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## ABSTRACT

During plug and abandonment, there can be a need for removing casing to ensure that a proper cement barrier can be set. The conventional method for doing this is by performing milling operations. Conventional milling operations are very time consuming, costly and also involves major HSE aspects. New technology for performing milling operations are developed with the purpose to perform this operation more safe and efficiently. During milling operations huge amounts of swarf is generated. By milling a section of 50 meters, one can actually generate 4 tons of swarf!

The swarf which is basically metal cuttings from the milled casing has to be transported away from the platform site. Some platforms have their own swarf handling units while others don't. Swarf may cause a lot of damages to equipment, and people and during transportation it may be self-firing. Roughnecks have to use special gloves when working with swarf due to its sharp edges. If one can improve the milling operations or implement better alternatives for removing casing it will be beneficial both economically and for HSE considerations.

Alternative technologies to milling exist; this will be further discussed in this thesis. The pro and cons with this alternative technology will be discussed, as well as the technology development within the milling operations.

To get the overall picture this thesis starts with a description of P&A, and some important terminology that it is important to have in place. Then the governing regulations from NORSOK D010 are presented with respect to P&A. The newest revision of NORSOK D010, rev 4 that was published in June 2013 is later compared with the previous revision of NORSOK D010, rev 3.

The latest part is more academic with some simulations in Matlab. For the simulation part an existing steady state two phase model is implemented. This steady state model is modified for its intended use. The purpose with this modified model is to study the ECD effects during milling operations. Different parameters such as the slip ratio and the mill rate will be adjusted, and the results will be visualised in excel. Steel has a large density and for large concentrations of swarf there can be a problem related to fracturing of the well. The model (programmed in Matlab) will be used to study the effects of different milling rates. The results are discussed to see the trends.

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## NOMENCLATURE:

**P&A:** Plug and Abandonment  
**PP&A:** Permanent Plug and Abandonment  
**NORSOK:** Norsk Søkkel Konkuranseposisjon  
**ECD:** Equivalent Circulating Density  
**ROP:** Rate of penetration  
**IRIS:** International Research Institute of Stavanger  
**RIH:** Run In Hole  
**POOH:** Pulling Out Of Hole  
**TD:** True Depth  
**TCP:** Tubing Conveyed Perforating  
**CBL:** Cement Bond Log  
**VDL:** Variable Density Log  
**LOT:** Leak off test  
**LWI:** Light Well Intervention  
**RLWI:** Riser Less Well Intervention  
**CT:** Coiled Tubing  
**SHU:** Swarf Handling Unit  
**BHA:** Bottom Hole Assembly  
**BHP:** Bottom hole pressure  
**BHT:** Bottom hole temperature  
**BOP:** Blow Out Preventer  
**MDR:** Modular Drilling Rig  
**TD:** Total Depth  
**OBM:** Oil Based Mud  
**WBM:** Water Based Mud  
**RPM:** Rotation Per Minute  
**CTV:** Cuttings Transport Velocity  
**CTFV:** Critical Transport Fluid Velocity  
**N/D:** Nipple Down  
**N/U:** Nipple Up  
**RLWI:** Riser Less Well Intervention  
**WBE:** Well Barrier Element  
**WBEAC:** Well Barrier Element Acceptance Criteria  
**XMT:** Christmas tree

## SYMBOLS

**$P_w$ :** Borehole pressure  
 **$P_p$ :** Pore pressure  
 **$P_{wf}$ :** Fracturing pressure  
 **$F_L$ :** Lift force  
 **$F_d$ :** Drag force  
 **$F_b$ :** Buoyancy force  
 **$F_g$ :** Gravity force  
 **$F_{van}$ :** Van der Waals forces

# 1. INTRODUCTION

The wells production rates are decreasing in the NCS, so cost effective and HSE friendly solutions for P&A will be of big importance in the future. More than 5880 current and future wells will be P&A the next twenty years [2].

Considering that it takes between 20-60 days to P&A one well by today's technology. By using an average of 35 days for each well, 15 rigs doing exclusively P&A operations is needed the next 40 years. This indicates a growing market for P&A technology and also a growing market for P&A technology improvements. P&A operations can generate up to 25% of the total drilling costs, so if we are able to perform the P&A operation rig less in the future, this would be very valuable.

Through this master thesis the objective is to:

- Look further into milling operations during plug and abandonment, together with its technology improvements, and alternative technology.
- Try to simulate the ECD impacts during a milling operation in Matlab.
- Comparing revision 3 and revision 4 of NORSOK D010, in order to observe the major differences when it comes to P&A.

Milling operations during plug and abandonment will be looked further into. This is very important for well integrity issues, and for the placement of a cement barrier.

Today the conventional way for performing P&A operations is by section milling. Section milling is very time consuming, costly, damaging and involves challenges that will be further discussed during this thesis. New and alternative milling technology will also be investigated and discussed later in this master thesis.

To be able to remove the casing this will again have impacts on the wells ECD and this master thesis will put emphasis on the ECD effect during milling. The milling operations effect on the ECD will be visualized by some simulations.

The simulations for the milling operations are performed by using a steady state two phase flow model in Matlab. New technology improvement for increasing the efficiency of the milling operations will be further investigated.

To be able to make these simulations in Matlab as reasonable as possible appropriate milling data were collected. I got some appropriate milling parameters from one person with great experience within P&A in Statoil (Siddhartha Lunkad). I also verified the data with Klaus Engelsjerd from Baker Hughes.

In order to solve this objectives it is necessary to get more knowledge about P&A, the regulations and also some more knowledge about milling operations and what challenges that are associated with it.

## 1.1 Introduction to P&A

P&A stands for Plug and Abandonment. As the production rates are decreasing we have to think about the latest phase of the well life cycle – the decommissioning phase. We have to make sure that the well and platforms are decommissioned in a safe manner. An article was published in Oilfield Review called “The beginning of the End: A Review of Abandonment and Decommissioning Practices” [1].

This paper describes the future growth of P&A, the challenges present, new technology and presented different case studies. According to this paper the estimated costs during the next three decades for decommissioning of the world’s 6500 offshore platforms is estimated to \$29 to \$40 billion [1].

P&A operations can generate up to 25% of the total drilling costs, small changes can therefore contribute with a lot of cost savings [14].

The paper gives a good overview of the headlines of the decommissioning practices.

A well can be abandoned permanently or temporary. The requirement for leaving the well depends upon if we choose a permanent or temporary abandonment solution. The overall goal of any well abandonment is that the formations are permanently isolated. Portland cement has been used as the traditional material for plugging the well, due to its sealing capability. If the primary cement job is performed the correct way the first time, this will reduce the chances for the development of micro channels, and future potential leak paths [1]. New types of plugging material have been developed and will be discussed further on in this thesis.

In order to permanently plug the well, the alive well has to be killed in advance, by pumping down certain fluids, or kill pills. Different types of equipment have to be removed from the previous well. The equipment that is inside the well depends of course of the wells history. The well consists of casing, and various completion equipment and control lines. This has to be removed from the well, as well as all radioactive sources. One of the weaknesses with logging tool is that it is impossible to log through several of casing strings. One therefore has to remove the inner casing before one is able to log through the next one. The conventional method for removing casing is by cut and retrieve, or by performing milling operations. Milling operations is mainly to drill out the old casing string by using a mill tool. The mill tool consists of cutter knives that are welded on the mill pipe. These cutter knives rotate down hole and the casing is milled away at desired depth. The disposal material is steel particles, which are most commonly referred to as swarf. Swarf is then deposited at top side of the platform and has to be transported away from the platform. Later on issues regarding the disposal will also be discussed.

The Petroleum Safety Authorities has regulations and standards for how the abandonment operation shall be performed. They have different standards and regulations that the companies have to follow. During this thesis emphasis will be put on the newest revision (rev 4) of the NORSOK D010 standard, which was published in June 2013. This standard describes the requirements for well integrity in drilling and well operations. NORSOK D010, rev 4 will be compared with the previous revision (rev 3) due to the major changes when it comes to P&A. If NORSOK D010 is mentioned, then it is the newest revision that is referred to [17][18].

In May Bente Larsen`s master thesis from 2013 she points out three main reasons for abandonment of a well which are the following [7]:

- **“Cease of production”**: The well is no longer profitable economically.
- **“Slot recovery”**: A new well bore is planned, and the well is abandoned at a certain depth, and the new well is side-tracked out from the old well track.
- **“Abandonment of pilot holes and exploration wells”**. No completion is installed, the well is plugged after being drilled and tested.

**This master thesis covers:**

**-An introduction to P&A (chapter 1)**

The P&A terminology will be introduced with some general terms and definitions, P&A operational sequences, and phases will be introduced, and then the rigs and vessels to perform P&A on subsea and platform wells will be discussed.

**-An introduction to well barriers (chapter 2)**

Well barriers with respect to NORSOK D010, rev 4 will be discussed here. The numbers of well barriers that is required, the length requirement and the positioning of them, and how permanent well barriers are verified will be further discussed in this section.

**-An introduction to plugging materials (chapter 3)**

What does NORSOK D010 say about plugging materials, cement will be discussed as plugging material, as well as alternative plugging materials such as ThermaSet™, Sandaband™ and Geopolymers, formation itself as an annular barrier will also be discussed.

**-An introduction to milling and cutter technology (chapter 4)**

In this chapter milling operations will be further investigated, as well as cutter and cutter technology. The challenges with milling operations will also be further looked into.

**-Transport mechanism (chapter 5)**

Transport mechanism in relevance to milling technology will be further investigated here. Subjects as: Lift and drag, development of beds, swarf in suspension and buoyancy will be looked further into.

**PWC Technology (chapter 6)**

In this chapter an alternative technology to milling will be discussed, the PWC technology, with its positive and negative sides. A lot of the information here about the tool etc. is provided after the meeting at HydraWell in Tananger.

**Comparison of NORSOK D010, rev 3 with NORSOK D010,rev 4 (chapter 7)**

The newest revision of NORSOK D010 has important changes when it comes to P&A. The major changes will be further discussed in this chapter.

**ECD modelling of a milling operation (chapter 8)**

In this chapter the modelling part will be discussed, with the mathematical models, and assumptions.

**Results (chapter 9)**

In this chapter the results from the modelling part is presented. The slip ratio and the mill rate is adjusted and the results are presented in this chapter by using excel.

**Discussion (chapter 10)**

The results from chapter 9 are further discussed in this chapter with the potential for improvements.

**Conclusion (chapter 11)**

The conclusion for this master thesis can be found in chapter 11.

## Some terms and definitions related to P&A in NORSOK D010

**Well Integrity** is defined according to NORSOK D010 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” [18].

**Plug** is according to NORSOK D010 defined as “a device or material placed in the well with intention to function as a foundation or as a qualified well barrier element” [18].

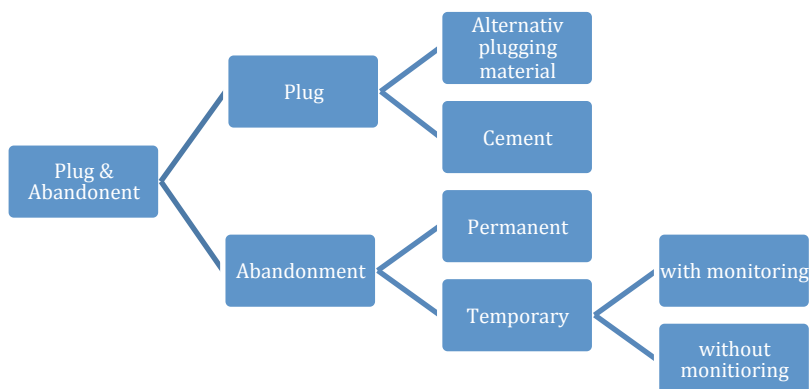
**Plugging** is in NORSOK D010 defined as an “operation of securing a well by installing required well barriers”. According to NORSOK D010 “the selected plugging materials shall be verified and documented”. During the design and placement of WBE the uncertainties related to shrinkage shall also be considered [18].

The different operations have different well barrier schematics, where the primary and secondary well barriers are defined. I will go through these more in detail when I later look more specifically at the well barrier schematics for a milling operation.

**Permanent abandonment** is according to NORSOK D010, defined as “Well status, where the well is abandoned permanently and will not be used or re-entered again” [18].

As the figure below illustrates it is possible to plug the well in two ways; either using conventional cement as plugging material or by using alternative plugging material such as Sandaband™ and Thermaset™ that will be further discussed later in the thesis.

Abandonment is divided into two parts; permanent abandonment and temporary abandonment as *Figure 1* below illustrates:

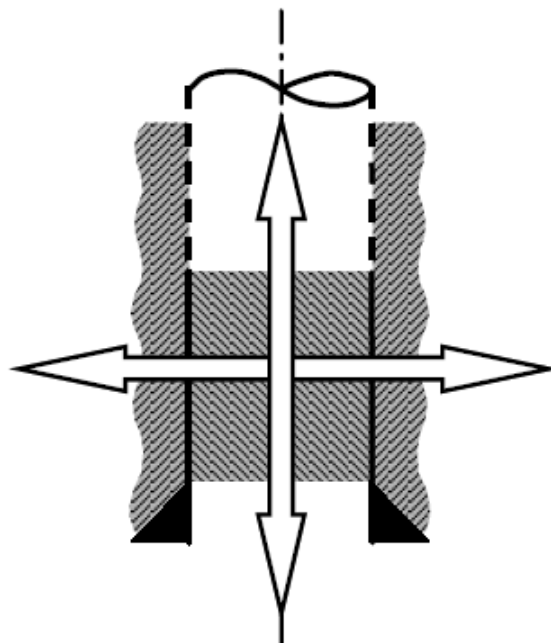


**Figure 1:** “Schematics of P&A”

## 1.1 P&A operational sequence

Below is a typical P&A sequence describes. This example is for a production well where there is suspected that the cement behind the 9<sup>5/8</sup>" casing is of poor quality. According to NORSOK D010, rev 4 there is a requirement that "permanent well barriers shall extend across the full cross section of the well include all annuli and seal both vertically and horizontally" as *Figure 2* below illustrates [18]

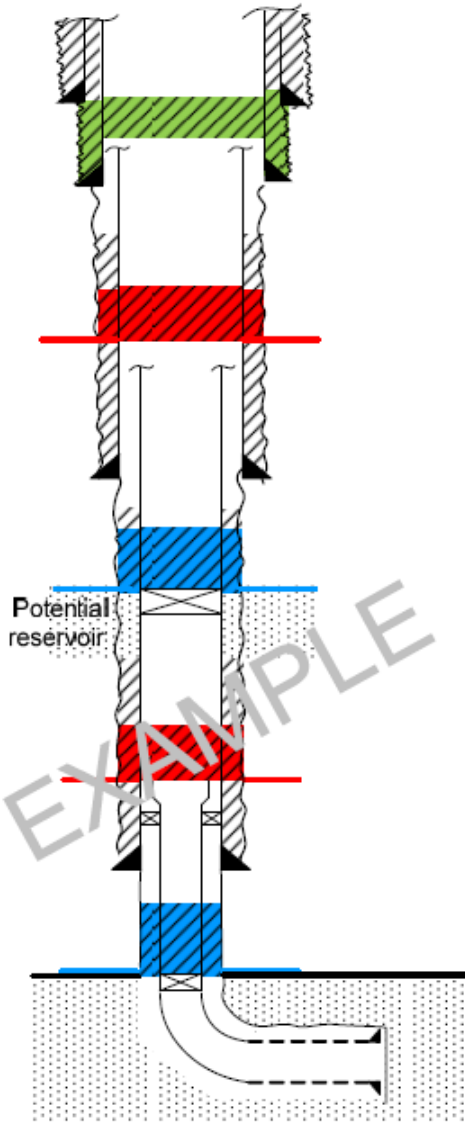
In this particular scenario we have suspect poor quality of the cement behind the 9<sup>5/8</sup>" casing, and we therefore may have a disconformity from the NORSOK D010 requirements above and it is necessary to do remedial actions.



**Figure 2:** "Permanent Well barriers"[18]

An example of a typical P&A Operational sequence for a platform well is described step by step. The well that is going to be PP&A is slotted liner in multiple reservoirs. A schematic of the well configuration is shown in *Figure 3* below [18].





**Figure 3:** «Schematics of well that is going to be PP&A» [18].

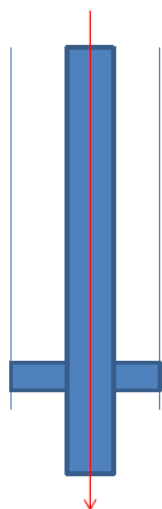
The P&A Operational sequence for this well is described step by step.

1. **Kill the well**
2. **Run CBL-Cement Bond Log to verify the cement quality**
3. **Cut tubing**
4. **Remove XMT and install BOP**
5. **Pull tubing**
6. **Establish well barriers; primary, secondary and open hole to surface**
7. **Cut and retrieve wellhead**

In this particular case we are going to P&A a well with slotted liner in multiple reservoirs. Since we are going to place a plug in the 7" liner it is necessary to perform step 2 from the operational sequence above.

### **1.Kill and secure well**

Before the XMT is removed, the well has to be killed. This can be performed in a process called "bullheading". The kill fluids are pumped down the production tubing. The kill fluids forces the hydrocarbons back into the formation



**Figure 4:** "Bullheading" [13]

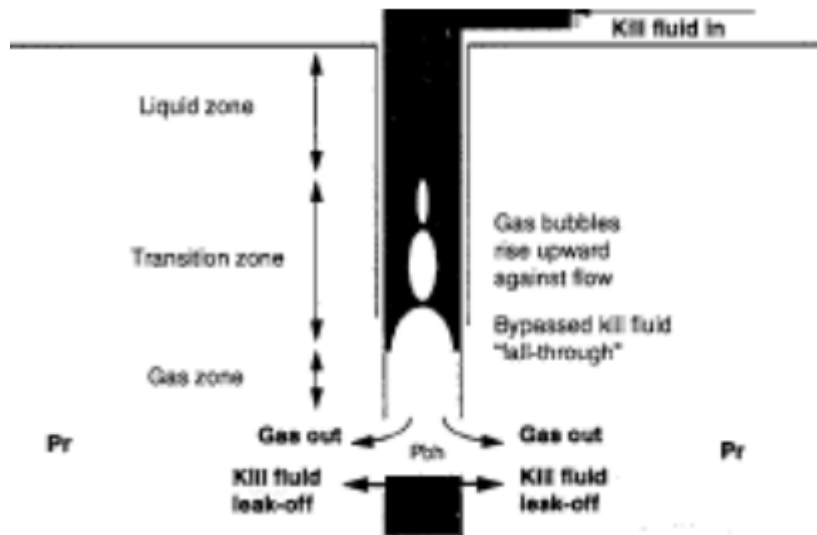
*This figure illustrates the principle of bullheading, where the kill fluid is pumped down the production tubing in order to force the hydrocarbons back into the formation.*

In 1994 a paper was published where the importance of designing proper pump rates and a proper kill fluid is mentioned in order to avoid high pressures and to be inside the design limitations. [12]

In this paper they mention that "the pressures that develop during bull heading at high rate must not exceed wellhead pressure rating, tubing or casing burst pressures or the formation breakdown gradient, since this will lead, at best, to a very inefficient kill job". The figure (Figure 5) below is taken from this paper and illustrates the wellbore processes during bull heading. During a bullheading job the wellbore pressure is bigger than the reservoir pressure; due to this the kill fluids are forcing the hydrocarbons back into the formation. Further in this paper the wellbore processes are divided in three phases, based upon their contamination of liquid, gas or both. The development of these three phases is also being described. These three phases are called the liquid zone, transition zone, and gas zone. [12]

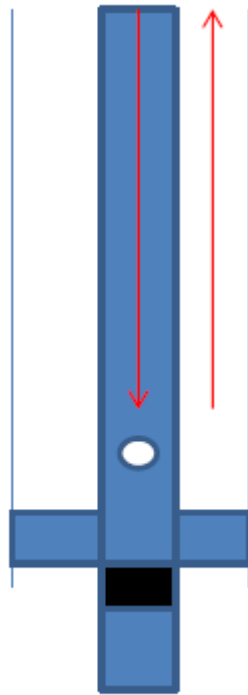
1.The lower part only contains gas in the beginning. As the kill process continues this amount of gas is gradually being reduced.

2. A transition zone can be found above the lower part of the well. This is a two phase area where both gas and liquid is present. "This zone will grow as more liquid is bypassed, until the first liquid arrives at the sand face and starts leaking off»
3. The upper part of the well is a liquid zone where the kill fluid is present and pumped down the well at high rate.



**Figure 5:** "The processes occurring in the wellbore during bull heading" [12]

After the well is killed, a deep mechanical plug is set, tubing is punched, and the annulus and tubing is displaced to kill fluid/brine.



**Figure 6:** “Punch tubing” [13]

*The figure above illustrates the principle of punch tubing and when annulus is displaced*

A plug is placed in the upper part of the tubing and annulus since the XMT is going to be replaced by the BOP.

## **2.Run CBL-Cement Bond Log to verify the cement quality**

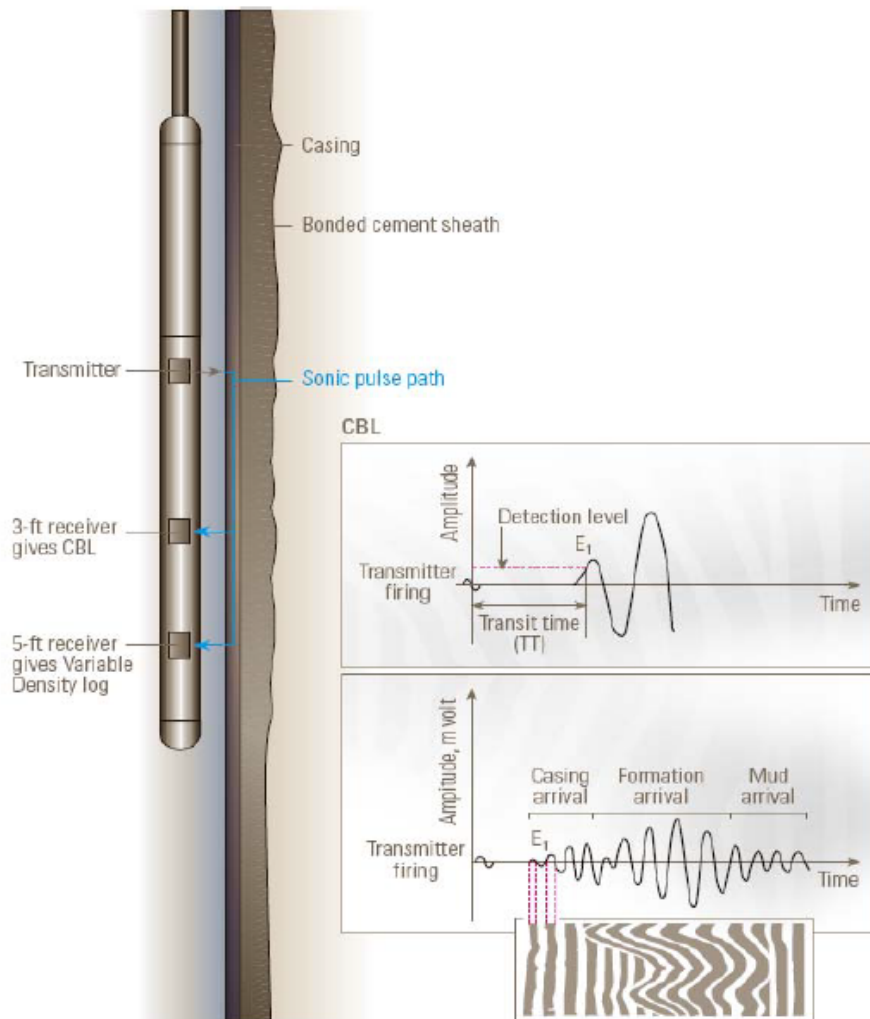
To be able to verify that the cement behind the casing is of good quality we can use cement bond logs.

Williams, Carlsen and Constable published a SPE paper in 2009 where they looked at identification and qualification of shale annular barriers using wireline logs during P&A operations. [5]

In this paper they describe the problems with shale formations from a drilling point of view, but also the advantages with this cap rock.

This paper describes the identification of shale by logging methods such as CBL (Cement Bond Log) and VDL (Variable Density Logs). These two types of logs are used for verification of well barriers. It is therefore reasonable to go more in detail of these two types of logs.

The figure below is taken from this paper, and shows a good illustration of the principle of these two types of logs [5]



**Figure 7:** “The main principle behind a CBL-Cement Bond Log” [5].

The instrument consists of one transducer and two receivers, where the first receiver is placed 3 feet away from the transducer and gives the input to the CBL, while the other one placed 5 feet away from the transducer gives the input to the VDL. The transmitter sends a signal that causes the vibration of the casing. One the figure we see the alphabet and the number E1 which is the first peak observed, which is reflecting the sonic wave that is received 3 feet away, while the next wave is reflecting the next transducer 5feet away. Based upon the wave height and transit time one can then determine if the casing cement has good bonding. This is due to the attenuation’s proportionality (strength of the signal) with the shear acoustic impedance. High amplitude (wave height) indicates that there is lack of cement, while a low amplitude indicates the opposite. [5]

But there are also other factors that may affect the results. In this paper they mention the effect of the casing size, weight and mud properties. As an example they mention that the value of the amplitude (wave height) increases as the casing thickness increases, and opposite when the casing size increases. The mud on the both sides of the casing will also

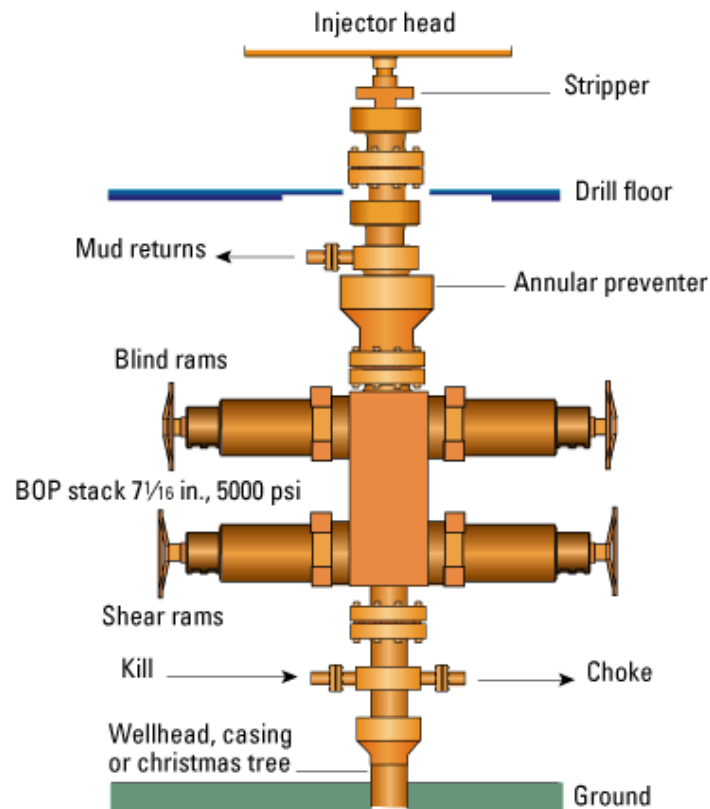
affect the results, as well as the centralization of tool. There are also issues related to logging through multiple casings. [5]

### **3. Cut tubing**

It is not possible to log through several casings. It is therefore necessary to cut the production tubing in order to log through the 9<sup>5/8</sup>" casing. The tubing is normally cut above the packer.

### **4. Remove XMT (N/D XMT and N/U BOP)**

In order to have well control the Christmas tree is nipple down, and the BOP is nipped up. The BOP is installed in order to have well control during the P&A operation. *Figure 8* below illustrates a typical BOP (bottom hole assembly).



**Figure 8:** "BOP" (Blow out preventer)

### **5. Pull tubing**

After the production tubing is cut and the BOP is installed, the tubing is pulled. To be able to handle this type of lifting operation on a platform well, it is necessary to utilize heavy machinery.

## 6. Establish well barriers; primary, secondary and open hole to surface

After the tubing is cut retrieved the next step is to log the cement on the outside casing, in our case this is the 9<sup>5/8</sup> casing. The purpose with this is to verify the quality of the cement.

Before establishing the barriers, one have to look in NORSOK D010, rev 4 under section 4.2.3. In this section it is stated that there shall be minimum **one well barrier** if there is: [18]

- *“Undesirable cross flow between formation zones”*
- *“Normally pressured formation with no hydrocarbon and **no potential to flow to surface**”*
- *“Abnormally pressured hydrocarbon formation with no potential to flow to surface (e.g tar formation without hydrocarbon vapour)”*

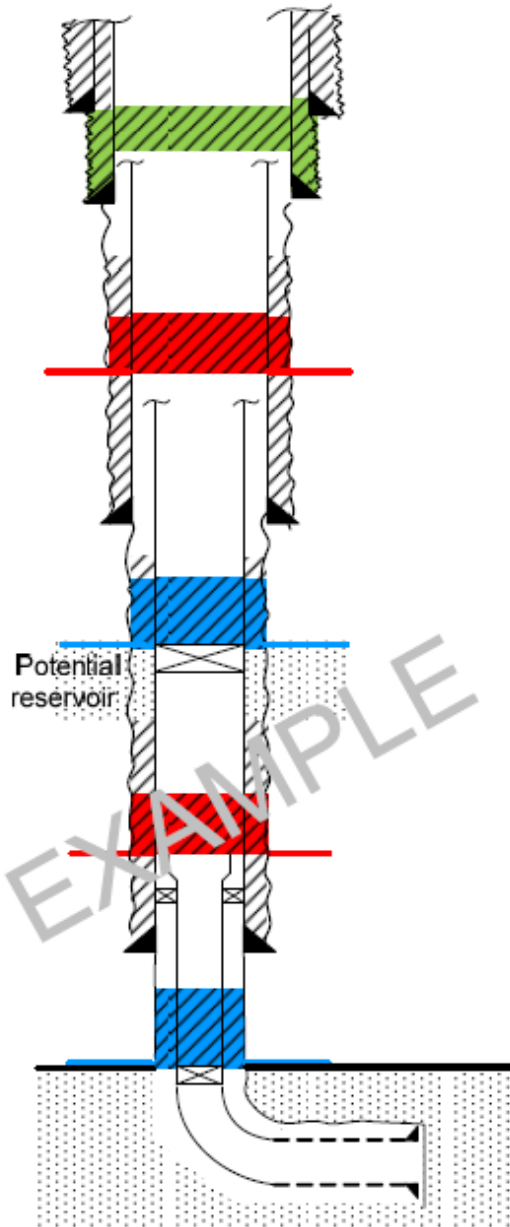
*“If there is “*

- *“Hydrocarbon bearing formations”*
- *“Abnormally pressured formation **with potential to flow to surface**”*

*“Then there shall be a **minimum of two well barriers present**”.*

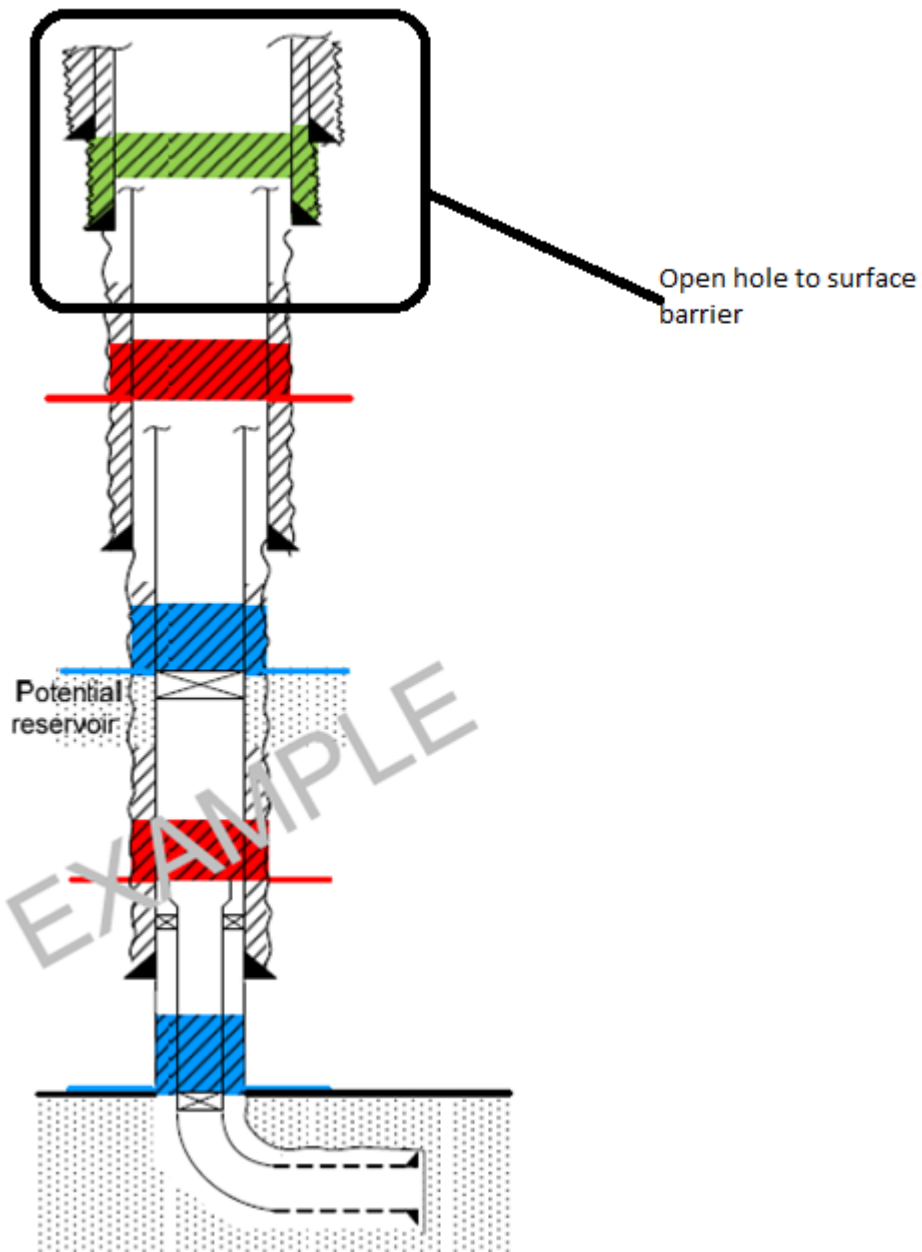
In our case this is a hydrocarbon bearing formations, so there shall be minimum two well barriers present.

Then the primary, secondary and environmental barrier is set. The next figures (figure 8&9) below illustrates the primary well barrier (blue colour) the secondary well barrier (red) and the open hole to surface well barrier (green)



**Figure 9:** “Primary, secondary and open hole to surface well barrier” [18].  
 Illustrates the primary well barrier (blue), the secondary well barrier (red) and the open hole to surface well barrier (green)





**Figure 10:** The well barrier schematics indicate the open hole to surface well barrier (in green) which consists of casing cement, casing and cement plug [18].

### **7. Cut and retrieve wellhead**

The last phase of the permanent P&A operation is to cut and retrieve wellhead. Below is a figure of the retrieval of a wellhead at Trolla [27].

PP&A is divided in three phases according to Oil and Gas UK[21] the removal of wellhead and conductor is the latest phase or phase 3.

In 2013 Williams et al. published a paper where they described a case history where they performed phase 3 by the utilization of intervention vessels [27].

For this case history a dedicated vessel was utilized in order to perform the job. This technology is called water jet technology, where water is pressurized somewhere between

60MPa and 120 MPa. This has HSE benefits since this eliminates the need for heavy lifts and operations with heavy equipment. The Trolla case history obtained the world record for this type of technology with a water depth of 270 metres.



**Figure 11:** Retrieval of wellhead at Trolla [27].

## 1.2 P&A operational phases:

According to [21] the well abandonment phases can be divided into three phases which are [27]:

### ***Phase 1: Reservoir Abandonment***

The first operational phase is reservoir abandonment. During this phase the reservoir is being isolated by placing the primary and secondary permanent barriers. When the well is fully isolated from the reservoir, this phase is considered to be finished. [47] Work that is performed in Phase 1 could typically involve:

- Running logs
- Kill well
- Punch tubing
- Set temporary plugs
- Retrieval of tubing

### ***Phase 2: Intermediate Abandonment***

During this phase the liners are isolated, milling operations are performed and the barriers are set against intermediate zones. This phase is considered to be finished when all the plugging operations are performed [47].

### **Phase 3: *Wellhead and conductor removal***

The last phase is to remove the wellhead. It is stated in NORSOK D010 [18]:

*“For permanent abandonment wells, the wellhead and casings shall be removed below the seabed at a depth which ensures no stick up in the future”.*

In the paper to Williams et al. where the case history at Trolla was presented the reduction of costs was described. In this paper they said that they were able to reduce the costs of exploration drilling by utilizing the dedicated vessel for cutting and retrieval of wellhead [27]. According to the paper this method is economical when at least two jobs are combined [27].

As we observe from the operational phases we start in the lower part of the well first, at the reservoir, and work our way upwards. It is not always necessary to perform all of the three phases. For slot recovery operation for instance; it is not preferable to remove the wellhead and the conductor as in phase 3.

The different P&A phases use different types of vessels. There has been a lot of research on performing P&A by utilizing different types of vessels instead of drilling rigs. Recently Aker had a contract with Statoil, where they tried to find a solution for performing the intermediate P&A phase by utilizing a category B vessel. They had to cancel this contract due to lack of technology [40].

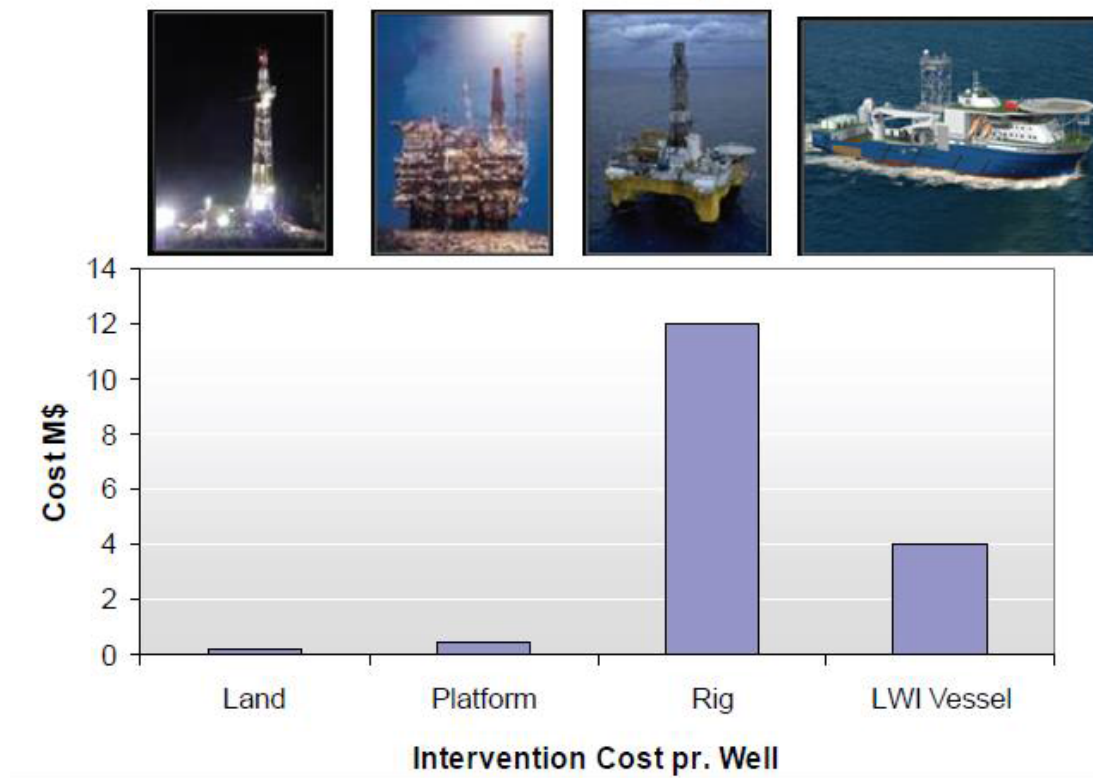
## **1.3 Rigs and vessels to perform P&A on subsea wells:**

There are main differences when it comes to performing P&A operations on platform wells, and for subsea wells. Due to limited access to the wells on subsea wells, dedicated vessels need to be utilized in order to permanent P&A subsea wells.

Fjærtøft et al. published a SPE paper in 2011 called “Success from Subsea Riserless Well Intervention” [38].

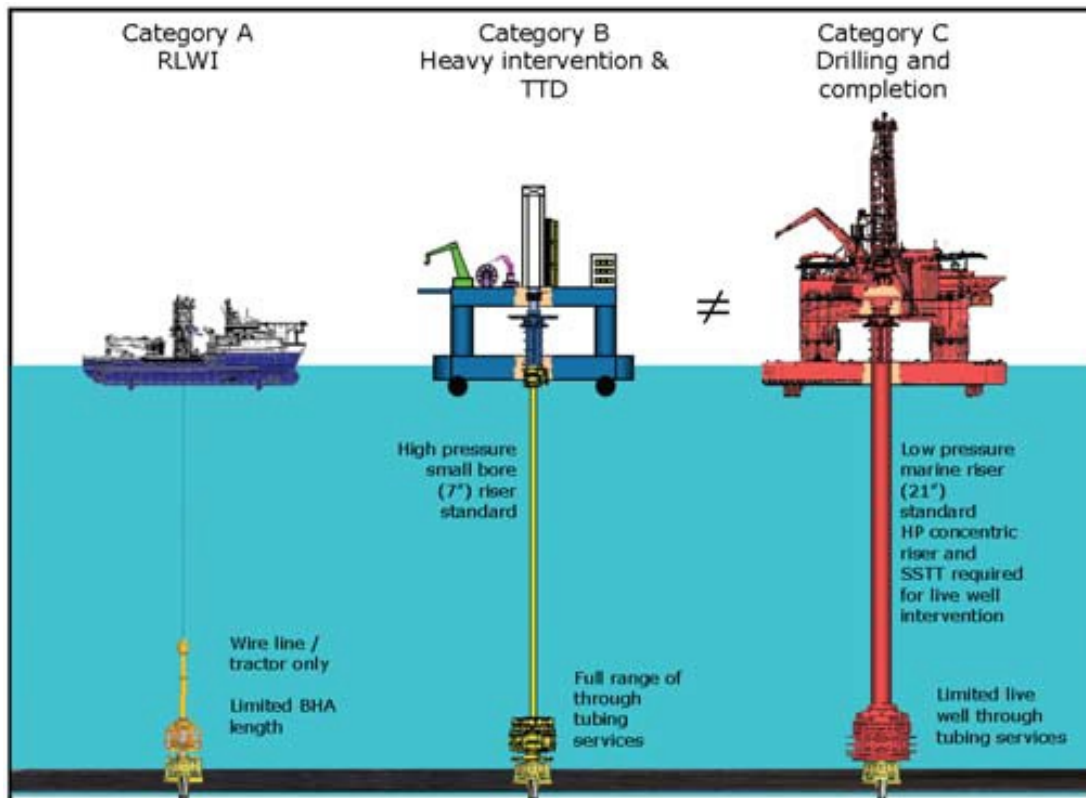
In this paper the benefits by utilizing subsea riser less well intervention are discussed. In Fjærtøft et G.Sønstabø paper, a figure is presented which illustrates the intervention costs per well by using different techniques. The cost can be dramatically reduced by introducing RLWI. Figure 12 illustrates the intervention costs per well [38].

## Intervention Cost pr. Well



**Figure 12:** This figure illustrates how the intervention costs per well can be significantly reduced by moving the intervention activities from the rig to alternative methods [38].

For subsea wells the P&A operations can be performed by utilizing three categories of intervention units; which are categorized to category A, B and C. The figure below (Figure 13) illustrates the three categories [13].



**Figure 13:** Shows the three intervention types: category A: RLWI, category B: heavy intervention and category C: semisubmersible rig [13].

**Category A:** Category A is performed by a dedicated vessel and is called RLWI (Riser Less Well Intervention). These types of vessels are used for subsea well intervention with wireline. A category A vessel can typically perform phase 1 and phase 3 of the P&A work that was described previously. As the name says the work is performed without utilizing a riser [38]. Island Offshore is one company that provides category A vessels. Some examples of their vessels are Island Frontier, Island Wellserver and Island Constructor which are shown in Figure 14 below:

| Island Frontier  | Island Wellserver  | Island Constructor  |
|--|--|---|
|   |   |   |
| <ul style="list-style-type: none"> <li>• Sub sea installation and module handling operations</li> <li>• Riserless well intervention services</li> <li>• Trenching</li> <li>• ROV operations</li> </ul> | <ul style="list-style-type: none"> <li>• Riser less light well intervention services</li> <li>• Installation and module handling operations</li> <li>• Trenching</li> <li>• ROV operations</li> <li>• P&amp;A Work</li> <li>• Construction work</li> <li>• Diving</li> </ul> | <ul style="list-style-type: none"> <li>• P&amp;A work</li> <li>• Construction work</li> <li>• Tower and module handling</li> <li>• Installation work</li> <li>• IMR work</li> <li>• Survey work</li> <li>• Crane work</li> <li>• Diving work</li> </ul> |

**Figure 14:** This figure illustrates three of Island Offshores RLWI vessels [13].

**Category B:** Category B is performed by utilizing heavy intervention vessels and is still under developing. Category B was earlier in development phase, where Aker solutions had a contract with Statoil about inventing a new category B vessel. The contract had to be cancelled in June 2013 due to lack of technology.

This category B was intended to have full range of through tubing services [40].



**Figure 15:** The category B [40].

**Category C:** Category C is a semi-submersible rig. Here a marine riser is used together with the BOP.

## 1.4 Rigs and vessels to perform P&A on platform wells:

For platform wells we are able to skid the derrick to the well that are going to be plugged and abandoned. But it is still preferable to use the derrick for other well activities than abandonment of wells. If we are able to move the platform P&A operations from the derrick to wireline and coiled tubing and jacking units it is therefore beneficial. The derrick should be used for drilling new wells, instead of P&A operations [13].

### **Archers modular rigs (MDR):**

Archer has invented a new modular rig, where the newest one is called Emerald. The purpose with this modular rigs, is to make the operations more cost efficient. At Archer's webpages one can find brochure about the MDR, and more information. At Archer brochure regarding the MDR they claim that the

*"MDR offers operational flexibility and cost efficiency unrivalled by any other modular offshore drilling units"[39].*

One of the application areas that are mentioned at their webpage is that the MDR can be used for P&A operations. This is another solution that may be used in the future in order to reduce the costs for the P&A operation [39].

### **Different permanent abandonment options:**

NORSOK D010, rev 4, section 9.6 covers permanent abandonment. "Permanent abandonment is defined as a well status, where the well is abandoned and will not be used or re-entered again"[18].

### **Different temporary abandonment methods**

As we mentioned previously we distinguish between temporary abandonment with monitoring and temporary without monitoring.

**Temporary abandonment with monitoring** is according to NORSOK D010, rev 4 defined as "well status, where the well is abandoned and the primary and secondary well barriers are continuously monitored and routinely tested

If the criteria cannot be fulfilled, the well shall be categorized as a temporary abandoned well without monitoring" [18].

There is not set any maximum time frame for the abandonment period when it is being monitored.

**Temporary abandonment – without monitoring is according to NORSOK D010, rev 4 defined as** "well status, where the well is abandoned and the primary and secondary well barriers are not continuously monitored and not routinely tested".

For temporary abandonment without monitoring the maximum abandonment period shall be three year [18].

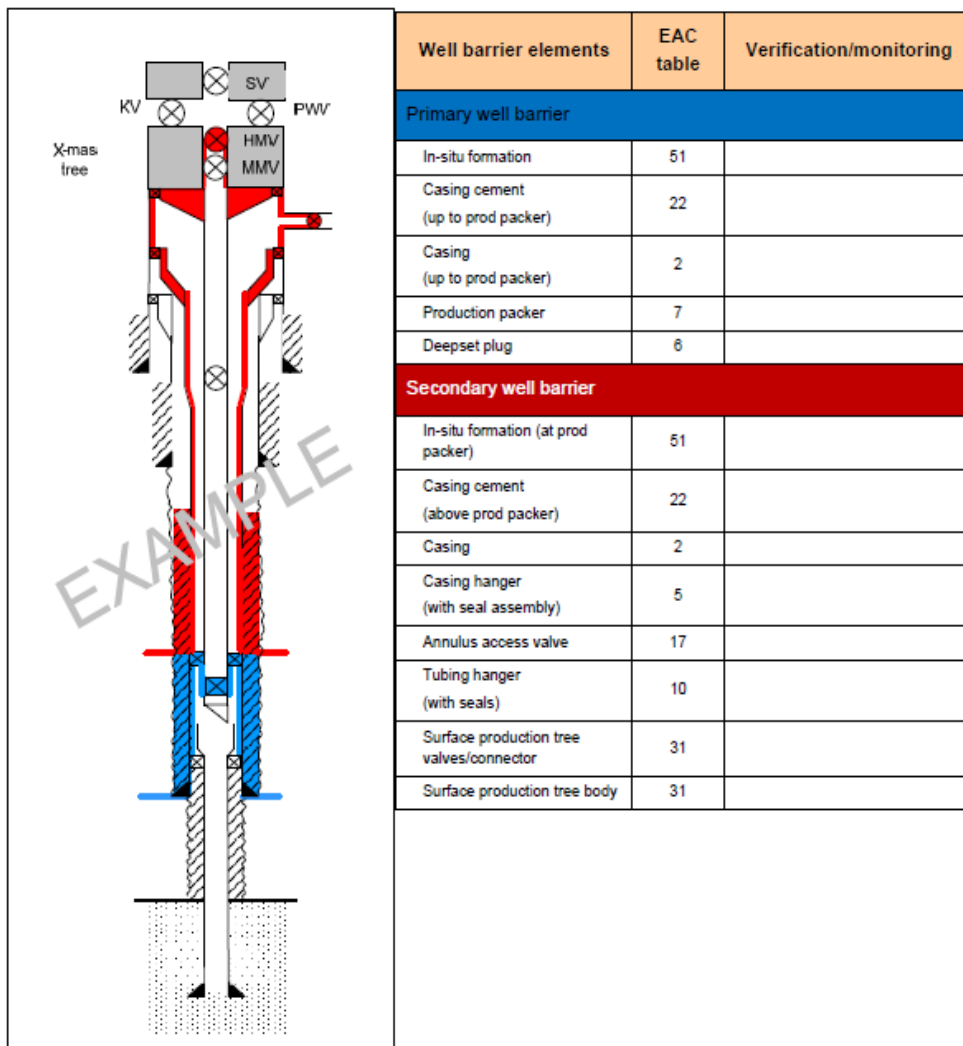
## 2. WELL BARRIERS

A **well barrier** is in Norsok D010 defined as an “envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment” [18].

**Well barrier element** is according to Norsok D010 “a physical element which in itself does not prevent flow but in combination with other WBE’s forms a well barrier [18].

We have two groups of barrier elements, dependent on their position based upon the flow direction. These are primary and secondary well barrier. The primary well barrier (blue) and the secondary well barrier (red) make a well barrier envelope.

In Norsok D010 there are different well barrier schematics covering different scenarios. Below the well barrier schematics from section 9.5.4 illustrated the well barrier with temporary abandonment with continuous monitoring. The well barrier envelope with its primary (in blue) and secondary (red) well barrier is listed in the table on the figures right side. The next two figures illustrate some examples of well barrier schematics.

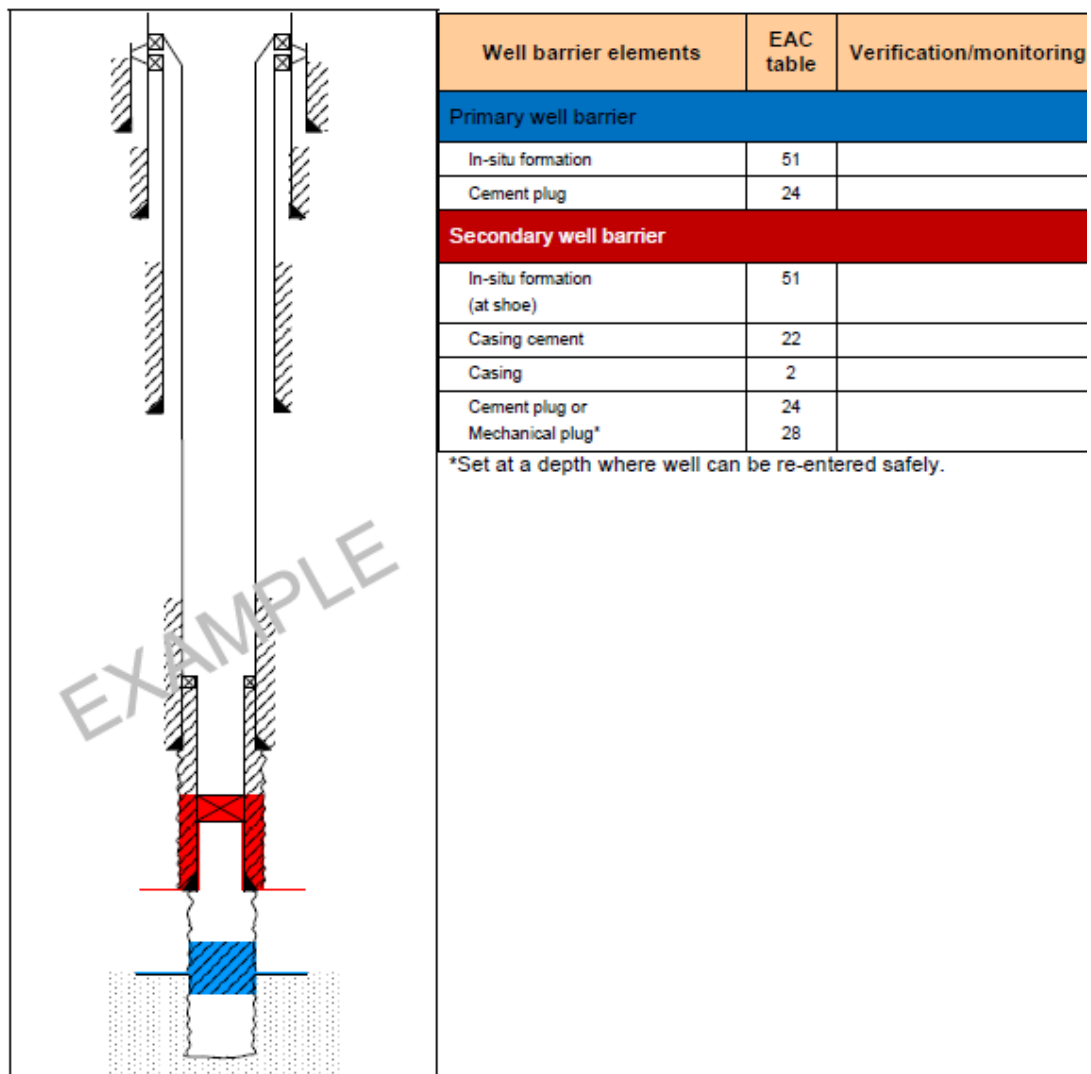


**Figure 16:** “Production well with deep set mechanical plug, continuous monitoring” [18].



The **primary well barrier** is according to NORSOK D010 defined as “the first well barrier that prevents flow from a potential source of inflow”[18].

While the **secondary well barrier** is defined as the “second well barrier that prevents flow from a potential source of inflow”[18].



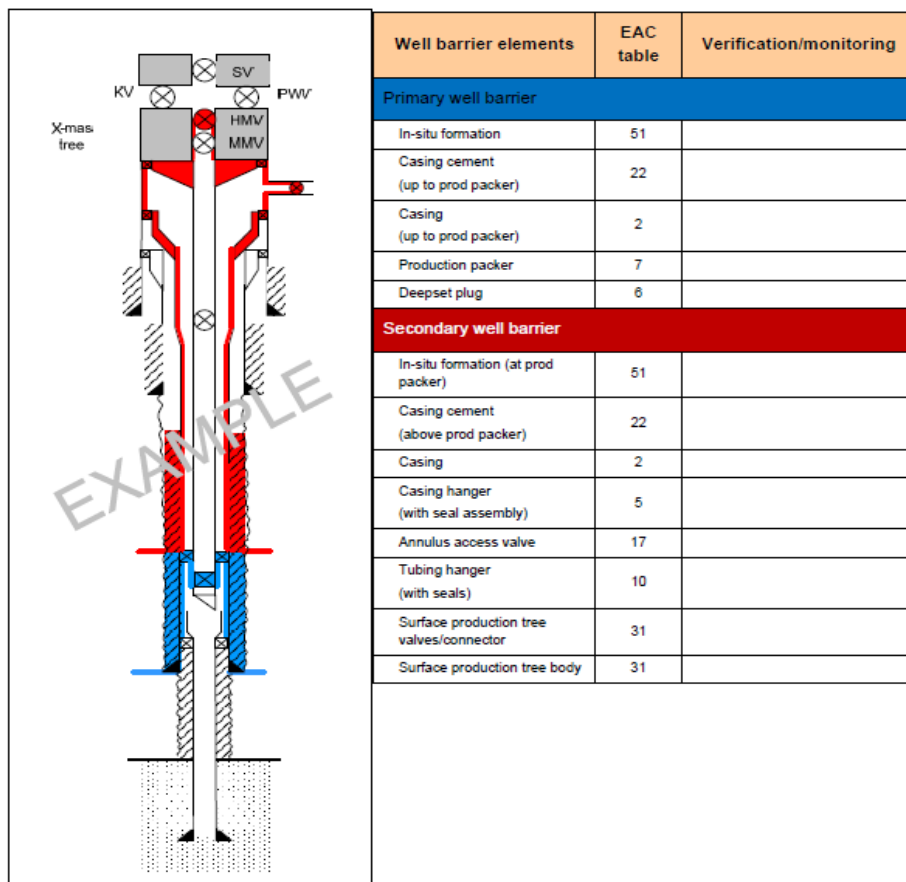
**Figure 17:** Temporary abandonment without monitoring [18].

The next two figures (*Figure 18 and Figure 19*) are taken from NORSOK D010 and show two well scenarios. The first figure, *Figure 18* shows the well configuration for a production well with deep set mechanical plug, continuous monitoring.

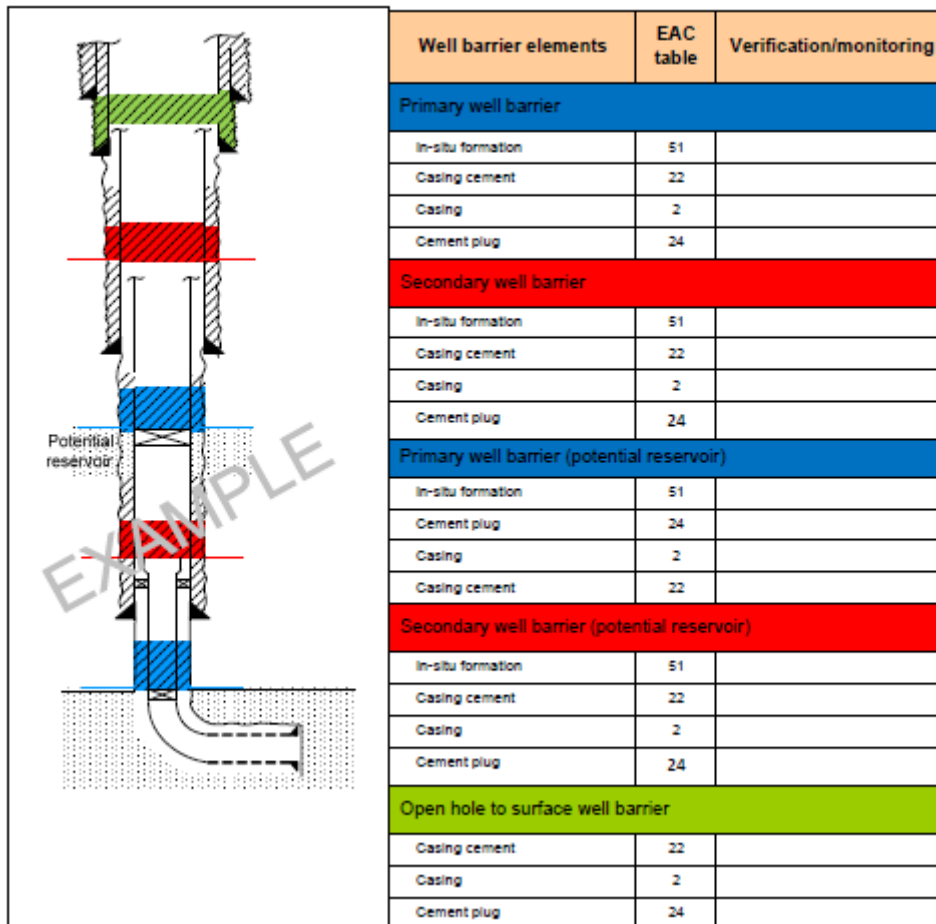
The next figure, *Figure 19* shows the well configuration after P&A for a slotted liner in multiple reservoirs.

By comparing these two figures one can easily observe that well barriers have been changed.

*Figure 19* is permanently plugged and abandoned and the primary well barrier is the in situ formation, casing cement, casing, and the cement plug. The secondary well barrier is now formation in-situ, casing cement, casing and the cement plug. The open hole to surface well barrier is casing, casing cement, and cement plug.



**Figure 18:** Well configuration before P&A [18].



**Figure 19:** The well configuration when the well is PP&A (permanently plug and abandoned). This is the well configuration for “A slotted liner in multiple reservoirs” [18].

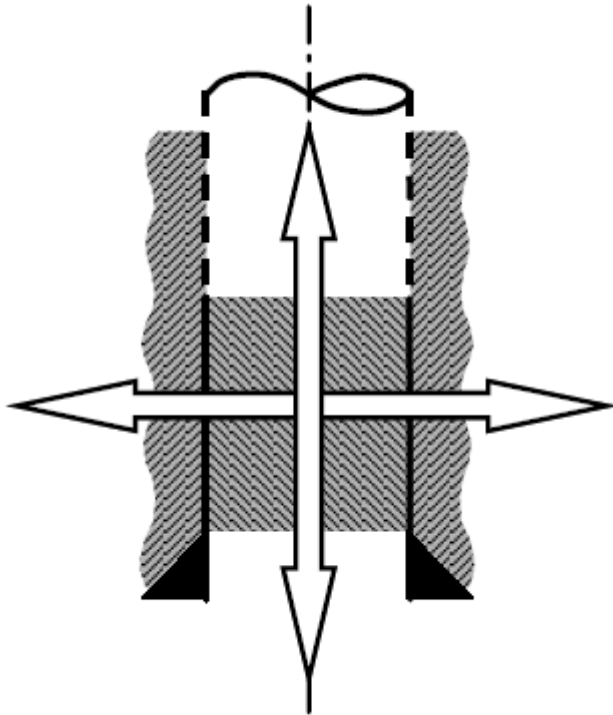
**A permanent well barrier** is according to NORSOK D010 defined as “Well status, where the well is abandoned permanently and will not be used or re-entered again”.

According to NORSOK D010 a permanent well barrier shall have the following properties [18]:

- Provide long term integrity (eternal perspective)
- Impermeable
- non shrinking
- able to withstand mechanical loads/impacts
- resistant to chemicals/substances (H<sub>2</sub>S, CO<sub>2</sub> and hydrocarbons)
- ensure bonding to steel
- not harmful to the steel tubulars integrity

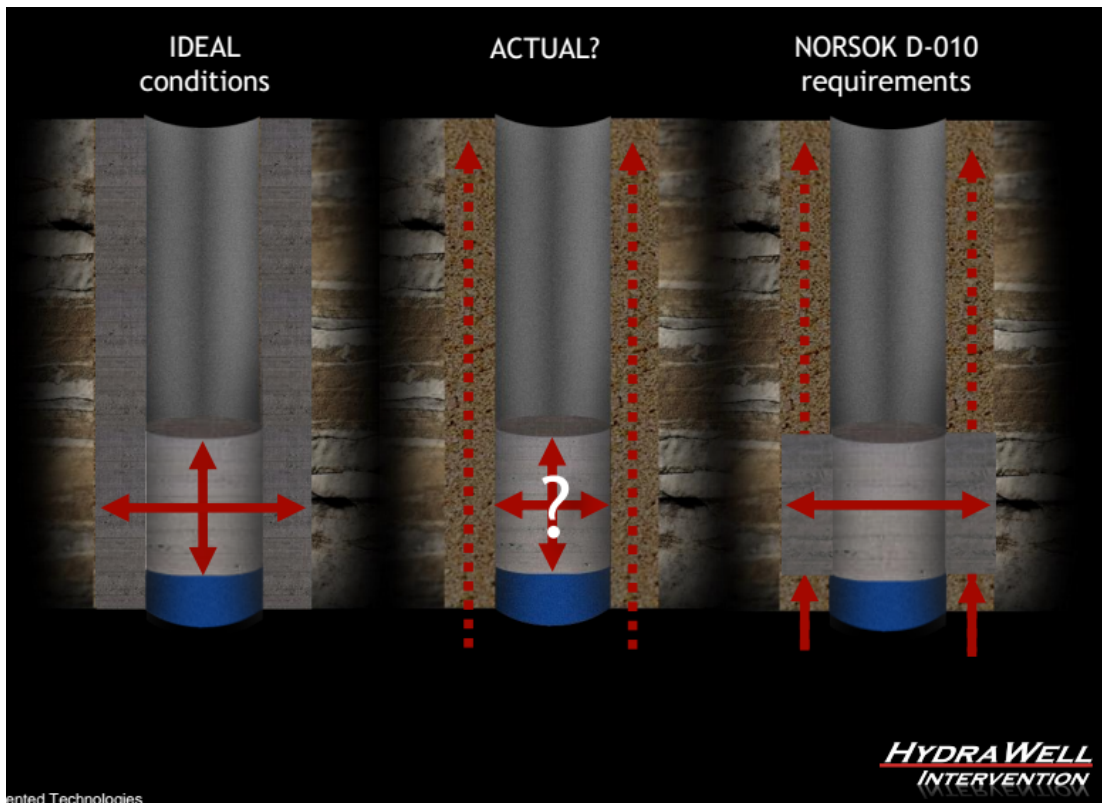
NORSOK D010 also states that “permanent well barriers shall extend across the full cross section of the well include all annuli and seal both vertically and horizontally”. The next

figure is taken from NORSOK D010, section 9.6.2.2 and illustrates this. This is very important to have in mind, during P&A, since this indicates the efficiency of the permanent plug to seal off the reservoir [2].



**Figure 2:** Permanent well barrier [18].

During a visit to HydraWell offices at Tananger in March 2014 Arne G Larsen went through a presentation. In one of his slide he spoke about the well barriers and the below figure is a good illustration of the ideal conditions vs the actual conditions and the NORSOK D010 requirements.



**Figure 20:** “Ideal conditions, actual conditions and NORSOK D010 requirements”[20].

The figure on the left side illustrates how to plug the well when there is cement on the outside of the casing from the original job. Then it is only necessary to place the plugs on the inside.

The figure in the middle shows the actual case for many wells. Here one observes that the cement on the outside of the casing is of bad quality or there is no cement present behind the casing. This can be observed by a detected pressure in the annulus from logging. In these types of scenarios it is necessary to place the plugging material on the outside of the casing.

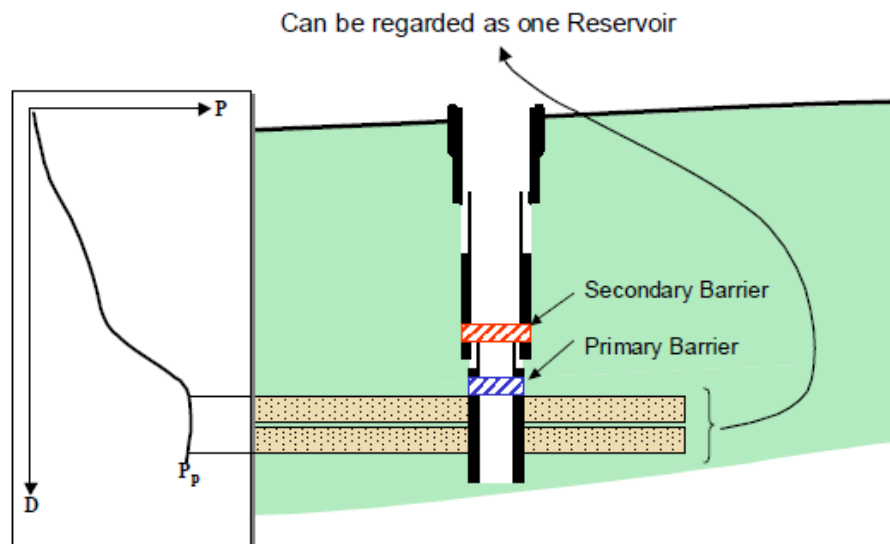
The figure on the right side illustrates the NORSOK D010 requirements [18].

In the previous section it was mentioned that a

*“permanent well barriers shall extend across the full cross section of the well include all annuli and seal both vertically and horizontally”.*

In multiple reservoirs where we have the same pressure conditions, it is according to NORSOK D010, rev 4 sufficient to use one primary and secondary barrier for the two zones. This is only valid when the two reservoirs are within the same pressure regime.

Figure 21 is taken from NORSOK D010 and illustrates this multiple reservoir scenario within the same pressure regime.



**Figure 21:** “Multiple reservoirs within the same pressure regime” [18].

#### Well barrier acceptance criteria for subsea wells:

Subsea wells that do not have the ability to being monitored shall according to NORSOK D010 have a yearly ROV inspection program [18]. Before we are able to start temporary abandonment the following requirements shall be fulfilled according to NORSOK D010, section 9.5.2.1:

- Production/injection packer and tubing hanger is pressure tested
- Tubing is pressure tested
- The DHSV is closed and pressure/function tested
- All valves in the subsea tree are pressure/function tested and are closed
- For wells with horizontal subsea free, the tubing hanger crown plug(s) is pressure tested.

“All valves shall be verified to have zero leak rate or plug(s) shall be installed to compensate for leaking valves” [18].

## 2.1 Well Barrier Requirements

In NORSOK D010, rev 4 under section 4.2.3 it is stated that there shall be minimum **one well barrier** if there is: [18]

- Undesirable cross flow between formation zones
- Normally pressured formation with no hydrocarbon and **no potential to flow** to surface
- Abnormally pressured hydrocarbon formation with no potential to flow to surface (e.g tar formation without hydrocarbon vapour)

If there is

- Hydrocarbon bearing formations
- Abnormally pressured formation **with potential to flow to surface**

Then there shall be a **minimum of two well barriers present.**

## 2.2 Length requirements of well barriers

In NORSOK, D010, section 9.6.3.2 there is a requirement for internal WBE`s.  
This states that:

*“An **internal well barriers** (ex cement plug) shall be positioned over the entire interval where this is a verified external WBE and shall be minimum 50 m if set on a mechanical plug/cement as a foundation, otherwise according to EAC 24” [18].*

EAC stands for Element Acceptance Criteria. There are various well barrier acceptance criteria, which can be found in chapter 15 in NORSOK D010. As an example is table 24 for Cement plug, and 52 for creeping formation.

*“**External WBE** (example: casing cement) shall be verified to ensure a vertical and horizontal seal. According to NORSOK D010, rev 4 it is required for external WBE to have 50metres 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 in order to act as a permanent external WBE. The interval shall have formation integrity” [18].*

In NORSOK D010, rev 4 there is a table (table 24) that describes the acceptance criteria for cement plugs which can be found in chapter 15 [18].

From Table 1 below, number 8 in this table one can observe that there are minimum cement plug depths that shall be defined according to the well scenario. As an example for open hole cement plugs, there shall be 100 m MD with minimum 50m MD above any source of

inflow/leakage point. If the plug is in transition from open hole to casing this table says that it should extend at least 50 m MD above and below casing shoe [18].

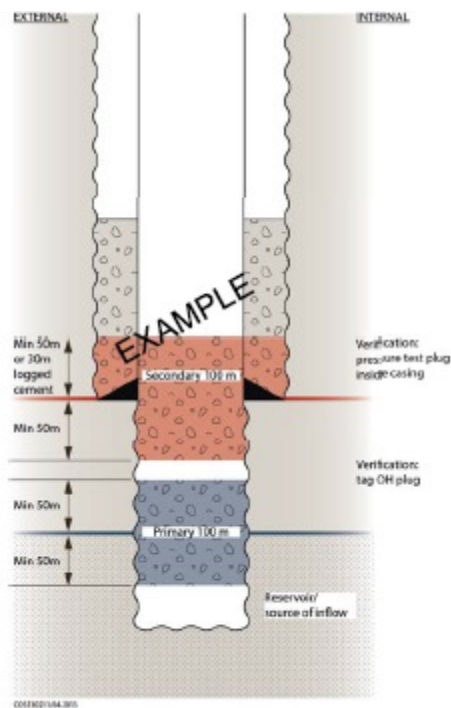
**Table 1 - Cement plug, acceptance criteria [18].**

| Features  | Acceptance criteria   | See  |                         |   |   |   |  |                        |
|---|---|--|-------------------------|---|---|---|--|------------------------|
| <b>A. Description</b>   | The element consists of cement in solid state that forms a plug in the wellbore.  |  |                         |   |   |   |  |                        |
| <b>B. Function</b>  | The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to surface/seabed.  |  |                         |   |   |   |  |                        |
| <b>C. Design, construction and selection</b>  | <ol style="list-style-type: none"> <li>1. A program shall be issued for each cement plug installation.</li> <li>2. For critical cement jobs, HPHT conditions and complex slurry designs the cement program should be verified by independent (internal or external) qualified personnel.</li> <li>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.</li> <li>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<sub>2</sub>, H<sub>2</sub>S).</li> <li>5. Permanent cement plugs should be designed to provide a lasting seal with the expected static and dynamic conditions and loads.</li> <li>6. It shall be designed for the highest differential pressure and highest downhole temperature expected including installation and test loads.</li> <li>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.</li> <li>8. The minimum cement plug length shall be: <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 33%;">Open hole cement plugs</th> <th style="width: 33%;">Cased hole cement plugs</th> <th style="width: 33%;">Open hole to surface plug (installed in surface casing)</th> </tr> </thead> <tbody> <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> </tbody> </table> </li> <li>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).</li> <li>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: <ol style="list-style-type: none"> <li>a. The cement plug shall extend 50m into the casing.</li> <li>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.</li> </ol> </li> <li>11. A casing/liner shall have a shoe track plug with a 25 m MD length.</li> </ol> | Open hole cement plugs                                   | Cased hole cement plugs | Open hole to surface plug (installed in surface casing) | 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. | 50 m MD if set on a mechanical/ cement plug as foundation, otherwise 100 m MD | 50 m MD if set on a mechanical plug, otherwise 100 m MD. | API Spec 10A Class 'G' |
| Open hole cement plugs  | Cased hole cement plugs   | Open hole to surface plug (installed in surface casing)  |                         |   |   |   |  |                        |
| 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. | 50 m MD if set on a mechanical/ cement plug as foundation, otherwise 100 m MD   | 50 m MD if set on a mechanical plug, otherwise 100 m MD. |                         |   |   |   |  |                        |



## Abandonment of open hole with cement plugs

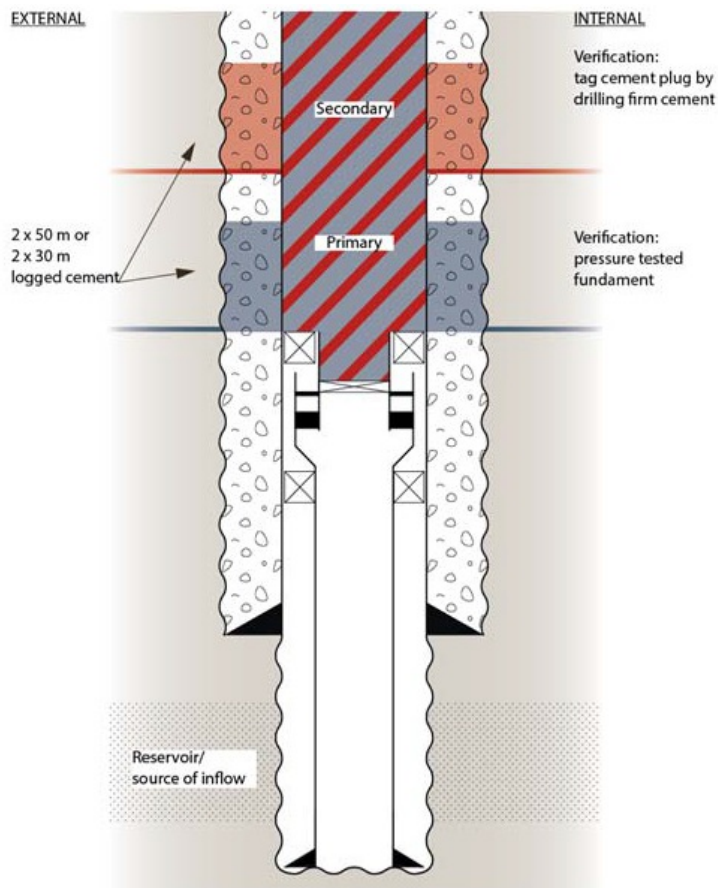
Abandonment of open hole with cement plugs is covered in section 9.6.6.1 in NORSOK D010. In this section one can find an example of how the last open hole section is permanently abandoned. The primary cement plug consists of 100 meter of cement across/above the reservoir, and a secondary cement plug 50 meters below and 50 meters above the casing shoe. This is an example of the well barrier acceptance criteria for cement plug which is in line with Table 1 above.



**Figure 22:** "Permanent abandonment, open hole and inside casing plugs" [18].

### Single cement plug in combination with mechanical plug

Abandonment of a wellbore where a mechanical plug is used in combination with cement plug is covered in NORSOK D010, Section 9.6.6.3 [18]. From Figure 22 below one can observe that the mechanical plug acts as a foundation for the single cement plug.



**Figure 23:** Permanent abandonment, single cement plug and mechanical plug as foundation [18].

## 2.3 Positioning of well barriers

According to the well barrier acceptance criteria, in section 9.6.2 in NORSOK D010, rev 4 the primary, secondary, the crossflow, and the open hole to surface well barriers shall have the following functions and depth positions as the table (Table 2) below illustrates [18].

**Table 2 - Well barrier depth positioning [18].**

| Name                                     | Function   | Depth position  |
|--|--|---|
| <b>Primary well barrier</b>              | To isolate a source of inflow, formation with normal pressure or over-pressured/ impermeable formation from surface/seabed.  | The base of the well barriers shall be positioned at a depth where formation integrity is higher than potential pressure below, see 4.2.3.6.7 Testing of formation. |
| <b>Secondary well barrier</b>            | Back-up to the primary well barrier, against a source of inflow  | As above  |
| <b>Crossflow well barrier</b>            | To prevent flow between formations (where crossflow is not acceptable). May also function as primary well barrier for the reservoir below.   | As above  |
| <b>Open hole to surface well barrier</b> | To permanently isolate flow conduits from exposed formation(s) to surface after casing(s) are cut and retrieved and contain environmentally harmful fluids. The exposed formation can be over-pressured with no source of inflow. No hydrocarbons present. | No depth requirement with respect to formation integrity  |

## 2.4 Verification of well barriers

In NORSOK D010 section 4.2.3.5 one can find the requirements for verification of well barriers. In this section it is stated that when a WBE has been installed, its integrity shall [18]:

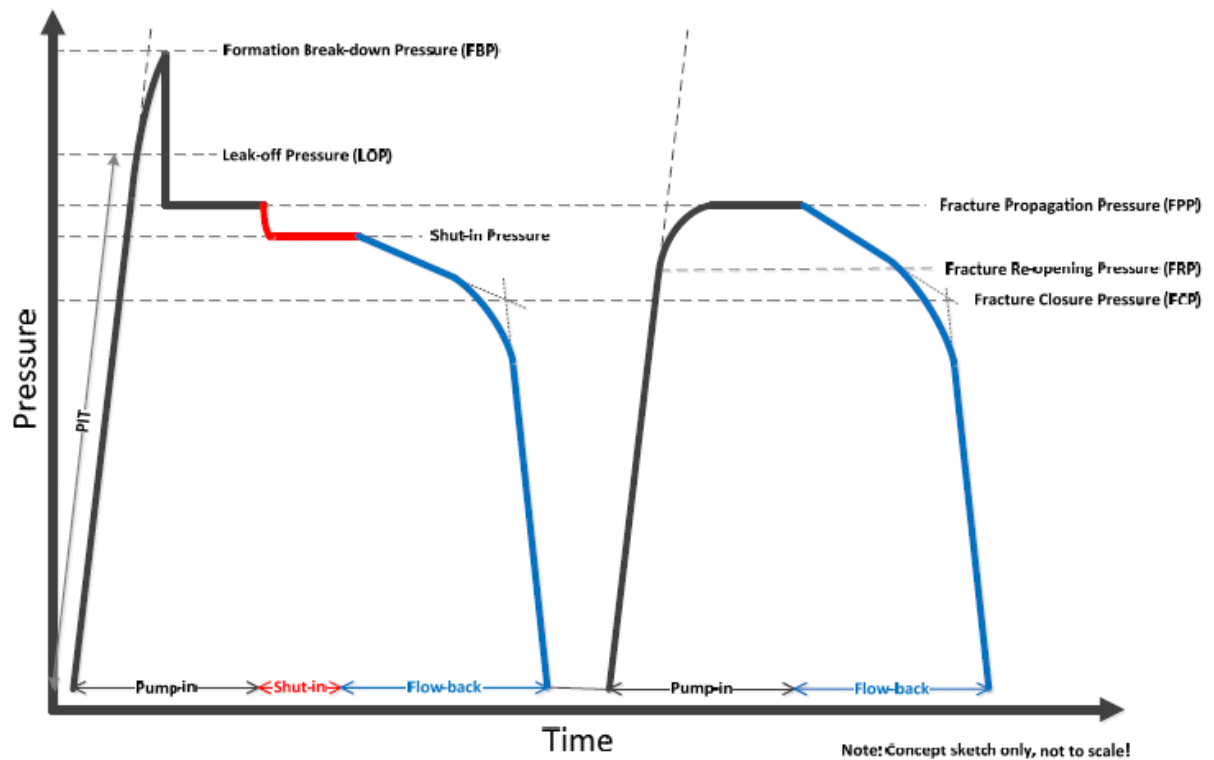
- a) Be verified by means of pressure testing by application of differential pressure, or
- b) When a) is not feasible, be verified by other specified methods.

WBE's that require activation shall be function tested.

A re-verification should be performed if:

- c) The condition of any WBE has changed, or:
- d) There is a change in loads for the remaining life cycle of the well (drilling, completion and production phase)

The figure below (*Figure 24*) is taken from NORSOK D010, rev 4 section 4.2.3.6.7.1 and shows the behaviour of a typical X-LOT in a non-permeable formation [18].



**Figure 24:** Illustrates XLOT pressure graph [18].

## 2.5 Verification of formation integrity

According to NORSOK D010, the permanent well barriers shall be tested according to the two tables (Table 3 and Table 4 below). These can be found in NORSOK D010, rev 4, section 4.2.3.6.7[18].

**Table 3 - Methods for determining formation integrity [18].**

| Method                                      | Objective   | Comment  |
|---|---|--|
| Pressure/formation integrity test (PIT/FIT) | To confirm that the formation/casing cement is capable of supporting a pre-defined pressure | Application of a pre-determined pressure to the formation and observe if stable.                       |
| Leak-off test (LOT)                         | To establish the pressure the wellbore wall/casing cement is actually capable of supporting | The test is stopped once a deviation from the linear pressure vs. volume curve is observed.            |
| Extended leak-off test (XLOT)               | Determine the minimum in-situ formation stress.   | The test propagates a fracture into the formation and establishes the fracture closure pressure (FCP). |

**Table 4 - Formation integrity requirements [18].**

| Well type/activities  | Minimum formation integrity   |  |
|---|---|--|
|   | New wells   | Existing wells   |
| Exploration wells (all activities including permanent abandonment)  | Formation integrity can be obtained by PIT/FIT or LOT. The measured values shall exceed the section design pressure taking hydrostatic pressure into account.   |  |
| Production wells – drilling activities and activities with mud in hole  |   |  |
| Production wells – completion activities with solid-free fluid, production/injection and abandonment activities | Minimum formation stress/fracture closure pressure (FCP) shall exceed the maximum wellbore pressure at formation depth. The expected wellbore pressure shall as a minimum be based on the reservoir pressure (minus hydrostatic pressure) for producers and maximum injection pressure (plus hydrostatic pressure) for injectors. | The formation integrity pressure (in the interval between LOP and FCP, see figure below) used in the original design can be used. The original design values shall be re-assessed prior to permanent abandonment of the well(s). |

According to NORSOK D010 section 9.6.2

*“The suitability of the selected plugging materials shall be verified and documented”*[18].

### 3. PLUGGING MATERIALS

#### 3.1 NORSOK D010 and plugging materials

It is very important to perform a good cement job during P&A, for the well integrity issues as the cement provides a sealing mechanism.

Portland cement is the most common plugging material [1]

This is due to its mechanical properties and relatively low cost. According to NORSOK D010, section 9.6.3 the casing cement shall be verified by pressure testing and the cement plug (inside tubing) shall be tagged and pressure tested.

The book “Well Cementing” by Eirik B Nelson [10] was observed to get a better understanding of the cementing process. It is important that the cement is of good quality, since this is sealing the reservoir. It is also important that the cement can withstand loads, without cracking or creating migration paths. According to Nelson`s books the different chemicals that we mix together with the cement is of big importance for increasing the cements properties. In his book he mentions calcium lignosulfonates as an example of additives for deep wells with a high bottom hole temperature.

As we mentioned in the introduction a permanent well barrier shall according to NORSOK D010 have the following properties:

- Provide long term integrity(eternal perspective)
- Impermeable
- Non-shrinking
- Able to withstand mechanical loads/impacts
- Resistant to chemicals/substances (H<sub>2</sub>S, CO<sub>3</sub> and hydrocarbons)
- Ensure bonding to steel
- Not harmful to the steel tubular integrity

It is also stated the following regarding plugging materials under section 9.6.2 well barrier acceptance criteria:

*“The suitability of the selected plugging materials shall be verified and documented”*[18].

#### Casing cement in primary and secondary well barriers

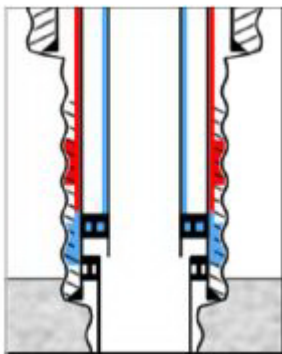
It is possible to use the same casing cement as WBEs for both primary and secondary well barriers. Then the acceptance criteria from section 15 in NORSOK D010, table 22 has to be fulfilled.

In section 4.2.3.3.1 in NORSOK D010 there is a section describing casing cement in primary and secondary well barriers.

In multiple reservoir zones where the pressure regimes are differently, the acceptance criteria in NORSOK D010 states that

*“there shall be 2 x 30mMD intervals of bonded cement, obtained by logs which have been verified by qualified personnel”*

When this criterion is fulfilled, the two distinct intervals will be elements in the primary and secondary well barriers, respectively (see Figure 25 below).



**Figure 25:** Illustrates when casing cement will be elements in the primary and secondary well barrier. The casing cement is not defined as common WBE [18].

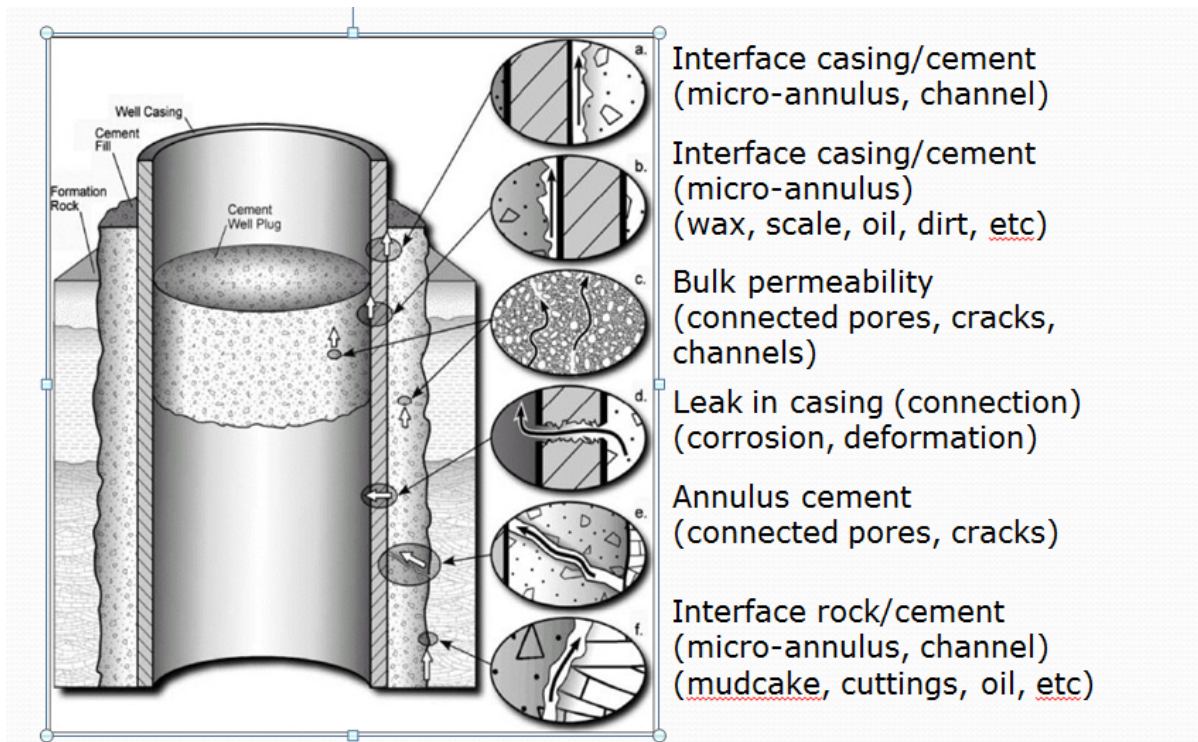
### 3.1 Cement leak paths

Rheology means the study of the deformation and flow of fluids. If fluid follows Newtons law of viscosity they are characterized as Newtonian fluids [44].

When cement is chosen as plugging material, we may have many potential leak paths. The figure below illustrates this in a good way, and was given by Alam Maqsd`s presentation at Wellcem [49].

As the figure below illustrates there are many potential leak paths for each layer. This figure points out 6 potential leak paths which are the following:

- in the interface rock /cement
- in the annulus cement
- inside the cement behind casing,
- inside the cement well plug
- interface casing/cement plug
- and the interface casing/cement on the outside of the casing.



**Figure 26:** Potential leak paths for cement plug [16].

An OTC paper called “Techniques and Materials for North Sea plug and abandonment operations” was published in 2013. In this paper different well barrier materials are discussed with their positive and negative sides. According to this paper the advantages with cement is listed in this table as the following [41]:

- Low fluid loss
- Adjustable slurry parameters
- High compressive strength

And the concerns are listed as the following:

- Corrosive environments
- HPHT
- Tectonic stresses
- Low tensile strength
- Low permeable
- Possible gas influx



### 3.4 ThermaSet® as an alternative to cement

WellCem AS is one of the vendor of an alternative to cement. WellCem AS has been working with their patented ThermaSet since 2008. SINTEF has also been performed a lot of research on the ThermaSet™.



**Figure 27:** Wellcem offices at Orstad [49].

I was so lucky that I was able to meet one of the employees Alam Maqad at their offices at Klepp and get more information about this plugging material. He has good knowledge about this plugging material since he has been working there since they started to investigate this patented technology [49].

ThermaSet™ is a polymer resin plugging material. ThermaSet™ is an alternative to cement, and one of the benefits of using the thermoset instead of cement will be discussed further in this section.

Portland cement is the most commonly used plugging material [1]. One of the challenges with using cement as a plugging material is that cement is eventually being deteriorated. Micro annulus can eventually be created, and this again gives the reservoir fluid ability to flow instead of being plugged [1].

ThermaSet™ can then be a good alternative due to its mechanical and physical properties. The substance itself has an orange/red colour as the figure below illustrates. One of the good things about this plugging material is the ability you have to adjust this plugging material dependent on your well [49].

The density can be adjusted from 0,7SG to 2.5SG and it is therefore applicable for many types of well scenarios [49].

The curing time is dependent on the bottom hole temperature (BHT). You can therefore adjust the curing time dependent on your BHT. It is possible to adjusting the curing time from few minutes to several of hours. This could as an example be very useful if you have a fluid loss scenario where you need to take remedial actions. WellCem AS has then conducted various experiments on curing time, and based upon these they have different tables for covering different well scenario. ThermaSet™ has especially been used successfully for lost circulation cases in the Middle East [49].

The figure below (*Figure 28*) illustrates a sample of the ThermaSet™ plugging material. On the left side is the ThermaSet™ in its original form. The ThermaSet™ is orange/red in colour and behaves like a Newtonian fluid before the curing initiator and the weight components are added [49].

On the right side is the ThermaSet™ when the weight component and the curing initiator is added. The fluid then changes its colour as well as its fluid behaviour; it now behaves like a Bingham fluid when the components are added. It is also hard to scratch the sample on the right side while the other is in liquid form [49].



**Figure 28:** ThermaSet™ (original form on the left side) when weight components and curing initiator is added (right side) [49]

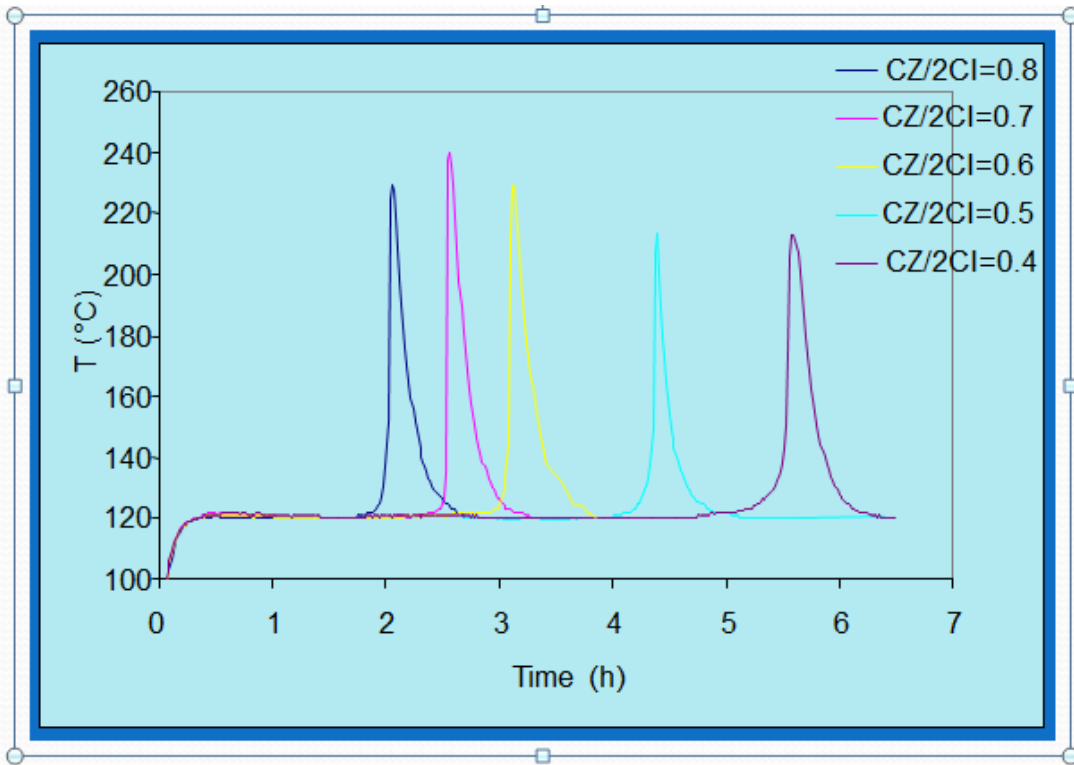
The people at the lab at WellCem are therefore communicating with the people at the rig site, so they don't have to do "experiments" offshore.

The ThermaSet™ plugging material have a density range from 0,7SG-2.5SG, the substance itself normally have a density of 1,03(the same as SW). By adding different weight components (white or transparent in colour) such as micromax and glass bubbles, makes it possible to adjust the density of the material. The figure below (*Figure 29*) illustrates one of the chambers where the weighing component is weighted [49].



**Figure 29:** One of the chambers where the weight components and curing initiator are weighted [49].

These polymers curing time is based upon the BHT. It is possible to adjust the curing time from a few minutes to several hours. The curing time is dependent on the (BHT) bottom hole temperature as the figure below (*Figure 30*) illustrates. It is possible to adjust the curing time dependent on your BHT. The people at the lab at WellCem are therefore communicating with the people at the rig site, so they don't have to do "experiments" offshore.



**Figure 30:** Curing time [49].

ThermaSet™ is being mixed offshore by utilizing the equipment for mixing that is being used for cement mixing. The equipment is therefore already in place at the rig site. Firstly the ThermaSet™ is mixed together with the weight component, and then the curing initiator is added. These are mixed together and pumped down at target depth. ThermaSet has various application areas, and can be used for both drilling, production and P&A issues. During Alams presentation he mentioned some of ThermaSet application area which were:

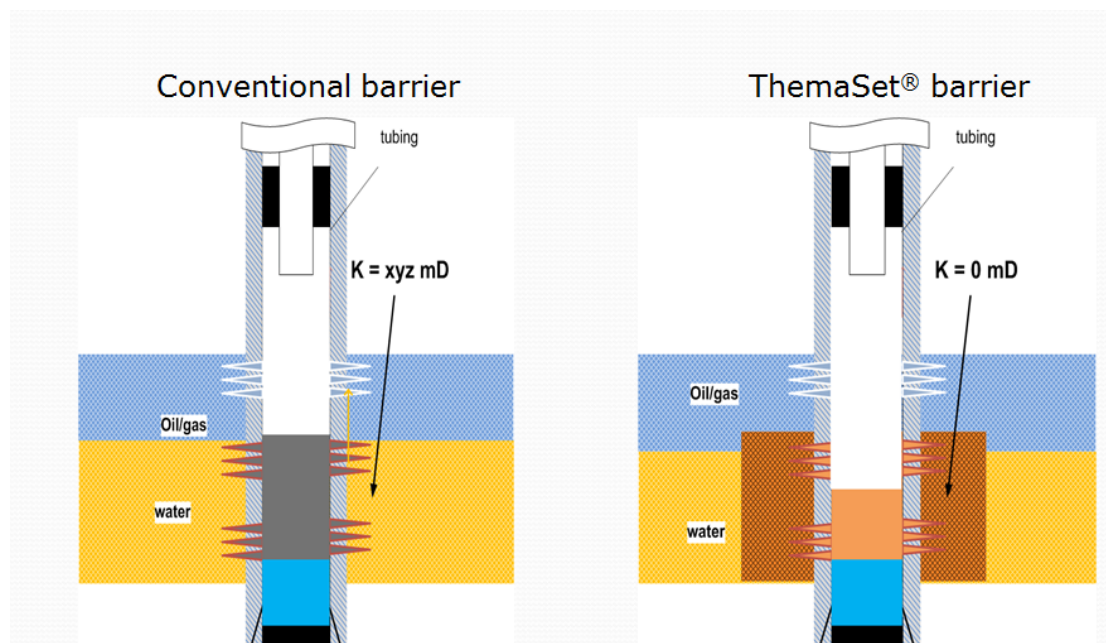
- Zonal isolation/shut off water and gas
- Plugging of control lines
- Squeeze jobs to seal off casing and tubing leaks
- Temporary plugging
- Plugs for P&A (environmental plugs, secondary plugs)
- Enable us to drill through Unconsolidated sand zones

When using ThermaSet™ as plugging material, it is not necessary to perform the operation several of times without success. One other important thing is that you are able to squeeze the plugging material in the BHA, or through the drill bit, and thereby not have to POOH and do several of trips [49].

### 3.5 Cement well barrier vs Thermaset well barrier

In a presentation given by Maqsad [39] the benefits by using this ThermoSet™ is highlighted due to its: Superior physical and mechanical properties, fast setting time which can be adjusted, the right angle setting and also the logistics issues [15].

During the presentation at Hydrawell, cement as a conventional barrier was compared with ThermoSet barrier. The behaviour of cement was compared with the principle of a coffee filter. Cement is solid powder that is mixed with water before it is pumped into the well. At the interface of well and reservoir (permeable zone) the water is squeezed out while the solid particles stay at the interface and form a layer or cake. ThermoSet on the other hand is a liquid that can penetrate through the permeable media and thereby plug the reservoir close to the well. The hydrocarbons are therefore kept away [39].



**Figure 31:** Comparing cement as a well barrier with ThermoSet™ as a well barrier [39].

## Thermaset vs Cement mechanical properties

The table (table 5) below illustrates the difference between Portland Cement and Thermaset

**Table 5 - Distinguish the different mechanical properties between Portland Cement and ThermaSet**

|                             | <u>Portland Cement</u> | <u>ThermaSet</u> |
|-----------------------------|------------------------|------------------|
| Compressive strength (MPa)  | 58                     | 77               |
| Flexural Strength (MPa)     | 10                     | 45               |
| <i>E-modulus (MPa)</i>      | <i>3700</i>            | <i>2240</i>      |
| Rupture Elongation (%)      | 0.01                   | 3.5              |
| Tensile Strength (MPa)      | 1                      | 60               |
| Failure flexural strain (%) | 0.32                   | 1.9              |

One of the challenges with Portland cement is that it may shrink during its settling period. These cracks may develop into future flow paths. A proper washing process is therefore needed as a prevention method. It is also preferable to have knowledge about the geology, wellbore geometry and pressures to be able to foresee leakages, and thereby perform a proper P&A job [1].

In the paper written by Barclay et al. we are advised to pay special attention to: cap rocks, cement and completion equipment as they may be typical fluid-migration paths [1]. In the same paper the FlexSTONE cementing technology is presented, which is used for optimization of the cement due to its ability to handle variations in pressure and temperature which is typically current in a well scenario [1].

### What about the environmental conditions?

ThermaSet™ in liquid state (original form) shall not be disposed or spilled in the environment, because it will have some negative impact. Just like any other chemical used in the industry, ThermaSet™ is transported in standard chemical tanks and pumped down the well without polluting the environment. On the contrary, in solid form (after curing) ThermaSet™ can be considered as normal waste [39].

### 3.6 Sandaband as an alternative to cement

Sandaband™ is another plugging material that may be used as an alternative to cement. Sandaband™ consists mainly of water and quartz, which forms an impermeable barrier [51]. The volume of Sandaband™ consists of 70% solid and 30% liquid. This has its basis in: particles (<1micron-2,5mm), 70-80 volume percent of sand and crushed rock & micro silica, 20-30 volume percent water plus liquid additives [50].

Sandaband™ follows the Bingham plastic rheology model and is a non-consolidating plugging material [50].

The most beneficial property of this material is according to Vidar Rygg, project manager in Sandaband™ that it does not set up. This enables Sandaband™ to self-repair when changes occur downhole during the life of the well. According to Rygg some people are questioning the strength of this plugging material. Rygg reply is then; how hard/strong does an O-ring has to be for its intended use? [50].

In order to use Sandaband™ as plugging material a foundation, either mechanical or non-mechanical, seems to be necessary since it cannot be placed on top of a liquid column. This would cause the particles to sink and become sorted by grain size [23].

At Sandaband™ webpages it is possible to see an animation of how phase 1 P&A can be done by utilizing Sandaband™ [51]. This animation illustrates how Sandaband™ filled in the perforations. To be able to get Sandaband™ behind the casing the perforator torch system is utilized. This equipment makes bigger perforations than normal perforation guns do. The holes are then 1-2" in diameter and are runned as normal wireline operations [51].

A previous master thesis was written were Sandaband™ was presented, in this thesis the P&A benefits of using Sandaband™ was listed as the following [7]:

- *"No need for milling when removing-save time"*
- *"Easier to place than cement-save time"*
- *"Does not set up prematurely-less risk"*
- *"No losses to formation"*
- *"Non-hazardous and environmentally friendly"*
- *"Ductile and adaptable, no fracture, no leaks"*
- *"No issue with downhole fluid contamination"*
- *"Robust and non-complex-relies purely on physical properties"*



**Figure 32:** Sandaband [7].

### Sandaband and Norsok D010

Section 15 in Norsok D010 consists of various well barrier acceptance criteria. Table 55 in Norsok D010 involves the usage of material in solid state that forms a plug in the well [18]

This table is relevant for Sandaband™ as plugging material. The first table (**Table 6**) presents the plug requirement for the plug that is placed inside a wellbore between formation zones and/or surface/seabed. The next table (**Table 7**) is relevant when Sandaband™ is used as an annular plug. These two tables are new, and were not added in the previous revision of Norsok D010 [18].

From **Table 6** one can observe that there are different minimum material plug length dependent on the well [18].



**Table 6 - Material plug, table 55, in NORSOK D010, section 15 [18].**

| Features  | Acceptance criteria   | See  |                           |                           |   |   |   |                         |
|---|---|--|---------------------------|---------------------------|---|---|---|-------------------------|
| <b>A. Description</b>   | The element consists of material in solid state that forms a plug in the wellbore.  |  |                           |                           |   |   |   |                         |
| <b>B. Function</b>  | The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to surface/seabed.  |  |                           |                           |   |   |   |                         |
| <b>C. Design, construction and selection</b>  | <ol style="list-style-type: none"> <li>1. A program shall be issued for each material placement operation.</li> <li>2. For critical material operations, HPHT conditions and complex material designs the material program should be verified independent (internal or external), qualified personnel.</li> <li>3. Properties of each batch of material produced shall be verified by laboratory testing to ensure sealing capability. This shall be documented in the batch certificate issued by the manufacturing plant.</li> <li>4. The annular barrier material recipe shall be lab tested with samples from the rigsite under representative well conditions</li> <li>5. Materials used for plugs to isolate sources of inflow containing hydrocarbons should be designed to prevent gas migration and be suitable for the well environment (e.g. CO<sub>2</sub>, H<sub>2</sub>S).</li> <li>6. Permanent material plugs should be designed to provide a lasting seal with the expected static and dynamic conditions and loads.</li> <li>7. It shall be designed for the highest differential pressure and highest downhole temperature expected, including installation and test loads.</li> <li>8. The minimum material plug length shall be: <table border="1" data-bbox="395 952 1034 1254"> <thead> <tr> <th>Open hole material plugs</th> <th>Cased hole material plugs</th> <th>Open hole to surface plug</th> </tr> </thead> <tbody> <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 plug as foundation, otherwise 100 m MD</td> <td>50 m MD if set on a mechanical plug, otherwise 100 m MD.</td> </tr> </tbody> </table> </li> </ol> | Open hole material plugs                                 | Cased hole material plugs | Open hole to surface plug | 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. | 50 m MD if set on a mechanical plug as foundation, otherwise 100 m MD | 50 m MD if set on a mechanical plug, otherwise 100 m MD.  | UK Oil and Gas<br>OP071 |
|   | Open hole material plugs  | Cased hole material plugs                                | Open hole to surface plug |                           |   |   |   |                         |
| 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. | 50 m MD if set on a mechanical plug as foundation, otherwise 100 m MD   | 50 m MD if set on a mechanical plug, otherwise 100 m MD. |                           |                           |   |   |   |                         |
| <b>D. Initial test and verification</b>   | <ol style="list-style-type: none"> <li>1. Cased hole plugs should be tested either in the direction of flow or from above.</li> <li>2. The plug installation shall be verified through evaluation of job execution taking into account hole enlargement, volumes pumped and returns.</li> <li>3. Its position shall be verified by: <table border="1" data-bbox="395 1467 1050 1848"> <thead> <tr> <th>Plug type</th> <th>Verification</th> </tr> </thead> <tbody> <tr> <td>Open hole</td> <td>Tagging</td> </tr> <tr> <td>Cased hole</td> <td>                     Tagging<br/>                     Pressure test, which shall:                     <ol style="list-style-type: none"> <li>a) be 70 bar (1000 psi) above the estimated LOT below casing/ potential leak path, or 35 bar (500 psi) for surface casing plugs; and</li> <li>b) not exceed the casing pressure test and the casing burst rating corrected for casing wear.</li> </ol>                     If the material plug is set on a pressure tested foundation, a pressure test is not required. It shall be verified by tagging.                 </td> </tr> </tbody> </table> </li> </ol>   | Plug type  | Verification              | Open hole                 | Tagging   | Cased hole  | Tagging<br>Pressure test, which shall: <ol style="list-style-type: none"> <li>a) be 70 bar (1000 psi) above the estimated LOT below casing/ potential leak path, or 35 bar (500 psi) for surface casing plugs; and</li> <li>b) not exceed the casing pressure test and the casing burst rating corrected for casing wear.</li> </ol> If the material plug is set on a pressure tested foundation, a pressure test is not required. It shall be verified by tagging. |                         |
| Plug type   | Verification  |  |                           |                           |   |   |   |                         |
| Open hole   | Tagging   |  |                           |                           |   |   |   |                         |
| Cased hole  | Tagging<br>Pressure test, which shall: <ol style="list-style-type: none"> <li>a) be 70 bar (1000 psi) above the estimated LOT below casing/ potential leak path, or 35 bar (500 psi) for surface casing plugs; and</li> <li>b) not exceed the casing pressure test and the casing burst rating corrected for casing wear.</li> </ol> If the material plug is set on a pressure tested foundation, a pressure test is not required. It shall be verified by tagging.   |  |                           |                           |   |   |   |                         |
| <b>E. Use</b>   | None  |  |                           |                           |   |   |   |                         |
| <b>F. Monitoring</b>  | For temporary abandoned wells: The fluid level/pressure above the shallowest set plug shall be monitored regularly, or inspected for leaks, when access to the bore exists.   |  |                           |                           |   |   |   |                         |
| <b>G. Common well barrier</b>   | None  |  |                           |                           |   |   |   |                         |

**Table 7- Casing bonding material [18].**

The table below is valid for Sandaband™ as the plugging material as an annular plug. This table can be found in NORSOK D010, section 15, Table 56 [18].

| Features                              | Acceptance criteria   | See                     |
|---------------------------------------|---|-------------------------|
| A. Description                        | This element consists of impermeable material in solid state located in the annulus between concentric casing strings, or the casing/liner and the formation.   |                         |
| 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 | <ol style="list-style-type: none"> <li>1. A design and installation specification (pumping program) shall be issued for each pumping job which covers the following:               <ol style="list-style-type: none"> <li>a) casing/liner centralization and stand-off to achieve pressure and sealing integrity over the entire required isolation length;</li> <li>b) use of fluid spacers;</li> <li>c) effects of hydrostatic pressure differentials inside and outside casing and ECD during pumping and loss of hydrostatic pressure prior to material placement;</li> <li>d) the risk of loss returns and mitigating measures during material placement.</li> </ol> </li> <li>2. For critical annular barrier operations, HPHT conditions and complex slurry designs the program should be verified by (internal or external), qualified personnel.</li> <li>3. Properties of each batch of material produced shall be verified by laboratory testing to ensure sealing capability. This shall be documented in the batch certificate issued by the manufacturing plant.</li> <li>4. The annular barrier material recipe shall be lab tested with samples from the rigsite under representative well conditions</li> <li>5. The properties of the set material shall provide lasting zonal isolation, structural support, and withstand expected temperature exposure.</li> <li>6. Materials used for isolating sources of inflow containing hydrocarbons shall be designed to prevent gas migration, including CO<sub>2</sub> and H<sub>2</sub>S if present.</li> <li>7. Planned material length:               <ol style="list-style-type: none"> <li>a) Shall be designed to allow for future use of the well (sidetracks, recompletions, and abandonment).</li> <li>b) <b>General:</b> Shall be minimum 100 m MD above a casing shoe/window.</li> <li>c) <b>Conductor:</b> Should be defined based on structural integrity requirements.</li> <li>d) <b>Surface casing:</b> Shall be defined based on load conditions from wellhead equipment and operations. TOM shall be inside the conductor shoe or to surface/seabed if no conductor is installed.</li> <li>e) <b>Production casing/production liner:</b> Shall be minimum 200 m above a casing shoe. If the casing/liner penetrates a source of inflow, the planned material length shall be 200m MD above the source of inflow.</li> </ol> </li> </ol> <p>NOTE If unable to fulfil the requirement when running a production liner, the liner material length can be combined with previous casing material to fulfil the 200m MD requirement.</p> | UK Oil and Gas<br>OP071 |

| Features                                | Acceptance criteria   | See |
|---|---|-----|
| <b>D. Initial test and verification</b> | <p>The material should be left undisturbed until it has met sufficient compressive strength.</p> <ol style="list-style-type: none"> <li>1. The material sealing ability shall be verified through a formation integrity test when the casing shoe/window is drilled out.</li> <li>2. The material length shall be verified by one of the following: <ol style="list-style-type: none"> <li>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.</li> <li>b) 100 % displacement efficiency based on record from the pumping operation (volumes pumped, returns during pumping, etc.). Actual displacement pressure/volumes should be compared with simulations using industry recognized software. In case of losses, the loss zone shall be above the planned TOM, this shall be documented. Acceptable documentation is job record comparison with similar loss case(s) on a reference well(s) that has achieved sufficient length verified by logging.</li> <li>c) In the event of losses, it is acceptable to use the PIT/FIT or LOT as the verification method, only if the casing material shall be used as a WBE for drilling the next hole section. (This method shall not be used for verification of casing material as a WBE for production or abandoned wells).</li> </ol> </li> <li>3. Critical casing material shall be logged and is defined by the following scenarios: <ol style="list-style-type: none"> <li>a) the production casing / liner when set into/through a source of inflow with hydrocarbons;</li> <li>b) the production casing / liner when the same casing material is a part of the primary and secondary well barriers;</li> <li>c) wells with injection pressure which exceeds the formation integrity at the cap rock.</li> </ol> </li> <li>5. Actual material length for a qualified WBE shall be: <ol style="list-style-type: none"> <li>a) above a potential source of inflow/ reservoir;</li> <li>b) 50m MD verified by displacement calculations. The formation integrity shall exceed the maximum expected pressure at the base of the interval.</li> </ol> </li> </ol> |     |
| <b>E. Use</b>                           | None  |     |
| <b>F. Monitoring</b>                    | <ol style="list-style-type: none"> <li>1. The annuli pressure above the casing material shall be monitored regularly when access to this annulus exists.</li> <li>2. Surface casing by conductor annulus outlet to be visually observed regularly.</li> </ol>   |     |
| <b>G. Common well barrier</b>           | None  |     |

Sandaband™ has to be placed in a position where it cannot disappear down, up or to the side. This means that it has to be placed at TD or with a foundation [50].

The foundations task is to hold the plug mechanically in place. By using Sandaband™ one is able to plug openings or cracks in an effective way. Out on the sides it has to stand against formation or casing with an isolation material behind such as cement or Sandaband™ [50].

It is important to make sure that the plug is placed at the right place, and doesn't transfer further up in the well. Therefore the plug itself is designed as long (MD) and high (TVD) that the maximum pressure it ever can be exposed to doesn't exceed this design pressure. An alternative is to anchor the plug at the top as using the same method as for the bottom of the plug. This can be done by using a mechanical plug, cement plug or another material that has the ability to connect to the wellbore wall [50].

The only thing that differentiates the temporary plug from the permanent plug is the brine above the plug. When one want to do temporary plugging it is possible to use heavier brine above the Sandaband™ column to help remain overbalance, while with permanent plugging they design with sea water gradient [50].

A paper was written by Arild Saasen et al. describes a P&A field case where they have used Bingham plastic unconsolidated plugging material. By using this unconsolidated plugging material they were able to reduce the costs of permanently plugging back the well called “Jetta” in the NCS. The positive HSE impacts and the reduction of operational risk were also pointed out as important factors [45]. The plug is placed successfully at TD in an open hole section as the figure below (Figure 33) illustrates, and the operation is also performed in a safe manner [45].

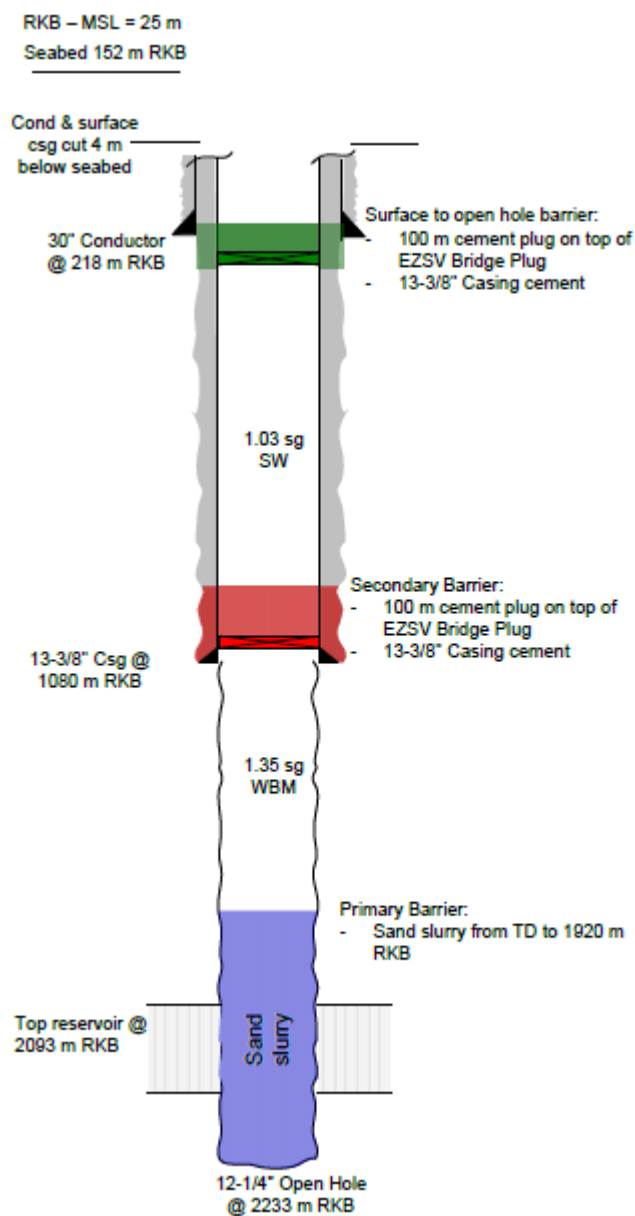


Figure 33: “Well abandonment schematics” [45].

In the same paper the verification of the plug is discussed. Verification of the Sandaband™ plug is different from the verification of a cement plug. A cement plug is tagged by using the drill pipe. Since the Sandaband™ plugging material consist of unconsolidated sand it is difficult to tag the plug in this manner. The paper describes the normal way of performing this, which is performed by a technique called “dressed off” [45].

The drill pipe is placed at the planned top of the plug while the return is circulated. It is possible to tag the top of the plug by looking at the shakers, when the top of the sand plug is reached, large volumes of sand can be seen at the shakers as the *Figure 34* below illustrates.

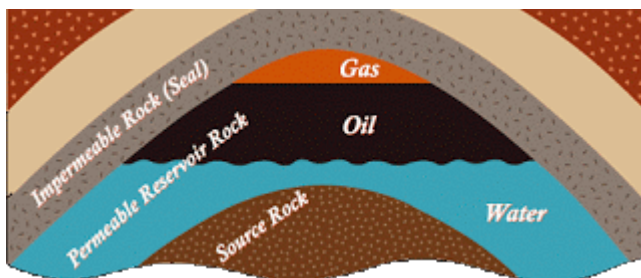


**Figure 34:** Normal well returns vs sand slurry returns [45].

### 3.7 Shale as an annular barrier

From basic petroleum geology we know that shale is often a cap rock which is placed on top of the reservoir, and seals off the reservoir zone due to its impermeable properties. Permeability is according to Schlumberger oilfield glossary: “The ability, or measurement of a rock's ability, to transmit fluids, typically measured in darcies or millidarcies” [52].

Sandstone is mentioned here as one permeable formation, while shales are mentioned as impermeable. Schlumberger Oilfield glossary further says that “Impermeable formations, such as shales and siltstones, tend to be finer grained or of a mixed grain size, with smaller, fewer, or less interconnected pores” [52].



**Figure 35:** “Caprock”

Williams, Carlsen and Constable published a SPE in 2009 called “Identification and Qualification of Shale Annular Barriers Using Wireline Logs During Plug and Abandonment Operations” where they look at the usage of shale as an annular barrier. In this paper they mention that shale is often considered as undesirable due to well close off. This paper focus on the positive mechanism that shale can cause, such as establish an annular barrier behind the casing. Due to shale’s properties as mentioned below, in some fields one may be lucky and have a “natural” annular well barrier behind the casing. Further this paper describes how the shale formations can be identified [5].

### NORSOK D010 and shale as an annular barrier

In the newest revision of NORSOK D010 under section 15 there is a new table (Table 52) that dictates the acceptance criteria for creeping formation, which is valid when shale formations are present.

**Table 8 - Creeping formation [18], table 52**

15.52 Table 52 – Creeping formation

| Features                                     | Acceptance criteria  | See |
|--|--|-----|
| <b>A. Description</b>                        | The element consists of creeping formation (formation that plastically has been extruded into the wellbore) located in the annulus between the casing/liner and the bore hole wall.  |     |
| <b>B. Function</b>                           | The purpose of the element is to provide a continuous, permanent and impermeable hydraulic seal along the casing annulus to prevent flow of formation fluids and to resist pressures from above and below.   |     |
| <b>C. Design, construction and selection</b> | <ol style="list-style-type: none"> <li>1. The element shall be capable of providing an eternal hydraulic pressure seal.</li> <li>2. The minimum cumulative formation interval shall be 50 m MD.</li> <li>3. The minimum formation stress at the base of the element shall be sufficient to withstand the maximum pressure that could be applied.</li> <li>4. The element shall be able to withstand maximum differential pressure.</li> </ol>  |     |
| <b>D. Initial test and verification</b>      | <ol style="list-style-type: none"> <li>1. Position and length of the element shall be verified by bond logs: <ol style="list-style-type: none"> <li>a) Two (2) independent logging measurements/tools shall be applied. Logging measurements shall provide azimuthal data.</li> <li>b) Logging data shall be interpreted and verified by qualified personnel and documented.</li> <li>c) The log response criteria shall be established prior to the logging operation.</li> <li>d) The minimum contact length shall be 50m MD with 360 degrees of qualified bonding.</li> </ol> </li> <li>2. The pressure integrity shall be verified by application of a pressure differential across the interval.</li> <li>3. Formation integrity shall be verified by a LOT at the base of the interval. The results should be in accordance with the expected formation stress from the field model (see table 15.51 In-situ formation).</li> <li>4. If the element has been qualified by logging, pressure and formation integrity testing, logging is considered sufficient for subsequent wells. The formation interval shall be laterally continuous. Pressure testing is required if the log response is not conclusive or there is uncertainty regarding geological similarity.</li> </ol> |     |
| <b>E. Use</b>                                | The element is primarily used in a permanently abandoned well.   |     |
| <b>F. Monitoring</b>                         | None   |     |
| <b>G. Common well barrier</b>                | None   |     |

### 3.8 Geopolymers as plugging material

Geopolymers are essentially inorganic material which is used as an alternative to cement or replacing binder in concrete. Simply, geopolymers are alumino-silicate materials which react in an alkaline environment whereas they can withstand high pressures and high temperatures [22]. Based on the used materials as a source, there are different types of geopolymers such as; fly ash-based, metakolin-based and rock based geopolymers.

Massive works have been done to study the mechanical properties of fly-ash based geopolymers. However, few works have been done to study the potential utilization of geopolymers in P&A operations. Khalief et al. studied the potential utilization of fly-ash based geopolymers for plug and abandonment operations [24].

Class C fly ash was used in their study as source. Their experiments have been carried out at high pressure and high temperature of curing condition. Based on their result class C fly ash-based geopolymers have the potential to be utilized as an alternative to cement in plug and abandonment operations [24].

However, there are some concerns regarding utilization of fly ash-based geopolymers as alternative material to cement. For example, Newtonian viscosity behavior and thickening time of geopolymers are issues that should be studied more [24].

A new rock-based geopolymer has been invented at University of Stavanger, Norway, which can withstand high pressures and high temperatures. The introduced geopolymer looks very similar to cement in appearance, Figure 28. The material has the potential to be used as alternative to cement and/or as foundation for the unconsolidated materials [23].

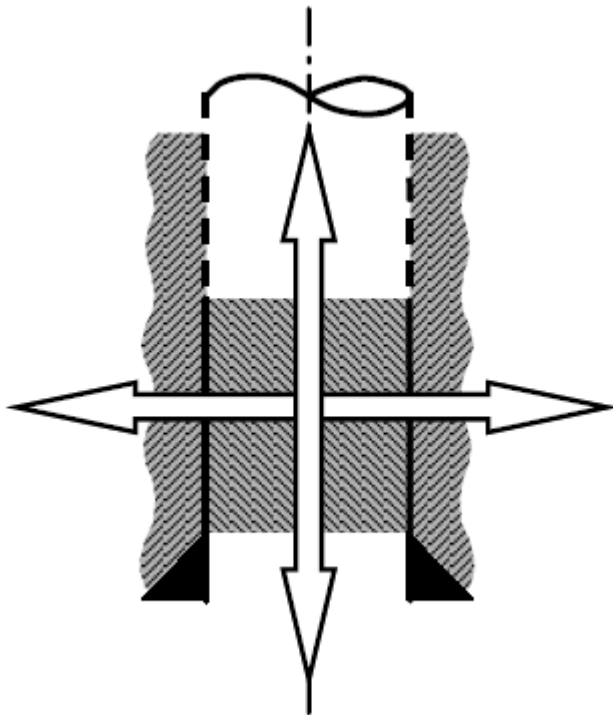


**Figure 36:** Sample of a rock based geopolymer from the University of Stavanger [23].

## 4. MILLING

### 4.1 Why performing a milling operation?

From the well barrier chapter in this thesis regarding well barriers it was mentioned that a “permanent well barriers shall extend across the full cross section of the well include all annuli and seal both vertically and horizontally” [18].



**Figure 2:** “Permanent well barrier” [18]

Sometimes the cement on the outside of the casing is very weak or not present at all. Then it is necessary to perform milling operations [28].

### 4.2 What is milling?

Milling is “an operation designed to break a solid material into smaller pieces” [29].

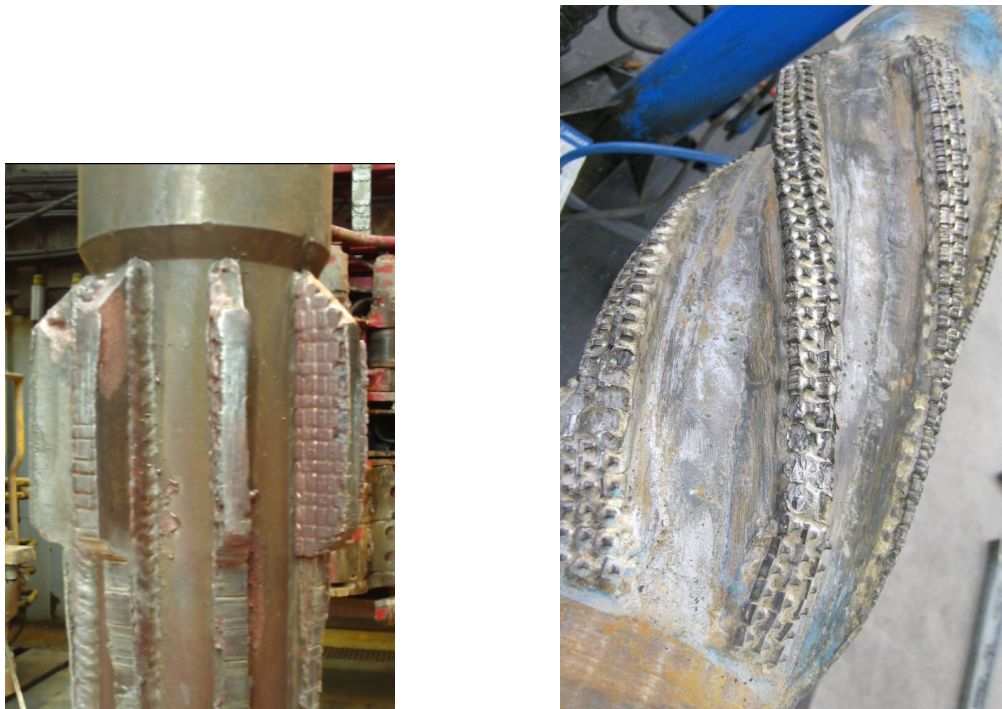
Milling operations performs removal of casing. The conventional way for placing a plug is to remove the casing where there is suspicion of bad quality of the cement behind is by performing section milling.

The tool that is used during section milling consists of a pipe, with cutter blades (P3 cutters) that are yielded on the pipe as the *Figure 37* below illustrates.





**Figure 37:** These two figures illustrate the P3 cutters (right side) and the mill (left side) [33].

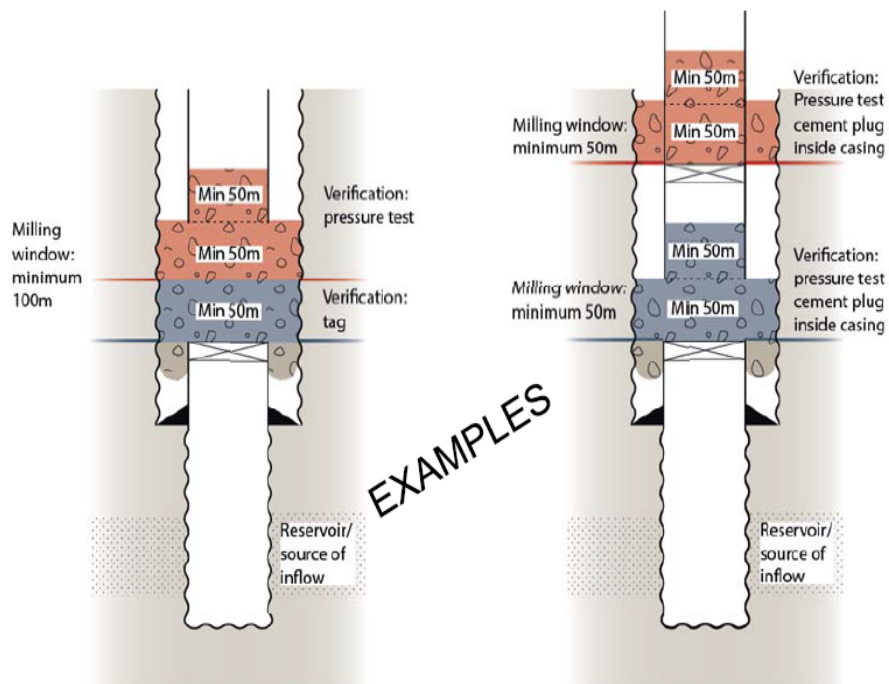


**Figure 38:** Mill cutter blades [33].

### 4.3 NORSOK D010 and milling operations

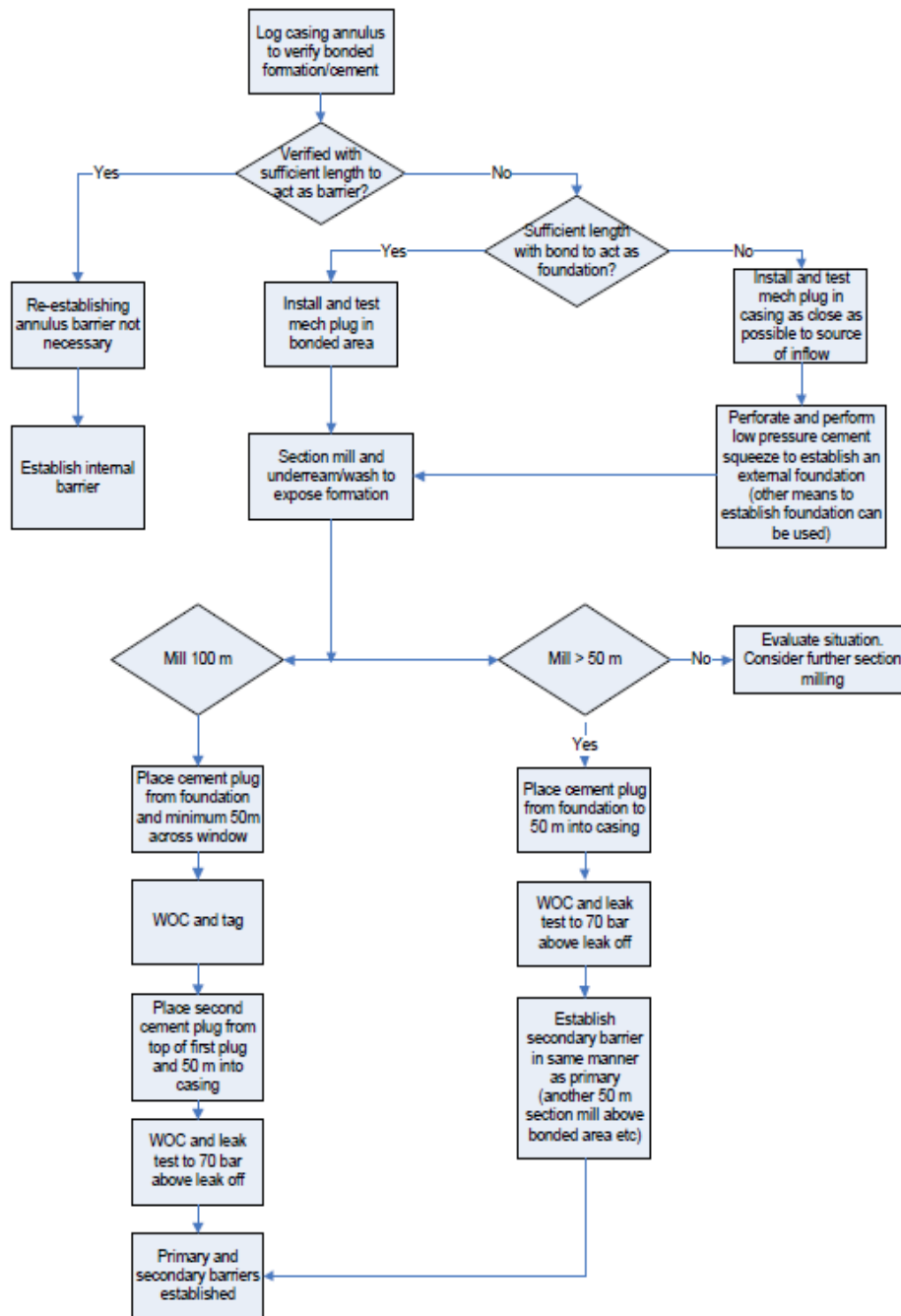
When section milling is performed large amounts of swarf is generated. By milling a window of 50metres, 4 tons of swarf is generated [48].

The figure below (*Figure 39*) is taken from NORSOK D010, rev 4 and shows two examples of section milling [18].



**Figure 39:** Examples of section milling [18], section 9.6.8)

In the newest revision of NORSOK D010 it has been extended with flow charts for performing section milling operations as *Figure 40* illustrates. As the flow charts show the first thing one do before one can perform a milling operation is to log casing annulus. This is to verify bonded formation/cement. Then the next step is to check if the casing annulus is verified with sufficient length to act as a barrier. According to NORSOK D010, the casing annulus shall be verified. If this is verified then it is not necessary to re-establish an annulus barrier. But if the answer is no then one has to check if it has a sufficient length with bond to act as a foundation. If the length is not sufficient, then the next step is to install and test a mechanical plug. This shall be placed in casing as close as possible to source of inflow. After this the well is perforated and low pressure cement is squeezed. This is performed in order to establish an external foundation. After this one can perform milling operations [18].



**Figure 40:** Flow chart for section milling [18]

#### 4.4 Wear of the mill

The three figures below *Figure 41*, *Figure 42* and *Figure 43* show the wear of the mill after drill out composite plugs using Glyphaloy™. [33].

As it can be seen from the three pictures the mill is in good shape after drilling out 78 plugs. In the meeting with Klaus Engelsgerd I asked him if the wear of the cutter blades were a limitation for the milling performance, and to that he replied that the surface handling is rather more limitation than the wear of the mill. And this composite plug milling record also shows this.



**Figure 41:** *New mill, courtesy of Baker Hughes [33].*



**Figure 42:** *After 41 plugs, courtesy of Baker Hughes [33].*



**Figure 43:** *After 78 plugs, courtesy of Baker Hughes [33].*

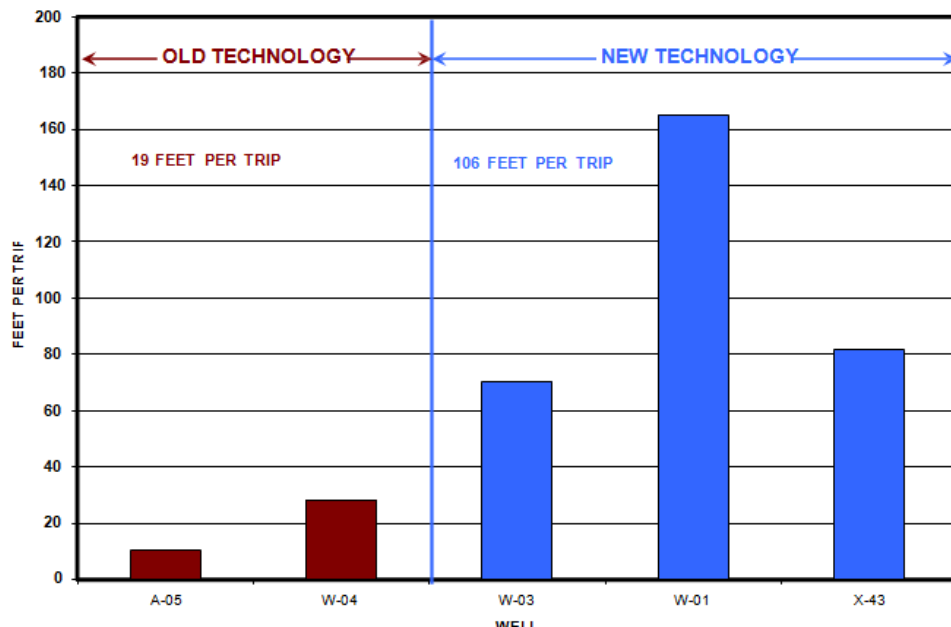
## 4.5 Cutters

### Improved cutter technology

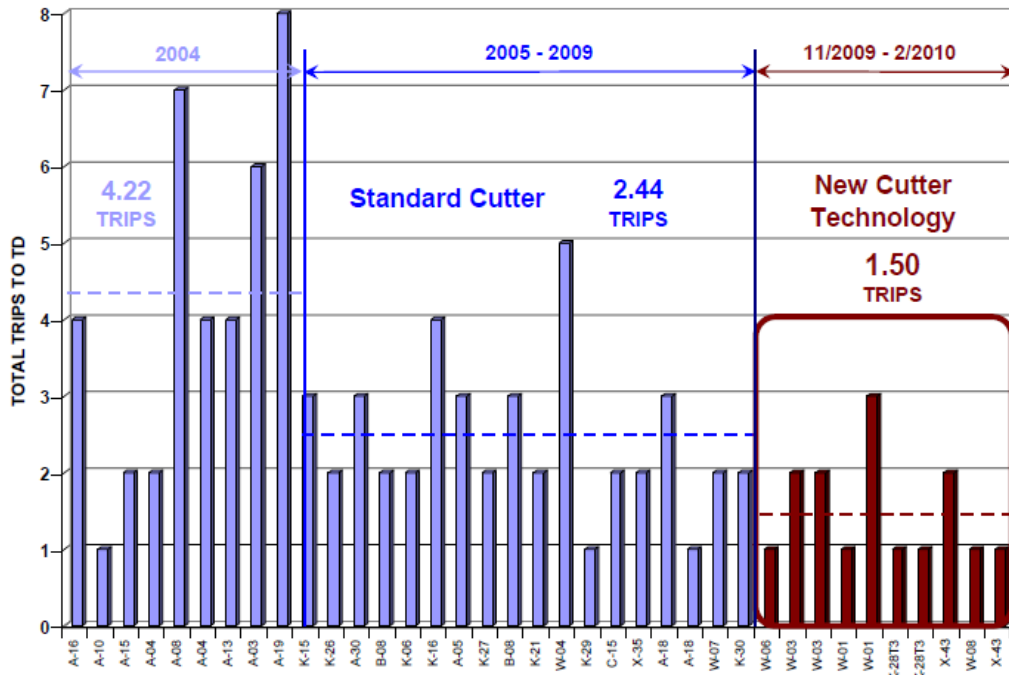
In 2011 Cal Stowe et.al (Baker Hughes) published a SPE paper called “Performance Advance in Section Milling Technology” [15].

In this paper they describe the traditional cutter material, which is tungsten carbide, and look at a new cutter technology. The key findings in this paper are the new “P cutter”, and by utilizing this they are able to mill a larger section and reduce the number of trips. With old technology they were able to mill in average 19 feet per trip, and with the new one they could increase this to 106 feet per trip, *Figure 44* illustrates this [15].

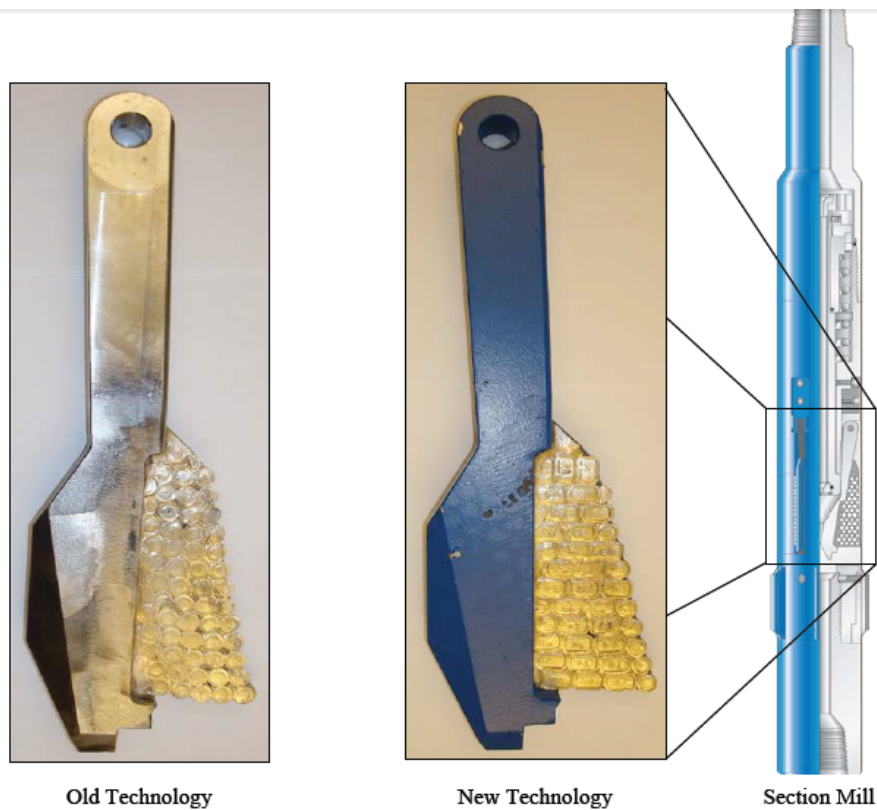
One of the figures below (*Figure 46*) illustrates the cutters placement in the section mill.



**Figure 44:** This figure illustrates the difference in length [ft] of the milled window per trip by utilizing the new technology instead of the old technology [15].



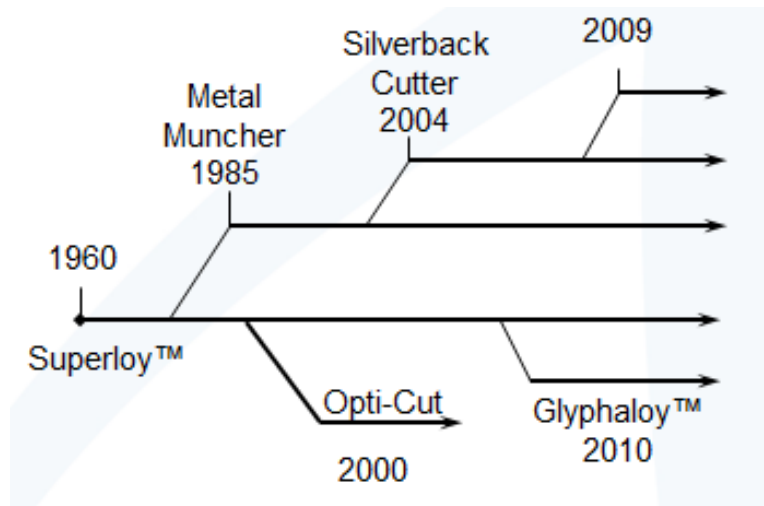
**Figure 45:** This figure illustrate the average number of trips by utilizing the new cutter technology instead of the standard cutter [15].



**Figure 46:** This figure illustrates the cutters placement in the section mill, and also the difference in appearance of the old technology vs the new technology [15].

## 4.6 Cutter technology improvements

The section mill consists of cutter blades. The cutter blades have gradually been improved as well as the material it is made of. Between 1945 and 60`s the most likely cutter material consisted of crushed carbide, while after 1960`s the dominant material was Superloy™ as the figure below (Figure 47) illustrates. In 1985 the METAL MUNCHER™ was introduced. By utilizing the METAL MUNCHER™, Baker Hughes was able to increase the milling efficiency/ROP, reduce the number of trips due to less wear [34].



**Figure 47:** courtesy of Baker Hughes [34].

## METAL MUNCHER™

The figure below (*Figure 48*) shows the METAL MUNCHER™ that is familiar within the cutter industry. This has been widely used since 1985. Some of the target applications to the METAL MUNCHER™ is [34]:

- *“High Volume Milling – Section or Pilot Milling”*
- *“Milling Exotic Materials (High Chrome and Nickel Content)”*
- *“Interrupted Cut-Packer Milling & Whipstock Operations”*




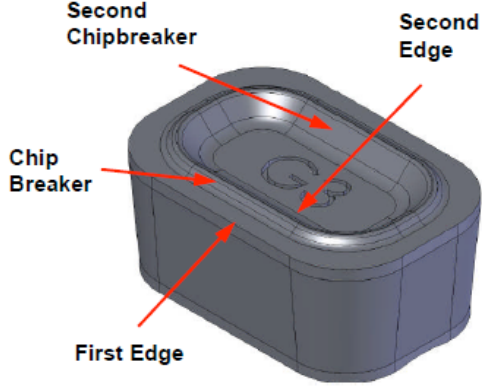

**Figure 48:** METAL MUNCHER™, *courtesy of Baker Hughes* [34]:


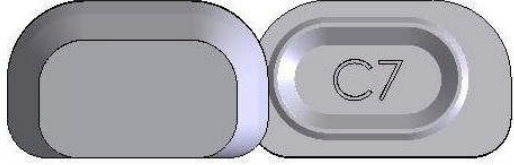


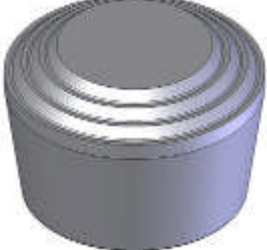
### 4.7 Different types of cutters:

Table 9 below has its basis in a presentation given by Klaus Engelsjerd in Baker Hughes. In this presentation various types of cutters are presented, with their application areas and picture [33].



**Table 9- Overview of different cutters, courtesy of Baker Hughes [33].**

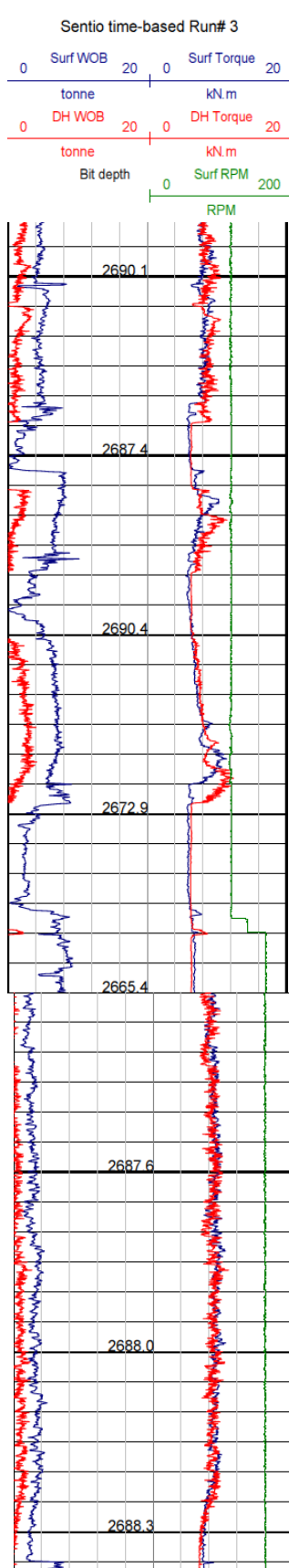
| Name                         | Application area:  | Picture  |
|------------------------------|--|--|
| <p>New “S” metal muncher</p> | <p>-Has been used for the last 25 years<br/>                     - The “S” type has been developed to increase life time, and harder steel capability<br/>                     -Has a second cutting edge, for heavy wear.</p>   |    |
| <p>“G” cutter</p>            | <p>-Improved resistance and sharpness<br/>                     -As picture shows it has two chipbreakers and two edges<br/>                     -This cutter is commonly used for pilot and section milling<br/>                     -In the Gulf of Mexico this “G3” cutter set the milling record, with one row of cutters it milled 47 feet of 7” casing.</p> |   |
| <p>“M” cutter</p>            | <p>-Rounded corners that may be used in some locations (ex:for blade corners)</p>  |  |

|                              |   |  |
|------------------------------|---|--|
| <p>“J4” cutters</p>          | <p>-As the picture shows this cutter has a bevel is the cutter structure, and may be used when this is beneficial</p> |    |
| <p>“C7” cutter</p>           | <p>-Is dominantly used for cutting in the mill center due to the necessary slow penetration rate when using this</p>  |    |
| <p>“N” cutter</p>            | <p>-One half oblong that is used on alternate blades.</p>   |   |
| <p>“L” cutter</p>            | <p>-Used when there is a need for a greater impact resistance than the Metal Muncher</p>                              |  |
| <p>High angle three step</p> | <p>-Used when there is a need for a rounded cutter, and maximum impact resistance</p>                                 |  |

## 4.7 Indication of worn knives:

As mentioned in the ECD section one can use the SENTIO™ service from Baker Hughes to monitor the ECD and the differential pressure during the milling operations [26].

The downhole optimization sub, provided by the SENTIO™ service has also other application areas, and may be used as an indication for worn out knives. The figure below (*Figure 49*) illustrates an example of this. From this figure one can observe the downhole WOB is decreasing, until there are no readings at all. At the same time the torque is decreasing [26].

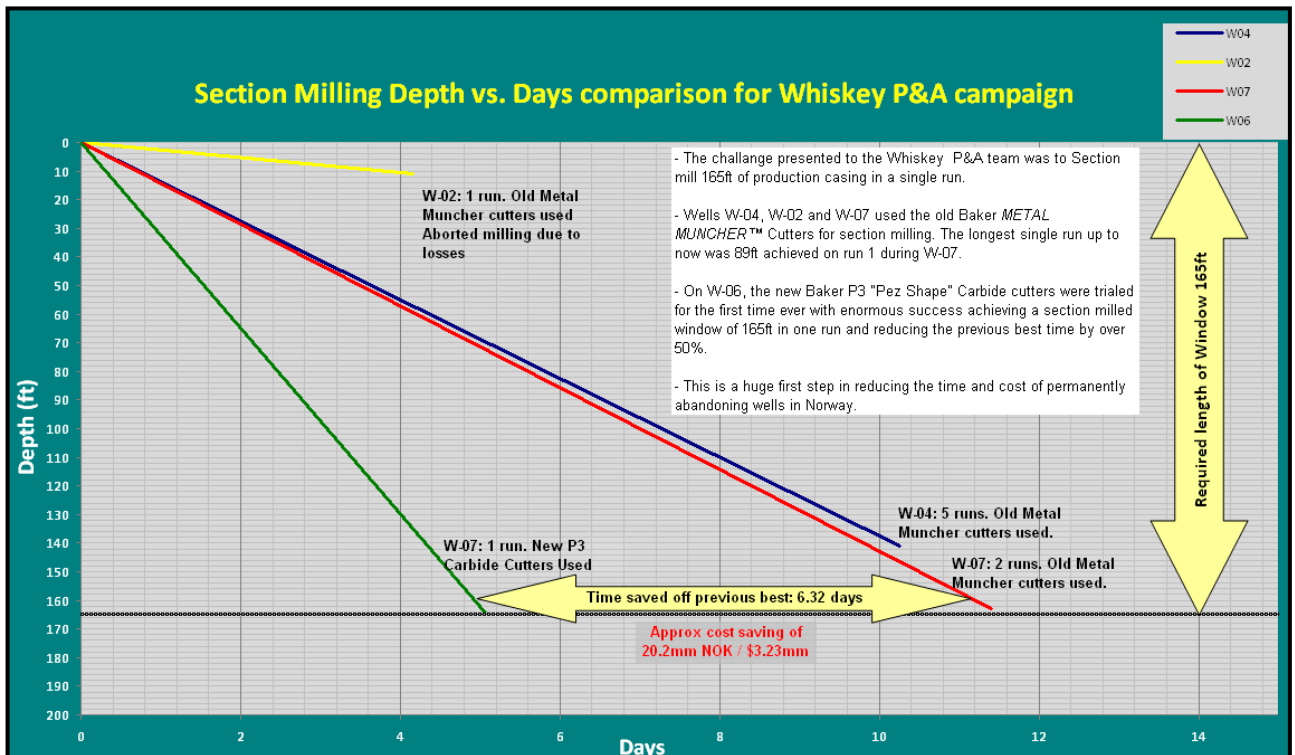


**Figure 49:** SENTIO™ service used as an indication of worn out knives, courtesy of Baker Hughes [26].

## 4.8 Cost and time savings during the Whiskey P&A campaign by utilizing P3 cutters

Baker Hughes had a field case where they were challenged to section mill 165 ft ≈50,3 meters of production casing by using one run [34]. For this they utilized the P3 carbide cutters. For well W-07 they were able to achieve huge cost savings by changing the knives from old METAL MUNCHER™ to the new P3 cutters [34].

The figure below (*Figure 50*) illustrates the cost savings after the P3 cutters were implemented.



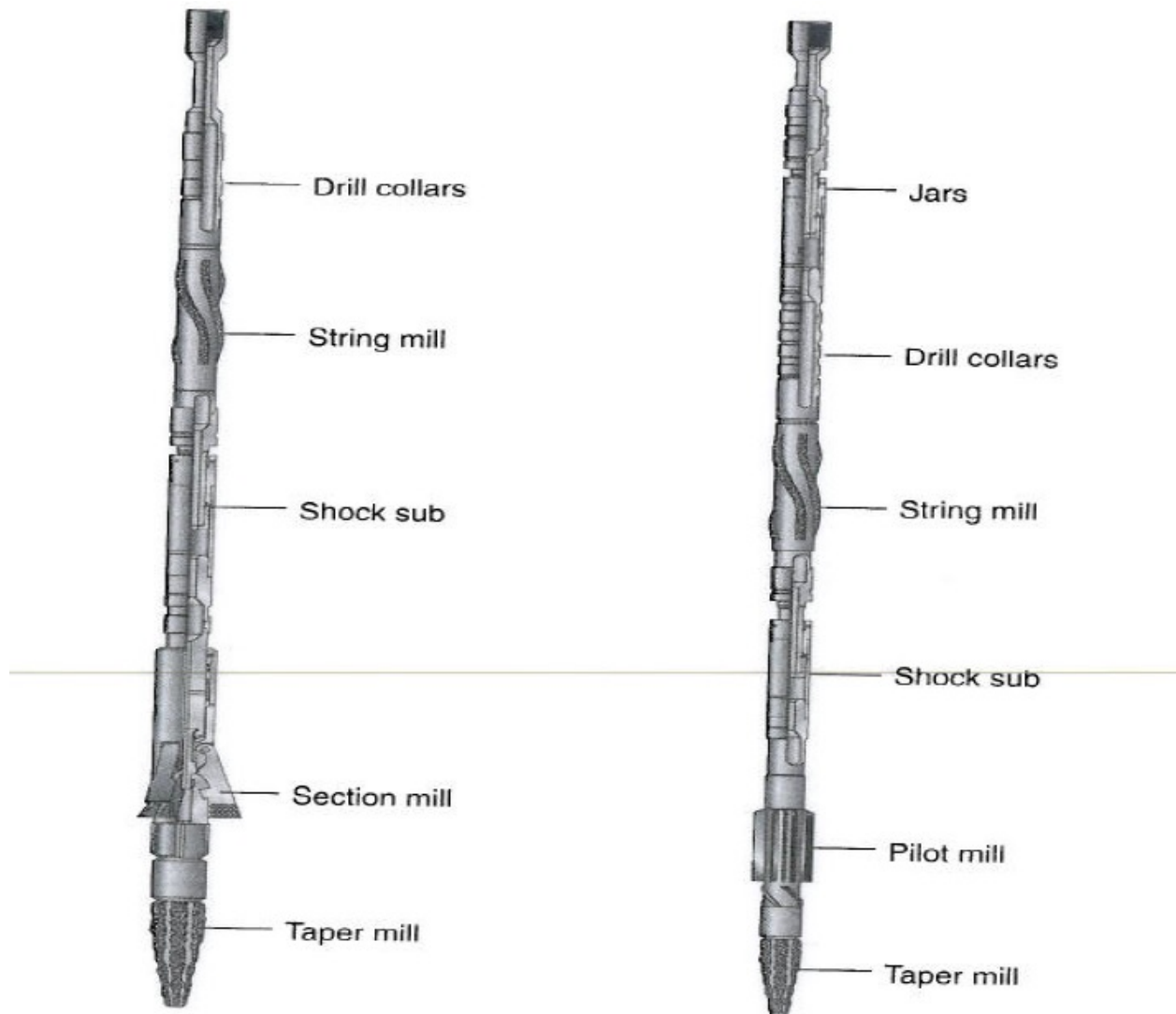
**Figure 50:** Shows huge cost savings by implementing P3 cutters, courtesy of Baker Hughes [34].

## 4.9 Different types of milling operations

There are two types of milling approaches, which are: section milling and pilot milling. Both types mill away huge amounts of steel.

The figure below is taken from the book "The guide to Oilwell Fishing Operations" [53]. In this book the difference between section milling (left side) and the pilot milling assembly at the right side is illustrated in a good way.

During pilot milling operation the entire casing is removed, while a section milling operation mill away a determined length (ex 75-100ft) that is sufficient for performing side-tracks. For pilot milling the casing is removed from the top to the mill stops [53].



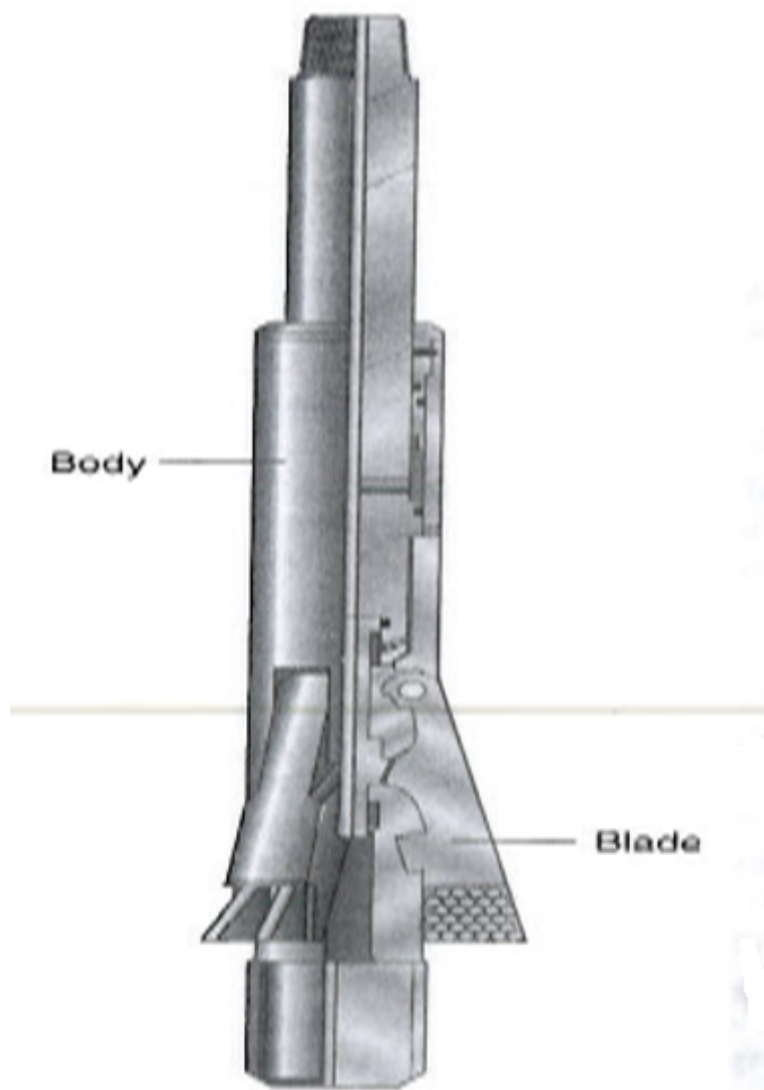
**Figure 51:** Illustrates the difference in assembly between a section mill (left side) and pilot mill (right side), courtesy of Baker Oil Tools [53]. The pilot mill has jars in addition to the other common equipment.

### Section milling

For sections milling the cutting blades are actuated by pump pressure. The blades are forced out by a piston and cylinder, which responds to the pump pressure. In order to stabilize the mill, drill collars are run above the section mill [53].

According to literature the special fluid that is able to remove the cuttings more efficiently is “a mixed-metal hydroxide” [53].

In order to use water-based mud, it shall according to literature have a “funnel viscosity of 90-100 CP and a yield of 50-60” [53].



**Figure 52:** Section milling tool, Courtesy of Baker Oil Tools [53].

### **Pilot mills**

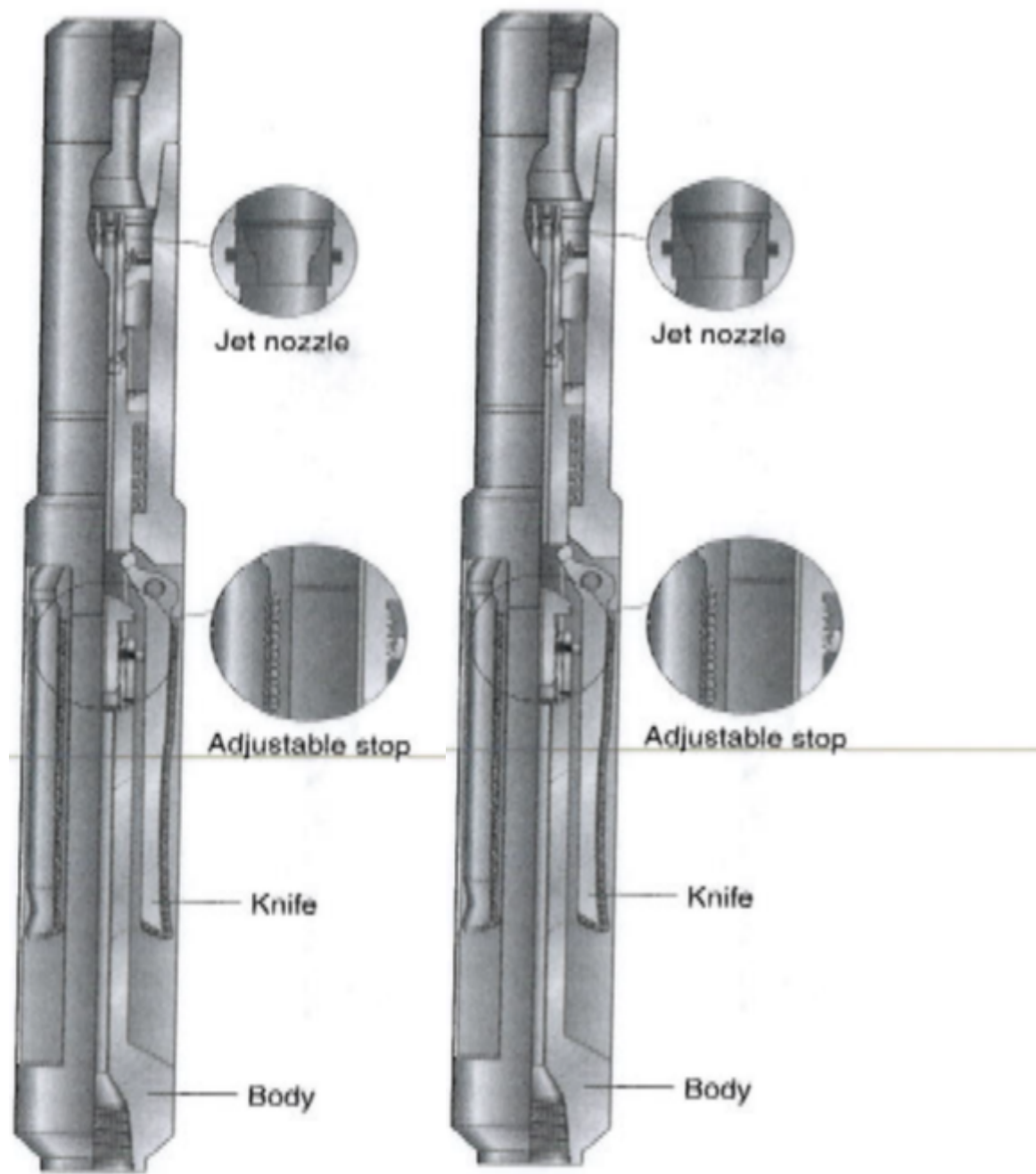
Pilot mills are often used for slot-recovery operations [53]. Slot recovery was introduced in the introduction of this thesis as one of the possible reasons for performing P&A operations. Before the pilot milling operation starts, a CBL is running in order to verify the quality of the cement behind the casing. If there is no cement behind the casing, the casing can be cut 100-200 feet below the casing shoe [53].

Then the casing is pulled, if this is not possible a new cut is made. This is typically 50-70ft above the shoe, and the casing is then removed [53]. Then the casing is tried pulled by jars, and if this doesn't work, then pilot milling operations are performed [53].

According to literature milling rates of 5-10 feet per hours is the optimal rate for optimal cutting removal. [53].

### Multiple string cutter

It is normal procedure to cement the casing strings together, for well control issues. It is therefore necessary to cut the casings at same depth. Utilizing a multiple-string casing cutter as *Figure 53* below illustrates can be a proper solution for this. The cutter can then contain knives long enough to cut through the 9<sup>5/8</sup>" , 13<sup>3/8</sup>" and the 16" casing [53].



**Figure 53:** Multiple string casing cutter, Courtesy of Baker Oil Tools [53].



## 4.10 SwarfPak™ upward milling tool

West Group [32] has introduced an upward milling tool, called SwarfPak™. The assembly consists of; mill tool, slips, and screen with stabilizer. At west group homepages one can see a video of how this work [32].

In the video one observe that the tool moves towards desired mill depth, and then the knives are actuated by a ball valve. Then the mill knives moves upwards and the inner casing is milled upwards in the well. The swarf is cut uniformly, and remains down in the well. At WestGroup homepage they mention three areas of use which are for P&A operations, slot recovery and general well milling. It is also mentioned at their webpages that the benefits by using SwarfPak™ is the following [32]:

- *“Precise and ultrafast milling speed”*
- *“Upwards milling leaves Swarf downhole”*
- *“Increased safety - no swarf in BOP”*
- *“Eliminates swarf handling on surface”*
- *“Eliminates vibrations”*



**Figure 54:** SwarfPak™ [32].

## 4.11 Challenges with milling operations

There are some challenges that are associated with milling operations. The challenges that are identified in this thesis are the following:

- Time consuming operation and a costly operation [4]
- HSE considerations[2]
- BHA failures [4]
- Pack off [26]

- Poor hole cleaning [4]
- Damage BOP [16]
- Plug cement stinger [16]
- Swarf Disposal issues [16]

### **Time consuming and costly [4]**

Conventional milling is time consuming and is very often challenging not only economical as it requires rig time but also in a well integrity aspect and safety aspects. If we are able to utilize improved technology or alternative methods for P&A this is preferable [2].

### **HSE**

During milling operations there are HSE aspect that has to be considered. The person that works with the swarf at top side has to wear special PPE (personal protective equipment). The swarf particles may have very sharp edges, it is therefore necessary to utilize special gloves and eye protection [2].

### **BHA failures**

In the paper by Scanlon et al. BHA is failure is mentioned as one of the negative side with milling operations [4].

According to Scanlon et al. bending moment gives you an idea of the condition to the BHA, especially in combination with high lateral vibration [4]. If the bending moment is higher than the acceptable limit, this may cause BHA failures. It is therefore important to consider the bending moment during a milling operation [4].

### **Pack off**

In the same paper by Scanlon et al. the importance of monitoring the ECD during a milling operation is mentioned [4]. By monitoring the ECD during the milling operation one can easier foresee and locate pack off scenarios [4]. As mentioned previously in this thesis this is possible by utilizing the SENTIO™ service from Baker Hughes [26].

### **Poor Hole Cleaning**

During milling operations there may be poor hole cleaning, which later may lead to further losses [4].

### **Damage BOP**

After a milling operations one may experience damaged BOP as a consequence of the milling operation [16].

It is important to obtain a proper cleaning and washing process of the BOP after a milling operation has been performed [16].

### **Plug cement stinger**

When Run In Hole (RIH) there is a possibility that the cement stinger is being plugged with swarf [16]. A preventative method for avoiding this is by breaking the circulation in every 10 stands [16].

### **Swarf handling**

During milling operations swarf is created on topside. Swarf is metal cuttings from the casing that has may have sharp edges [32].

Milling one 50 meter section of the 9<sup>5/8</sup>” casing can actually generate 4000 kg of swarf [32]. This large amount of swarf has to be handled at topside and transported away from the rig site. Some platforms have a swarf handling unit, while others not.

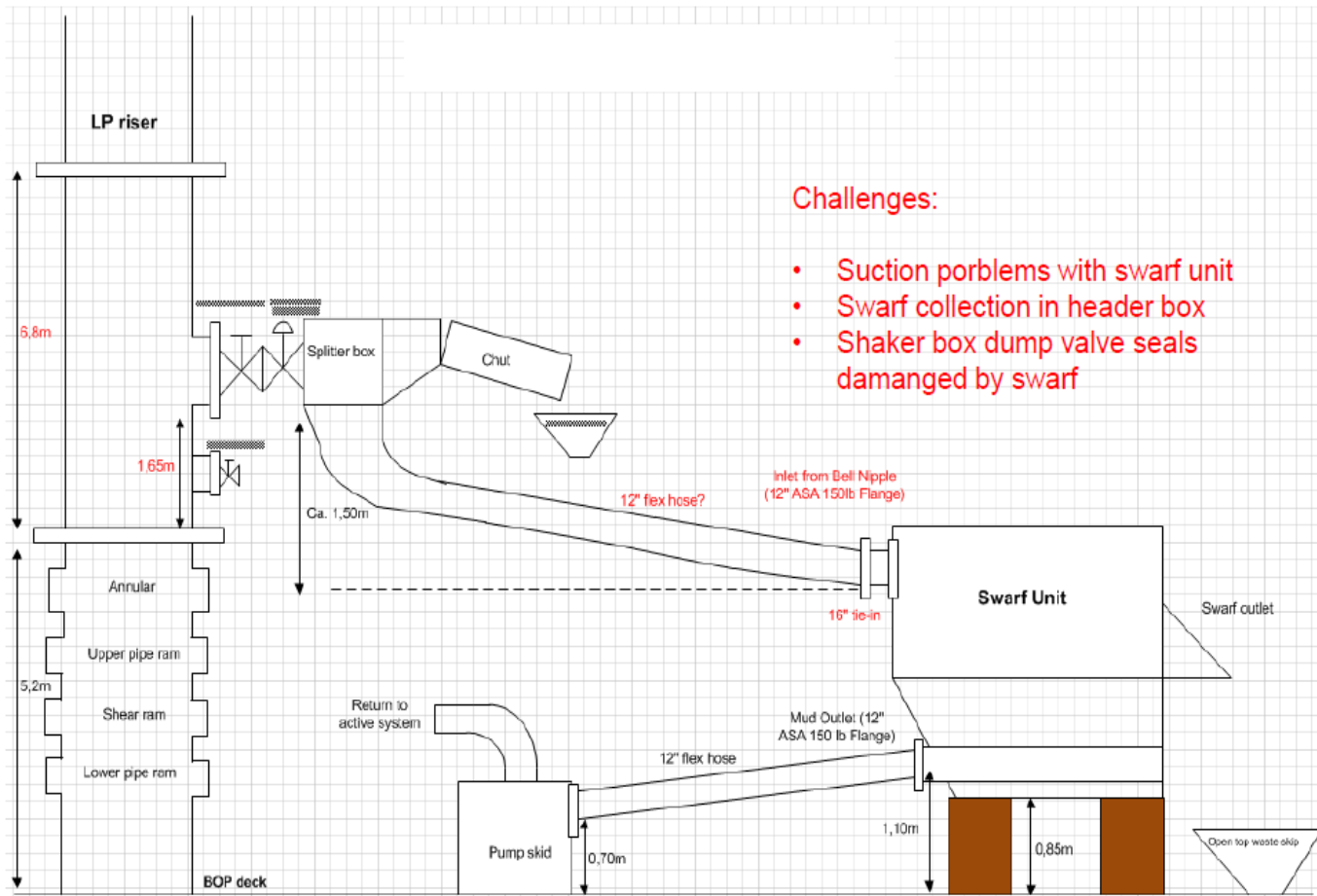
Some of the challenges which are associated to the swarf handling unit, and mentioned in Lunkad`s presentation [16] are the following:

- “suction problems with swarf unit”
- “swarf collection in header box”
- “shaker box dump valve seals damaged by swarf”

*Figure 55* below illustrates the swarf handling unit; this swarf handling unit is from the North Sea at the platform Statfjord A [16].



**Figure 55:** Swarf handling unit from Statfjord A [38].

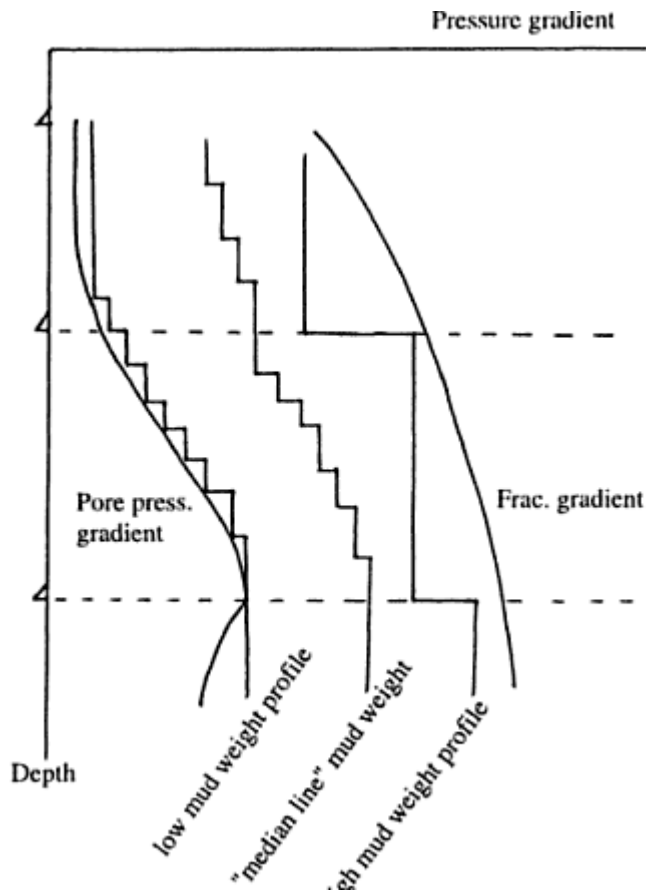


**Figure 56:** Swarf handling unit set up from Gullfaks A [38].

**Milling and impact on ECD:**

ECD stands for Equivalent Circulating Density. During milling operation steel from the casing is cut by the mill and transported from the well to top side. To be able to transport the steel it is important to design a fluid that has high enough weight and viscosity. The weight is important for hole stability considerations, and the viscosity for the fluid, swarf and debris transport when milling the casing [9].

By designing a mud weight that is between our pore pressure gradient and fracture gradient we can avoid problems during drilling. This method is often referred to as the “median line principle” [9]. *Figure 57* below illustrates this “median line” mud weight.

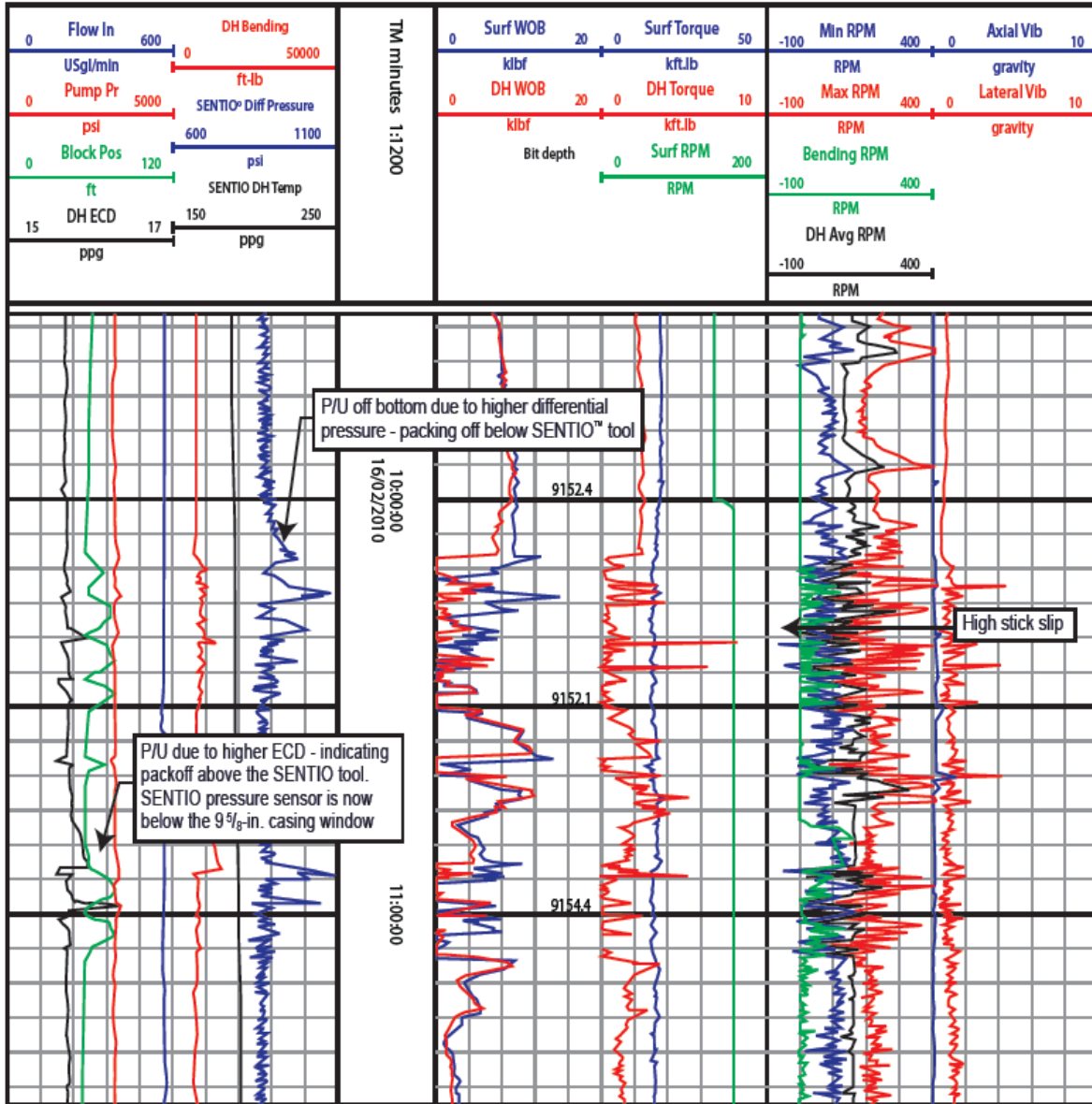


**Figure 57:** The “median line principle” is illustrated in this figure [7].

Baker Hughes has invented a service called SENTIO™ service, which can be applied during milling operations. At Baker Hughes webpages they show a case study where the SENTIO™ service has been utilized in order to optimize a P&A campaign [54].

When utilizing this tool they were able to monitor the differential pressure and the ECD during milling operations. The ECD and the differential pressure are important parameters that may indicate when and where we will have a pack-off scenario. But to interpret these logs, one has to understand how they work. To get a better understanding of how this works a figure is taken from the case study [54].

The figure below shows that by monitoring the differential pressure and the ECD, Baker Hughes was able to find out if the pack off took place above or below the down hole performance sub. By utilizing the SENTIO service Baker Hughes reduced the time spent on the section milling operation, and the rig time was reduced by 5 days [54].



**Figure 58: "Sentio Service" [54].** An increase in differential pressure and decrease in ECD values indicates that the pack off is below the down hole performance sub. If pack off is above the tool the ECD will increase, and sometimes one can observe a decrease in differential pressure, Courtesy of Baker Hughes [54].

## 5. TRANSPORT MECHANISM

It is important to have some basic knowledge about transport of swarf in order to understand the simulation part later in this thesis. In this section lift and drag will be introduced, and slip velocity and buoyancy. During the simulation part the slip velocity will be adjusted, as well as the mill rate, and we will try to simulate the transport of swarf.

### 5.1 Lift and drag forces

When cuttings are transported there are various forces that are acting on the cuttings, where two of these are lifting forces and drag forces. Drag forces are the forces in the flow direction which is exerted by the fluid and on the solid.

#### **Drag force:**

The drag force is defined as the following [8]:

$$F_D = \frac{\pi}{8} d_p^2 \rho_f v_s^2 \cdot C_D$$

Where

$C_D$ : drag coefficient

$v_s$ : Solid Particle velocity

### 5.2 Physics behind cutter transport:

In Jiimaa Gimaa master thesis from 2013 called "Cutting transport models and parametric studies in vertical and deviated wells" [8] he explains the physics related to the transport and how this is determined by the forces acting on it. Cuttings are exposed to the following forces [8]:

$F_L$ = Lift force

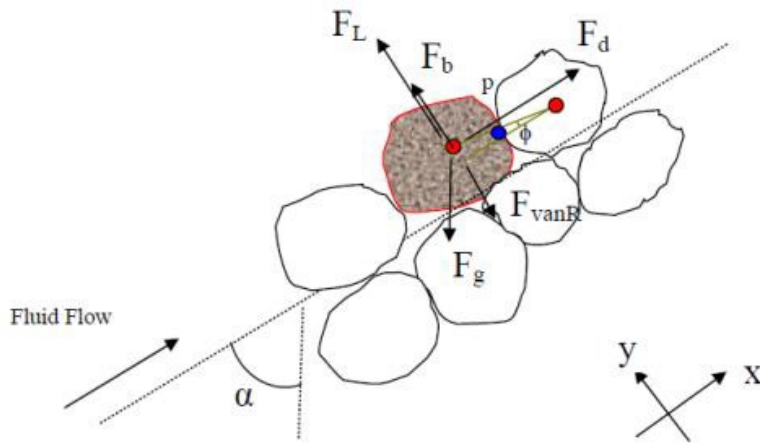
$F_d$ = Drag force

$F_b$ = Buoyancy force

$F_g$ = Gravity force

$F_{van}$ = Van der Waals forces

According to Duan et al. [42] the Buoyancy force ( $F_b$ ) and the gravity force ( $F_g$ ) are static forces. The drag force ( $F_d$ ) and the lift force are ( $F_L$ ) hydrodynamic forces. The Van der Waals forces are colloidal forces. The figure below (*Figure 59*) illustrates the forces that are acting on the cuttings when they are at the surface of cuttings bed [42].



**Figure 59:** This figure illustrates the forces that are acting on cuttings on the surface of cuttings bed [42].

**Gravitational forces:**

The gravitational forces are defined as [42]:

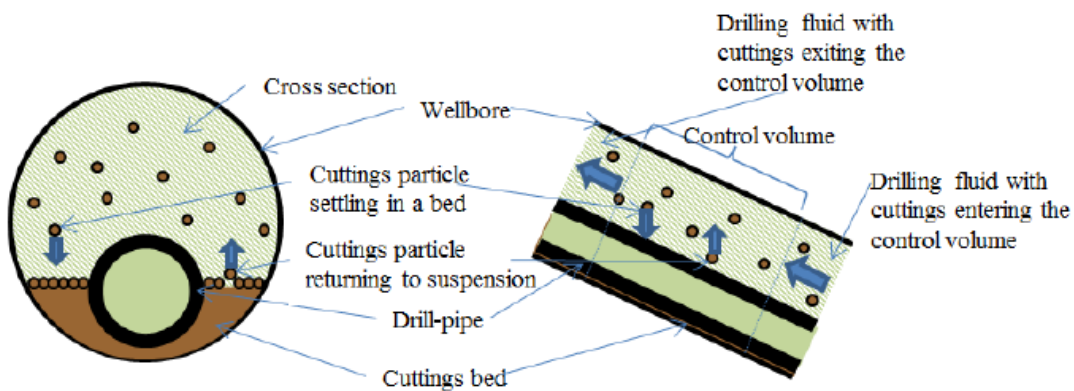
$$F_g = \pi \frac{d_p^3}{6} (\rho_p - \rho_f) \cdot g$$

Where

$d_p$  : particle size

$\rho_p$  : particle density

$\rho_f$  : fluid density



**Figure 60:** This figure illustrates the mass exchange [42].



### 5.3 Slip velocity

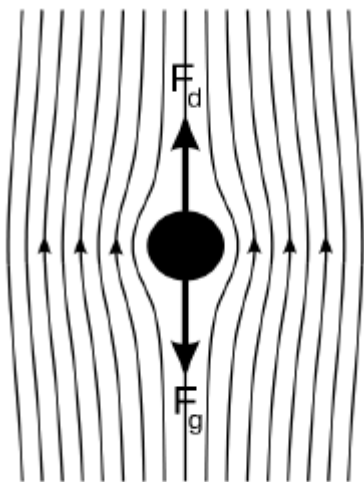
In Giimaa`s thesis he defines particle slip velocity [8].

In his thesis the Particle slip velocity is defined as

*“the velocity at which a particle tends to settle in a fluid because of its own weight.”*

The slip velocity varies with the following properties [42]:

- Particle size
- Geometry
- Density
- Fluid rheological properties

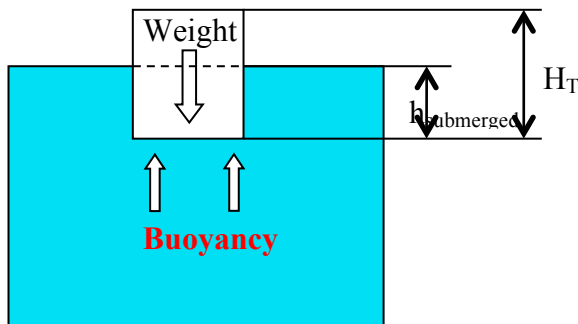


**Figure 61:** This figure shows the drag forces on a solid which is suspended in fluids [42].

Girmaa mention in his master thesis that it is of great importance for hole cleaning considerations, to find the slip velocity [8]. The cuttings may accumulate if the annular velocity does not exceed the slip ratio. From the slip velocity, the flow rate can be adjusted accordingly, and thereby remain a successful hole cleaning [42].

## 5.4 Buoyancy

Buoyancy is a force that's acting upwards. It is caused by the weight of displaced fluid as *Figure 62* below illustrates [44].



**Figure 62:** Illustrates the principle of Buoyancy [44].

The weight of the displaced fluid is directly proportional to the volume of the displaced fluid (if the surrounding fluid is of uniform density).

Assuming Archimedes' principle to be reformulated as follows,

Apparent immersed weight = Weight in air - Weight of fluid displaced

$$W_{\text{apparent}} = W_{s\_air} \left( 1 - \frac{\rho_f V_f}{\rho_s V_T} \right)$$

$$W_{\text{apparent}} = W_{s\_air} \left( 1 - \frac{\rho_f h_{\text{submerged}}}{\rho_s H_T} \right)$$

For totally immersed,  $h_{\text{submerged}} = H_T$

$$W_{\text{apparent}} = W_{s\_air} \left( 1 - \frac{\rho_f}{\rho_s} \right)$$

When floating,  $h_{\text{submerged}} = 0$ , the apparent weight = Weight in the air.

When the density of fluid = density of object, the apparent weight = 0. It means that the weight in air is balanced by the up thrust force. This results in floating [44].

## 5.5 Previous experience- cutting transport

During drilling operations it is important to carry the cuttings up to the surface in order to have a clean well [31].

If the cuttings remains in the well this may cause problems such as; pack off, plugging of the well, and as a consequence to this the pump pressure increases. Then the formation may fracture, and the well may experience big mud loss. One other consequence when the cuttings are not carried to the surface may be a stuck pipe scenario. In worst case one has to plug the well, and drill a side track, and by this perform a so called slot recovery operation [31].

T.I Larsen published a paper called “Development of a new Cuttings-Transport Model for High Angle Wellbores Including Horizontal Wells [46].

In this paper cutting transport for wells with an inclination from 55- 90° is discussed and later modelled based upon theoretical and experimental input.

In this paper the Critical Transport Fluid Velocity is defined as “the minimum fluid velocity required maintaining a continuously upward movement of the cuttings”. “In other words, at CTFV and higher no cuttings will accumulate on the low side of the wellbore” [46].

The Subcritical Fluid Flow (SCFF) is explained as the following “If the annular fluid velocity is lower than the CTFV, cuttings will start to accumulate in the wellbore”. “Any flow rate corresponding to an annular velocity below the CTFV is referred to as SCFF”[46].

There are various parameters that are controlling the cutting transport. In the same paper by Larsen et al. these parameters and their impact on the cutting transport is based upon more than 700 tests. These were performed in order to investigate the CTFV and the SCFF.

Briefly the parameters and their impacts are the following [46]:

- When there is **higher viscosity a larger flow rate is required** in order to reach CTFV. According to Larsen et al. low viscosity muds or water perform better in high-angle wells [46].
- According to Larsen et al. the tests indicates that **smaller cutter sizes needs a larger flow rate** in order to reach CTFV [46].
- **Higher velocity is required, when the ROP is increased.**
- **Increase in mud weight (MW) will improve cuttings transport**

A lot of effort is therefore been used to try to explain the phenomena of cutter transport due to its operational and economic importance. In the compendium called “solving non-linear equations” the factors that have an impact on cutting transport have been summarized, as the following [31]:

- **Increase the flow rate:** If the flow rate is increased this will have a positive outcome for the transport of cuttings.
- **Drillpipe rotation:** Drill pipe rotation will increase the cutter transport due to distribution of cutter beds, and suspension
- **Decrease the ROP:** If the ROP (Rate of penetration) is increased, more cuttings are generated, and the potential for cuttings beds are increased.

- **Cutting size particles:** Bigger cuttings are easier transported, and the shape is also relevant for the cutter transport.
- **Inclination:** Vertical, Horizontal, or inclined. It is easiest to transport cuttings in a vertical well.
- **Drillpipe eccentricity**
- **Hole size**
- **Mud weight:** By increasing the drilling fluid density this will increase the buoyancy and thereby increase the cuttings transport.
- **Fluid rheology and flow patterns:** The viscosity of the fluid may influence the cuttings transport in both a positive and negative way. It is preferable to have laminar flow and a high viscous fluid in a vertical well. While the opposite is preferable for a horizontal section. There one may prefer to have a low viscosity mud and a turbulent flow regime to be able to prevent the development of cutting beds.

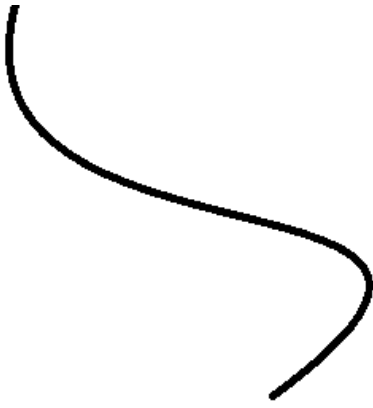
## 5.7 Transport mechanism for milling operations

*So how can the knowledge of conventional cutter transport be used for swarf transport during a milling operation?*

As mentioned previously huge amounts of swarf is generated in several shapes and sizes. For example milling 50 m of 53,5lb/feet 9<sup>5/8</sup> casing creates about 4000 kilos of swarf [8].

It is therefore a great challenge to find models that can describe the transport mechanism. Siddhartha Lunkad was mentioned previously in this thesis, and held a guest lecture on P&A and milling operations in MPE 710 Advanced Well technology autumn 2012 at the University of Stavanger.

He found the topic of my thesis interesting. Therefore he met me and my supervisor Kjell Kåre Fjelde at the University of Stavanger for a discussion on the topic. Siddhartha Lunkad has been working with milling operations and P&A for a long time. Below is an outline of the main findings based upon his experience within milling transport mechanism, as an example a S shaped well was used.



**Figure 63:** Sketch of a typical S-shaped well, 50-60°inclination [48].

- **OBM (oil based mud) systems** regardless of limited low-end rheology has shown good performance with milling operations, while WBM systems are generally considered as preferable milling fluid [48].
- **WBM systems** can offer higher low-end rheology profile meaning more viscous fluid system that assists in keeping the swarf in suspension in case the flow stops (e.g. at connections or in case of surface equipment failure). Also, WBM systems have limitations on inhibition characteristics with regard to hole stability in formations e.g swelling clay. In such scenario OBM systems has shown good performance as milling fluid. Experience indicates that the swarf lifting mechanism is a combined effect of fluid density, viscosity and flow rate [48].
- **Cutting size particles:** Big and irregular sizes where one also have big pieces, may cause potential traps where other swarf particles are collected. This may develop into “bird nests”. Such nests can also be responsible for the development of pack off situations both downhole and on surface mud handling equipment. The cutter structure on milling knives, will affect the particle size of the swarf, as well as the RPM and WOB based on Torque response. It is always very critical in milling operations to monitor the torque response and swarf returns (size and shape) to optimize RPM and WOB for steady milling performance [48].
- **Loss circulation scenario:** Pack off seems to be the most challenging issue when it comes to swarf transport. In situations where the milling parameters are not optimized for small and uniform swarf in returns, it will lead to non-uniform particle size distribution in swarf that is generated downhole. This usually results in excessive bridging of smaller size swarf over bigger swarf bird-nests results in a pack-off in annulus, causing restricted flow and increase in pump pressures. In severe cases when open hole is exposed sudden increase in pump pressure may lead to pack-off induced mud losses [48].

## 6. PWC TECHNOLOGY

### 6.1 Introduction to PWC

The different companies try to minimize the rig time and make milling operations more efficiently and safe. As mentioned earlier it is beneficial for the companies to avoid milling operations.

A SPE paper called “Novel Approach to More Effective Plug and Abandonment Cementing Techniques” was published in 2011 by Thomas E. Ferg et al.

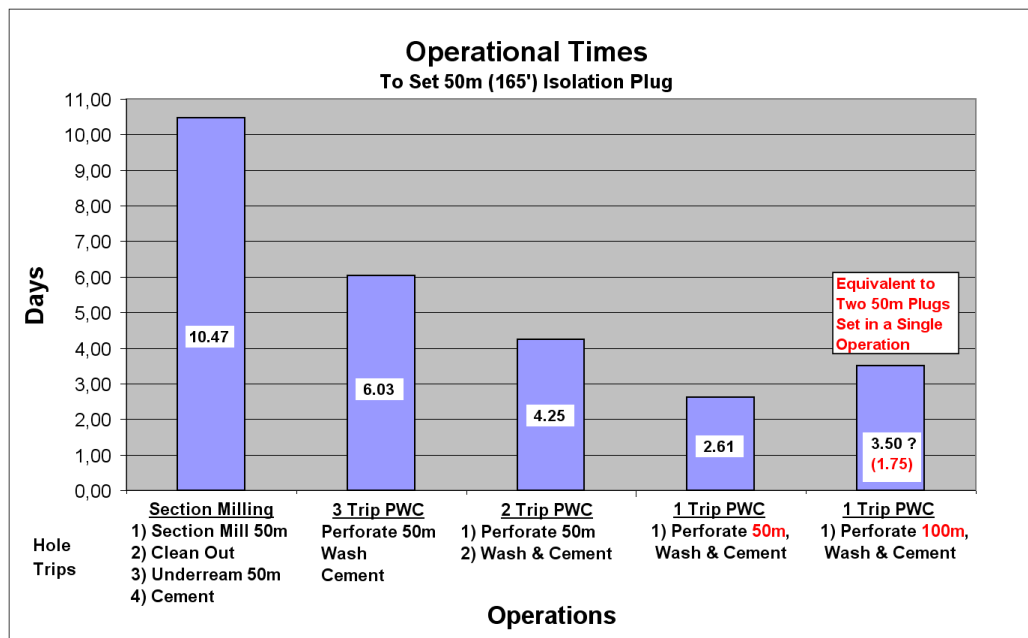
In this paper a new approach is introduced, and by utilizing this technology the problems related to section milling can be eliminated. This new approach is called PWC system [2].

The three letters PWC stands for Perforate, Wash, and Cement, which are the three steps in this process.

### 6.2 Time savings & Rig time

As the figure below (Figure 64) illustrates the time savings by using the PWC Technology instead of traditional milling is huge. As the figure below illustrates one are able to perform a P&A operation in one trip within 2, 61 days instead of 10, 47 days as it is with milling. If one then assume an average rig time cost of 0, 5 million dollar each day the cost savings are then  $10, 47 - 2, 61 = 7, 86 \text{ days} * 0, 5 = 3, 93 \text{ million dollars}$  each plug [2].

A milling operation is often very costly, time consuming and there is also HSE and disposal issues related to it. The PWC technology eliminates section milling, and also minimizes the HSE issues and the disposal issues related to this operation. The well integrity issue is also an important argument [2].



**Figure 64: “Time saving with PWC technology” [2]**

This figure shows the time savings by utilizing this PWC technology. By setting one plug they are able to perform this in average of 2.61 days compared to 10.47 with traditional section milling [2].

## 6.3 HydraWell

To get a better understanding of how the PWC Technology works, I contacted Arne G.Larsen, Technical Manager at HydraWell. He invited me to their offices in Tananger for a presentation of the company and the different tools.

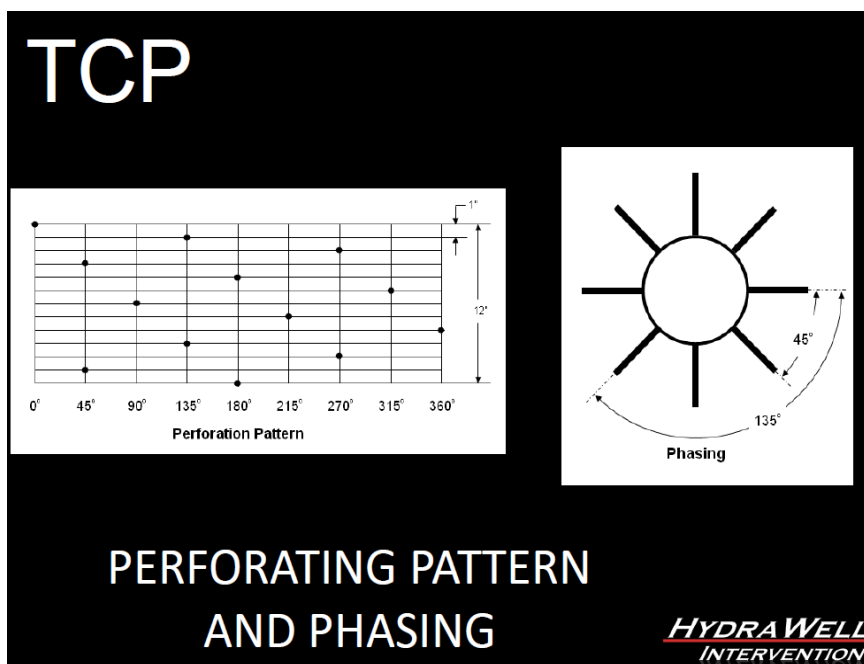
Arne G Larsen informed me that HydraWell recently got the patent for the HydraWash system. Their customers are worldwide and they have offices in both Canada and Houston. Arne told me that they find the challenges exciting, and they helped Conocco Phillips with minimizing the rig time for the P&A operations at the Ekofisk field. According to NORSOK D010 it is required to have 2 plugs that extend 50 metres for each reservoir. At the Ekofisk field where they additionally had a zone with shallow gas, hence it was necessary to place 4 plugs in every well [2].

## 6.4 Perforate, Wash & Cement

### Perforate

The perforation is performed by utilizing a TCP gun [2].

The perforation gun consists of 12 shots per feet, and the pipe itself is 50 meters. The phasing of the perforations is  $135/45^\circ$  as *Figure 65* below illustrates [2].



**Figure 65:** The figure above shows the perforation pattern and the phasing of the perforations. HydraWash uses a  $45-135^\circ$  phasing (HydraWell 2014) [20].

The next figure (*Figure 66*) illustrates “Burr” which is created on the outside and inside of the casing, and caused by the perforations [20].



**Figure 66:** The picture above illustrates the “Burr” [20]. Burr is present on the outside of the casing as well as on the inside. The tools are therefore made with steel reinforced rubber cups so they can pass through the casing without being worn out (HydraWell 2014) [20].

**Wash**

A typical washing process takes between 12 and 48 hours [20]. In order to obtain a proper washing process they use regular mud [20]. In order to plug the well without performing milling operation the HydraWash™ system was developed [55]. In the annulus behind the casing there may be debris that has to be washed and cleaned out, for this application the HydraWash™ Tool is used [55].



**Figure 67:** This figure illustrates the HydraWash™ tool (HydraWell 2014) [55].

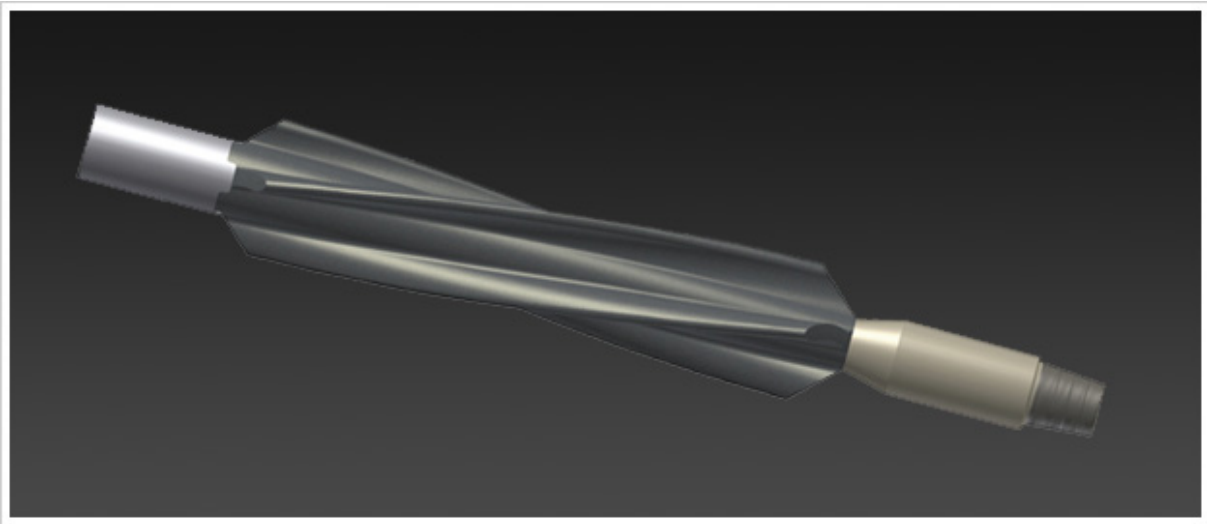
**Cement**

The latest stage in the process is to cement the well, for this issue the HydraArchimedes™ is a good alternative, as shown in Figure 68 below. The HydraArchimedes™ is positioned above the HydraWash™ tool. The HydraArchimedes™ squeezes the cement out in the perforations [55].

According to Hydrawell homepages the HydraArchimedes™ has the following benefits [55]:



- *“One trip plugging system”*
- *“Enhanced plugging efficiency”*
- *“Simple design and operation”*
- *“Replaceable blades”*
- *“Available for all casing sizes”*



**Figure 68:** This figure illustrates HydraArchimedes™ (HydraWell 2014) [55].

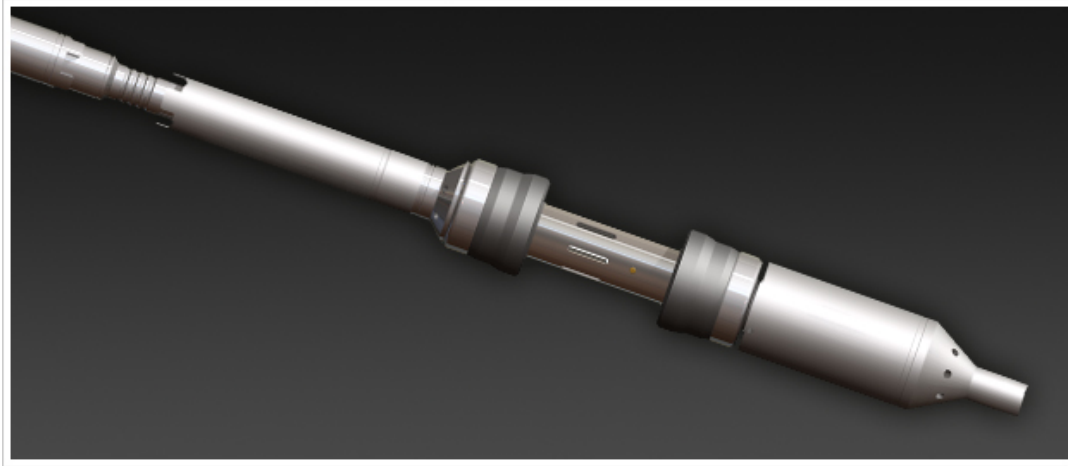
## 6.5 HydraWash™ system

By utilizing the HydraWash™ system, it is possible to perforate, wash and cement in one run, but this can also be performed in two runs if not rathole is available for used TCP guns [20]. Today this can be performed by a LWI with riser. But in the future they hope that it is possible to use LWI with CT.

The typical procedure is to perforate 50 meters and then wash. If the formation is oil wetted this can cause problems for the cement to bond. A spacer is used to make sure that the formation is water wetted prior to pumping the cement [20].

At HydraWell homepage the benefits by using the HydraWash™ system is the following [55]:

- *“One trip plugging system”*
- *“No milling is required”*
- *“Allows full flow when tripping in and out”*
- *“Simple design and operation”*
- *“Base for plugging material”*
- *“Available for all casing sizes”*



**Figure 69:** This figure illustrates the HydraWash™ system (HydraWell 2014) [55].

## 6.6 HydraHemera™ system

The HydraHemera™ can be utilized for multi casing P&A systems. The HydraHemera™ tool is activated by a ball drop. The HydraHemera™ system consists of the two tools; HydraHemera™ Jetting Tool and the Hydra Hemera™ Cementing Tool [55].

At Drawwell homepages the benefits by utilizing the HydraHemera™ are the following [55]:

- *“One trip plugging system”*
- *“No milling required”*
- *“Allows full flow when tripping in and out”*
- *“Simple design and operation”*
- *“Ideal for cleaning multiple annuli”*
- *“Available for all casing sizes”*



**Figure 70:** This figure illustrates the HydraHemera™ (HydraWell 2014) [55].

## 7.COMPARISION OF NORSOK D010, REV 3 AND NORSOK D010 REV 4

As mentioned earlier NORSOK D010 is describing the well integrity in drilling and well operations. When comparing revision 3 and revision 4 of NORSOK D010, there are major differences when it comes to P&A. Below is some of the changes that was observed after comparing NORSOK D010, rev 4 and NORSOK D010, rev 3 [17,18].

### 7.1 Well barrier acceptance criteria

The well barrier acceptance criteria for plug and abandonment have been revised. Well barrier acceptance criteria is defined in NORSOK D010, rev 4 as the

*“technical and operational requirements and guidelines to be fulfilled in order to verify the well barrier element for its intended use”*

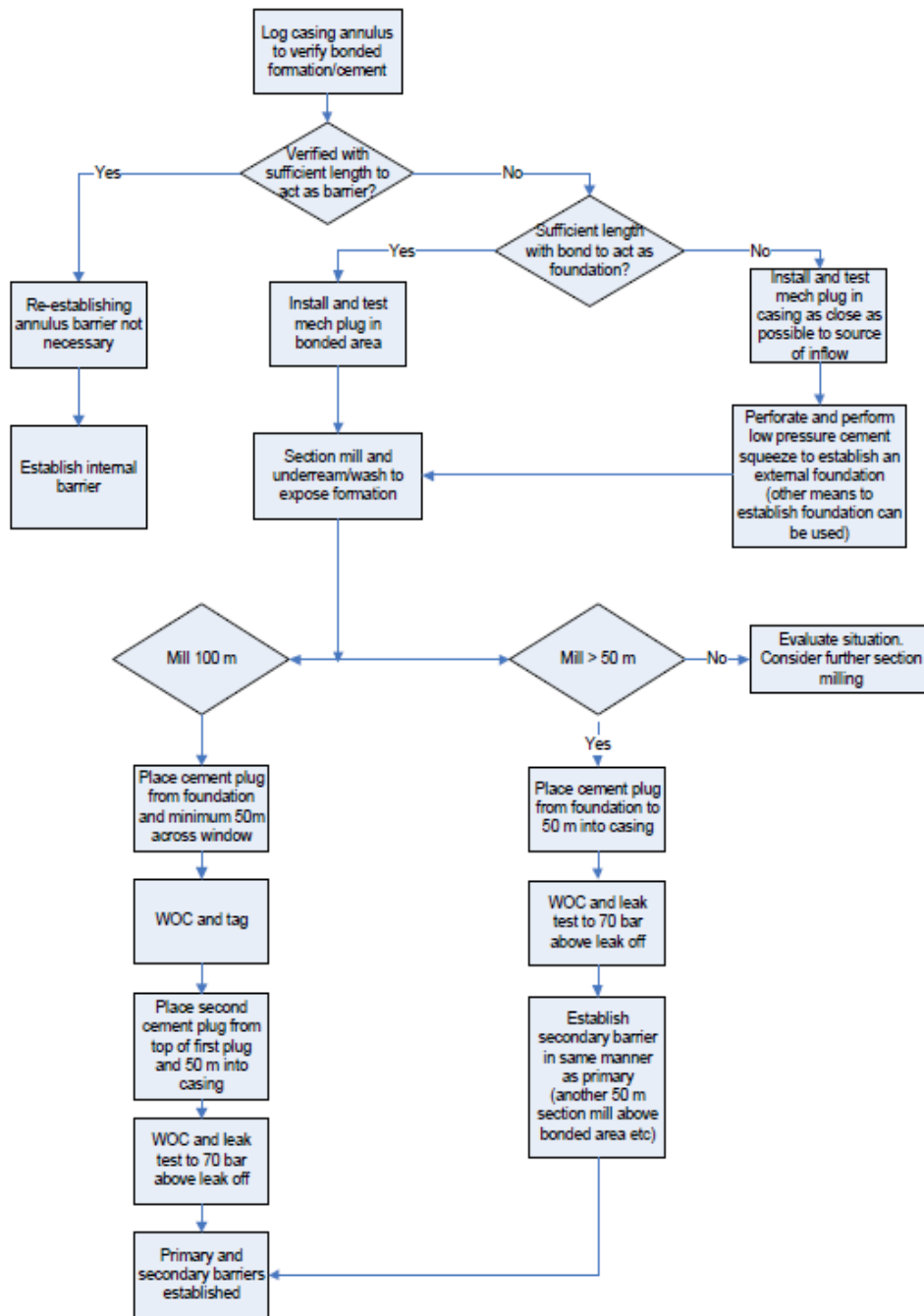
In the previous revision, rev 3 it was defined as:

*“technical and operational requirements that need to be fulfilled in order to qualify the well barrier or WBE for its intended use”*

Here it is observed that the new revision also refers to guidelines that have to be fulfilled, and deals with well barrier element not well barrier. In the introduction it was mentioned that a well barrier could not alone prevent flow, but in combination with other WBE`s form a well barrier.

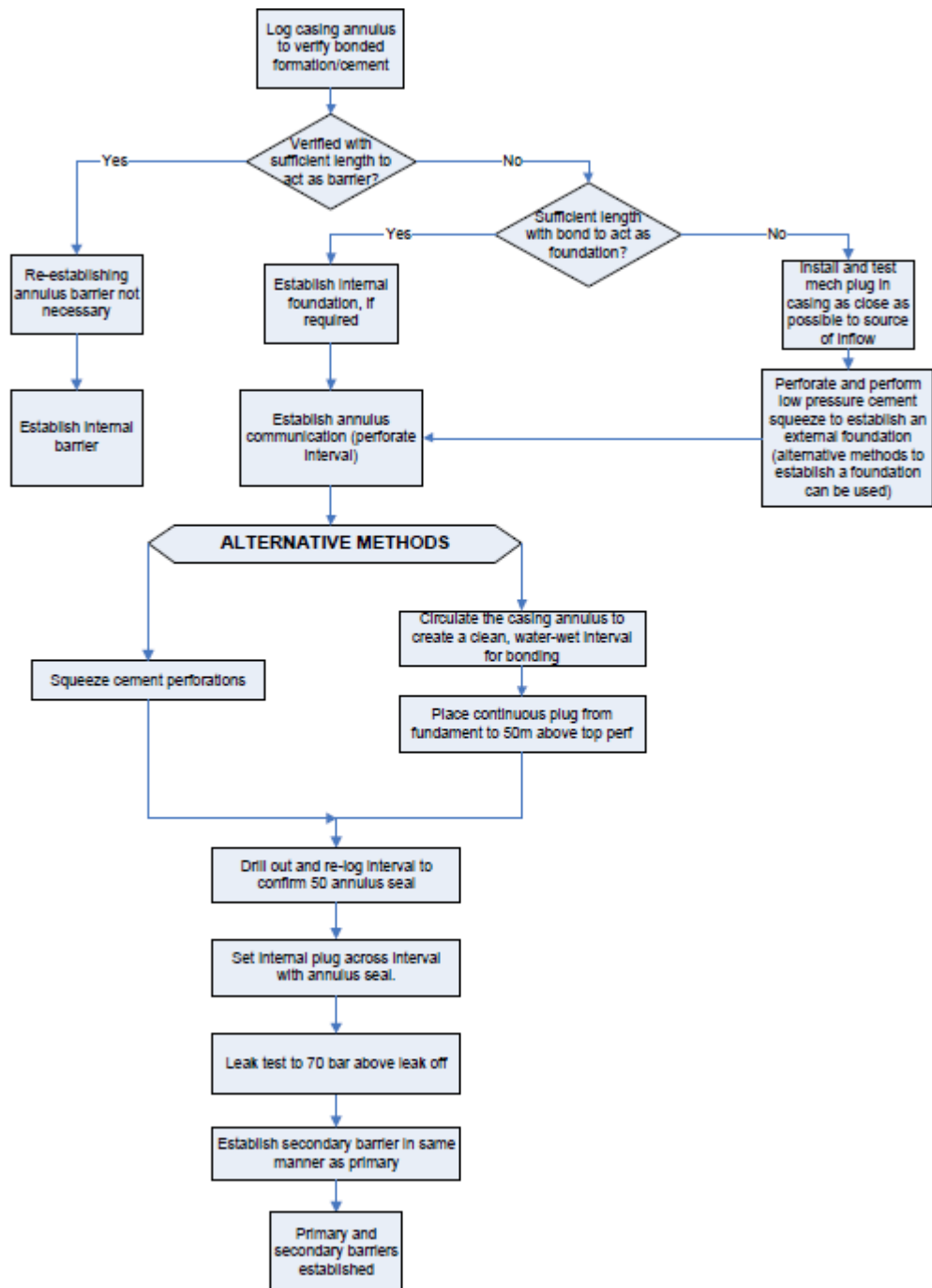
### 7.2 New flow chart for execution of milling operations

By comparing the old revision of NORSOK D010 by the new one there has been some important changes when it comes to the execution of section milling. In the new revision the way of performing section milling is extended and more detailed explained by figure and charts. As we see from the figure section milling is performed after the logging of the casing annulus, show us that the length is insufficient to act as a barrier.



**Figure 71: “Workflow for milling operations according to NORSOK D010” [18].**The workflow for performing milling operations according to NORSOK D010 [18].

Below are schematics for alternative abandonment method. This can be found in NORSOK D010, rev 4 section 9.6.9. By comparing the two flow charts one can easily observe that the first figure illustrates the workflow when performing section milling operations, while the other one describes alternative methods such as PWC technology.



**Figure 72:** The workflow for alternative method [18].

### 7.3 Temporary abandonment period

From the previous revision of NORSOK D010 (rev 3) temporary abandonment did not divide temporary abandonment into whether it was monitored or not. It was also not indicated any clear number for how long it could be temporarily abandoned when it was not monitored.

In the previous revision of NORSOK D010 (rev 3 ) [17] temporary abandonment is

*“within a specified time frame (from days up to several years)”*

According to NORSOK D010 rev 4 [18], section 9.5.1 it states that for temporary abandonment

*“the maximum abandonment period shall be three years”*

The newest revision of NORSOK D010 has been extended with new tables.

## 7.4 WBEAC Examples

The newest revision of NORSOK D010 (rev 4) has been extended with more tables for well barrier element acceptance criteria in chapter 15 [18].

### 7.4.1 New table for Creeping formation, Table 52

As mentioned in chapter 3 regarding plugging materials, a new table (table 52) has been included in the newest revision of NORSOK D010 [18].

This table can be found in chapter 15: “Well barrier elements acceptance tables” in section 15.52 in NORSOK D010 [18].

### 7.4.2 New table for In-situ formation, Table 51

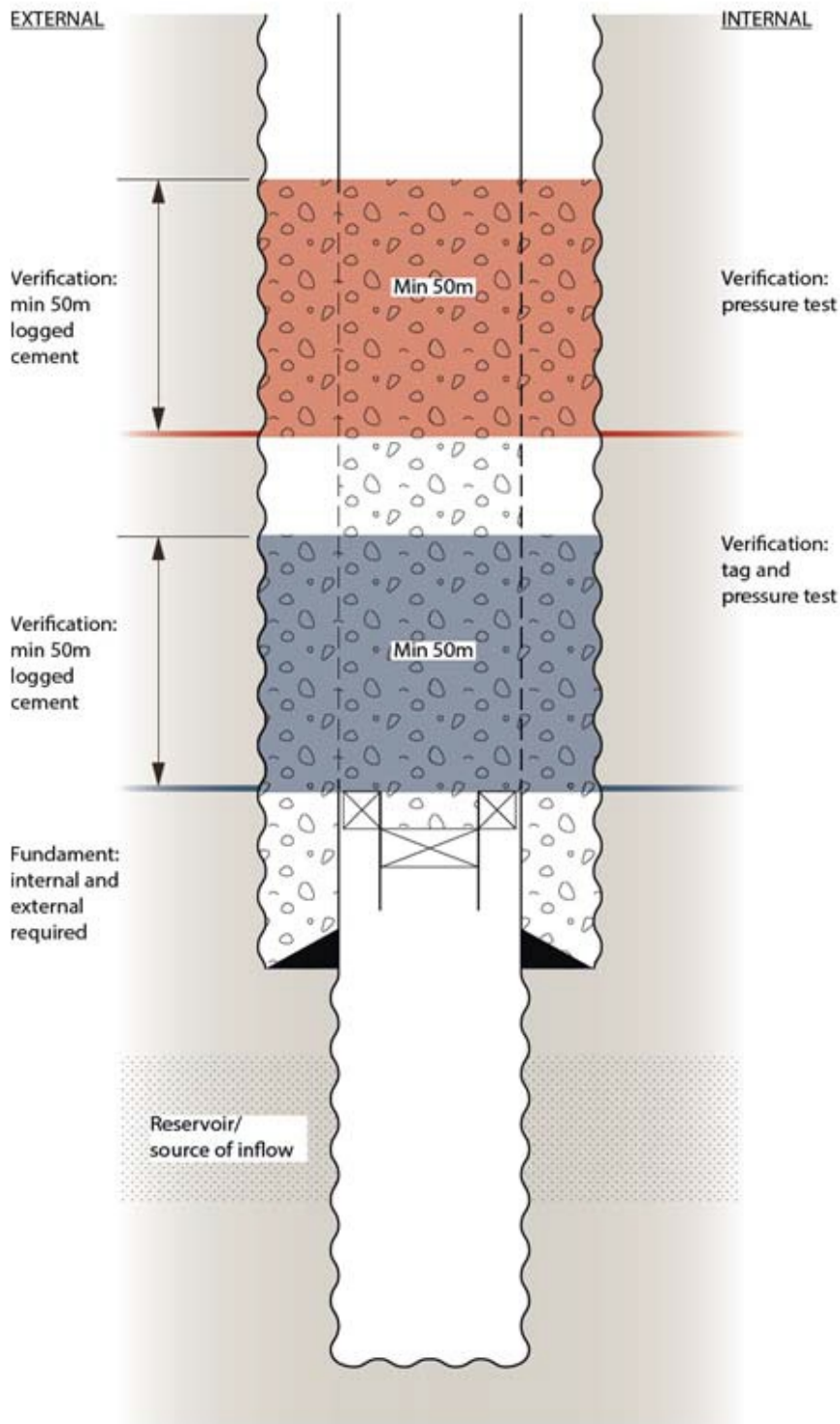
A new table (table 51) for in-situ formation has also been included in the newest revision of NORSOK D010, rev 4.

The new table can be found in chapter 15: “Well barrier elements acceptance tables” in section 15.51. This is for the “formation that has been drilled through and is located adjacent to the casing annulus isolation material or plugs set in the wellbore” [18].

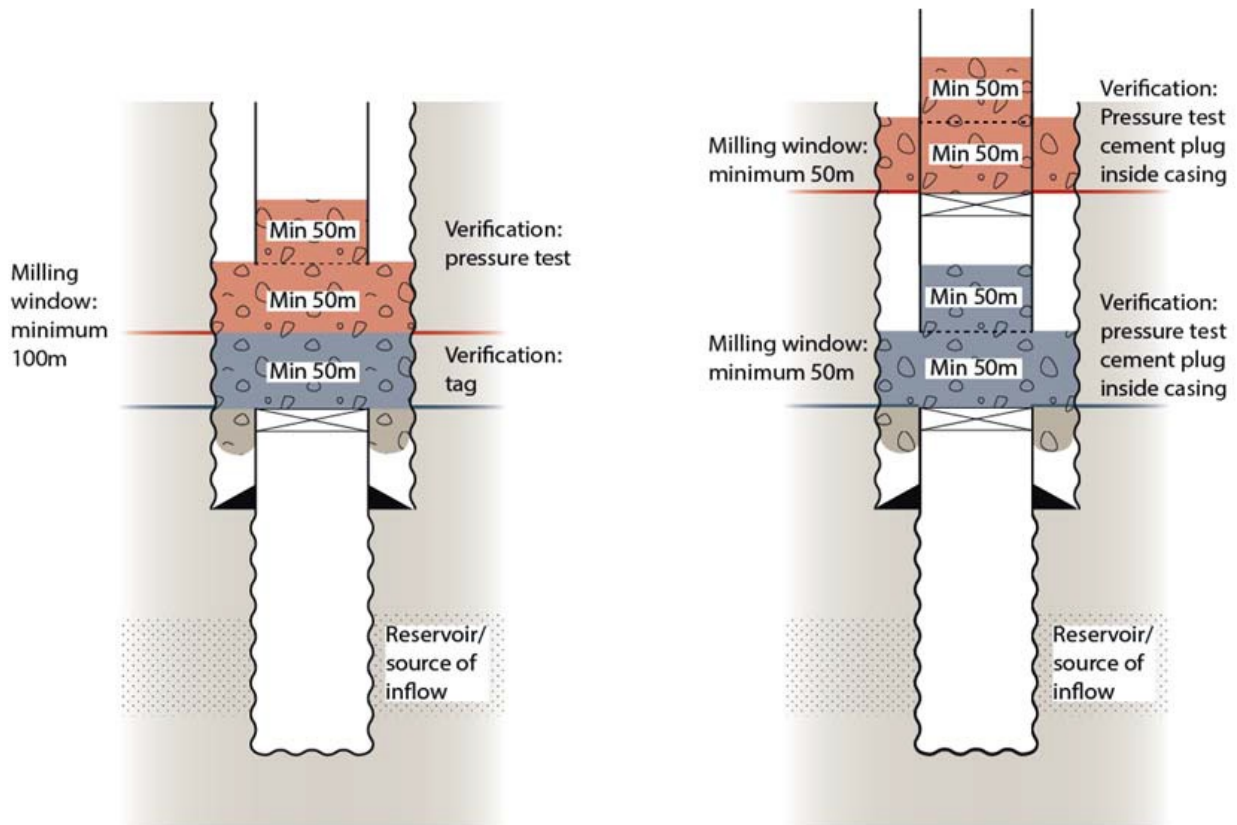
## 7.5 Placement of well barriers for milling operations, and an alternative method

A new example for placement of well barriers for permanent abandonment using the alternative method has been included in the newest revision of NORSOK D010, rev 4. This can be found under section 9.6.9.1, and illustrated by *Figure 73* below [18].

A new example for placement of well barriers for permanent abandonment for wells where section milling is performed has also been included in the newest revision of NORSOK D010, and can be found under section 9.6.8.1, and illustrated by *Figure 74* below [18].



**Figure 73:** Illustrates placement of well barriers for permanent abandonment, alternative method [18]



**Figure 74:** Illustrates placement of well barriers for permanent abandonment, section milling [18].

## 7.6 XMT removal extended

In the newest revision of NORSOK D010, there have been added tables. These tables can be found in Section 9.7.2 and 9.7.3 in the newest revision of NORSOK D010. Well barrier that has to be in place when removing vertical and horizontal Christmas XT has been included in this section [18].

For the removal of vertical XT removal there has been established a new table (table 26) Table 10 below:



**Table 10 – Removal of vertical XT [18].**

| Fluid                        | Possible to monitor primary well barrier?                        | Primary WBE  | Secondary WBE   | Compensating measures  |
|------------------------------|--|--|---|--|
| Light fluid (under-balanced) | Yes (downhole pressure gauge or tubing to annulus communication) | Deep set mechanical bridge plug  | Inflow tested DHSV and drop protection device – accepted if DHSV has zero leakage, or a BPV/tubing hanger plug, or a shallow set mechanical bridge plug | Status of primary well barrier to be monitored at all times on DHPG or A-annulus pressure  |
|                              | No   | Deep set mechanical bridge plug  | a BPV/tubing hanger plug, or a shallow set mechanical bridge plug   | Inflow tested DHSV as compensating measure due to not able to monitor primary barrier      |
| Heavy fluid (over-balanced)  | Yes (tubing to annulus communication)                            | Deep set mechanical bridge plug and brine/mud above plug, or Kill pill and brine or kill mud from perforations/screen to surface | Inflow tested DHSV and drop protection device – accepted if DHSV has zero leakage, or a BPV/tubing hanger plug, or a shallow set mechanical bridge plug | Fluid level or applied pressure to be monitored on A-annulus                               |
|                              | No   | Deep set mechanical bridge plug and brine/mud above plug   | Inflow tested DHSV and drop protection device – accepted if DHSV has zero leakage, or a BPV/tubing hanger plug, or a shallow set mechanical bridge plug |  |
|                              | No   | Kill pill and brine or kill mud from perforations/screen to surface  | a BPV/tubing hanger plug, or a shallow set mechanical bridge plug   | Inflow tested DHSV as compensating measure due to not able to monitor primary well barrier |

For removal of horizontal XMT a deep set plug shall be installed [18].

## 7.7 Cutting depth

In section 9.6.4 in the newest revision of NORSOK D010 it is stated that

*“For permanent abandonment wells, the wellhead and casings shall be removed below the seabed at a depth which ensures no stick up in the future. Required cutting depth shall be sufficient to prevent conflict with other marine activities. Local conditions such as soil and seabed scouring due to sea current should be considered. For deep water wells it may be acceptable to leave or cover the wellhead/structure. Mechanical or abrasive cutting is the preferred method for removal of the casing/conductor at seabed” [18].*

In the previous revision of NORSOK D010, rev 3 it was specified to cut 5 m below seabed, but it didn't say anything regarding the preferred method for removal of casing/conductor at seabed. From section 9.7.2 in the previous revision of NORSOK D010, rev 3 [17] it was stated that:

*“For permanent abandonment wells, the wellhead and the following casings shall be removed such that no parts of the well ever will protrude the seabed. Required cutting depth below seabed should be considered in each case, and be based on prevailing local conditions such as soil, sea bed scouring, sea current erosion, etc.. The cutting depth should be 5 m below seabed. No other obstructions related to the drilling and well activities shall be left behind on the sea floor” [17].*

## 7.7 Definition of permanent abandonment

In the previous revision of NORSOK D010, permanent abandonment was defined as

*“well status, where the well or part of the well, will be plugged and abandoned permanently, and with the intention of never being used or re-entered again” [17].*

In this definition it says that the intention is that it shall not be used or re-entered again. In the newest revision of NORSOK D010 permanent abandonment is defined as:

*“well status, where the well is abandoned permanently and will not be used or re-entered again” [18].*

In this definition it is more precisely said that it **shall not** be used or re-entered again, while the previous revision said that it shall have **the intention** of never being used or re-entered again. In the newest revision of NORSOK D010, it also says that the well **is abandoned permanently** while the previous revision said that the well **will be plugged and abandoned permanently**.

## 8. ECD MODELLING OF A MILLING OPERATION

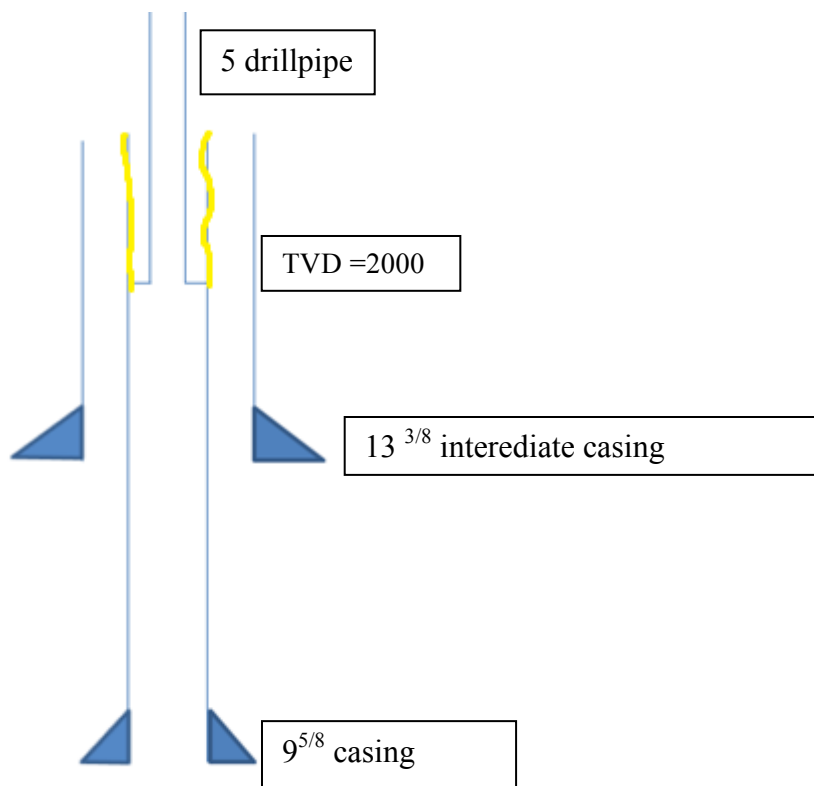
### 8.1 Background for model

The modelling part has a basis in a steady state model and is performed in Matlab. An existing code has been modified for this issue. The ECD during a milling operation is the friction loss + the hydrostatic pressure. The idea here is to visualize how the ECD will be affected when the milling rate is adjusted as well as the slip relation.

The slip relation is adjusted as well as milling rates. Milling rates and casing and drill pipe sizes has been set using realistic numbers. These data were obtained from Siddhartha Lunkad `s in a meeting with him in April 2014 and has basis in his experience with milling.

The background for using steady state for modelling milling was to see if it was possible to simulate the effects that swarf has on the hydrostatic pressure. The milling rate and the slip relation are adjusted in the code. The effect on this is further investigated by looking at the swarf concentration, the ECD in the well and the velocity profiles.

For this simulation an example well is used. The milling window is 50 meters, at the entering point is at 2000 m TVD. The casing that is going to be milled is the 9<sup>5/8</sup> casing. The density to mud is 1,5SG and the density of swarf is 7,85SG. The liquid rate is 3000litres/min.



**Figure 75: "Well geometry"**

**Table 11 - Well data**

|                     |   |
|---------------------|---|
| OD (outer diameter) | $13^{3/8} \cdot 0,0254 = 0.3136$ [m]              |
| ID (inner diameter) | $5 \cdot 0,0254 = 0,127$ [m]                      |
| Area                | $\pi/4 (OD^2 - ID^2) = 0,06457$ [m <sup>2</sup> ] |
| Velocity            | 0,7743 [m/s]                                      |
| Flow rate           | 3000L/60=0,05 [m <sup>3</sup> /s]                 |
| Density of mud      | 1,5 [SG]  |
| Density of swarf    | 7,85 [SG]   |

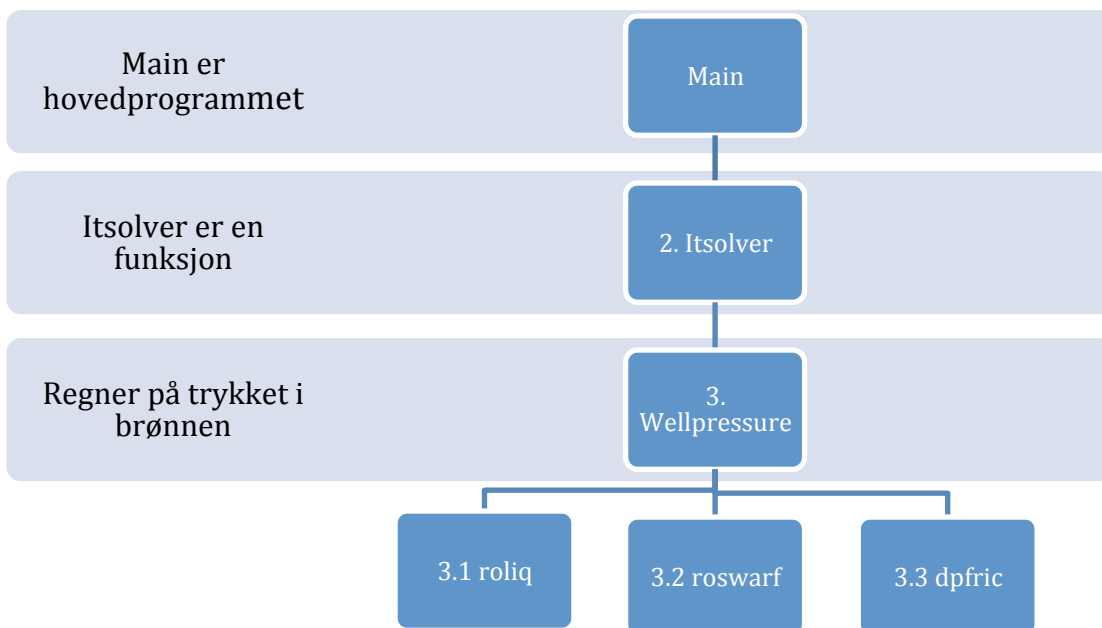
## 8.2 Detailed description of numerical approach:

The well is first discretized into a certain number of cells. Then conservation laws for mass and momentum are solved. The solution approach is based on a shooting technique where the calculation starts at bottom and upwards. If the calculated pressure at the outlet matches the real condition a solution is found [31].

The Bisection method is used in order to find the numerical solution. Another word for the Bisection method is “*the method of halving the interval*” [31].

## 8.3 Program structure

The program structure is the following:



**Figure 76: “Program structure for modelling”**

## 8.4 Solution approach for chosen model:

The model that is chosen is a two phase steady state model. To be able to solve the two phase model by a mathematical approach, one has to use the following three steady state conservation laws (eq 1.1, eq.1.2 and eq 1.3) [30]

$$\frac{\partial}{\partial z}(A\rho_l\alpha_l v_l) = 0 \Leftrightarrow \frac{\partial}{\partial z}(A\rho_l v_{SL}) = 0$$

(Eq.1.1)

$$\frac{\partial}{\partial z}(A\rho_g\alpha_g v_g) = 0 \Leftrightarrow \frac{\partial}{\partial z}(A\rho_g v_{SG}) = 0$$

(Eq.1.2)

$$\frac{\partial}{\partial z} p = -(\rho_{mix} g + \frac{\Delta p_{fric}}{\Delta z})$$

(Eq 1.3)

The superficial velocities of liquid and swarf are defined as the following

Superficial velocities of liquid: For the modelling part, we modify the model, and define our liquid as mud [30].

$$v_{SL} = \alpha_l v_l$$

(Eq 1.4)

Superficial velocities of gas: For the modelling part we modify the model and define our gas as the steel [30].

$$v_{SG} = \alpha_g v_g$$

(Eq 1.5)

Mixture velocity: The mixture velocity is the sum of the superficial velocity of liquid (from Eq 1.4) and the superficial velocity of gas (from Eq.1.5) [30].

$$v_{mix} = v_{SL} + v_{SG}$$

**Slip relation:** the slip relation is defined as [30]:

$$v_{\xi} = K(v_{SL} + v_{SG}) + S$$

(Eq 1.6)

When we have **no slip conditions** ( $K=1, S=0$ ) then the holdup is: (%fraction of swarf)

$$\text{Holdup (\% fraction of swarf)} = V_{SG}/(V_{SG}+V_{SL})$$

(Eq 1.7)

Equation 1.7 will be modelled as  $V_G = V_{MIX}-S$

Where  $S$  will be adjusted, and we will see how this affects the holdup. From Eq 1.7 one observes that the slip is subtracted. This means that the transport of swarf is slower than the fluid.

## 8.5 Some main principles and calculations

Steel has a density of 7,85SG which is 5, 23 times more than the density of mud (1,5SG). Only a little amount of steel inside the mud will have a big impact on the mud weight. As an example if we have 10% steel mixed together with the mud the specific gravity will change from 1,5SG to 2,14SG from the equation below (Eq.1.8)

With 10 % steel:

$$SG_{\text{mud}} \cdot X + SG_{\text{steel}} \cdot Y$$

(Eq.1.8)

$$1,5 \cdot 0,9 + 7,85 \cdot 0,1 = 2,135SG.$$

$SG_{\text{mud}}$ : Specific gravity of mud

$SG_{\text{steel}}$ : Specific gravity of steel

$X$ : Fraction of mud (90%)

$Y$ : Fraction of steel (10%)

If the well pressure exceeds the fracturing pressure the well will fracture. We will therefore try to model different milling rate, and see how the ECD is affected by this.

The milling rate or rate of penetration is dependent on the area of the casing that we are milling.

$$V \cdot A = Q$$

The milling operation is basically the same principle as the principle behind the drilling operation. But instead of using a drill bit we are using a mill.

## 8.6 Mill rates

After the meeting with Klaus Engelsgjerd at Baker Hughes typical milling rates were discussed again [56]

The plan was to adjust the mill rate from 2m/hr, 5m/hr,10 and to 20m/hr. Engelsgjerd pointed out that the limiting factor is not the milling rate but the waste handling aspect [56]. With today's technology they are able to mill with a very high mill rate but the huge amounts of steel that is generated also need to be handled properly [56].

**Table 12 – Typical mill rates:**

|        | ROP(Rate of penetration)/Mill rate |
|--------|------------------------------------|
| Normal | 1-2 m/hr                           |
| Medium | 5m/hr                              |
| High   | 10-20 m/hr                         |

### Some calculations of swarf generated:

If one assumes a mill rate of 2 m/hr, this will generate 2 meters of steel length per hr, if one mill continuously day and night shifts without any breaks, it will take approximately 1 day to mill 48 meters of steel. Then 3837,708 kilos of swarf will be generated.

The amount of swarf that is generated at topside is then:

$$7850[\text{kg}/\text{m}^3] * 48[\text{m}] = 376800 \text{ kg}/\text{m}^2$$

$$\text{OD } (9^{5/8} \text{ casing}) = 9^{5/8}[\text{in}] * 0.0254[\text{m}/\text{in}] = 0,2448$$

$$\text{ID } (9^{5/8} \text{ casing}), 53,5\text{lb}/\text{ft}, (\text{from API casing specification APPENDIX D}) = 8,535 * 0,0254 = 0,2167$$

$$\text{Area } = A = \frac{\pi}{4} (\text{OD}^2 - \text{ID}^2) = 0,010185$$

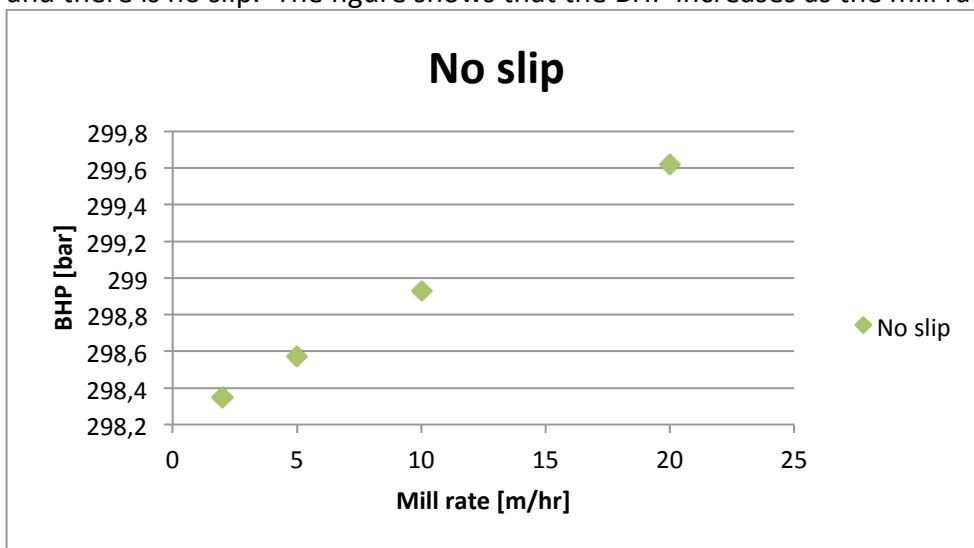
$$0,010185 * 376800 = 3837,708 \text{ kilos}$$

## 9. RESULTS

After adjusting the mill rate and the slip relation in our model the results that were obtained was illustrated in several graphs. First the mill rate was plotted again the BHP (bottom hole pressure). The purpose with this was to check how the BHP changed when the mill rate and slip ratio was adjusted. For  $S=0$  we have no slip conditions and when  $S$  becomes more and more negative, the swarf will move more and more slowly compared to the liquid.

### 9.1 No slip

The figure below (*Figure 77*) illustrates how the BHP changes when the mill rate is increased, and there is no slip. The figure shows that the BHP increases as the mill rate increases.

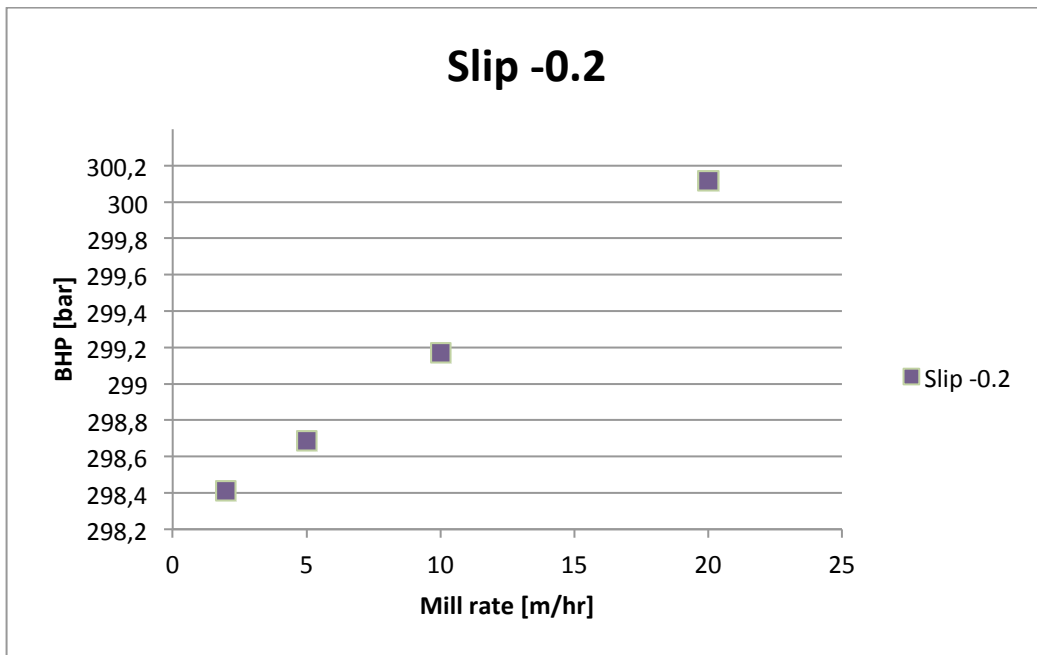


**Figure 77:** This figure illustrates how the bottom hole pressure varies when the mill rate is adjusted. In this particular case there is no slip. The BHP reaches its maximum at 299,6 bar and with a mill rate of 20m/hr.

### 9.2 Slip=-0,2

The next figure (*Figure 78*) below represents the BHP variations when the slip ratio remains constant at -0, 2 and the mill rate is increased. The same trend can be observed here as in the previous example.

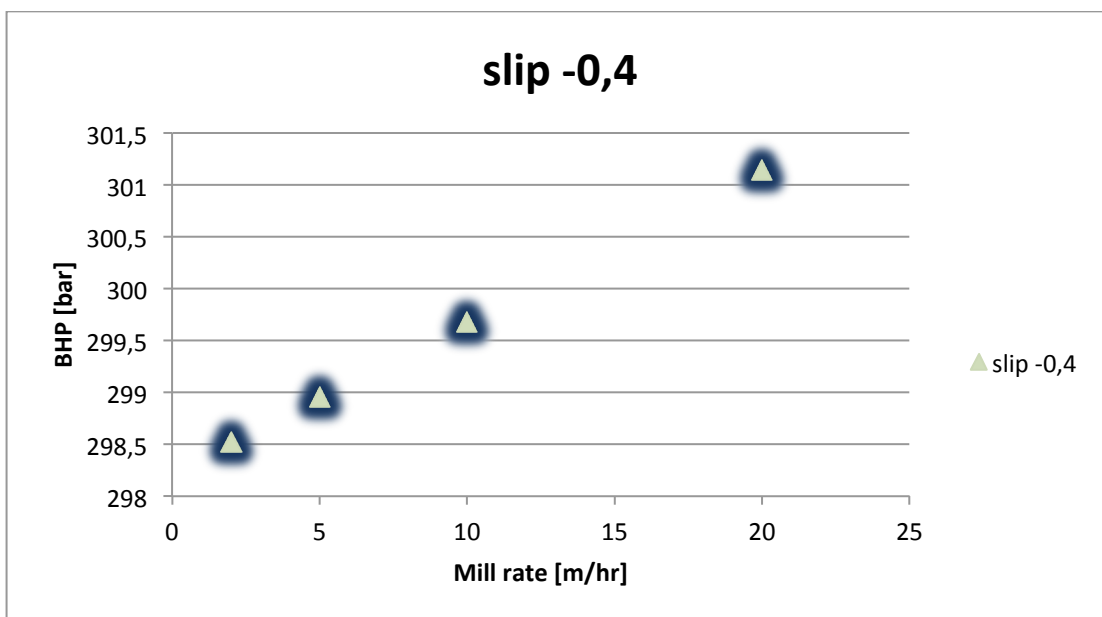




**Figure 78:** This figure illustrates how the bottom hole pressure varies when the mill rate is adjusted. In this particular case the parameter  $S = -0.2$ . The BHP reaches its maximum at 300,12 bar and with a mill rate of 20m/hr.

### 9.3 Slip=-0, 4

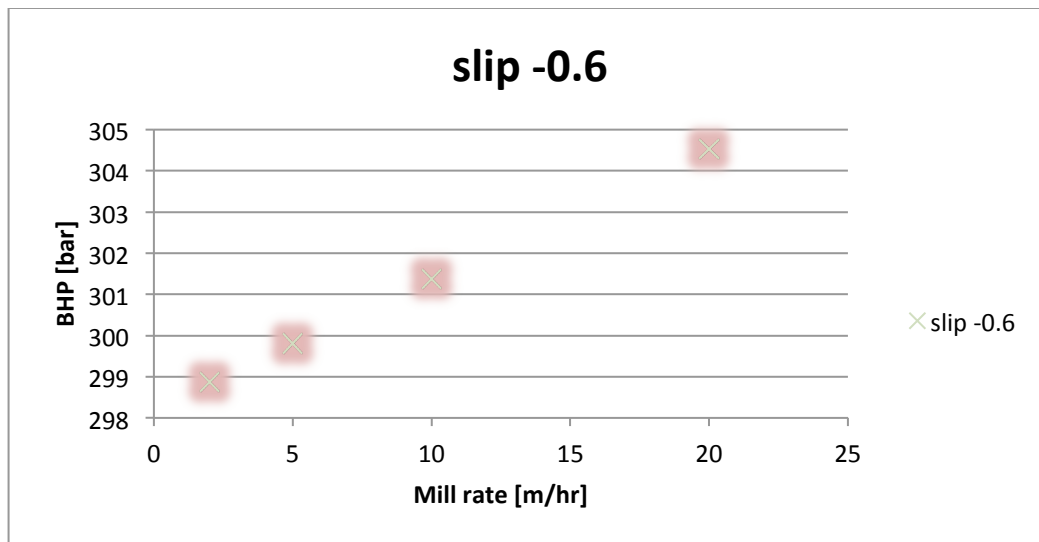
The next figure (Figure 79) below represents the BHP variations when the parameter  $S$  remains constant at  $-0,4$ , and the mill rate is increased. The trend is also the same here, the BHP increases with an increasing mill rate.



**Figure 79:** This figure illustrates how the bottom hole pressure varies when the mill rate is adjusted. In this particular case the parameter  $S = -0.4$ . The BHP reaches its maximum at 301,14 bar and with a mill rate of 20m/hr.

## 9.4 Slip=-0, 6

The next figure (*Figure 80*) below represents the BHP variations when the parameter S remains constant at -0,6, and the mill rate is increased. The trend is also the same here, the BHP increases with an increasing mill rate.

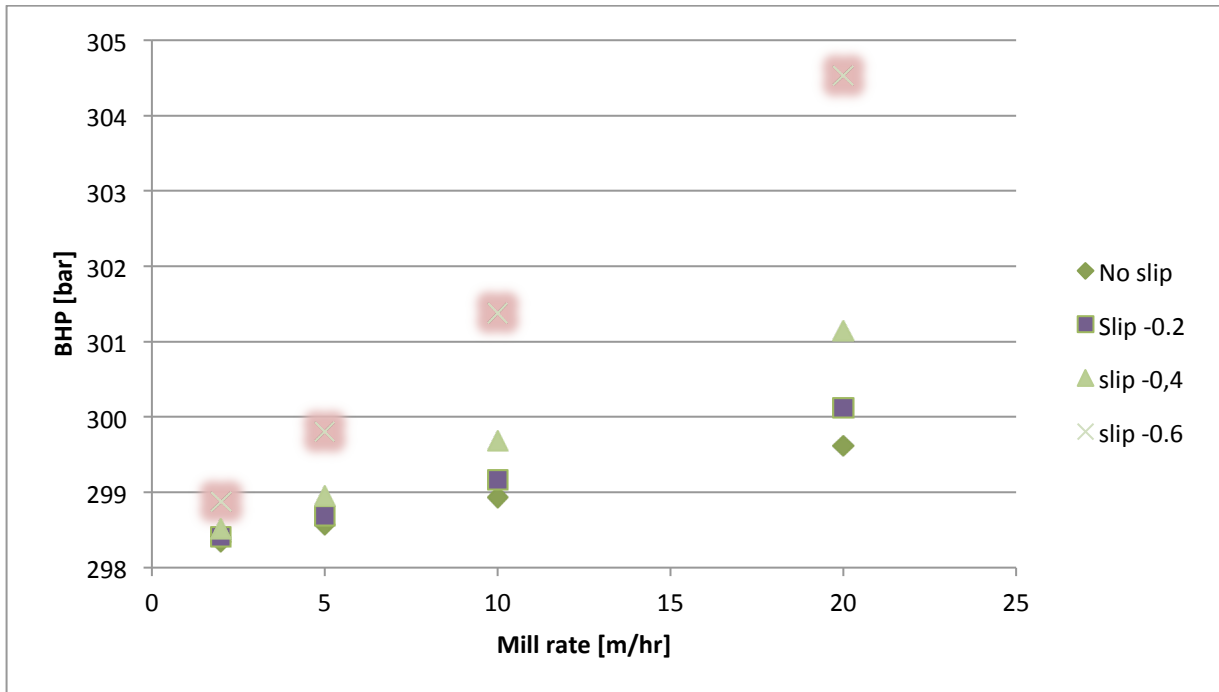


**Figure 80:** This figure illustrates how the bottom hole pressure varies when the mill rate is adjusted. In this particular case the parameter  $S = -0.6$ . The BHP reaches its maximum at 304,53 bar and with a mill rate of 20m/hr.

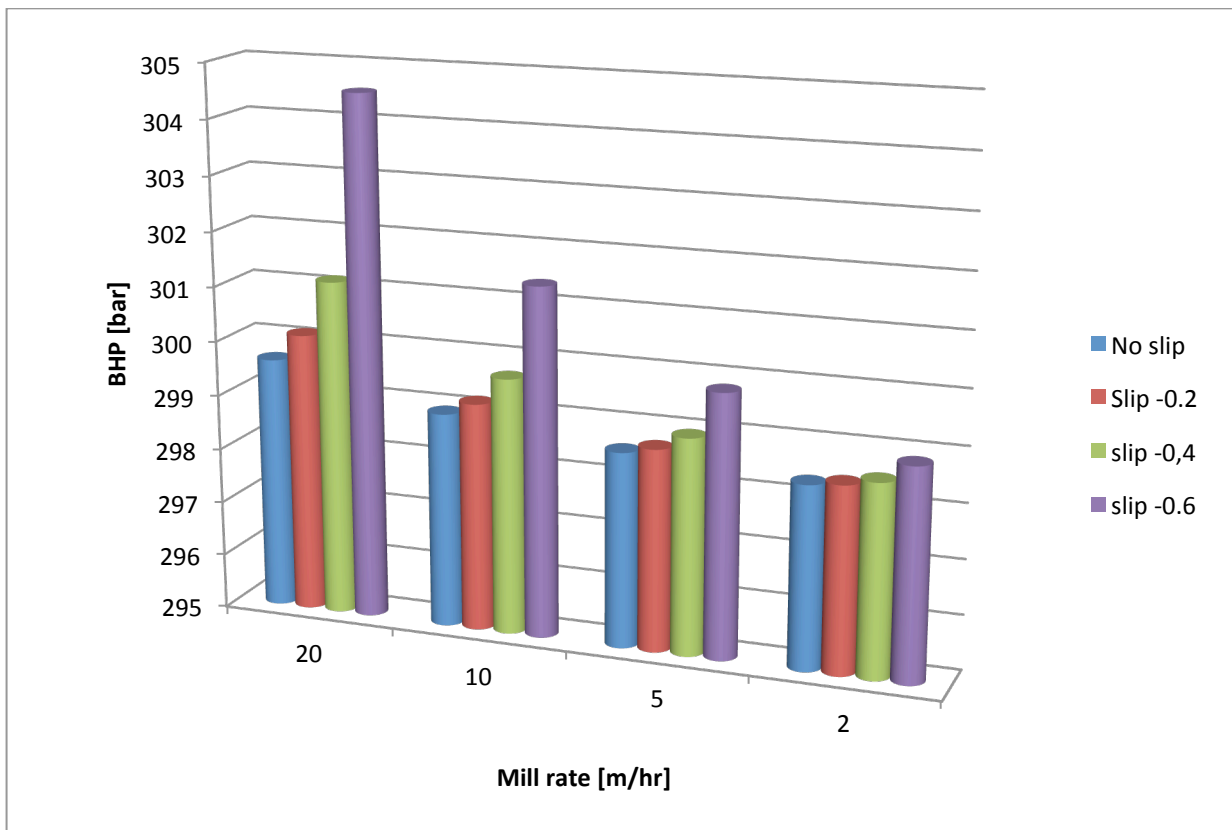
## 9.5 Comparing results

Both the next figures below (*Figure 81 and Figure 82*) illustrate the same thing. These two figures are made by combining the figures above (*Figure 74, Figure 75, Figure 76, and Figure 77*).

The purpose with this is to easier compare them with each other. By looking at the figures one can easily observe that the BHP is at the highest level when the mill rate is at maximum (in this case 20m/hr) and when the parameter  $S = -0.6$ . When the mill rate is reduced to respectively 10m/hr, 5m/hr and 2m/hr one observe the same thing; the BHP is highest when the parameter  $S$  is at its minimum. By looking at the numbers one observe that the BHP varies from 304,53bar (with the parameter  $S = -0.6$  and mill rate of 20m/hr) to 298,35 bar (with  $S=0$  and a mill rate of 2m/hr). The more negative value for  $S$ , will lead to more concentration of swarf in the well and this will be reflected in an increase in hydrostatic pressure.



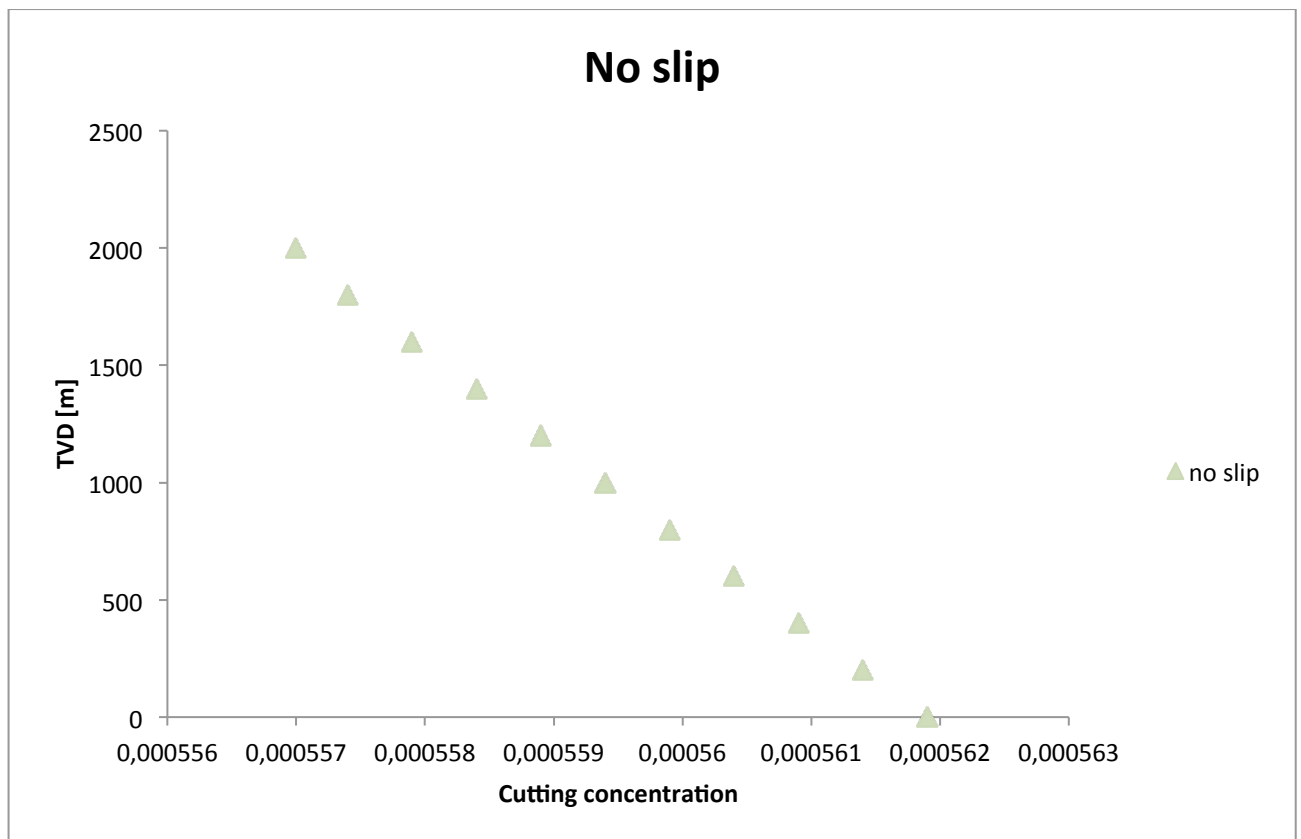
**Figure 81:** This figure illustrates how the BHP increases as the mill rate is increasing and the slip ratio is decreasing. The BHP is at the lowest rate when there is no slip, and at the lowest mill rate 2m/hr.



**Figure 82:** This figure illustrates the same as the Figure 81 above, but the data is represented in another way.

## 9.6 Cutting concentration varies with depth when no slip

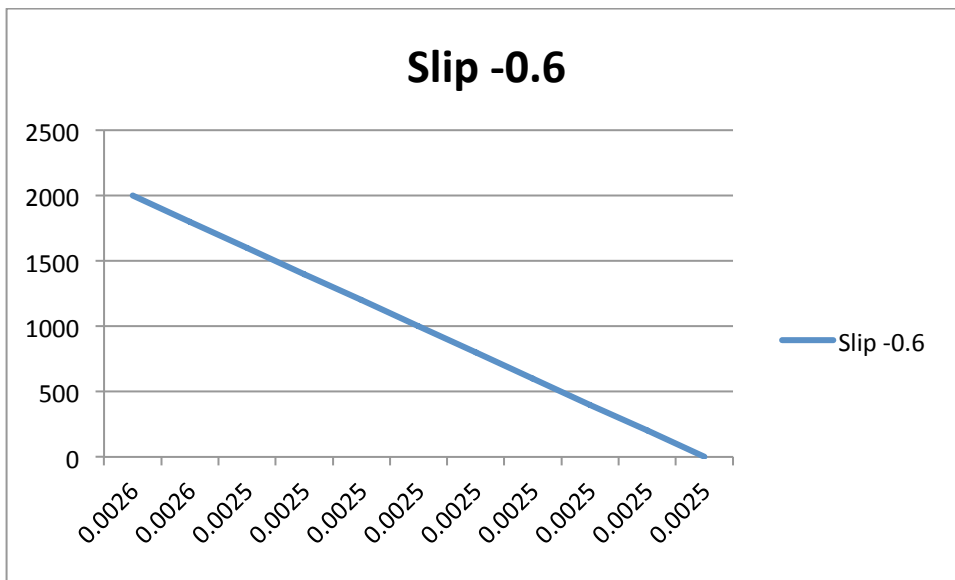
For the next simulations the mill rate was set to 10m/hr, and the slip ratio was set to 0. The purpose here was to see how the cutting concentration varies with the TVD (true vertical depth). From *Figure 83* below it is possible to observe that the cutting concentration is quite low and doesn't vary much with TVD since steel is an incompressible fluid, and the fluid is not a very compressible fluid.



**Figure 83:** This figure illustrates the cutting concentration vs the TVD. When the slip ratio is zero one can easily observe that the cutting concentration increases with increasing depth.

## 9.7 Cutting concentration varies with depth when slip ratio=-0.6

For the next simulations the mill rate was set to 10m/hr, and the slip ratio was set to -0.6. The purpose here was to see how the cutting concentration varies with the TVD (true vertical depth). From the Figure 84 below it is possible to see that the cutting concentration remains almost constant with TVD. By comparing the two figures (*Figure 80 and Figure 81*) one observe that the cuttings concentration is increasing when the parameter S=-0.6. This it was lead to an increase in BHP when the parameter S becomes more and more negative value.



**Figure 84:** This figure illustrates the cutting concentration vs the TVD. When the slip ratio is -0,6 one observe that the cutting concentration remains almost constant, but at a higher level than in the previous figure (Figure 83).

## 9.8 Bottom hole pressure variations

During the modelling part of this thesis, the main objective was to see the trends on the ECD during milling operations.

As the table below (Table 13) illustrates the BHP varies from 304,53bar (with a slip ratio of -0.6 and mill rate of 20m/hr) to 298,35 bar (with no slip and a mill rate of 2m/hr).

This change in BHP is not significant. This may indicate that there are other factors that are more limited factors for milling operations than the variations in BHP. One suggestion may be that pack off situations is more critical than the variations in BHP.

**Table 13: BHP as mill rate and slip ratio is adjusted**

| BHP[bar] | Mill rate [m/hr], slip ratio |
|----------|------------------------------|
| 298,35   | 2, no slip                   |
| 298,41   | 2, -0,2                      |
| 298,52   | 2, -0,4                      |
| 298,57   | 5, no slip                   |
| 298,69   | 5, -0.2                      |
| 298,87   | 2,-0.6                       |
| 298,93   | 10, no slip                  |
| 298,95   | 5, -0.4                      |
| 299,17   | 10, -0.2                     |
| 299,62   | 20, no slip                  |
| 299,68   | 10, -0.4                     |
| 299,81   | 5, -0.6                      |
| 300,12   | 20, -0.2                     |
| 301,14   | 20, -0.4                     |
| 301,38   | 10, -0.6                     |
| 304,53   | 20, -0.6                     |

**Table 13:** Illustrates the BHP variations from smallest value, to highest value.

The model used in this thesis has potential for improvements, which is identified and listed below.

- **Search the literature for more realistic models**  
For the modelling part, one should search the literature for more realistic models. These simulations have their basis in a modified Matlab code for two phase flow where the parameter S and the mill rate are adjusted.
- **New software solution:** Siddhartha Lunkad [48] mentioned that they used an alternative software solution called AnsysFluent. At IFT Dehli Institute of Technology they had access to this. For further studies related to this, it could be an idea to try to model milling impact on ECD by adapting AnsysFluent or similar models.
- **Friction pressure loss:** This model is made with basis on a Newtonian fluid, and the swarf viscosity is neglected. Non-Newtonian pressure loss models should be considered.
- **Experiments can be performed** [48] to support modelling and to visualize the transport mechanism of swarf. This could be performed by dropping swarf down in a stagnant fluid, to measure the time the swarf takes before it fall to the bottom. Another idea is to have a fluid pumped upwards in a chamber, and drop swarf inside, and to observe whether the swarf particles fall upwards or downwards, or if they are hold in suspension.

## 10. DISCUSSION & CONCLUSION

It was mentioned in the introduction of this thesis, objectives of this master thesis was to:

- Look further into milling operations during plug and abandonment, together with its technology improvements, and alternative technology.
- Try to simulate the ECD impacts during a milling operation.
- Comparing revision 3 and revision 4 of NORSOK D010, in order to observe the major differences when it comes to P&A.

In order to solve the objectives based upon the literature study and the results from the simulations, the discussion and conclusion of this thesis are summarized in the following sub categories:

- *Milling operations - Technology improvements and alternative technology*
- *Numerical part – Simulation on the ECD impacts during a milling operation*
- *NORSOK D010 – with its major changes in a P&A aspect*

### **Milling operations - technology improvements and alternative technology**

Through this thesis milling operations during plug and abandonment was further investigated with its technology improvements, and alternative technology. The conventional way for performing P&A operations is by section milling as mentioned in the introduction.

Further in this thesis the challenges with section milling were highlighted. In some cases there are no other alternatives than performing milling operations.

In the paper by Eamonn Scanlon et al. it was shown that milling operations could be improved, one solution to this was by improving equipment and cutters used in the operation. In this paper new cutter technology and down hole optimization sub is presented, and by utilizing this they were able to improve some of the negative views of section milling. They were thereby able to schedule the operation in agreement to time frame, and thereby save money. Due to the real time data transfer from the BHA it was easier to make the right decision during the operation. The overall uncertainty with the operation was reduced after introducing these two new technology improvements [4].

Another option for improving milling operation was presented by Baker Hughes [34]. Baker Hughes had a field case where they were challenged to section mill 165 ft ≈50,3 meters of production casing by using one run [34]. For this they utilized the P3 carbide cutters. For well W-07 they were able to achieve huge cost savings by changing the knives from old METAL MUNCHER™ to the new P3 cutters [34].

It was mentioned that swarf handling at topside can be eliminated by utilizing the SwarfPak™ from WestGroup AS [32].

In this thesis the SENTIO service was presented, which may be used in order to optimize the milling performance.

PWC technology has been introduced in this thesis as an alternative technology to milling operations. In this thesis the advantages with utilizing PWC technology is considered for both economically but also for HSE and disposal issues. Maybe there will be more alternative technologies to milling in the future.

### **Numerical part – Simulation on the ECD impacts during a milling operation**

For the numerical part the object was to see if it was possible to simulate the ECD impacts during a milling operation.

During a milling operation it is reasonable to assume that the BHP should increase. From the results it was observed that the BHP is at the highest level when the mill rate is at maximum (in this case 20m/hour) and when the parameter  $S = -0.6$ . When the parameter  $S$  decreases, the swarf flow will also decrease compared to the liquid.

The trend from the simulations was that as the parameter  $S$  became more negative in value and the mill rate was increased, it was observed that the BHP increased also, but the variations were not significant. This may indicate that there are other factors that are more limited factors for milling operations than the variations in BHP.

As the parameter  $S$  becomes more negative it was observed an increase in swarf concentration in the well, but this was not significant. An increase in swarf concentration causes a higher bottom hole pressure that corresponds with the numerical results.

This may indicate that there are other factors that are more limited factors for milling operations than the variations in BHP. Maybe pack off is a more limited factor for this type of well, since small variations in BHP can be seen from this model.

### **NORSOK D010 – with its major changes in a P&A aspect**

After comparing the previous revision of NORSOK D010 (rev 3) by the newest revision of NORSOK D010 (rev 4) it was observed the following:

In the newest revision of NORSOK D010 there have become major changes within the P&A area.

The well barrier acceptance criteria for plug and abandonment have been revised. It is now possible to find more WBEAC tables in chapter 15 in NORSOK D010 such as table 52, table 55 and table 56.

The way of performing section milling is extended and the information is explained in details by figure and charts. The workflow for performing alternative methods such as PWC technology is also presented in the new revision of NORSOK D010. The definition of temporary abandonment period has become more precise and is now stated as a maximum abandonment period of three years [18]. More examples of well barrier schematics have been included in the new revision.



## 11. APPENDIX A – MATLAB CODES

### 11.1 Matlab Code from 2: Itsolver

```
function [pbot,error] = itsolver(nopoints,boxlength,welldepth,gasrate,liquidrate)
```

```
% The numerical solver implemented here for solving the equation  $f(x)=0$   
% "wellpressure(pbot)= 0" is called the  
% Method of Halving the Interval (Bisection Method)
```

```
% You will not find exact match for  $f(x)=0$ . Maybe  $f(x) = 0.0001$ . By using  
% ftol we say that if  $f(x)<ftol$ , we are satisfied. Since our function  
% gives results in Pascal, we say that  $ftol = 1000$  Pa gives us a quite good  
% answer.
```

```
ftol = 1000;
```

```
% Specify the search interval". xguess is the pressure you guess for the  
% bottomhole. We here use hydrostic pressure of liquid in the well as our  
% initial guess. This is of course not nes. correct since we have gas and  
% friction effects in addition. But it might be a good starting point for  
% the iteration. (Remember x is in Pa). 1 Bar = 100 000 Pa.
```

```
% Set number of iterations to zero
```

```
noit = 0;
```

```
xguess = 1500*9.81*welldepth;  
xint = 40000000;  
x1 = xguess-xint/2.0;  
x2 = xguess+xint/2.0;
```

```
f1 = wellpressure(x1,gasrate,liquidrate,nopoints,boxlength);  
f2 = wellpressure(x2,gasrate,liquidrate,nopoints,boxlength);
```

```
% First include a check on whether  $f_1f_2<0$ . If not you must adjust your  
% initial search intervall. If error is 1 and zero pbot, then you must  
% adjust the intervall here.
```

```
if (f1*f2)>=0  
    error = 1;  
    pbot = 0;  
else
```

```
% start iterating, we are now on the track.
```

```
    x3 = (x1+x2)/2.0;  
    f3 = wellpressure(x3,gasrate,liquidrate,nopoints,boxlength);
```

```
    while (f3>ftol | f3 < -ftol)  
        noit = noit +1 ;
```

```

if (f3*f1) < 0
    x2 = x3;
else
    x1 = x3;
end

x3 = (x1+x2)/2.0;
f3 = wellpressure(x3, gasrate, liquidrate, nopoints, boxlength);
f1 = wellpressure(x1, gasrate, liquidrate, nopoints, boxlength);

end
error = 0;
pbot = x3
noit
end

```

## 11.2 Matlab code from 3, Wellpressure

```
function f = wellpressure(pbotguess, gasrate, liquidrate, nopoints, boxlength)
```

```

% NB, At first stage we assume that our outlet pressure is 1 Bar (atm
% pressure). This is the physical boundary condition that we have to ensure
% that our model reaches. If a choke is present. The surface pressure will
% be different. It means that if the choke pressure is 100 000 Pa then the variable below should be
% set to this. You change it here:

```

```
prealsurface = 100000;
```

```

% We now start by the deepest box with the pressure we assume: pbotguess and
% for each box, we calculate the pressure and flowrates. In the end, we end up with some surface
% rates and a surface outlet pressure. The calculated outlet surface
% pressure should equal the physical outlet condition (now 100 000 Pa). We
% can therefore define our wellpressure(pbot)=pcalcsurface-prealsurface.
% The function will be zero if the correct bottomhole pressure is found.

```

```

% Set outer/inner diameter of annulus. Define effective flowarea. Assume a
% 13 3/8 casing (ID 12.347") and a 5 " drillpipe.

```

```
do = 0.3136;
di = 0.127;
```

```
flowarea = 3.14/4*(do*do-di*di);
```

```
% Specify viscosities [Pa s]. In real life they depend on pressure and temp
```

```
viscl = 0.01;
viscg = 0.01; % Assume viscosity of steel is the same as mud (of course wrong)
% May not use this value

```

```
% Define slippage parameters. k = 1.0, s = 0 corresponds to no slip.
```

```
% We skal let be negitve (-0.2,-0.4,-0.6) and compare results
```

```
k = 1.0;
```

```
s = -0.6;
```

```
% gas gravity
```

```
g = 9.81;
```

```
% The mass rate is the same at surface/atmosphere and at bottomhole since we have steady state. This is later  
% used to find the rates at downhole conditions.
```

```
liqmassratesurf = liquidrate*roliq(100000.0);
```

```
liqmassratebhp = liqmassratesurf;
```

```
gasmassratesurf = gasrate*rogas(100000.0);
```

```
gasmassratebhp = gasmassratesurf;
```

```
% Now we loop from the bottom to surface and calculate accross all the  
% segments until we reach the outlet.
```

```
% Define the variables needed. Initialise them first for comp efficiency.
```

```
% vl - liquid vel, vg -gas velocity,
```

```
% vgs,vls are superficial velocities.
```

```
% eg-el - phase volume frac gas and gas
```

```
% p - pressure., rhol liquid density, rhog gas density
```

```
vl = zeros(nopoints,1);
```

```
vg = zeros(nopoints,1);
```

```
vls = zeros(nopoints,1);
```

```
vgs = zeros(nopoints,1);
```

```
eg = zeros(nopoints,1);
```

```
el = zeros(nopoints,1);
```

```
p = zeros(nopoints,1);
```

```
fricgrad = zeros(nopoints-1,1);
```

```
hydgrad = zeros(nopoints-1,1);
```

```
% Before we loop, we define all variables at the inlet of the first  
% segment(at bottom). As starting point we use the fact that we know the mass  
% rate of the different phases (same as on top of the well)
```

```
% First find the rates in m3/s (downhole)
```

```
liquidratebhp = liqmassratebhp /roliq(pbotguess);
```

```
gasratebhp = gasmassratebhp/rogas(pbotguess);
```

```

% Find the superficial velocities
vls(1) = liquidratebhp/flowarea;
vgs(1) = gasratebhp/flowarea;

% Find Phase velocities

vg(1) = k*(vls(1)+vgs(1))+s;
eg(1) = vgs(1)/vg(1);
el(1) = 1-eg(1);
vl(1) = vls(1)/el(1);

% Set pressure equal to guessed pressure
p(1) = pbotguess;

% Now we loop across the segments.

sumfric = 0;
sumhyd = 0;

for i =1:nopoints-1

% use the inlet values for each seg. to calculate hydrostatic
% and friction pressure across each segment.
hydgrad(i) = (roliq(p(i))*el(i)+rogas(p(i))*eg(i))*g;
% hydgrad(i) = roliq(p(i))*g;
fricgrad(i) = dpfric(vl(i),vg(i),el(i),eg(i),p(i),do,di,viscl,viscg);
p(i+1)=p(i)-hydgrad(i)*boxlength-fricgrad(i)*boxlength;
vls(i+1)=vls(i)*roliq(p(i))/roliq(p(i+1));
vgs(i+1)=vgs(i)*rogas(p(i))/rogas(p(i+1));

vg(i+1) = k*(vls(i+1)+vgs(i+1))+s;
eg(i+1) = vgs(i+1)/vg(i+1);
el(i+1) = 1-eg(i+1);
vl(i+1) = vls(i+1)/el(i+1);

sumfric = sumfric+fricgrad(i)*boxlength;
sumhyd = sumhyd+hydgrad(i)*boxlength;
end

pout = p(nopoints);
f = pout-prealsurface;

% Nedenfor skriver vi ut variablene til skjerm

sumfric
sumhyd
vl
vg % Swarf velocity
eg % Swarf concentration

% eg

```

```

% liqvel = liquidratebhp/flowarea;

% fricgrad = dpfric(liqvel,pbotguess,do,di,viscl,viscg);

% pbotguess

% pout = pbotguess - 1000.0*9.81*roliq(pbotguess)-fricgrad*1000;

% f = pout-prealsurface;

```

## 11.3 Matlab code from 3.1 Roliq

```

function rhol = roliq(pressure)

% A simple liquid dens model wich takes into pressure varations vs. density
% is implemented. P0 is the atmosperic pressure. D0 is density at surface
% conditions. Note temperature has been neglected.

po = 100000;
do = 1500.0; % Corresponds to a 1.5 sg mud.

rhol = do + (pressure-po)/(1500*1500);

```

## 11.4 Matlab code from 3.2 Roswarf

```

function rhog = rogas(pressure)

% Density of swarf.
rhog = 7850;

```

## 11.5 Matlab code from 3.3 Dpfric

```

unction friclossgrad = dpfric(vl,vg,el,eg,pressure,do,di,viscl,viscg)

% Works for two phase flow. The one phase flow model is used but mixture
% values are introduced.

rhol = roliq(pressure);
rhog = rogas(pressure);
romix = rhol*el+rhog*eg;
viscmix = viscl*el+viscg*eg;

```

```

vmix = vg*eg+vl*el;

% Calculate mix reynolds number
re = romix*vmix*(do-di)/viscmix

% Calculate friction factor. For re > 3000, the flow is turbulent.
% For re < 2000, the flow is laminar. Interpolate in between.

if (re >= 3000)
    fricfactor = 0.052*re^(-0.19);
elseif ( (re<3000) & (re > 2000))
    f1 = 24/re;
    f2 = 0.052*re^(-0.19);
    xint = (re-2000)/1000.0;
    fricfactor = (1.0-xint)*f1+xint*f2;
else
    fricfactor = 24/re;
end

% fricfactor

% calculate friction loss gradient (Pa/m)

friclossgrad = 2*fricfactor*romix*vmix*abs(vmix)/(do-di);
% vl
% do
% di
% re

```

## 11.6 Matlab code from 1.Main (hovedprogram)

```

% A program developed for calculating well pressures in a
% well where we have both liquid and gas flow. The model assumes that we
% have steady state conditions (constant flowrates at surface) and no time
% variations. The model is based on calculating the correct bottomhole
% pressure for certain gas and liquid flow rates and takes into account
% both the hydrostatic pressure and frictional pressures.

% All calculations are done using SI units (Pa for pressure),m3/s for
% rates.

clear;

% Here we specify the vertical depth of the well and
% and the number of boxes we want in our calculations.
% Based on this, the boxlength is found and used in the calculations.

welldepth = 2000;

```

```
nobox = 10;  
nopoints = nobox+1;  
boxlength = welldepth/nobox;
```

% nopoints is an index array keeping track of the end point of the boxes.

% Other initialisations like fluid properties and viscosities etc are done  
% deeper down in the code structure. Please note that you have the change  
% values there if you want to do changes in these routines. This is also  
% true for the inner/outer diameter of the annulus.

% Now we will call a function that calculates the pressure along the well  
% for a given liquid flowrate and a gas rate. We call this function  
% solver because it is the zero point solver (e.g. regula falsi that  
% iterates until it finds the correct pressure. This solver routine again  
% calls upon a function "f(Pbottom)" called wellpressure. The routine  
% solver actually finds the correct bottomhole pressure that makes the  
% function wellpressure become zero "f(Pbottom) = 0". Then we have found the correct  
% pressure profile.

% INPUT variables  
% Rates are given in m3/s. We assume only liquid flow first.  
% Liquid rate is 3000 l/min. Convert to m3/s  
% Gas rate is in m3/min. Convert to m3/s

```
liquidrate = 3000/1000/60;
```

```
steelarea = 3.14/4*(0.2445^2-0.2168^2)
```

```
millrate = 20 % m/hour
```

```
steelrate = steelarea*millrate/3600; % m3/s
```

```
[pbot,error] = itsolver(nopoints,boxlength,welldepth,steelrate,liquidrate);
```

## 12. APPENDIX B - RESULTS IN MATLAB

### 12.1 Results in Matlab when adjusting mill rates, slip remains constant at -0.6

| <b>Slip:-0.6</b>  |               |        |  |        |            |  |            |            |
|-------------------|---------------|--------|--|--------|------------|--|------------|------------|
| <b>Mill rate:</b> | <b>20m/hr</b> |        |  |        |            |  |            |            |
| vl =              |               | vg =   |  | eg =   | sumfric =  |  | sumhyd =   | pbot =     |
| 0.7718            |               | 0.1687 |  | 0.0051 | 1.5268e+05 |  | 3.0201e+07 | 3.0453e+07 |
| 0.7724            |               | 0.1694 |  | 0.0051 |            |  |            |            |
| 0.7731            |               | 0.1701 |  | 0.0051 |            |  |            |            |
| 0.7738            |               | 0.1707 |  | 0.0051 |            |  |            |            |
| 0.7745            |               | 0.1714 |  | 0.0050 |            |  |            |            |
| 0.7751            |               | 0.1721 |  | 0.0050 |            |  |            |            |
| 0.7758            |               | 0.1728 |  | 0.0050 |            |  |            |            |
| 0.7765            |               | 0.1735 |  | 0.0050 |            |  |            |            |
| 0.7772            |               | 0.1742 |  | 0.0050 |            |  |            |            |
| 0.7779            |               | 0.1749 |  | 0.0049 |            |  |            |            |
| 0.7785            |               | 0.1756 |  | 0.0049 |            |  |            |            |

| <b>Slip: -0.6</b> |               |        |        |  |            |  |            |            |
|-------------------|---------------|--------|--------|--|------------|--|------------|------------|
| <b>Mill rate:</b> | <b>10m/hr</b> |        |        |  |            |  |            |            |
| vl =              |               | vg =   | eg =   |  | sumfric =  |  | sumhyd =   | pbot =     |
| 0.7699            |               | 0.1683 | 0.0026 |  | 1.5125e+05 |  | 2.9887e+07 | 3.0138e+07 |
| 0.7705            |               | 0.1690 | 0.0026 |  |            |  |            |            |
| 0.7712            |               | 0.1697 | 0.0025 |  |            |  |            |            |
| 0.7719            |               | 0.1704 | 0.0025 |  |            |  |            |            |
| 0.7726            |               | 0.1710 | 0.0025 |  |            |  |            |            |
| 0.7732            |               | 0.1717 | 0.0025 |  |            |  |            |            |
| 0.7739            |               | 0.1724 | 0.0025 |  |            |  |            |            |
| 0.7746            |               | 0.1731 | 0.0025 |  |            |  |            |            |
| 0.7753            |               | 0.1738 | 0.0025 |  |            |  |            |            |
| 0.7760            |               | 0.1745 | 0.0025 |  |            |  |            |            |
| 0.7766            |               | 0.1752 | 0.0025 |  |            |  |            |            |



| <b>Slip=-0.6</b>  |              |        |        |  |            |            |  |            |
|-------------------|--------------|--------|--------|--|------------|------------|--|------------|
| <b>Mill rate:</b> | <b>5m/hr</b> |        |        |  |            |            |  |            |
| vl =              |              | vg =   | eg =   |  | sumfric =  | sumhyd =   |  | pbot =     |
| 0.7689            |              | 0.1681 | 0.0013 |  | 1.5054e+05 | 2.9730e+07 |  | 2.9981e+07 |
| 0.7696            |              | 0.1688 | 0.0013 |  |            |            |  |            |
| 0.7703            |              | 0.1695 | 0.0013 |  |            |            |  |            |
| 0.7709            |              | 0.1702 | 0.0013 |  |            |            |  |            |
| 0.7716            |              | 0.1708 | 0.0013 |  |            |            |  |            |
| 0.7723            |              | 0.1715 | 0.0013 |  |            |            |  |            |
| 0.7730            |              | 0.1722 | 0.0013 |  |            |            |  |            |
| 0.7736            |              | 0.1729 | 0.0012 |  |            |            |  |            |
| 0.7743            |              | 0.1736 | 0.0012 |  |            |            |  |            |
| 0.7750            |              | 0.1743 | 0.0012 |  |            |            |  |            |
| 0.7757            |              | 0.1749 | 0.0012 |  |            |            |  |            |

| <b>Slip = -0,6</b> |              |           |            |            |            |  |
|--------------------|--------------|-----------|------------|------------|------------|--|
| <b>Mill rate:</b>  | <b>2m/hr</b> |           |            |            |            |  |
| vl =               | vg =         | eg =      | sumfric =  | sumhyd =   | pbot =     |  |
| 0.7683             | 0.1680       | 1.0e-03 * | 1.5011e+05 | 2.9635e+07 | 2.9887e+07 |  |
| 0.7690             | 0.1687       |           |            |            |            |  |
| 0.7697             | 0.1694       | 0.5139    |            |            |            |  |
| 0.7704             | 0.1701       | 0.5118    |            |            |            |  |
| 0.7710             | 0.1707       | 0.5098    |            |            |            |  |
| 0.7717             | 0.1714       | 0.5077    |            |            |            |  |
| 0.7724             | 0.1721       | 0.5057    |            |            |            |  |
| 0.7731             | 0.1728       | 0.5037    |            |            |            |  |
| 0.7737             | 0.1734       | 0.5017    |            |            |            |  |
| 0.7744             | 0.1741       | 0.4998    |            |            |            |  |
| 0.7751             | 0.1748       | 0.4978    |            |            |            |  |
|                    |              | 0.4959    |            |            |            |  |
|                    |              | 0.4939    |            |            |            |  |

## 12.2 Results in Matlab when adjusting mill rates, slip remains constant at -0.4

| <b>Slip = -0,4</b> |               |        |            |            |            |
|--------------------|---------------|--------|------------|------------|------------|
| <b>Mill rate:</b>  |               |        |            |            |            |
|                    | <b>20m/hr</b> |        |            |            |            |
| vl =               | vg =          | eg =   | sumfric =  | sumhyd =   | pbot =     |
| 0.7697             | 0.3688        | 0.0023 | 1.5130e+05 | 2.9863e+07 | 3.0114e+07 |
| 0.7704             | 0.3694        | 0.0023 |            |            |            |
| 0.7711             | 0.3701        | 0.0023 |            |            |            |
| 0.7717             | 0.3708        | 0.0023 |            |            |            |
| 0.7724             | 0.3715        | 0.0023 |            |            |            |
| 0.7731             | 0.3722        | 0.0023 |            |            |            |
| 0.7738             | 0.3728        | 0.0023 |            |            |            |
| 0.7745             | 0.3735        | 0.0023 |            |            |            |
| 0.7751             | 0.3742        | 0.0023 |            |            |            |
| 0.7758             | 0.3749        | 0.0023 |            |            |            |
| 0.7765             | 0.3756        | 0.0023 |            |            |            |

| <b>Slip = -0,4</b> |               |        |            |            |            |
|--------------------|---------------|--------|------------|------------|------------|
| <b>Mill rate:</b>  |               |        |            |            |            |
|                    | <b>10m/hr</b> |        |            |            |            |
| vl =               | vg =          | eg =   | sumfric =  | sumhyd =   | pbot =     |
| 0.7688             | 0.3684        | 0.0012 | 1.5056e+05 | 2.9718e+07 | 2.9968e+07 |
| 0.7695             | 0.3690        | 0.0012 |            |            |            |
| 0.7702             | 0.3697        | 0.0012 |            |            |            |
| 0.7709             | 0.3704        | 0.0012 |            |            |            |
| 0.7715             | 0.3711        | 0.0012 |            |            |            |
| 0.7722             | 0.3717        | 0.0012 |            |            |            |
| 0.7729             | 0.3724        | 0.0012 |            |            |            |
| 0.7736             | 0.3731        | 0.0012 |            |            |            |
| 0.7742             | 0.3738        | 0.0012 |            |            |            |
| 0.7749             | 0.3745        | 0.0012 |            |            |            |
| 0.7756             | 0.3752        | 0.0012 |            |            |            |

| <b>Slip= -0.4</b> |        |           |            |            |            |
|-------------------|--------|-----------|------------|------------|------------|
| <b>Mill rate:</b> |        |           |            |            |            |
| <b>5m/hr</b>      |        |           |            |            |            |
| vl =              | vg =   | eg =      | sumfric =  | sumhyd =   | pbot =     |
| 0.7684            | 0.3682 | 1.0e-03 * | 1.5019e+05 | 2.9645e+07 | 2.9895e+07 |
| 0.7691            | 0.3688 |           |            |            |            |
| 0.7697            | 0.3695 | 0.5863    |            |            |            |
| 0.7704            | 0.3702 | 0.5853    |            |            |            |
| 0.7711            | 0.3709 | 0.5842    |            |            |            |
| 0.7718            | 0.3715 | 0.5831    |            |            |            |
| 0.7724            | 0.3722 | 0.5821    |            |            |            |
| 0.7731            | 0.3729 | 0.5810    |            |            |            |
| 0.7738            | 0.3736 | 0.5799    |            |            |            |
| 0.7745            | 0.3743 | 0.5789    |            |            |            |
| 0.7752            | 0.3749 | 0.5778    |            |            |            |
|                   |        | 0.5768    |            |            |            |
|                   |        | 0.5757    |            |            |            |
|                   |        |           |            |            |            |

| <b>Slip= -0.4</b> |        |           |            |            |            |
|-------------------|--------|-----------|------------|------------|------------|
| <b>Mill rate:</b> |        |           |            |            |            |
| <b>2m/hr</b>      |        |           |            |            |            |
| vl =              | vg =   | eg =      | sumfric =  | sumhyd =   | pbot       |
| 0.7681            | 0.3680 | 1.0e-03 * | 1.4997e+05 | 2.9601e+07 | 2.9852e+07 |
| 0.7688            | 0.3687 |           |            |            |            |
| 0.7695            | 0.3694 | 0.2346    |            |            |            |
| 0.7702            | 0.3701 | 0.2342    |            |            |            |
| 0.7708            | 0.3707 | 0.2338    |            |            |            |
| 0.7715            | 0.3714 | 0.2333    |            |            |            |
| 0.7722            | 0.3721 | 0.2329    |            |            |            |
| 0.7729            | 0.3728 | 0.2325    |            |            |            |
| 0.7735            | 0.3734 | 0.2321    |            |            |            |
| 0.7742            | 0.3741 | 0.2316    |            |            |            |
| 0.7749            | 0.3748 | 0.2312    |            |            |            |
|                   |        | 0.2308    |            |            |            |
|                   |        | 0.2304    |            |            |            |

### 12.3 Results in Matlab when adjusting mill rates, slip remains constant at -0.2

| <b>Slip = -0.2</b> |        |        |            |            |            |
|--------------------|--------|--------|------------|------------|------------|
| <b>Mill rate:</b>  |        |        |            |            |            |
| <b>20m/hr</b>      |        |        |            |            |            |
| vl =               | vg =   | eg =   | sumfric =  | sumhyd =   | pbot       |
| 0.7691             | 0.5688 | 0.0015 | 1.5089e+05 | 2.9761e+07 | 3.0012e+07 |
| 0.7698             | 0.5695 | 0.0015 |            |            |            |
| 0.7704             | 0.5701 | 0.0015 |            |            |            |
| 0.7711             | 0.5708 | 0.0015 |            |            |            |
| 0.7718             | 0.5715 | 0.0015 |            |            |            |
| 0.7725             | 0.5722 | 0.0015 |            |            |            |
| 0.7732             | 0.5729 | 0.0015 |            |            |            |
| 0.7738             | 0.5735 | 0.0015 |            |            |            |
| 0.7745             | 0.5742 | 0.0015 |            |            |            |
| 0.7752             | 0.5749 | 0.0015 |            |            |            |
| 0.7759             | 0.5756 | 0.0015 |            |            |            |

| <b>Slip:-0.2</b>         |        |           |            |            |            |
|--------------------------|--------|-----------|------------|------------|------------|
| <b>Mill rate: 10m/hr</b> |        |           |            |            |            |
| vl =                     | vg =   | eg =      | sumfric =  | sumhyd =   | pbot =     |
| 0.7685                   | 0.5684 | 1.0e-03 * | 1.5036e+05 | 2.9667e+07 | 2.9917e+07 |
| 0.7692                   | 0.5690 |           |            |            |            |
| 0.7699                   | 0.5697 | 0.7596    |            |            |            |
| 0.7705                   | 0.5704 | 0.7587    |            |            |            |
| 0.7712                   | 0.5711 | 0.7578    |            |            |            |
| 0.7719                   | 0.5718 | 0.7569    |            |            |            |
| 0.7726                   | 0.5724 | 0.7560    |            |            |            |
| 0.7733                   | 0.5731 | 0.7551    |            |            |            |
| 0.7739                   | 0.5738 | 0.7542    |            |            |            |
| 0.7746                   | 0.5745 | 0.7533    |            |            |            |
| 0.7753                   | 0.5752 | 0.7524    |            |            |            |
|                          |        | 0.7515    |            |            |            |
|                          |        | 0.7506    |            |            |            |

| <b>Slip: -0.2</b>       |        |           |            |            |            |
|-------------------------|--------|-----------|------------|------------|------------|
| <b>Mill rate: 5m/hr</b> |        |           |            |            |            |
| vl =                    | vg =   | eg =      | sumfric =  | sumhyd =   | pbot =     |
| 0.7682                  | 0.5682 | 1.0e-03 * | 1.5009e+05 | 2.9620e+07 | 2.9869e+07 |
| 0.7689                  | 0.5688 |           |            |            |            |
| 0.7696                  | 0.5695 | 0.3799    |            |            |            |
| 0.7703                  | 0.5702 | 0.3795    |            |            |            |
| 0.7709                  | 0.5709 | 0.3790    |            |            |            |
| 0.7716                  | 0.5715 | 0.3786    |            |            |            |
| 0.7723                  | 0.5722 | 0.3781    |            |            |            |
| 0.7730                  | 0.5729 | 0.3777    |            |            |            |
| 0.7737                  | 0.5736 | 0.3772    |            |            |            |
| 0.7743                  | 0.5743 | 0.3768    |            |            |            |
| 0.7750                  | 0.5749 | 0.3763    |            |            |            |
|                         |        | 0.3759    |            |            |            |
|                         |        | 0.3755    |            |            |            |

|                   |              |           |            |            |            |
|-------------------|--------------|-----------|------------|------------|------------|
| <b>Slip:-0.2</b>  |              |           |            |            |            |
| <b>Mill rate:</b> | <b>2m/hr</b> |           |            |            |            |
| vl =              | vg =         | eg =      | sumfric =  | sumhyd =   | pbot =     |
| 0.7681            | 0.5680       | 1.0e-03 * | 1.4993e+05 | 2.9591e+07 | 2.9841e+07 |
| 0.7687            | 0.5687       |           |            |            |            |
| 0.7694            | 0.5694       | 0.1520    |            |            |            |
| 0.7701            | 0.5701       | 0.1518    |            |            |            |
| 0.7708            | 0.5707       | 0.1516    |            |            |            |
| 0.7714            | 0.5714       | 0.1515    |            |            |            |
| 0.7721            | 0.5721       | 0.1513    |            |            |            |
| 0.7728            | 0.5728       | 0.1511    |            |            |            |
| 0.7735            | 0.5734       | 0.1509    |            |            |            |
| 0.7742            | 0.5741       | 0.1507    |            |            |            |
| 0.7748            | 0.5748       | 0.1506    |            |            |            |
|                   |              | 0.1504    |            |            |            |
|                   |              | 0.1502    |            |            |            |

## 12.4 Results in Matlab when adjusting mill rates, slip remains constant at 0

| <b>Slip: 0</b>   |               |        |            |            |            |
|------------------|---------------|--------|------------|------------|------------|
| <b>Mill rate</b> | <b>20m/hr</b> |        |            |            |            |
| vl =             | vg =          | eg =   | sumfric =  | sumhyd =   | pbot =     |
| 0.7688           | 0.7688        | 0.0011 | 1.5069e+05 | 2.9712e+07 | 2.9962e+07 |
| 0.7695           | 0.7695        | 0.0011 |            |            |            |
| 0.7701           | 0.7701        | 0.0011 |            |            |            |
| 0.7708           | 0.7708        | 0.0011 |            |            |            |
| 0.7715           | 0.7715        | 0.0011 |            |            |            |
| 0.7722           | 0.7722        | 0.0011 |            |            |            |
| 0.7729           | 0.7729        | 0.0011 |            |            |            |
| 0.7735           | 0.7735        | 0.0011 |            |            |            |
| 0.7742           | 0.7742        | 0.0011 |            |            |            |
| 0.7749           | 0.7749        | 0.0011 |            |            |            |
| 0.7756           | 0.7756        | 0.0011 |            |            |            |

| <b>Slip:0</b>     |               |           |            |            |            |
|-------------------|---------------|-----------|------------|------------|------------|
| <b>Mill rate:</b> | <b>10m/hr</b> |           |            |            |            |
| vl =              | vg =          | eg =      | sumfric =  | sumhyd =   | pbot =     |
| 0.7684            | 0.7684        | 1.0e-03 * | 1.5026e+05 | 2.9642e+07 | 2.9893e+07 |
| 0.7690            | 0.7690        |           |            |            |            |
| 0.7697            | 0.7697        | 0.5619    |            |            |            |
| 0.7704            | 0.7704        | 0.5614    |            |            |            |
| 0.7711            | 0.7711        | 0.5609    |            |            |            |
| 0.7718            | 0.7718        | 0.5604    |            |            |            |
| 0.7724            | 0.7724        | 0.5599    |            |            |            |
| 0.7731            | 0.7731        | 0.5594    |            |            |            |
| 0.7738            | 0.7738        | 0.5589    |            |            |            |
| 0.7745            | 0.7745        | 0.5584    |            |            |            |
| 0.7752            | 0.7752        | 0.5579    |            |            |            |
|                   |               | 0.5574    |            |            |            |
|                   |               | 0.5570    |            |            |            |

| <b>Slip: 0</b>   |              |           |            |            |            |
|------------------|--------------|-----------|------------|------------|------------|
| <b>Mill rate</b> | <b>5m/hr</b> |           |            |            |            |
| vl =             | vg =         | eg =      | sumfric =  | sumhyd =   | pbot =     |
| 0.7682           | 0.7682       | 1.0e-03 * | 1.5004e+05 | 2.9607e+07 | 2.9857e+07 |
| 0.7688           | 0.7688       |           |            |            |            |
| 0.7695           | 0.7695       | 0.2810    |            |            |            |
| 0.7702           | 0.7702       | 0.2808    |            |            |            |
| 0.7709           | 0.7709       | 0.2805    |            |            |            |
| 0.7715           | 0.7715       | 0.2803    |            |            |            |
| 0.7722           | 0.7722       | 0.2800    |            |            |            |
| 0.7729           | 0.7729       | 0.2798    |            |            |            |
| 0.7736           | 0.7736       | 0.2795    |            |            |            |
| 0.7743           | 0.7743       | 0.2793    |            |            |            |
| 0.7749           | 0.7749       | 0.2790    |            |            |            |
|                  |              | 0.2788    |            |            |            |
|                  |              | 0.2786    |            |            |            |

| <b>Slip:0</b>    |              |           |            |            |            |
|------------------|--------------|-----------|------------|------------|------------|
| <b>Mill rate</b> | <b>2m/hr</b> |           |            |            |            |
| vl =             | vg =         | eg =      | sumfric =  | sumhyd =   | pbot       |
| 0.7682           | 0.7682       | 1.0e-03 * | 1.5004e+05 | 2.9607e+07 | 2.9835e+07 |
| 0.7688           | 0.7688       |           |            |            |            |
| 0.7695           | 0.7695       | 0.2810    |            |            |            |
| 0.7702           | 0.7702       | 0.2808    |            |            |            |
| 0.7709           | 0.7709       | 0.2805    |            |            |            |
| 0.7715           | 0.7715       | 0.2803    |            |            |            |
| 0.7722           | 0.7722       | 0.2800    |            |            |            |
| 0.7729           | 0.7729       | 0.2798    |            |            |            |
| 0.7736           | 0.7736       | 0.2795    |            |            |            |
| 0.7743           | 0.7743       | 0.2793    |            |            |            |
| 0.7749           | 0.7749       | 0.2790    |            |            |            |
|                  |              | 0.2788    |            |            |            |
|                  |              | 0.2786    |            |            |            |

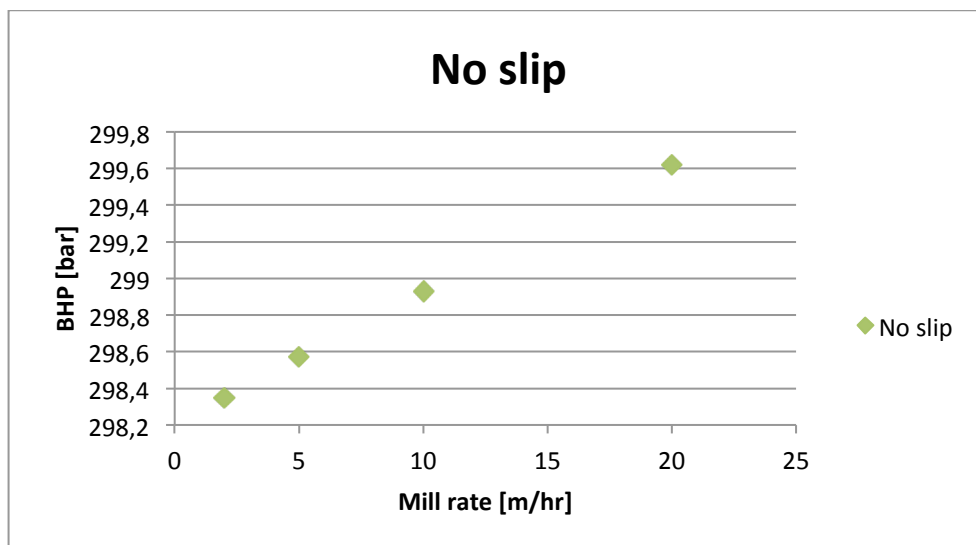


## 13. APPENDIX C – DATA FOR GRAPHS

### 13.1 Data for Graph 1: No slip

| BHP        | Mill rate | KONSTANT Slip = 0 | BHP [bar] |
|------------|-----------|-------------------|-----------|
| 2.9962e+07 | 20        |                   | 299.62    |
| 2.9893e+07 | 10        |                   | 298.93    |
| 2.9857e+07 | 5         |                   | 298.57    |
| 2.9835e+07 | 2         |                   | 298.35    |

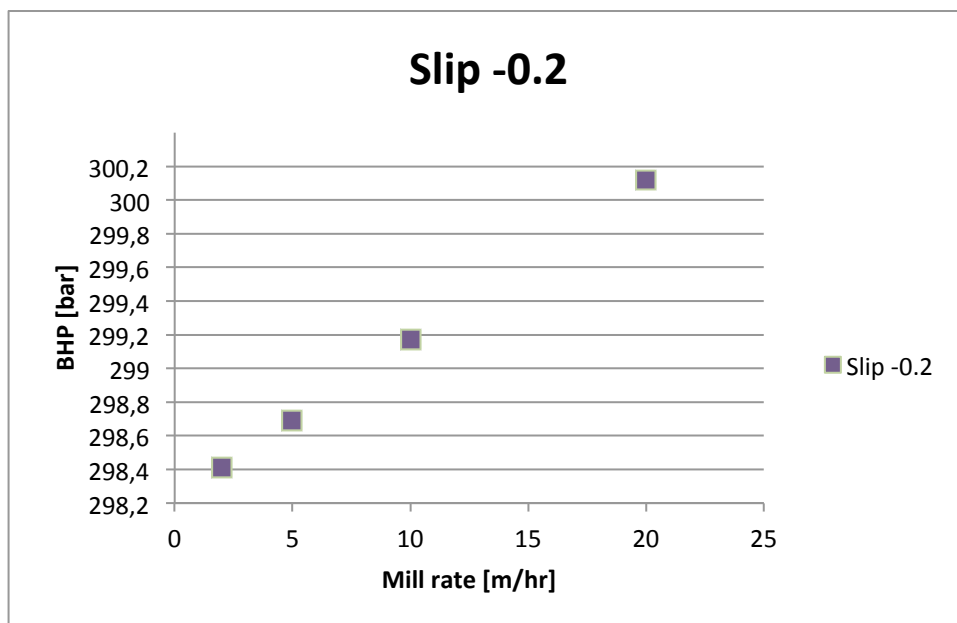
Graph 1: No slip:



## 13.2 Data for Graph 2: Slip= -0.2

| BHP        | Mill rate | KONSTANT<br>Slip = -0.2 | BHP [bar] |
|------------|-----------|-------------------------|-----------|
| 3.0012e+07 | 20        |                         | 300.12    |
| 2.9917e+07 | 10        |                         | 299.17    |
| 2.9869e+07 | 5         |                         | 298.69    |
| 2.9841e+07 | 2         |                         | 298.41    |

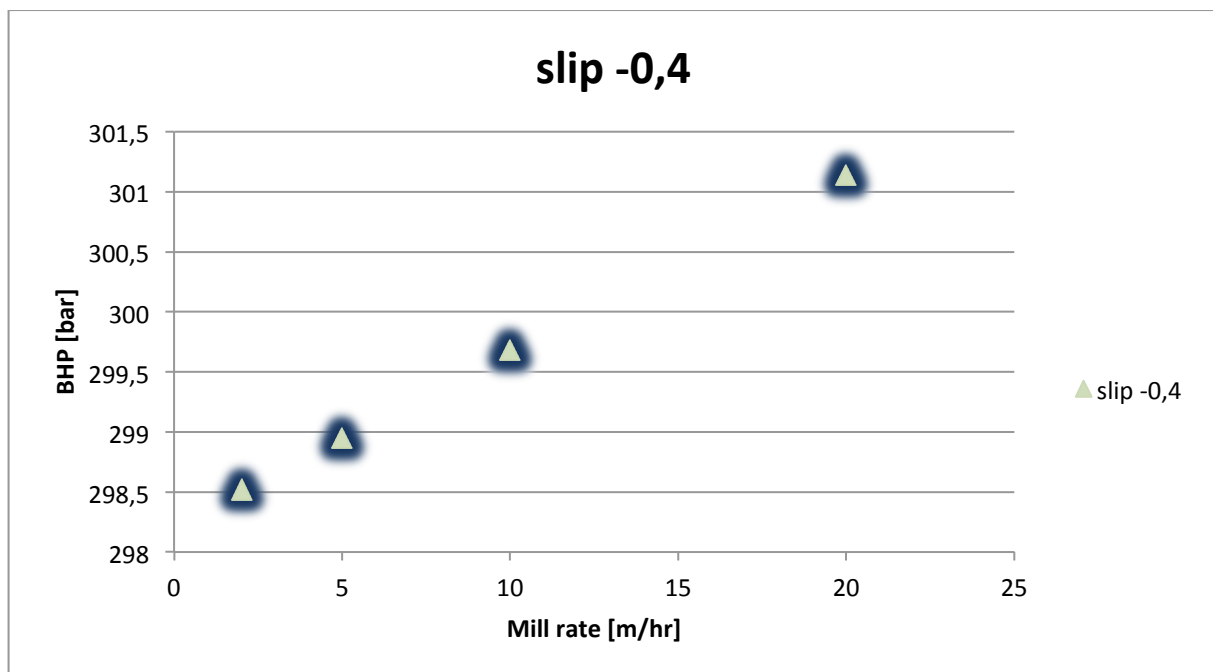
Graph 2: Slip=-0.2:



### 13.3 Data for Graph 3: Slip= -0.4

| KONSTANT   |           |             |  |
|------------|-----------|-------------|--|
| BHP        | Mill rate | Slip = -0.4 |  |
| 3.0114e+07 | 20        | 301,14      |  |
| 2.9968e+07 | 10        | 299,68      |  |
| 2.9895e+07 | 5         | 298,95      |  |
| 2.9852e+07 | 2         | 298,52      |  |

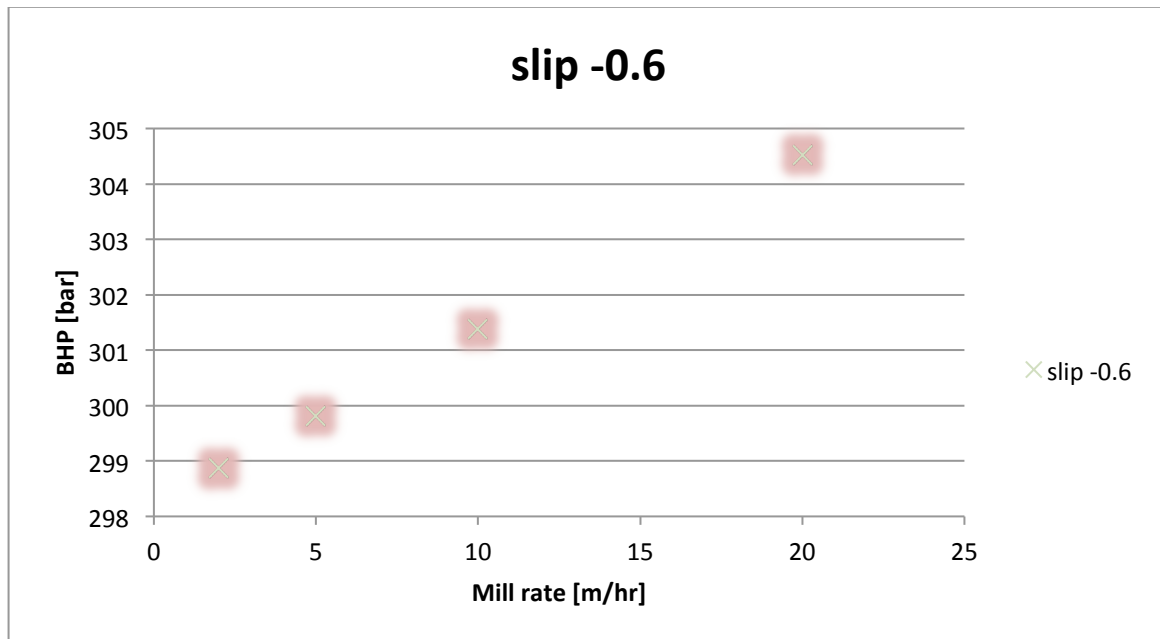
Graph 3: Slip= -0.4



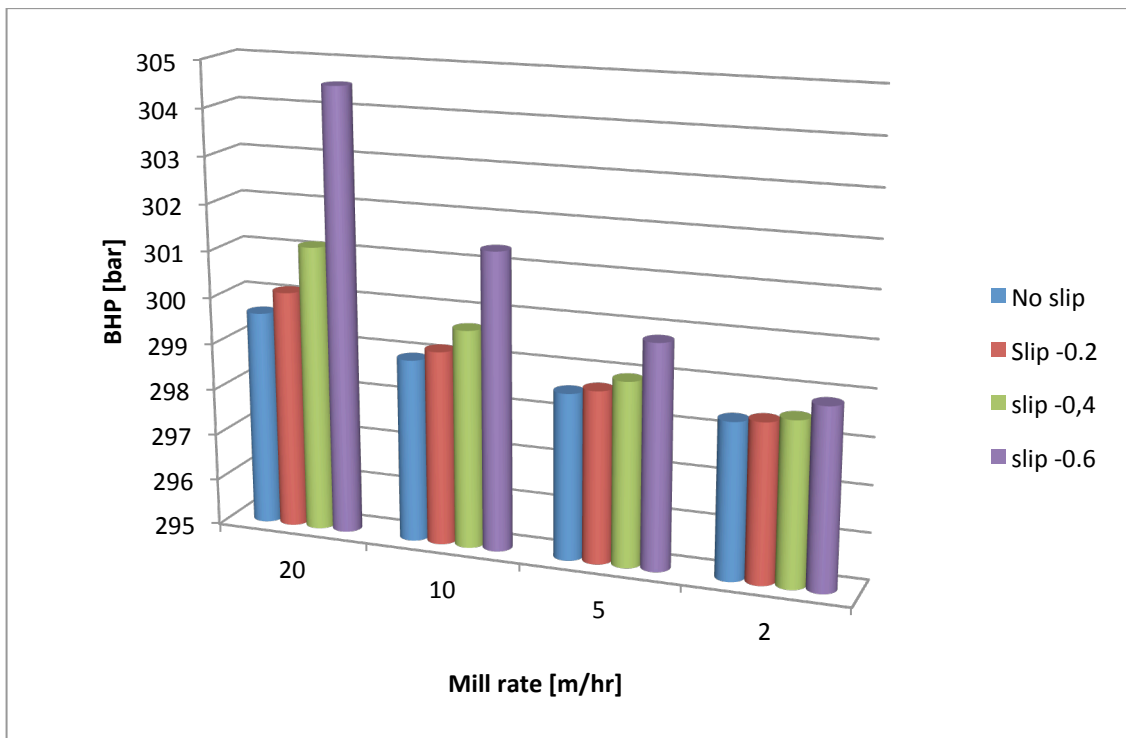
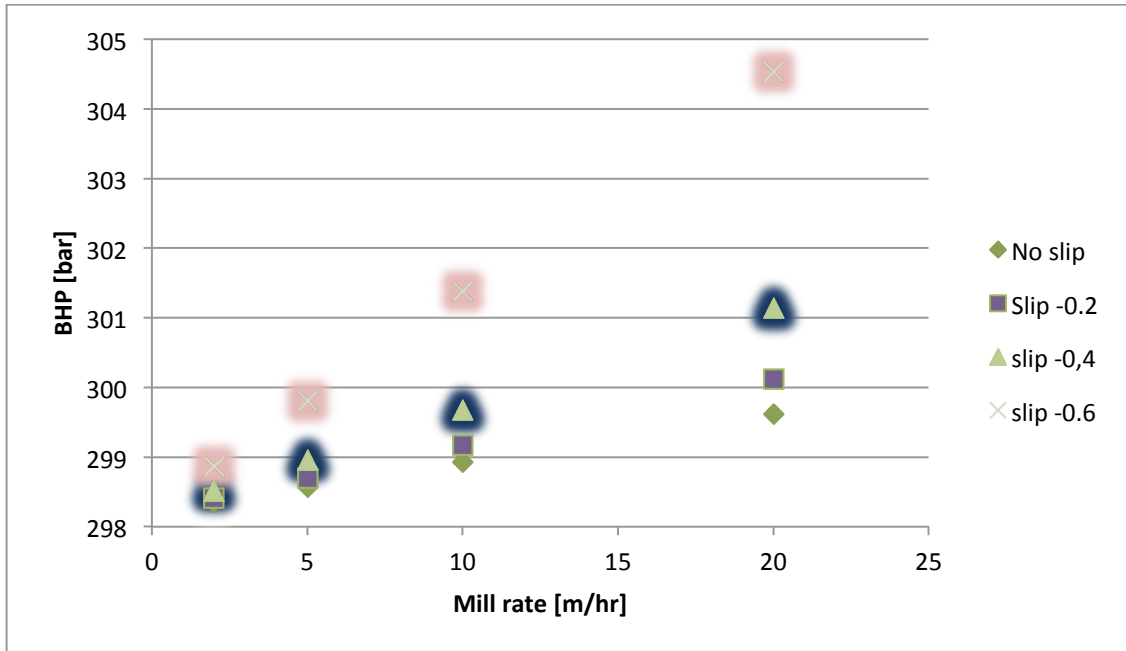
### 13.4 Input Data for Graph 4: Slip= -0.6

| KONSTANT   |           |             |           |
|------------|-----------|-------------|-----------|
| BHP        | Mill rate | Slip = -0.6 | BHP [bar] |
| 3.0453e+07 | 20        |             | 304,53    |
| 3.0138e+07 | 10        |             | 301,38    |
| 2.9981e+07 | 5         |             | 299,81    |
| 2.9887e+07 | 2         |             | 298,87    |

Graph 4: Slip= -0.6



### 3.5 Graph 5&6 : Combines graph 1,2,3 and 4 in the same graph



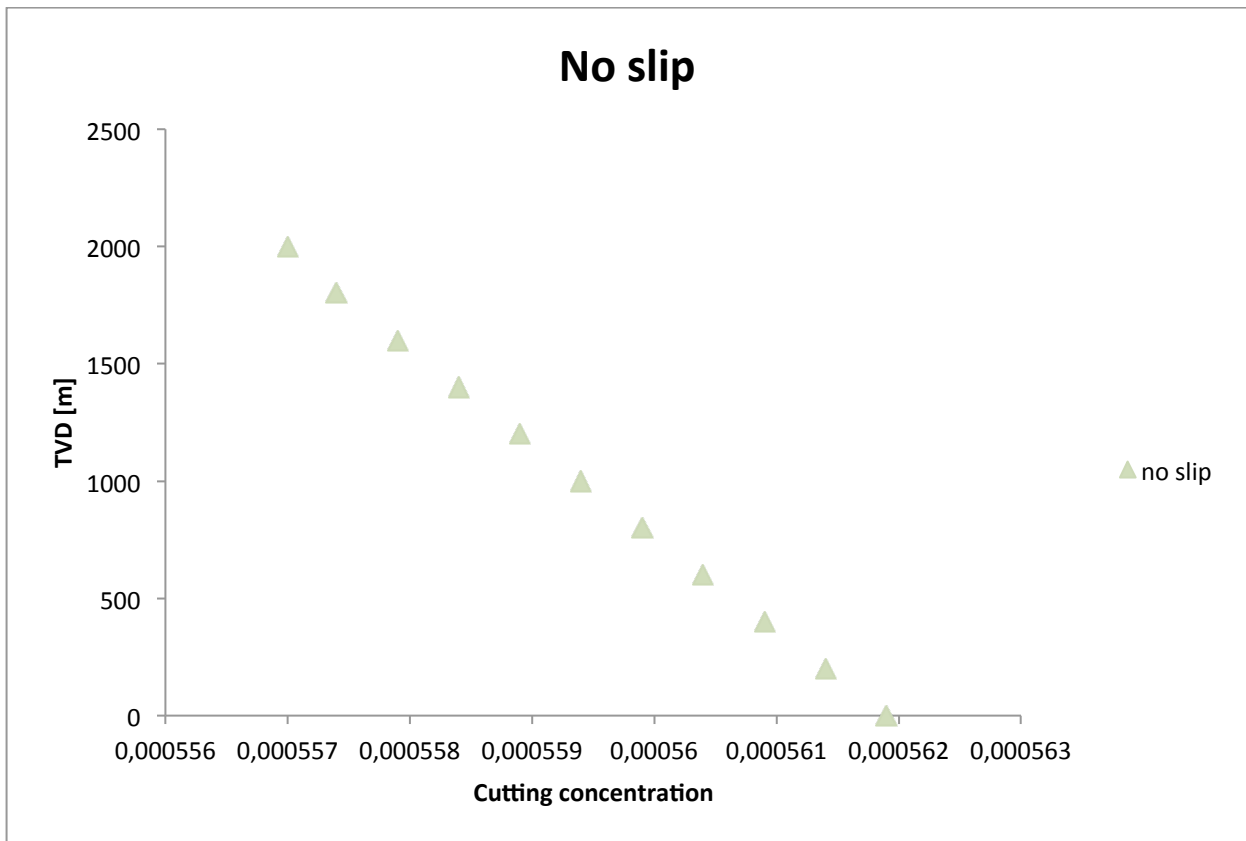
**Graph 6**

### 13.6 Table with input data for graph 7:

| No slip          | TVD  | Cuttings concentration |
|------------------|------|------------------------|
| Millrate 10 m/hr | 0    | 0,000557               |
|                  | 200  | 0,0005574              |
|                  | 400  | 0,0005579              |
|                  | 600  | 0,0005584              |
|                  | 800  | 0,0005589              |
|                  | 1000 | 0,0005594              |
|                  | 1200 | 0,0005599              |
|                  | 1400 | 0,0005604              |
|                  | 1600 | 0,0005609              |
|                  | 1800 | 0,0005614              |
|                  | 2000 | 0,0005619              |

### 13.7 Graph 7: Slip= 0, no slip

The mill rate it set to 10m/hr and the TVD is plotted against the cutting concentration.



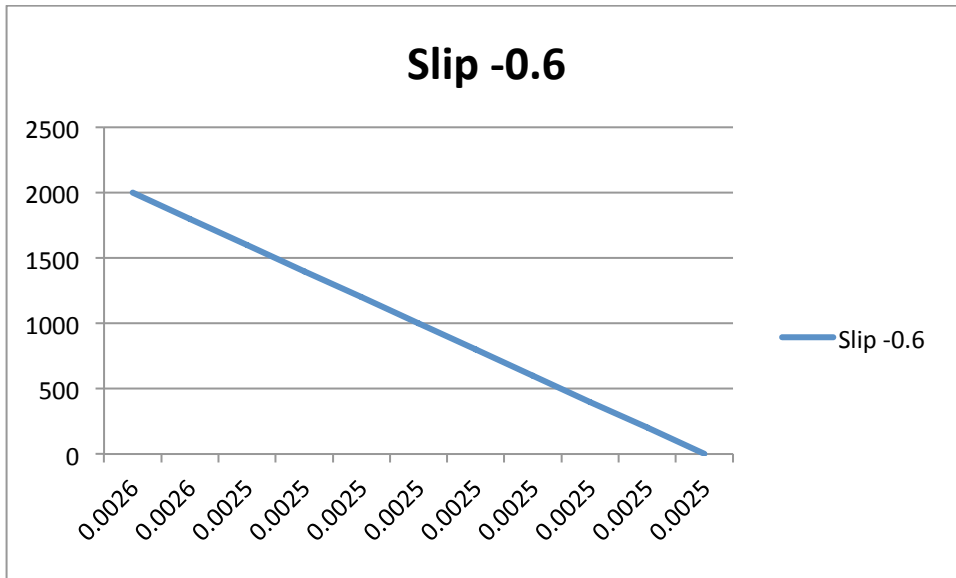
**Graph 7**

**13.8 Table with input data for graph 8:**

| Slip: -0.6       | TVD  | Cuttings concentration |
|------------------|------|------------------------|
| Millrate 10 m/hr | 0    | 0,0000025              |
|                  | 200  | 0,0000025              |
|                  | 400  | 0,0000025              |
|                  | 600  | 0,0000025              |
|                  | 800  | 0,0000025              |
|                  | 1000 | 0,0000025              |
|                  | 1200 | 0,0000025              |
|                  | 1400 | 0,0000025              |
|                  | 1600 | 0,0000025              |
|                  | 1800 | 0,0000026              |
|                  | 2000 | 0,0000026              |

**Graph 8: Slip= -0.6**

The mill rate it set to 10m/hr and the TVD is plotted against the cutting concentration.

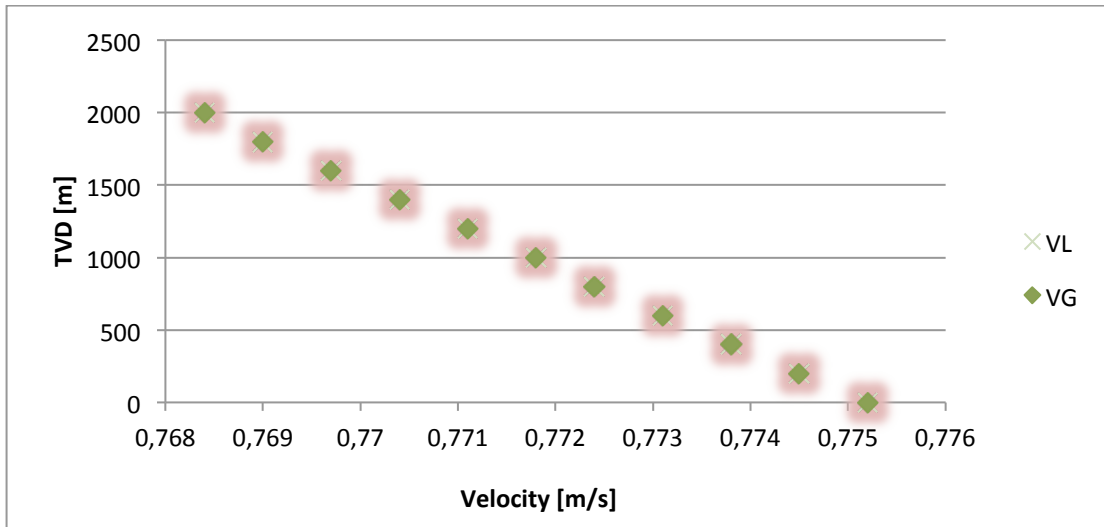


### 13.9 Table with input data for graph 9

| No slip          | TVD | vm   | vg     |
|------------------|-----|------|--------|
| Mill rate 10m/hr |     | 0    | 0,7752 |
|                  |     | 200  | 0,7745 |
|                  |     | 400  | 0,7738 |
|                  |     | 600  | 0,7731 |
|                  |     | 800  | 0,7724 |
|                  |     | 1000 | 0,7718 |
|                  |     | 1200 | 0,7711 |
|                  |     | 1400 | 0,7704 |
|                  |     | 1600 | 0,7697 |
|                  |     | 1800 | 0,7690 |
|                  |     | 2000 | 0,7684 |

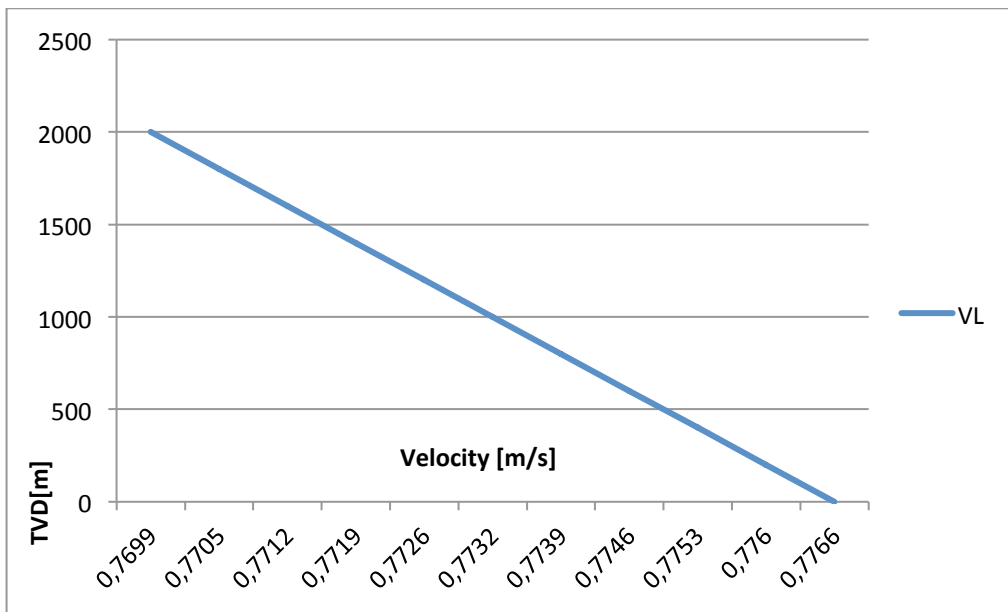
Graph 9 : Velocity of cuttings vs velocity of mud, no slip, mill rate 10m/hr

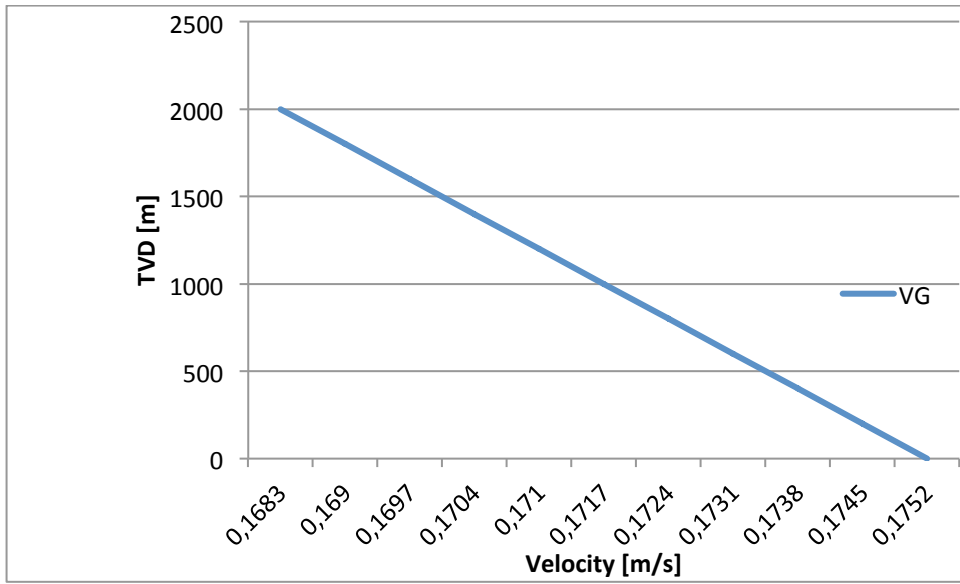




Graph 9

Graph 10 : Velocity of cuttings vs velocity of mud, slip: -0,6, mill rate 10m/hr







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