University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore Technology	Spring semester, 2014 Open
Writer: Kristoffer Halsos	………………………………………… (Writer's signature)
Faculty supervisor: Eiliv Janssen External supervisor(s):	
Thesis title: How to detect the surface casing cement level with existing technology	
Credits (ECTS): 30	
Key words: Wellhead fatigue analysis Cementing Logging	Pages: ………40………… + enclosure: ……0…… Stavanger, ……16/06/2014………….. Date/year

Acknowledgements

This thesis is the final work to fulfil my master degree in Offshore Technology at the faculty of science and technology at the University of Stavanger.

I would like to send my sincere gratitude to my supervisor Eiliv Janssen for all feedback and for guiding me through this process.

Last, I would like to thank my fellow students for 5 incredible years and giving me motivation to complete this master thesis.

Kristoffer Halsos

Abstract

The increased awareness regarding wellhead fatigue has led to an ongoing joint industry project led by Det Norske Veritas (DNV). There is lack of a standardized procedure of performing a wellhead fatigue analysis. The joint industry project aims to develop a new recommended practice in how to perform a thorough wellhead fatigue analysis. A PhD written by Lorents Reinås studies the surface casing cement boundary condition and its effects on the fatigue analytical models. It proves that the cement level between the conductor and the surface casing is a sensitive input parameter in terms of fatigue calculations.

This thesis will investigate how to detect this particular cement level in large sized casings, i.e. 20”, by utilizing existing technology.

Common practice is to cement the surface casing all the way up to the mudline. However, the actual cement level is never measured. Pressure testing, displacement calculations and cement returns is the common documentation of a successful cement job, however none of this can provide sufficient information to document the cement height. By locating this cement level, one could provide a more accurate fatigue calculation. The conservative assumptions used in fatigue calculation today provides conservative fatigue estimates. By not knowing, one have to perform preventive measures. The reason for wanting to detect this cement level is to enable a better utilization of the wellhead.

The industry provides several methods of locating top of cement, but not many are compatible with logging in large sized casings. After investigating the most common cement evaluation methods available, some of the existing methods proves to support logging in 20” surface casings.

Table of Contents

1 Introduction

1.1 Background

There is an increased concern in the offshore industry regarding wellhead fatigue. Subsea wells have had to shut down due to fatigue failure, and riser based well intervention cannot proceed due to the risk of exceeding the fatigue limitation. Because of this, the industry is looking for a better way to assess and prevent potential fatigue failures. In the absence of a standardized procedure in analyzing wellhead fatigue, a joint industry project (JIP) led by Det Norske Veritas (DNV) has been developing a recommended practice with the aim to improve the methodology of wellhead fatigue analysis [6]. Loss of integrity could result in serious consequences which could have a large impact on the economic perspective of the business, but more important, the possibility for an environmental disaster.

In order to carry out a thorough fatigue analysis, accurate information regarding important boundary condition has to be included. Only by knowing key boundary conditions, one is able to simulate the expected behavior. Getting hold of this information can be challenging, and sometimes even impossible. In such case, the common practice is to apply conservative measures. Conservative measures may prevent accidents or unwanted events, but it could also have a negative effect in the utilization of the component`s full potential.

One of the critical boundary conditions in terms of wellhead fatigue is the height of cement between the conductor and surface casing relative to the seabed, referred to as top of cement (TOC). A PhD written at the University of Stavanger by Lorents Reinås investigates the surface casing cement boundary condition and the effect it has in conjunction with wellhead fatigue analysis [3]. It turns out that fatigue calculations is very sensitive to the location of TOC, but then again, locating TOC in large sized casings is still a challenge. By not knowing the exact height of cement, one has to apply preventive measures, which results in assuming the worst level of cement. If one could detect this cement level in a reasonable way, it would help to provide a more accurate fatigue capacity estimate. Thus, the ability to utilize and plan well operations in a more safe and efficient way.

1.2 Objective

This thesis will look into how one could detect top of cement between a large sized conductor and surface casing based on the available technology. Today, one assumes the worst level of cement, a conservative measure that results in conservative fatigue calculations. By looking into the common technology and methods used in terms of cement evaluation, the objective is to suggest and elaborate methods that could provide a documentation of TOC. To detect this cement level in old wells is challenging because of several layers of casings and cement placed in front of the conductor/surface casing. The area of interest in this work is to locate TOC in new wells, mainly after cementing the surface casing and before installing new casings inside the surface casing.

1.3 Method

As the cement-level of interest is a parameter in a complex and multi-disciplinary wellhead fatigue analysis. A theoretical part, divided into three subjects, will explain wellhead fatigue, cementing and the most common logging services provided in terms of cement evaluation. A final discussion will discuss whether current technology is fit for this purpose. How it can detect the cement level, its limitations, and elaborate pros and cons related to the different techniques and methods. Figure 1 shows an illustration of the cement level of interest.

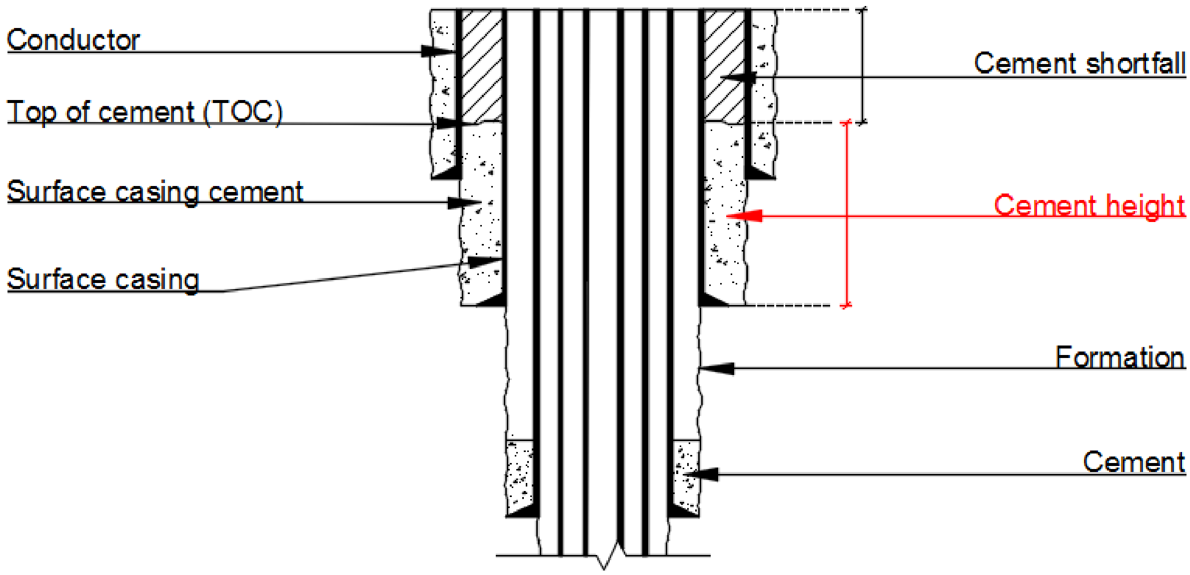

Figure 1 - Illustrating Surface casing cement level, TOC

2 Theory

2.1 Wellhead fatigue

Wellhead fatigue has received an increasing attention when it comes to control and monitoring of a safe operational design in the offshore industry. Although the fatigue issue of a wellhead system always has been a well-known concern, an establishment of a common industry practice for calculating fatigue capacity has been missing. This is about to improve with the ongoing joint industry project (JIP) led by DNV together with Statoil, Marathon, Lundin, Eni, Total, ExxonMobil, BP, BG Group, Talisman, Det Norske and Shell [6]. The objective of this JIP is to provide a detailed procedure for fatigue damage assessment, which intends to provide the basis for further decision making in proper well integrity management.

2.1.1 Fatigue introduction

Mechanical fatigue is a process of repeated cyclic stresses on a structure or material. These stresses are below the material ultimate capacity, but when a load within a certain threshold is repeatedly applied, the material weakens. The material weakening is a result of microcracks created along areas subjected to high shear stress led by the cyclic loading and unloading. These cracks are not visible, but if the stress cycles continue, the microcracks joins and form larger cracks. The crack will continue to grow until the remaining cross-section of the material no longer manage to support the loading, and the material will eventually fracture.

S-N curves present the allowable stress to cycle relationship. In the fatigue damage assessment, relevant S-N curves from DNV-RP-C203 provides information needed in fatigue calculation. Actual fatigue capacity is obtained from laboratory testing.

2.1.2 Typical subsea well construction

As seen in figure 2 a typical subsea well construction consists of several steel pipes locked together. The outermost steel pipe is the conductor, and it is the first barrier against the surrounding formations. As well as preventing formation caving into the borehole, a conductor serves as one of the primary load bearing components. At the top of the conductor sits the conductor housing. A weld joins the conductor and conductor housing, and the conductor housing constitutes the landing shoulder for the next tubular section called surface casing. Like the conductor, the surface casing holds a wellhead welded on top of it, and together with the conductor, they represents the primary load bearing components of the well. Further, intermediate casing and production casing are fitted with casing hangers and hung of inside the wellhead. Cement locks the casings together in a way they normally would not be able to retrieve again. Usually the production tubing is the only retrievable tubing in such well system, hence the only one replaceable. It exists different configurations of subsea wells, and the one illustrated is only an example. The main objective for a successful well design is to ensure the well to operate safely through its lifetime.

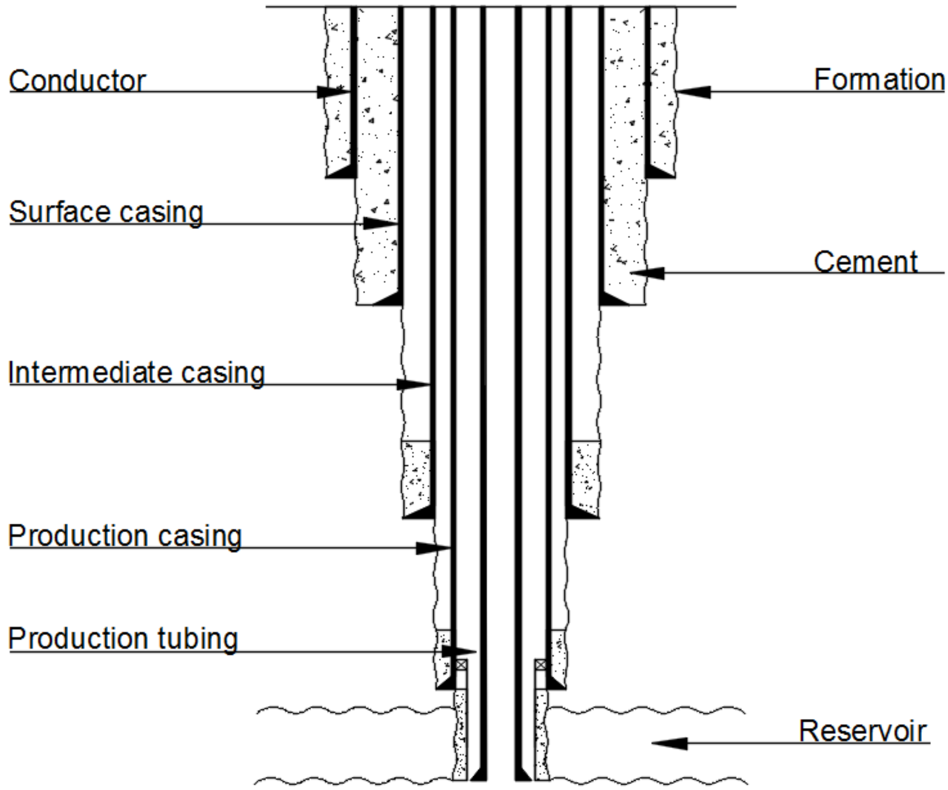

Figure 2 - Typical subsea well construction

However, it is the lateral support and bonding between conductor and surface casing that is of special interest in this work.

2.1.3 Subsea wellhead

As one of the main bearing components, the wellhead is an obvious key component in a well system. The wellhead is located just above seabed, integrated either in a template structure or as a satellite well without any surrounding structural support. With a standardized interface, different operational equipment connects to the wellhead and necessary work commence. In other words, it act as a connection point between the well and different equipment related to well operations. Operating as the link between connectable equipment and the well, the wellhead has to withstand both external- as well as internal loads. Internal loads are loads acting from the reservoir and the structural well configuration itself, while external forces is largely work related to drilling and intervention. Landing large BOPs with drilling risers extending to mobile drilling units (MODU) creates dynamic movements, which again generates forces transmitted from the riser system down to the wellhead. This multifunctional purpose requires the wellhead to function as both a pressure vessel and a structural load-bearing component.

A reliable and predictable wellhead is critical to operate in a safe way within acceptable levels of loadings. Fatigue damage is as explained a result of cyclic loading above a certain threshold. If exposed to enough cyclic loading a wellhead may fail due to fatigue damage and the pressure vessel function is lost. As the wellhead tends to be a well barrier, a wellhead failure may result in an increased risk to the well integrity.

2.1.4 Well integrity

As stated in Norsok standard D-10: The definition of well integrity is to be an "application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well" [5]. This means, to achieve well integrity one or several well barrier elements, separately or together, have to form a primary or secondary well barrier. The intention of any well barrier is to stop any unwanted release or influx of any fluid related to the well and Norsok refers to two main categories:

- *Primary well barrier:*
  A well barrier element that is or might be in direct contact with the formation fluid and functions as the first safety barrier any fluid has to pass in case of an uncontrolled release. The primary well barrier forms the inner frame of protection against the formation fluid.
- *Secondary well barrier:*
  A well barrier element that has prevent any further release of formation fluids if the primary well barrier fails.

The categorization of different well barrier elements (WBE) depends on the completion setup and the operational activity of each well. A well barrier element may be e.g. in-situ formation, casing, casing cement, different valves, tubing hanger, packers, wellhead, x-tree etc. In some situations, it is not possible to make two independent barriers. When the primary and secondary well barrier element constitutes the last barrier, the standard refers to the barrier as a common well barrier element. In such case, it is necessary to apply risk-reducing measures and to perform a thorough risk analysis [5]. Before commencing any activity or operations, the need and planning of a well barrier schematic (WBS) is required. The WBS identifies which WBE is required, their acceptance criteria and monitoring method. A new or updated WBS should be made available [5]:

- When a new well component is acting as a WBE;
- For illustration of the completed well with XT (planned and as built);
- For recompletion or workover on wells with deficient WBEs; and
- For final status of permanently abandoned wells.

Norsok provides a detailed description of the contextual requirements regarding a WBS in Norsok D-10, section 4.2.2. The outline of this scheme is however an illustrating drawing of the well barriers, showing and separating the primary and secondary well barriers respectively with blue and red color. Along with the barrier illustration, a brief description is made of the different barrier elements and their monitoring methods. Every element holds a number that refers to the element acceptance criteria (EAC) table. A table that contains different requirements ranging from functionalities to use and monitoring. See Norsok D-10, section 15, for complete tables.

2.1.5 Wellhead fatigue analysis

In order to understand the origin and effects of fatigue exerted on a wellhead system, it is important to perform detailed analysis assessing various input parameters. During the life cycle of a well, it roughly undergoes three major phases:

- Initial construction
- Production/workover/sidetrack drilling
- Plug and abandonment

The phase contributing the most in terms of fatigue damage is the initial construction of the well. This is normally the phase where the well system experience the longest period connected to a BOP and riser system. Knowing that the riser loads constitutes the largest part of fatigue damage, the time these components are connected is the time fatigue damage accumulates the most. As wells are being drilled in increasing depths, larger thus heavier drilling systems are used. An increase in both size and depth naturally results in larger forces exerted on the wellhead.

There has not been a unified method of performing fatigue analysis in the industry. No international codes or standards have provided the guidance needed in how to conduct a thorough review of a wellhead fatigue performance. The analysis methodology has differed within the industry, which has made the results difficult to compare and verify by a third party [6]. However, the ongoing JIP intends to develop guidelines for wellhead analysis, which in a larger extent standardizes the methodology making it easier to compare. A simplification of the flowchart provided by the JIP shows an overview of the analysis methodology in figure 3.

A wellhead fatigue analysis generally consist of a global load analysis, local response analysis and a fatigue damage assessment. The global load analysis examines how loads generated by the system setup transfers to the component of interest, which in this case is the wellhead system. Since drilling and workover activities accounts for most of the cyclic loadings applied to the wellhead system, a drilling setup is what constitutes the global analysis model. The lower boundary condition is set at the wellhead datum, which is a result of the local response analysis. The objective of a global analysis is to establish the loads acting on the well. Since the results of the local response analysis is the lower boundary conditions in the global analysis, the local analysis is the first to be completed. By building a FE-model of the wellhead system, detailed described in the JIP RP [6], one wants to check the local reaction of forces subjected to the wellhead for different bending moments. The result of the local analysis are load-to-stress curves, which together with the global load-time series provides the stress time series of each hotspot. See section 2.1.5.2 for an explanation and illustration of hotspots.

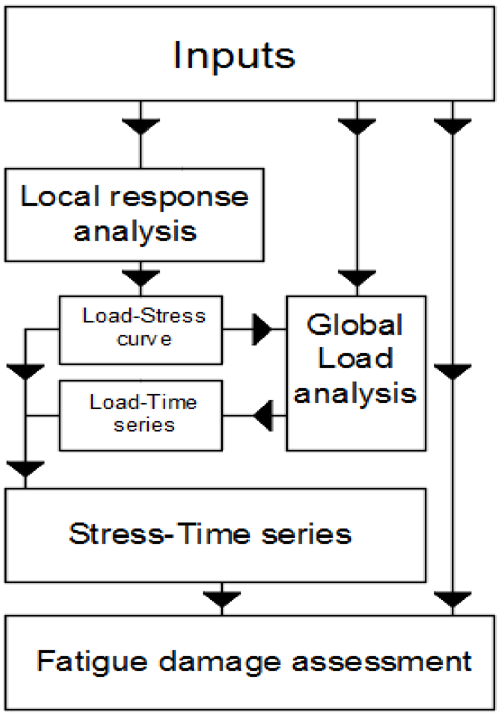

Figure 3 – Analysis methodology

2.1.5.1 Parameters affecting Wellhead fatigue

There are many contributing factors in the accumulation of wellhead fatigue. During a wellhead fatigue analysis, these parameters constitutes the basis for the resulting analytical behavior. Some parameters influence the system response more than other. By changing the values of the respective parameters, one is able to study the system response based on the various inputs.

In order to perform a detailed wellhead fatigue analysis, one need comprehensive field and equipment data. Gathering all this information takes time and requires dedicated and skilled personnel. To make the gathering of relevant data faster and more efficient, a database containing relevant data is established [3]. Unfortunately, it is not possible to gather all necessary information in one database, because some date is well specific. The surface casing cement level is an example of information that requires individual detection of each well.

Important input parameter that could affect the wellhead fatigue performance:

- *MODU motions*
  MODU`s normally have systems to compensate for some degree of movement. In case of exceeding this system, the MODU movement will transfer to the riser system and further to the wellhead. This movement generates forces exerted to the wellhead.

- *Sea state*
  Waves and currents can have a large impact on both MODU and riser motion. Larger movements generates larger forces transmitted to the wellhead. Currents can create vortex-induced vibrations that could make the riser system to vibrate if hitting resonance. To reduce vortex-induced vibration, the riser system could be fitted with vortex shedding to break up the current velocity and prevent the riser system to hit resonance.

- *Soil interaction*
  The surrounding soil provides structural support to the conductor. The resistance of this soil depends on the soil characteristics, which varies by the different layers with depth. Loads from the riser system transfers through the wellhead system and into the surrounding soil. This stress distribution of the varying layers is of importance regarding horizontal support of the conductor.

- *Surface casing cement level*
  This particular cement level is very sensitive with respect to fatigue calculation. Stress concentrations in hotspots varies as the cement level varies. Ensuring that the cement level reach the optimal height is important with respect to stress distribution. Stresses experienced at the different hotspots will then decreases and fatigue life increases.

- *Wellhead design*
  The wellhead connection between the conductor and surface housing is classified either as a rigid or non-rigid lockdown. In a rigid lockdown, the wellhead can move between the conductor- and surface housing. This movement creates larger bending moments in the surface casing, hence lower fatigue life. The rigid lockdown do not allow this movement, but in case of cementing the surface casing up to the seabed, the non-rigid lockdown will become more like the rigid lockdown.

- Casing design
  Joints are the weakest links at a string, hence a hotspot potential. Placing connectors/welds between housings and/or casings away from areas subjected to high bending loads could increase fatigue life.

2.1.5.2 Wellhead fatigue hotspots

During drilling and intervention, the wellhead system experiences bending moments generated by the MODU and riser system. While exposed to these forces, certain areas of the wellhead experiences large concentrations of stress. This is the fatigue critical locations, referred to as hotspots. Typical hotspots are:

- Welded connection between Conductor and conductor housing
- Welded connection between Surface casing and wellhead
- Connection points and welds between conductors and between surface casings.

Figure 4 shows an illustration of the typical hotspots.

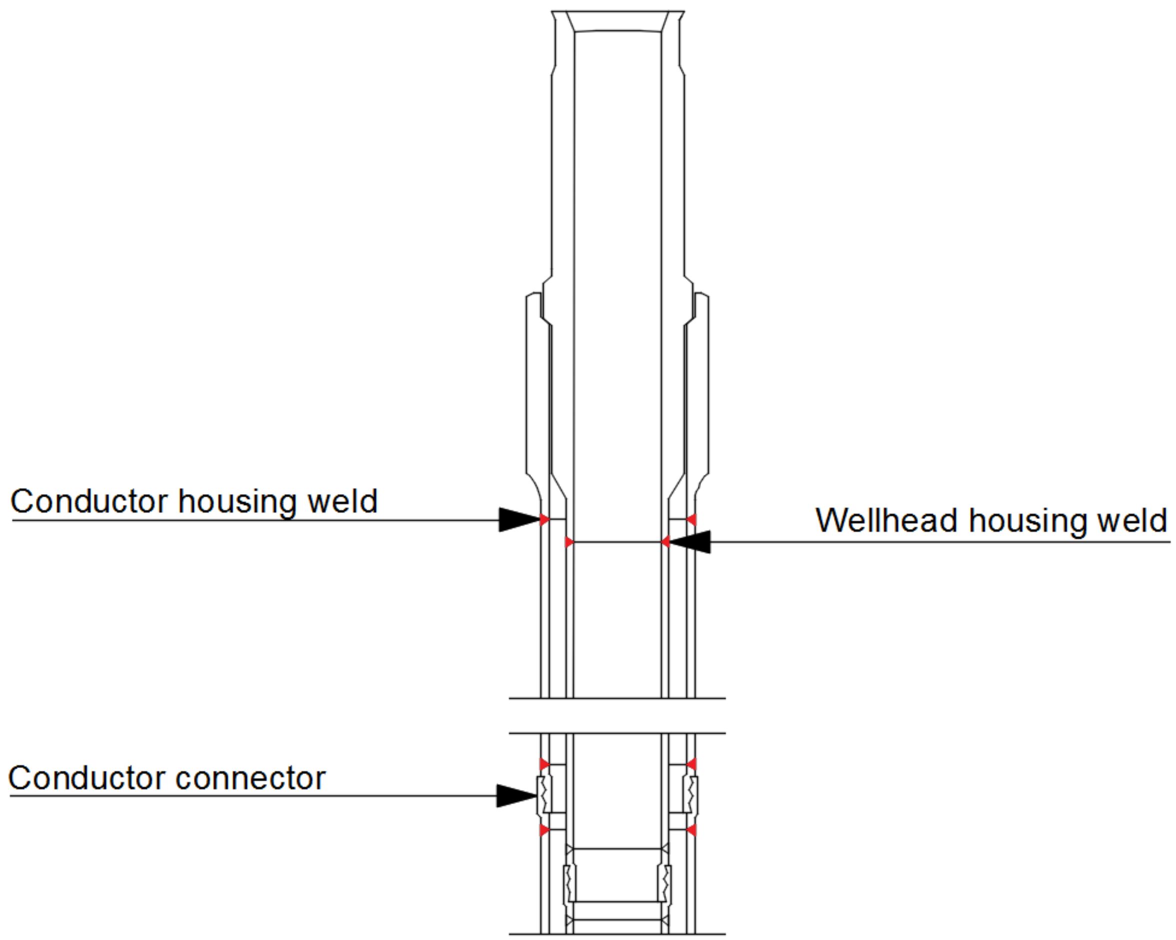

Figure 4 - Showing fatigue critical locations, Hotspots

2.1.5.3 Fatigue damage assessment

Fatigue damage assessment is a product of the local response- and global load analysis. By combining load stress curves obtained from the local response analysis and the load-time series or load range histograms from the global analysis, the result are stress-time series or hotspot stress-histograms for the varying load ranges [3,6].

The Miner-Palmgren hypothesis and relevant S-N curves obtained from applicable codes is used to perform the fatigue damage calculation. The fatigue calculation combines the stress-time series for all applicable sea states and scatter diagrams containing statistical wave information in the area and period of interest to obtain the accumulated fatigue. Only by knowing the history of previously and expected sea states in the area, it is possible to obtain a relatively accurate fatigue estimates.

Fatigue damage only accumulates during drilling or riser-based intervention work. If the calculated fatigue life is estimated assuming the worst level of cement, the calculated fatigue life could be very conservative. Over time, activities related to drilling and well intervention can accumulate enough fatigue damage to reach the calculated fatigue life estimate. In such case, problems which otherwise could have been resolved by workover or riser-based intervention cannot be performed due to the risk of exceeding the fatigue limit. In other words, the worst-case scenario could lead to a shut down even if the well still could produce for a long time.

Conservative measures is very good in a safety perspective, but in an economic and operational point of view, it can be negative. It may not have been necessary to perform a shutdown if the TOC was or could be located. If so, remaining or new fatigue life calculation could have approved more work on the well and the problem solved. Conservative measures is important to maintain well integrity, but could be optimized in terms of collecting actual inputs instead of making conservative assumptions.

2.1.6 Fatigue failure consequences

In case of exceeding the acceptable fatigue limitations, the wellhead could fail if exposed to extra fatigue damage. The wellhead is a multipurpose component in a well system and a part of the second well barrier during drilling. Serving several important functions in terms of well integrity, a fatigue failure could lead to serious consequences. A fracture in the wellhead can possibly ruin the ability to contain pressure. In such case, a wellhead failure could cause uncontrolled leakage of fluids to the environment. An event that potentially could cause severe environmental damage and the huge economic losses.

2.2 Cementing

Well integrity is a critical aspect in any well completion and to ensure well integrity, it is important to provide zonal isolation in oil, gas and water wells. After drilling new sections, tubular lengths are lowered downhole to serve as outer pressure barriers for the production line. The purpose is to ensure that the well do not collapse and is able to handle the applied loads when in production. To prevent any possibility of unwanted fluid or gas to enter or escape the well, it is important to create a seal between the casings and against the formation. By pumping cement into the annulus, the cement cures and hardens through an exothermic hydration reaction and seals off between the casings or against the formation. There are several methods of performing a cement job. However, for the cementing operation to fulfill its objectives, the cement design must include four basic types of well data [2]:

- Depth and dimensional data
- Wellbore environment, including pressure regime and drilling fluid engineering
- Temperature regime
- Any parameter that may affect the integrity of the cement sheath and the quality of isolation during the well`s productive lifetime and after abandonment

Well data like these creates the basis for choosing the correct cement properties for any given well.

There is two main categories within cementing:

- Primary cementing
- Remedial cementing

Jobs referred to as "*primary cementing*" addresses completion work, while the term "*remedial cementing*" addresses cement jobs with the aim to repair and/or improve primary cement jobs, or to plug and abandon wells. As sub categories within the remedial cementing segment, there are:

- Squeeze cementing
- Plug cementing

To ensure a good cement job it is very important to establish and document its purpose and goals. The objective of a cement job may differ, but a clear statement of the job procedure and its functional requirements after placement are necessary to perform a good job evaluation.

2.2.1 Primary cementing

Primary cementing is the placement of cement between the casings and the formation and the annular between casings. The main objective is to isolate and create a hydraulic seal so no formation fluid enters or escapes the well. A successful primary cementing job is critical in terms of well integrity. Fixing unsuccessful cement jobs are very difficult if not impossible, meaning there is only one chance to complete the job successfully. Quality assurance is therefore essential in order to be do a good job and is a result of thorough planning and execution of the job. An unsuccessful job may cause expensive remedial repairs and prevent the well to reach its full potential [2].

2.2.1.1 Surface casing cementing

When placing cement between the conductor and surface casing, it is normal procedure to cement all the way to the seabed [2, 3, 12]. Besides creating a seal between the pipes, this cement also serves as a structural support. The conductor and the surface casing constitutes the main load-bearing components in a well system. Loads acting on the wellhead transfers down the wellhead/surface casing, through the cement and conductor and into the surrounding soil. To get a good distribution of forces between conductor and surface casing, cement has to form a degree of bonding between the pipes. The height and bonding of cement surrounding the surface casing is important in terms of load distribution and fatigue calculations.

At this stage of well construction, there is no BOP connected to the wellhead. The cementing will be performed in an open system and drilling and cement returns left at the seabed. A typical surface-casing cement job consists of pumping a lead cement slurry and a tail cement slurry down the wellbore and into the annulus. A lead slurry consists of a higher water/cement ratio than optimal to reduce density and the exerted pressure on the surrounding formation. It is important that the cement do not exceed the formation fracture pressure in order to avoid loss of cement into the formation. In case of a formation fracture, the cement slurry may escape into the formation and fail to perform its intended function. To prevent this, it is common to use special additives and lightweight cement slurries (section 2.2.3 and 2.2.4).

In case of lost circulation or fluid loss to the formation, a cement shortfall could occur (2.2.5). This could potentially have a huge impact on the zonal isolation capability of the cement, but also in terms of fatigue capacity of the wellhead. Studies of cement shortfall shows the surface casing cement level to be a very sensitive parameter input in fatigue calculations [3, 12].

To check if the cement placement is a success the common practice is to pressure test the cement [2]. In such case, it is important to ensure that the cement has allowed to set properly. The cement has to reach a compressive strength of 50psi before initial setting is considered. To know the set time and other cement properties, pre laboratory testing is required. It is important to keep the cement undisturbed for the required amount of time, referred to as wait on cement (WOC), to avoid a potential failure of the cement sheath due to pressure testing or other well activities. Because of high operating costs, WOC is kept to a minimum.

Pressure testing is the only way to perform a physical cement evaluation. It is however not possible to verify an exact placement of the cement height by this method. To detect this cement level one could perform cement evaluating logging surveys, which utilizes non-physical measuring (section 2.3).

2.2.1.1.1 Standards, Norsok

Standards and codes usually provides the guidance and applicable requirements needed in order to operate in a safe and efficient way. In terms of TOC, Norwegian regulations states that the height shall be set to allow for future use of the well. In general, TOC shall be a minimum of 100m measured depth (MD) above the casing shoe, but for the surface casing, TOC shall be set to reflect the loads acting on the wellhead. The recommended height proposed by Norsok is at the seabed surface [5].

2.2.2 Remedial Cementing

The term remedial cementing is generally used about repair jobs and is often referred to as a result of poorly done primary cementing. That is however not a very accurate description, since there is many unknown scenarios during drilling and the well`s lifetime that could cause the need for a cement job. There are two main ways of remedial repairs and that is by squeeze cementing or plug cementing.

2.2.2.1 Squeeze cementing

Squeeze cementing is the process where applied pressure force the cement slurry to enter voids in the casing/wellbore. The troublesome area is isolated and the pressurized cement fills cracks, fissures, micro annulus, channels, casing splits, insufficient cement height in the annulus or seals off lost circulation- or depleted zones etc. before it sets and intentionally solves the initial problem.

2.2.2.2 Plug cementing

Plug cementing is the placement of a cement slurry at a predetermined spot to form a hydraulic and mechanical seal. The harden cement forms a plug, which intends to prevent fluids between formations or between the formation and surface. Some of the most common reasons performing plug cementing are: Abandonment, lost circulation, well control, wellbore stability, zonal isolation and sidetrack drilling.

2.2.3 Cement properties

During the life cycle of a well, cement serves many important functions. Whether it is in the initial construction or the well closure, there is most likely a cement job involved. In line with the technological developments, drilling in deeper waters and more remote locations results in new operational conditions. The mechanical properties of cement is greatly dependent on its composition, but equally important, the conditions which it is exposed to during curing and through its lifetime. Choosing the right cement is essential with respect to well integrity, hence a good knowledge of downhole conditions is required.

The mechanical properties depends on what purpose the cement is set to serve. In terms of primary cementing, short-term strength development has been the focus, but seen in conjunction with the total life cycle of the well, long-term mechanical properties is as important to withstand changing well conditions through its lifetime [2].

New operational conditions has driven the development of cement properties correspondingly to suit new wellbore conditions. By the use of additives, one is able to control the performance of cement and to modify it accordingly to suit the individual well requirements. Additives can affect the strength, density, set time and allow the cement to gain many other advantages in favor of a successful cement job.

To obtain the intended cement properties, the liquid cement mixture undergoes a hydration process. A major factor influencing the speed of this process is temperature [2, 3]. The time to reach initial setting of cement varies greatly with the curing temperature and cement composition. A study performed on typical subsea well cements at low curing temperatures, showed a large variance in the time to reach initial setting between a typical lead cement and tail cement [15]. Deep water and typical North Sea conditions shows to yield low curing temperatures [3]. This proves that the lead cement used in top casing cementing will need longer time to achieve acceptable compressive strength before exposed to significant loads. If subjected to significant loads before the initial setting has occurred, the cement may lose its designated function, such as zonal isolation or structural support.

2.2.4 Cement design procedure and its impact on cement evaluation

Each well holds different wellbore conditions, which demand different cement properties. In order to perform a successful cementing job, it is critical that the cement meets its designated objectives and suits the wellbore conditions. Cement design starts long before performing the cement job. Wellbore conditions may change during the start of planning to the finalized cement design, which calls upon a continuously preparation of the cement design against the changing well data. Logging instruments collects well data such as temperature, fracture gradients, pore pressure and wellbore dimensions, which provides inputs to the cement design. Laboratory testing and computer simulation ensures that the cement design meets its required specifications. It also provides the rheological properties of the cement slurry expected during downhole conditions. However, a high-quality cement tested and prepared at surface does not guarantee an equal quality downhole. A loss in cement quality can be a result of contamination with mud and other wellbore materials.

A well consist of many different layers of formation. These layers could be considered weak, highly permeable or be of a composition that requires a special cement system in order to not fracture or collapse. In cases where special wellbore conditions poses a threat, regular class G cement may not suit the wellbore requirements. Wells containing highly permeable or low fracture gradient formations may require low-density fluids to prevent any further damage or loss of fluid to the formation. It is possible to obtain strong low-density cement slurries with high compressive strength by controlling particle size and additives. The use of lightweight cement has shown effective in low fracture gradient wells and as lead cement when performing top casing cementing. Because of its lower density, it exerts less pressure against the formation per unit volume. This could be enough to keep weak formations intact and prevent any unwanted fluid loss to the formation before the cement sets. However, utilizing lightweight and mechanically modified cement makes it harder to perform good cement evaluation. The change in density makes it more challenging to differentiate between drilling mud and cement. That is, the acoustic properties of the two materials is too close to separate, thus it very hard to distinguish between a solid and a liquid material using an acoustic evaluation tool. Table 1 shows different material properties and that the density and acoustic properties of mud and cement actually can be similar.

Table 1 – Material properties, illustrates the small difference between mud and lightweight cement [17]

Material	Density (kg/m^3)	Compressional velocity (m/s)	Acoustic Impedance (MRayl)
Gas	1.3-130	330	0-0004-0.04
Water	1000	1500	1.5
Drilling mud	1000-2000	1300-1800	1.5-3.0
Lightweight cement	1000-1400	2200-2600	3.0-3.6
Class G cement	1900	2700-3700	5.0-7.0

2.2.5 Reasons and consequences of cementing failures

A thorough planning and execution is the best way to prevent any cement failure. The wellbore has to be properly prepared before advancing to a cementing operation, and the cement design should account for and be able to counter many of the problems that may occur downhole.

Some important problems that may cause cement failure is:

Channeling:
Certain events during cementing can create channels in the cement sheath, against the casing or against the formation. In order to provide zonal isolation, communication between zones cannot happen. Channels may provide a way for wellbore fluids to travel between production zones. This could affect well integrity and influence the well performance. Reasons of channeling can be due to poor casing centralization, failure to move casing while cementing, free water from the hydration process, but most important due to poor mud removal. Channels is an important factor in terms of cement evaluation.

Fluid loss:

When pumping the cement against permeable formations, the pressure forced on the cement can make the aqueous phase of the cement slurry to escape into the formation. The remaining solids that does not migrate into the formation contributes to an increased viscosity of the cement slurry. The cement slurry may have lost important substance to obtain its intended properties and this could be a reason to cementing failure [2]. Some of the circulated material done prior to the cementing may have filtrated some of the formation and could help mitigate fluid loss. Adding fluid loss-control agents in the cement slurry is another mitigating fluid loss alternative.

Lost circulation:

During drilling or cementing, mud or cement-slurries may escape into the surrounding formation. This could be the result of highly permeable formation, the mud or cement exceeding the fracture hydrostatic pressure gradient of the formation or fracture induced by drilling [2]. If cement escapes into the formation, the remaining amount of mud or cement may not be enough to ensure a successful job. The reduction in cement height may not be sufficient to provide zonal isolation and in terms of structural support, this could influence the wellhead fatigue estimate. To mitigate problems related to lost circulation, one have to obtain as much knowledge of the wellbore conditions as possible. Only this way one can perform preventive measures such as squeeze cementing and including lost circulation preventive additives in the cement.

Pressure testing:

While pressure testing of the cement, stress cracks in the cement sheath may form. This can be another contribution to creation of a micro annulus. [18]

Poor mud removal

2.2.6 Cement job evaluation

There are many ways of evaluating a cement job, and the method of choice greatly depends on what to examine. The requirements to obtain a satisfactory result varies from local regulations to customer requests, but in order to perform a good evaluation regardless of method used, a proper understanding of the initial objective need to be understood. The purpose of a cement job evaluation is to confirm the placement of cement, and to determine the degree of success based on predetermined goals for the cement job.

Depending on the functional intention of the cement, there are different evaluation methods. Examining cement downhole usually requires logging methods utilizing tools that is able to make measure through the casing wall. These tools, if properly used, can provide important information about the cement placed behind the casing.

Another possibility is to pressure test the cement. Pressure testing is common when evaluating zonal isolation and communication between productive zones.

In order to utilize sonic tools the cement has to reach a compressive strength of 250 psi and good bounding to ensure good acoustic coupling [18]. This is required for transmittal of sonic signals.

2.3 Logging

Well logging is the most important method to obtain information about a wellbore today. The objective of logging may vary, but the main purpose is to gather as accurate and much details about a wellbore and its surroundings as possible. There are many types of logging tools on the provided and the choice of tool depends on what to examine. To date, there are two ways of performing a log run. Either by wireline or logging while drilling. The tool itself is a piece of equipment mounted on the end of a wireline, or as part of the drill string lowered down into the wellbore. When reached target depth, the tool activates and starts collecting data while tripping in or out in a controlled speed. If there is direct connection with the tool through fiber optics or other communication methods, the surface logging crew could receive live data transferred directly through the run. If live transmitting of data is not necessary or possible, data is stored in a memory section of the tool and collected when reached surface.

The data collected are processed and presented in a well log, which is a document consisting of graphs and in some cases scanned images representing various information of the well. Log analysts uses the well log to obtain information depending on what they want to examine e.g. well integrity conditions or the possibility to recover hydrocarbons. By utilizing the advantages of the different logging techniques, it is possible to make good predictions. After all, the log interpretation decides whether to continue completing a well or to plug and abandon it. However, the area of interest in this work is logging related to certain cementing issues i.e. cement bonding and top of cement detection. The most common logging techniques used in cement evaluation are:

- Temperature logging
- Noise logging
- Nuclear logging
- Acoustic logging
    - Sonic
    - Ultrasonic

2.3.1 Quality control

When making big environmental and monetary decisions, good and reliable data is a crucial factor. By performing a log run one can obtain such data, but since there is no way to physically check and verify the results, the log provides no guarantee for making the right decisions. In order to utilize the information gathered in a log, it is equally important to be aware of the different uncertainties related to it. There are several ways to ensure a better quality of the data gathered, and an especially important one is logging a “repeat section” [7]. The repeat section is a short section of the well, normally about 65m, immediately logged before the main pass. Conditions during the repeat section run and the main run should be identical, and the intention is to verify the repeatability of the tool when passing the same section twice. If the readings appear identical, the repeatability is good. However, there is still no assurance of accuracy in the information logged.

The transit time curve is another measure to control the credibility of a log. By controlling the expected transit time of a wave with the measured time, one could better control tool eccentering. Since eccentering has a great influence on the tools performance, this is a critical factor (further explained in next section) in obtaining reliable results.

In case of cement bonding evaluation, in-situ calibration of CBL tools is very important. Laboratory testing will provide expected values of bonding under simulated downhole conditions, but by logging a free-pipe section and a fully bonded section in the actual well, one obtains the real log response in terms of good or poor bonding.

2.3.2 Parameters affecting log quality

The influence of surrounding conditions that may affect the credibility of a log is dependent of the method and tool used. Factors that effects the log quality of one tool may not be equally important when using a different tool. To choose the right tool and to understand its limitations is essential to obtain a reliable result.

During a log run, one could divide the influencing factors into three categories: [2] [9]

1. Partly controllable factors during a log run:

- *Tool eccentering*
  Tool eccentering is the placement of the tool relative to the center of the borehole. Many tools are very sensitive to eccentering and the effect of a tool not in center may result in very inaccurate results. To control the centralization of a tool, a transit time (TT) curve is used. The TT curve shows the time taken from a wave being fired from a transmitter to it is reflected back from the casing wall and picked up by a receiver. Knowing the measures of the casing and borehole fluid one can calculate the expected travel time and compare it with the measured time to see if the tool is eccentered. Other factors that could affect the TT signals is fast formation and cycle skipping. The problem of tool eccentering is a bigger problem in deviated wells.

- *Tool calibration*
  In case of sonic measuring, the range of frequencies used may vary. Many downhole conditions affects the wave as it travels, but one do not necessary want to measure every signal. By configuring the tool to register only signals within or over a certain threshold, one receives only signals of a certain amplitude. One calibrate the tool to receive information of importance.

- *Microannulus*
  The creation of a microannulus can cause serious trouble in terms of logging. Signals that normally would have propagated further into the cement, reflects back from the casing wall earlier than expected. A microannulus is the presence of a tiny gap, 0,01 – 0,1 mm, between the casing and the cement sheath. This causes poor acoustic bonding between the casing and cement, leaving the returning signals with a higher amplitude than in case of a good acoustic coupling. A microannulus may occur due:

  - Temperature changes making the casing to expand and retract leaving a microannulus as the cement sets
  - Failing of mud removal before cementing
  - Exposing the casing to loads before the cement has set properly

In case of a microannulus, it is possible to pressurize the casing while logging the section again. The pressure intends to minimize the gap between the casing and the cement sheath; hence give a more reliable logging result.

- *Cement setting time*
  When placing the cement, the cement slurry enters its intended place in a liquid state. As the cement sets, the cement hardens and gain new mechanical and acoustic properties. Logging the cement before it has set properly could lead to poor or pessimistic logging results. The time and conditions for a cement mixture to set depends greatly on its composition and the downhole conditions.

- *Wellbore fluid properties*
  Properties of the wellbore-fluid effects the behavior of signals passing through it. Both the CBL amplitude and the transit time depends on the acoustic properties of the chosen fluid.

2. Controllable factors during construction and the cementing operation:

- Casing eccentering
  Predicting bonding between casings and against formation demands a good centralization of the casing. This is a bigger problem in deviated wells were poorly centralized casings may touch the formation wall and prevent presence of cement at the low side.

- Channeling / Mud cake
  Before cementing, it is important to properly circulate and wash the casing and formation wall free of mud and other fluids. If not it could prevent the cement to bond properly to the casing and formation and channels may occur. Channels can contain liquids, gas or air, which could affect the log interpretation. It is however very hard to detect channels on a log.

3. Wellbore and formation factors:

- Casing size and thickness
  Increased casing size equals longer travel distance in case of acoustic measuring, except tools that are in direct contact with the casing wall. This normally implies an increase in the wave attenuation, which results in a decrease of the measured signal amplitude. However, increased casing size generally means an increased casing thickness providing a smaller attenuation rate.

- Cement thickness
  A thin cement sheath could make the wave reflected at the cement/formation interface interfere with the returning casing signals. This could lead to misinterpretation in cement bonding. In case of a cement sheath smaller than ¾ in, the signal attenuation will decrease

- Cement composition
  The cement composition influence the density and other important properties in terms of logging. It has to be a sufficient difference between the material properties in order to distinguish fluid, casing and cement signals from each other.

- Formation characteristics
  Different formation holds different acoustic properties. Attenuation of acoustic energy is much higher in unconsolidated than in consolidated formations. In terms of cement evaluation, it is common to distinguish between *fast* and *slow* formation. If the formation is characteristic as a *fast*, the wave velocity through the formation is larger than along the casing. Unconsolidated formation can be very slow formations, with a high attenuation rate. Fast formation may pose a challenge due to arrival of the formation signal before the casing signal.

2.3.3 Cement related logging principles and techniques

A common method of verifying cementing jobs are by using logging services. By utilizing tools that interpret cement properties through fluid and steel walls, one can decide whether the cement fulfills its required function or not.

2.3.3.1 Temperature logging

After placing the cement slurry at its intended place, it starts curing during an exothermic hydration reaction. Due to the hydration, heat generates making the wellbore temperature to deviate from its normal temperature gradient. With a temperature logging tool one can detect the change in temperature during curing, which makes it possible to determine top of cement in a relatively accurate way. The heat generation caused by the cement hydration process normally peaks after 4-12 hours. After this a higher than normal temperatures difference will be presence for at least 24 hours [2]. Modern temperature tool comprises of temperature sensitive elements that records the temperature in a wellbore. The preferred temperature sensor is a platinum element. This is because the electrical resistance in the material behaves linearly with temperature changes in a wide range and is stable over time. This is an important property since logging temperatures may vary in a large extent over short distances. Depending on the cement composition and downhole conditions, logging should happen within 12-24 hours [2].

Table 2 - SWOT analysis of Temperature logging	
Strengths: - Able to determine TOC - Able to determine lost circulation - Relatively cheap to perform	Weaknesses: - No recording of the bond quality - Limited period of use - Sensitive to light weight slurries, less heat during the exothermic reaction - Sensitive to small annulus, less cement less heat from the exothermic reaction - Sensitive to high well temperatures, hard to detect changes in cement temperature
Opportunities: - Used in conjunction with noise logging tools to detect channeling and lost circulation - Fiber optic cables can be permanently installed and provide constant monitoring	Threats :

2.3.3.2 Nuclear logging

Nuclear logging is unique in terms of its capability of penetrating materials. The use of nuclear logging techniques are more common in other aspects of well logging, but the main area of use in relation to cement logging is to identify the presence of cement behind the casing and to locate top of cement [2]. By mixing radioactive materials in the cement mixture, the radioactive material functions as tracers. A gamma ray log have to be run before and after the placement, and when the two logs are compared, the radiation intensity should increase where the cement has been placed. By locating the point where the intensity starts deviating from the first run, one can decide the TOC.

Table 3 SWOT analysis of Nuclear logging	
Strengths: - Good at detecting TOC - Nuclear radiation is strong, easy to detect	Weaknesses: - No recording of bond quality - Not widely used
Opportunities: - Tracers can be detectable for a long time	Threats : - Serious risks considered to health issues handling radioactive material

2.3.3.3 Acoustic logging

Acoustic logging is the most common method in terms of cement evaluation [2]. In recent decades, the interest in acoustic logging and its potential has resulted in significant advances in the research of understanding downhole acoustic measuring [8]. By utilizing the knowledge of sound, and how it behaves in relation to various mediums, it is e.g. possible to interpret cement quality and bonding after cement placement.

2.3.3.3.1 Acoustic properties

There are four measurable acoustic properties:

- velocity
- amplitude
- amplitude attenuation
- frequency

The purpose of an acoustic tool is to measure one or more of these properties [8]. An acoustic tool operates by transmitting and receiving sound waves in a predetermined frequency into and from its surroundings.

There are two basic types of wave, longitudinal and transverse. The difference of the two is the direction it propagates. The longitudinal wave, called *compressional wave*, propagates in the direction it travels and is the fastest type of wave. The transverse wave, called *shear wave*, propagates in a perpendicular direction of which it travels and is a slower type of wave. Opposit to the compressional wave the shear wave cannot be transmitted in fluids [2][8]. As the wave travels through different mediums, material characteristics of the passing mediums causes the wave to lose energy (amplitude) and velocity. The loss of energy and change in velocity, called *attenuation* and *refraction*, are examples of material characteristics that affects the sound wave [19]. When hitting adjacent materials such as mud, formation, casings, cement etc. the signal either reflects, travels along or passes through the medium. Receivers at a fixed distance from the transmitter, normally 3- and 5ft, picks up signals within a configured range and converts it into readable measures for log analysts. The parameters of especial interest is the amplitude, attenuation and transit time- the time it takes for the receivers to detect a signal after being fired.

To get a good interpretation of the material surrounding the tool, it is important that the layers of materials have good acoustic coupling between them. For instance, if a micro annulus has formed behind the casing wall and against the cement sheath, it will have a large effect on the traveling wave. The ability to lead sound efficiently is an essential criterion in order to get a good reading through the layers of interest. Figure [5] and [6] presents a sonic waveform nomenclature and the idealized waveforms picked up by the receiver. The composite wave represents a mixture of all the different waves.

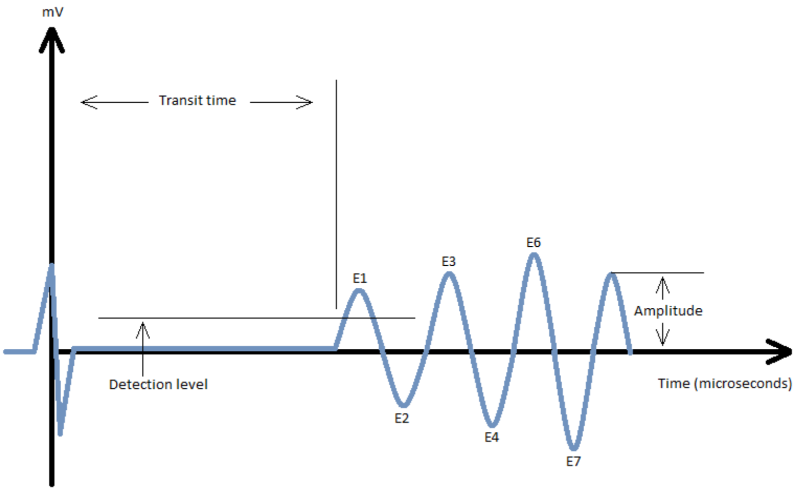

Figure 5 Sonic waveform nomenclature

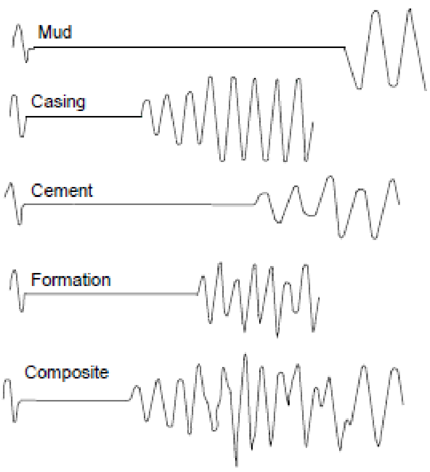

Figure 6 Idealized waveforms of returning sonic waves

When knowing the acoustic characteristics of a material, it is possible to predict the behavior of sound waves in it by use of acoustic theory and wave propagation. By comparing the results from the theoretical expected behavior and the actual log response one can interpret properties of the mediums logged.

In terms of cement evaluation, the use of acoustic logging is to measure TOC, cement bonding, presence of cement and caliper logging for calculating cement volume.

2.3.3.3.2 Sonic tools

Sonic tools have been used in cement evaluation since the 1960`s, and is still a widely used method. In general, two types of cement evaluation tools dominates, sonic- and ultrasonic [10]. Sonic tools operates by transmitting sound waves at a relative low acoustic frequency, and modern tools normally consists of several piezoelectric transducers that converts electric signals into acoustic energy and back again. The piezoelectric receivers starts to ring or oscillate by the pressure variation created by an acoustic wave. As a result, the oscillation develops a small voltage, and an oscilloscope transforms the voltage into a waveform. When it comes to cement evaluation, the most interesting feature of the returning sonic waveform is its amplitude and attenuation. The operating range of a conventional sonic tool is 10-40 kHz, but newer tools operates as low as 1-12 kHz and even up to 100 kHz.

Having more than one transmitter and receiver, makes the tool more reliable and less affected by borehole conditions and tool calibration, such tools are called borehole-compensated tools [2][8]. Modern tools usually have two or more transmitters and receivers.

Table 4 - SWOT analysis of Sonic logging	
Strengths: - Well-proven technology - Slightly affected by mud weight - Measures cement-formation bonding - unaffected by inner casing conditions - Detects TOC	Weaknesses: - Highly affected by channeling and microannulus - Cannot locate channels - Only qualitative evaluation - Highly affected by lightweight cement - No azimuthal measuring, only average measurements
Opportunities: - Performed by wireline and LWD	Threats :

2.3.3.3.3 Ultrasonic tools

Ultrasonic tools operates at a higher frequency than sonic tools. The frequency of the transmitted pulse range from 200 to 700 kHz and provides a higher resolution than of smaller sonic frequencies. Modern ultrasonic tools uses a rotating traducer that emits short ultrasonic pulses. Ultrasonic tools records travel time, amplitude and signal echoes. As illustrated in figure 7, the ultrasonic signal path bounces between materials creating an echo picked up by the transducer. The amount of reflected energy depend on the acoustic impedance of the materials at the adjacent interface, and the strength of the returning signal is a function of the material density which the sonic pulse is traveling through. Returning echoes provides four measurements: [2]

- Echo amplitude (indication of casing condition)
- ID of casing (transit time of first echo)
- Casing thickness (resonant frequency)
- Acoustic impedance of the material behind the casing (From resonance)

The combination of ultrasonic tools and conventional CBL tools is common to get the cement/formation interpretation by the VDL log.

Table 5 - SWOT analysis of Ultrasonic logging

Strengths:	Weaknesses:
- High vertical and radial resolution - Azimuthal measuring - Channel identification - Less sensitive to liquid filled microannulus - Quantitative measures - Does not rely on knowing the cement properties - Manages lightweight cement designs	- Short radial range - Limited by mud weights - Performance limited by contaminated mud - Affected by casing conditions - No formation evaluation, only casing-cement
Opportunities: - Can provide casing inspection in the same run - Quantitative measuring during LWD - Combinable with other tools	**Threats :**

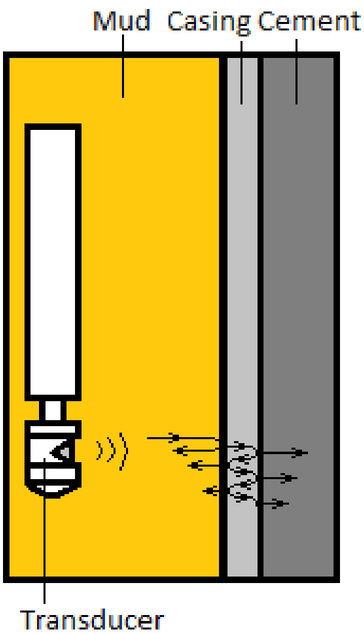

Figure 7 Ultrasonic pulse echo signal path

2.3.4 Cement evaluation methods

2.2.4.1 Cement bond logs

A cement bond log is supposed to give information about the cement bonding between casings, or between casings and the formation. A proper cement placement is as mentioned important to isolate zones, prevent leakage and to support casings. To verify the result of a cement job, the only diagnostic technology available is by running acoustic tools [9]. Sonic or ultrasonic tools utilizes acoustic measuring, which intends to evaluate the degree of bonding often as a value of a bond index (BI) ranging from 0 to 1, or as a percentage 0 to 100 (BPI). [2]

Acoustic bond logs measures the loss of acoustic energy as it propagates through the casing. In case of good bonding, there will be a greater loss of energy due to a good acoustic coupling between the casing and cement or against the wellbore. A low amplitude of the returning wave normally indicate good bonding, while large amplitudes may indicate free pipe, poor cement bonding or no cement. Figure 8 illustrates various paths a sonic wave may travel from the transmitter to the receiver.

In conventional cement bond logs, one measures the height of the amplitude in mV. The amplitude only represent a part of the total waveform, and represents the measure of casing to cement bonding. To ensure a larger degree of certainty in the measurement, the CBL is seen in conjunction with a log showing the total waveform, a variable density log (VDL). In case of ultrasonic tools, it is normal to correlate the result with a CBL.

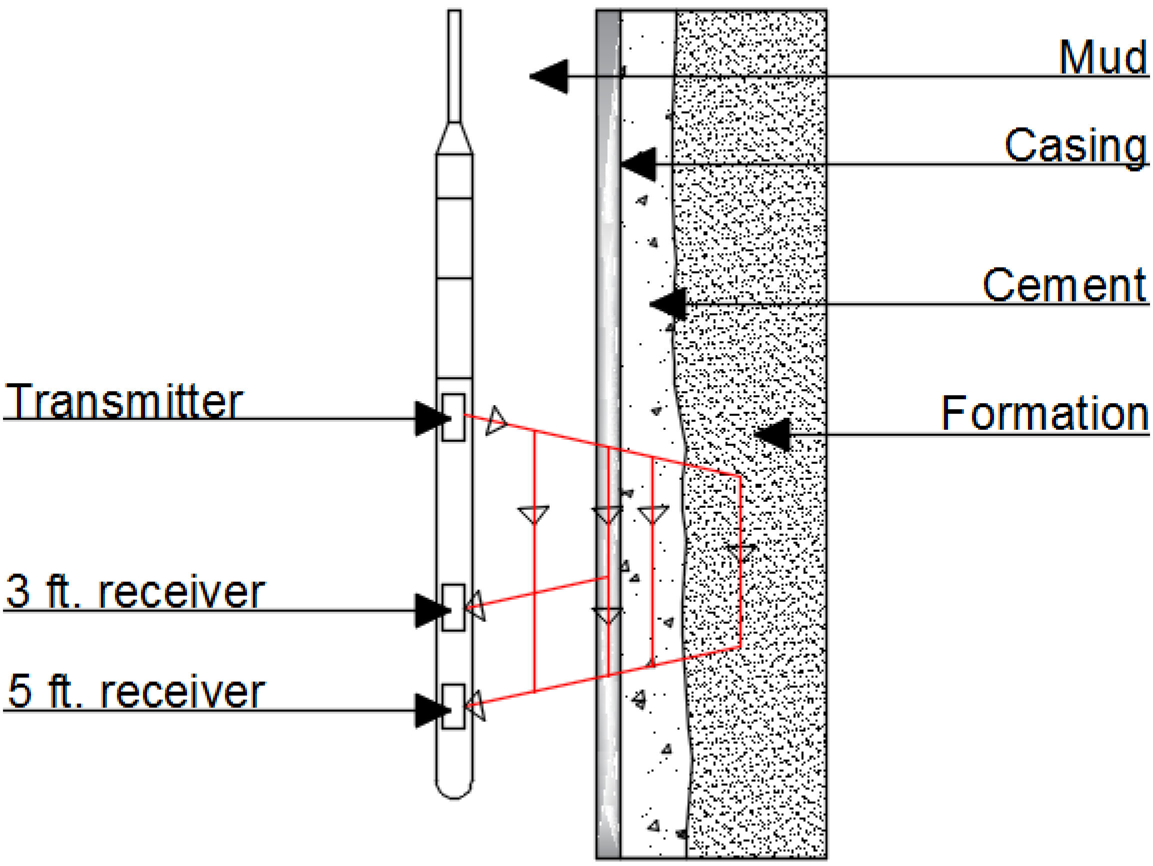

Figure 8 – Illustrates the various acoustic signal paths, conventional CBL configuration

2.3.4.2 Cement bonding tools

Cement bonding tools do not measure cement quality, but the degree of acoustic coupling of cement. Thus, it is possible to make a qualitative and even a quantitative prediction of the cement bonding.

Some of the available cement bonding tools:

Sonic:

- Borehole-compensated bond tool (CBL tool)[2, 11]

  The modern CBL tool comprises of two or more receivers and transmitters. Well centralized and configured, the tool repeatedly fires sonic bursts omnidirectional towards the casing wall. The acoustic signal travels along the mud, casing, cement or formation before eventually receivers picks up the signals. The returning waveform is processed and presented in logs as amplitude measurements normally recorded by the first casing arrival at the 3-ft spaced receiver. The 5-ft receiver process the total waveform and presents it in a VDL or micro seismogram. The amplitude and total waveform measurement intends to evaluate two bonds: casing to cement and cement to casing/formation.

  The strength of the returning casing signal indicate if the acoustic coupling between casing and cement is good. If the returning amplitude is low, it normally indicates a good bonding, while a high amplitude may indicate poor bonding or no cement.

- Segmented bond tool (SBT)[2]

  Segmented bond tools differentiates from regular CBL tools by physically touching the casing wall while logging. Several pads with transmitters and receivers are oriented around the tool improving the azimuthal information. Since the tool is in constant connection with the inner casing wall, the tool is not as sensitive to eccentering as conventional CBL tools. The operating frequency is 100 Hz, slightly above what is normal in conventional CBLs, and the short spacing between transmitters and receivers makes it less sensitive to fast formations.

- Radial bond log tool (RAL tool)[10]:
  The radial bond tool is an improvement of the conventional CBL tool. Besides having the 3- and 5 ft receiver, the radial bond tool has up to 8 extra radially spaced receivers. The radial receivers increases the coverage around the casing, and instead of predicting an average of the total circumference of the cement sheath, it makes up to 8 independent measures.

Ultrasonic:

- Ultrasonic imaging tool (USIT) Schlumberger
  By utilizing the advances in ultrasonic measuring, one can now get a much higher resolution of the cement sheath than by the conventional bond logs. The USIT has one transducer

attached to a rotating sub at the bottom of the tool. While running the tool the transducer rotates and emits a pulse in the range of 200- to 700 Hz that hits the casing wall and cause it to resonate, figure 7. The returning echo provide the information needed to calculate casing thickness, the impedance of material behind the casing and localize the tool position in terms of tool eccentering.

- Cement evaluation and casing inspection tool (CAST-V) Halliburton
  The CAST-V tool offered by Halliburton utilizes a similar rotating transducer as the USIT tool. By ultrasonic measuring, the CAST-V tool performs basically the same measuring's as the rival USIT tool. There is however a difference in the layout of the log.

2.3.5 Conveyance of logging tools

There are two ways performing a log run. Either by wireline or by logging while drilling (LWD).

2.3.5.1 Wireline logging

This is the oldest and most developed method in terms of looking for downhole answers. Wireline logging services provides the broadest range of tools and measurements and operates by lowering tools down the wellbore by a cable. Depending on the tool, logging may happen either while lowering the tool or when pulled. The tool, connected at the end of the cable, saves the logged information in a memory section or if the cable is fitted with communication technology, it could provide live feedback during the operation. Wireline logging demands certain expertise and a specialized crew, which usually arrives with needed equipment to mount, calibrate, run and analyze the results. Wireline depends on having a BOP

Table 6 – SWOT analysis of wireline

Strengths: - Real time measuring - Offers the broadest range of tools - Tool do not affect signal attenuation - Utilizes ultrasonic measuring -	Weaknesses: - Deviated wells - Depending on a BOP - Centralization in large casings - Have to perform an individual run when logging
Opportunities: - Is able to combine ultrasonic and sonic measuring - Can be run in smaller tubing`s than LWD	Threats : - If not well centralized the log response may yield to pessimistic or to optimistic results.

2.3.5.2 Logging while drilling (LWD)

Logging while drilling is a technique where logging happens during drilling or tripping in or out of the well. This method utilizes much of the same technique as wireline logging, but instead of having to perform individual logging runs, logging could happen simultaneously with the drilling operation. Rapid technological developments in the LWD segment has made it very attractive as a logging alternative. LWD offers a huge potential in time- and cost savings and is not depending on a BOP to operate. LWD transmitters and receivers are generally located closer to the casing wall due to the size of drilling equipment, which indirectly implies better possibilities to log larger sized casings. Centralizing is in most situation better due to the rigid steel assembly. However, LWD is in the middle of a compact steel assembly, which provides a challenge regarding signal attenuation caused by the drill collar [4, 16]. The casing arrivals and the collar arrivals can be difficult to differentiate and the potential noise from the drilling could affect the log quality.

Table 7 – SWOT analysis of Logging while drilling	
Strengths: - BHA is tripped through casing at least twice, chance to log same section several times gives the opportunity for cement evaluation over time - Logging tool may be integrated at different locations along the drillstring - Real time measuring - Do not need an individual run to log, can be done in conjunction with other drilling activity	Weaknesses: - Noise while drilling affects acoustic logging - Only qualitative bond measuring, presence of cement or not -
Opportunities: - Quantitative bond measuring - Performing typical wireline surveys - Saves rig time, potentially large cost savings - Perform logging before installing a BOP	Threats : - LWD collar and casing signal arrivals can be hard to differentiate. - Not able to solve the signal attenuation problem

BHA – Bottom Hole Assembly

Table 8 – Presents possible combinations of logging principles, conveyance and logging objective

Logging principles	**Logging tool conveyance methods**		**Logging objective**			
	LWD	Wireline	CBL	TOC	Quantitative	Qualitative
Temperature		X		X		X
Nuclear	X	X		X		X
Acoustic						
- **Sonic**	X	X	X	X	X	X
- **Ultrasonic**	X	X		X	X*	X

* Not available in conjunction with LWD

3 Discussion

The cement evaluation process comprises of many well-established methods and technologies. As a part of the quality assurance and a well-integrity safety measure, cement evaluation has always been an industry requirement. However, the technological developments and the increasing knowledge of structural mechanics, challenges the utilization of existing technologies into new applications. Instead of applying conservative measures, one wants to obtain actual measures and use them as inputs in extensive analysis. In this case, detecting the actual surface casing cement level could extend the utilization of the wellhead and reduce the need of conservative measures.

3.1 The importance of TOC as an input parameter

A varying cement level between the conductor and surface casing proves to be very sensitive in terms of fatigue calculations [3, 12]. Norsok D-10 recommends TOC at the seabed surface, which is a common practice when cementing the surface casing. However, during a fatigue analysis, one assumes the worst level of cement. Analysis performed at cement shortfall shows that the worst level of cement is located some meters below the mudline and not at the mudline. Hence, calculating fatigue performance assuming the worst level of cement is conservative if the intention is to place TOC at the mudline.

Even if the intention is to cement all the way up to the seabed and the cement outlet port, unexpected wellbore and operating conditions may cause a cement shortfall. However, a cement shortfall does not necessary mean loss of fatigue capacity. Studies of programed cement shortfall shows that fatigue life decreases with the cement level until it reaches a certain point some meters below the mudline [3, 12]. This is where the surface casing weld experiences the largest level of stress, the worst level of cement, but as the cement-level drops further, stress starts to decrease again. The parabolic stress to cement-level relationship shows that by controlling the cement shortfall, the fatigue life does not necessary need to get worse. That is, TOC needs to be a distance either above or below the critical cement level to avoid minimum fatigue life. See figure 9 and 10 for illustration, red line shows the cement level that yields minimum fatigue life.

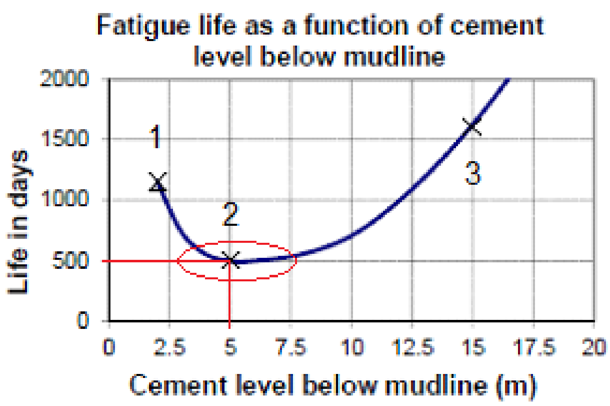

Figure 9 – Fatigue life-cement level relationship [3]

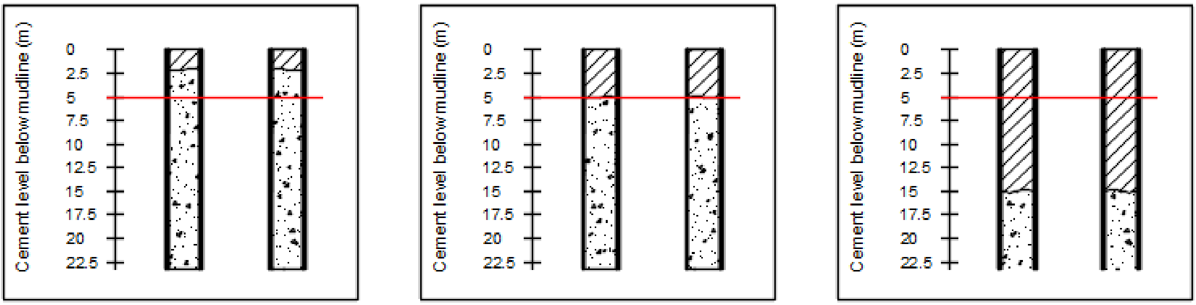

Figure 10 – Illustration of the different cement levels in Figure 9

The TOC as an input parameter proves to be important. Unexpected events may cause the planned TOC to change, hence the need of preventive assumptions. That is, if the documentation of TOC could happen in a more accurate way, this measure could replace the "worst level" assumption and enable a more precise fatigue calculation.

3.2 When to log TOC, operational limitations

Another important issue in the detection of TOC is the question of when to perform the log-run. One of the limitations in this case is clearly the time window between cementing the surface casing and installing the intermediate casing. Logging through several layers of casings and cement is impossible with current technology, thus it is critical to perform the logging before installing new casings. Drilling and completion is very expensive and rig rates may extend up to 432000$/day [14]. Any extra activity that may require additional rig time will increase the costs, thus a thorough planning and execution of any operational activity is very important to avoid costly overruns.

There are two ways of performing a log survey, either by wireline or by LWD. At this stage of the well construction, the combination of operational requirements and provided services will much likely be decisive for whether to use wireline or LWD. Wireline needs a BOP connected to the wellhead system in order to operate. This basically exclude the use of wireline until the BOP is installed, which in North sea operations is approximately 24 hours after cementing the surface casing [3]. This is also the first time the BOP is connected to the wellhead during well completion, which practically means that wireline is not available before this time. Using wireline would require the completion process to stop after landing the BOP in order to perform a run, hence a time consuming and costly alternative.

LWD, which is the other alternative, does not require a BOP in order to operate. The measuring could happen during drilling or tripping the well. Performing a log run considering time savings, LWD offers an advantage compared to wireline. This of course assumes that LWD offers the same services as wireline, see further discussion below.

Temperature and acoustic logging both have different individual requirements in terms of providing a reliable log. Temperature logging tools relies on detecting the heat difference created by the hydration process during cement curing and the normal wellbore temperature. Because the hydration is a time-limited process, temperature logging must happen within 12-24 hours after cementing.

Sonic measuring needs the cement to have gained a certain amount of compressive strength to be able to detect it. Generally, this is about 250 psi and complete acoustic coupling. The time needed to reach 250-psi compressive strength largely depends on the curing temperature and cement composition. Low seabed temperatures will affect the curing process of the upper part of the cement between the conductor and the surface casing [3]. Considering that this part of the cement column often consist of lead cement with higher W/C ratio and longer curing times, the optimal time to log will depend on the lead cement properties and curing conditions.

3.3 Existing TOC detection methods and functional limitations

There are several methods of locating TOC with existing technology. All the described cement evaluation methods except noise logging are capable of detecting TOC when operated within their limitations. The problem in this case, is logging inside a large sized surface casing which cause a larger distance between the tool interface and the casing wall.

-Temperature tool

Temperature logging utilized the chemical reaction that happens when cement hardens. The heat generated makes it possible to detect and differ between the normal well temperature gradient and the cemented areas that emitting heat. This is a relative cheap and accurate method in terms of detecting TOC and is possible to use by wireline or LWD. The increased heat is only detectable in approximately 24 hours after cementing. This limits the use of temperature logging in this phase of well construction. The time between cementing and landing the BOP is about 24 hours. Wireline tools is dependent on landing the BOP before use. Hence, the period of increased heat difference in the well is much likely over before a temperature logging tool is operative. The only alternative would be to perform the measuring by LWD. LWD do not depend on a BOP to operate and could possibly performed the log run before landing the BOP. However, in conversation with a drilling manager, he did not recommend such a solution. He argued that if something went wrong with the cementing, and cement remained in the casing, the drillstring and logging equipment could get stuck.

This is worst-case scenario, and logging from the bottom of the wellbore should not be necessary. Theoretically, if only logging the area of interest, the maximum length to log would be the length of the FE-element model used in the local fatigue analysis, which is set to 50m [3]. If it is possible to perform LWD at this time of well completion, it should be possible to locate TOC by temperature logging.

-Acoustic tools

Acoustic tools are only able to provide reliable logging results when operated a certain distance from the casing wall. If this distance becomes too large, it will cause a signal reduction. Another problem is the casing thickness, the surface casings normally has a larger thickness than smaller casings, thus yields a larger attenuation rate. Acoustic tools are depending on returning signal arrivals within a magnitude that makes it possible to distinguish between mud, casing and cement arrivals. The combination of increased signal traveling distance and casing thickness highly affects the returning signals. When the signal becomes too low, the signal arrivals are unreliable and thus very difficult to interpret [4].

If to perform a log run with acoustic tools, the only way would be by wireline. LWD do not yet provide tools that is able to perform logging in 20” casings [4].

3.3.1 How to utilize existing technology

Technologies to interpret cement behind casings already exist. The challenge is to make it operate in larger dimensions. Casing diameter seems to be the largest limitation for existing acoustic tools, but as seen in table 9, some tools already qualifies for casing sizes up to 20”. However, it is currently only wireline tools available for 20” casings.

Developing larger tools for lager casings should be manageable. By getting transmitters and receivers closer to the casing wall, the signal reduction issue could be significantly reduced and thereby allow good signal interpretation.

Another tool capable of logging large dimensions is the sonic scanner provided by Schlumberger. It is confirmed that a 20” casing was logged and the results was satisfactory by the client. The problem in this case was the centralization of the tool, but by using large centralizers and a 4 armed caliper tool, the log run proved to provide satisfactory results in a 20” casing.

3.4 Comparison of wireline and LWD

Wireline and LWD are the two methods of conveyance in terms of well logging. Wireline still provides the broadest and most sophisticated range of logging tools, but unique LWD benefits like the potential of significant time- and cost savings makes it an attractive alternative. Both methods provides TOC services, but currently LWD do not manage to perform acoustic logging in a 20” casing [4].

One of the problems with LWD is the signal attenuation created by the drillstring and drill collar. This is not a problem considering wireline tools [16]. Noise created by drilling could infer with the signal frequencies picked up by the receivers and affect the log interpretation. TOC detection in a 16” casing is however tested and deemed successful [4]. This proves that it is possible to log TOC in casings larger than the limits set by the service providers, thus there is no guarantee for success.

Table 9 – Limitations of different available logging tools that detects TOC [20,21]

	Output	Min casing size	Max casing size	Wireline	LWD
Temperature	TOC	-	-	X	X
Nuclear	TOC	-	-	X	X
Acoustic					
Sonic:					
-DSLT *	TOC, 3-ft amplitude, CBL 5-ft VDL	5.5 in	13.375 in	X	X
-RBL+	TOC, CBL	2 in	13.375 in	X	
-FWST-A+	TOC,CBL, MSG	4.13 in	20 in	X	
-Sonic scanner *	TOC,VDL, Cement bond quality	4.75 in b	22 in b	X	
Ultrasonic:					
-USIT *	TOC, Impedance, cement to casing bonding, casing ID, casing thickness	4.5 in	13.375 in	X	
-Isolation scanner *				X	
-CAST-V+	TOC, Cement evaluation, imaging, casing ID, casing thickness	5.5 in	13.375 in	X	
-FASTCAST+	TOC, Cement evaluation, imaging, casing ID, casing thickness	5.5 in	20 in	X	

Sclumberger*
b- Borehole dimension
Halliburton+
b- Borehole dimension

DSLT- Digital Sonic Logging Tool

SBL- Segmented Bond Tool

RBL- Radial Bond Tool

USIT- UltraSonic Imager Tool

FWST- Full Wave Sonic Tool

CAST-V- Circumferential Acoustic scanning Tool-Visualization

4 Conclusion

It is not common to log the surface casing cement level as of today. The biggest challenges in terms of logging TOC is the size of casing and the limited time to perform the log-run.

By considering the technology available there are obviously possibilities to perform a TOC detection in a 20” casing. As seen in table 9, both Schlumberger and Halliburton offers acoustic services that performs cement evaluation up to 20” casings. However, the only tools available are wireline tools. This would require the entire completion process to stop in order to perform a separate wireline run after installing the BOP. This will generate the need of extra rig time and a dedicated wireline crew.

This is however the only available method, and seen in an overall perspective, this could prove very beneficial. By locating the actual TOC, it could result in an increased fatigue life estimate, which could extend the allowable amount of work performed on the well compared to the “worst level” estimate. This of course assumes that the detected level differs from the critical level and contributes to improve fatigue calculations. There are examples of wells that operators would like to work on, but due to fatigue reasons are forced to not.

Acoustic TOC detection during LWD is a common method in the industry, however it is not yet available for logging TOC in 20” casings. If the attenuation issues were solved, this could possible provide a huge benefit in terms of time and financial savings. Successful test in a 16” casing suggest that there is reasons to believe this will be possible in the future.

5 References

[1] SPE webinar "Challenges with Cement Evaluation- What We Know and What We Don't", viewed on February 10 2014, http://eo2.commpartners.com/users/spe/session.php?id=9053

[2] Nelson, E. B., Guillot, D., 2006, *Well Cementing, Second Edition,*

[3] Reinås, L., "Wellhead Fatigue Analysis: Surface casing cement boundary condition for subsea wellhead fatigue analytical models",2012, PhD

[4] Blyth, M., Hupp, D., Whyte, I., Kinoshita, T., 2013, "LWD Sonic Cement Logging: Benefits Applicability and Novel Uses For Assessing Well Integrity", SPE

[5] NORSOK Standard D-10, Rev.4, June 2013 "Well integrity in drilling and well operations"

[6] Grytør, G., Hørte T., Lem, A. I., 2011, "Wellhead Fatigue Analysis Method", Det Norske Veritas, Report JIP Structural Well Integrity

[7] Theys, P. P., 1994, "A Serious Look at Repeat Sections", SPWLA

[8] Holstein, E. D., Lake, L. W., 2007, "*Petroleum Engineering Handbook, Volume V, Reservoir Engineering and Petrophysics*", SPE

[9] Boyd, D. A., Al-Kubti, S. A-R., Khedr, O. H., Khan, N., Al-Nayadi, K. G., Degouy, D., Elikadi, A., Al-Kindi, Z. L., 2006, "Reliability of Cement Bond Log Interpretations Compared to Physical Communication Tests Between Formations", SPE

[10] Frisch, G. J., Fox, P. E., Hunt, D. A., Kaspereit, D., 2005, "Advances in Cement Evaluation Tools and Processing Methods Allow Improved Interpretation of Complex Cements", SPE

[11] Serra, O. & L., 2004, *"Well logging, Data Acquisition and Application",* Serralog

[12] Britton, J. S., Henderson, G., 1987, "Improving wellhead performance by programmed cement shortfall", SPE

[13]http://www.slb.com/~/media/Files/production/product_sheets/well_integrity/cement_bond_logging_tools.pdf

[14] Rigzone 2014, "Rig dayrates", viewed on Mai 24 2014, https://www.rigzone.com/data/dayrates/

[15] Reinås, L., Hodne, H., Turkel, M. A., 2011, "Hindered Strength Development in Oilwell Cement due to Low Curing Temperature", SPE

[16] Kinoshita, T., Izuhara, W., Valero, H-P., Blyth, M., 2013, "Feasibility and Challenge of Quantitative Cement Evaluation with LWD Sonic", SPE

[17] Guo, H., Wang, G., Wang, Z., 2012, "New Practices for Cement Integrity Evaluation in Complex Environment of Xinjiang Oil Field", SPE

[18] Benge, G., 2012, Cement Evaluation course presentation notes, Baker Huges

[19] Johnson, D. E., Pile, K. E., 2002 "*Well logging in a nontechnical language*", PennWell

[20] Halliburton "Halliburton Wireline and Perforating Services", viewed on May 29 2014, http://www.halliburton.com/public/lp/contents/Books_and_Catalogs/web/WPS_PS_Catalog/Web/WPS_PS_CAT.pdf

[21] Schlumberger "Cement bond logging tools", viewed on May 29 2014, http://www.slb.com/~/media/Files/production/product_sheets/well_integrity/cement_bond_logging_tools.pdf