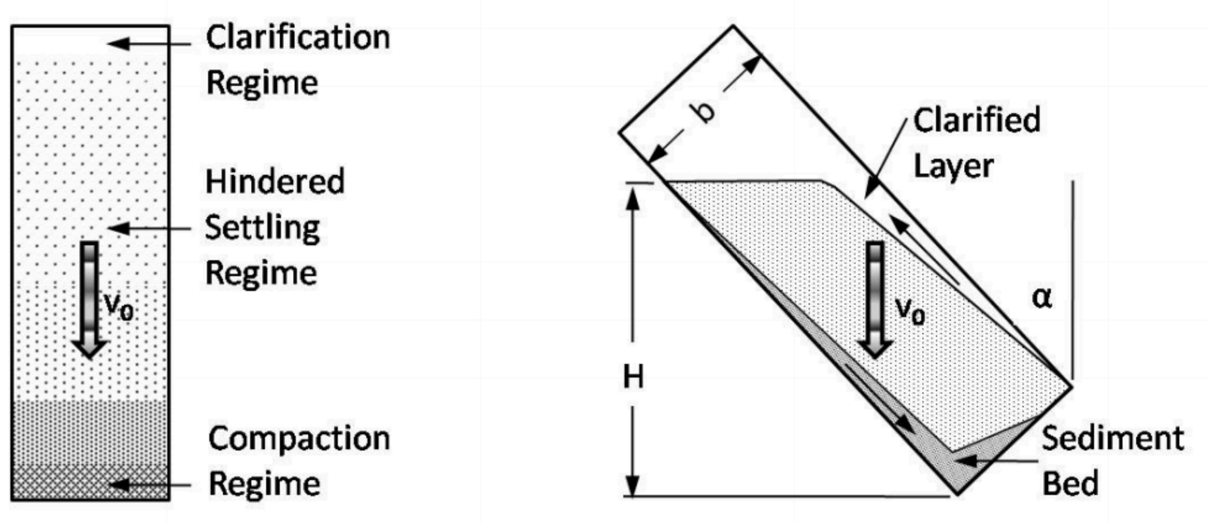

Figure 2. 4 Hindered and Boycott settling kinetics (Zamora, 2009)

Figure 2.4 is obtained from (Zamora, 2009). The drawing to the left illustrates settling in a vertical tube, also referred to as hindered settling. The settling regimes can be divided into clarification, hindered settling and compaction regime, and the concentration of particles increases from bottom to top. In the clarification regime Stokes laws applies. The few reminding particles do not interfere with the tube walls, and the particles in this regime settle individually. In the hindered settling regime, the concentration of particles is sufficiently high, this may cause the particles to agglomerate and form clusters. The settling rate of these clusters can be somewhat higher than individual particles due to their increased size. The compaction regime at the bottom of the tube consists of particles that support each other mechanically, and the fluid in the compaction regime is squeezed out upwards as the bed compacts (Zamora, 2009).

As right drawing in Figure 2.3 illustrates, the kinetics are changed noticeably during settling in an inclined tube. Particles still settle vertically but the path that the particle travels until it reaches the sediment bed is reduced. The clear-fluid layer referred to as the clarified layer in the illustration, forms quickly on the top side along the tube. Excess fluid from the sediment bed in the bottom flows upward along the boundary between the clarified layer and the denser layer due to buoyance. The clarified layer provides a pathway for displaced fluid to escape efficiently. Particles accumulate on the low side faster, and the sediment bed grows and slumps downwards and concentrates at the bottom of the tube. Maximum clarified layer velocity occurs when the inclination is around 45°. If the inclination is increased the buoyance effect on the clear layer is reduced and settling rate also reduces proportionally (Zamora, 2009). Because of the settling kinetics, sagging happens at a faster rate in inclined tubes than in vertical tubes. Hindered settling also applies for horizontally placed tubes (Zamora, 2009). There are also several other parameters effecting settling, some of these will be discussed in the following.

2.4.2 Settling under dynamic conditions

Saasen et al., 1995, where among the pioneers who experimented and tested barite sag settlement in inclined tubes (Saasen et al., 1995). Experiments were preformed to evaluate the barite settlement under static conditions. After a while experiments showed that settlement occurred not only under static but also dynamic conditions. (Skalle et al., 1999) research showed that the settling rate increased during laminar flow conditions. In 2009 several experiments conducted by (Nguyen et al., 2009) showed that particle settling in tubes could be decreased by lowering rotation speeds. Taguchi and ANOVA methods where used to design several experiments to investigate the effects of drilling parameters on settling of particles under dynamic conditions. The results implied that the drilling parameter which affected the settling of barite particles the most was the fluid velocity (Nguyen et al., 2014). Research has also shown that increased drill string rotation leads to significant higher settling rate (Omland, 2009). Vibration of a fluid affects fluid structures and removes fluid yield stresses, this contributes to accelerate the sag process (Saasen and Hodne, 2016). When studying barite settlement between the annular space between two canings, the last point about how vibration affects the sag process is more relevant than drill string rotation. Drilling or tripping in and out of hole, could lead to casing vibrations in the casings around the drill string. This vibration is transferred to the fluid in the annular space behind the casing, and may accelerate the settlement of weighing agents such as barite in the annular fluids.

2.4.3 The effect of fluid density

There are two factors affecting sag of weight material in drilling fluids that can be related to the drilling fluids density. The lower the density of the drilling fluid, the less is the consequence of sag on the density of the fluid. When a particle is moving in a liquid, a counter flow of fluid fills the volume from where the particle is moving from. If the density of a fluid is low, meaning that there are only a few weight material particles in the fluid, the velocity obtained in this counter flow is not significant. If a drilling fluid is denser, this means a large volume of weight material will be settling, and a great volume of fluid will be active in the counter flow. This means that an increased drilling fluid velocity results in an increased resistance toward settling motion (Saasen, 2002).

Calculations on settling and resistance to settling showed that the drilling fluid density where sag problems could be most difficult to manage is equal to 1,55 s.g in water-based drilling fluids, and somewhat lower in oil-based drilling fluids (Saasen, 2002).

2.4.4 Additional parameters impacting sag

Temperature, wellbore angle, dynamic condition and viscosity are parameters affecting the settlement of barite particles. Omlands PhD identified the following additional parameters to have a significant impact on sagging (Omland, 2009):

- The particle shape has a meaningful impact on sag mechanisms, experiments showed that particles with a broad size distribution had a lower settling rate then narrow size distributions
- Vibration can increase the settling rate dramatically. For drilling and completion operations this would have a negative effect, however, for operations where enhanced settling is required this could be a technique.
- The amount of shear energy applied to the fluid, is inversely proportional to settling potential of the fluid.

CHAPTER 3

BARITE AS A PERMANENT BARRIER MATERIAL

The question regarding barite as a permanent barrier material is still unanswered in the industry today, and the answer to this question will most likely have to be found in several stages. Numerous questions must be answered and experiments conducted before this idea can be out into practice. This chapter provides an overview of which stages the industry must go through before barite, or barite mixed with other solids, can be considered as a permanent barrier material. Each stage is so comprehensive, it could alone be the subject of one or several theses.

A recommendation on how annulus cement can be verified is given in NORSOK D-010. Casing cement is by far the most used external WBE in the industry today, and therefore the recommendations in the guidelines for casing cement would be our reference point in this work. NORSOK D – 010 states that the external WBE shall be verified to ensure a vertical and horizontal seal, and the requirement is 50 meter with formation integrity at the base of the interval. If the casing cement is verified by logging, a minimum of 30 meter interval with acceptable bonding is required to act as a permanent external WBE (NORSOK, 2013).

3.1 Barite plug

Barite plugs have been used in the industry, and are made from barite weighting materials, water and a thinner. The barite plugs are effective in means of controlling active gas zones in wells while regaining circulation, searching for a transition zone or tripping (Messenger, 1969). The slurry is pumped through the drillpipe and is placed at the bottom of a wellbore as near to the active zone as possible. The weighing material settle but do not set solid, however the unconsolidated plug can provide effective and low cost pressure isolation. The plug is easily removed, and is often used as a temporary facility for pressure isolation or as a platform enabling treatments above the plug. Barite has shown good sealing capabilities due to these properties:

1. Low viscosities and yield points: allows the barite to settle to form a plug in a short amount of time
2. High density: they increase the hydrostatic head on the active zone and helps with pressure isolation
3. High filter loss: they may dehydrate to form a solid plug downhole and they may cause the hole to slough and bridge itself

The effects of barite concentration, phosphate thinners, salinity of the mixing water and PH are discussed in (Messenger, 1969), and properties of many fresh water barite plug slurries are recorded.

3.2 Research questions

It is a broad process defining and developing a new well barrier material. Primarily the process starts with an idea, which is thoroughly studied and investigated, this may include several laboratory tests and preliminary testing. Khalifeh, M. 2019, developed a flow chart with research questions, which needs to be answered when investigating a new potential method or material for permanent plug and abandonment (Khalifeh, 2019b). The research questions can be seen in Figure 3.1.

There are some differences in investigating a new potential plugging material, and investigating an annular barrier, which has already been made several years ago. The barite has already settled in the annular space, and have been there for several years. The composition of the settled barite mixed with other solids vary from well to well to well, depending on which fluid was used to drill that specific section years ago. Thus, the material is not easy to recreate in exactly the state it is found in, in the field, cause the substance and mix of solids found in the annulus has been compacting under high temperatures and pressures over many years. The main focus of this chapter will be the questions regarding the sealability of the material, but identification and verification of barite are processes which also are going to be discussed.

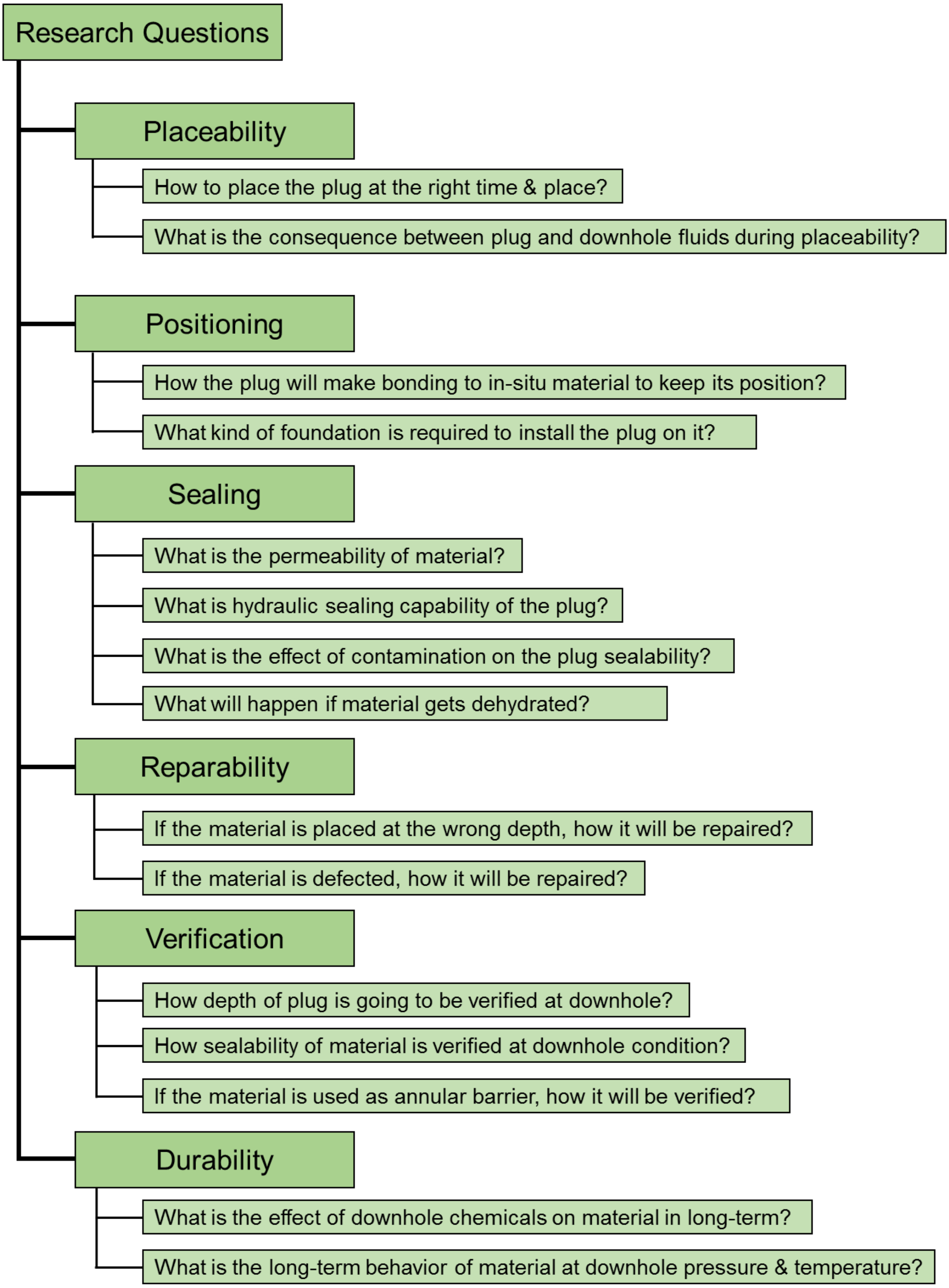

Figure 3. 1 Research questions (Khalifeh, 2019b)

3.3 Barite and other solids settled behind casing

When drilling a new hole section, an appropriate mud for that section is used. After drilling, casing is run and cemented in place. During cementing, the drilling mud used to drill that specific section is pushed upwards by the cement. After a timeframe of several years, the drilling fluid on top of the cement is separated into several phases due to gravitational forces on the particles suspended in the drilling fluid. A simplified illustration of this separation of drilling fluids can be seen from Figure 3.2. The particles suspended in the static drilling fluid will separate into different phases, and two processes occur in parallel. Barite and other particles will agglomerate and create clusters. Between these clusters there will be created void spaces, where pure liquid may migrate to the top, and escape to the free liquid phase. This process is called syneresis (Saasen, 2018). The second process that occurs is the sag process itself, which is the process where particles settle in a less dense fluid.

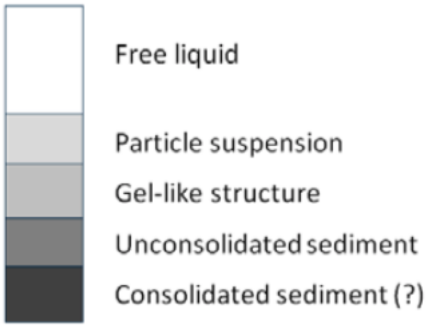

Figure 3. 2 Simplified illustration of typical sediment phases of gravity separated drilling fluids (Saasen, 2018)

This results in a situation as illustrated in Figure 3.2, the heaviest particles settle at the bottom and may form a consolidated sediment, the rate of compaction is dependent on the temperature and pressure of the system(Saasen, 2018). Smaller and lighter particles settle in the intermediate phase and may form a gel like structure (depending on which drilling fluid was used). On top, a layer of clarified fluid, or free liquid forms. If one could utilize this consolidated or unconsolidated settled barite as an annular barrier, valuable time during the P&A operation could be saved. The idea of using the settled barite as an annular barrier, will be based on the pre-condition that any other cement jobs on outer casings are already approved for use as a barrier, and that the settled solids are at a depth where formation strength and permeability satisfies the requirements for barriers against the identified reservoirs.

There are suspicions that the clean unconsolidated barite may not hold gas or other fluids back as a qualified barrier since it will be too willing to move upwards or downwards, or that it is permeable. This would need to be further tested in laboratories, and is a part of the experimental section of this thesis. If the settled barite acts like a compacted and solid annular sediment, the bonding to the casing may be sufficient, and the factor of a movable barrier could be removed. Another detail which one would need to think about regarding the settled solids behind the casing, is that it may not only be clean barite, but maybe a large percent of clay or other particles typically used in drilling muds. Practically you would rarely find an interval with just clean barite in the annulus, there would also be other particles mixed in the interval. Therefore, laboratory information on how other additives to a barite plug may affect the plugs sealability would be beneficial to investigate.

Barite which is used in drilling fluids is a grounded and powdered mineral, and in clean barite there are no smaller particles that glue or stick the grounded barite particles together. It can be compared to flour used when you bake. The flour is just a powder, you need certain additives like for example water, oil or milk to make the flour in to a sticky dough. It is the same case with barite, you need other chemicals and additives to be able to make the barite to a solidified WBE. And this is also a part which needs to be investigated in laboratories, which compositions of solids mixed with barite would be able to form an acceptable barrier.

3.4 Identification of settled barite

The first challenge the industry faces in the utilization of settled barite as a permanent barrier, is to establish a method or a logging tool which can show a certain length of interconnected barite or barite mixed with other solids behind the casing. As mentioned earlier, an interval of barite is rarely, or close to never just settled barite. The interval contains other particles, as well as fluid pockets, which makes it challenging to log an interval and interpret the result. The technology trends in cement job evaluation using logging tools are developing, and the engineering done here is of great importance when developing a method or tool for our purposes.

Top of cement is often followed by an interval of settled barite mixed with other particles, this is shown when logging top of cement. Already existing logging methods and tools for logging cement behind casing is our starting point to finding the most efficient way of identifying barite. Acoustic and ultrasonic logging tools are the standard tools used for cement quality measurement. However, these tools have some limitations regarding the measurements and interpretation accuracy. Adding to this, logs don't provide a continuous, real-time and long term monitoring of the external well barrier quality (Khalifeh et al., 2017). The industry has therefore strived to develop technology to deal with these shortcomings, and this technology includes:

- Temperature logging
- Noise logging
- Resistivity logs
- Oxygen activation logs
- X-Ray measurements
- Gamma-Gamma density measurements

- Neutron-Neutron logging
- Fiber optic measurements

Critical properties affect the measurements done by these tools. Some of these properties are downhole temperature and pressure, casing size and thickness, wellbore fluid properties, external well barrier element thickens, with many more. Trends in the cement logging tools technology indicate that acoustic measurements may be the leading technique in the near future for cement evaluation, because they are commercially available and they provide spatial resolution (Khalifeh et al., 2017). Noise logs are primarily used for examining well integrity issues. Oxygen activation logs have potential to be used for cement job evaluation, and X-ray measurements may have the potential as well. Could some of these methods be used or further developed for our purposes of logging a barite interval? The response of different tools to the settled barite interval, is still unknown.

When it comes to identification of settled barite, there are many techniques and methods worth investigating. The answer to the questions above, and many more, would need to be answered before a commercially available tool or method for barite identification is available. This topic is one of the main stages in utilizing settled barite as a permanent barrier material, and could alone be the subject of a bachelor not only one, but several student theses.

3.5 Verification of barite as a permanent barrier

After identifying an interval of settled barite, a method needs to be established on how to verify the interval as an acceptable annular barrier. NORSOK D-010 have recommendations and guidelines on how to verify different well barrier elements, and the methods used for quality checking barriers during permanent P&A is described in subchapter 1.7. NORSOK D-010 also have an own chapter containing "Well barrier elements acceptance tables" (WBEAT), which are tables describing acceptance criteria for well barrier elements. The tables describe the function, design, construction and selection of the barrier, as well as the initial verification procedures and monitoring of the barrier. In this thesis, Table 22 – Casing cement, and Table 24 – Cement plug are of special interest. As described earlier, cement should be used as a point of reference for the following work for barite. The two tables mentioned above can be found in the appendix of this thesis.

There are many mechanical defects that can happen under or after a cement job, typically after the cement has set. One example of a defect is microannuli. Microannuli are debonding channels between the external WBE and casing or between formation and the external WBE (Khalifeh et al., 2017). The main purpose of a cement job evaluation is to find out if any of these defects are present.

This would also be the purpose when logging the external WBE, whether it is settled barite or other solids.

When investigating barite as an annular barrier, one of the key questions is how it could be verified? Could we use some of the approaches described in today's guidelines, or do we have to develop a completely new approach? Could we investigate logs of barite, and be able to state that the annular barrier is good enough? The WBEAT for a cement pug states in point three that the cement recipe should be lab tested under representative well conditions. Should this also be done for the annular barite barrier? And from this, a new challenge arises, a method to take a sample of the external WBE needs to be in place before one can be able to test it in laboratories.

Earlier in the thesis, a problem regarding plug length and verification was briefly mentioned. Today's pressure test methods give a yes or no answer if the barrier can withstand a certain pressure. However, these results cannot be correlated with the requirements for plug length. WBEAT number 24 recommends plug lengths under point 8, and in cased hole the requirement is a plug of 50 meter measured depth. The 50-meter plug could in a worst-case scenario have just a few meters of good cement or other external WBE, but this would still be able to hold the pressure. In long term perspective, this barrier with just a few meters of good cement or good annular barrier would be more exposed to failure. This taken into perspective, one would have to find a suitable length of logged barite or other solids behind the casing to be suitable for vertical and horizontal sealing.

If logging is not sufficient to verify the annular barrier, an alternative method could be pressure testing the annular barite. This could be done by perforating and pressure testing intervals of interest to verify hydraulic sealing. One could pressure test each interval to minimum horizontal stress, and observe what happens. Another method could be to perforate the zone of interest and lowering the wellbore pressure and observe if there is a pressure build up at the surface. If there is no migration of pressures, hydraulic sealing is verified.

How to verify and quality check barite and barite mixed with other solids, as an annular barrier is an essential part of the equation when investigating how to utilize barite as a permanent barrier material. As introduced in the two last subchapters, identification and verification of barite as a barrier material are topics so comprehensive they could alone be the subject of a thesis.

3.6 Laboratory investigation of settled barite

Another phase in the investigation of barite as a potential well barrier material, is the laboratory testing that must be conducted to answer some of our questions. Questions regarding the permeability of the material, the hydraulic bonding properties, the durability of the material, and many more properties could be investigated in laboratories.

Alongside describing an approach of which stages the industry must go through to utilize barite as a permanent barrier material, laboratory investigation of barite is the second main topic of this thesis. Some basic tests will be conducted to give us information about the hydraulic sealing capability of the material. The laboratory work conducted in this thesis could be divided into three parts, the first part being an investigation of barite settlement in fluids with different viscosities. Based on this investigation, a fluid with the capability of making a barite plug is going to be recommended for further testing. After this stage, one of the samples is going to be pressure tested in large scale test set up. This is done to get a starting point, a value of how much pressure a clean barite plug could take before it fails. At a later stage, one can change the properties of the barite plug, for instance add another material, and then pressure test once more to see which impact the added material have on the sealability of the plug. A simplified set-up to pressure test barite and other material is manufactured with the intention of inspiration other students as well to investigate further on the topic. A third part of the laboratory investigation of barite done in this thesis, consists of testing a sample of settled barite using an Ultrasonic Cement Analyzers (UCA) device to analyze how the sample responds when running compressional waves through the sample. This could give us valuable information on the compressive strength of the sample, as well as it can give us information regarding what we can expect when logging barite intervals.

3.6.1 Settlement investigation

The first part, which consist of studying settlement of different mud samples, is done for two purposes. The main purpose is to understand the settlement process of the mud sample, because settlement of barite is an essential part of the thesis. Without understanding the settlement process, it is hard trying to figure out how the settled barite would look like in an inclined well for example. The other purpose of examining the settlement of different mud samples, is to be able to recommend one of the mud samples for testing in a larger scale.

When drilling, settlement of particles is a challenge, so ideally drilling fluids are designed to avoid this problem. But in this thesis, we want to expedite the settlement process to create a plug of settled material.

3.6.2 UCA testing

We are going to use Ultrasonic Cement Analyzers on mud samples congaing large amount of barite, to see if there can be extracted some applicable information. Even though the UCA device is primarily designed for test on cement samples, it could be interesting trying it out on a sample of settled barite to see if it could be successful. The UCA device gives an indication of a sample's compressive strength over time, while the sample is being cured under downhole temperature and pressure conditions.

3.6.3 Large scale pressure testing

After we have chosen a mud which we are going to test, a large scale set up described in the next chapter is going to be filled with the mud. The purpose of the large-scale test is to investigate how much pressure the settled barite in the set up can withstand before the barrier of settled barite fails.

The first testing would be conducted with a clean barite plug as possible. This would give us an indication on how much pressure clean barite could withstand, and could be used as a set point for other test. The same test done for the clean barite plug could then be conducted with barite and an increasing amount of other particles, for example clay. The goal here would be to see how other solids mixed with the barite affects the plugs ability to hold back pressure.

The pressure test done is a very simplified test. Its intention is creating a start point to a comprehensive process of testing and investigation. More tests must be done, and parameters investigated before conclusions can be made if settled barite is suitable as a permanent barrier material. In Chapter 5, a significant part is dedicated for discussing recommendations for future work, based on the testing initiated during this thesis. Here, numerous parameters are going to be discussed and recommended for further testing, to continue the work in assessing barite as a potential barrier material.

3.6.5 Study of rheological properties of barite sediment phases

An investigation of which sediment compositions are best fit as an annular barrier is essential in the work of utilizing settled barite as a barrier. A study investigating rheological properties of barite settlements obtained from different WBM gave some interesting results, and conducting tests similar like these might give us valuable information on which sediments can form acceptable barrier materials.

Vrålstad, Saasen and Skorpa conducted some preliminary studies on rheological properties of sediment phases obtained from two different water-based drilling fluids (Saasen, 2018). One fluid was a KCl/polymer based fluid, and one was bentonite-based. A picture of the two fluids after centrifugation at 3000 rpm, compared to a water and barite fluid as reference can be seen in Figure 3.3 below.

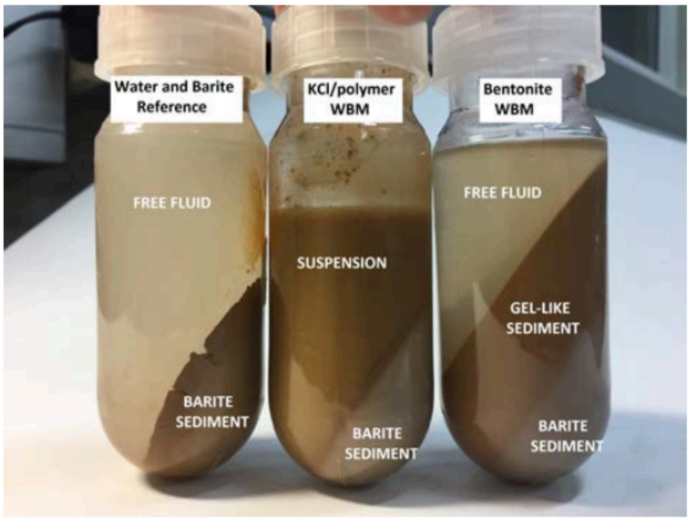

Figure 3. 3 Three drilling fluids after centrifugation at 3000 rpm and at 40℃ (Saasen, 2018)

The testing sowed significant qualitative differences between the sediments obtained from the two different WBM. The KCl/ polymer WBM separates into only two phases as shown in Figure 3.3, a barite sediment at the bottom and a liquid suspension phase at the top. The bentonite OBM separates into three different layers: barite sediment at the bottom, followed by a gel like intermediate sediment, and a free fluid phase at the top. The testing also showed that the sediment from KCL/polymer WBM deforms easier, and starts to flow at lower shear stress values than barite sediments form the bentonite WBM (Saasen, 2018).

With respect to both number of sediment phases and the yield and flow stress values obtained from these tests, there is an indication that it is harder to remove a casing when there is a bentonite WBM in the annulus. In the purpose of using the settled sediment behind the casing as an annular barrier, this could indicate that settlements obtained from bentonite WBM may have better properties like better bonding and less deforming, than the barite sediment from KCL/polymer WBM.

3.7 Acceptance and guidelines

As described in this chapter, it is a broad process defining a well barrier material. Primarily the process starts with an idea, which is thoroughly studied and investigated, this may include several laboratory tests and preliminary testing. After successful testing, general acceptance criteria and requirements must be established for the industry guidelines. In NORSOK D-010, this would for instance require a new Well Barrier Element Acceptance table. To be able suggests such a table for a new annular barrier material, one can use the tables for Casing cement and Cement plug as a reference pint and inspiration to create a new table.

CHAPTER 4

EXPERIMENTAL METHODS

4.1 Chemicals

During the experimental work done in this thesis several recipes of mud where mixed for testing. This chapter gives an overview of which chemicals where used for which experimental section, and all the recipes used can also be found here. Barite will not be described under this section, as it is thoroughly described in the previous chapters.

4.1.1 Turbiscan fluids

The fluids tested in the Turbiscan, are fluids consisting of only water, barite and Xanthan Gum (XG), also known as XC polymer. The Xanthan Gum is a biopolymer, which is used commonly used in the drilling industry. Biopolymers are polymers which are made from living organisms. The polymer is a thickening agent, it is very effective when trying to increase viscosity of a liquid. It can also serve as a stabilizer to prevent the ingredients from separating (UiS, 2015). The polymer is difficult to dissolve in water, without creating fisheyes. One need to be careful when mixing it. The four recipes tested with the Turbiscan can be seen in the tables below. Recipe 1 have a much higher concentration of Xanthan Gum then a usual drilling fluid would have.

Table 4. 1 Recipes with Xanthan polymers

Recipe 1	
Water	350 ml
Xanthan	3 gr
Mix for five minutes	
Barite	30 gr
Mix for five minutes	

Recipe 3	
Water	350 ml
Xanthan	1 gr
Mix for five minutes	
Barite	30 gr
Mix for five minutes	

Recipe 3	
Water	350 ml
Xanthan	0,5 gr
Mix for five minutes	
Barite	30 gr
Mix for five minutes	

Recipe 4	
Water	350 ml
Xanthan	0,25 gr
Mix for five minutes	
Barite	30 gr
Mix for five minutes	

4.1.2 Oil based mud with barite

In the UCA machine an invert oil based mud was tested. Invert emulsion means that water is emulsified in an oil, the oil would be in a continuous or external phase while water droplets are in the internal phase. A list of the chemicals used, and their main properties are listed below:

- Mineral oil EDC 95-11

Mineral oil EDC (Environmental Drilling Compound) 95-11 is a synthetic base fluid. Its designed by Totals Special Fluids department to minimize environmental risks, and maximizing operator safety, as the oil based muds introduces several HSE issues.

- $CaCl_2$ solution

The water phase in the mud consists of a particular saline solution. Which saline solution to use is decided by which salinity you want your mud to have, depending on where you are going do drill. The saline solution used in this recipe is $CaCl_2$.

- Emulsifier One-Mul

The principle of the emulsifier is to reduce the surface tension between the two immiscible fluids. The ONE-MUL liquid emulsifier provides exceptional emulsion stability, filtration control and temperature stability (Schlumberger, 2010).

- $Ca(OH)_2$

$Ca(OH)_2$ also called lime, is added to make Ca^{2-} ions to make the surfactants work as they should.

- Versa Vert Vis

This is an organophilic clay which is added to the mud such that the mud achieves the sufficient gel strength for its purpose.

- Versatrol

Versatrol is a naturally occurring asphalt used as a filter loss reducing agent. It is designed to use in high temperature high pressure (HTHP) cases

Table 4. 2 Recipe 5 - OBM

Recipe 5 – OBM with extra barite		
1	Mineral oil (EDC95-11)	206 ml
2	$CaCl_2$ - solution	60 ml
	Mix for two minutes than observe the fluid	
3	Emulsifier (ONE-MUL)	10 ml
4	$Ca(OH)_2$	8,5 g
	Mix for two minutes and observe the fluid	
5	Organophilic clay (Vera Vert Vis)	5,5 g
	Mix for five minutes	
6	Filter loss reducing agent (Versatrol)	6 g
	Mix for two minutes	
7	Barite	130g
	Mix the fluid ten minutes	

4.2 Equipment

The experimental work done in this thesis can be divided into several parts. The first part is preparation of drilling fluids and measurements of the prepared fluids properties. This part gets a section of its own when describing the equipment used. The second part of the experimental work consists of studying the barite settlement of the prepared drilling fluids, by visual inspection and by using a machine called Turbiscan. The third part is the testing done with the UCA device. The fourth and last part of the experimental work of the thesis consists of pressure testing a barite plug obtained by a predetermined drilling fluid. Equipment used in the different sections is described in more detail in the sections below.

4.2.1 Mixing and measuring drilling fluids

When preparing the drilling chemicals as described under section 5.1 where used. The equipment used to prepare the recipes described is: a weight, plastic vessels, a transparent measuring cylinder and a blender. The mixing of mud is performed in laboratories at The University of Stavanger (UiS), and therefore also the equipment available there was used. The blender which was used for Recipe 5 can be seen in Figure 4.1, and it is a standard Hamilton Beach Scovill mixer.

Figure 4. 1 Mixing equipment

Figure 4. 2 Fann Viscometer

For mixing Recipe 1-4, a more modern mixer called Heidolph was used. After mixing the fluid, the viscosity of the fluid vas measured using a viscometer. The model used in these experiments was the Fann Model 35. This viscometer is widely known as the standard of the industry for drilling fluid viscosity measurements, and it can be seen in Figure 4.2.

4.2.2 Turbiscan

The Turbiscan machines are used to characterize the dispersion state of different fluids. The machines have a wide range of application, not only the Petroleum business but also in the pharmaceutical and cosmetics business for example. Changes in terms of size and concentration of the content of the fluid are continuously monitored. This enables faster and more relevant characterization of a fluid sample compared to common methods such as visual observation or centrifugation of the fluid.

The principle of the Turbiscan is a technique consisting of sending photons into a sample. These photons are being scattered numerous times by objects in suspension like for example droplets, solid particles or gas bubbles. The scattered photons emerge from the sample and are detected by the measurement device of the Turbiscan, either a backscatter (BS) detector or a transmission (T) detector. Illustrations of the device can be seen in Figures 4.3 and 4.4.

Figure 4. 3 Turbiscan device

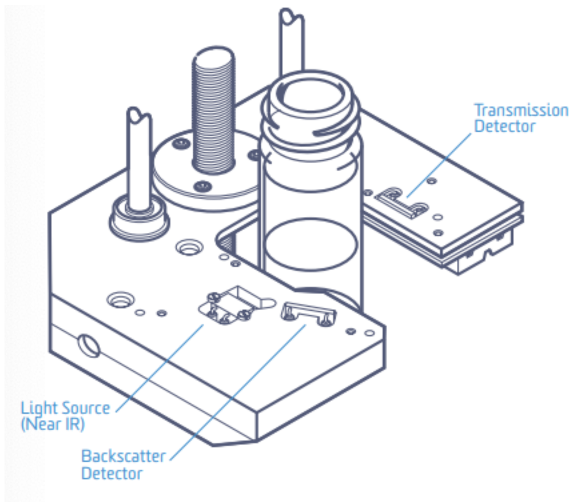

Figure 4. 4 Turbiscan concept (Formulaction, 2017)

The Turbiscan software then interprets the obtained data. The measurement enables qualification of several parameters, such as BS and T which are values linked to particles average diameter and the volume fraction. Based on the measurements, the software also creates a few plots which can be interpreted to analyze the stability, particle migration and particle variation of the sample (Formulaction, 2017). An example of these plots is shown if Figure 4.5.

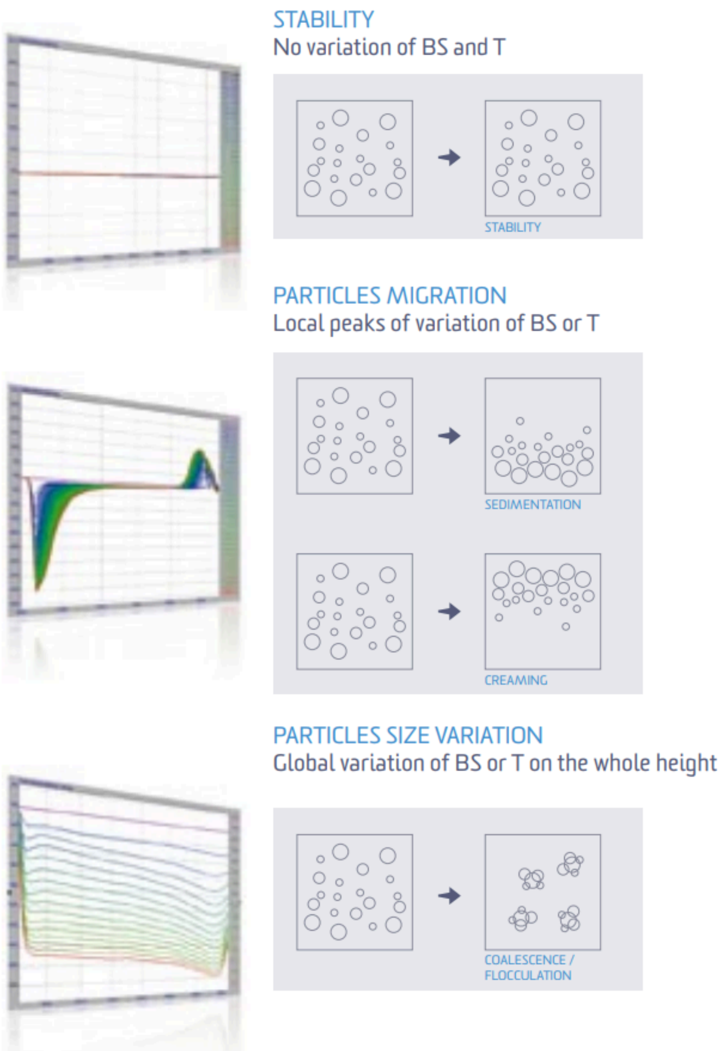

Figure 4. 5 Output plots from Turbiscan software (Formulaction, 2017)

No variation of BS and T indicates a stable sample, and local peaks of variation of BS or T illustrated in the plot in the middle of Figure 4.5, indicates particle migration. A global variation of BS and T overall height of the plot indicates a high variation in particle sizes. Another output of the Turbiscan is The Turbiscan Stability Index (TSI), which is a number single number that characterizes the stability of the sample. Further description of the output graphs will be given in in Chapter 5, results and discussion.

4.2.3 Transparent pipe

After studying and analyzing a few drilling fluid samples, one of the samples is going to be pressure tested in a large scale set up. This setup is modified, and it consist of a 3.5-meter long transparent pipe with a diameter of 5 cm. The tube is placed vertically along a rod which it is attached to. Along the tube there are four pressure measuring gates which are connected to two pressure gauges. Gauge one is measuring the pressure difference across pressure port one and pressure port three, while gauge two is measuring the pressure difference between pressure port two and four. The distance between the pressure ports are 75 cm.

The top of the pipe is open and the intention is to fill the pipe from above with the desired fluids. There is placed a gate valve at the bottom of the pipe, to be able to open the bottom when emptying the contents of the pipe. Right above the valve, there is a pressure input which is connected to an ISCO pump. The pump is going to be used for pressure injection by injection water. A camera is going to be set up to record the pressure testing, so one can visually inspect the several times.

Figure 4. 6 Pressure gauges

Figure 4. 7 Inlet at the top side of the pipe

Figure 4. 8 Pressure inlet and gate valve to open and close the pipe

In Figure 4.9 a simplified technical drawing of the large-scale pressure test set up can be seen. In the lower end, one can see the gate valve, and above it the round pressure inlet. The four squares represent the pressure ports, which are connected to the gauges. In Table 4.3, a small summary of the main measurements of the pipe are given. Our preliminary studies show that a typical 1 m barrier should be able to hold up to 3 bar. This value was estimated for a reservoir with 150 bar pressure and at 1200 m TVD.

Table 4. 3 Main specifications of pipe

1	Inner diameter pipe	5 cm
2	Length pipe	3.5 m
3	Length in between pressure ports	75 cm

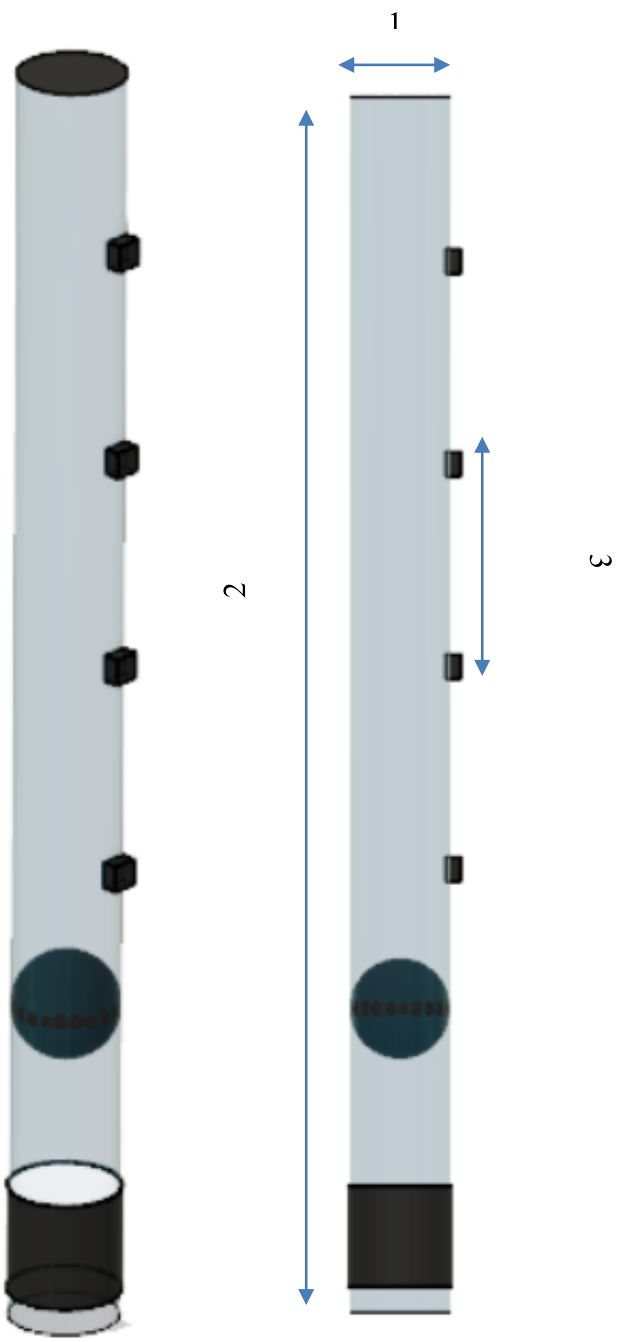

Figure 4. 9 Simplified technical drawings of the pipe

4.2.4 UCA device

The ultrasonic cement analyzers (UCA) device provides data on the compressive strength of a cement sample. The concept of the device is sending compressional waves through a sample, and measure the travel time of the ultrasonic waves through the sample. This is done while the sample cures under simulated high temperature and high pressure conditions. The sonic signal is correlated to the transit time. When a sample has a high compressive strength, the transit times are minor compared to less dense samples.

4.3 Experimental Methods

4.3.1 Preparing drilling fluids

A short approach on how to prepare fluid 1 to 4 is given below:

1. Measure 350 ml of water, and pour it in the cup you are going to mix the fluid in.
2. Weigh the right amount of XG for the recipe.
3. Put the cup with the water underneath the Heidolph mixer, and set the mixing speed to 500.
4. Gradually pour the XG in the cup, while mixing. Be careful to pour a little as possible, because you want all the XG to dissolve in the fluid.
5. After all the XG is poured in the fluid, you mix it for 5 minutes. This part is important to dissolve all the chemicals in the fluid. While its mixing, you can weigh the barite.
6. Pour the barite gradually into the fluid.
7. Mix for five minutes.

After a fluid was ready, it was run in the Fann Vicometer. This gave us some data on the viscosity of each fluid. This was done by pouring the fluid into the cup that belongs to the Viscometer, and then running the fluid in the machine on 600, 300, 200, 100, 6 and 3 rotations per minute (RPM) respectively.

4.3.2 Turbiscan

In the Turbiscan machine, Recipe 2, 3 and 4 was analyzed. After mixing the fluids, it was important to time the time between the fluid was mixed, and put in to the Turbiscan machine. This time was set to 5 minutes, such that the time was the same for all samples. This is important because settling can happen quite fast after mixing, especially in the fluids wherewith low concentration of Xanthan Gum. An approach on how to test fluids in the Turbiscan is given below:

1. Pour a predetermined volume of the fluid you want test in the small glass test tube which belongs to the machine
2. Press open on the Turbiscan, and put the glass tube in the machine.
3. On the computer that is connected to the machine, open the Turbiscan software, and fill out the total time you want to test your sample.
4. Fill out the sampling interval, press start to start the measurements

4.3.3 Pressure testing in large vertical pipe

After the large vertical pipe was modified, it was primarily tested with water to investigate for leakages. After observation, one of the pressure ports was leaking, and this was fixed before the first experiment could be conducted. The pipe was intended to use for two projects this semester. The first project is about pressure testing quick clay. After these tests are conducted, the pipe needs to be thoroughly washed and prepared for tests on fluids containing barite.

The procedure consists of filling the set up with the desired fluid from the top side, until the desirable length of fluid is achieved. The fluid is designed in such a way that after some time a barite plug will form at the end of the pipe. After this plug is established, the pressure testing can start. A camera will be placed to film the pressure testing, so that actual footage of the experiment results can be made. This together with the pressure gauges mounted to the pipe, and the pressure monitor on the pump can give us an indication on when or if the plug fails. The plug fails as soon as it moves, or let pressure pass through.

CHAPTER 5

RESULTS AND DISCUSSION

Chapter 5 will start off with a discussion on the potential and benefits of utilizing barite as a permanent barrier material. The second part of this chapter is a summary and discussion of the proposed approach to investigate barite as an annular barrier, as described in chapter three. After this, the results from the experimental work of this thesis are presented and discussed. Being that the objective of this thesis is to be a starting point and an inspiration for further investigation of barite as a permanent barrier material, a natural result of such a thesis would be suggestions for further laboratory testing. Therefore, further testing based on our results, and other ideas for investing barite in laboratories, will be presented in this chapter as a part of the result of the thesis.

5.1 Potential and benefits

Permanent plug and abandonment of wells is becoming a more important part of the petroleum industry, as the infrastructure on several oil fields worldwide is aging. The NCS is no exception, the estimated number of wells to permanently plug on the NCS is more than two thousand wells within the next decade. The potential for new technology within this part of the business is enormous.

As described earlier, the main expense of the P&A process is the costs connected to cutting and pulling caning. The work associated with this part of the P&A process, stands for approximately 50% of the total cost for the P&A operations. If one could develop technology for minimizing the time used cutting, pulling and milling casing, it could mean enormous economical savings during the P&A process. Furthermore, it would be even better if one could avoid these time-consuming operations, and this thesis suggests a potential way of doing this. Should annular barite be accepted as an annular barrier element of good quality, one could avoid some of the time-consuming operations of cutting and pulling casing. If it is possible to use the existing casing strings, and annular barite interval as well barrier elements, the cost of a plug will expense only the cost of placing an additional cement plug inside the casing.

5.2 A suggested approach

The first stage would be finding a way to identify the settled barite in the annulus. This is a challenging task, as the interval above TOC rarely will be a clean barite interval, but more an interval of settled barite mixed with other particles, as well as containing fluid pockets. It is hard to decide on the best tool to use for logging the interval, when you don't quite know what you are logging. It would be a good starting point to have a student investigate logs of barite intervals as a bachelor or master thesis, and to compare the response of different tools on the substance behind the casing.

After identifying an interval of desired length, field verification of the interval must be conducted. A method or technology to verify the annular barite must also be established. This could also be the subject of a thesis, where the student investigates one or several approaches for verifying barite as an annular barrier. If logging of the interval is not an option or is not sufficient, a method of perforating intervals of the casing and pressure testing the annular barrier for hydraulic sealing has been suggested. This could be further investigated. The pressure test could be conducted either by pressuring the annulus to minimal horizontal pressure, and studying the pressure for a given time to verify the sealing capability. One could also lower the pressure in the annulus, and observe the pressure buildup at surface. If these tests sow no leakage, the annular barrier is verified. Whether this solution is feasible or not, would need to be further investigated.

A third section, and by my opinion the most important section, of potentially exploiting barite as an annular barrier, is all the theory and laboratory knowledge that needs to be in place regarding properties of barite under different settings. This is also the primary focus of this thesis, providing some basic theory and laboratory information on barite, which can be used for further investigation. Later in this chapter, some suggestions on further laboratory work will be tested.

The last step in the process would be to establish general acceptance criteria and requirements for the industry guidelines. In NORSOK D-010, this would for instance require a new Well Barrier Element Acceptance table. This could also be a good suggestion for a thesis. To take inspiration from the WBEAT for casing cement, and based on the research done suggest such a table for annular barite.

5.3 Experimental results

5.3.1 UCA Results

Testing Recipe 5 in the UCA device gave us no results. The recipe was tested at a temperature of 70°C. If the device was used to test a water, oil or cement sample, the result would be a graph showing transit times through the samples. Testing Recipe 5 resulted in error in the output of the transit time, and the output can be seen in Figure 5.1.

Figure 5. 1 UCA results Recipe 5

If the concept was working as a blue graph following the transit time lines would have been shown. The error in transit time might be explained by the fact that the recipe we tested, consist of barite particles which may disturb the signal of the device. This shows some of the concerns when logging a barite interval, cause the interval is not a solid like cement, and there could be difficulties in logging and interpreting it.

5.3.2 Barite settlement and fluid viscosity

Fluid Recipe 1 to 4 where made to study barite settlement in fluids with different viscosities, and to ultimately recommend one of the fluids for further testing. It was desirable to create a fluid with good settling capabilities, as well as the settled particles should be able to stick together and compact somewhat. The intention is to fill this fluid in a large scale set up, let the barite particles settle and thus form a barite plug. All the fluids where first made in a small scale with 350 ml water and 30 grams of barite, but with varying degree of Xanthan Gum. The decision to use the Xanthan Gum polymer was primarily based on the fact that this polymer is an effective thickening agent. Another factor which made Xanthan Gum the best choice for our purpose, is that Xanthan Gum serves as a stabilizer to help the barite particles “stick together” in the fluid, a property which is positive when trying to make a plug of barite. Results from the viscosity measurements can be seen in Table 5.1 below.

Table 5. 1 RPM Readings of Recipe 1 to 4

	Reading (θ)			
RPM	Recipe 1	Recipe 2	Recipe 3	Recipe 4
600	40	31	15	10
300	26	21	9	7
200	24	17	7	4
100	18	13	4	2
6	5	4	2	1
3	4	3	1	0

The idea in the beginning was to study the settlement by visual inspection. As the end of the thesis was approaching, the Turbiscan machine was made available for me to use, and it was possible to get more accurate data on the settlement process. Therefore, both the pictures from the visual inspection and the graphs from the Turbiscan will be discussed.

When the first recipe with 3 g Xanthan Gum was made, the conclusion that the fluid was too viscous for our application was made quickly. The fluid was inspected over three days, with no visual difference. The barite particles were suspended in the fluid, and there was no sign of barite settling. The fluid was very viscous, and was a gel like substance. This recipe was a starting point to investigate how much XTG should be used, and a decision to mix the next fluid with 1 g Xanthan Gum was made. Recipe 2 vas also also quite viscous. However, we spotted a small difference after three days observation. There was a very thin layer of settled barite particles at the bottom, but we could not spot a clarified layer on the top of the sample. Recipes 1 and 2 where both too viscous for our application, there was barely any sign of barite settlement, so a decision was made to reduce the concentration of Xanthan Gum to 0.5 g, which became Recipe 3.

Recipe 3 showed a different trend than the two previous mixed recipes. After 24 hours, we could observe a layer settled barite at the bottom of the sample, as well as a clarified layer at the top of the sample. The sample was again observed after three days, and almost no changes were visible. In Figure 5.2 a, it can clearly be seen that the concentration of particles increases with depth. There is no clear boundary between the clarification regime, and the settled particles, more a smooth transition between the two regimes. In the large scale set up testing, it would be beneficial to observe this boundary clearly. If you observe a clear barite plug, it is also easier to detect movement of the plug. And if the plug moves, it implies that the plug has failed. We decided to decrease the concentration to 0.25 g Xanthan Gum, and this became Recipe 4.

Figure 5. 2 a) Recipe 3 after 24 hrs *b) Recipe 4 after 24 hrs*

The fluid with the smallest concentration of Xanthan Gum was quite different from the other recipes. Right after mixing it seemed much less viscous than the other fluids. Settling of particles was also observed within ten minutes after the sample was mixed. After 24 hours, one could easily detect a clear boundary between the settled barite particles and the clarified liquid.

5.3.3 Turbiscan results

The Turbiscan software calculates the evolution of a sedimentation over time. The graphs represented in Figure 5.3 and 5.4 are outputs with examples of samples where there is migration of particles during the analysis. Sample with Recipe 2 was scanned over a period of 24 hours, with an acquisition cycle of one scan every 15 minutes. Sample with Recipe 3 had an acquisition cycle of one scan every 10 minutes over a period of five hours. Sample with Recipe 4 was scanned every 5^{th} minute, over a period of four hours. Different intervals where chosen because it was suspected that one would detect migration of particles much sooner in the sample containing Recipe 4, and thus a smaller time interval was chosen. To understand the output of the software, one must understand the concept of the machine. The more particles the emitted photons hit, the more backscattering is observed. This means that a peak on the graph will be observed where the concentration of particles is the highest. If there is migration of particles, the highest concentration of fluid would be observed at the bottom of the sample, which is represented to the left in the plots. An ideal output for a migrating sample would show a peak in the bottom of the sample indicating a sediment formation. At the top of the sample, which is to the right on the x-axis, a clarification front could be observed with lower backscattering values.

When I got access to the Turbiscan machine, Recipe 2 to 4 were mixed one more time with the intention of testing the samples in the machine. Turbiscan testing started with Recipe 2, suspecting that there was no point in testing Recipe 1 because of the high viscosity observed earlier. The results of testing Recipe 2, confirmed that there was no point in testing Recipe 1. After 24 hours in the Turbiscan machine, there was almost no difference in the output from the machine, meaning that there was no settling of barite in the sample over the 24 hours. The Turbiscan results of Recipe 3 were more interesting, and the results can be seen in Figure 5.3 below. The x-axis of the plot represents the sample height which was 49mm, while the y-axis represents backscattering. To the right in the figure, is possible to see the time intervals in which the test was conducted. The time intervals are color coded, so it is easy to see the development as time goes by. The blue lines represent the tests conducted within the first hours, followed by the next hour in green and so on. The first and last scan is represented by a red graph.

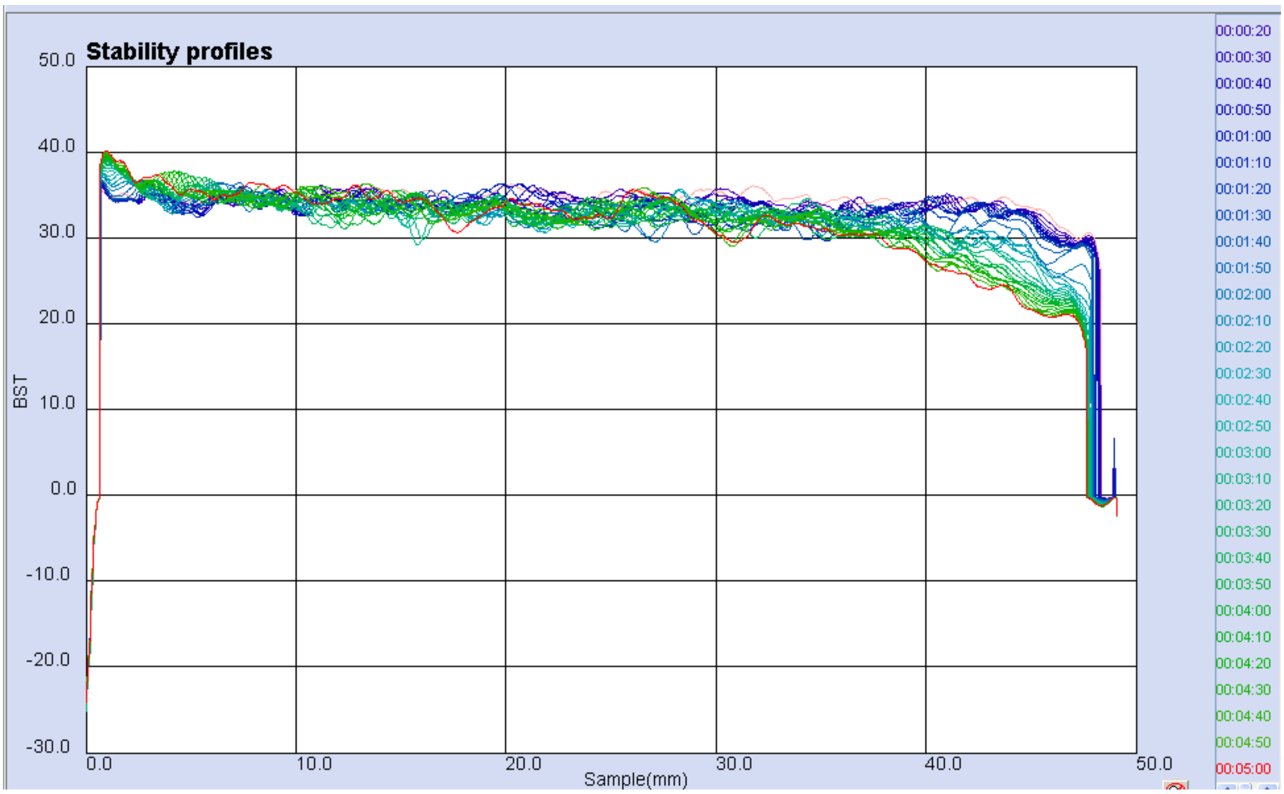

Figure 5. 3 Turbiscan results Recipe 3

The result from Recipe 3 show a small peak of backscattering at the bottom of the sample, and the peak stars developing after approximately two hours. This indicates that the barite sedimentation starts after two hours. The clarification front is moved by approximately three millimeters. The results from the visual inspection of the sample where we observed a clarified layer of approximately five mm, but this was after 24 hours. The visual inspection of the sample after three days showed very little difference from what was observed after 24 hours. An explanation to this can be that the viscosity of the fluid prevents the migration of the smaller barite particles, only the biggest particles are able to settle. Samples of Recipe 3 indicate a trend of particle settling both by visual investigation and in the Turbiscan results; however, the settlement is not as clear and effective as desired for our purposes.

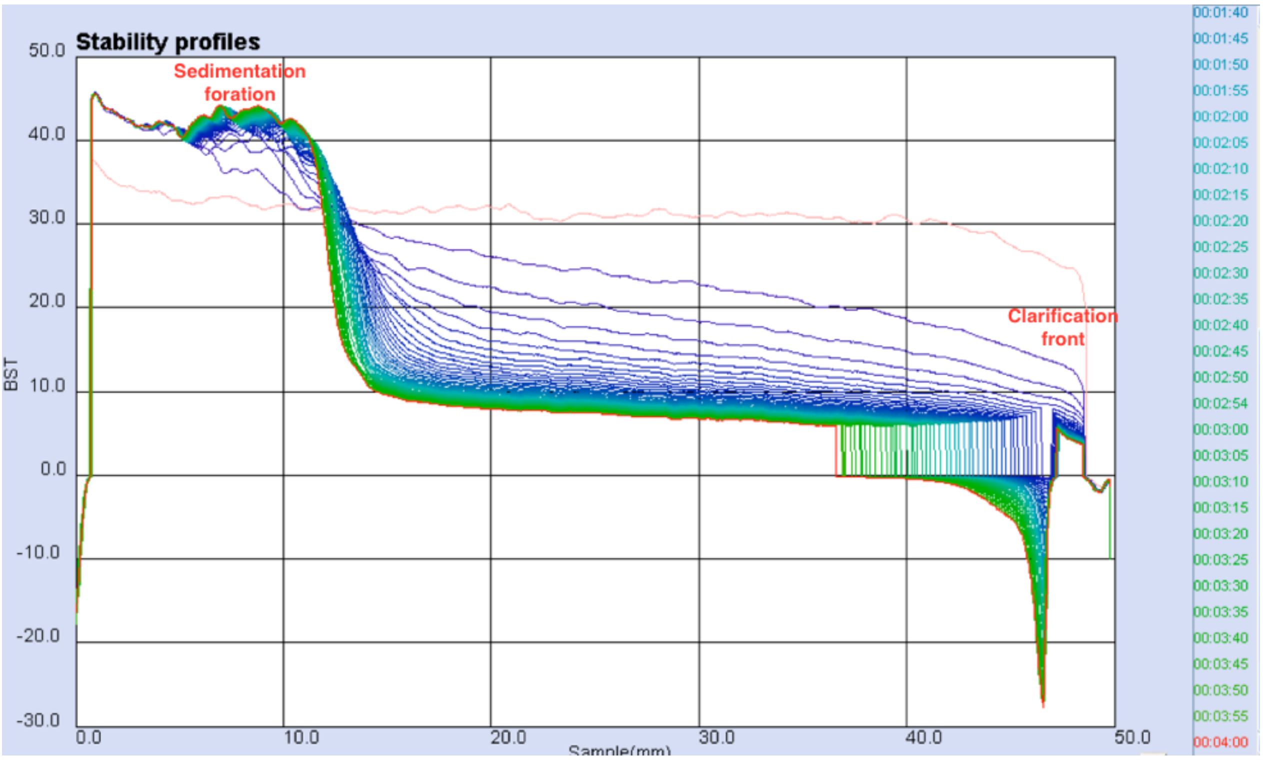

Figure 5. 4 Turbiscan results Recipe 4

The results from Recipe 4 differ from the other recipes. A clear sediment formation is detected from the bottom of the sample to approximately 12 mm. The faded red line represents the first scan, and sedimentation is observed as fast as in the second scan. After one hour, the majority of the barite particles have settled. Recipe 4 showed rapid settling of barite, and a clear layer of barite was observed. The fluid was not that viscous, and allowed almost all the barite particles to migrate down to the bottom of the sample. This is beneficial, rather than just having a plug of big barite particles. Variable size distribution of barite particles could make the plug less porous and permeable, since the smaller particles fill the void space in-between the big particles, as described in the section about unconsolidated sand slurries. A disadvantage of having a small concentration of Xanthan Gum polymer could be that you lose some of the bonding effect you would have in the higher concentration samples. However, the advantage of a denser and clearer plug makes me recommend Recipe 4 for further testing in the large scale set up. Another argument for using Recipe 4, is that we want to test a “clean” barite plug as possible in the beginning to use as a reference point, and adding lots of polymers might influence the results. Clean barite and water would not be possible to use, since the migration of particles happens immediately, making it hard to work with. Thus, a fluid like Recipe 4 would be a good solution.

5.3.3 Pressure testing in large vertical pipe

The intention in the beginning when work with this thesis started was to perform a pressure test, to see how much pressure a barite plug could withstand before it breached. There were several discussions on which fluid to use in the large vertical pipe for pressure testing. One of the first suggestions where contacting M-I SWACO to get an already prepared fluid from them for testing. The benefit with this solution would be that we test a real fluid used in the field. With this fluid, one would get a much more representative plug regarding to what we can expect to find over top of cement in the field today. This would not be achieved by just designing a simple fluid ourselves. However, the challenge with this solution is that these fluids are designed to prevent barite settling, as barite sag is a serious concern while drilling. If using a fluid like this, there would be no guarantee that a barite plug would form within the timeframe we have for testing in this thesis. Another argument against using a drilling fluid prepared for field usage, is the fact that we want to simplify the testing as much as possible. The testing we are doing is just to get an indication on how much a simple barite plug can withstand, so that further testing of other parameters can be compared to this value.

After we decided to go for a simple fluid with the capability of forming a barite plug rapidly, laboratory work started to find and prepare a fluid for our purposes. As earlier described, I ended up with recommending Recipe 4 for further testing. My goal was to test the plug formed from Recipe 4 in the large scale set up, to further change the composition of the fluid, and do the same tests to see which impact this had on the pressure resistance of the plug. By this method, one could get an indication of which compositions are best suited to form an acceptable barrier. I wanted to add a predetermined amount of clay (for example start with adding 10% clay, then 20% etc.) to the recipe to observe which changes this would lead to regarding how much pressure the plug could withstand before failing. This could give us some results on how clay affect the sealing capability of the plug, which could be valuable information because clay is a typical ingredient used in drilling muds. The goal here would be to explain how the ability to hold back pressure with increasing amount of clay mixed in the barite interval. As the equipment for the large-scale test set up arrived late, the modified model was not ready for testing before June. The test results are not included in this thesis, as the first test is done after delivery of my thesis. However, an article describing the test, equipment and results will be published after the preliminary testing is done, so that others could continue the work based on the results obtained for preliminary testing.

5.4 Potential laboratory investigation of barite

Suggestions regarding identification and verification of barite as a permanent barrier material have been discussed earlier. This section will focus more on the laboratory investigation of the properties of settled barite mixed with other solids. The criteria defined in NORSOK D-010 for well barrier materials mentioned in subchapter 1.3.1 and the research questions presented in Chapter 4 are taken into consideration when suggesting ideas for further investigation.

5.4.1 Barite settlement in inclined tubes

A key factor in investigating barite mixed with other solids as a barrier material, is understanding how the barite settles in the annulus under different conditions. It would be beneficial to study barite settlement under different angles for example. Then one can get an indication on how the settled barite will be placed in the annulus in the field, as the section of interest for our purposes is rarely a vertical section, but an inclined wellbore. These tests could be done with an easy set up. The set up may consist of a plate, or a wall with Plexiglas tubes attached in different angles. The student could then observe how the barite settles in the different angled tubes, to get some laboratory knowledge of how the settling would look in the field.

5.4.2 From unconsolidated slurry to a solid

As earlier described in the thesis, settled barite that is not compacted acts like an unconsolidated sand slurry, and not like a solidified cement for example. After years, the settled barite and other solids compacts and may have the ability to solidify. According to conversations with Arild Saasen, the settled barite in the annulus may solidify under certain conditions, due to surface chemistry of the particles and electrostatic bonds. An idea could be to make a test sample and let it compact somewhat, under a predetermined temperature and pressure, with the aim of compacting and solidifying the sample as much as possible at the laboratory. If this process is successful, the solidified sample may be tested by traditional laboratory verification methods described in the introductory chapter, providing useful information on the porosity and permeability of the compacted barite. Aging tests could also be conducted, to be able to extract information about the durability of the barrier material.

5.4.3 Investigation of compositions

Laboratory information of which compositions can form an acceptable barrier is needed. A pressure test of a clean barite plug is initiated through this thesis. Furthermore, it would be a good idea to do the same pressure test for the fluid when adding an increasing amount of a substance which is typically found in drilling fluids. Testing initiated in this thesis is a start point. I earlier mentioned doing it with barite and clay, and document the difference in how much pressure a plug with a less clean barite substance can withstand. This could give us an indication on which compositions of solids are able to form acceptable barriers.

5.4.4 Correlation between plug length and pressure resistance

It would be interesting to investigate if double plug length hold double pressure. One approach to investigate this could be testing two different plug lengths. The student can for instance set up a plug of half a meter, and another plug of one meter, to see if length has a linear effect on the capability of holding back pressures. Then based on the results, the student could calculate how many metes of settled barite would hold how much pressure.

5.4.5 Pressure testing in annulus set up

If the pressure testing in the simplified vertical set up described in this thesis implies a big potential, a new set up with more similarities to a real scenario could be modified. This would be much more work than the simplified testing described in this thesis, and is therefore suggested as a PhD thesis. The modified set up could be a scale down form a typical 9 5/8" casing inside a 13 3/8" casing, set up in a predetermined inclination. Here one could fill the annulus between the casings with a drilling fluid which has shown tendencies of barite sagging, and then after the plug has set, preform a pressure test to see how much pressure the plug can take before breaching. Such a large set up will include a lot of engineering, and input from operators. This set up may give valuable information on how the barrier will act in a real scenario in the field, and the results here would be much more representative than all the simplified testing done.

SUMMARY

Today, significant P&A time is used milling, pulling and cutting casing. The time consumption, and complexity of the operation determines the cost of the operation. If the idea of utilizing settled barite as a permanent barrier material in the annulus becomes feasible, the time of a P&A operation can be significantly reduced. Thus, the potential financial savings for the operator companies, and the state are enormous. Through the thesis, a "foundation" is made for further investigation of settled barite as a permanent barrier material. This is done through a literary study on barite, and trough initiation of some basic laboratory testing. The objective of this thesis is to introduce barite settlement as an opportunity and not only a challenge to the industry.

To do this, a literary study was conducted. Chapter 2 and 3 of the thesis provides a description of barite and which problems the industry must solve in order to take advantage of the idea of settled barite as an annular barrier. Methods for further investigation regarding identification and varication of barite behind casing are given. Ideas on how others could continue the work are also given. Research done on fluids with barite has also been included to give theoretical knowledge on the mechanisms of settled barite in different fluids.

Furthermore, to investigate the potential of utilizing barite as a permanent barrier material, some laboratory experiments were conducted. Settlement of barite in different fluids was studied, to be able to recommend a fluid with good barite settling capabilities for further testing. The fluid described under Recipe 4 is recommended for pressure testing of a barite plug. The main experiment of the thesis, is a pressure test of a barite plug in a vertical plexiglass tube. The details and results of the large-scale pressure test set up, are going to be presented in a paper and published, so it can be used as a set point for further investigation. Several ideas for further testing of the sealing capability and investigation of other properties of barite are also presented, as the aim of the thesis is to be an inspiration and start point for further investigation on the topic.

Ultimately, the thesis has shown the enormous potential of utilizing settled barite as a permanent barrier material.

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8 APPENDIX

WELL BARRIER ELEMENT ACCEPTANCE TABLE 22 – CASING CEMENT (NORSOK, 2013)

Features	Acceptance criteria	
A. Description	This element consists of cement in solid state located in the annulus between concentric casing strings, or the casing/liner and the formation. NOTE The shoe track cement is covered in table 24.	
B. Function	The purpose of the element is to provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below, and support casing or liner strings structurally.	
C. Design, construction and selection	1. A cement program shall be issued for each cement job, minimum covering the following: a) casing/liner centralization and stand-off to achieve pressure and sealing integrity over the entire required isolation length; b) use of fluid spacers; c) effects of hydrostatic pressure differentials inside and outside casing and ECD during pumping and loss of hydrostatic pressure prior to cement setting up; d) the risk of lost returns and mitigating measures during cementing. 2. For critical cement jobs, HPHT conditions and complex/foam slurry designs the cement program shall be verified independent (internal or external), qualified personnel. 3. The cement recipe shall be lab tested with dry samples and additives from the rigsite under representative well conditions. The tests shall provide thickening time and compressive strength development. 4. The properties of the set cement shall provide lasting zonal isolation, structural support, and withstand expected temperature exposure. 5. Cement slurries used for isolating sources of inflow containing hydrocarbons shall be designed to prevent gas migration, including CO_2 and H_2S, if present. 6. Planned casing cement length: a) Shall be designed to allow for future use of the well (sidetracks, recompletions, and abandonment). b) **General**: Shall be minimum 100 m MD above a casing shoe/window. c) **Conductor**: Should be defined based on structural integrity requirements. d) **Surface casing**: Shall be defined based on load conditions from wellhead equipment and operations. TOC should be at surface/seabed. e) **Production casing/liner**: Shall be minimum 200m MD above a casing shoe. If the casing penetrates a source of inflow, the planned cement length shall be 200m MD above the source of inflow. a. Note: If unable to fulfil the requirement when running a production liner, the casing cement length can be combined with previous casing cement to fulfil the 200m MD requirement.	API RP 10B ISO 10426-1

Features	Acceptance criteria	
D. Initial verification	Cement should be left undisturbed until it has reached sufficient compressive strength. 1. The cement sealing ability shall be verified through a formation integrity test when the casing shoe/window is drilled out. 2. The cement length shall be verified by one of the following: a) Bonding logs: Logging methods/tools shall be selected based on ability to provide data for verification of bonding. The measurements shall provide azimuthal/segmented data. The logs shall be verified by qualified personnel and documented. b) 100 % displacement efficiency based on records from the cement operation (volumes pumped, returns during cementing, etc.). Actual displacement pressure/volumes should be compared with simulations using industry recognized software. In case of losses, it shall be documented that the loss zone is above planned TOC. Acceptable documentation is job record comparison with similar loss case(s) on a reference well that has achieved sufficient length verified by logging. c) In the event of losses, it is acceptable to use the PIT/FIT or LOT as the verification method only if the casing cement shall be used as a WBE for drilling the next hole section. (This method shall not be used for verification of casing cement as a WBE for production or permanent abandonment.) 3. Critical casing cement shall be logged and is defined by the following scenarios: a) the production casing/production liner when set into/through a source of inflow with hydrocarbons; b) the production casing/production liner when the same casing cement is a part of the primary and secondary well barriers; c) wells with injection pressure which exceeds the formation integrity at the cap rock. 4. Actual cement length for a qualified WBE shall be: a) above a potential source of inflow/ reservoir; b) 50 m MD verified by displacement calculations or 30 m MD when verified by bonding logs. The formation integrity shall exceed the maximum expected pressure at the base of the interval. c) 2 x 30m MD verified by bonding logs when the same casing cement will be a part of the primary and secondary well barrier. d) The formation integrity shall exceed the maximum expected pressure at the base of each interval. e) For wells with injection pressure exceeding the formation integrity at the cap rock: The cement length shall extend from the upper most injection point to 30 m MD above top reservoir verified by bonding logs.	
E. Use	None	
F. Monitoring	1. The annuli pressure above the casing cement shall be monitored regularly when access to this annulus exists. 2. Surface casing by conductor annulus outlet should be observed regularly.	
G. Common well barrier	It is not acceptable for use as a common WBE. When casing cement is a part of the primary and secondary well barriers, this is defined as critical casing cement and the criteria in D. Initial verification applies.	

WELL BARRIER ELEMENT ACCEPTANCE TABLE 24 – CEMENT PLUG (NORSOK, 2013)

<table>
<tr><th>Features</th><th>Acceptance criteria</th><th>See</th></tr>
<tr><td>A. Description</td><td>The element consists of cement in solid state that forms a plug in the wellbore.</td><td></td></tr>
<tr><td>B. Function</td><td>The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to surface/seabed.</td><td></td></tr>
<tr><td>C. Design, construction and selection</td><td>
1. A program shall be issued for each cement plug installation.
2. For critical cement jobs, HPHT conditions and complex slurry designs the cement program should be verified by independent (internal or external) qualified personnel.
3. The cement recipe shall be lab tested with dry samples and additives from the rigsite under representative well conditions. The tests shall provide thickening time and compressive strength development.
4. Cement slurries used in plugs to isolate sources of inflow containing hydrocarbons should be designed to prevent gas migration and be suitable for the well environment (CO_2, H_2S).
5. Permanent cement plugs should be designed to provide a lasting seal with the expected static and dynamic conditions and loads.
6. It shall be designed for the highest differential pressure and highest downhole temperature expected including installation and test loads.
7. A minimum cement batch volume shall be defined to ensure that a homogenous slurry can be made, taking into account all sources of contamination from mixing to placement.
8. The minimum cement plug length shall be:
<table>
<tr><td>Open hole cement plugs</td><td>Cased hole cement plugs</td><td>Open hole to surface plug (installed in surface casing)</td></tr>
<tr><td>100 m MD with minimum 50 m MD above any source of inflow/leakage point. A plug in transition from open hole to casing should extend at least 50 m MD above and below casing shoe.</td><td>50 m MD if set on a mechanical/ cement plug as foundation, otherwise 100 m MD</td><td>50 m MD if set on a mechanical plug, otherwise 100 m MD.</td></tr>
</table>
9. Placing one continuous cement plug in a cased hole is an acceptable solution as part of the primary and secondary well barriers when placed on a verified foundation (e.g. pressure tested mechanical/cement plug).
10. Placing one continuous cement plug in an open hole is an acceptable solution as part of the primary and secondary well barriers with the following conditions:
a. The cement plug shall extend 50m into the casing.
b. It shall be set on a foundation (TD or a cement plug(s) from TD). The cement plug(s) shall be placed directly on top of one another.
11. A casing/liner shall have a shoe track plug with a 25 m MD length.
</td><td>API Spec 10A Class 'G'</td></tr>
</table>