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Evaluation of Methods and Quality Barriers in Plug and Abandonment

Technology Advances, Physical and Governing Requirements

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Abstract

Improving the present P&A operation with respect to costs and safety is of current interest to the petroleum industry. This is because this operation will frequently be performed in the future due to the large number of drilled wells. Due to this, it is an increased interest in providing and ensuring the long-term integrity in the well since this is critical for the success of an abandoned well. This requires a good understanding of the integrity in the well, and models, methods and technologies to understand, determine and ensure this integrity are crucial for improving the operation.

This thesis will investigate one of the most fundamental parts of the P&A operation, which is to ensure a sufficient barrier in the well. On request from AF Offshore Decom AS, the thesis will look into challenges with the present P&A of old wells where little or no integrity information is available. In addition, the possibility for solving these challenges and at the same time save costs will be investigated. Specifically, investigate if there are significant savings in a scenario where technology development allows logging through multiple strings.

The thesis evaluates the annular integrity in depth by using a finite-element method model of the permanent formation-cement-casing barrier. In addition to these physical requirements, the regulatory requirements are taken into account when searching for improvements in the P&A operation. Furthermore, the present methods to evaluate the cement in the well are investigated, which includes acoustic logging. Limitations are identified, and the opportunity to use technologies and methods from other industries to evaluate the annular cement is studied. This includes technologies as computed tomography, magnetic resonance imaging, and the use of drill and borescope. Lastly, possibilities to improve the P&A procedure itself, and make it independent of the logging methods are investigated. For instance, removing the strings more efficiently by using undeveloped methods such as laser or corrosion. Based on the research in this thesis, it is not unlikely that technology advances and new methods will make the present issues with logging irrelevant. Be aware that the recommendations suggested in this thesis are only meant as guidelines and where to go further.

Developing and improving this area are a large task, and solving one challenge often results in another challenge. However, it includes huge opportunities for the right ideas. At the moment, there is no best practice, there is only *better* practice.

Samandrag

Forbetring av P&A-operasjonen med omsyn til kostnadar og sikkerheit er spesielt viktig for petroleumsindustrien dag. Dette kjem av at denne operasjonen kjem til å bli aktivt bruka framover då det er eit stort tal brønnar som er vorte bora i dag. Dermed er det auka interesse for å sikre langsiktig integritet i brønnen då dette er essensielt for at stenginga av brønnen er vellykka. Dette krev at ein har god forståing av integriteten i brønnen, og modellar, metodar og teknologiar til å forstå, bestemme og sikre denne integriteten er avgjerande for å forbetre operasjonen.

Denne masteroppgåva vil undersøke ein av dei mest fundamentale delane av P&A-operasjonen, som er å sikre ein tilstrekkeleg barriere i brønnen. På førespurnad frå AF Offshore Decom AS vil oppgåva sjå på utfordringar med dagens P&A av eldre brønnar der lite eller ingen integritetsinformasjon er tilgjengeleg. I tillegg vil moglegheita til å løyse desse utfordringane og samstundes redusere kostnadane, bli undersøkt. Spesielt moglegheita til å spare pengar i tilfelle der det er mogleg å logge gjennom fleire fôringsrøyr vil bli sett på.

Oppgåva gjer ei grundig evaluering av ringromsintegriteten ved hjelp av ein modell av den permanente formasjon-sement-fôringsrøyr barrieren. Denne modellen er modellert ved hjelp av elementmetoden. I tillegg til desse fysiske krava, er myndigheitskrav teke inn til vurdering når ein ser etter forbetringar for P&A-operasjonen. Vidare er dagens metodar til å evaluere sementen i brønnen undersøkt, som inkluderer akustisk logging. Avgrensingar er identifisert og moglegheita til å bruke teknologiar og metodar frå andre industriar til å evaluere ringromssementen, er undersøkt. Dette inkluderer teknologiar som computertomografi, magnetresonanstomografi, og bruk av boring og inspeksjonskamera. Til slutt undersøkast moglegheita til å forbetre P&A-prosedyren uavhengig av loggemetodane. Dette kan til dømes vere ved å fjerne røyr meir effektivt ved å bruke lite utvikla metodar som korrosjon eller laser. Basert på studiane i denne oppgåva er det ikkje usannsynleg at teknologiske framskritt og nye metodar vil gjere dagens problemstillingar med logging irrelevante. Ver merksam på at anbefalingane som er gitt i denne oppgåva berre er meint som retningslinjer og kvar ein kan gå vidare.

Utvikling og forbetring av dette området er ei stor oppgåve, og ei ny utfordring oppstår ofte når ei anna utfordring blir løyst. Likevel er det store moglegheiter for dei rette ideane. I dag er det ikkje noko som kan kallast best praksis, det er berre *betre* praksis.

Preface

This thesis is written as a part of my Master of Science degree (MSc) within Petroleum Engineering at the Faculty of Engineering at the Norwegian University of Science and Technology in Trondheim. The thesis was written in cooperation with AF Offshore Decom AS, and started in January 2017. It was finalized in June 2017. The thesis aims to improve the present P&A operation, with particular focus on ensuring the barriers in the well and saving costs.

Doing research shall be fun and provide learning. This is how I have experienced the last five months. It has been really interesting to write this thesis and I have had a steep learning curve. This is first thanks to my supervisor at NTNU, Bjørn Brechan. Thank you for the excellent guidance, support and feedback throughout the work of this thesis, both via meetings and in countless e-mails. I am grateful for the knowledge you have shared and for the valuable discussions. You are a great part of this work.

Furthermore, I want to thank AF Offshore Decom AS which gave me the opportunity to investigate the P&A operation in depth. Thanks to Odd Magne Grøntvedt which had confidence in me and suggested this thesis. Thank you for your availability and for the feedback. Also thanks to Lee Hanlon that has contributed with valuable information and feedback. I will also thank both of you for giving me the opportunity to get to know AF Offshore Decom AS as a company.

In addition, I want to express my gratitude to Jesus De Andrade for helping me with the simulations done in Ansys and for providing me with a useful FEM model on short notice. The model would not have been possible without your help.

Finally, I want to thank my classmates for the encouragement during the writing of this thesis. Thank you for making the last semester in Trondheim a good one. Also thanks to my mum that always has confidence in my decisions and encourages me to achieve my goals.

Trondheim
June 2017

Mona Øygarden Aasnes

Nomenclature

Symbol	Description	Unit
E	Young's modulus/elastic modulus	[Pa]
P_a	Internal pressure	[Pa]
P_b	External pressure	[Pa]
r_a	Internal radius	[mm]
r_b	External radius	[mm]
T	Temperature	[°C]
T_o	Ultimate tensile strength of cement	[Pa]
t	Wall thickness	[mm]
UCS	Unconfined compressive stress	[Pa]
UF	Utilization factor	[-]
α	Linear thermal expansion coefficient	[1/°C]
ε_H	Hoop/tangential strain	[-]
ε_R	Radial strain	[-]
ε_Z	Axial/longitudinal strain	[-]
$\sigma_1, \sigma_2, \sigma_3$	Least, intermediate and max principal stress	[Pa]
σ_H	Hoop/tangential stress	[Pa]
σ_R	Radial stress	[Pa]
σ_Z	Axial/longitudinal stress	[Pa]
$\sigma_{m,2}$	Effective mean stress	[Pa]
τ_{max}	Max shear stress	[Pa]
τ_{oct}	Octahedral shear stress	[Pa]
ϑ	Poisson's ratio	[-]
φ	Internal friction angle	[deg]

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
BI	Bond index
CBL	Cement bond log
CT	Computed tomography
FEM	Finite-element method
HSE	Health, safety & environment
LIH	Left in hole
MRI	Magnetic resonance imaging
MT1C	More than one casing
NCS	Norwegian continental shelf
NMR	Nuclear magnetic resonance
NPD	Norwegian Petroleum Directorate
P&A	Plug and abandonment
PC	Pitch-catch
PE	Pulse-echo
PSA	Petroleum Safety Authority
PWC	Perforate, wash & cement
RF	Radio-frequency
SBL	Segmented bond log
SBT	Segmented bond tool
TT	Transit/travel time
UF	Utilization factor
USIT	Ultrasonic imaging tool
VDL	Variable density log
WB	Well barrier
WL	Wireline

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1 Introduction

Improving the plug and abandonment (P&A) operation is a topic of current interest due to the number of mature fields, including more and more fields reaching the end of their productive lifetime. At this stage, the fields are no longer economically profitable to produce. The number of wells that require abandonment increases continuously and several challenges are, and will be faced.

There are common and widely used methods related to the P&A operation, but the costs and risks provide motivation for searching for safer and more time-efficient methods. P&A is an operation with no financial return and significantly high costs, especially offshore. Thus, one of the overall goals for the petroleum industry is to make the P&A operation as cost-effective as possible, without compromising the quality or the safety. This is especially important nowadays, as the oil price is fluctuating. In addition, the petroleum industry deals with more hostile downhole conditions than earlier, resulting in higher risks for the operation. At the same time, the regulations that ensure the safety of the operations are getting stricter.

One of the most fundamental parts of the P&A operation is to ensure a sufficient barrier in the annulus, thus; ensure well integrity. This can be both challenging and time-consuming, especially for old wells with no integrity information available. At present, cement is the most common material used to establish a barrier in the annulus due to its similar properties to the rock it is replacing (Oil and Gas UK, 2012). If the cement provides seal, protection and support for the casing, in addition to bond to the casing and to the formation, it is valid as a barrier and well integrity is ensured (King, 2012).

The common logging methods used to evaluate the annular cement contain several limitations which might result in misinterpretation of the logs. This might lead to wasting large amounts of money on operations not necessary to ensure an annular barrier or to validation of a barrier which is not a safe barrier. It is therefore of high interest to the operators and the service companies to investigate new technologies and methods for evaluating and ensuring the barrier in the well. Developing new technology might be costly. However, new technology has potential to save money in the long run. Not only is there a large upside in saving money, but improved integrity means improved safety as well.

Together with AF Offshore Decom AS, this thesis will investigate the present cement evaluation methods, identify its challenges and look into more safe, cost-efficient and future-oriented methods for evaluating the cement and for the P&A operation itself. This requires a deep understanding of the annular integrity, and an annular integrity analysis will be performed.

The study is mainly intended for the permanent P&A operation, but applies to the slot-recovery operation as well. Furthermore, it is especially of interest for old wells, but the research is valid for new wells as well.

1.1 Background

The first well on the Norwegian Continental Shelf (NCS) was drilled on 19th of July 1966. Since then, the development and production of oilfields on the NCS have had a major role in Norway. Despite the fluctuating oil price the last years, wells have been drilled continuously. In 2012, there were 350 platforms with more than 3700 production wells (Abshire et al., 2012), and recently well number 6000 was registered as completed in the Norwegian Petroleum Directorate's Fact Pages (2017). Only 50 production wells were plugged in 2016 (Norwegian Petroleum Directorate, 2017) and thousands of wells need to be safely plugged for permanent abandoned over the next few decades. This will be both time-consuming and costly, and there will be no revenues.

The Norwegian Oil and Gas Association has considered a worst-case estimate of the costs related to the P&A operations on the NCS. The estimate is close to 900 billions, which includes 15 rigs and 20 years of time (2017). The rigs used for this purpose will not be able to be used as drilling rigs at this time and there will be no monetary source due to this. The costs of this operation are therefore important to reduce and the technology has to keep up with this to both reduce the costs and ensure the safety. This will be beneficial for the industry as well as for the nation which covers 78% of the costs associated with the this operation (Norwegian Petroleum Directorate, 2011).

Norsk Olje og Gass has made a road map for new P&A technologies which presents focus areas and futuristic technologies within this area (Straume, 2016). The road map is shown in figure 1.1 below. The background for the map is mainly to save costs, but improving the HSE aspects is important as well. The map gives an indication of what the operators, the legislators and the governing bodies within the industry are looking for in this area and will be used as a guide through this thesis.

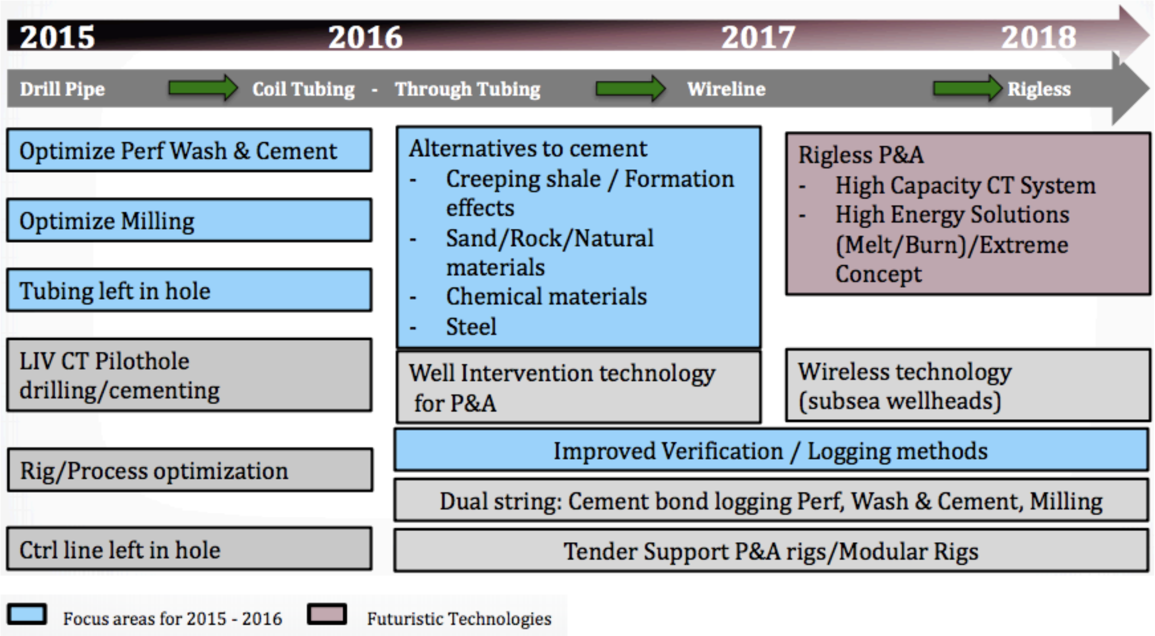

Figure 1.1 - Roadmap for new P&A technologies (Straume, 2016)

The roadmap shows that there are several areas that have potential for being further developed. The focus areas are marked in blue, where “Improved Verification/Logging methods” is included and emphasizes the importance of being aware of the conditions in the annulus. This will be highlighted in this thesis. Norsk Olje og Gass also states that the technology has to be developed for logging through MT1C (Straume, 2015).

Furthermore, it was recently an article in the Norwegian oil and gas magazine “Midt-Norsk Olje & Gass” that promoted the need to improve the present P&A operation (March 2017). In this article, the acting research director in SINTEF, Malin Torsæter, said that Norway is capable of and shall become world-leading in P&A technologies, just as Norway became world-leading in subsea technology. Indeed, the field development costs in Norway were reduced with 50% from 2014 to 2016 due to the low oil price (Norwegian Petroleum Directorate, 2017)[1]. This underlines the potential Norway has to develop new technology and methods. Torsæter wants to develop a P&A technology that is adequate for the whole petroleum industry, which for example can be done by using technologies from other sectors or by using formation as a

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[1] The Norwegian Petroleum Directorate investigated 7 field developments.

barrier. This will reduce the P&A costs and will result in revenues to Norway due to the sale of technology and services. This will in turn convert the future P&A problems into opportunities for Norway.

In addition, the Norwegian University of Science and Technology (NTNU) has been in touch with the industry and asked for their need for the future. One of the outcomes was to investigate and improve the field extension, including P&A. This was also emphasized at SINTEF's conference about P&A in March 2017.

Summarized, the need for developing and improving the P&A operation is evident and improving and/or replacing the present annular barrier evaluation methods will contribute to enhance this operation.

1.2 Objective and Scope

The objective of this thesis is to improve the present P&A operation to reduce the costs and enhance the safety of the operation. This is a large topic to look into and the following points will be kept in mind throughout the thesis:

- Successful P&A operation
- Ensuring well integrity
- Reducing the costs
- Improving and/or replacing the present methods for evaluating the annular barrier

It is important that the P&A operation acts in accordance with the regulations and at the same time is in accordance with the physical forces downhole. The annular barrier, consisting of cement, is often used as an external barrier in a plugged well and has to be sufficient to ensure well integrity. However, it might be challenging to evaluate and ensure this barrier in an old well. In addition, the cement covers a big part of the failures downhole and sealing for the eternity is challenging (Yuan, 2012). Therefore, a huge part of the scope of this thesis is to investigate methods to evaluate and ensure this barrier. This requires an understanding of the present methods and the annular integrity, which is crucial for a successful P&A operation.

Furthermore, it has to be considered if it is most profitable and safe to improve the present logging methods, to innovate in new logging methods or to change the P&A procedure itself. Suggestions is for instance using technologies from other industries, logging through multiple casings or modifying the P&A procedure by technology advances. It is obvious that measures are necessary to meet today's challenges with the P&A operation, however, the question is what measure is the best solution. This will be investigated and discussed in this thesis.

The ideal situation would be that the P&A operation was successful in the first attempt and was performed in the safest and most cost-efficient way. This is the goal for several companies and countries as it will be advantageous for everyone involved. The objective and scope of this thesis are therefore of current interest and are illustrated in figure 1.2 below.

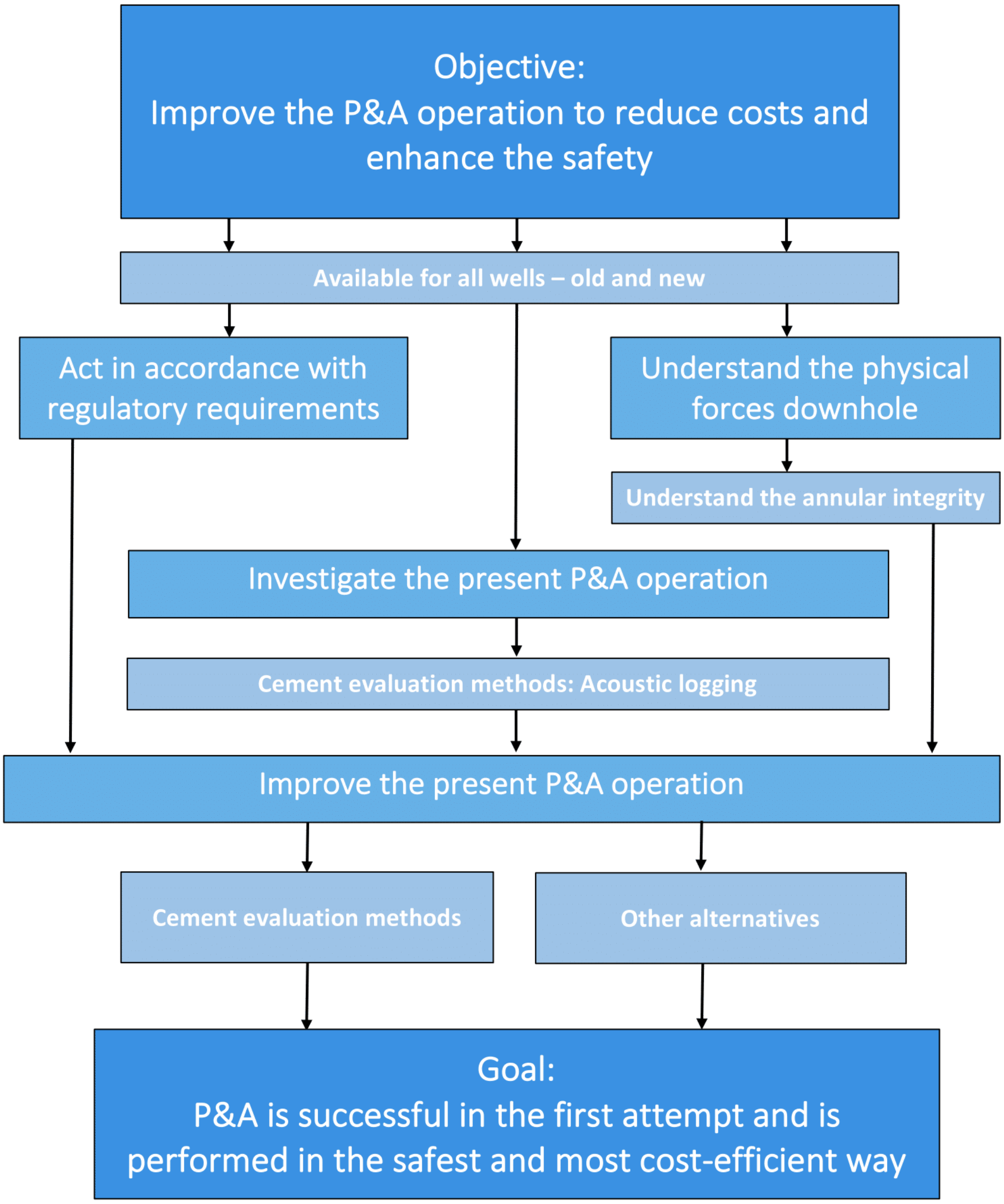

Figure 1.2 - Objective and scope of the thesis

2 Requirements

P&A is always about putting well control first. It is not acceptable to risk the technology to fail when it is placed in the well. Therefore, for every well operation the different companies are obliged by law to make sure that the operation is completed in accordance with regulatory requirements. These requirements contribute to ensure well integrity and shall be met in the most efficient way. In addition to these requirements, the companies have to act in accordance with the physical conditions downhole as every well operation is dependent on these conditions. P&A is about ensuring barriers for the eternity, which requires a fully understanding of the physical conditions in the well throughout the life of the well, including the annulus.

Summarized, to achieve a successful P&A job in the first attempt and avoid problems both during and after the operation, the operation has to act in accordance with the regulatory requirements and the physicals conditions downhole.

2.1 Regulatory Requirements

The Petroleum Safety Authority Norway (PSA) is delegated the authority to issue regulations covering safety, emergency preparedness and the working environment in the Norwegian petroleum industry. PSA ensures that all phases in the well operation are pursued in a prudent manner and develops regulations for the industry to follow up. Another directorate is the Norwegian Petroleum Directorate (NPD). NPD sets framework, stipulates regulations and makes decisions in areas where it has been delegated authority (Norwegian Petroleum Directorate).

The Petroleum Act[2], “Petroleumsloven”, provides the general legal basis for sound resource management. In addition, the NORSOK D-010 standard is widely used by the industry today. PSA recommends using this standard as a minimum functional requirement for all well operations in Norway. This ensures that the petroleum related operations on the NCS are carried out in a safe manner and that well integrity is maintained.

NORSOK ensures adequate safety, adds value and ensures a cost-effective operation. The standard supports and, in some cases, replaces the individual oil company specifications and

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[2] Act of 29 November 1996 No. 72 pertaining to petroleum activities.

other guidelines. “NORSOK D-010, Well Integrity in drilling and well operations” defines requirements and guidelines to ensure integrity in the well during the different operations (Standards Norway, 2013).

It is possible to challenge the present regulations with new methods and technologies as long as they are backed up with scientifically valid methodology and do not increase the risk level. The current regulations might lead to overdesigned solutions and unnecessary remedial operations which result in unnecessary costs. Developing an acceptance criteria that is less expensive and still safe is therefore interesting. However, this is out of the scope of this thesis.

2.1.1 Well Integrity and Well Barriers

The regulations are made in accordance with the safety where the aim is to ensure well integrity. The regulations state that no operation can be performed without this in place and the integrity of the well shall be carefully evaluated and proven. If the well integrity is missing or if uncertainties are presented, operations to ensure it have to be performed.

NORSOK D-010 defines well integrity as “an application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the lifecycle of the well”. Furthermore, the PSA’s facility regulations state: “Well barriers shall be designed such that well integrity is ensured and the barrier functions are safeguarded during the well’s time. (…) When a well is temporarily or permanent abandoned, the barriers shall be designed such that they take into account well integrity for the longest period of the time the well is expected to be abandoned.” (2015).

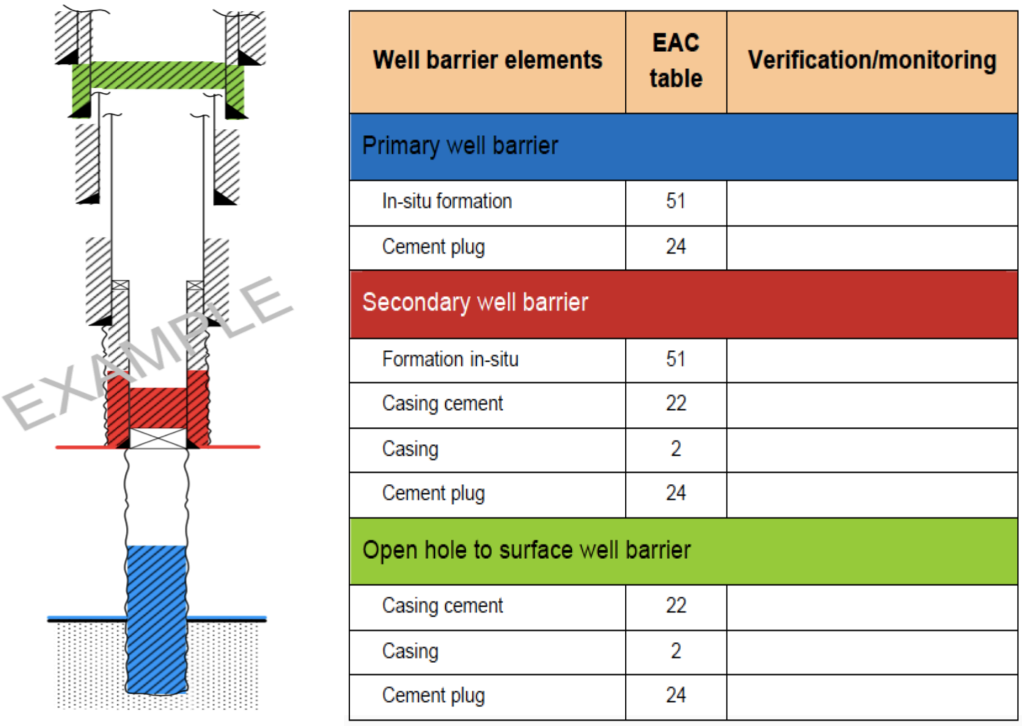
It is obvious that a well barrier (WB) is important and is defined as an “envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment” (Standards Norway, 2013). In other words, the WB depends on the conditions downhole. Chapter 4 in NORSOK D-010 states the general principles for a WB, however, from here, WBs during a permanent P&A operation are studied, which can be found in chapter 9.

The required characteristics of a permanent WB according to NORSOK D-010 are:

- Long term integrity with no deterioration over time
- Impermeable material to prevent any fluid migration through the material

- Non-shrinking material to prevent the formation of micro-annulus
- Ductile, non-brittle material to compensate for changes in stress, pressure and temperature
- Material that is resistant to downhole fluids and gases such as CO_2, H_2S and hydrocarbons
- Material that is able to bond to the casing and the formation

When planning a well today, the WBs in the well are arranged in a well barrier schematic (WBS) to ensure well integrity. A WBS is shown in figure 2.1. The different WBs are marked with colors in the WBS, where the blue plug is the primary WB, the red plug is the secondary WB, while the green plug is the open-hole-to-surface barrier required when permanent plugging a well. These plugs have to be independent from each other and permanently seal a source of inflow. The WBs take often advantage of the cement in the annulus as shown in figure 2.1. The cement will then act as an external WB element. According to NORSOK this external WB element shall be verified to ensure a seal and if it is going to be used as a primary or secondary barrier, logging of the cement is required if the primary cement job was critical (2013). According to this, it is important to always be aware of the status of the cement in the annulus to be able to ensure well integrity.



Well barrier elements	EAC table	Verification/monitoring
Primary well barrier		
In-situ formation	51	
Cement plug	24	
Secondary well barrier		
Formation in-situ	51	
Casing cement	22	
Casing	2	
Cement plug	24	
Open hole to surface well barrier		
Casing cement	22	
Casing	2	
Cement plug	24	

Figure 2.1 - Permanent abandonment, open hole (Standards Norway, 2013)

For permanent abandonment, the acceptance criteria for a WB is stated as "Permanently abandoned wells shall be plugged with an eternal perspective taking into account the effects of any foreseeable chemical and geological processes. The eternal perspective with regards to re-charge of formation pressure shall be verified and documented. (…) Permanent well barriers shall extend across the full cross section of the well include all annuli and seal both vertically and horizontally" (Standards Norway, 2013). This is also stated in PSA's facility regulations and illustrated in figure 2.2.

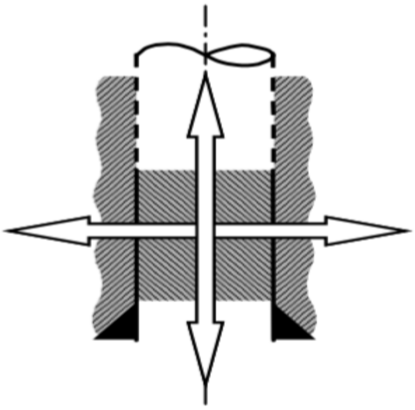


Figure 2.2 - Permanent well barrier sealing in all directions (Standards Norway, 2013)

Even though the regulations, requirements and standards contribute to ensure well integrity and the WBs are designed and placed in accordance with these, the barriers might fail and leakage occurs. This phenomenon is probably the most difficult part to handle at the abandonment stage and several factors have an impact on this phenomenon. Due to this, it is essential to understand the integrity in the well where the annular integrity is an important part.

2.2 Annular Integrity

The implementation of the present P&A operation is dependent on the annular barriers in the well which often consist of cement. To be able to perform an appropriate P&A operation, it is important to understand the status of this cement; what loads the cement is exposed to, which failures that might occur and how this affects the integrity of the well. In other words, to ensure well integrity during and after P&A it is essential to understand the annular integrity. If the integrity in the annulus fails, the integrity of the well is lost.

To understand and determine the integrity in the annulus, the physical forces in the annulus, including the radial and tangential stresses, can be modelled (Laidler et al., 2007). These forces affect the cement, and the physical and chemical behavior of the cement will change from its initial behavior (Wilcox et al., 2016). This will in turn affect the integrity of the well and is important to be aware of when planning the well and the P&A operation.

The thermo-elastic behavior of a cylindrical wellbore section and the cement sheath stresses can be estimated from an analytical or numerical model. It is an increased interest in annular cement sheath modeling as the cement sheath integrity is an important factor in the success of the well and failures within the cement are important to detect. Thus, several studies within this area are performed and used to optimize the primary cement job to ensure both short- and long-term integrity. In addition, such model can be used to determine the status of the cement after span of years by understanding the parameters involved and how the cement has evolved during its lifetime. In other words, a reliable annular integrity model can be used to plan an optimal P&A operation for a particular well. An analytical model is derived below.

It is reasonable to assume that the cement is non-porous and that the structural interaction of a cased wellbore section is primary affected by operating loads when deriving an analytical model. Due to this, a composite cylinder with axisymmetric geometry can be considered. In addition, the in-plane strain for calculating the mechanical response is a typical approach and the strain normal to the wellbore cross-section is defined as zero. Using this approach does not include the impact of imposed vertical tectonic stresses caused by subsidence and depletion, however, the approach is still useful.

The derivation shown in this thesis is based on the studies done by De Andrade (2015)[3] and Wilcox et. al. (2016). In all cases, the model is derived from the linear relationship among stresses, strain and temperature, that is given by:

$$\varepsilon_R = \frac{\sigma_R}{E} - \frac{\vartheta}{E}(\sigma_H + \sigma_Z) + \alpha T \tag{1}$$

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[3] Note that in Appendix A in De Andrade's PhD thesis from 2015, the sign in front of the last part of equation A-7 and A-8 is switched. A-7 should have minus, while A-8 should have +. The author has investigated those formulas against three others references: Bourgoyne, A. T. et. al (1991), Brechan, B. (2015) and Wilcox, B. et. al. (2016).

$$\varepsilon_H = \frac{\sigma_H}{E} - \frac{\vartheta}{E}(\sigma_R + \sigma_Z) + \alpha T \tag{2}$$

$$\varepsilon_Z = \frac{\sigma_Z}{E} - \frac{\vartheta}{E}(\sigma_R + \sigma_H) + \alpha T = 0 \tag{3}$$

where

ε_R: Radial strain [-]

ε_H: Hoop strain [-]

ε_Z: Axial/longitudinal strain (in this case: in-plane strain) [-]

σ_R: Radial stress [Pa]

σ_H: Hoop stress [Pa]

σ_Z: Axial/longitudinal stress [Pa]

ϑ: Poisson's ratio [-]

E: Young's/elastic modulus [Pa]

α: Linear thermal expansion coefficient [1/°C]

T: Temperature change [°C]

The different stresses in equation (1), (2) and (3) are dependent on the cylinder considered. The casing is based on a thin-walled cylindrical geometry, which gives the following hoop stress for the casing:

$$\sigma_H = \frac{pr}{t} \tag{4}$$

where

p: Internal pressure [Pa]

r: Inner radius [mm]

t: Wall thickness [mm]

The cement and formation are based on a thick-walled cylindrical geometry, and Lamè's equations for thick cylinders are used:

$$\sigma_H = \frac{r_a^2 \cdot P_a - r_b^2 \cdot P_b}{r_b^2 - r_a^2} + \frac{r_a^2 \cdot r_b^2 \cdot (P_a - P_b)}{r^2 \cdot (r_b^2 - r_a^2)} \tag{5}$$

$$\sigma_R = \frac{r_a^2 \cdot P_a - r_b^2 \cdot P_b}{r_b^2 - r_a^2} - \frac{r_a^2 \cdot r_b^2 \cdot (P_a - P_b)}{r^2 \cdot (r_b^2 - r_a^2)} \tag{6}$$

where

r_a, r_b: Internal and external radius [mm]

P_a, P_b : Internal and external pressure [Pa]

Figure 2.3 can be used to understand the different parameters in the equations.

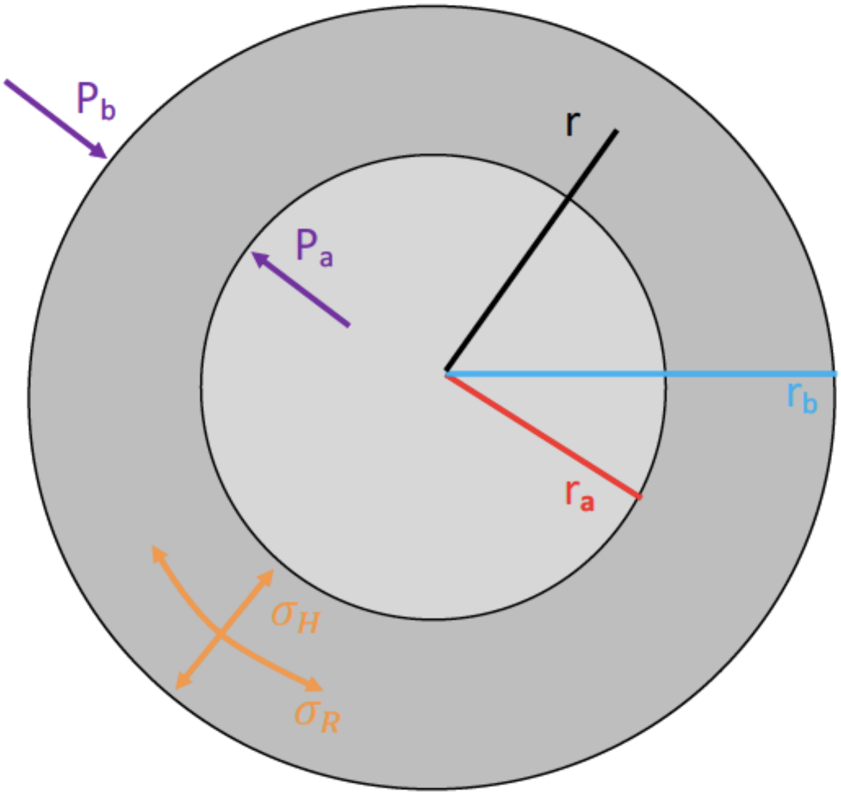

Figure 2.3 - Cylinder cross-section; internal and external pressure and radii

The longitudinal stress is found from equation (3) when assuming in-plain strain:

$$\sigma_Z = \vartheta \cdot (\sigma_R + \sigma_H) - E\alpha T \tag{7}$$

To find the different stresses and failures of the cement sheath, the contact pressures at each interface have to be determined. These pressures can be further used to determine the radial and tangential distribution of stresses for each cylinder. To find the contact pressures, the interaction between the casing, cement sheath and rock formation has to be considered. It is assumed that the interfaces are fully mechanically coupled, which makes the radial stresses the same across the boundary.

The casing-cement interface and cement-formation interface are analyzed separately. Figure 2.4 is useful to understand the scenario and shows the different radii used in the derivation.

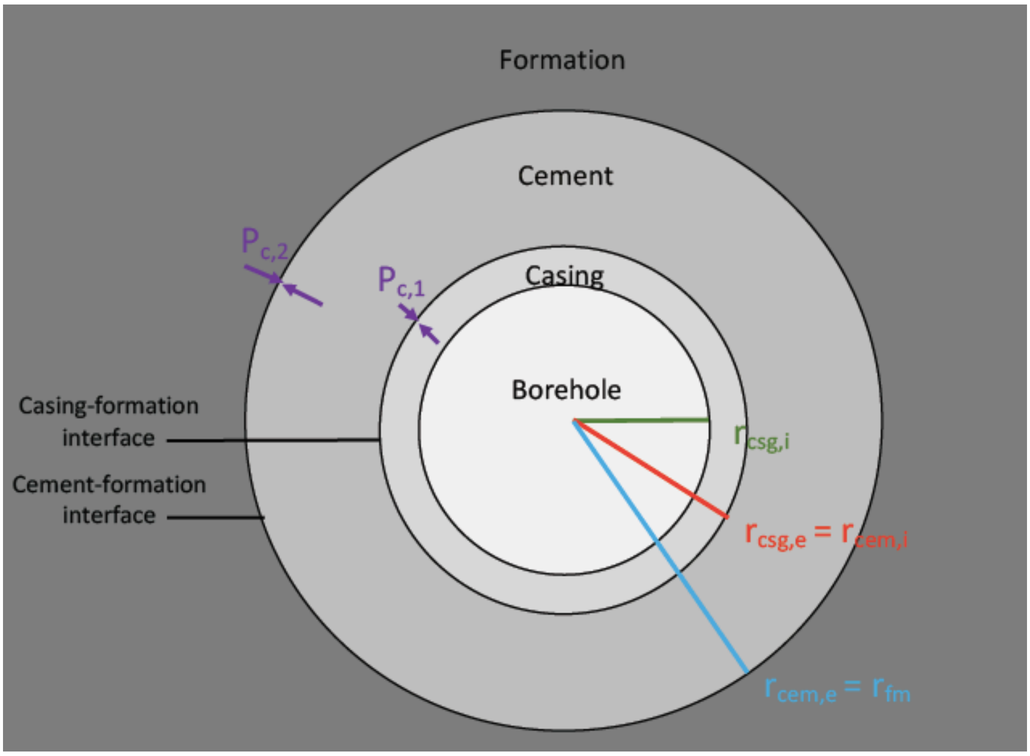

Figure 2.4 - Cylinder cross-section of the scenario analyzed ($P_{c,1}$: Contact pressure at the casing-cement interface, $P_{c,2}$: Contact pressure at the cement-formation interface)

The casing-cement interface are first considered. The radial strain at the different interfaces is derived from equation (1). The radial strain for the casing at casing-cement interface becomes

$$\varepsilon_{R,csg}(r_{csg,e}) = \frac{1}{E_{csg}}\Big(\big(\sigma_{R,csg}(r_{csg,e}\big) - \vartheta_{csg}\Big(\big(\sigma_{H,csg}(r_{csg,e}\big) + \big(\sigma_{z,csg}(r_{csg,e})\big)\Big)\Big) \tag{8}$$

The radial strain for the cement at the casing-cement interface becomes

$$\begin{aligned}\varepsilon_{R,cem}(r_{cem,i}) = \frac{1}{E_{cem}}\Big(\big(\sigma_{R,cem}(r_{cem,i}\big) \\ - \vartheta_{cem}\Big(\big(\sigma_{H,cem}(r_{cem,i}\big) + \big(\sigma_{z,cem}(r_{cem,i}\big)\Big)\Big)\end{aligned} \tag{9}$$

The radial expansion formulas in equation (8) and (9) can be equated to each other due to the fully mechanically coupling at the casing-cement interface.

$$\varepsilon_{R,csg}(r_{csg,e}) = \varepsilon_{R,cem}(r_{cem,i}) \tag{10}$$

which is the same as

$$\begin{aligned}\frac{1}{E_{csg}}\Big(\big(\sigma_{R,csg}(r_{csg,e}\big) - \vartheta_{csg}\Big(\big(\sigma_{H,csg}(r_{csg,e}\big) + \big(\sigma_{z,csg}(r_{csg,e}\big)\Big)\Big) \\ = \frac{1}{E_{cem}}\Big(\big(\sigma_{R,cem}(r_{cem,i}\big) \\ - \vartheta_{cem}\Big(\big(\sigma_{H,cem}(r_{cem,i}\big) + \big(\sigma_{z,cem}(r_{cem,i}\big)\Big)\Big)\end{aligned} \tag{11}$$

When the longitudinal stresses, σ_z, in equation (7), hoop stresses, σ_H, in equation (4) and (6), and the radial stresses, σ_R, in equation (5) are solved with the right boundaries and substituted into equation (11), the equation will be dependent on both the casing-cement contact pressure, $P_{c,1}$, and the cement-formation contact pressure, $P_{c,2}$.

The cement-formation interface is analyzed in the same way as the casing-cement interface. The radial strain for the cement at this interface is:

$$\begin{aligned}\varepsilon_{R,cem}(r_{cem,e}) = \frac{1}{E_{cem}}\Big(\big(\sigma_{R,cem}(r_{cem,e}\big) \\ - \vartheta_{cem}\Big(\big(\sigma_{H,cem}(r_{cem,e}\big) + \big(\sigma_{z,cem}(r_{cem,e}\big)\Big)\Big)\end{aligned} \tag{12}$$

The radial strain for the formation at the cement-formation interface is:

$$\varepsilon_{R,fm}(r_{fm}) = \frac{1}{E_{fm}}\Big(\big(\sigma_{R,fm}(r_{fm})\big) - \vartheta_{fm}\Big(\big(\sigma_{H,fm}(r_{fm})\big) + \big(\sigma_{z,fm}(r_{fm})\big)\Big)\Big) \tag{13}$$

Equation (12) and (13) can be equated to each other because of the mechanical coupling at the cement-formation interface, which gives:

$$\varepsilon_{R,cem}(r_{cem,e}) = \varepsilon_{R,fm}(r_{fm}) \tag{14}$$

which is the same as

$$\frac{1}{E_{cem}}\Big(\big(\sigma_{R,cem}(r_{cem,e}\big) - \vartheta_{cem}\Big(\big(\sigma_{H,cem}(r_{cem,e})\big) + \big(\sigma_{z,cem}(r_{cem,e})\big)\Big)\Big) = \frac{1}{E_{fm}}\Big(\big(\sigma_{R,fm}(r_{fm})\big) - \vartheta_{fm}\Big(\big(\sigma_{H,fm}(r_{fm})\big) + \big(\sigma_{z,fm}(r_{fm})\big)\Big)\Big) \tag{15}$$

Substituting the longitudinal stresses, σ_z, hoop stresses, σ_H, and radial stresses, σ_R, into equation (15) with the right boundaries gives an equation dependent on both contact pressures. Equation (11) and (15) can then be used to calculate the contact pressures, which in turn can be used to calculate the stresses at any radius in the cross-section of the wellbore with equation (4), (5) and (6). These stresses can be used to calculate the risk of cement sheath failures which will be studied further down.

To improve the accuracy of the annular integrity model, it can be modelled numerically. In this thesis, a simplified model is modelled in the software Ansys Workbench[4]. The model is based on the model Jesus De Andrade investigated in his PhD thesis from 2015, but is modified for this thesis where it is the cross-section of the well that is investigated, including the formation,

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[4] The simulation software Ansys Workbench can be used to perform and post-process simulations of various load-cases to analyze the annular cement sheath, in addition to statistical analyses. In this software, pressure, stress and cement properties are used in a FEM to get an understanding of the integrity in the annulus.

cement and casing. The cross-section studied in Ansys is shown in figure 2.5 and the model's assumptions and input values can be found in appendix A.1.

Ansys uses a finite-element method (FEM) to investigate the annular integrity. The system is partially discretized in multiple dimensions and the finite-element analysis mathematics are solved simultaneously across the wellbore. This makes it possible to provide an efficient model of the pressure and temperature effects downhole and to perform a structural and thermal analysis (Teodoriu et al., 2010).

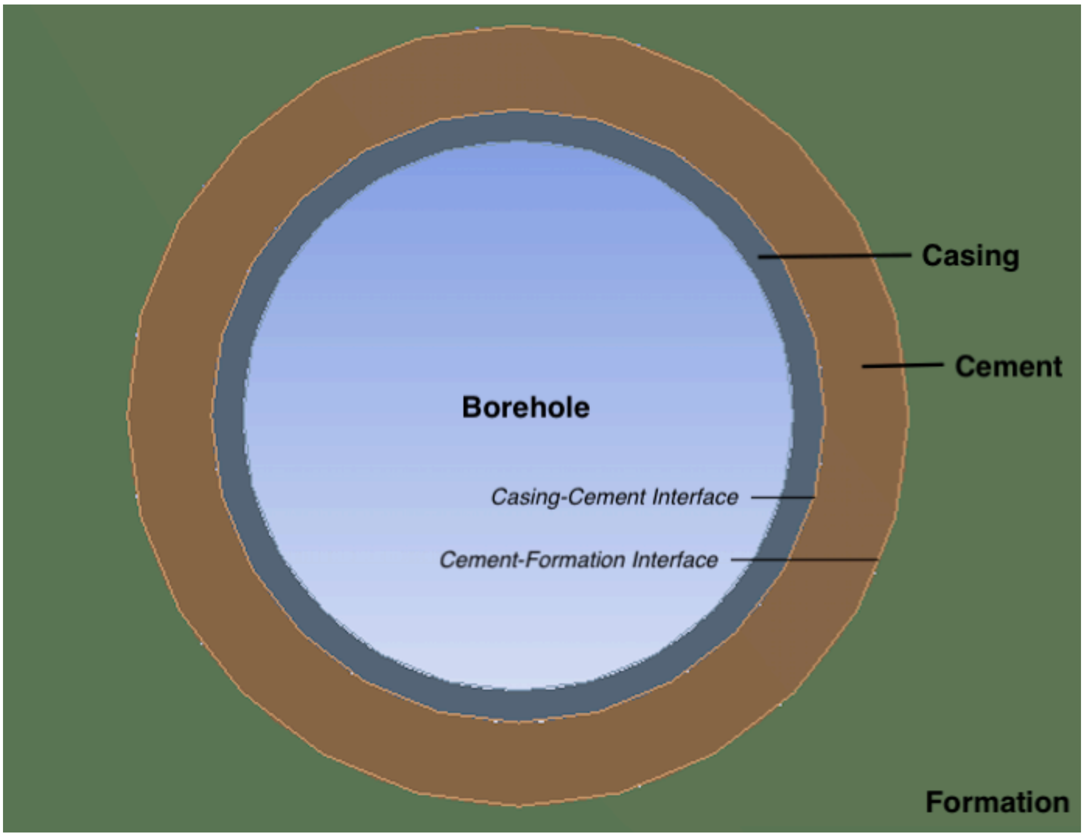

Figure 2.5 - Cross-section of the well

Basically, the steps of a FEM are:

1. Build the model
2. Meshing
3. Applying boundary conditions
4. Solve the system
5. Post-process

The FEM model makes it possible to vary the different properties of the cement and formation in the model to see how they affect the integrity of the annulus and important parameters for the cement behavior will be identified. The findings can be compared with other studies within this area and laboratory tests can be performed to verify the model. However, lab work is out of the scope of this thesis.

Both the analytical and numerical model can be used to identify any failures and to determine the critical stresses for these failures. There are three failure modes to study (Ugwu, 2008):

1. De-bonding between the interfaces in the well (casing-cement and/or cement-formation). This is usually caused by cement shrinkage and tensile stresses that overcome the contact stress at the interface but may also occur due to shear failure.
2. Radial cracking within the cement sheath. Cracking is caused by hoop stresses overcoming the ultimate tensile strength of the cement.
3. Plastic deformation caused by loading, which permanently deforms the cement sheath. This might result in a shear failure and cracks within the cement might occur.

The operational loads affect the annular integrity differently and might lead to a failure propagating both radially and longitudinally, becoming possible leak paths, as shown in figure 2.6 below. De-bonding at the interfaces occurs in a), b) and f), while c), d) and e) present pathways through the different materials, where e) is caused by cracks in the cement.

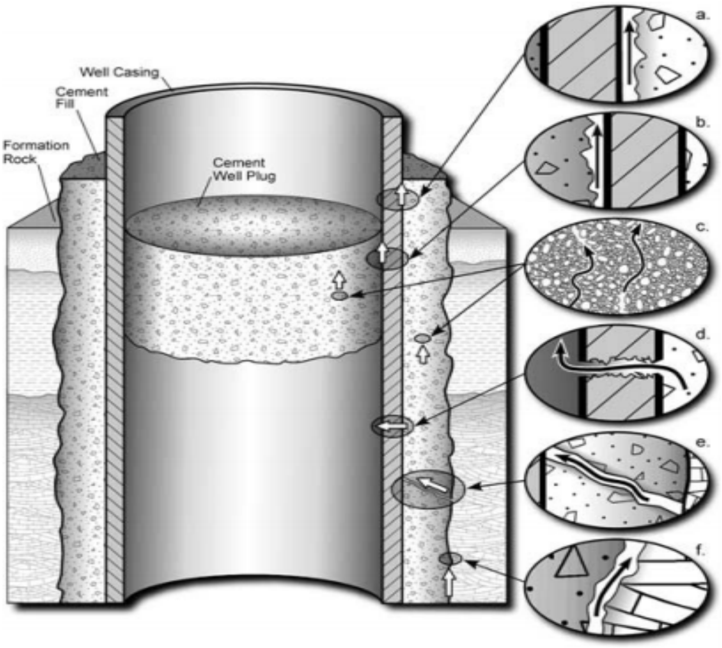

Figure 2.6 - Potential leakage paths (Celia et al., 2005)

In the numerical model used in this thesis, De Andrade's utilization factors (UFs) are used to determine if failure has occurred (2016). The UFs are calculated from the estimated stresses downhole and are based on the widely used failure criterions that determine the allowable stresses to avoid different failures. For shear failure, the Mohr-Coulomb criterion is common used to define the limit of elasticity in a material and the beginning of plastic deformation. For more complex stress conditions, the Mogi-Coulomb criterion is used. These criterions relate the shear failure envelope to the unconfined compressive strength and the internal friction angle. This relationship is derived from the following equations.

$$\tau_{max} = c \cdot cos\varphi + sin\varphi \cdot \sigma_{m,2} \tag{16}$$

$$\sigma_{m,2} = \frac{\sigma_1 + \sigma_3}{2} \tag{17}$$

$$c = \frac{UCS \cdot (1 - sin\varphi)}{2 \cdot cos\varphi} \tag{18}$$

The criterion becomes:

$$\tau_{max} < \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \tag{19}$$

where

τ_{max}: Max shear stress [Pa]
φ: Internal friction angle [deg]
$\sigma_{m,2}$: Effective mean stress [Pa]
UCS: Unconfined compressive strength [Pa]
σ_1: Max principal stress [Pa]
σ_2: Medium principal stress [Pa]
σ_3: Least principal stress [Pa]

Shear failure occurs if the criterion in equation (19) is fulfilled.

Tensile failure will occur when the least principle stress is higher than the ultimate tensile strength of the cement. As the stress becomes negative when it is in tension, the criterion becomes:

$$\sigma_3 < -T_o \tag{20}$$

where

T_o: Ultimate tensile strength of cement [Pa]

By using these criterions, the UF becomes (De Andrade and Sangesland, 2016):

$$\frac{Load}{Capacity} \leq UF \tag{21}$$

where

$Load$: Representative stresses along the cement sheath [Pa]

$Capacity$: Maximum allowable working stress to avoid certain failure [Pa]

UF: Utilization factor [-]

If the criterion above is fulfilled, the well is sealed and zonal isolation exists. The magnitude of the UF has to be less than 1 to avoid failure. However, when including the uncertainty involved in the mechanical problem and the quantification of the failure, the UF has to be less than 0.8 to avoid failure (De Andrade and Sangesland, 2016). To simplify the UF criterion, each failure mode is defined separately which is expressed by the following equations and illustrated in figure 2.7 below.

$$UF_{Dbi} = UF_{Dbo} = \frac{\sigma_R}{-T_0} \tag{22}$$

$$UF_{RadCr} = \frac{\sigma_H}{-T_0} \tag{23}$$

$$UF_{Shear} = \frac{\tau_{oct}}{\tau_{max}} \tag{24}$$

where

UF_{Dbi}: Utilization factor inner de-bonding [-]

UF_{Dbo}: Utilization factor outer de-bonding [-]

UF_{RadCr}: Utilization factor radial cracks [-]

UF_{Shear}: Utilization factor shear stress [-]

τ_{oct}: Octahedral shear stress [Pa]

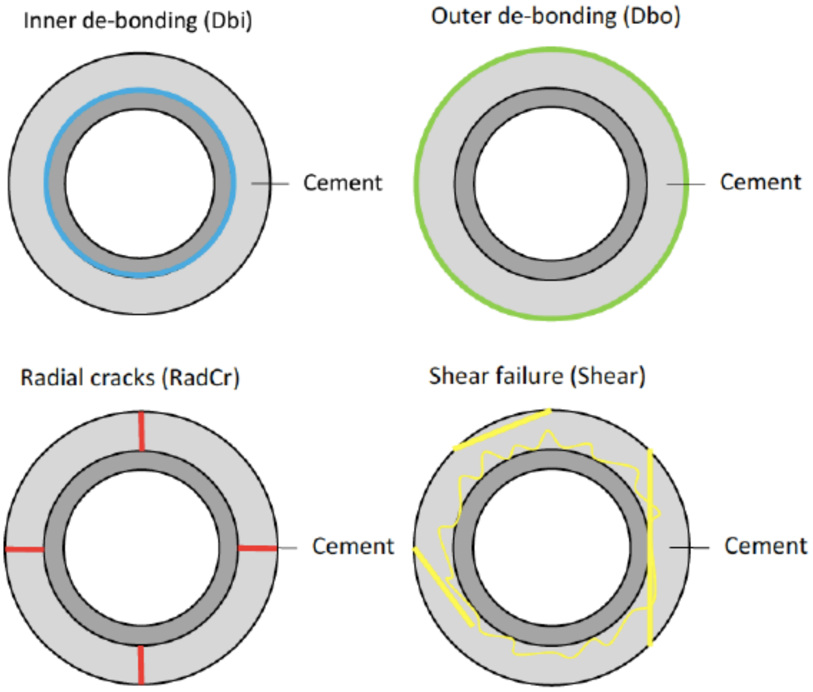

Figure 2.7 - Illustration of the different failure modes

The inner and outer de-bonding and the radial cracks are calculated along each cement-sheath interface, while the shear failure is calculated within the cement sheath. Be aware that the FEM model used in this thesis is not that complex and considers the failure modes separately. It is impossible to determine the order of the different failures and the failures impaction on each other is not considered; a single failure can prevent or contribute to another failure. The exact location and size of the failure are not determined either. However, the model is still useful for understanding the integrity in the annulus and will identify failures and weak points in the cement. The model can also be used to support ambiguous cement logs that will be introduced later. Most important, the model increases the understanding of the annular integrity, which in turn can be used to enhance the present P&A operation. However, be aware that the reliability and efficiency of the software used have to be taken into account. This is out of the scope of this thesis, but validating the model with experimental data are preferred.

3 Qualification of the Annular Barrier During P&A

The purpose of the P&A operation can either be to permanent plug the well or to plug it temporary and re-use the slot later. The scope of this thesis is mainly permanent P&A, which NORSOK D-010 (2013) defines as a “well status, where the well is abandoned permanently and will not be used or re-entered again”. This means that the natural integrity of the formation that has been penetrated during drilling shall be restored and maintained for the eternity. Well barriers that got known in chapter 2 are set to seal the well in all directions and shall isolate the well from permeable and hydrocarbon bearing formations and prevent fluid migration. The status of this barrier shall be known and ensured prior abandoning the well. This is how well integrity is ensured and the well is ready to be abandoned. The same principles apply for the slot-recovery operation.

Common steps for the P&A operation can be found in chapter 7 in Vibeke Henriksen’s thesis (2013). However, even though there are some common steps in the P&A operation, the operation differs from well to well due to different conditions downhole. The conditions and available information about the well determine the operations required to ensure an annular barrier prior a P&A operation. For instance, if information about the primary cement job, stresses in the annulus and cement logs are available, the P&A operation can be planned from this. However, if no such information exists, which is common for old wells, it is necessary to evaluate the annular cement in the well before it can be used as an external barrier. In this case, logging operations are required and the time of the P&A operation increases. It might be difficult to determine if there is integrity and the evaluation of the cement has to be carefully planned to obtain a reliable result (Benge, 2014). However, it is important that the cement is sufficient if it is going to be used as a barrier in the plugged well and its long-term sealing is crucial for the P&A operation to be successful. In other words, the status of the annular cement is an important factor throughout the well life cycle as it can contribute to well integrity. More about the primary cement operation can be found in appendix B.1.

It is important to take into consideration that even though the cement quality is high immediately after the cement is set, loss of cement integrity might occur over time as the cement cures and the initial conditions evolve due to additional loads, which was studied in chapter 2.2. The cement can fail either by a man-made load or a naturally-made load. For instance, the risk for failure increases as the pressure and temperature increase since it might result in an excessive load. Loss of annulus isolation might occur, which in turn increases the risk for flow behind the casing (Teodoriu et al., 2010). This underlines the need for understanding and ensuring the annular barrier prior the P&A operation. Old wells have to be logged if no logs exist, while wells with existing logs do not need to be logged. The risk of using previous logs to plan the P&A operation can be further investigated due to the cement degradation, however, this is out of the scope of this thesis.

If a well is not properly abandoned, the probability of fluid migration increases and the cement is no longer a barrier in the well. This constitutes a safety risk, which is critical for the surroundings, and detrimental consequences might occur, which BP's Macondo blowout in the Gulf of Mexico in 2010 is an example of. This is a worst-case scenario, however, it is important that the well is properly abandoned. It is costly to remediate or re-abandon a leaky well, and if several runs are required, the operation becomes time-consuming and costly. To avoid these operations, it is important with both a successful primary cement job and a successful P&A operation. For especially old wells, this requires fully reliable cement evaluation methods or other, more efficient and reliable operations for ensuring a barrier in the well. Practice, careful observation and learning from experiences increase the chances for a successful operation (American Petroleum Institute, 2008).

The ideal situation is that the status of the annular cement is known and is of high quality and that the long-term integrity is ensured such as this cement can be used as an external barrier for the eternity. In this case, a cement plug is placed within the casing, which is referred to as cased hole cement plug. This is an easy and cost-efficient operation. However, often more time-consuming operations are necessary, such as cut and pull the casing. If the casing is stuck in this case, section milling the casing or another remedial operation are necessary. The removal of tubulars is presented in appendix B.2.2 and B.2.3, and discussed further chapter 5.2.

The industry does not afford any failures and to avoid this, the barriers in the well are important to ensure. In the subsequent chapters, the logging methods currently used for cement evaluation and their challenges are investigated. The possibility to use other technologies are also studied.

3.1 Present Cement Evaluation Methods

Acoustic cement logs have been used for decades to evaluate cement jobs. The acoustic technology is run with wireline (WL) well logging and the technology consists of sound waves that propagate through the surrounding environment and get affected by the acoustic properties. The aim of the logs is to determine the status of the cement; it is preferred that the tools provide information about the cement location, height, quality, level of hydraulic and mechanical bonding, presence of cracks, pockets and channels, and distinguish between the cement and the formation.

The cement quality is found from the degree of acoustic coupling of cement to the casing and to the formation. The transmitter emits a signal, a sound wave, which propagates through the bore fluid, casing, cement and formation, while the receiver detects the signal and measures the response (American Petroleum Institute., 2008). It is the attenuation of energy that is measured, which is the loss of acoustic energy between transmitters and receivers. Thus, it does not measure the hydraulic isolation directly, but logs with high resolution can contribute to determine this isolation. In addition, the transit/travel time (TT) is measured, which is the time of the signal from the transmitter to the receiver. This information is used to interpret the log and the results have to be quality controlled by calibration and measurement repeatability (Nelson, 1990). If there is correspondence between the expected and the actual log responses the interpretation of the log is adequate. The logs will contribute to determine the integrity of the well.

The acoustic logging methods are divided into sonic and ultrasonic methods, where their area of application differs due to the different frequencies and other characteristics:

- Sonic logs: Operation frequency: 20 Hz.
    - Cement bond log (CBL)
    - Variable density log (VDL)
    - Segmented bond log (SBL)
- Ultrasonic logs: Operation frequency: 80 to 700 Hz.
    - Pulse-echo technology (PE)
    - Pitch-catch technology (PC)

The function of the logging tools is further studied in appendix B.3, but briefly summarized, the CBL and VDL are common used to determine the bonding, where CBL determines the casing-cement bonding and the VDL determines the bonding at the cement-formation interface. The SBL tool is able to determine the bonding condition for a specific azimuth. The ultrasonic log has higher resolution and is more capable of determining the hydraulic isolation, in addition to bonding. However, determining the hydraulic isolation depends on the fluid inside the cracks and channels, if any. The main concern with the acoustic methods is therefore determining the hydraulic isolation since the acoustic coupling does not count for this directly.

Even though the measurements presented on a CBL and VDL can be reliable, the logging tool has certain limitations. The ultrasonic tool can overcome some of these limitations, but has some limitations itself. Thus, the ultrasonic tool is not a replacement for the CBL tool, rather a supplement. It is beneficial to combine the different logs to improve the reliability. However, an important point is stated by Bigelow in the Journal of Petroleum Technology (1985): *As with any logging service, the analyst must understand each measurement – not only how it is made, but also its accuracy and inaccuracy under different circumstances*. By keeping this in mind, it is not always the tool that is the limitation, but the interpreter as well.

An overview of the limitations of the tools and possible solutions is given in table 3.1 below. The figures referred to in the table can be found below the table.

Table 3.1 - Limitations and solutions for the present logging tools

Impacted by (Reference)	**Indication** ***Consequence***	**Explanation (Figure)**	**Solution**
CBL/VDL			
Cycle-skipping (Economides et al., 1998)	TT increases. *Not valid to use this TT to interpret the log.*	The detection threshold is too high and the first signal arrival is not detected. (Figure 3.1 - Lower part)	Be aware when interpreting the log.
Cable noises/ forerunners (Economides et al., 1998)	TT decreases. *Not valid to use this TT to interpret the log.*	It is not the signal itself that triggers the receiver but cable noises/forerunners. (Figure 3.1 - Shows the detection level)	Be aware when interpreting the log.

Casing eccentricity – touching formation	High amplitude. Late signal arrivals on the VDL with zigzag pattern.	The pipe is most likely free, but is touching the formation at one side. The zigzag pattern is caused by formation arrivals, while high amplitude indicates inadequate cement. (Figure 3.2)	Be aware when interpreting the log. Combine the CBL with VDL.
Casing eccentricity	Low amplitude. TT changed from its baseline (increased or reduced). *Do not conclude with good cement before verifying the results.*	When eccentricity increases, the annulus will be reduced at one side, which will reduce the TT. If the annulus is increased, the TT will increase.	Be aware when interpreting the log. The cement might be good, but it is difficult to determine the exact bond status. Quality control with other logs. Combine the CBL with VDL.
Light-weighted cement (Benge, 2014)	*Difficult to distinguish between mud and cement.*	Cement density close to the density of the mud (i.e. foamed cement) makes it difficult to distinguish between the materials.	If the cement used is known this shall be included when interpreting the log. Using an ultrasonic tool with PC technique will also be helpful.
Fast formation (Bigelow, 1985) (Catala and Henry, 1984) (Economides et al., 1998)	Low TT (lower than the baseline). High and low amplitude. *The amplitude cannot be used to calculate and derive the attenuation, compressive strength of the cement or the BI.*	Fast formations have very high velocity and the acoustic signal from the formation will often reach the receiver ahead or at the same time as the pipe signal. This will result in an amplitude measured from the formation instead of the pipe. However, the bond to the formation and pipe might be good and the cement might be of high-quality even though the amplitude is high. (Figure 3.4)	Do not associate fast formations with noises or eccentricity. The VDL can be used to determine if the signal is from the pipe or formation; if the first arrival on the VDL differs in arrival time when tracing the log up and down, the signal is from the formation. To compensate for these effects, a small enough spacing can be used.

Impacted by (Reference)	**Indication** *Consequence*	**Explanation (Figure)**	**Solution**
CBL/VDL			
Micro-annulus (Economides et al., 1998)	Strong formation signal on the VDL. High/moderate amplitude. *The CBL/VDL does not see the cement when a gap is filled with liquid.*	A micro-annulus is generally caused by pressure variations in the casing fluid after set cement and the casing will expand or contract. These micro-annuli are usually very small and not an effective conduit for fluids to migrate, thus, the cement can be bonded and of high-quality even though micro-annuli exist. (Figure 3.5)	Pressurize the casing to overcome the micro-annuli or use an ultrasonic tool which is not sensitive to liquid-filled micro-annuli. Be aware that if there is one or several micro-annuli; in the case of several, it might affect the isolation of the cement.
Mud cake (Bigelow, 1985)	Weak VDL. Low amplitude. *Do not conclude with good cement.*	When the cement is set across permeable zones where a mud cake is presented, the cement will not bond to the mud cake. When the mud cake dries and shrinks away from the cement it results in a void space at the interface, and poor acoustic coupling to the formation. (Figure 3.6)	Use a combination of logs to reveal this impaction and do not use the log to determine the status of the cement.
Channels (Benge, 2014) (American Petroleum Institute., 2008) (Smolen, 1996)	*It is difficult to detect a liquid-filled gap with CBL/VDL. Furthermore, distinguish between a high-strength cement with a channel and a low-*	If the formation signal on the VDL is strong and the amplitude on the CBL is high without identifying any micro-annuli when pressurizing the casing it might indicate a channel.	Using an ultrasonic tool with higher resolution which is less impacted by a liquid-filled gap is necessary. However, identifying channels is the main concern with the

(King, 2012)	*strength cement without a channel is not possible as they have the same amplitude.*	However, the CBL/VDL is dependent on the shear coupling which is sensitive to liquid and gas and the cement becomes invisible in this case. The CBL measurement is also an average around the wellbore which means that the amplitude for a high-strength cement with a channel is similar to the amplitude for a low-strength cement without a channel.	acoustic logs as gas-filled gaps are not possible to identify.
Low resolution (Bybee, 2007)	*This applies to every CBL/VDL that is run.*	The attenuation attribute is averaged for all azimuths during the measurement.	Use a tool with higher resolution, such as the segmented bonded tool or ultrasonic tool.
Casing size (Rabia, 2001)	*The CBL is only valid for 9 5/8" casings and less.*	This is caused by the construction and function of the tool.	Ultrasonic tools can log casings up to 20" due to the flexible position of the transducer.
Cement thickness	Thin cement sheath.	The cement sheath has to be of a certain thickness to ensure reliable evaluation.	Use an ultrasonic tool.
ULTRASONIC TOOLS			
Gas-filled channels	*In the case of a gas-filled channel, the cement becomes invisible on the log.*	When gas is presented in the cement, the acoustic impedance will be reduced and the cement becomes invisible. This is because the acoustic logs depend on the acoustic coupling and not the hydraulic isolation of the cement.	This is the main challenge with the acoustic logs, which makes it challenging to determine the hydraulic isolation.

Impacted by (Reference)	**Indication** *Consequence*	**Explanation (Figure)**	**Solution**
ULTRASONIC TOOLS			
Heavy mud (Nelson, 1990)	The level of received energy will be low or prevented when using the PE tool. *Not valid measurement.*	The heavy mud result in a large attenuation of the high-frequency ultrasound, which in turn result in receiving low energy.	The heavy mud can be compensated for by using the PC ultrasonic tool.
Light-weighted cement and low impedance contrast (Schlumberger, 2011)	*Difficult to distinguish between materials with low impedance contrast for PE ultrasonic tools.*	PE ultrasonic tools rely highly on the impedance contrast between the materials, which makes the measurements unreliable in this case.	The PC ultrasonic tools are a better tool to use when the impedance contrast of the materials is low.
Tool eccentricity	Same as for the CBL/VDL.		

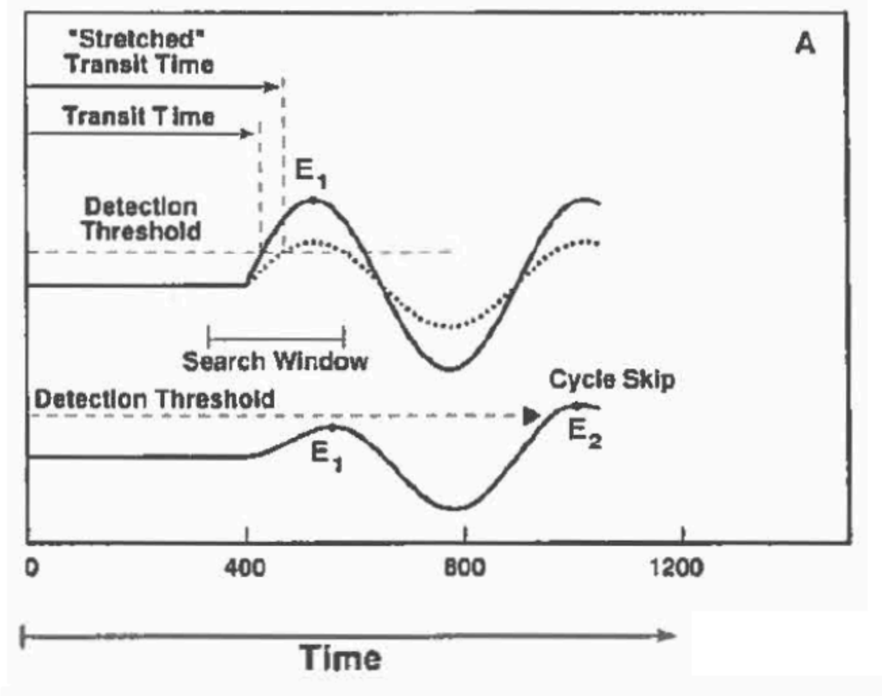

Figure 3.1 - TT, detection threshold and cycle skipping (Economides et al., 1998)

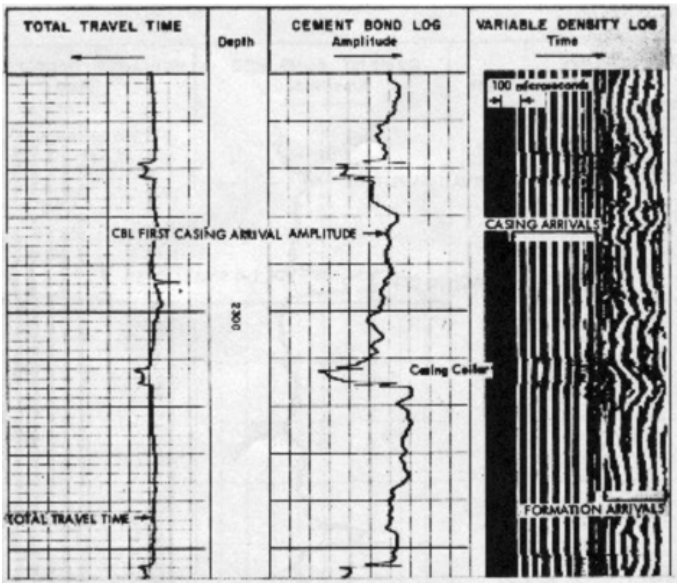

Figure 3.2 - CBL and VDL affected by casing eccentricity

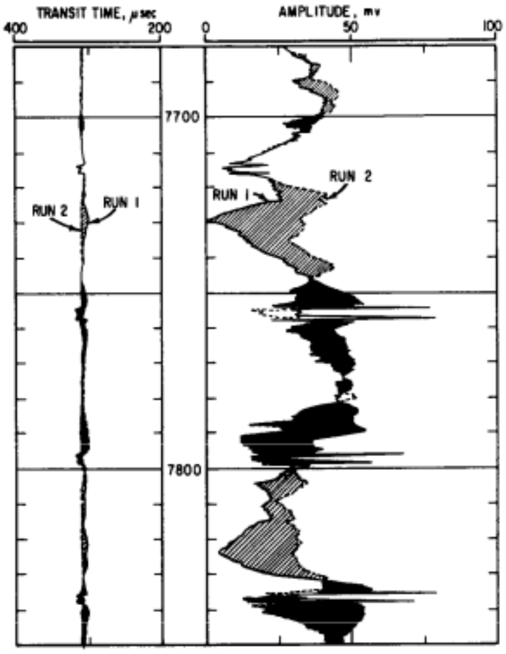

Figure 3.3 - CBL affected by tool eccentricity (run 2 with additional centralizers) (Fertl et al., 1974)

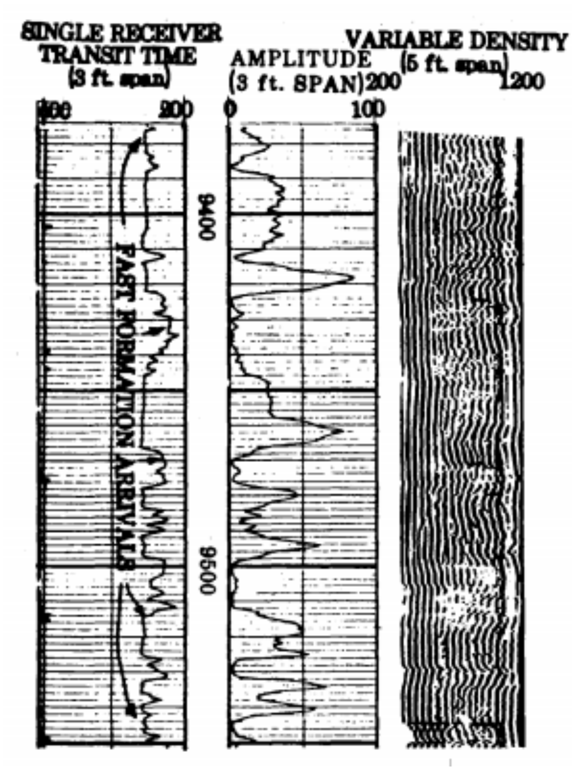

Figure 3.4 - CBL and VDL affected by fast formations (Bigelow, 1985)

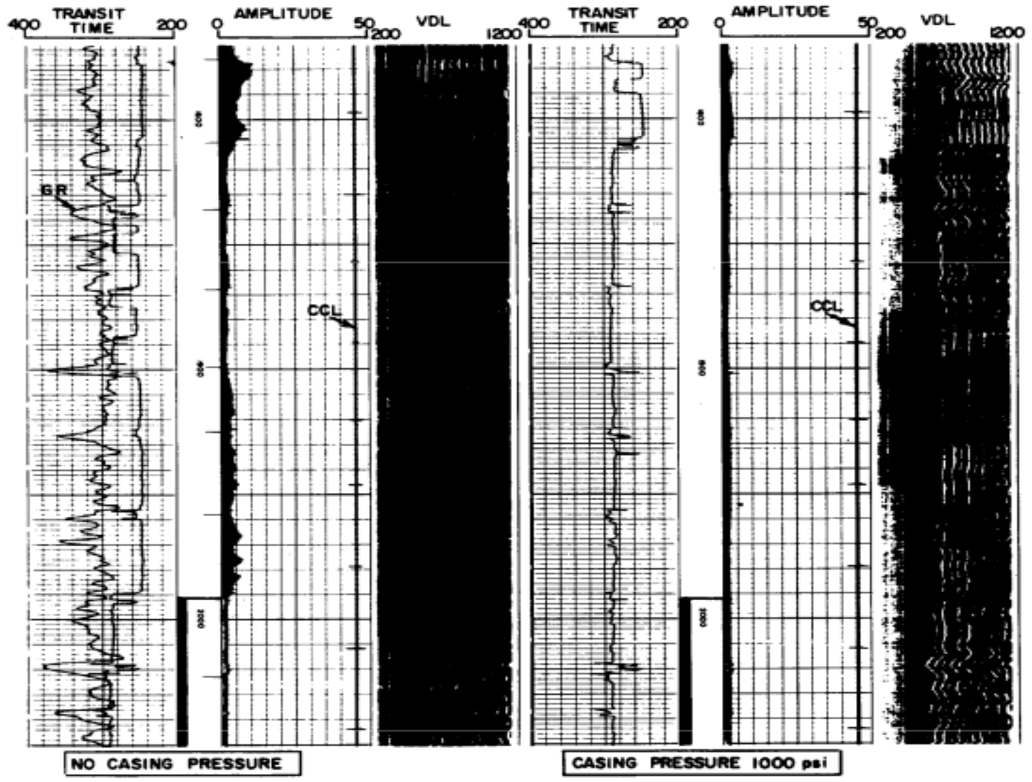

Figure 3.5 - CBL and VDL affected by a micro-annulus without and with casing pressure (Fertl et al., 1974)

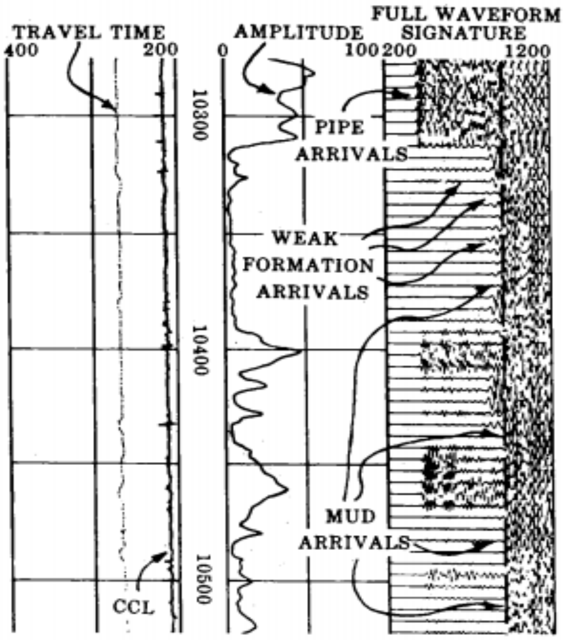

Figure 3.6 - Logs affected by permeable zones caused by a mud-cake (Bigelow, 1985)

3.2 Potential Cement Evaluation Methods

Acoustic logging methods to evaluate the cement are challenged to meet new environmental conditions and regulatory requirements, in addition to the already existing limitations identified in the last chapter. Furthermore, the oil and gas industry is challenged by enormous costs. This provides the basis for examining other potential methods which are able to visualize the downhole well environment in a more accurate, efficient and safe way. Methods investigated in this thesis are technologies from the medical sector; computed tomography (CT) and magnetic resonance imaging (MRI), in addition to the possibility to use drill and borescope to evaluate the cement downhole. Logging through multiple casings is also included here. The different technologies and methods are described briefly in the following subchapters and discussed further in chapter 5.

3.2.1 Computed Tomography

A CT Scan combines the power of X-rays with computers and provides a 360 degrees cross-sectional view of the scanned body by images. In the medical sector, the CT Scan is able to detect details of bony structures or injuries, diagnosing lung and chest problems and detecting cancers.

Different from the ultrasound, the CT uses X-rays, which is ionizing radiation, instead of sound waves. This is a disadvantage by using CT. The CT technology is also a bit more expensive. However, it is said that the X-ray imaging in the medical sector is one of the fastest and easiest ways to view the internal organs and conditions of bones. If these advantages are utilized when evaluating the cement, the CT technology becomes of high interest.

It has already been investigated if it is possible to use CT to evaluate the cement. So far, Albawi et al. (2014) and De Andrade et al. (2014) have performed downscale tests in the laboratory, where CT scans of the cement are conducted. The setup is shown in figure 3.7 below. The CT scans have been consistent with similar studies.

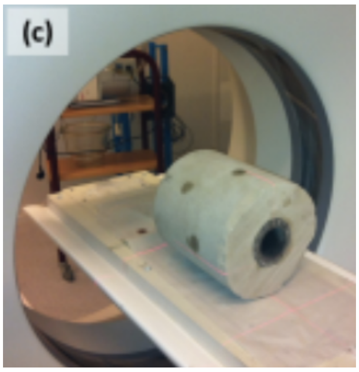

Figure 3.7 - CT scans of a cement sheath in the laboratory (Albawi et al., 2014)

When applying the technology for cement evaluation, a small amount of X-ray radiation is emitted from an X-ray source and an X-ray backscattering process is used to penetrate the casing material. The X-ray beams passes through the casing and into the cement, where the casing, cement and different gap materials lead to elastic and inelastic interaction between the emitted X-ray beam and the materials. These interactions result in an intensity attenuation of the beam and the remaining photons are detected at the receivers. The detected photons will provide an indication of the density of the material and contribute to generate a density map of the casing and cement. The X-ray beams penetrate easily through low density material, but not through materials with high density. Dense objects appear white on the X-ray film, while lighter objects appear grey, and might be difficult to see (HU and Guo, 2016). This density contrast makes it possible to distinguish between the materials, where increased number of photons indicates low density, which might represent a void. Thus; this technology has a potential for being used for cement evaluation.

The CT scans of the cement from the studies performed by De Andrade et. al. are shown in figure 3.8; a) and b) are in 2D, c) shows how 2D data are processed to obtain a 3D visualization, which is shown in d) and e) (2015). The failures are also clear in a), b), d) and e).

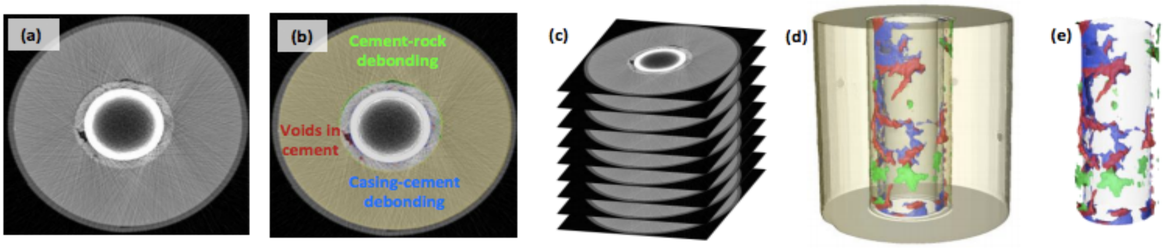

Figure 3.8 - 2D and 3D visualization of a cement sample by using CT (De Andrade et al., 2014)

The azimuthal rotation of the X-ray tool makes it possibly to measure a 3D energy spectrum for the backscattered photons. The reflection points of the photons ensure that the entire diameter of the cement is investigated as the tool moves through the well (HU and Guo, 2016). This makes it possible to achieve a detailed evaluation of the cement, where geometry, size and defects in the cement, such as gaps or bubbles, can be identified. The X-ray tool can be located in a WL tool housing, and a rig is not necessary.

Furthermore, the company Visuray has developed a Downhole X-Ray Platform based on other industries, which uses X-ray scattering to produce clear images within the downhole environment. The backscattering technology works in any borehole fluid, while the forward scattering technology makes it possible to investigate the environment through multiple casings. This is possible due to the brightness of the X-ray source. At present, Visuray develops a tool, VR360, which are able to evaluate advanced cement downhole, and according to themselves this tool is superior to the common used cement evaluation technology. In this tool, X-ray photons are emitted radially from the tool to evaluate the cement integrity and detect mechanical anomalies. It is a direct measurement of the cement distribution and has been successfully tested in full-scale, both in single – and dual-casing well environments. Limitations with this tool are not known yet[5] (Visuray, Unknown). However, the CT technology's ability to directly evaluate cement distribution and determine the integrity is proven.

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[5] The author has been in touch with Visuray about the VR360 tool. Unfortunately, they were not in position to discuss the tool as it is still in development. It was preferred to get more information about the development, technology and limitations, however, Visuray referred to their web page where some information will be shared from time to time (www.visuray.com).

3.2.2 Magnetic Resonance Imaging

MRI is widely used in the medical field to visualize the internal structures of soft tissues in the human body by measuring the water content. The last decades, the MRI technology has been tried in other fields as well, such as investigating the reservoir fluids and formation's permeability and porosity in an open hole. MRI has also been applied when evaluating concrete in the laboratory.

The MRI combines an advanced computer system, radio-frequency (RF) pulses and a powerful magnetic field to provide accurate and detailed pictures of a body. The magnetic field is utilized to manipulate the magnetic elements inside the body and produces highly detailed images (Marfisi et al., 2005). The magnetic field aligns all the hydrogen nuclei presented, and the RF pulses change its orientation. When the field is removed, the axis of the hydrogen nuclei returns to its original equilibrium state, and a signal is produced at the same time, which is detected by the receiver and further analyzed. The signal is proportional to the density of the hydrogen, thus; indirectly related to the water content. This can be used to measure the bulk properties of a cement sample and is known as nuclear magnetic resonance (NMR). If the cement is still wet or if the fractures in the concrete are filled with water, it is possible to determine the status and structure of the cement, in addition to detect the fractures and possible voids. It is possible to provide a 3D representation of the body and it is preferred to take two types of images. One image which shows clearly the structure and one image that shows the fractures. This makes it easier to distinguish between matrix and fractures as both might show up in grey. In this way, the MRI can be used to both study the internal geometry and measure the fractures (Marfisi et al., 2005).

Two time constants are measured for the MRI response. The first time constant is the longitudinal relaxation time, T_1, which expresses the process of return to thermal equilibrium after disturbed by a radio wave. The second time constant is the transverse relaxation time, T_2, which expresses the process of loss of magnetization in the transverse plane. These constants provide insight to the materials properties, such as molecular, magnetic and physical properties. To generate an NMR image, the criteria is that it has to be possible to encode spatial information in an NMR signal in a time of the order of the T_2. Liquids have long enough time to enable imaging, while imaging in solids is more difficult since the time of imaging is shortened

(Jezzard et al., 1991). However, it has been found that several natural rock properties are correlated with the NMR amplitude and the relaxation time (Foley et al., 1996).

Various cement types including holes and their responses on the NMR imaging have been studied by others, both immediately after the cement is set and after it is hardened. After hardening, the ordinary Portland cement occurred to show a minor loss of circularity in the image of the water in the holes, in addition to loss of circular beaker. This is illustrated in figure 3.9a). The reason for this is that the Portland cement contains iron, which is a paramagnetic material, Magnetic elements disturb the magnetic field, which has to be very homogenous to achieve reliable measurements. White Portland cement is investigated the same way, and shows very little distortion from the original dimension. However, the circular beaker is not visible after hardening of this cement neither, which is shown in figure 3.9b). The reason for this is that the MRI signal is decreased gradually to zero when the cement hardens. This applies for both Portland and white cement. The MR signal depends on the mobile water and when the water and cement powder transform into a solid material, the MR signal is no longer detectable as T_1 and T_2 are decreased due to tightly bounded hydrogen nuclei and hydroxides (Marfisi et al., 2005).

When studying plaster in the same way as the Portland and white cement, both the holes and plaster were clear and easy to detect, both before and after hardening. This is illustrated in figure 3.9c). Note that these tests were performed with a sample in the laboratory (Marfisi et al., 2005).

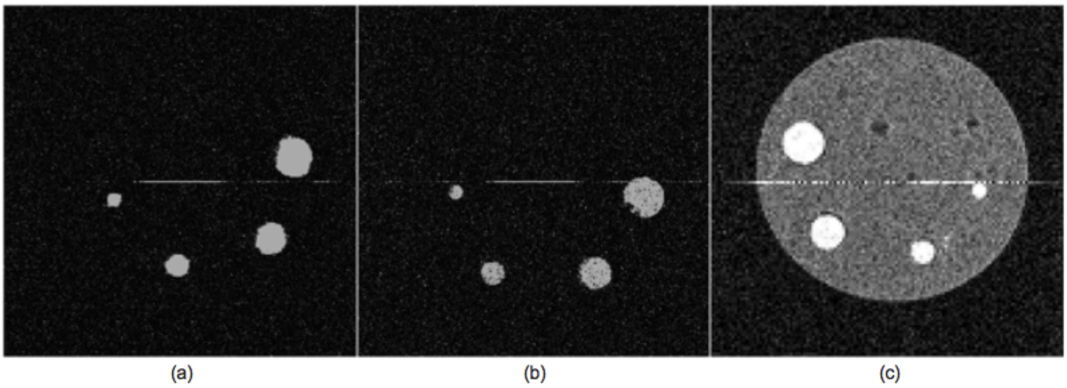

Figure 3.9 - MRI response of different cement types: (a) Portland cement (b) White cement (c) Plaster (Marfisi et al., 2005)

Furthermore, the system that is exposed to MRI has to be calibrated for each case and it is necessary to have knowledge about the physical characteristics of the material. This knowledge is important to reveal impactions on the signal. It is also found that it is not possible to use MRI when studying concrete reinforced with steel due to the distortion of the MRI Scans (Marfisi et al., 2005). Thus, using it in the well consisting of several casings will be inappropriate, which is discussed further in chapter 5.1.2.2.

3.2.3 Drill and Borescope

The borescope is an optical device which makes it possible to inspect inaccessible areas and places that are not visible by the naked eye. The tool consists of a tube with an eyepiece on one end and an objective lens on the other end. A camera is connected to the eyepiece. Light from the tool is directed towards the inner reflecting surface which is going to be inspected. The reflected light will be monitored.

The borescope can replace time-consuming and expensive activities, and is common to use when inspecting different engines and turbines (Viktorov, 1993). In addition, the borescope is used in investigations of hydraulic structures and when inspecting the interior of bores (Smart, 1995). A core sample from the structure is extracted and evaluated, and in the case of defects, the borehole can be inspected by the borescope. The borescope is a half cylinder consisting of a mirror at an angle of 45 degrees and a 12 W electric bulb. The tool is lowered on wires into a dry borehole, which makes it possible to see the borehole walls by illumination reflected in the mirror (Viktorov, 1993). This makes it possible to inspect the quality of permanent structures in a simple, clear and inexpensive way. By using this tool, unnecessary maintenance can be prevented.

The author has not found any references for using this tool when evaluating the cement in a well, however, the possibility for applying this is discussed in chapter 5.1.2.3.

3.2.4 Logging Through Multiple Strings

By being able to log through multiple casings, the removal of the strings might be unnecessary for logging the outermost casing, and it might become possible to leave the tubing in the well. Time will then be saved. However, how much time that will be saved has to be studied further to see how profitable it is. In addition, it has to be studied if it is possible to log through MT1C, and it that case, the reliability has to be verified.

Viggen et. al. (2016) investigated the opportunity to use the PC technology to log through multiple casings, which is further investigated in appendix B.3.3.2. The study indicates that it is possible to log beyond the second casing in a well by utilizing the Lamb wave packets. Furthermore, Visuray's X-ray tool from chapter 3.2.1 seems to be able to log through at least two strings as well.

The opportunity, advantages and disadvantages for logging through MT1C are further discussed in chapter 5.1.3.

3.3 Potential P&A Procedure Improvements

Improvements for the P&A procedure itself are also investigated as it is likely to believe that the right improvements will affect the costs and safety of the present operation significantly. The operations of interest in this thesis are about removing the tubulars efficiently. At present, cutting and pulling the casing is common to remove the tubulars downhole, where multiple cut and pull operations might be necessary to complete the job, which is time-consuming. In addition, a suitable interval to cut the casing has to be found to avoid additional problems with pulling the casing. It is preferable that the casing is free in this area and finding such interval is done by logging. If the logging tools are unsuitable for the conditions or the interpretation of the logs contains errors, as proven earlier in this thesis, the cut and pull operation might become even more complex. This is because if the logs show that annulus is filled with fluid when it is actually filled with cement and the casing is bonded, it becomes difficult to pull the casing. Time is then spent on trying to loosen the casing and if the casing is stuck, time-consuming and risky operations such as section milling or PWC are the solution. An introduction to the section milling and PWC operation is given in appendix B.2.2 and B.2.3. Furthermore, respectively Thomas Ringe's thesis (2015) and Torleiv Midtgarden's (2013) thesis are recommended.

In addition to the time, the safety is exposed due to the swarf generation, wear and vibrations during the section milling operation. The PWC operation is safer to perform than the section milling operation, however, improvements are still preferred. Not surprisingly, it is most preferable to complete the P&A operation in one run, at least in as few runs as possible, but operations such as section milling and PWC increase this number. Possibilities to make the removal of the strings more efficiently are therefore briefly described below, and includes corrosion of the steel and using laser to remove the strings. The possibility to leave the tubing in the well is also looked into. Common for these operations is that they can be performed without a rig. They are not fully developed and little research are done within the areas, at least published research. However, it is known that different companies have looked into them to see if it is beneficial for the P&A operation. The methods will be discussed further in chapter 5.

- **Using controlled corrosion to remove the strings:**
  By turning the corrosion of the strings into an opportunity, the corrosion can be used to remove the strings in the well in a cheap and environmental-friendly way without using a rig. This can be done by controlling the dissolution by either chemical or electrochemical methods (Bjørgum, 2017). SINTEF has proven high dissolution rates of casing by controlled corrosion in the lab[6].

- **Using laser to remove the strings:**
  By using a high-power laser downhole, it is most likely possible to burn an interval of the casing in a short time, and the casings and cements can be removed in one run. When the tubulars and cements are removed, it will be possible to place a complete horizontal and vertical barrier in this interval. In this case, no rig will be necessary and the existing annular barriers are not important for the operation. This operation seems to have a huge potential to improve the present P&A operation.

- **Leaving the tubing in the well:**
  By leaving the tubing in the well time will be saved on not removing this. There is no need for a rig to pull the tubing and costs are reduced. Studies and full-scale tests are conducted on this topic and it is proven that it is possible to obtain a good cement placement and achieve a sufficient barrier when the tubing is left in hole (LIH) (Aas et al., 2016). The advantage of leaving the tubing in the hole and if it is practically possible is discussed in chapter 5.

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[6] This topic was discussed at SINTEF's P&A conference in Trondheim in March 2017 by Astrid Bjørgum from SINTEF. The author has been in touch with SINTEF, however, the method is only in the initial phase. SINTEF will continue the research during the fall/winter of 2017.

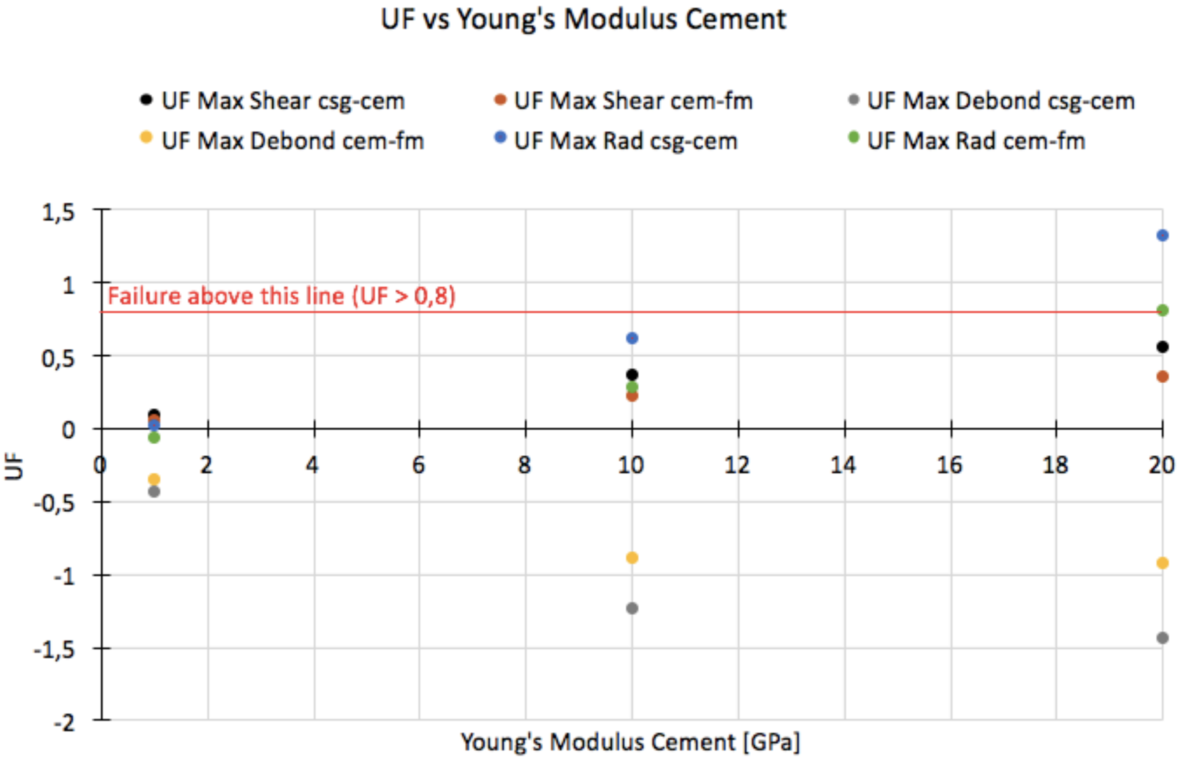
4 Results

The results from the research in chapter 2 and 3 are presented in the subchapters, and discussed further in chapter 5.

4.1 Annular Integrity Analysis

The numerical annular integrity model was used to vary different parameters in the well to see how they affected the annular cement, which is important to be aware of when planning a P&A operation. By using the UFs from chapter 2.2, it is possible to identify any failures and determine the risk of failure. The Young's modulus of the cement, the Young's modulus of the formation and the wellbore pressure were varied separately in the model to see the effect on the cement integrity. The UFs for the different scenarios were calculated from equation (22), (23) and (24) from chapter 2.2 and are presented in the plots below. The pressures used to calculate the UFs are estimated by the numerical model as well, and are presented in appendix A.2.

Plot 4.1 shows the UFs when varying the Young's modulus of the cement.

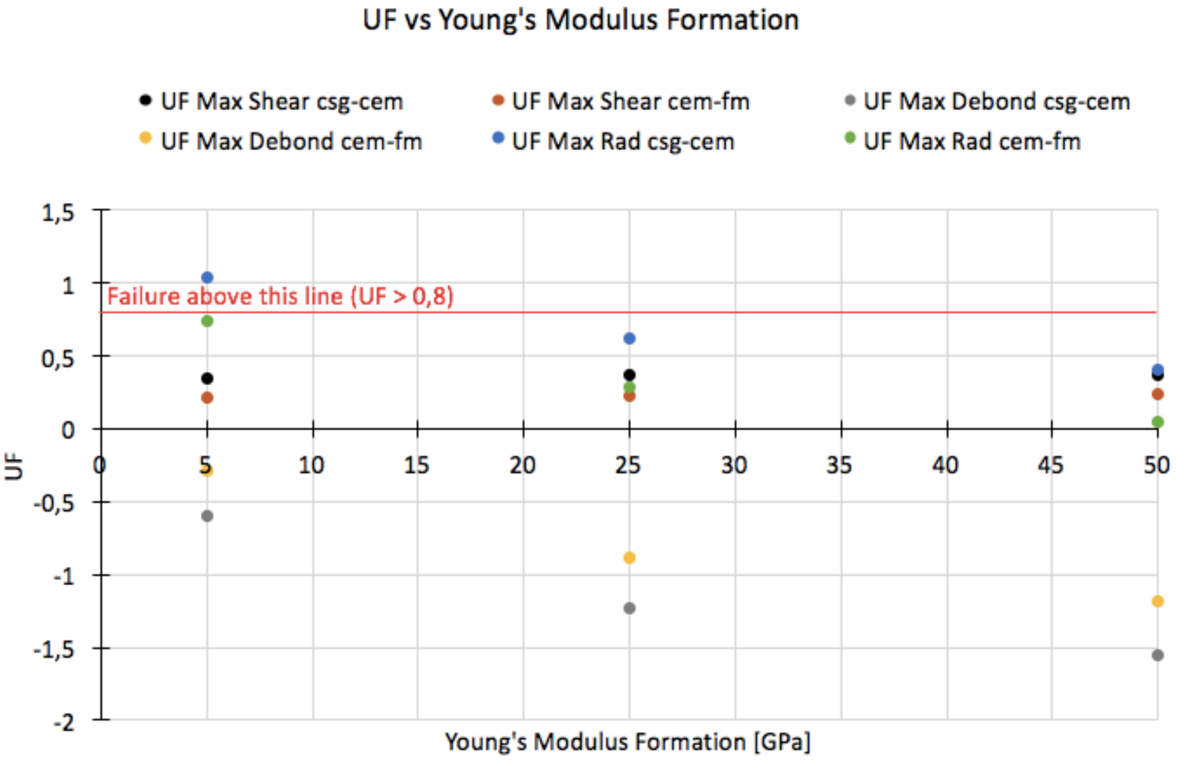


Plot 4.1 - UF as a function of Young's modulus of the cement

Seen from the plot above, the probability of de-bonding decreases with increased Young's modulus of the cement, while the probability of shear failure and radial cracks increases. With

Young’s modulus of the cement equal to 25 GPa, which means that the cement is stiff, radial cracks occur at both interfaces. The failure is most severe on the casing-cement interface.

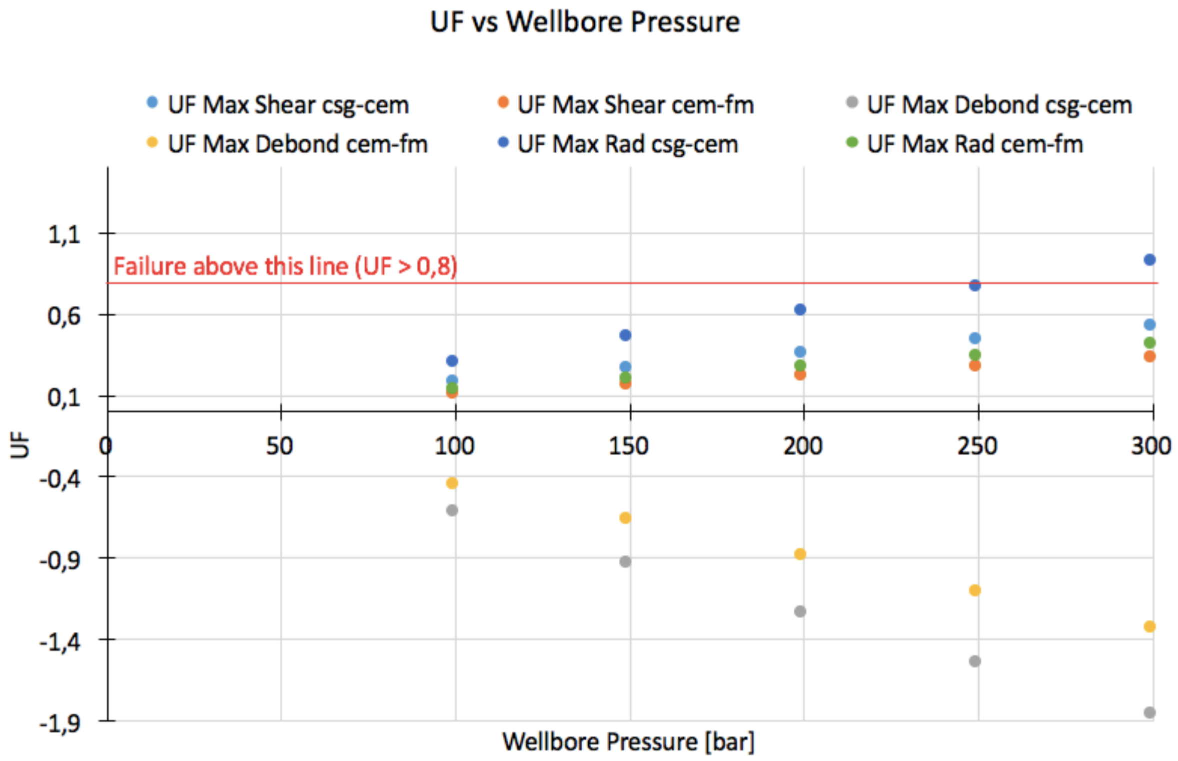
Another parameter investigated is the Young’s modulus of the formation. Varying this property gives the UFs presented in plot 4.2.



Plot 4.2 - UF as a function of Young's modulus of the formation

From the plot above one can see that when the Young’s modulus of the formation is increased, the risk of radial cracks and de-bonding failures decrease. It is still the radial crack failure at the casing-cement interface caused by the tangential tensile stress that is the most critical failure. It is especially critical with low Young’s modulus of the formation. Deformation is therefore prevented when the Young’s modulus of the formation is high. The sharp eye will notice that the risk for shear failure increases when increasing the Young’s modulus of the formation. However, this increase is not significant.

The wellbore pressure affects the failure modes as well. This is presented in plot 4.3 below and shows that the risk for de-bonding decreases with increased wellbore pressure, while the risk for the other failure modes, shear failure and radial cracks, increases with increased wellbore pressure. Radial cracks at the casing-cement interface are the most critical failure here as well.



Plot 4.3 - UF as a function of wellbore pressure

What was found from the model in Ansys is summarized in table 4.1 below and discussed further in chapter 5.3. Arrow pointing upwards indicates increasing value, while arrow pointing downwards indicates decreasing value.

Table 4.1 - Results from the annular integrity model

		Radial stresses	**Tangential stresses**	**Probability of failure**		
				De-bonding	**Shear failure**	**Radial cracks**
E$_{cem}$	↑	Compressive radial stresses increase	Tensile tangential stresses increase	↓	↑	↑ (Failure)
	↓	Compressive radial stresses decrease	Tensile tangential stresses decrease and become compressive	↑	↓	↓

		Radial stresses	**Tangential stresses**	**Probability of failure**		
				De-bonding	**Shear failure**	**Radial cracks**
E_{fm}	↑	Compressive radial stresses increase	Tensile tangential stresses decrease	↓	↓	↓
	↓	Compressive radial stresses decrease	Tensile tangential stresses increase	↑	↑	↑ (Failure)
E_{well}	↑	Compressive radial stresses increase	Tensile tangential stresses increase	↓	↑	↑ (Failure)
	↓	Compressive radial stresses decrease	Tensile tangential stresses decrease	↑	↓	↓

4.2 Potential Cement Evaluation Improvements

The different cement evaluation methods studied in chapter 3, both present and potential, are summarized in table 4.2 below. The methods are discussed further in chapter 5.1.

Table 4.2 - Present and potential cement evaluation methods

	Sound waves	**CT**	**MRI**	**Drill & borescope**
Applicable	Yes	Yes, but not used in the field yet	No (Limited by impactions on the magnetic field)	No (Limited by the procedure)
Reliability	Depends on the conditions and the interpreter	Unknown	-	-
Costs	Cheap	Not as cheap as sound waves	-	-
Size of tool	Small	Unknown	-	-
Determine bonding	Yes	Yes, according to the studies	-	-

Determine hydraulic isolation	Not directly, but can identify cracks and channels if the resolution is high and if they are not filled with gas	Yes, according to the studies	-	-

In addition, the possibility to log through multiple casings is on the agenda. So far, it seems like using the PC technique or X-rays make it possible to log through MT1C. This is discussed further in chapter 5.1.3.

4.3 Potential P&A Procedure Improvements

It has been looked into possibilities to improve the P&A procedure itself as well. What was found in chapter 3.3 is summarized in table 4.3 and discussed in chapter 5.2.

Table 4.3 – Potential P&A procedure improvements

	Logging to ensure barriers	**Laser to remove strings**	**Corrosion to remove strings**	**Leave tubing in the well**
Possible	Yes, but contains limitations at present	Yes, but under development	Yes, but under development	Yes, but under development
Reliable	Depends on the conditions and the interpreter at present	Most likely	Unknown	Yes
Costs	Cheap	Unknown	Cheap	Cheap
Time-efficient	Depends on the runs required to log and ensure integrity	Most likely	Unknown, depends on the time of the corrosion	Yes
Rig-less	Yes, as long as the strings can be LIH	Yes	Yes	Yes
Main advantage	Well-known today	One operation for everything and not dependent on existing barriers	Cost-effective and environmental-friendly	Not necessary to spend time on removing the tubing

5 Discussion

Safety, time and costs trigger the challenges related to the P&A operation. Reducing the time of the P&A operation without exposing the safety is therefore of high interest, and will reduce the costs of the operation as well, especially offshore. From the first part of this thesis, it is no doubt that the widely used cement evaluation methods consist of several limitations and might become both time-consuming and risky to use. The interpreter of the logs limits the reliability of the logs as well. However, at present, the industry is forced to use and rely on these logs as there is no alternative method for evaluating the cement which is preferred to be used as an external barrier when the well is abandoned.

"Most likely", "Probably", and "Possibly" are widely used when interpreting a cement log. This is neither reliable or sufficient when the objective is to ensure well integrity. In addition, the time spent on ensuring well integrity increases when there are problems related to the logging operation and the interpretation of these. Therefore, improvements within this area is necessary and has to be developed in accordance with the regulatory requirements and physical conditions downhole, which was emphasized in chapter 2.

A more time-efficient and safe P&A operation will have a large group of users, both in Norway and worldwide. Hence, it will be a high source of income for the developer, and the problems related to the P&A operation will indeed be turned into an opportunity. Norway has a high standard with high accuracy and expertise and has the opportunity to become just as leading in P&A technology as Norway is in subsea technology.

An illustration of the a well prior P&A and common plug locations are shown in figure 5.1, and a flowchart of the P&A operation is shown in figure 5.2[7]. The flowchart shows that there are multiple alternatives when plugging a well, dependent on the conditions and the information available, while figure 5.1 can be used to understand the different scenarios that will be discussed. Be aware that the flowchart is simplified and has not included every step necessary for the execution. There might be other possibilities as well, however, it is only meant as a

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[7] The colors in the chart indicates how preferred the certain step is. Green is safe and efficient, yellow requires more time-consuming steps and are more complex, while the grey indicates an unlikely step.
Abbreviations: alt – alternative * ann – annulus * cem – cement * csg – casing * int – integrity * tbg – tubing

facility to understand how and why the P&A operation differs from well to well, which is important to understand to be able to improve the operation.

From the flowchart in figure 5.2, it can be seen that the most time-efficient P&A operation is when the P&A operation is planned for in the planning phase. However, including this operation in the planning phase is only done for more recent wells, while the scope of this thesis is to be able to plug older wells as well. It is therefore assumed from here that the P&A operation of the well is not planned for in the planning phase.

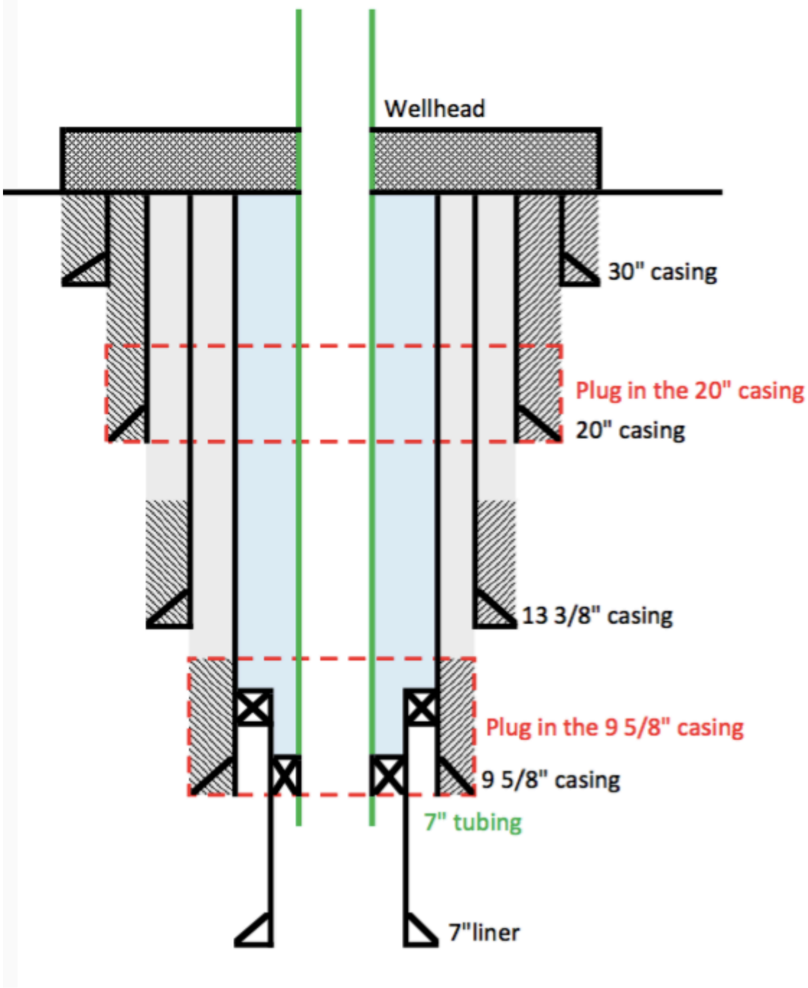

Figure 5.1 - Common well layout prior a P&A operation (plug locations marked with red)

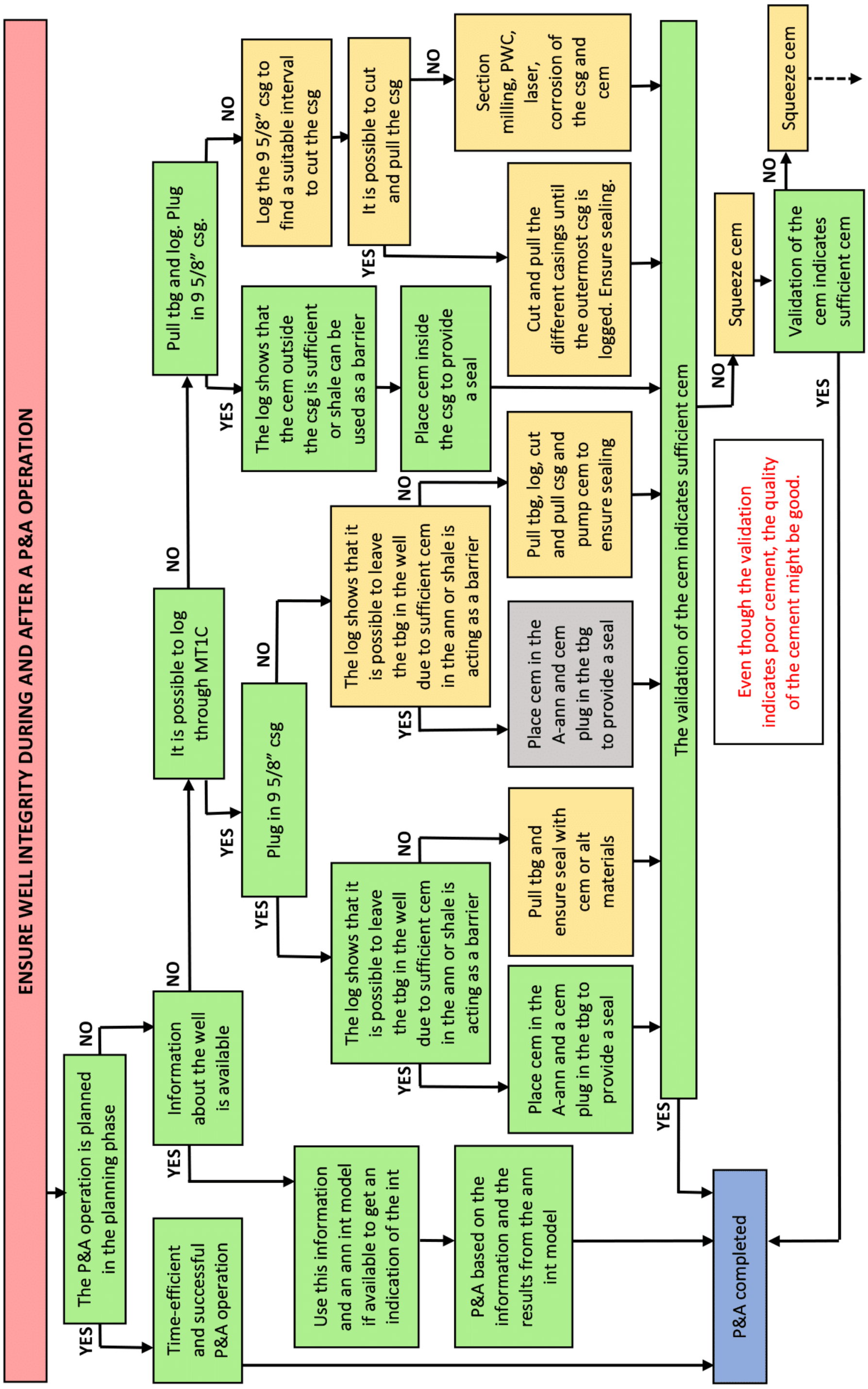

Figure 5.2 - Flowchart of the P&A operation

If there is known information about the well, such as stresses, cement properties and the primary cement job and a cement log exists, it becomes less time-consuming to plan the P&A operation as this information is used to design an appropriate operation. In addition, the information can be implemented into an annular integrity model, if available, to contribute to determine the status of the cement and to determine the necessary P&A operation. Such model was explained in chapter 2.2 and will be discussed further in chapter 5.3. Anyway, the model can for instance give information about the weakest point within the cement and failures can be detected, and then be compensated for. Using these results and available information about the well when interpreting a cement log will increase the reliability of the interpretation and the probability of a successful P&A operation increases. The more data, the better. Using an annular integrity model is discussed further in chapter 5.3. However, if information about the well is not available, logging the well is necessary to retrieve as much information as possible about the cement and conditions in the annulus.

If it becomes possible to log through multiple casings, time might be saved. However, this depends on the tool being available, reliable and the function of the tool. The possibility to log through multiple casings will be discussed in chapter 5.1.3. However, assuming that logging through MT1C is possible, two scenarios are considered from figure 5.2:

- When establishing a plug in the in the 9 5/8” casing (see figure 5.1 for location), which is common for the primary or secondary barrier, it is possible to obtain a time-efficient operation. When it is possible to log through MT1C, it is not necessary to remove the tubing as it is possible to log through it, through the A-annulus and through the 9 5/8” casing. If sufficient cement exists outside the 9 5/8” casing, this will be used as an external barrier and it is only necessary to place cement in the A-annulus and in the tubing. Be aware that setting a cement plug in a small hole has higher probability of contamination of the cement, which can be challenging when setting the plug in this casing and tubing. The possibility to leave the tubing in the well is not a common procedure, but is discussed further in chapter 5.2.3. However, if the cement outside the 9 5/8” casing is poor, remedial, more time-consuming operations have to take place. For instance, with the present P&A, the tubing has to be pulled.

- When establishing the plug in the 20” casing (see figure 5.1 for location), which is common for the open-hole-to-surface-barrier, the conditions outside this casing have to be determined. Theoretically, when it is possible to log through multiple casings it is not necessary to remove the tubulars, but this depends on how many strings it is possible to log through. In addition, it is unlikely that it exists a horizontal barrier across the entire well section at the planned barrier depth, which can be seen from figure 5.1. Thus, the strings have to be removed regardless of the possibility to log through MT1C. This makes it more interesting to look into how this removal can be done as fast as possible and how a sufficient barrier can be established in an efficient way. This is discussed further in chapter 5.2.

When it is not possible to log through MT1C, the strings have to be removed to evaluate the different annuli and to ensure a horizontal barrier across the entire well section. Two scenarios are studied from figure 5.2:

- For the plug in the 9 5/8” casing, the tubing has to be removed before logging the 9 5/8” casing and a rig is necessary with the present P&A operation. However, the operation becomes quite simple if the logging of the 9 5/8” casing shows a sealing barrier outside the casing. Then only a cement plug has to be placed inside the casing to provide a horizontal and vertical seal in the well. However, if the cement outside the 9 5/8” casing is poor, remedial operations have to be performed, which complicates the operation. This stage is not included in the flowchart.

- Plugs in the 20” casing requires removal of the tubulars to log and evaluate the conditions outside the casing.

Common for all scenarios discussed above is that if the cement outside the casing is poor and not sufficient to be used as an external barrier, it is necessary to remove the strings to be able to establish a barrier. At present, cut and pulling the casing is used for this removal, however, if the logs says it is bad bond where good bond exists, the casing might be stuck which requires removing the strings by section milling or perforate, wash & cement (PWC). These operations are explained in appendix B.2. In this case, logging through multiple casings becomes less useful, which is discussed in chapter 5.1.3. More reliable logging methods are preferred to avoid misinterpretation of the logs; however, it is still time-consuming to remove and log one and one casing if this is necessary. This gives grounds for looking into more efficient methods for removing the tubular. This is discussed further in chapter 5.2.

Furthermore, if the cement is going to be used as a barrier, it has to be verified, both as an external barrier and as an internal barrier. If the cement is insufficient, a remedial operation is necessary. This might include squeeze cement which is explained in appendix B.2.1. This is not preferred since there is no guarantees that this will work. The new cement has to be validated as well and if it is successful after the remedial operation, the P&A operation is completed. If not, another remedial operation is necessary and the cement has to be verified again. This increases the number of runs, and time and costs increase. However, this is required until a barrier is established, which is shown in the flowchart in figure 5.2.

Different scenarios are discussed above and it is obvious that with the present methods for P&A, the cement in the annulus is an important factor but might be challenging to evaluate and ensure. Methods to ensure the cement will therefore be further discussed.

5.1 Potential Cement Evaluation Improvements

To achieve a trustworthy evaluation of the cement sheath in the annulus, an appropriate tool and method have to be used. In addition, a challenge is that the present technologies are being challenged to meet new environmental conditions. The wells are getting deeper and the regulations are continuously getting stricter. Thus, the industry is always looking for more time-efficient and reliable cement evaluation tools. This can either be done by enhancing the present methods or by developing new methods within this area. Some potential developments were explained in chapter 3 and will be discussed further in the subsequent chapters. The more methods, the more information, the higher reliability.

However, developing new methods have some challenges as well. For instance, going from downscale to full-scale might require significant adjustments of the method. The conditions and dimensions in the lab differ from downhole and need to be compensated for to avoid detrimental consequences. However, this is not studied further in this thesis, but its limitations are interesting to look into.

5.1.1 Improving the Present Cement Evaluation Methods

The present logging tools are the sonic tool and the ultrasonic tool, which are able to provide an accurate determination of the cement quality and cement bond with the right downhole conditions. These tools have been introduced in chapter 3.1 and are explained further in appendix B.3. Both the sonic tool and the ultrasonic tool depend on the acoustic coupling between the materials in the well, and measuring the acoustic coupling does not measure the hydraulic isolation directly. However, ultrasonic tools with higher resolution have been developed and can be visualized in 3D, which makes it possible to identify defects within the cement sheath in some cases. Anyway, the hydraulic isolation is still the main concern when using the present logging tools. Especially gas-filled gaps are difficult to identify and makes the cement invisible on the log. In this case it is not possible to evaluate the cement correctly, and the time spent on logging and ensuring a barrier in the well increases. Due to this, and the challenges discussed from the flowchart in figure 5.2, the present cement evaluation methods are continuously studied to provide enhancement.

However, there have been no ground-breaking developments for the acoustic logging tools the lasts 10 years according to Kevin Constable which work as a discipline advisor for Cased Hole Logging in Statoil[8]. Constable states that Schlumberger's Isolation Scanner with the PC technology is the last pioneering development within this area. Due to this, it is reasonable to believe that the present logging methods are getting exhausted and other possibilities for logging shall be investigated to detect cement failures more efficiently. Developing new tools by using other technologies will give another view of the situation, which will be beneficial for the evaluation. It might be challenging to develop, but it is likely to believe that it will be profitable in the long run. In addition, it will be beneficial to have several opportunities when evaluating the cement due to the varying downhole conditions, and in this case be able to compensate for each other limitations. Potential undeveloped methods for evaluating the cement are therefore discussed further below.

5.1.2 Potential Cement Evaluation Methods

When searching for new methods to evaluate the cement, existing technologies from other industries are interesting. The fact that the ultrasonic PE technology is used in the petroleum industry as well as in the medical sector shows the possibility to transfer technology from one industry to another. The potential methods to evaluate the cement downhole discussed in this thesis are the possibility to use technologies applied in the medical sector; CT and MRI, in

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[8] The author was in touch with Kevin Constable due to his expertise within the logging area. He shared his experiences with logging and told about the limitations with the different tools.

addition to the possibility to use drill and borescope. The results from the research in chapter 3.2 were presented in chapter 4.2 and are discussed below.

5.1.2.1 Computed Tomography

Using CT to evaluate the cement is on the agenda. Some studies are done within this area, and it seems like CT is possible to use to evaluate the cement downhole and is able to both determine the hydraulic isolation and the bonding properties. Furthermore, Visuray is developing a tool that uses X-rays to evaluate the cement downhole, which underlines the usability of this technology for this purpose. Visuray's tool makes it possible to log through at least two casings as well, which might be beneficial in some cases. However, the limitations of the tool is not announced yet, and has to be further investigated.

The author has not identified any significant limitations by using CT to evaluate the cement at this point, unless the radiation exposure and the size of the tool. However, it is likely to believe that the people working with this tool will not be exposed to the radiation, as the tool will not be active at or near the surface. Furthermore, at present, CT applied for cement evaluation is done in the laboratory, which uses a large machine where the cement sample is placed inside the machine. In the well it is necessary that the tool fits inside the wellbore, however, it seems like Visuray has solved this challenge. Other limitations will most likely get known when the method is applied in the field.

The CT technology reveals some of the limitations with the traditional acoustic logging methods. For instance, the hydraulic isolation seems to be more reliable when using CT, and the X-rays distinguish easier between the different fluids which gives a more reliable evaluation. In addition, logging through MT1C seems to be possible by using CT. However, using the CT technology for this purpose has to be further studied and tested.

5.1.2.2 Magnetic Resonance Imaging

NMR and MRI are both used in well logging, however, they are only used for open-hole logging so far. In addition, the MRI can be used to investigate the structure and fractures of a concrete sample.

From the research in chapter 3.2.2, it is found that the MRI can be used to investigate the cement structure; however, this is dependent on the type of cement. Widely used Portland cement contains a small amount of iron which is magnetic, which in turn will affect the MRI response and make the measurements invalid. For the MRI operation to be successful, the magnetic field has to be really homogenous, which it is not when it is disturbed by other magnetic objects. Local distortions occur and the MR will then be messed up. In addition, the structure of the cement body becomes invisible when the cement hardens. Thus, using MRI in old wells with Portland cement is not a good option.

Another significant limitation by using MRI to evaluate the cement, is the casing steel. Evaluating the cement downhole includes interaction with the casing, and when this steel is magnetic, it will affect the magnetic field and MRI response. In addition, the casing is electrically conductive, which will serve as an antenna for the RF signal. The RF energy will be detected by the casing and transformed into heat. This will decrease the MRI response and the casing will be heated, which might result in consequences as expansion of the steel and other damages. Thus, using the MRI to evaluate the cement in the annulus downhole is inappropriate.

The size of the tool used to perform the MRI operation in the well is also crucial in this case, as it has to be quite small to fit in the well. Another challenge is how to determine if it is bonding or not with this technology. The MRI technology is also expensive in use. However, these limitations are not necessary to study further as the use of MRI for cement evaluation is prevented by other limitations.

5.1.2.3 Drill and Borescope

It is interesting to investigate if it is possible to use drill and borescope when evaluating the cement in a well. At present, it seems like the borescope is not widely used in the petroleum industry, however, it is likely to believe that the cement in the well can be inspected the same way as hydraulic structures and it is possible to perform without a rig.

However, using drill and borescope for cement evaluation consists of some limitations as well. First, the area of inspection is only a small part of the cement sheath. This makes the investigation local and it is difficult to say anything about the whole cement sheath without extracting lots of cores. Secondly, with regards to the thin cement sheath, cores extracted from the sheath might affect the cement integrity, and result in poor cement quality. Third, it is difficult to say anything about the bonding conditions without investigating the whole cross-section with cement. In addition, challenges as accessing the annuli, and time exist.

Summarized, it is difficult to evaluate the whole cement sheath by using this tool. In addition, the cement might be damaged. This method is therefore not appropriate when evaluating the cement downhole.

5.1.3 Logging Through Multiple Strings

An operation that is said that will most likely save both time and money when it comes to logging is the opportunity to log through multiple casings. At present, there are no proven or reliable methods used for this purpose but based on the little research done within this area, it seems like the PC technique is able to log through at least two strings. However, what was found about using PC pulses for this purpose from Viggen et. al.'s study cannot be applied directly in practical situations and has to be further investigated and developed. Furthermore, CT can be used for logging through at least two casings according to Visuray. At present, CT is not common used to evaluate the cement in the well, however, its potential is interesting to look into, as discussed earlier.

Today, the inner casing has to be removed to log through the next casing. This takes time, and by making it possible to log through MT1C, it is likely to believe that the P&A operation will become more efficient as less runs are necessary to log the different casings. Indeed, if it is possible to log through multiple strings, it might be possible to left most of the tubular in the well, including the tubing, as long as an annular external barrier exists. At least this is the ideal situation, but might be practically impossible in several cases.

When implementing it in the field, the idea behind logging through multiple strings might actually not be that efficient for the P&A operation as first thought. From the discussion related to the flowchart in figure 5.2, it became known that the time spent on placing the plugs in the well is dependent on the cement in different annuli. When this cement is poor, it is necessary to remove the strings to establish a barrier and logging through MT1C is not that helpful. In addition, when placing the plug in the 20" casing, the strings most likely have to be removed to establish a barrier that seals horizontally (figure 5.1). It might be that a logging run will be saved in between when it is possible to log through multiple casings, however, the time saved is dependent on how many strings it is possible to log through and how beneficial this method is compared to other alternatives.

In addition, it will be challenging to develop a method which is based on a method that already contains difficulties and uncertainties. The uncertainties with CT are not known yet, however, if the method for logging through MT1C is based on the use of PC, limitations exist. The interpretation of the log becomes more complex as well when it is possible to log through multiple strings. When the logging reliability is poor, it might be more profitable to just remove the strings instead of spending time on logging and interpreting with uncertain tools. This, in addition to the previous discussion, underlines the idea to make the P&A operation independent of the logging methods and the cement in the annulus, and again, it is more interesting to look into removing the strings in an efficient way instead of looking into the logging tools. This will be discussed in chapter 5.2.

Summarized, it is important to be aware that developing a method to log through multiple casings will not solve all the problems related to the time used on cement evaluation. It might be advantageous in some cases, however, each well and section are unique and an appropriate P&A operation has to be performed for the particular scenario. In other words, it seems like logging through MT1C is not ground-breaking for the industry, and it might be more beneficial to look into how the P&A procedure can be improved itself, instead of trying to improve the cement evaluation methods. This is discussed in the next chapter.

5.2 Potential P&A Procedure Improvements

Working with the P&A operation for an old well consists of a lot of challenges. As discussed earlier, it seems like it is not improving the cement evaluation methods that is the most appropriate solution for improving the P&A operation, but improving the P&A procedure itself. For instance, when the barrier in the well is poor, it is not the logging methods that is the challenge but ensuring this barrier. This might take time, and cement failure might occur at a point in time as well, as studied in chapter 2.2. Furthermore, the requirements become stricter, and it is important to achieve a reliable P&A operation where the barriers do not fail. Due to this, it is interesting to look into if there are any possibilities to make the P&A operation independent of the logging methods and the cement in the annulus. This seems to be an efficient and safe solution with a huge potential, and will be applicable for all wells. The potential improvements studied in this thesis are efficient removal of the tubulars, which were briefly described in chapter 3.3, and will be discussed further in the subsequent chapters based on the results from chapter 4.3.

In addition, when looking into the possibility to change the P&A procedure, a rig-less operation shall be prioritized since this is a futuristic goal for the industry, based on the roadmap in figure 1.1 in chapter 1.1. Indeed, the rig costs are about 40-50% of the total costs of the P&A operation, and enabling a full P&A operation on WL will reduce the costs significantly as it is possible to use a vessel in this case. Other things to investigate is the possibility to use the formation as an external barrier, such as shale, or to develop a material that is resistant to every load and actually seals for the eternity. However, this are not investigated further in this thesis, but is recommended to study further.

5.2.1 Corrosion of Steel

Deformation of steel is restricting during drilling and production, but might become an aid in the P&A operation if it is possible to utilize it such as the tubular removal becomes both cheap and fast. The deformation includes for example corrosion of steel.

By using corrosion of steel to remove the tubulars downhole, there will be no need for a rig, and it will therefore be cost-efficient compared to present methods. SINTEF has conducted lab tests in this area, and has had successful dissolution of the casings. So far, the advantages with this method are that it is cost- and time-efficient and environmental friendly compared to present methods. In addition, it is not necessary to observe the corrosion of the strings and it is possible to perform other tasks in the meanwhile. However, when not using a rig, the electrical power available is limited by a conventional WL cable, which will be a challenge if the corrosion shall be achieved by an electrochemical method. In addition, there might be some safety risks that is not taken into account at this point and a solution for removing the waste and cement behind the casing is needed. This technique has to be further investigated and tested to be able to be used in the field.

5.2.2 Laser

Another recently discussed technique to remove the tubulars downhole in an efficient way is the use of a laser. By using a high-power laser downhole, it is possible to burn an interval of the casing in a short time. In other words, the tubulars and cement downhole will be removed, and it is possible to place a complete barrier that seals both horizontal and vertical in this interval. This eliminates the need for section milling and PWC, which in turn eliminates the costs and risks associated with these operations. Using a laser will most likely be more time-efficient than section milling the casings one by one and there will probably be less wasting material as well. Thus, it becomes easier to clean the interval, and it is more likely to place a high-quality barrier that will bond to the formation. Another advantage with this method is that a rig is most likely not required even though the power supply will be limited on a vessel.

The use of laser is in the initial phase as well and is not used in the petroleum industry yet. It seems to have a huge potential, but needs further investigation to determine if it actually is an appropriate method. More research and testing have to be done, however, this is out of the scope of this thesis.

5.2.3 Leaving the Tubing in the Well

If it is possible to remove the strings with the operations discussed above, it might be possible to leave the tubing in the well to save time as well. It is also possible to leave the tubing in the well if it is possible to log through multiple casings. However, as discussed earlier, it might be necessary to remove the tubular due to the execution of the operation. Anyway, if it is possible to leave the tubing in the hole, time on pulling it will be avoided. In addition, there is no need for a rig if the, which reduces the costs significantly.

However, there exist some challenges when the tubing is LIH. First of all, the fluid in the annulus has to be properly displaced by the cement where the P&A plug is planned to be placed. It has to be ensured that the control lines and cables do not become possible flow channels. In other words, it might be difficult to ensure barriers when the tubing and its lines are LIH. However, studies and full-scale tests are conducted on this topic and it is proven that it is possible to obtain a good cement placement and achieve a sufficient barrier in this case.

Another challenge when leaving the tubing in the well, is the location of the barriers with the present P&A operation. Theoretically, it is possible to perforate the tubing above the production packer, and then circulate cement into the A-annulus. In this case, cement will be presented both inside and outside the tubing. However, when the open-hole-to-surface plug is set, the tubulars have to be removed to establish a horizontal barrier in the well. Anyway, if it becomes possible to remove the strings without evaluating the cement and without the need for section milling the casings, these challenges are avoided and the tubing can be LIH. If laser is used to burn the strings or if corrosion removes the strings, the tubing will not be a limitation as long as the tool fits in the tubing. Thus, dependent on the P&A procedure, there is a possibility that leaving the tubing in the well will not have a significant impact on the P&A operation other than saving time.

However, leaving the tubing in the well is more interesting for wells offshore that requires a rig for this removal. If the well is onshore, the time spent on the operations becomes less important due to the eliminated rig costs. Indeed, possibilities as re-using the tubing can be worth considering onshore, which will be time-consuming offshore. Anyway, it is interesting to perform a cost analysis for different scenarios to determine if the best option is to leave the tubing in the well or not. However, this is out of the scope of this thesis as it is the NCS that is of interest.

5.3 Annular Integrity Analysis

The discussion about improving the cement evaluation methods in chapter 5.1 underlined the need for a P&A operation that is independent of the logging methods. The regulations require that the cement seals for the eternity, which is not ensured by evaluating the cement and it is common known and experienced that cement failures occur. Thus, the present P&A operation which is dependent on the logging methods and the annular cement is not sufficient in all cases, and improvements for the P&A operation itself have been discussed in chapter 5.2. For these solutions to be sufficient, and successfully improve the P&A operation, an understanding of the integrity in the annulus is important. Chapter 2.2 explained the theory behind this integrity and derived an analytical model, in addition to introduce a suitable FEM model for this purpose. In this chapter, an analysis of the annular integrity is performed to state its importance. This analysis makes it possible to understand the impact of different properties and how they affect each other, in addition to the occurrence of failure. This is essential understand and be aware of to be able to develop an appropriate P&A operation. The discussion is based on table 4.1 in chapter 4.1.

When the conditions downhole change, it affects the integrity of the annulus. As seen from the derivation in chapter 2.2, Young’s modulus’ of the materials affect the contact pressures and is therefore analyzed further in this chapter, in addition to the wellbore pressure. The critical failure when increasing the Young's modulus of the cement, E_{cem}, decreasing the Young's modulus of the formation, E_{fm}, or increasing the wellbore pressure in the FEM model was radial cracks at the interfaces in all three cases, especially at the casing-cement interface. This is because of the significant tangential tensile stresses. The tangential stresses for the different scenarios are presented in appendix A.2.

If the tangential stress in the cement goes from tension to compression, the cement becomes stronger and will provide a better cement sheath support for the casing. This means that a more severe load is needed to induce failure. This happens when the E_{cem} is reduced, and the probability of radial cracks will be reduced. In this way, it is possible to take advantage of the rock mechanical support when using a low E_{cem}. However, if the E_{cem} cement is significantly reduced, the radial compressive stresses are reduced, and the risk of de-bonding increases. If the radial stresses become tensile, as they do with really low E_{cem}, the risk becomes critical. However, de-bonding did not occur in the simulations in this thesis and the critical stress is the tangential stress in tension. The advantage of using a low E_{cem} has been proven in other studies as well (De Andrade, 2015, Teodoriu et al., 2010, Bosma et al., 1999, Goodwin and Crook, 1992, Yuan, 2012). Knowing the E_{cem} used in a cement operation increases the possibility to identify any failure within the cement, and can support the cement logs.

When the E_{fm} is increased, the radial compressive stresses increase, while the tangential tensile stresses decrease. The tangential stresses become compressive at one point, which lead to a stronger formation. This will prevent deformation, but de-bonding might occur if shear failure is induced due to the significant compressive stresses around the rock which increases its stiffness. However, this is not happening in this case. When the E_{fm} is reduced, the tangential tensile stresses are increased, and radial cracks occur at the casing-cement interface at a very low value. Thus, it is preferred that this value is high. Comparing the results with more complex analysis, the results are roughly validated (De Andrade, 2015, Yuan, 2012). Insignificant deviations might occur, but this is most likely due to the different cases investigated as a sealant resistance to shear failures is sensitive to the load case. Knowing the E_{fm} can help to understand what is happening in the annulus. If the cement log is ambiguous when it comes decide if there is a micro-annulus or not, the E_{fm} can contribute to determine if it is likely that this is the case. Different combinations of E_{cem} and E_{fm} are studied further in appendix A.2.

Furthermore, the effect of wellbore pressure is investigated. When increasing the pressure, it is expected that the casing expands and the compressive radial stresses and tangential tensile stresses in the well increase. This will respectively reduce the risk of de-bonding and increase the probability of inducing radial cracks. If the wellbore pressure decreases significantly, the radial stresses might become tensile and become the critical stress. This is not the case in this study, however, if it happens, de-bonding might be more critical than radial cracks. Also note that de-bonding might occur due to significant shear stresses. Comparing with other references, the effect of changing the wellbore pressure is verified (Goodwin and Crook, 1992, Thiercelin et al., 1998, De Andrade and Sangesland, 2016).

A sensitivity analysis of the properties investigated above is done in table 5.1. There are several properties to investigate when using a model like this to see how the different properties affect the cement integrity. For instance, it would have been interesting to see the effect of the thermal expansion of the materials, the effect of Poisson's ratio of the materials, and the effect of horizontal stress. However, the aim of analysis in this thesis is to show the importance and utility of such model, and these properties are not studied further.

Table 5.1 - Sensitivity analysis of different properties affecting the annular integrity

Parameter	**Impact on the integrity**	**Main risk**	**Preferred to be**	**Advantage if optimized**
Young's modulus cement, E_{cem}	High impact	Radial cracks	Low	Ductile cement Lower tensile tangential stress Lower compressive radial stress
Young's modulus formation, E_{fm}	Moderate impact	Radial cracks Shear stress	High	Preventing deformation Low risk failure if E_{fm} high and E_{cem} low
Wellbore pressure	High impact	Radial cracks Shear stress	Neither high or low	Unlikely that de-bonding occurs.

From the discussion above, a complex model is not necessary to get an indication of the impact of different parameters. Be aware that the cases are investigated separately and will most likely have an impact on each other in real life, either strengthen or weaken each other. However, the model shows that the conditions of the cement will be affected throughout the lifetime of the well and cement failures occurs. Thus, the annular integrity model underlines the need for a P&A operation independent of this cement and its logging methods.

6 Conclusion

Considering all the drilled wells, the P&A operation is come to stay, and it should be as cost-effective and safe as possible. This operation is highly dependent on the physical conditions downhole, which have to be taken into account when planning and performing the P&A operation, in addition to regulatory requirements. At present, several companies are investigating this area, and the industry should encourage the companies to test and innovate in better solutions to achieve an improved P&A operation.

- Requirements should ensure well integrity but failures occur. Especially the risk of cement failure is important to consider and understand to ensure the long-term-integrity of a well. It is possible to develop and use an annular integrity model for this purpose, which considers the different loads the well has been exposed to and determines the status of the cement. In this thesis, such model proves that cement failures occur, which is important to take into consideration in a P&A operation.
- The PC tool combined with CBL/VDL seems to be the best logging tool at present. However, the present logging methods used for evaluating the cement are not sufficient for todays' use, where the main challenge is to determine the hydraulic isolation. Furthermore, it seems like the present logging tools are exhausted and new techniques should be developed rather than improving the present ones.
- Combining new logging techniques with the present ones might be the solution for a reliable cement evaluation. The more logs and data, the higher reliability of the evaluation. In addition, different tools give different view of the situation and will fit for different conditions. 3D visualization of the cement will also increase the reliability as defects within the cement become clearer.
- Using CT to evaluate the cement downhole is on the agenda, and shall be further investigated. Advantages by using CT are for instance determining the hydraulic isolation and logging through at least two casings. A tool that uses CT for cement evaluation is being developed by Visuray, but is not announced yet.
- It is not possible to use MRI to evaluate the cement downhole since both the iron in the Portland cement and the casing steel will affect the measurements.
- Using drill and borescope to evaluate the cement in the well increases the risk for damaging the cement due to the collected samples. The cement evaluation shall be a non-destructive method, which makes the use of drill and borescope inappropriate.

- Logging through multiple strings is not that useful if the strings have to be removed to establish an external barrier, which is the case if the cement is poor or if establishing a plug in the 20” casing. In the case of a deeper plug, a logging run can be saved if it is possible to leave the tubing in the hole. However, the time saved by using this method is most likely not that significant.
- Since the strings in the well in many cases have to be removed to evaluate and/or establish a barrier in an old well, it seems more useful to improve the P&A procedure itself instead of improving the logging methods. This can for instance be by removing the tubulars more efficiently. Potential methods for this are using a laser to burn the strings or to utilize the corrosion of the strings.
- The possibility to leave the tubing in the well depends on the P&A operation. For instance, for the present permanent P&A operation the tubing has to be removed to establish a plug in the 20” casing. However, by modifying the P&A operation, it might be possible to leave the tubing in the well.

Through this thesis, it is experienced that when one challenge in the P&A operation is solved, another challenge often occurs. This reflects the importance of improving the P&A operation as there are several challenges with this operation at present. Based on the research in this thesis, an appropriate solution is to modify the P&A procedure itself. It is likely to believe that this will result in a more cost-efficient and safe P&A operation than if only the cement evaluation logging methods are improved. Indeed, technology advances in the P&A operation might make the logging methods irrelevant. Developing a safe and time-efficient P&A procedure independent of the present logging methods has a huge potential and it is likely to believe that this is one of the main keys to reduce the costs of the P&A operation significantly.

7 Further work

It is challenging to limit the content when writing about P&A. Due to this, it is several possibilities to study the topic further. Some suggestions are listed below.

- At present, it is no need for running a new log to verify the annular barrier as long as a log exists prior a P&A operation. However, the cement degrades over time and it is likely to believe that the risk of cement failure increases. It is therefore interesting to look into if there are any significant risks when using previous logs. What is the consequences?
- Investigate the advantage by using the annular integrity model to reveal uncertainties and ambiguities in the cement logs. Study how the logs comply with the model.
- The analytical annular integrity model in this thesis can be further derived and compared to other models for the same purpose.
- The numerical FEM model is also possible to improve to make it more detailed.
- There are several possibilities to perform laboratory work based on the research in this thesis:
    - Perform laboratory work to verify the annular integrity model.
    - Investigate the PC technology do identify limitations with this method. Add more receivers to hopefully increase the reliability.
    - Investigate the possibility to use CT to evaluate different cements in a well. Identify the advantages and limitations.
    - Investigate the possibility to log through multiple casings with the different technologies. Identify the advantages and limitations.
- The effects of going from downscale to full-scale can also be investigated.
- Investigate if there is a possibility to avoid evaluating the annular barrier. Is there a time-efficient, safe method that can seal the well independent of the annular barriers? For instance, the use of laser and a new sealing material? Compare different scenarios to see the benefits and to determine what is most profitable, considering both costs and safety.
- Investigate the possibility to use laser as a replacement for section milling and PWC. Identify limitations and benefits with the different methods. Especially time and costs are important factors. Support the research with laboratory work.
- Another important factor is the material used to seal the well. Is it possible to develop a material that will seal completely and for the eternity?
- Using shale as a barrier can be studied further as well.

- Leaving the tubing in the well can be further investigated and scenarios shall be compared to determine if it is best to remove it or leave it in the well.
- If the P&A procedure is changed, how will the regulations change?

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Appendix A Annular Integrity Model

To understand the importance of the integrity in the annulus, an annular integrity FEM model has been developed in Ansys to be used this thesis. The assumptions and input values used are presented in appendix A.1 below and some of its results are presented in appendix A.2.

A.1 Numerical Model – Assumptions and Input Values

The assumptions behind the model is:

- In-plane strain approach for calculating the mechanical response.
- Linearly elastic and isotropic materials. This makes it possible to identify the probability of having a certain failure mode without rigorously modelling it.
- The mechanical behavior of the cement is considered once fully set.
- The casing properties are fixed due to minor variability and uncertainty in these properties.
- The casing-cement and cement-formation interfaces are fully mechanical coupled.
- Cement sheath failure is defined by comparing the stresses with a failure criterion. The size and exact location of the cracks and micro-annuli are not calculated in this model.
- The model considers non-coupled thermal and mechanical response to calculate the combined effects of pressure and thermal loads. The temperature distribution is first calculated for a steady-state condition and then applied with internal casing pressure to compute the mechanical response of the well section.
- The outer edges of the formation are exposed to horizontal stresses, where these stresses are assumed to be of the same magnitude. These stresses will impact the in-situ stresses around the borehole, in addition to pressure/thermal loads applied inside the casing. This stress is included to count for creep of formations, changes in reservoir pore pressure or reservoir temperature.
- Good cement job.
- Anisotropy in the well bore is not considered. Including this in another model might increase the risk for shear failure and the occurrence of a micro-annulus.

To ensure that stress calculations are independent of the number of nodes in the model, the mesh quality and size have been validated.

The input values used in the model can be found in Table A.1.

Table A.1 - Input values for the annular integrity model

Parameter	**Value**
Casing thickness, t [mm]	12,7
Unconfined compressive strength, UCS [J/m^3]	3.9113E7
Young's modulus cement, E_{cem} [GPa]	10
Young's modulus formation, E_{fm} [GPa]	25
Poisson's ratio cement, ϑ_{cem} [-]	0,2
Poisson's ratio formation, ϑ_{fm} [-]	0,3
Coefficient of linear thermal expansion casing, α_{csg} [°C^{-1}]	0,000013
Coefficient of linear thermal expansion cement, α_{cem} [°C^{-1}]	0,000012
Coefficient of linear thermal expansion formation, α_{fm} [°C^{-1}]	0,000014
Friction angle, φ [deg]	20
Ultimate tensile strength of cement, T_o [Pa]	5293727

A.2 Results

The UFs have been calculated from the equations in chapter 2.2. The UFs for the base case are presented in Table A.2 below, which are calculated from the radial and tangential stresses presented in Table A.3.

Table A.2 - UFs for the base case

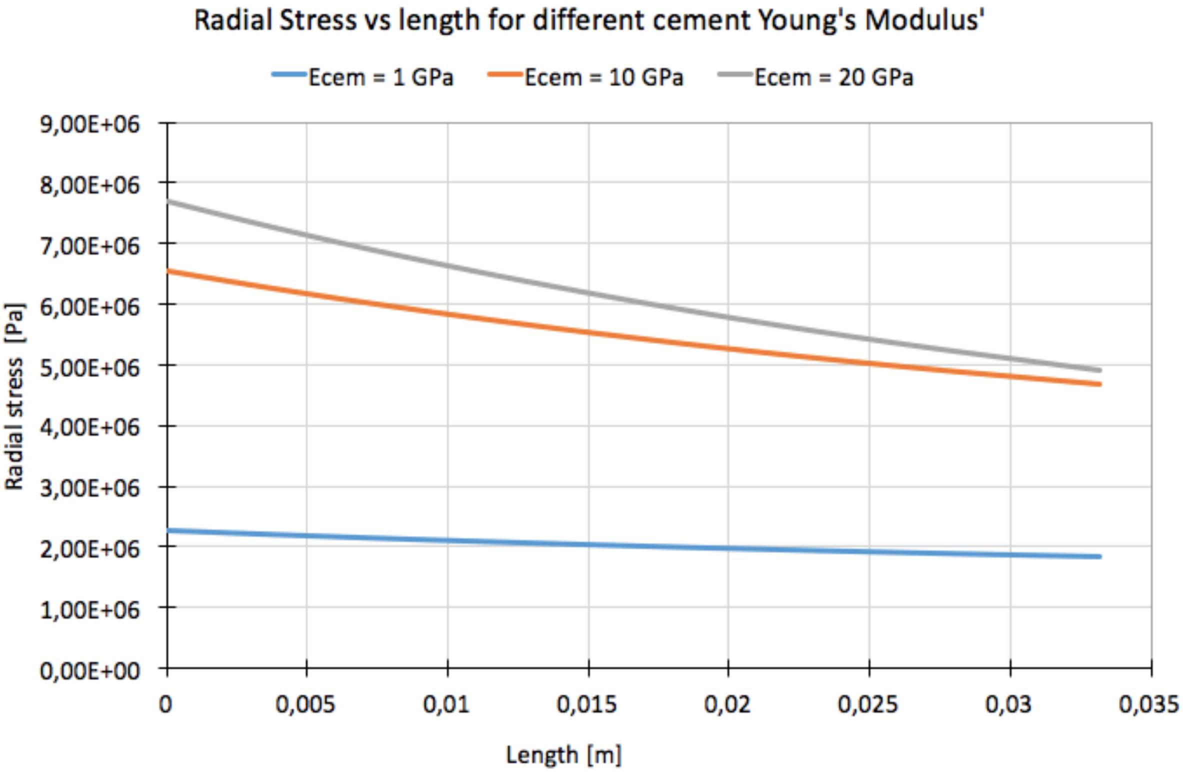
	Minimum UF	**Maximum UF**
UF Shear csg-cem	0,36299	0,36331
UF Shear cem-fm	0,22781	0,22897
UF Debond csg-cem	-1,2306	-1,2283
UF Debong cem-fm	-0,89198	-0,87985
UF Radial Crack csg-cem	0,61876	0,61945
UF Radial Crack cem-fm	0,27395	0,2791

Table A.3 - Radial and tangential stresses for the base case

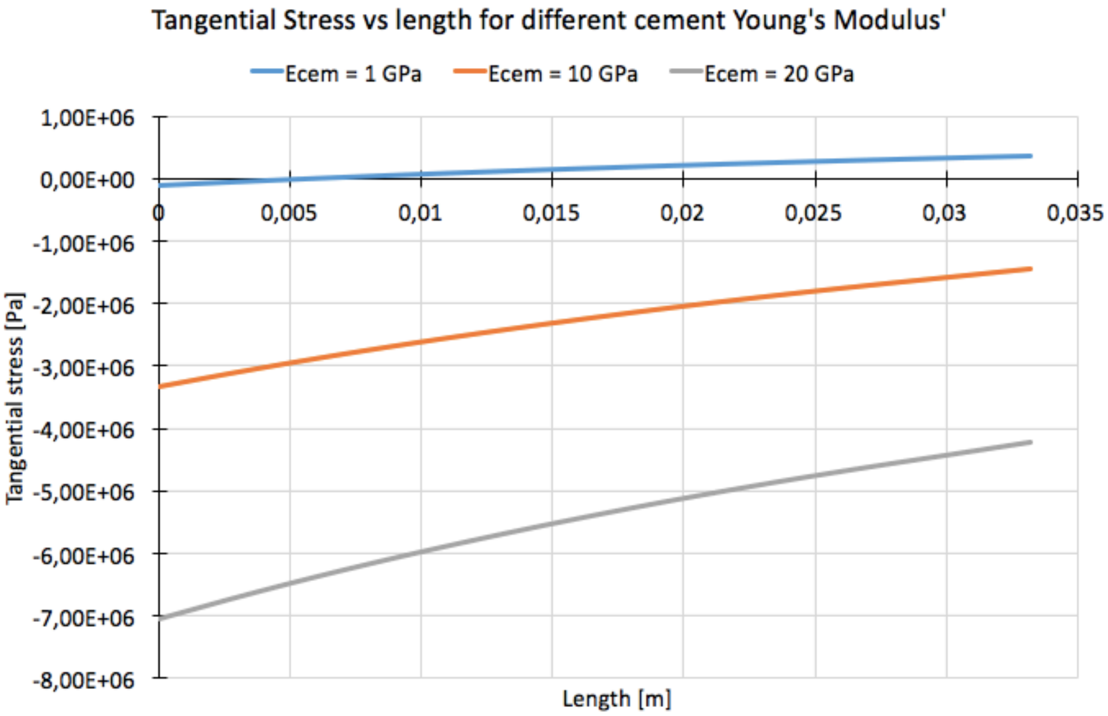
Length [m]	**Radial stress [Pa]**	**Tangential stress [Pa]**
0	6,56E+06	-3,33E+06
3,02E-03	6,32E+06	-3,09E+06
6,04E-03	6,10E+06	-2,87E+06
9,05E-03	5,90E+06	-2,67E+06
1,21E-02	5,71E+06	-2,48E+06
1,51E-02	5,53E+06	-2,30E+06
1,81E-02	5,36E+06	-2,13E+06
2,11E-02	5,21E+06	-1,98E+06
2,41E-02	5,06E+06	-1,83E+06
2,72E-02	4,93E+06	-1,69E+06
3,02E-02	4,80E+06	-1,56E+06
3,32E-02	4,68E+06	-1,43E+06

The UFs tell us that failure does not occur for the base case. The closest failure is radial cracks at the casing-cement interface. This is due to the significant tensile tangential stress.

In addition to the base case, different scenarios are studied to see the effect of different parameters on the cement sheath and the effect on the annulus integrity. The following plots present the radial and tangential stresses in the well during these scenarios; when varying the Young's modulus of the cement, the Young's modulus of the formation and the wellbore pressure. Increased Young's modulus of the cement will increase the compressive radial stresses and tensile tangential stresses, as shown in Plot A.1 and Plot A.2 below.

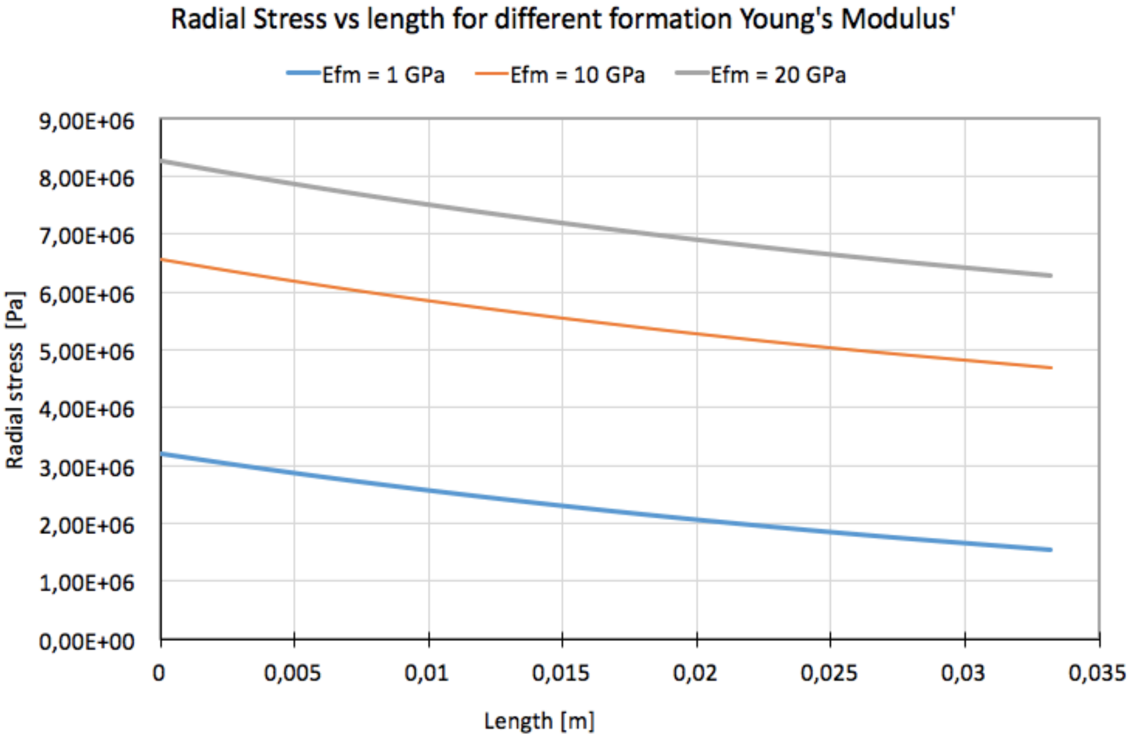


Plot A.1 - Radial stresses when varying Young's modulus of the cement

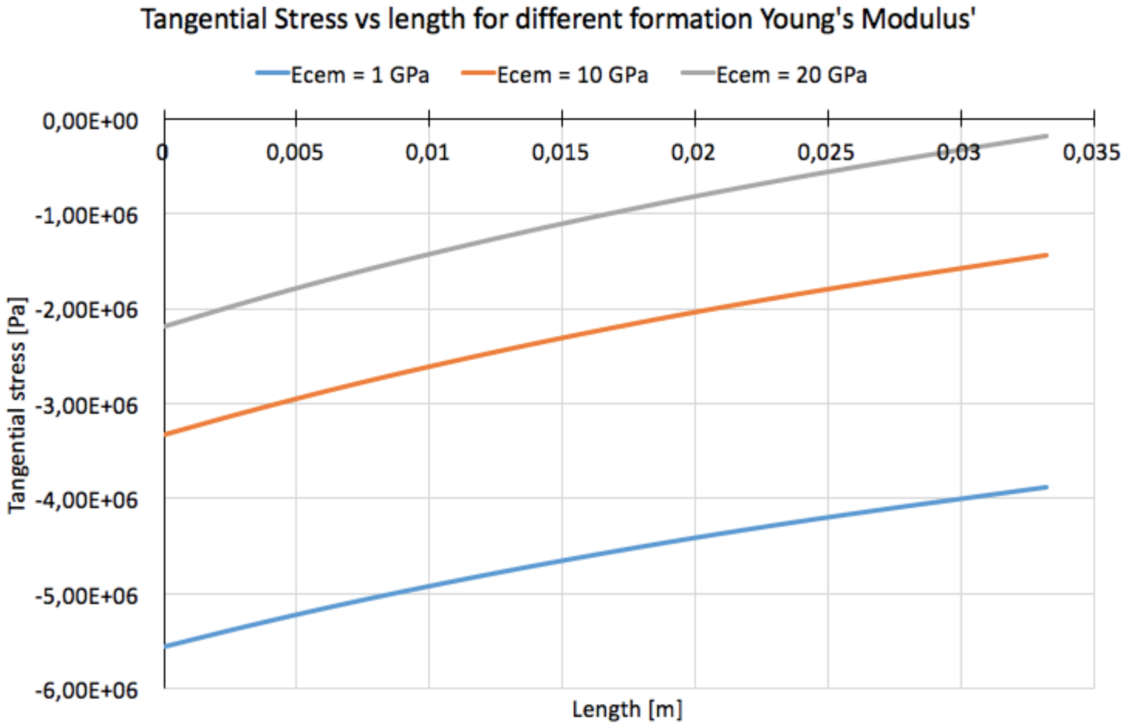


Plot A.2 - Tangential stresses when varying Young's modulus of the cement

When it is the Young's modulus of the formation that is increased, the radial compressive stresses increase and the tangential tensile stresses decreases as shown in Plot A.3 and Plot A.4.

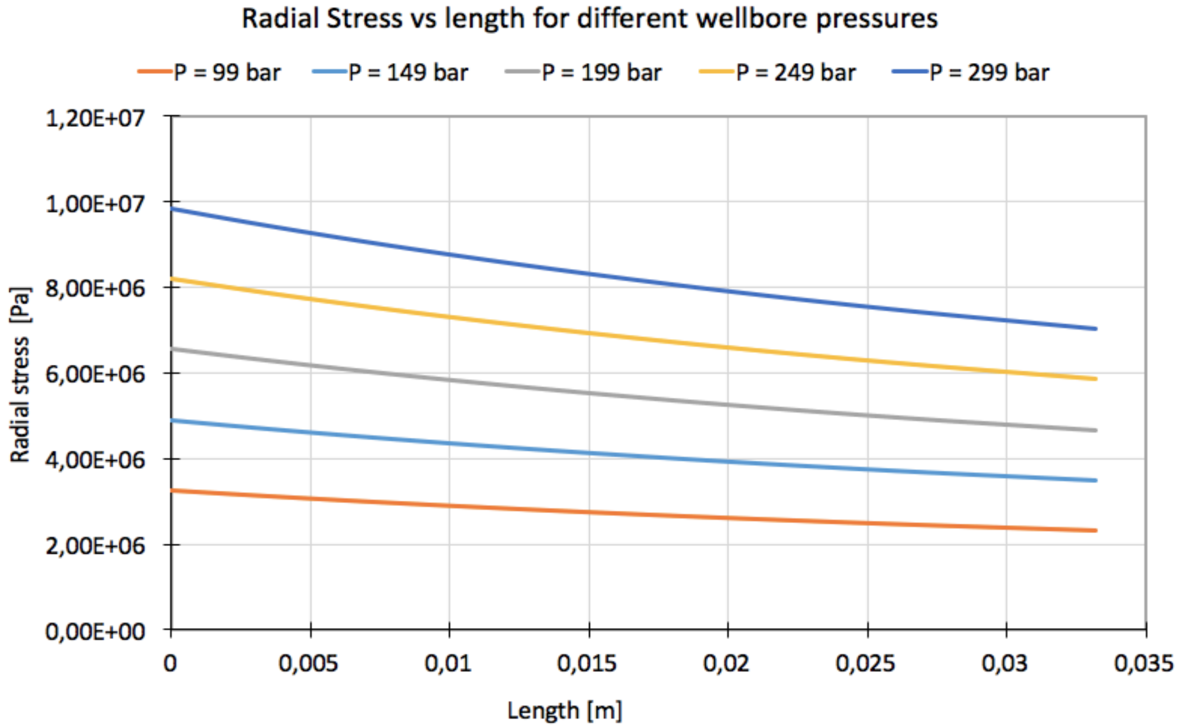


Plot A.3 - Radial stresses when varying Young's modulus of the formation

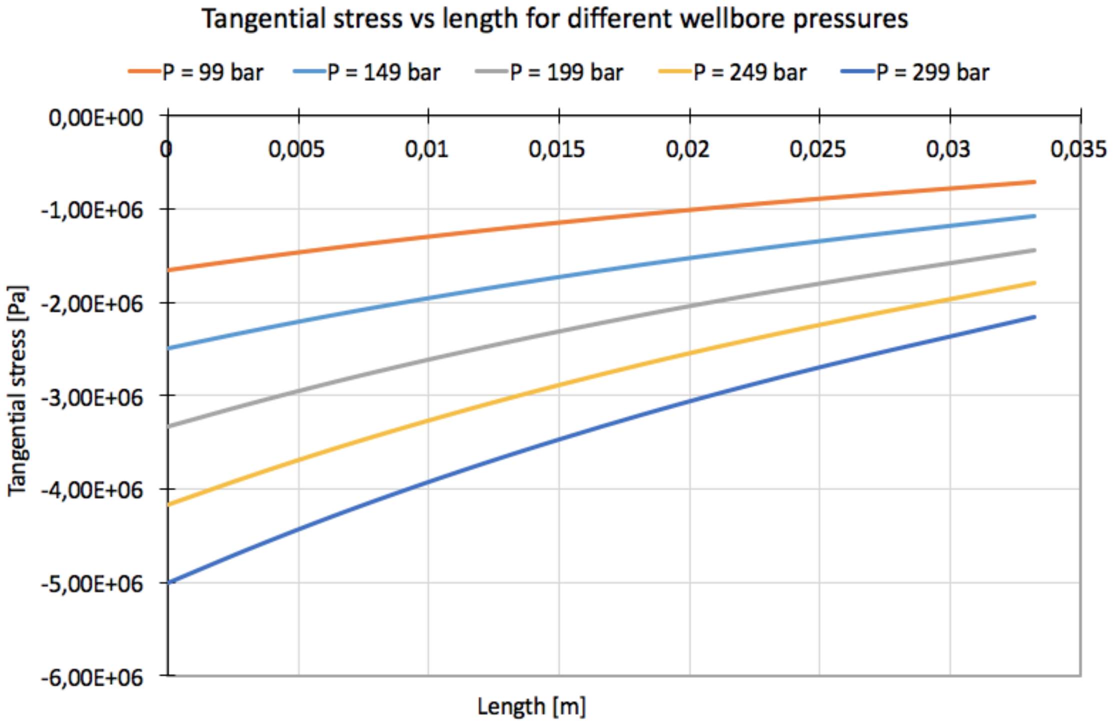


Plot A.4 - Tangential stresses when varying Young's modulus of the formation

The last parameter varied in this thesis is the wellbore pressure. Plot A.5 and Plot A.6 show increasing radial compressive and tangential tensile stresses when increasing wellbore pressure.



Plot A.5 - Radial stresses when varying the wellbore pressure

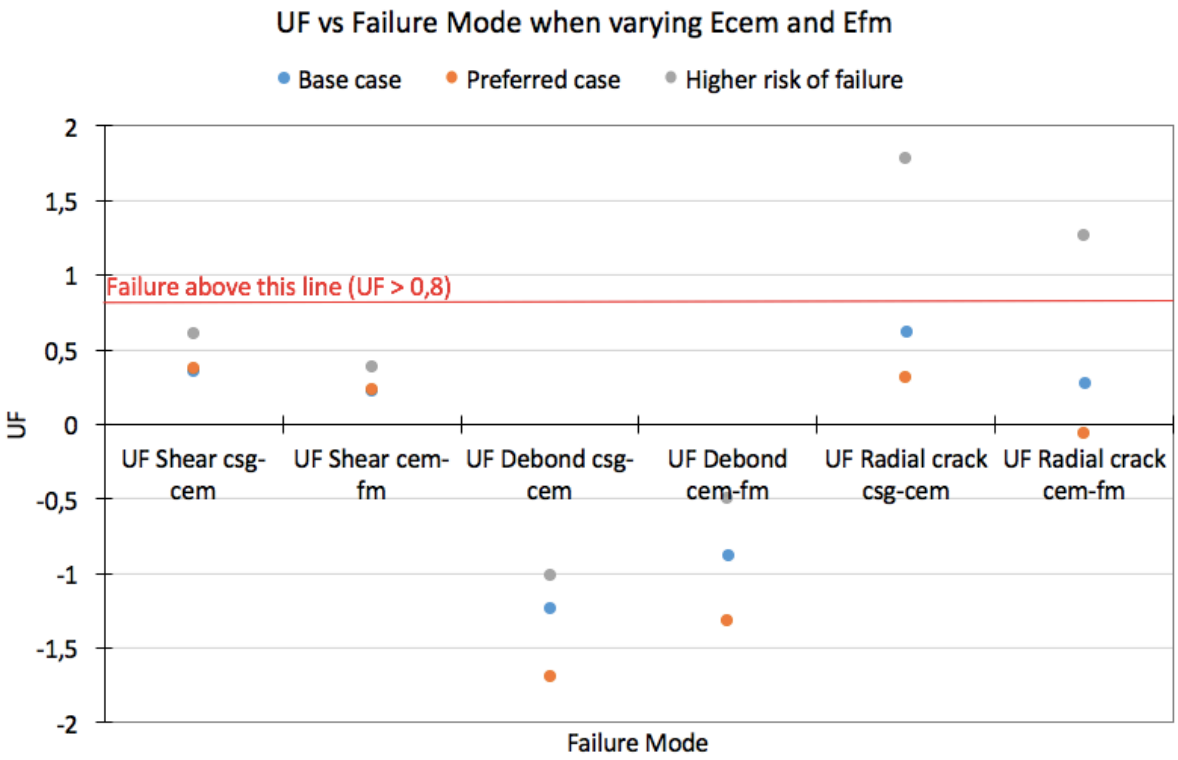


Plot A.6 - Tangential stresses when varying the wellbore pressure

From the annular integrity analysis, it seems like the Young's modulus of the cement, E_{cem}, is preferred to be low and the Young's modulus of the formation, E_{fm}, is preferred to be high. Yuan (2012) did also get this conclusion in his study of low-cycle fatigue behavior. Simulating this case, and the opposite (high E_{cem} and low E_{fm}) gives the result in Table A.4 and underlines the conclusions already made. When E_{cem} is low and E_{fm} is high (column 2 in Table A.4), there is less risk of failure compared to the case with high E_{cem} and low E_{fm} (column 4 in Table A.4). This is illustrated in Plot A.7.

Table A.4 - UFs when E_{fm} and E_{cem} vary

	Base case **E_{cem} = 10 GPa** **E_{fm} = 25 GPa**	**Preferred case** **E_{cem} = 10 GPa** **E_{fm} = 70 GPa**	**Higher risk of failure** **E_{cem} = 20 GPa** **E_{fm} = 10 GPa**
UF Shear csg-cem	0,36331	0,37408	0,6051
UF Shear cem-fm	0,22897	0,2356	0,38094
UF Debond csg-cem	-1,2283	-1,6909	-1,0164
UF Debond cem-fm	-0,87985	-1,3163	-0,49228
UF Radial crack csg-cem	0,61945	0,30996	1,778
UF Radial crack cem-fm	0,2791	-6,00E-02	1,2623



Plot A.7 - UF and failure mode when varying E_{cem} and E_{fm}

Appendix B Cement Operations

B.1 The Importance of the Primary Cement Operation

The primary cement operation is an important part of the well operation as it establishes barriers in the well. The main purpose of the primary cement job is:

1. Support the casing (American Petroleum Institute., 2008)
2. Provide effective zonal and permanent isolation of the formation behind the casing (Economides et al., 1998).

Cement is valid to use as the annular barrier material since it has similar properties as the cap rock. This makes the cement able to both support the casing and seal the well. The cement shall have mechanical bond to support the casing and hydraulic bond to block the flow of fluid at both the casing-cement and cement-formation interface (Havira, 1982). The cement has to fill the area around the pipe, where an interval of the cement column needs to be free for channels to achieve effective isolation. In addition, the cement has to withstand the effects of pressure, temperature and formation fluids downhole (Laidler et al., 2007). If this is fulfilled, the cement will act as a barrier and isolate the well, and in this way, ensure well integrity. The cement will prevent unwanted fluid movement out or into the well, as well as fluid movement behind the casing, such as gas migration (King, 2012). This makes it more likely for the well to produce effectively, safe and economically (Yuan, 2012). The fluid migration after cementing is studied further in appendix B.1.1.

The quality of the primary cement job is important as it becomes an important part of the present P&A design. A good cement design is based on several factors and the properties of the cement is a critical factor in the success of the well (Bosma et al., 1999). The cement is a function of the geometry of the wellbore, the wellbore stresses and temperature changes, and the linear-elastic properties of the set cement and formation (Thiercelin et al., 1998). Laidler et al. (2007) stated that the key materials of the cement and formation for a successful cement sheath are the Young’s modulus, tensile strength, Poisson’s ratio and the compressive strength. In addition, the cement design depends on the pipe properties and centralizing of the casing (King, 2012, Fertl et al., 1974). The displacement of the cement is also important for a successful cement job.

For the cement to achieve zonal isolation, all the drilling cuttings and mud have to be removed from the annulus and be replaced with cement slurry. This slurry has to undergo hydration, and when it has reached the solid phase, properties to prevent flow of fluids and to support the casing shall have been developed (Economides et al., 1998). The ideal situation is that the cement has these properties throughout the lifetime of the well, which in turn will make the cement withstand all the operations during the lifetime. However, even though good cementing practices exist and are the key to structural integrity and well integrity, a lot of challenges related to the cement job exist as well. These problems have to be taken into account when planning the cement job and when planning the P&A operation.

The result of the cement operation might be different from what was expected. Pressure testing the wellbore after this operation helps understanding the status of the cement in the annulus. If the isolation test fails, the cement operation was not successful and the cement does not provide hydraulic seal and isolation. Failure can also occur on a later stage. In both cases, remedial operations have to be performed, which is studied further in appendix B.2. Logs can also be used to evaluate the cement. Temperature logs can identify the top of the cement, while acoustic logs can give information about the cement fill behind the pipe. However, the different cement evaluation tools have their own advantages and disadvantages. The logging tools are studied in appendix B.3.

B.1.1 Fluid Migration After Cementing

Migration of fluids after the primary cementing has affected the well-completion industry since the introduction of oil well cementing and is a complex problem (Economides et al., 1998). The fluid flowing can be either gas or water, where gas is most common. This flow may occur immediately after the cement operation or it may occur months after completion of the well due to a pressure increase that makes leak paths. The size of the problem depends on the size of the flow. In the case of small flow, pressure buildup will occur in the annulus, while a more significant flow can result in blowout or loss of the well (Economides et al., 1998). Preventing this migration during the primary cementing is desirable as it is difficult to repair the problem once it occurs.

Cement evaluation has to be performed after the cement job. The most difficult part of this evaluation is to evaluate the hydraulic seal of the cement, which is also the most important part (Economides et al., 1998). It is important to continuously be aware of the annulus integrity, both right after the cement job and after 15 years when it is time to abandon the well. Just as when the well is operating, it is equally important that the barriers in an abandoned well will endure all the forces it will be exposed to.

Gas flow prevention

In the early stages of construction, the potential for gas migration problems can be analyzed and planned for. For gas migration problems occurring immediately after the cement is set, it exists several possibilities to prevent it to become a permanent problem. Alternatives are alternation of the gel-strength development, permeability modification, physical gel-strength disturbance, a mechanical method or changing the cement composition.

However, it is more difficult to predict and prevent the long-term gas leakage. To prevent this leakage, it is required to have maximum possible fill of cement in the annulus. It is also required to prevent shrinkage of the cement caused by hydration or damage to the cement caused by well-intervention operations (Economides et al., 1998). Prevention of the gas migration should always be considered as the best solution above remedial repair. Remedial repair is much more difficult and time-consuming, which will get known in appendix B.2 below.

B.2 Remedial Operations

A barrier that seals the well from unwanted flow has to be presented in the well at any time. It is common that the cement in the annulus is a part of this barrier. Thus, it is important that this cement is sufficient. The cement is important during P&A as well as it often work as an external barrier. However, it might be that the cement in the annulus is not sufficient and need to be repaired or replaced. This requires operations such as squeeze cement, section milling or PWC, dependent on the situation.

B.2.1 Squeeze Cement Operation

The squeeze cement job is performed to reinforce flawed or damaged cement in the wellbore by injecting cement slurry into a certain spot by applying hydraulic pressure. This is done to permanently block the entry of undesirable fluids to the wellbore or to fill channels and voids in the cement behind the casing to improve the cement.

During this operation, a cement slurry is designed specifically to the certain case and pumped down the wellbore to the depth of the spot. It is important that the cement particles are small enough to be squeezed into the desired zone, such as channels and voids, by applying hydraulic pressure. The area is then plugged and hopefully isolated.

When planning a squeezing operation, points like the magnitude of the problem, the risk factors and economics shall be considered. This operation is relatively cheap and fast, however, it has some limitations as well. To form an impenetrable barrier, a proper design is required in the correct location in the well. In addition, it is difficult to improve the cement if the cement is already poor and many remedial runs may be required during the job, which in turn results in a low success ratio. Thus, careful consideration about the situation and job is important prior a squeeze job. If the job is unsuccessful, time and costs increase rapidly. If the well is going to be abandoned, section milling or PWC might be a more proper solution (Skjerve, 2013).

B.2.2 Section Milling

If a well is going to be abandoned and it is poor or no cement outside a stuck casing, it is not possible to place an approved, permanent plug over the current interval without removing the tubulars. Section milling casing by casing makes it possible to remove the tubulars and cement, which in turn makes it possible to set a barrier that seals both horizontal and vertical.

In the case of section milling, a section of the casing is milled by using a rotary tool with section mill knives where weight is applied to push the mill in a downward direction (Stowe and Ponder). The contaminated, poor cement behind the casing is milled as well. The operation results in a permanent removal of the solids and permits a cement plug to be formed both inside and outside of the casing to make a proper seal.

Pressure is applied when the tool is at the desired depth and a force is then applied on the knives. The knives will extend and start to cut the casing while the tool is rotating. When the casing is cut, the milling continues until the desired depth. The hole is cleaned and enlarged, and then exposed to fresh formation. This results in good bonding when setting the cement plug.

Even though the section milling can provide a barrier, it is clear that the operation is time-consuming and thus, an expensive operation (Scanlon et al., 2011). In addition to this, challenges as wear, swarf generation, plug verification and vibrations exist (Ringe, 2015). Therefore, the operation shall only be performed when absolutely necessary and not when only suspicions about poor cement exists. However, evaluating the cement to determine whether section milling is necessary is difficult and the interpretation might be wrong. If the evaluation method shows that the quality of the cement is of bad quality, but the quality of the cement is actually good, unnecessary section milling might occur. This will in turn result in significant cost.

The section milling operation is just easily explained above. More reading about this topic can be found on page 31-41 in “Guidelines for Effective Milling” (Weatherford, 2006). In addition to this, a section milling flowchart and examples of section milling could be found in NORSOK D-010 (2013) on page 107-108. Thomas Ringe’s thesis (2015) is also recommended.

B.2.3 Perforate, Wash & Cement

It is proven that with respect to the time used and the additional HSE risks related to the section milling operation, the PWC operation is a superior operation (Midtgarden, 2013). In this case, time-consuming operations are replaced with more time-efficient alternatives as the well can be perforated, washed and cemented in one run.

The PWC method access the annulus through perforations, and set a full cross-sectional barrier. It consists of three sequences:

1. Perforate a selected interval of an un-cemented casing
2. Wash the annular space in the perforated interval
3. Mechanically place a cement plug across the wellbore cross section

In addition to this, an evaluation of the annular content shall be conducted prior the PWC operation. This can be done by logging tools.

The PWC method can be conducted with a single run, which in turn results in significantly less rig time compared to section milling. In addition to this, regulatory requirements are met and no swarfs are generated. However, the PWC operation cannot guarantee a fully cemented cross-sectional area. With respect to that, the section milling operation is superior to PWC in achieving a cement to formation barrier.

However, as in any other well operations, a detailed planning phase is essential for a successful operation. The job has to be designed for the specific well and desired location in the well. For example, if a fluid is occupying the annular space, it is important to know what type of fluid it is to be able to design a suitable washing fluid. Another important aspect is that the PWC tool has to be designed such as it is allowed to enter in the well at the desired depth.

The PWC method is explained briefly above and it is clear that it overcomes some of the shortcomings of the section milling operation. However, a disadvantage is the reduced probability of ensuring a fully cemented cross-sectional area. The PWC method is not studied further at this point, but is studied in depth in several theses; Thomas Ringe's thesis from 2015 and Torleiv Midtgarden's thesis from 2013.

B.3 Cement Logging Tools

Different logging tools are common used to evaluate the cement. The present tools utilize the acoustic coupling at the interfaces to determine the presence of cement and are further discussed in the subchapters. In addition to these, there are several measurements that can contribute to evaluate the cement. Examples are noise measurements, temperature logs, hydraulic tests and nuclear measurements. These methods are not studied further here, however, for further reading, chapter 16-2 and 16-3 in "Well Cementing" by Erik Nelson (1990) are recommended. Also note that by combining several logs, the reliability increases.

B.3.1 Cement Bond Log and Variable Density Log

One of the traditional cement logging tools is the sonic tool. This tool produces the CBL that was introduced in the 1950's and its purpose is to (Bigelow, 1985, Benge, 2014):

1. Determine the presence or absence of cement over certain depth intervals.
2. Determine whether cement is bonded to the pipe, the formation or both.

The CBL is a relatively inexpensive tool almost every WL company has a version of. In addition, this cement evaluation method is time-efficient and covers large parts of the casing (Bybee, 2007). However, to avoid erroneous conclusions, the understanding of how the CBL tool works and how it is run are important (Fertl et al., 1974). For instance, in the case of gas cut or foamed cement, this tool might be inappropriate (Economides et al., 1998).

Function and Structure

It is common that the sonic logging tool contains one transmitter and two receivers. Sonic energy is emitted by the transmitter, and this energy propagates spherically in all directions – through the borehole fluid, pipe, cement and formation – until it is detected by the receiver. The "setup" is shown in Figure B.1. The operation frequency is about 20 kHz, and the wave velocity, frequency and amplitude of the signal are affected by the surroundings (Havira, 1982).

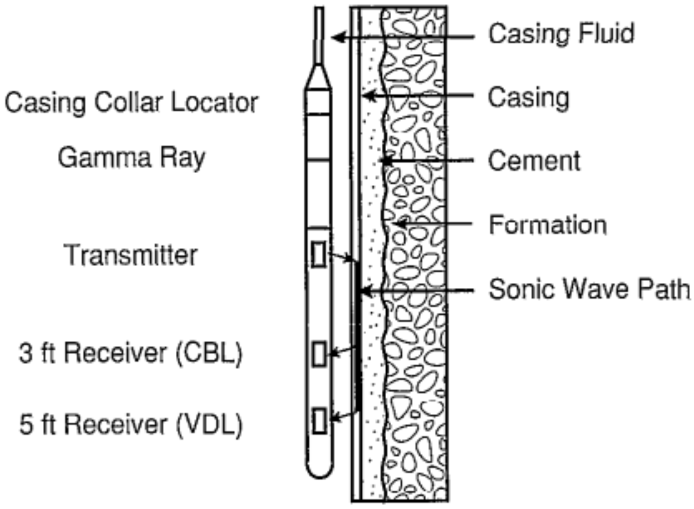


Figure B.1 - CBL/VDL tool (Nelson, 1990)

When the wave front reaches the casing interface, some of the energy will be refracted and some will be reflected according to Snell's law (American Petroleum Institute., 2008):

$$\frac{V_1}{\sin \alpha_1} = \frac{V_2}{\sin\ \alpha_2} \tag{25}$$

where

V_2: Velocity of the sound in the respective media
α: Angle of incidence and refraction

The refracted energy will be transferred into the steel, cement and formation and attenuate as it propagates along the materials before it is detected by the receiver as a reflection at a later stage (Economides et al., 1998). The attenuation of the signal, which determines the size of the amplitude, is caused by loss of energy to the surroundings due to shear coupling. Higher shear coupling results in more energy lost to the environment (Nelson, 1990). If there is fluid in the annulus, the energy loss is small. The sonic wave paths and time through the different materials are illustrated in Figure B.2.

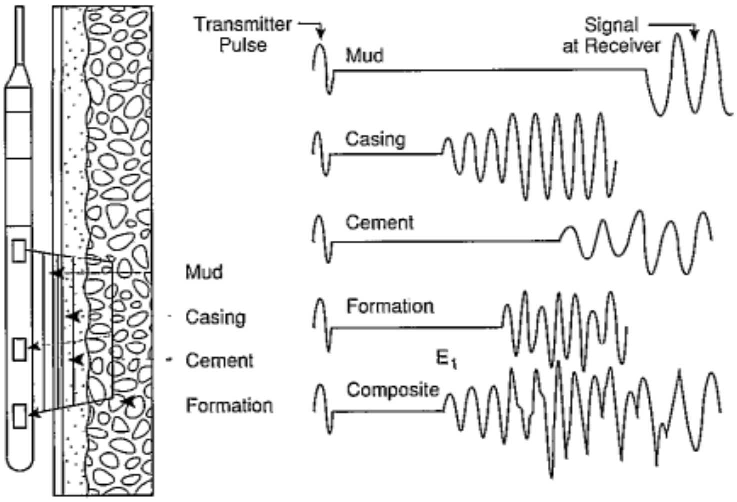


Figure B.2 - Sonic wave paths and times (Nelson, 1990)

The signals detected by the receiver are displayed on a log including a pipe-amplitude curve. This is illustrated in Figure B.3. The amplitude is affected by several factors, however, most of these are constant and the cement content can be directly related to the amplitude reading (Rabia, 2001). Thus, the amplitude is a function of the cement content and its bonding properties, and gives an indication of the percentage of the circumference of the casing that is acoustically coupled to cement (Economides et al., 1998).

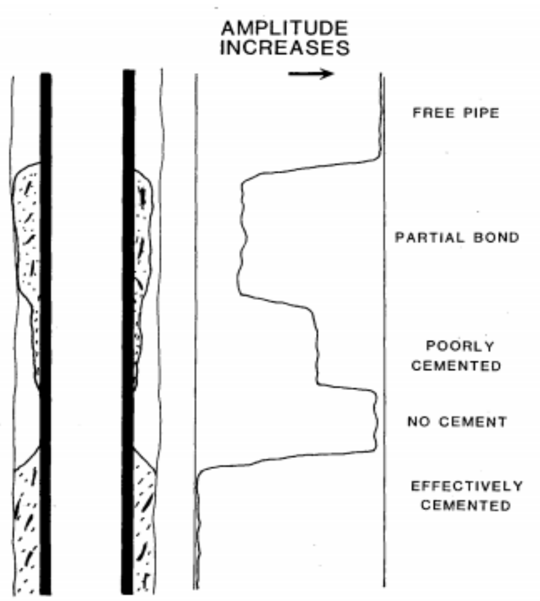


Figure B.3 - Amplitude curve from cement logging (Bigelow, 1985)

The attenuation of the signal is calculated from the amplitude and represents the loss of energy during transmission. The compressive strength of the cement is derived from the attenuation and increases with decreasing amplitude. The bond index (BI) is also derived from the amplitude, and expresses the bonding properties. The BI is a qualitative measure of the ratio of measured attenuation to maximum attenuation. However, it is not fully valid to only use the BI to evaluate the cement since it is an average measurement, and the logs have to be carefully interpreted (Economides et al., 1998).

Anyway, the cement bond is basically good if

- The amplitude is low with slighter longer TT
- The attenuation is high
- The BI is high

The value measured by the tool is the first arrival of the acoustic signal above a certain threshold that has traveled through the pipe (Abshire et al., 2012). In other words, the amplitude is measured. This is illustrated in the upper part of Figure B.4. Cycle skipping might occur if the amplitude is decreased for some reason and the peak is below the detection threshold (Economides et al., 1998). Then a peak above the detection threshold that not represent the first arrival will be detected on a later stage, which is illustrated in the lower part of Figure B.4.

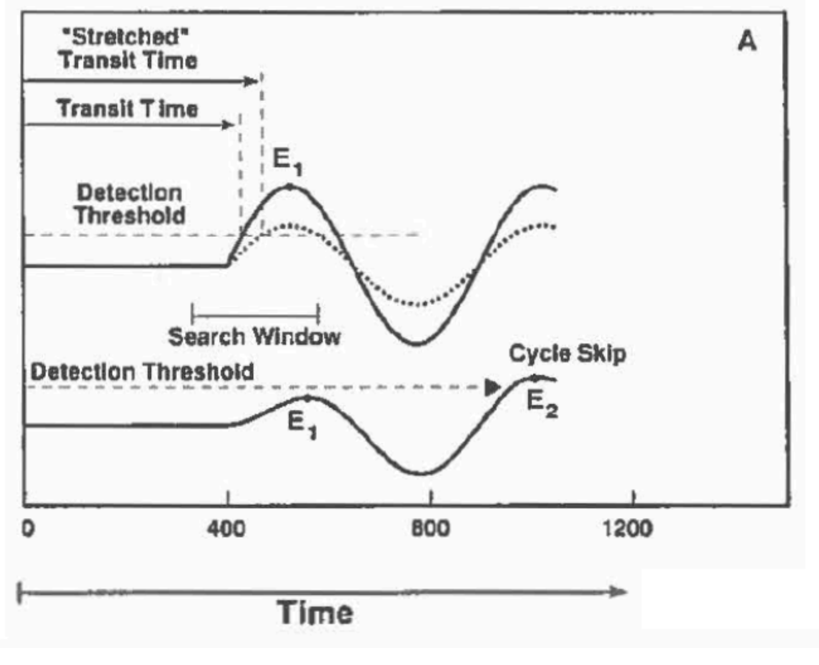


Figure B.4 - TT, detection threshold and cycle skipping (Economides et al., 1998)

To measure a specific part of a wave train, it is necessary to know how the tool is gated (Fertl et al., 1974). If not, logs run in the same well can give different amplitude curves. Gates are time periods during which measurements are made and can either be fixed or floating. A logging tool with a fixed gate is independent on the time the acoustic signal arrives at the receiver as the gate only opens at a definite portion of the wave train. In other words, the time the gate is open, the gate width is fixed. A fixed-gate system is commonly used for amplitude measurements. The floating gate has not a fixed gate width, and scans across the acoustic signal until it finds an amplitude high enough to trigger the system (Fertl et al., 1974). At this time, the response is recorded as TT.

The TT is the time from the signal is emitted until the amplitude is detected at the receiver at a certain detection threshold, dependent on the gate (Economides et al., 1998). The TT measurement is usually included as a separate log as a supplement to the amplitude signal, which is shown in Figure B.5. This is because relying only on the amplitude curve alone might lead to an incorrect result. In other words, the TT log is used to quality control the amplitude log. The TT depends on the bulk density of the material, which in turn depends on the porosity (Fanchi, 2010).

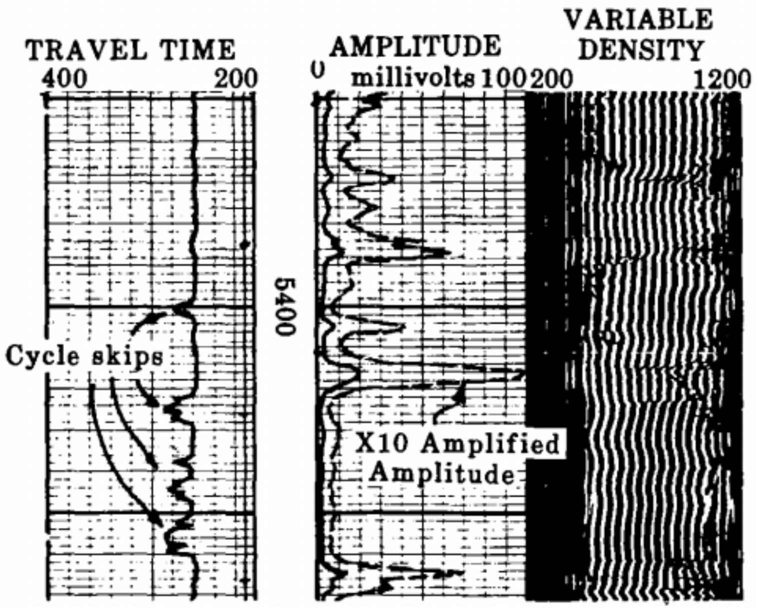


Figure B.5 - TT, amplitude and VDL (Bigelow, 1985)

To make the most reliable and best possible evaluation from a CBL, well parameters, cement job events, and pre- and post-job well histories are required. With these parameters, the logged result can be compared to the expected result, and deviations between these logs, if any, will be revealed (Nelson, 1990). When this information is missing, as for many old wells, the interpretation of the log becomes challenging.

Variable Density Log

To support the CBL, the VDL is used. A VDL makes the evaluation more reliable and can be used to determine the bonding between the cement and formation. The acoustic signal travels along various paths through the borehole fluid, pipe, cement and formation and the full wave-form will be recorded. This wave-form is translated to a variable density, which is illustrated on a VDL, as seen in Figure B.6.

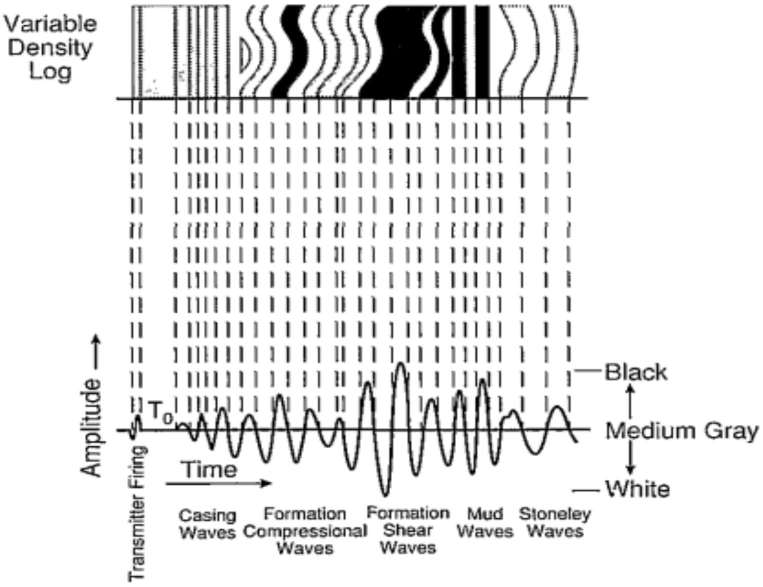


Figure B.6 - Amplitude translated to variable density (Nelson, 1990)

The VDL is a graphical resolution, and gives a visual indication of the free or bonded pipe to the formation and in this way, reveals some of the features that is not easily recognizable on a single waveform presented in a CBL. This log displays the amplitude in varying shades from black to white, along with the time versus depth scale (Bigelow, 1985). Basically, straight lines, no formation signals in the VDL and high amplitude corresponds to free pipe and fluid arrivals. A zigzag pattern with weak or no casing arrivals, but strong formation signals, indicates good cement bond to casing and formation (Fertl et al., 1974). Using the CBL and VDL together can determine the status of the cement and bonding properties. For instance, Figure B.7 below shows a fully cemented pipe, while Figure B.8 shows a free pipe, which is determined by using both CBL and VDL. Track 1 in Figure B.7 shows a low amplitude (dashed curve) and track 2 shows the full waveform (VDL) where the casing signals are weak while the formation signals are strong, which indicates a fully cemented pipe. Figure B.8 has a high amplitude in track 1 and the position of the casing collar is evident. Track 2 shows straight lines in the VDL with a W-shaped pattern at the collars. This indicates a free pipe.

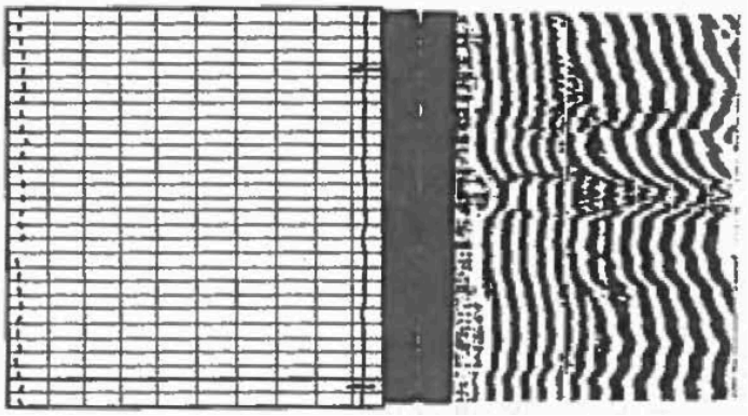


Figure B.7 - CBL/VDL: Fully cemented pipe (Economides et al., 1998)

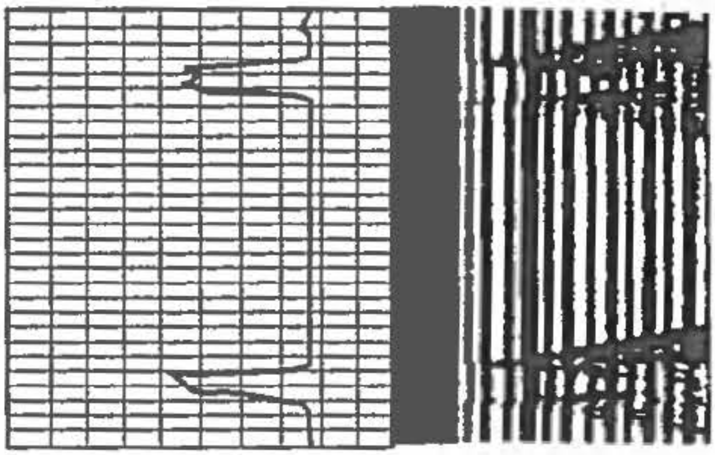


Figure B.8 - CBL/VDL: Free pipe (Economides et al., 1998)

The acoustic energy spectrum can be presented as a full wave signature as well, as presented in track 4 in Figure B.9 below. The full wave signature is a display of the received signal, as observed on the oscilloscope (Bigelow, 1985). The advantage is that the user can observe the amplitude of each pulse, however, it can be difficult to use, especially in heterogeneous formations where intermixing of the waveforms may occur.

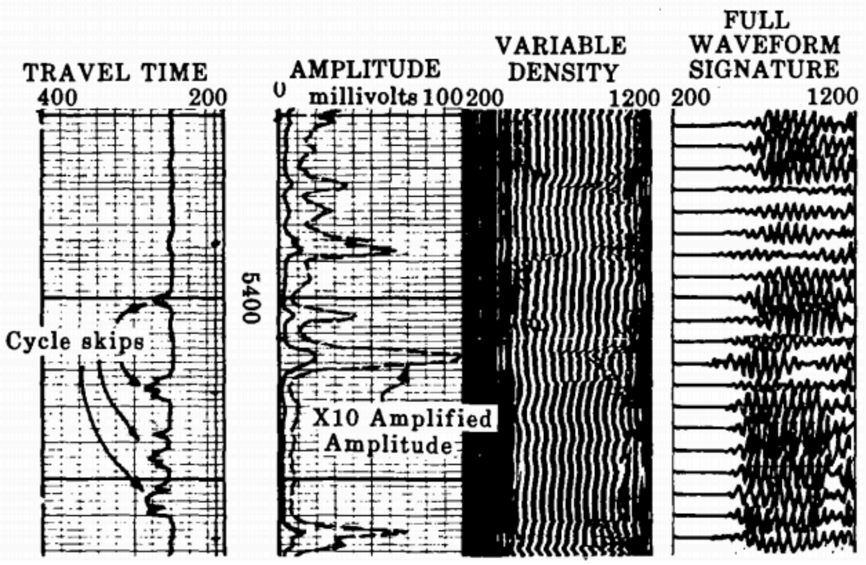


Figure B.9 - Full waveform signature presented to the right (Bigelow, 1985)

Traditionally, the pipe amplitude curve explained earlier (CBL) is used to determine the quality of the pipe-to-cement bond, while the waveform explained here (VDL) is used to determine both the cement-to-formation bond and the pipe-to-cement bond. These are combined in a logging tool containing multiple transmitters and receivers with different spacing. The spacing typically range from 3 to 5 ft, where the shorter spacing, typically 3 ft, records the casing wave, and measures the amplitude and the TT. The longer spacing, typically 5 ft, provides greater separation of the casing and formation-signal arrival times, and is therefore recording the full wave-form (Benge, 2014). The utility of using the logs together gives a more reliable evaluation. The more data, the better. Using other logs as well is preferred, such as the ultrasonic log that will be studied in appendix B.3.3.

B.3.2 Segmented Bond Log

The segmented bond tool (SBT) is a small-scale technique and is a combination of CBL/VDL and pad sonic devices. This tool provides a low-resolution map of the cement condition behind the cement and many of the problems common to the conventional logging methods are eliminated (Tyndall, 1990, Bybee, 2007). For instance, this tool provides an evaluation of the cement both radially and longitudinally around the entire casing periphery and does not average the signal around the wellbore (Benge, 2014, Bigelow et al., 1990). This makes it possible to determine the bonding condition for a specific azimuth. The SBT has six pads which are in contact with the casing during the logging operation. Each pad covers one segment of 60 degrees each, which results in a cement evaluation of 360 degrees (Bigelow et al., 1990). The pads have one transducer each, which contain one acoustic transmitter and one receiver. The energy is transmitted at one pad and detected by the neighboring pads, which results in examining all the six sections.

A SBL is illustrated in Figure B.10 in two presentation formats. Two presentations are necessary to allow ease of interpretation (Tyndall, 1990). On the left of the figure, the primary SBT presentation is presented. This includes the conventional logs, in addition to a minimum attenuation curve and an average attenuation curve. The right part of the figure, the segmented array presentation, includes a variable attenuation log, also called a cement map, and a display of all six segments of compensated attenuation. The colors in the cement map is used to determine the bond rating (Tyndall, 1990), and in this illustration, the darkest part of the cement map indicates higher bond rating, while white parts represent free pipe.

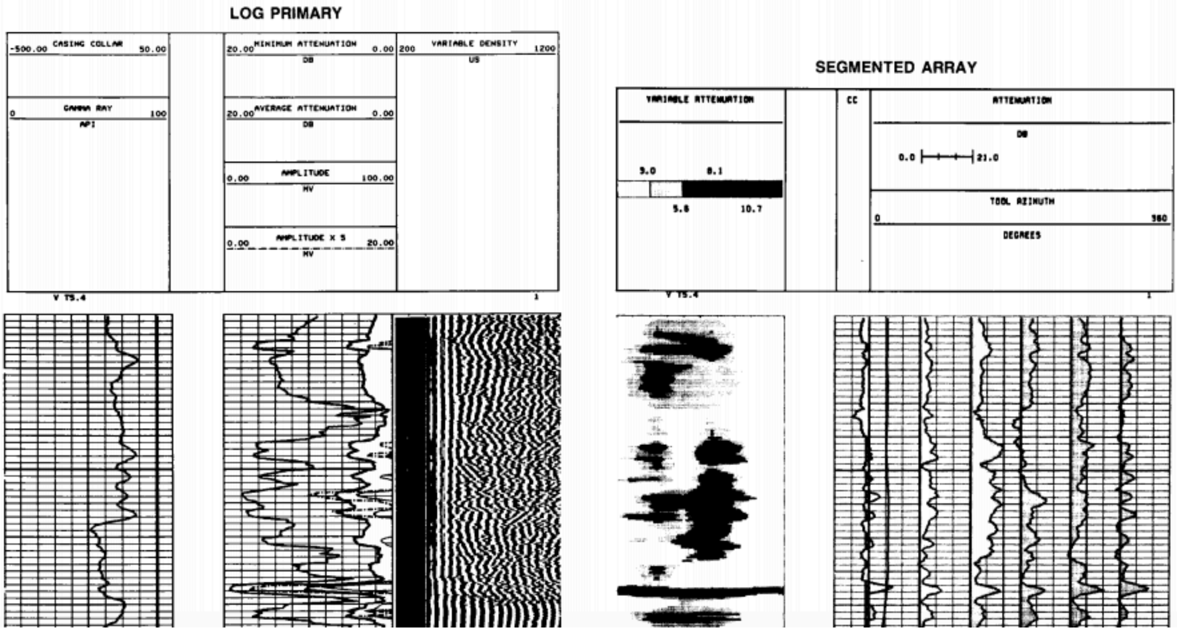


Figure B.10 - SBL (Bigelow et al., 1990)

Figure B.11 includes colored logs, which is helpful when interpreting the logs as the contrasts become more significant. This log shows good bonding at the top, then a section with partial bonding and then a section with free pipe between X688 and X714. The cement map is close to white when there is poor bonding. The cement map and the attenuation give the same information, but in different views.

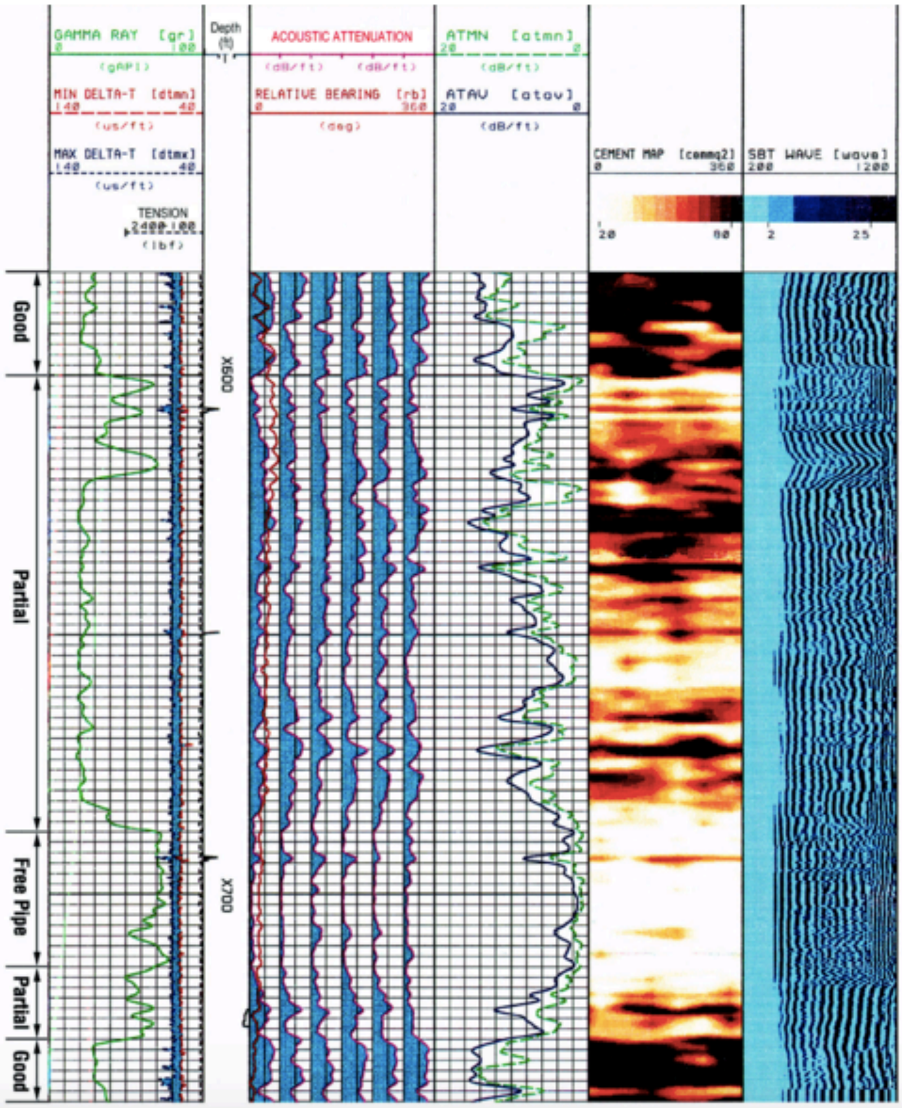


Figure B.11 - SBL with colors (Petrowiki)

This method is insensitive to transmitter and receiver variations and removes the uncertainty between compressive strength and annular fill to the conventional bond logs in a great extent (Smolen, 1996). The tool is not affected by fast formations either, as the transducer spacing is short and gate selection is early. Most of the centering problems associated with other bond logs tools are also eliminated (Bigelow et al., 1990).

However, even though this tool overcomes some of the problems with CBL/VDL logging, it has some limitations as well. There is still questions related to the BI, and the tool is sensitive to micro-annulus, cement curing time and coatings on the outside of the pipe (Smolen, 1996, Benge, 2014).

B.3.3 Ultrasonic Tools

To overcome the shortcomings of the CBL and VDL, the focus areas are (Havira, 1982):

1. Provide hydraulic isolation in the presence of micro-annulus.
2. Identify the material next to the pipe.
3. Achieve sufficient circumferential resolution to permit the detection of channeling.

For instance, none of the sonic bond logs measure isolation directly and they have low resolution. Tools that overcome these limitations are therefore preferred. Due to this, ultrasonic tools have been developed and is able to determine the hydraulic isolation in a greater extent. Ultrasonic means using ultrasounds, which is a high frequency sound with a frequency greater than 20 kHz. Ultrasonic includes the range of sound beyond what is perceptible for the human ear, and the ultrasonic tools emit ultrasonic pulses.

The ultrasonic PE tool was introduced by Sheives et. al. in 1986, and has one transducer that acts as both a transmitter and a receiver (Sheives et al., 1986). The other ultrasonic tool is the PC tool which contains one transmitting transducer and one or more receiving transducers. This is called the isolation scanner cased-hole imager and was developed with respect to the limitations of the PE technique (American Petroleum Institute., 2008). The PE technique fails to image beyond the cemented region adjacent to the casing and will therefore not give a fully evaluation of the annulus, which is possible for the PC technique. The PC tool has two modes, a flexural mode and a resonance mode. The flexural mode has the potential to probe the full annulus with its particle-displacement and spectral characteristics. However, the modes have to be combined to be able to distinguish between liquid and solid (American Petroleum Institute., 2008).

The ultrasonic tool is a radial-cement evaluation tool as the SBT, and overcomes some of the deficiencies of the traditional sonic logging tool (Wang et al., 2016). For instance, ultrasonic tools are much less affected by liquid-filled micro-annulus than the sonic tool (Bybee, 2007).

The logs from both the sonic and the ultrasonic tool are shown in Figure B.12, where the impedances are from the ultrasonic tool.

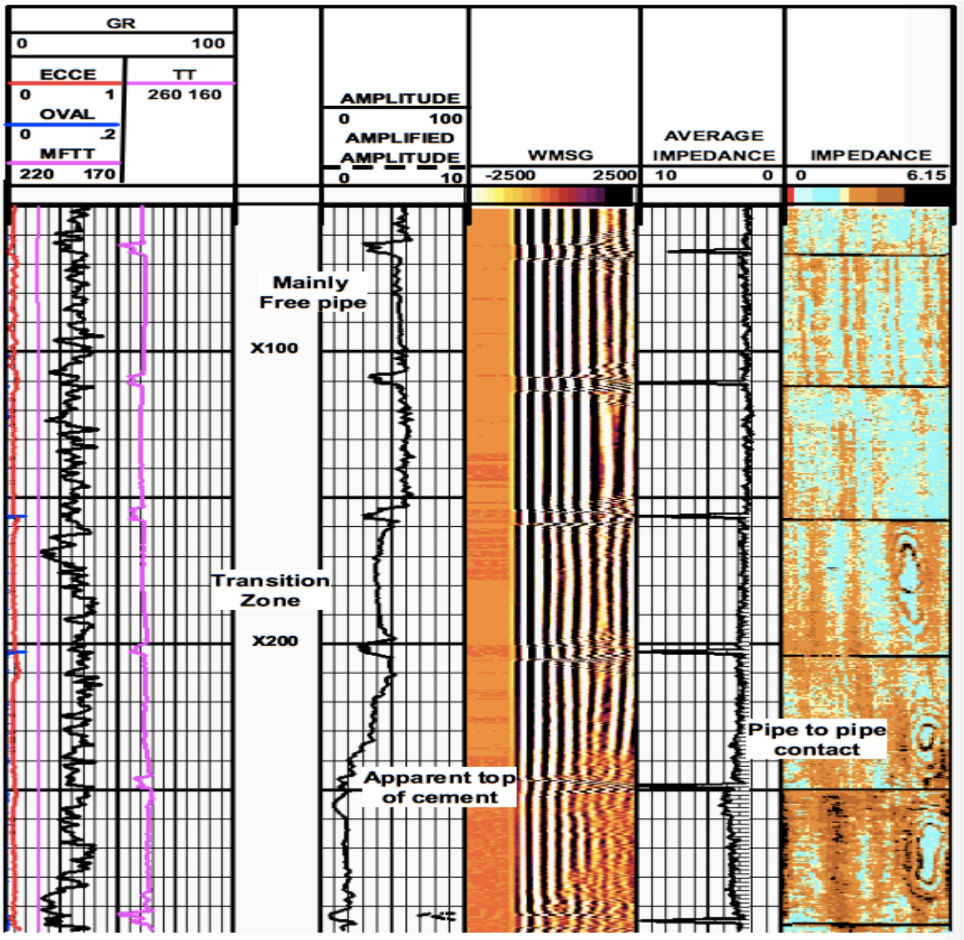


Figure B.12 - Sonic and ultrasonic logs (Shook and Lewis, 2008)

B.3.3.1 Pulse-Echo Technique

The PE tool uses a single transducer, which serves as both a transmitter and a receiver and is common known as the ultrasonic imaging tool (USIT). Either a series of individual transducers are used to measure around the whole casing or the transducer is rotating (Economides et al., 1998). A ultrasonic signal with a frequency between 80 Hz and 700 Hz is produced, and allows an evaluation of the casing condition and cement sheath in the annuli next to the casing (Shook and Lewis, 2008, Benge, 2014). This is shown in Figure B.13.

The attenuation rate of the pulse is dependent on the material that is penetrated and the signals create resonance that is detected at the receivers. Every time the wave strikes an interface, the wave is divided into reflected and transmitted parts, as illustrated in Figure B.14 (Havira, 1982).

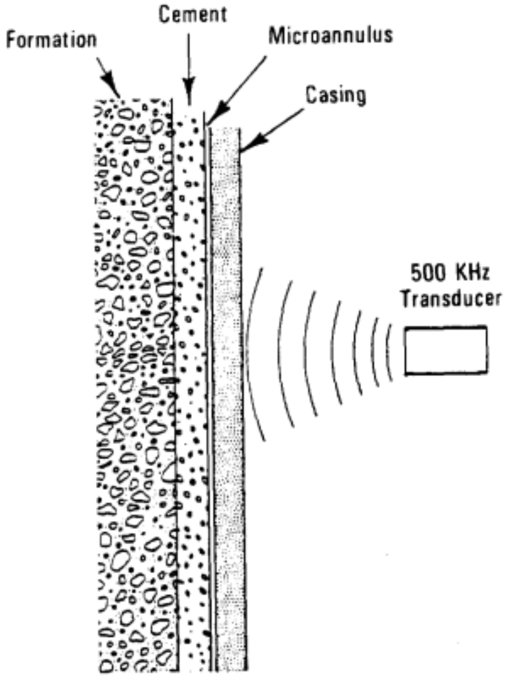


Figure B.13 - Ultrasonic signal (Havira, 1982)

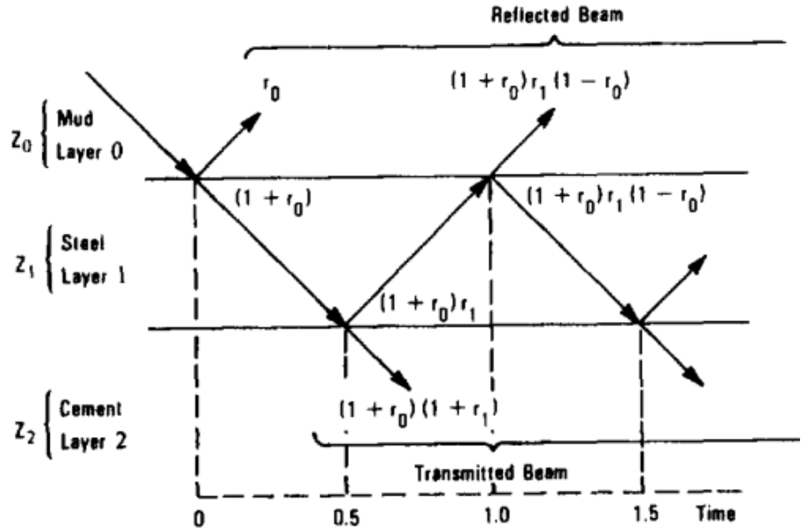


Figure B.14 - Reflections and transmissions of a wave (Havira, 1982)

It is possible to determine the two way TT from the transducer to the casing, the frequency of the signal and the response decay from the ultrasonic waveform analysis (Shook and Lewis, 2008). These measurements can be used to determine the casing radius, thickness and impedance of the material, which in turn can be used to make a detailed analysis of both the casing and cement sheath. The impedance contrast in the materials behind the casing makes it possible to distinguish between the cement and fluids, and to determine the material behind the casing, independent of the densities presented.

There are several advantages by using the USIT and the major advantages is that (Nelson, 1990):

1) It has good spatial resolution, which makes it easier to determine the hydraulic isolation of the cement more precisely.
2) Not necessary with perfect shear coupling between the pipe and the cement for valid interpretation.

The different advantages with the USIT are described further below. Its challenges were studied in chapter 3.1.

Advantages

High resolution

The images of the surface of the casing are obtained through the rotating measurement of the USIT. These measurements provide a high-resolution, 360° scan of the condition of the casing-to-cement bond (Bybee, 2007). This is an improvement from the sonic logging tool, as the CBL/VDL only measures omnidirectional. Higher resolution gives better indication of hydraulic isolation.

Impedance contrast

The ultrasonic tools use the impedance of the materials to determine the status of the cement as there is a sharp contrast in impedance between good and bad bond conditions. This contrast can be expressed by the reflection coefficients, as shown in Figure B.16.

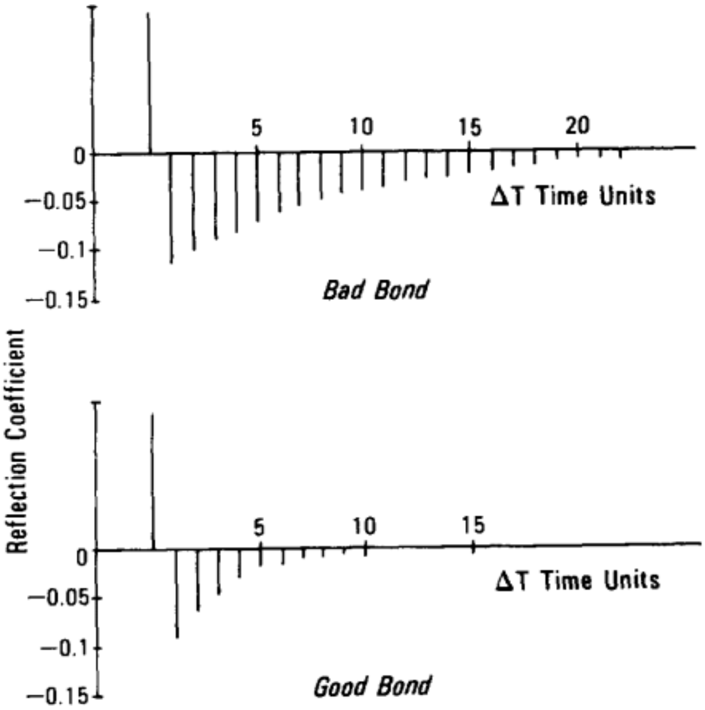


Figure B.15 - Exponential decay of the ultrasonic signal (Havira, 1982)

A simplified calculation of the reflection and transmission coefficients are given below.

$$R = \frac{Z_n - Z_m}{Z_n + Z_m} \tag{26}$$

where

R: Reflection coefficient [-]

Z_n: Acoustic impedance of the material n [rayl]

Z_m: Acoustic impedance of the material m [rayl]

The reflection coefficient is presenting the reflection at the boundary between material *m* and *n*, and expresses the amplitude decay rate. The transmission coefficient is given by

$$T = \frac{2Z_n}{Z_n + Z_m} \tag{27}$$

where

T: Transmission coefficient [-]

The transmission coefficient and the reflection coefficient are dependent on the energy returning to the transducer, which are related to the impedances of the materials on each side of the casing boundary. The impedance of a material is dependent on the wave density and density as shown in equation (28) below (Economides et al., 1998).

$$Z = \rho V \tag{28}$$

where

Z: Impedance [rayl]
ρ: Bulk density [kg/m^3]
V: Compressional wave velocity [m/s]

The reflections coefficients can be used to determine the material behind the casing. The higher the impedance of the material behind the casing, the greater is the acoustic contrast with the drilling fluid (American Petroleum Institute., 2008), and the faster decay of the reflection coefficients as shown in Figure B.16.

Since the impedance of the mud is close to constant, and the impedance of the casing is known, changes in the amplitude decay are expressed by the material behind the casing, which in turn is related to the impedance of this material. In other words, knowledge about the energy emitted from the transducer – the reflection coefficients – can be used to determine the material behind the casing by calculating the acoustic impedance of the material (Rabia, 2001).

An acoustic-impedance map of the cement can be made from recording the waveform, which can in turn contribute to indicate channels. The impedance map shall correlate with the amplitude and the full waveform log.

Transparent micro-annulus

Another advantage by using the USIT, is that the liquid-filled micro-annulus will be presented as a good bond rather than a bad bond (Havira, 1982). To prevent any effects of the micro-annulus on the response, it must appear to be ultrasonically transparent. This can be done by a continuous wave analysis since the energy presented to the micro-annulus is basically at the resonant frequency of the casing. In addition to this, the ultrasonic tools are not dependent on the shear coupling in the same extent as the CBL tools. The micro-annulus will then appear as good hydraulic seal (Havira, 1982).

Liquid-filled Channels

Due to the resolution of the USIT tools, it becomes easier to detect a liquid-filled channel and its location. However, the tool is still sensitive to gas-filled gaps.

Cement sheath thickness

The ultrasonic tool will also overcome the challenge related to thin cement sheath. The CBL might indicate a channel when the cement thickness is less than 1”, while the ultrasonic measurement will see the cement and give a more realistic and reliable approach (Catala and Henry, 1984).

B.3.3.2 Pitch-Catch Technique

An improvement to the PE technique, is the PC technique, which makes it possible to image beyond the cemented region, in addition to the advantages with the PE tool. When attempting to evaluate cements with low acoustic impedance, cements contaminated with mud and light-weight cement, the use of the CBL and PE technique might result in ambiguity. These methods rely on a significant contrast in acoustic impedance between the material, while the PC technique provides more certainty at this point (Schlumberger, 2011). The PC tool combines two modes; one resonance mode as for the PE tool and one flexural mode. Thus, the PC technique combines the PE techniques with another ultrasonic technique which enhances the evaluation of the cement. The waveforms and their envelopes are illustrated in Figure B.16, where it can be seen that the signal from the formation is strong for the flexural wave (blue) compared to the PE wave (red).

When combining these modes, the tool will act as the PE tool in addition to generate temporally echoes arising from propagation along the pipe, which is the flexural wave. The tool will therefore provide reflections at the cement-formation interface as well. This will give a deeper investigation in the radial direction, which increases the probability of revealing defects within the cement sheath and at the cement-rock interface, such as channels. In other words, by using the PC technique, the cement evaluation is improved and uncertainties reduced (van Kuijk et al., 2005).

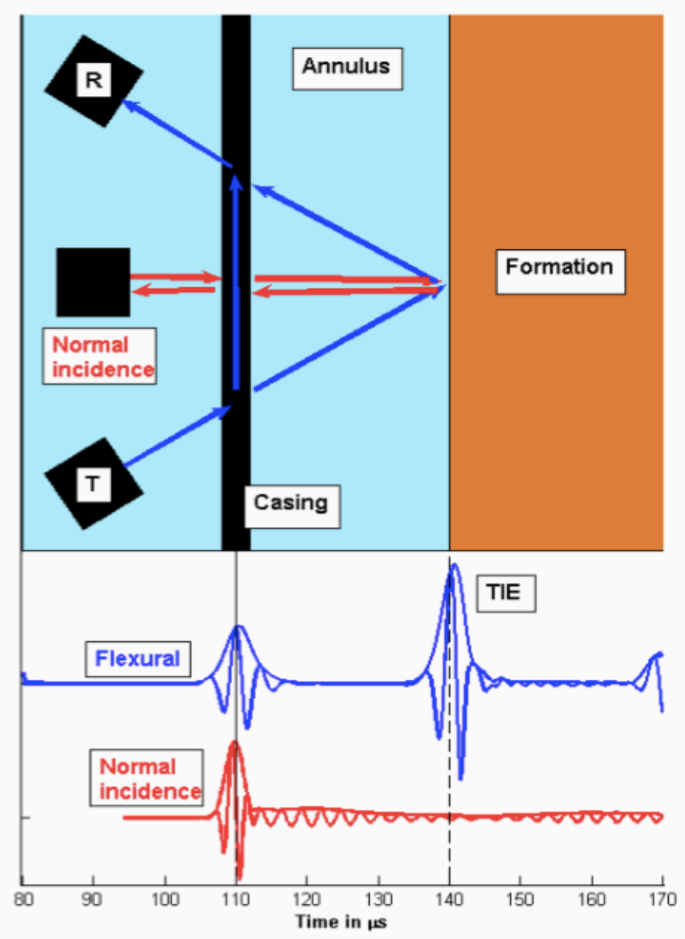


Figure B.16 - Waveform and envelope for resonance mode (red) and flexural mode (blue) (van Kuijk et al., 2005)

Due to its deeper investigation, Viggen et. al. (2016) have investigated the possibility to log through MT1C by using the ultrasonic technology. Ultrasonic techniques were adequate according to NORSOK D-010 which requires high-resolution and azimuthal data (2013). Therefore, Viggen et. al. investigated the untapped potential of the existing two-receiver ultrasonic PC tools. The investigation proves that the present technologies and tools might have potential to be further developed to make the P&A operation more efficient.

Viggen et. al. (2016) used a double-casing geometry as shown in Figure B.17, which could be used with different materials and thicknesses. More about the setup can be found in “Simulation and modeling of ultrasonic PC through-tubing logging” by Viggen et. al. (2016).

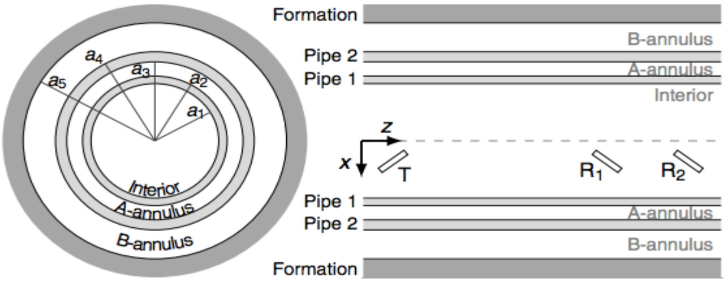


Figure B.17 - Double-casing simulation setup for PC studies (Viggen et al., 2016)

By using the geometry shown in Figure B.17 and foamed cement, the behavior of the transmitted pulse will be as illustrated in Figure B.18. From this figure, it can be seen that the ultrasonic pulse is transmitted in a), and the primary wave packet is generated in b). In c), a leaky flexural Lamb wave packet has been generated on pipe 1. The Lamb wave packet propagates along the pipe, while it leaks a continuous pressure wave front into the A-annulus which reaches pipe 2. The figure shows that earlier wave packets affect the later ones. The secondary wave packet is generated in d), and both the primary and secondary wave packet are acting on pipe 1. In addition, a corresponding leaky Lamb wave packet is generated on pipe 2. e) and f) show when the waves reach the receivers. Then, measurements can be made.

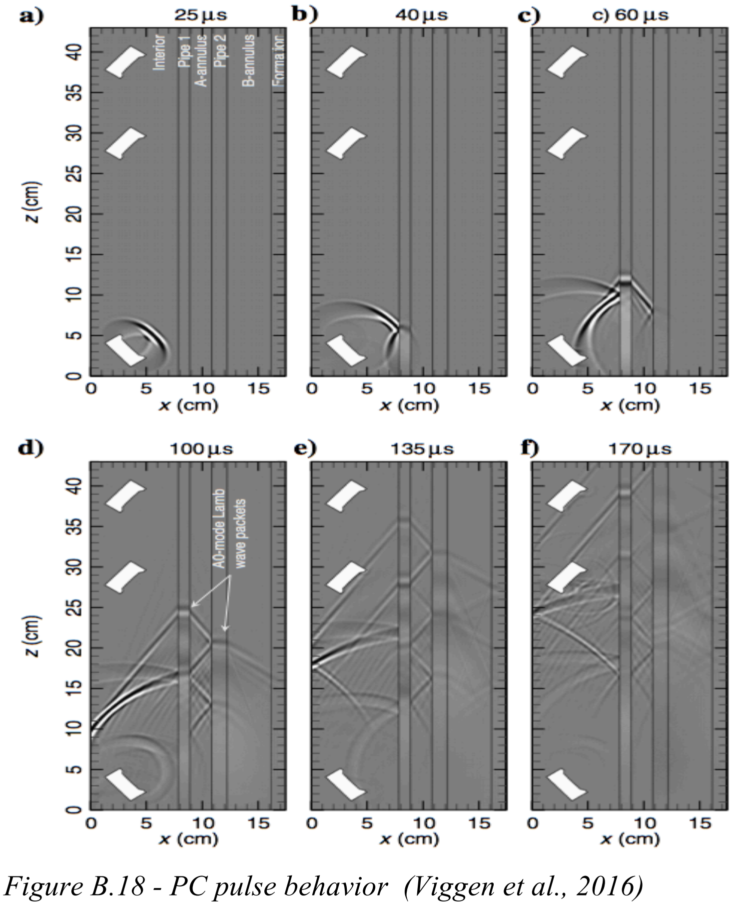


Figure B.18 - PC pulse behavior (Viggen et al., 2016)

A heuristic mathematical model where developed by Viggen et. al. based on the studies above. The aim of the model was to track the evolution of wave packets' amplitudes in a double-pipe geometry (2016). Any wave packet is affected by all preceding wave packets and its own leakage. Viggen et. al. expressed this through the following ODE:

$$\frac{dB_n(t)}{dt} = T\lambda_A \sum_{i=1}^{n-1} R^{n-(i+1)}\, B_i[t-(n-i)\Delta t] - \lambda_n B_n(t) \tag{29}$$

where

$$\lambda_n = \begin{cases} (\lambda_I + \lambda_A) & for\ n\ odd \\ (\lambda_A + \lambda_B) & for\ n\ even \end{cases} \tag{30}$$

where

$B_n(t)$: Wave packet amplitude n [-]

T: Transmission coefficient [-]

λ : Decay constant dependent on the impedance of the material [s^{-1}]

R: Reflection coefficient [-]

t: The time the wave packet amplitude $B_n(t)$ enters the system [µs]

Δt: Time-of-flight between adjacent wave packets [µs]

The assumptions and theory behind equation (29) can be found in "Simulation and modeling of ultrasonic PC through-tubing logging" by Viggen et. al. (2016).

The possibility to log through multiple casings with the PC technique is interesting and has to be studied further to identify possible limitations, as well as making it possible to use it in the field. Logging through one casing with the PC method uses the same principles as described above, where only one casing-cement-formation interface is studied which makes the interpretation less complex.