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Evaluation and Testing of Thermoset Polymer Resin for Remedial Repair of Sustained Casing Pressure

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Summary

The number of petroleum wells exhibiting pressure build-up in the annulus as a result of lost cement integrity is evident, this is known as Sustained Casing Pressure (SCP). There are several factors contributing to lost integrity, among them are a poor primary cementing operation and casing expansion resulting in cement sheath failure due to alternations in pressure and temperature. Fluid migration (mainly gas) can happen over the cemented column over the entire life-cycle of a well, the remedial methods available for mitigation or minimizing of this migration requires a large workover intervention where cement is used as the sealing material. Cement does present in many cases a challenge to successfully achieve a long-term integrity due to its brittleness, limited strength, low flexibility and poor shear bond properties. The need for alternative plugging materials and placement methods are therefore apparent. One possible alternative is a thermosetting polymer based system, which gives a higher tensile and compressive strength, more flexible and a higher adhesion to other materials.

This thesis will focus on remedial treatment of a typical SCP application, hence cement is present in the annulus. The placement method focused on is the electric wireline conveyed CannSeal tool provided by a Norwegian technology company. The tool perforates the casing and injects a sealant into the annulus. The tool and method have been run for different operator companies for sealing an open annulus (no cement present) in relations to Enhanced Oil Recovery (EOR) operations. Presented and discussed in this thesis is a test project where four large-scale annulus tests cells filled with cement was built, then leak tested as an "SCP" application. After the leak rate was established, the CannSeal tool was fed into the cell, made a communication to the cement sheet by perforating and then injected a sealant resin (epoxy) into the cemented annulus. The conclusion for the results was that using the CannSeal technology and injecting a resin sealant into the cemented annulus significantly reduced the gas leak. On all four cells the measured average gas breakthrough differential pressures including all cells were 25 bar prior to injection, and 130 bar after injection and curing of the resin.

Because of the positive results achieved in this project, the concept of remedial repair of SCP with injecting a resin will be field trialed at the Shell test center in Rijswijk summer 2017.

Sammendrag

Antall petroleums brønner som opplever gjentatt trykk-oppbygging i ringrommet som et resultat av tapt sement integritet er et stort problem. Det er flere faktorer som kan bidra til denne tapte sement integriteten, deriblant en dårlig utført primær sementering operasjon og/eller foringsrør ekspansjon som skader sementen som følger av trykk eller temperatur forandringer. Fluid migrasjon (i hovedsak gass) kan forekomme over den sementerte kolonnen over hele livsløpet til brønnen, og de metoder som er tilgjengelige for å fjerne dette problemet krever store inngrep, hvor også sement brukes som forseglende materiale. Det er et materiale som har vist seg å ha store problemer med å oppnå langsiktig isolering, som følger av at er sprøtt, har begrenset styrke, lite fleksibel og binder seg dårlig til andre overflater. Det er derfor et klart behov for alternative plugge materialer og plasserings metoder. Et alternative kan være et polymer basert materiale, som adresserer flere av problemene som oppleves med sement. Deriblant, har høyere stekk- og kompresjons styrke, er mer fleksible samt binder seg bra til andre materialer.

Denne masteroppgaven fokuserer på reparasjon av et sementert ringrom. Plasseringsmetoden vil være et intervensjons verktøy kalt CannSeal, som er utviklet av et norsk teknologiselskap basert i Stavanger. Vertøyet perforerer foringsrøret for å deretter injisere en epoksy resin inn i ringrommet. Verktøyet og metoden har blitt kjørt for ulike operatørselskap for tetting av et åpent ringrom (ingen sement tilstede) i relasjon til økt oljeutvinning. Presentert og diskutert i denne avhandlingen er fire store celler med et sementert ringrom som ble lekkasjetestet som et lekkende oljebrønn tilfelle. Etter lekkasjeratene var etablert, ble CannSeal verktøyet plassert inni cellen der kommunikasjon ble opprettet med det sementerte ringrommet ved å perforere, for å deretter injisere en resin. Resultatene konkluderte med i korte trekk at bruk av CannSeal teknologien og injeksjon av resin medførte betydelige reduksjon av gass lekkasje igjennom cellene. For de fire cellene var den målte gjennomsnittlige gass gjennombruddstrykket på 25 bar før injeksjon og 130 bar etter injeksjon og herding av epoksyen.

Konseptet ved å injisere en resin inn i ringrommet for å gjenopprette integriteten vil bli felttestet ved Shells testsenter i Rijswijk sommeren 2017. Dette vil bli gjort som følger av de positive resultatene oppnådd i dette prosjektet.

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Chapter 1

Introduction

1.1 Well integrity

Well integrity is defined by NORSOK D-010 as:

"Application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of a well".

The plugging material sealing off against flow may be exposed to several different pressure and temperature regimes, mechanical loads and chemical degradation over the entire life-cycle of a well. Therefore, leaking of fluids can happen years into production or when the well has been Plug and Abandoned (P&A). The importance of maintaining well integrity is essential in the view of Health, Safety and Environment (HSE). NORSOK D-010 specifies that:

"There shall be two well barriers available during all well activities and operations, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the external environment".

In all aspects of the well-cycle, a Well Barrier Schematic (WBS) needs to be defined including these two barriers.

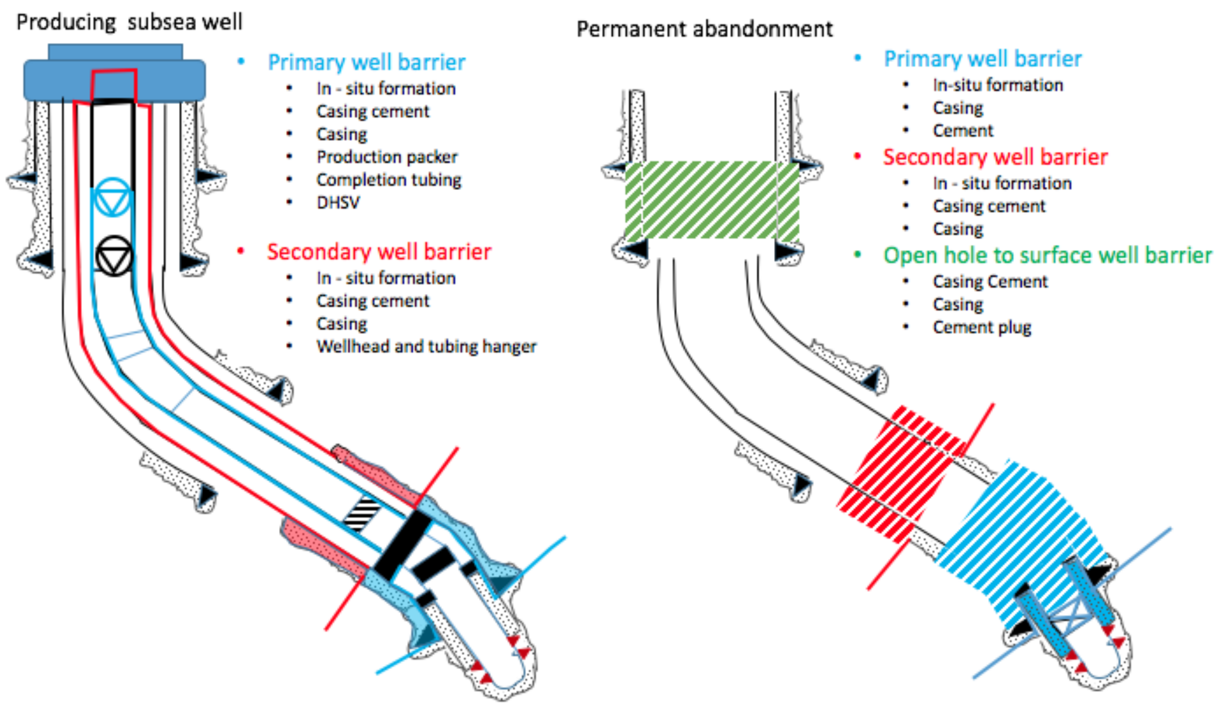


Figure 1.1: Sketched WBS for a producing and P&A well.

An integrity issue that is arising as fields mature is problems related to Sustained Casing Pressure (SCP). This is a pressure that rebuilds after initial bleed off and should not be confused with single annular pressure buildup, that is commonly due to liquid pressurization of heated fluids. The precise reason for SCP can be hard to determine, but common causes are tubing and casing leaks, poor primary cementing operations and/or damaged to cement sheath due to casing expansion. The result is a fluid migration to surface as a result of cement sheath integrity loss. Thereby, the two required barriers are not longer functional.

A study on well integrity that included 217 wells on Norwegian Continental Shelf (NCS) by SINTEF verifies this integrity issue. The results showed that 20-30 % of wells had at least leaked ones [35]. And the greatest challenge is evaluating the integrity after the well has been Permanently Plug and Abandoned (PP&A), when have no longer access to the wellbore, as cement sheath failure and fluid migration can be a time-dependent process. In Alberta, Canada, around 6 % of 300 000 wells have recorded surface-casing vent flow also known as SCP. Studies have also shown that approximately 60 % of offshore wells in the Gulf of Mexico have recorded SCP [5]. These studies most likely give a good representation of this problem worldwide.

Cement is the primary plugging material used by the petroleum industry, including when the primary cement has failed and remedial work needs to be performed. Cement sheath failure and associated fluid migration (mainly gas) can happen over the entire life-cycle of a well, some of the causes are directly associated to the cement poor properties in regards to brittleness and poor adhesion to other materials. The available technology for remedial repair for a producing or to be plugged well requires large workover intervention operation, which can be both time-consuming and expensive. All of the methods uses cement as a plugging material. The need for other available methods that used alternative materials and placement methods are evident. One alternative can be the CannSeal tool run on wireline which perforates and inject a resin into the annular. As previously mentioned, this concept has been successfully deployed for open annular thermosetting polymer plugs, this thesis will investigate its potential for restoring the integrity of cemented annular.

1.2 Scope of Thesis

This thesis will cover the main reasons for fluid migration through a cemented column, the resulting consequence of migration which is primarily SCP. Then give the reader an understanding of which diagnostic methods are available, especially focusing on cement evaluation tools and their principles, strengths and limitations. In addition which preventive and remedial methods are available for minimization or elimination of fluid migration. Finally in the literature review part, the use of alternative plugging materials such as epoxy resins and alternative placement methods, the CannSeal tool. Thereafter, the experimental set-up for large-scale testing of epoxy resin pumped into cemented annulus for sealing and finally, results are presented and discussed.

The tests described in this master thesis, performed by CannSeal (and myself), is an ongoing Joint Industry Project (JIP) between Shell, Mærsk and CannSeal.

Chapter 2

Literature Review

This chapter is a literature review for covering the basics and most important information prior to performing experimental tests with alternative plugging material and placement method. Starting with the main reasons how fluid migration occurs, the extent of the problem, how to detect, prevent or remove with today's available technology and their strengths and associated weaknesses. Thereafter, giving an introduction and overview of alternative plugging materials and the CannSeal placement method.

2.1 Fluid Migration Through a Cemented Column

Will cover the main factors contributing to gas leak through a cement matrix or at the interfaces between formation (or casing)-cement-casing. Understanding these factors are important for both preliminary and remedial work for maintaining or restoring cement integrity. Annular gas migration can happen during drilling, well completion operations and/or after the well has been PP&A.

The main objective of a primary cementing operation is achieving zonal isolation against the permeable zones located behind the casing. The industry is finding this as a huge challenge, especially regarding migration of gas to the surface leading to SCP.

Several effects may contribute to cement losing its seal. Firstly, a proper cement job needs to be performed, involving proper mud removal, correct cement slurry design with fluid-loss additives, density-control, optimal cement hydration process and centralization of the casing. After the cement has set, it should after all intent be impermeable. However, even if the cement job is well executed and proper cement system has been used, a leak can still happen after the cement has set. Cement sheath failure can happen as a result of alternations in pressure and temperature, which causes expansion and contraction of the casing and surrounding cement.

Of main interest are the so-called "highways" where fluid can flow with larger rates, this is the voids and larger channels. These can come from a poor cement job, with a present mud-cake. Use of the term microannulus and its extent, varies slightly with the literature and professionals from the industry. For the sake of this document, a microannulus is a small channel where fluid (mainly gas) can be present and flow at smaller rates if interconnected.

2.1.1 Density Control

Gas can only invade the cement slurry if the formation pressure exceeds the hydrostatic pressure, shown in figure 2.1. Hence, choosing the correct slurry density is very important. The exerted hydrostatic pressure will not be constant during the cementing operation, because of the density differences of mud, pre flushers, spacer and the cement slurry. Special considerations need to be taken to avoid lost circulation or fracturing of different zones. If gas were to invade the cement slurry, this may lead to an irreversible gas entry process [7].

2.1.2 Mud Removal

Proper removal of drillings fluids prior to cementing operations is key for achieving long-term zonal isolation. There are several techniques that can be applied for optimizing mud removal. It may be necessary conditioning the mud with different density and rheology properties, thereby improving cleaning and displacement efficiency. A spacer fluid needs to be pumped between the mud and cement slurry, in order to prevent mixing of the two fluids, thinning and weakening of the mud-cake and leave the formation and casing water-wet for optimal cement bonding. If the casing is not centralized, this can create uneven displacement of the mud, due to spacer and cement slurry that will flow path of least resistance. This will lead to mud-channels shown in figure 2.1, water can later be drawn from these channels leading to shrinkage induced cracking and development of fluid migration paths [9].

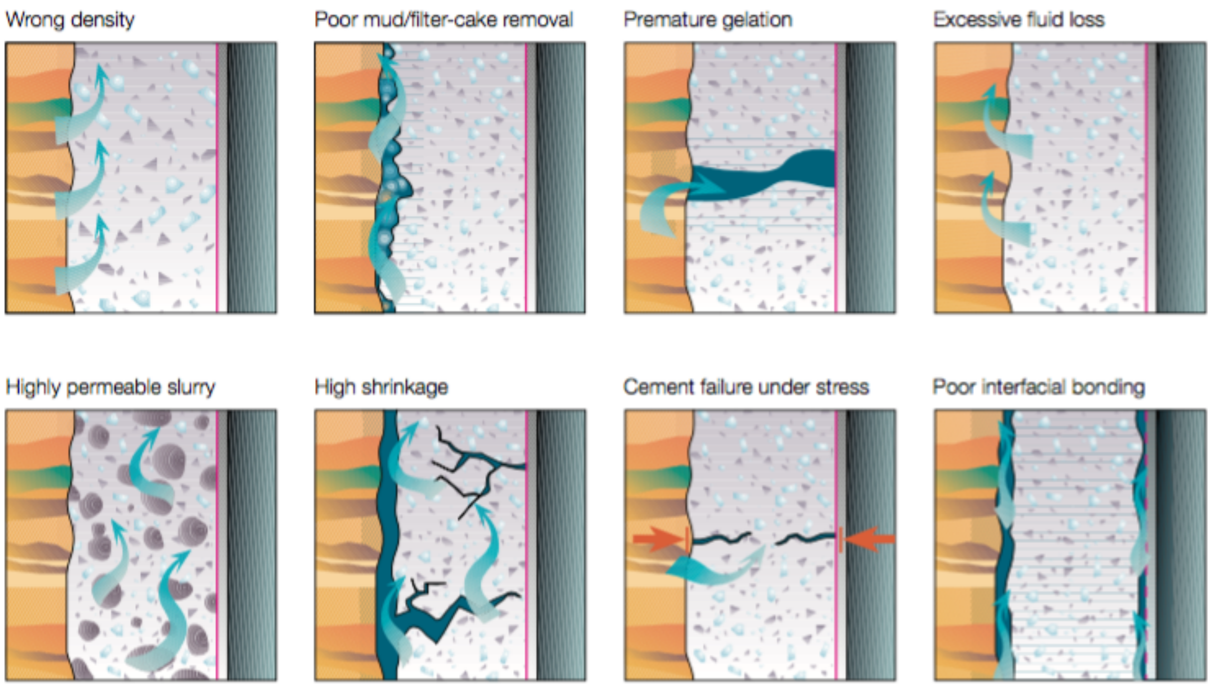


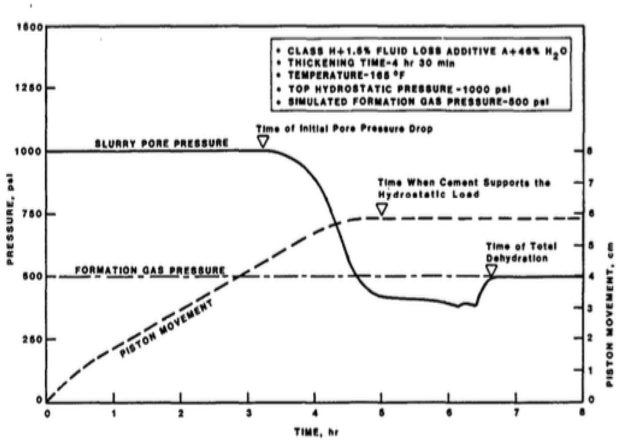
Figure 2.1: Wrong density may result in flow of fluids from the formation into the cement system. Poor mud removal may contribute to mud-channeling or poor bonding between formation-cement. Premature gelation leads to loss of hydrostatic pressure control. Excessive fluid-loss may lead to cement pores being filled with fluids like gas. Highly permeable cement will create a pathway for migration. High shrinkage may lead to a formation of microannulus. Cement failure may come as a result of stress changes in the formation or pressure and temperature alternations in the wellbore. Poor bonding between formation-cement-casing may create microannulus [9].

2.1.3 Cement Hydration Process

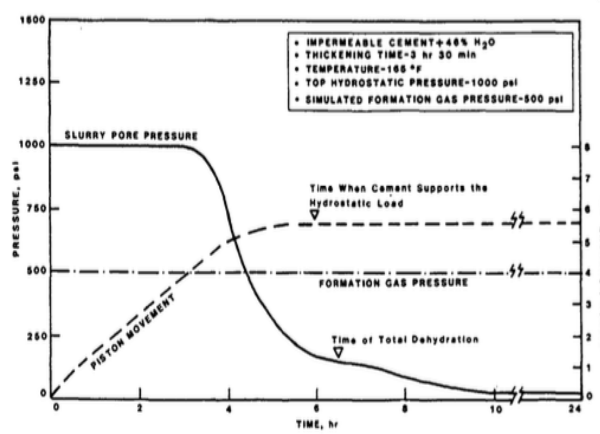
When water is added to the components present in the cement, hydration process is initiated resulting is a phase transition of the cement slurry from liquid to a solid cement plug. The hydration process is an exothermic chemical reaction, consequently, heat is generated during settling and hardening of the cement.

After the slurry is placed in annulus and pumping has stopped, it will transmit full hydrostatic pressure and no gas will invade the cement matrix when overbalance is achieved. The slurry pressure will however decrease because of a combination of gelation, fluid-loss and bulk shrinkage [9]. The pressure drop is mainly due to gelation or dehydration, as the cement slurry is going from a true hydrostatic fluid to a highly viscous mass showing some solid characteristics [16].

In this transition, gas may invade the cement matrix and potentially create a leak pathway. This phenomenon can be seen in figure 2.2a, here a test was performed with setting a cement plug within a small apparatus measuring gas flow across, with a piston measuring the movement of cement slurry/plug due to dehydration. The cement slurry consisting of a fluid-loss additive, which primary objective is to prevent gas invasion by forming a filter cake at the interface between cement and permeable zones.



(a) Slurry containing fluid-loss additives.



(b) Impermeable cement system.

Figure 2.2: Pore pressure versus time for different slurry compositions [16].

The tests performed by P.R Cheung and Robert M. Beirute [16] given in figure 2.2a, indicated that no gas invaded the cement slurry when had an overbalance in pressure. When the cement slurry started dehydrating and slurry pressure drops below formation gas pressure, initially there was not enough gas volume for creating a continuous pathway. But, when enough filtrate was lost, gas was able to "recharge" the lattice to a value equal to gas formation pressure, this phenomenon is shown in figure 2.2a. The test suggested that if fluid was mobile inside the cement pores, it could be displaced by gas, so fluid-loss additives seemed incapable of immobilizing the fluid. Another test was performed, shown in figure 2.2b, with an "impermeable cement system" consisting of polymeric materials and bridging agents, immobilizing the fluid within the pore spaces. This lead to no "recharge" of slurry pressure or development of migration paths with gas within the cement.

There will be a decrease in absolute volume during setting of cement, as the volume of the hydrated products is less than the volume of the hydrated components [7]. Only the external volume change will contribute to the generation of microannulus, this volume change is referred to as the bulk shrinkage. The bulk shrinkage stops after the rigid structure is formed (specimen has developed enough compressive strength to hold its own weight), however, chemical shrinkage continues by an increase in internal cement porosity, while the external volume remains constant. Expansive cement systems have been designed for giving a controlled expansion to help seal microannulus. Laboratory experiments have however shown that cement shrinkage is negligible for generation of a continuous microannulus development for most well conditions [8]. One explanation could be, that when cement shrinks the Top of Cement (TOC) could be lowered to compensate for the shrinkage, as the bulk shrinkage happens when cement is in a liquid state.

2.1.4 Cement Shrinkage Leading to Circumferential Fracture

A conceptual model presented by Maurice B. Dusseault, Malcolm N. Gray, and Pawel A. Nawrocki [17], explains the possibility of gas migration as a result of shrinkage of the cement leading to the development of a circumferential fracture ("microannulus"), that over time grows vertically. This theory will be presented and discussed.

In the previous subsection, it was mentioned that when cement sets it will no longer transmit hydrostatic pressure. Thereafter, stresses in the cement can be referred to as vertical and horizontal. The radial stress (σ_r) between the cement and formation (rock) will be reduced if the cement shrinks, the tangential stress (σ_θ) will however increase. This causes the hydraulic fracture condition to be reached, given in equation 2.1.

$$\sigma_3^{'} \leq -T_0 \tag{2.1}$$

where

$\sigma_3^{'}$ is the minimum principal stress [Pa]

T_0 is the tensile strength [Pa]

The minimum principal stress is equal to the radial stress and tensile strength is assumed to be zero. Also, applying the definition of effective stress gives the relationship in equation 2.2.

$$\sigma_r \leq p_0 \tag{2.2}$$

where

p_0 is the pore pressure [Pa]

When the criterion given in equation 2.2 is reached, this leads to the development of a circumferential fracture. The fracture will develop in the direction of the smallest horizontal stress (σ_h) of the formation. The condition of $p_o \geq \sigma_r(\sigma_3)$ is still not a condition for vertical growth. This growth can be explained by the imbalance of pressure (fluid) gradient in the fracture and the stress gradient in the rock, this principle is shown in figure 2.3. As gas flow into the fracture (normally by a diffusion process) it has a much lower gradient than the lateral stress, leading to an even greater excess fracture propagation force at the upper tip. So if it can fracture the cement lower down, it will do this with even greater force at the tip. Also, fracture growth in the vertical direction can be aided by pressure and temperature cycles.

The fracture will grow very slowly and it will take a long time before potential observed an increase in annular pressure, gas could also enter shallow strata, therefore well could be leaking even with no observed pressure increase at the surface. The potential long time before evident pressure increase can be explained by two-rate limiting aspects, the low diffusion rate and hydraulic conductivity only allowing very small rates of gas migration. Also, during production due to expanded casings from pressure and thermal forces leading to the closing of the fractures.

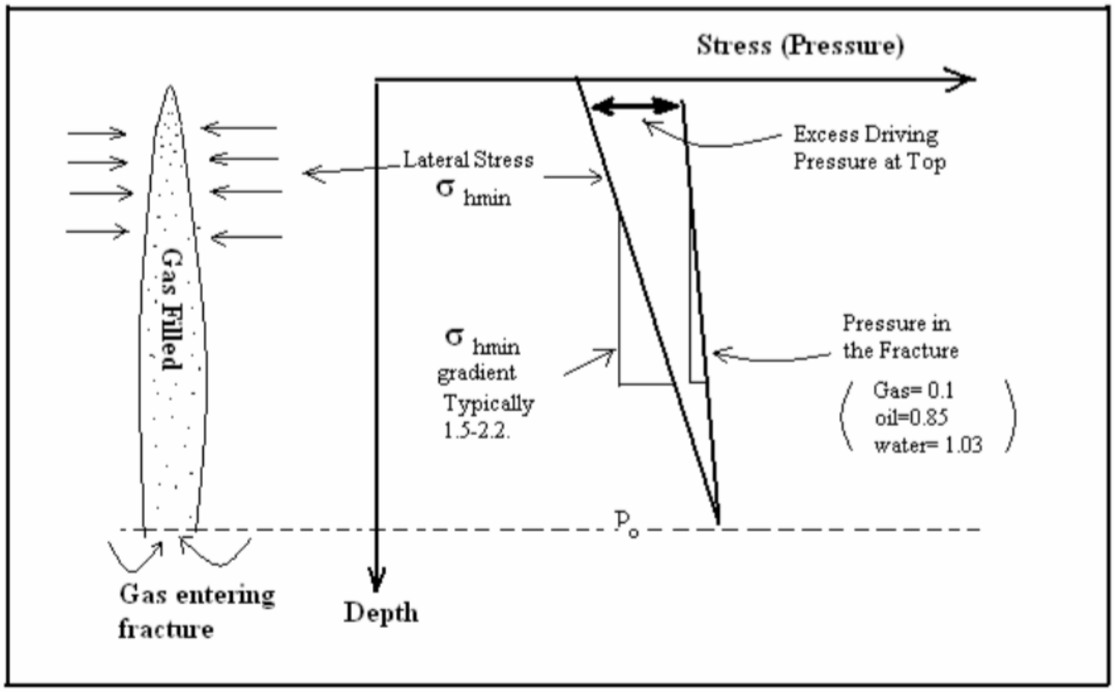


Figure 2.3: Fracture driving force from gradient differences between fluid in the fracture and lateral stresses [32].

This theory is one possible explanation of the delayed observed increase in annular casing pressure that rebuilds after initial bleed off.

2.1.5 Pressure Variations in the Wellbore

An increase or decrease in pressure, the casing will expand and contract accordingly. Due to the greatly different mechanical expansion properties of the casing and cement sheath, this can result in the development of microannulus(es). When the internal pressure in the wellbore increases, a ballooning effect will occur. The cement in the annulus will counteract these forces from the expanded wellbore, inducing stresses in the cement. If these stresses exceed the cement strength a failure will occur in the cement sheath [46]. Such a failure could develop both radial and axial failures, potentially creating a continuous pathway for fluid migration.

Such alternations in pressure could typically occur in operations such as integrity tests, leak-off tests, stimulation, remedial cementing, perforation, changing mud-weights for drilling of next section or displacing to completion fluid.

The radius variation of a casing subjected to pressure alternations can be calculated by the equation 2.3. This equation is for thin walled pipe, assuming that casing is free to move and therefore not bonded to the cement sheath.

$$\Delta r_{casing} = \frac{r_{casing}^2 \Delta p}{h_{casing} E} \tag{2.3}$$

[1]

where

Δr_{casing} is the change in casing radius	[mm]
r_{casing} is the mean casing radius	[mm]
h_{casing} is the casing wall thickness	[mm]
Δp is the change in pressure	[Pa]
E is the Young's modulus of steel (1.80×10^{11})	[Pa]

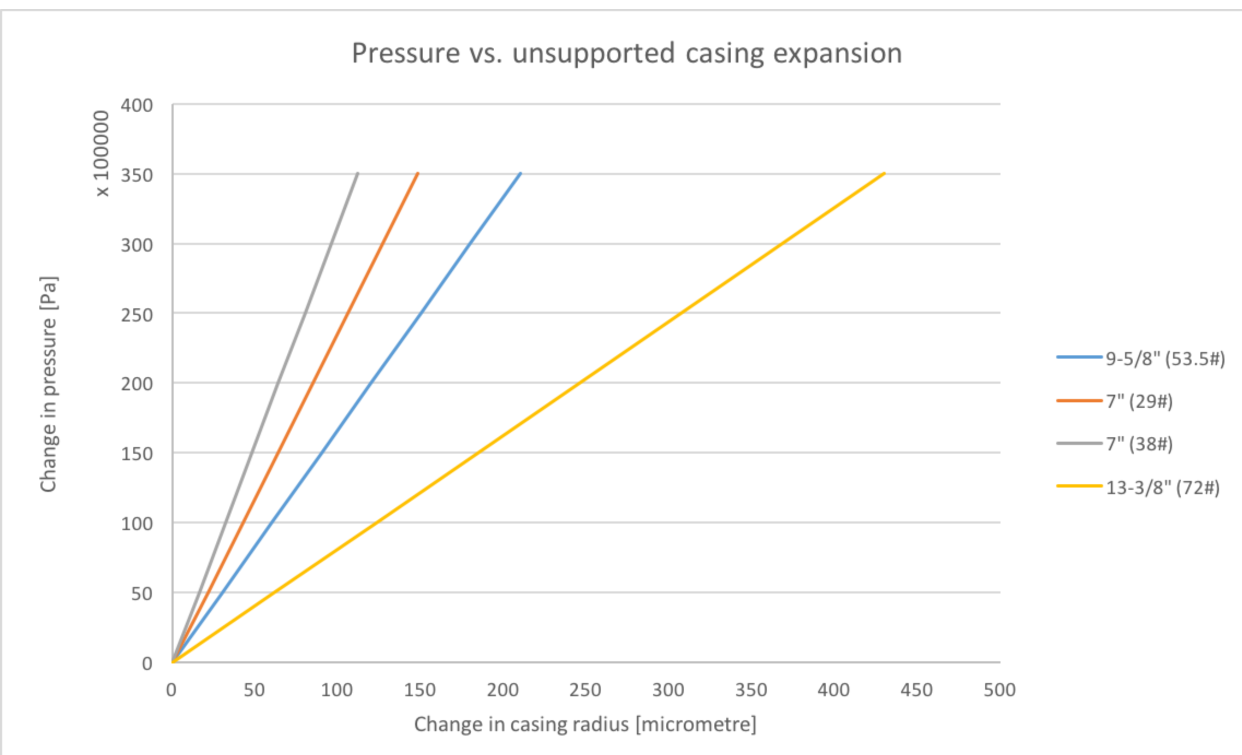


Figure 2.4: Pressure versus unsupported casing expansion for different casings sizes.

Equation 2.3 has been used to generate graph given in figure 2.4, showing the expansion of unsupported casings as a function of a change in pressure. A decrease in wellbore pressure could happen when circulating well to a lighter completion fluid, this decrease could break the adhesion between casing and cement forming a microannulus. If a 9-5/8" (53.5#) casing has been set at 2500 m TVD and the cement has been circulated with a 1800 $\frac{kg}{m^3}$ mud. If the wellbore then were circulated with a completion fluid with density of a 1400 $\frac{kg}{m^3}$, this would result in a change in pressure of approximately 100 bar. According to equation 2.3, developing a 60 μm microannulus that could lead to SCP.

2.1.6 Temperature Variations in the Wellbore

This phenomenon has similar effects as pressure alternations, as casing expand and contract with respectively higher and cooler temperatures. With excessive temperature increase, this causes diametrical and circumferential casing expansion. This expansion as with pressure increase will eventually induce tensile tangential stresses in the cement. If this tangential stress reaches the tensile limit of the cement, a crack initiates at the casing-cement interface, this can be seen in the upper part of figure 2.5. This crack may propagate to the cement-formation interface shown in the lower part of figure 2.5, if this occurs over a sufficient vertical distance, a channel is formed which gas can flow through the cement plug and integrity is lost [16].

Temperature cycles which induce thermal stresses may be observed in operations such as production, steam injection, cold fluid injection (water), cement hydration (exothermic reaction). Generally, during production when the casing is expanded due to increased temperature, the presence of stress cracks in the cement sheath is not a problem. However, when casing "relaxes" due to temperature reduction after production has stopped, these cracks could open sufficient to permit annular flow.

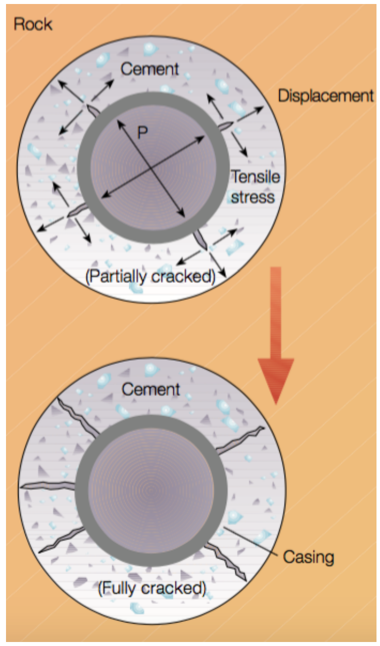


Figure 2.5: Pressure and/or thermally induced radial cracks in the cement sheath [16].

The radius variation of a casing subjected to temperature cycling can be calculated by equation 2.4. Assuming pipe is free to move, hence cement is not bonded to the casing.

$$\Delta r_{casing} = \alpha r_{casing} \Delta T \tag{2.4}$$

[6]

where

ΔT	is the change in temperature	$[^\circ C]$
α	is the coefficient of thermal expansion of steel	$[(^\circ C)^{-1}]$

Figure 2.6 shows the results from a Computed Tomography (CT) scan with 3D volume reconstructions before and after a thermal cycling experimental [44]. The casing-cement debonding is present already before the thermal cycling, with potentially continuous pathways. This can be due to the poor shear bond of cement (poor adhesion), better bonding to steel pipe has been observed with larger roughness and sandblasted casing surfaces. The specimen was cycled from a temperature span between 6 C° to 106 C° with holding times of 4 hours [44]. From the CT-scan

it is evident that this cycling leads to a poorer cement integrity. The casing will expand more than the annular cement, this will induce compressional stresses in the cement sheath, which can promote radial cracking and debonding. The same principle applies when the specimen is cooled, here the casing will contract to a larger extent than the cement. Thereby inducing tensile stresses in the cement which can lead to cracking and debonding [6].

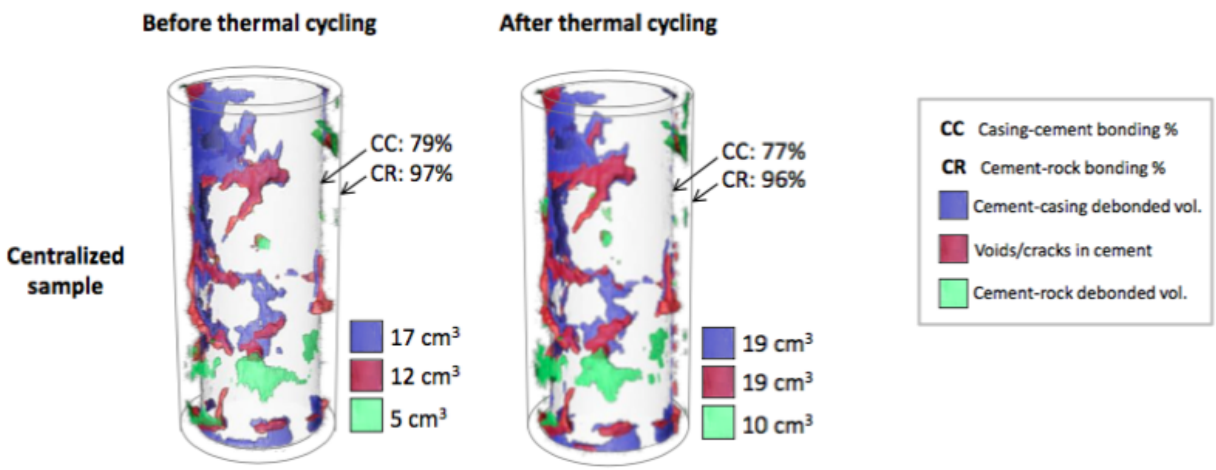


Figure 2.6: Results from CT-scan with 3D volume reconstruction before and after thermal cycling [44].

2.1.7 Mechanical Fatigue and Chemical Degradation

Mechanical fatigue of the cement can be a result of mechanical stresses and vibrations from drilling operations. Especially in parts of the well where drillpipe will be in constant contact with the casing, such as kick-off points. Field experience has shown that gas migration on intermediate strings could occur days after the primary cementing operation, this after drilling was resumed [7]. A possible explanation was that the stresses imposed by the drillstring on the cement lead to failure and thereby creating migration paths for the gas.

Cement subjected to chemical degradation may lose it beneficial properties such as mechanical integrity and hydraulic conductivity. Over time, this can result in loss of integrity. An example is an attack from carbon dioxide (CO_2) and/or hydrogen sulfide (H_2S), both will decrease the strength of the cement system, by increasing the permeability and porosity [6].

2.2 Sustained Casing Pressure (SCP)

SCP is defined as casing pressure that rebuilds after initial bleed of. This pressure should not be confused with single annular pressure buildup, which is caused by pressure and temperature fluctuations after the well has started flowing. When this volume is bleed off due to liquid pressurization and the well has reached steady-state flowing condition, if this pressure rebuilds in annulus the well is exhibiting SCP [11].

This problem can arise from start of production to the well is to be PP&A, and needs to be handled and repaired safely. SCP can occur in all annuli, and the most likely causes are listed below and visualized in figure 2.7.

- Poor primary cement
- Damage to primary cement
- Tubing and casing leaks

The first two listed above concerning primary cement has been throughly discussed in Section 2.1. Other causes are shown in figure 2.7 are seal assembly, wellhead or packer leaks. Tubing and casing leaks can be a result of poor thread connection, corrosion, thermal-stress cracking or mechanical rupture of inner pipe [11]. Tubing leaks and associated pressure build-up in production casing has the greatest potential for causing a significant problem. This is due to production casing is designed to withstand the formation pressure, however, this may not be the case for the outer strings. Hence, if the production casing fails this can have catastrophic consequences such as an underground blowout [11].

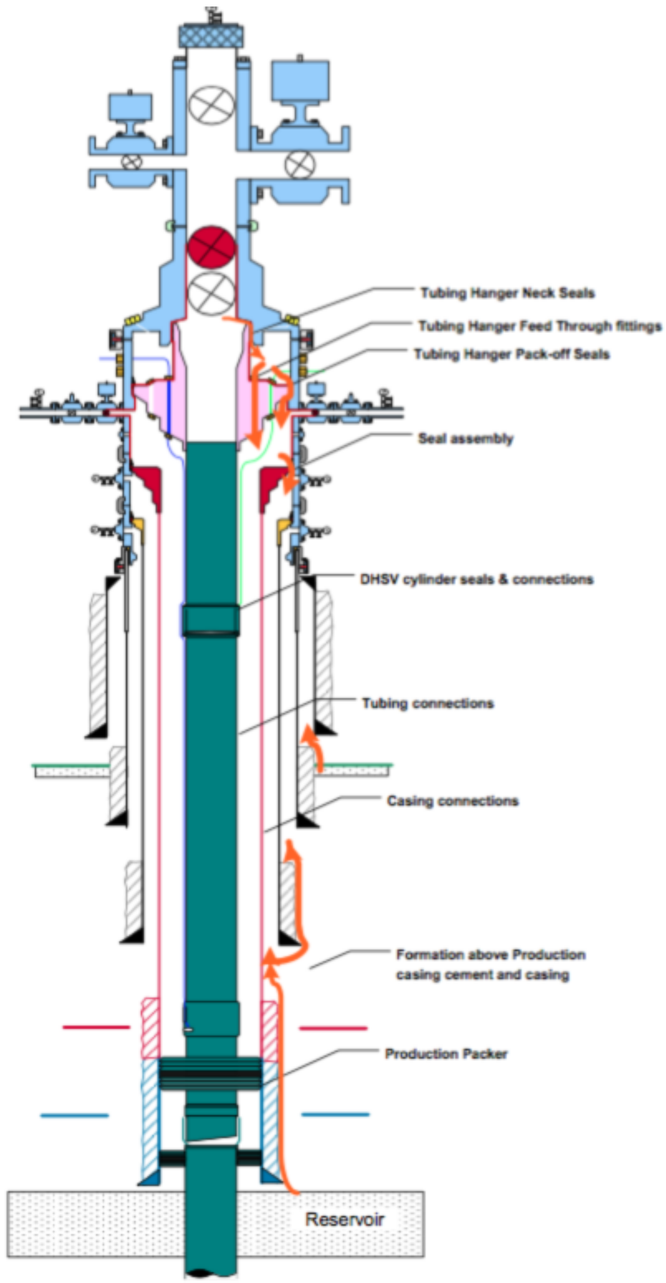
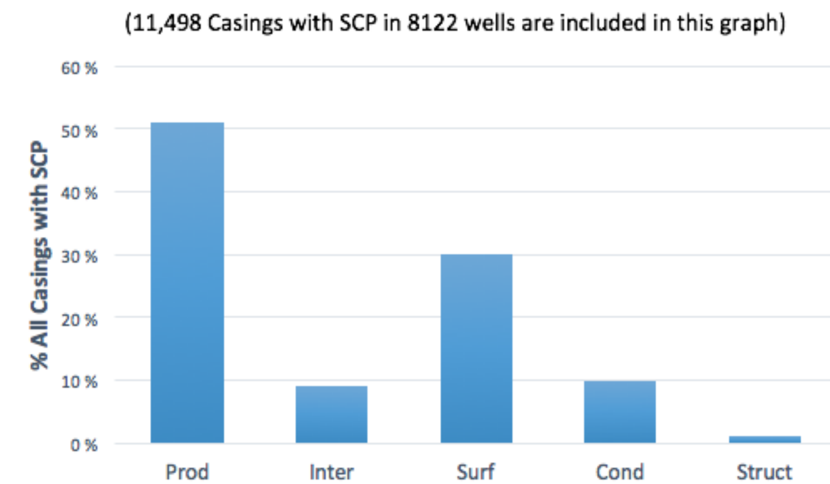
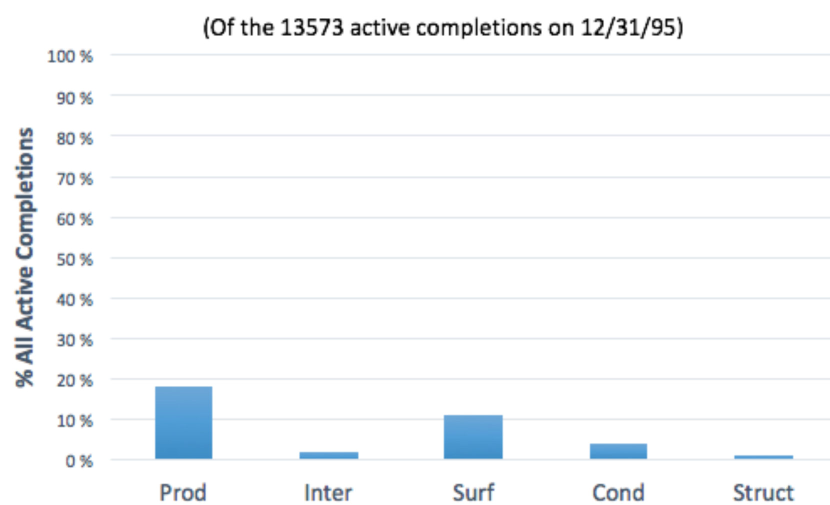


Figure 2.7: Examples of different leak scenarios resulting in SCP [33].

SCP was observed in 11 498 casing strings in over 8000 wells on the Outer Continental Shelf (OCS) [10]. These numbers came from a study performed by a research team at Louisiana State University (LSU), the study also concluded that over 50 % of casing strings having SCP was production casings, these statistics are given in figure 2.8a. The diagram provided in figure 2.8a also shows that respectively 10 % and 30 % of casing strings exhibiting SCP are from intermediate and surface casings. The wells having SCP in A-annulus will be easier to diagnose and repair compared to the outer strings. The study also concluded that only about a third of the total number of wells having SCP was active and producing wells, the majority of wells, therefore, are shut-in or temporarily abandoned [10]. The following producing wells with associated SCP on different strings are given in figure 2.8b. These numbers most likely give a good representation of SCP challenges worldwide.



(a) Detected SCP sorted by casing strings on OCS.



(b) Percentage of all active completions with SCP on OCS.

Figure 2.8: Graphs from study performed by LSU research team on SCP [10].

If observed SCP, depending on which country the well is located it will have an acceptance rate regarding pressure build-up before needs to stop production and the operator needs to fix the issue. NORSOK D-010 states that [14]: *"The pressure in all accessible annuli shall be monitored and maintained within the minimum and maximum pressure range limits. All accessible annuli should be maintained with positive pressure for leak detection and pressures should be kept with differential pressure between all annuli."*. In contrast to US-regulations that has a specific limit of pressure not exceeding 20 % of yield strength and/or that can bleed off to zero pressure through a 0.5-inch needle valve in 24 hours [10]. NORSOK D-010 refers to "Norwegian Oil and Gas Association, Guideline no. 117" [33] for defining the annulus pressure operating envelopes. This guideline does not give a specific criteria, but states that: *"The objective when determining acceptance criteria for annulus pressure, Maximum Allowable Annulus Surface Pressure (MAASP) at the wellhead, is therefore, to identify a pressure at which the probability of failure is as low as reasonably practicable and normal operation of the well is allowed".* It is therefore up to the operator for determining this safe annulus pressure.

A great challenge related to subsea completions in regards to SCP is that only able to monitor and bleed-off pressure in the A-annulus. The operator have no information about potential leaks in the outer strings based on pressure monitoring, this is a great concern.

2.3 Preventive, Diagnostic and Remedial Methods

When designing a well program, the long-term perspective of maintaining well integrity has to be taken into account. That includes what preventive methods such as cementing systems and placement methods will increase the success rate of the primary cementing operation. However, due to the several factors that can lead to loss of cement integrity covered in Section 2.1, many wells today leaks over several annuli, this will most likely be the situation also in the future. These leaks need to be diagnosed, that is finding the root cause(s) of fluids migration and thereafter eliminating these by remedial methods. These methods today includes the traditional squeeze cementing and section milling, but also the relative new technology Perforate, Wash and Cementing (PWC), which is an improvement of squeeze cementing.

2.3.1 Preventive Methods

Designing the cement system in terms of stresses most likely to be experienced and fluids which will be exposed to, will increase the probability of achieving long-term zonal isolation. First, to fully take advantage of the cement system, the slurry needs to be placed effectively all around the casing in the annulus. Correct cement placement practice such as proper mud removal, correct spacers, casing centralization and movement will all help to achieve this result, no cement system can be a substitute for good cementing practices.

The special cementing systems to be mentioned are only a few of the one's available today, for a more complete overview see Table 7-25 in Well Cementing 2. Edition [8]. Some of the cementing system available are listed below and will be reviewed briefly.

- Flexible cements
- Thixotropic cements
- Expansive cements
- Polymer based cementing systems

Flexible Cements

This cementing system will have lower Young's modulus than the conventional cement, research has shown that risk of rupture (stress induced failure) of cement sheath is decreased when having a lower Young's modulus and higher tensile strength [15]. Implying that ratio between tensile strength and Young's modulus should be increased. When Young's modulus is lowered, the material becomes more flexible (more strain with less applied stress). Thus, should be better suited to withstand expansion and contraction of the casing due to pressure and temperature cycles in the wellbore. Some of the ways to modify the elasticity of the cement is by adding flexible particles in the slurry such as rubber [8].

Thixotropic Cements

The thixotropic cementing system is mainly used for gas prevention and lost circulation problems. When in a liquid state, this slurry acts as Bingham fluid under stress, meaning that behaves as a rigid body at low stresses but flows as a viscous fluid at high stresses (like tooth path), illustrated in figure 2.9. When applied stress (pumping and mixing) the slurry are very thin but develops a high strength almost immediately after placement [2]. In Subsection 2.1.3, the phenomena of gas migration during hydration was described. This issue seemed to be a time-dependent process during the transition period when cement hydrates from a liquid to a solid state. With thixotropic cement system, this period is significantly reduced, thereby the probability of gas migration occurring in this period.

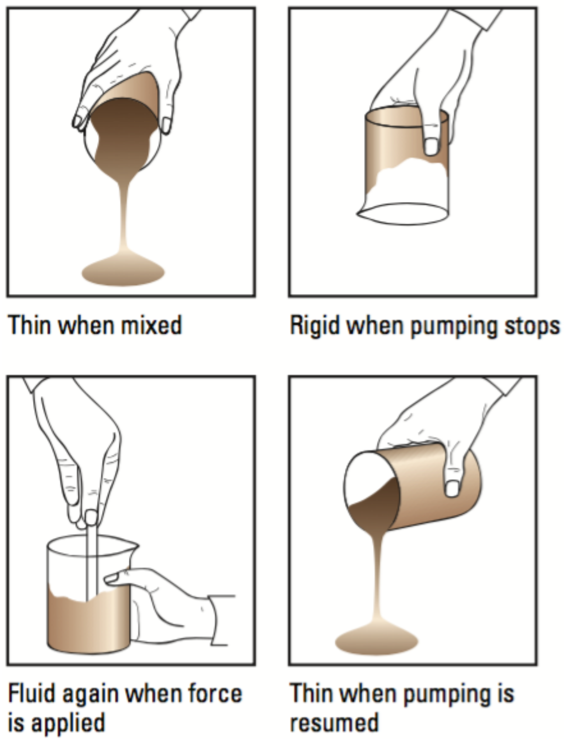


Figure 2.9: Illustrating thixotropic behavior [8].

Expansive Cements

The cement shrinkage is a result of the volume of the hydrated products is less than the volume of hydrated components. As previously discussed, the shrinkage leading to external volume change is referred to as bulk shrinkage, this can result in microannulus between cement and the casing. This shrinkage ceases when the cement has developed compressive strength and a rigid structure has formed. The bulk shrinkage can be between 0.5 to 5 % [8].

The expansive cement system is designed to expand slightly after setting, hence improving bonding between the different interfaces. Expansive cement need to have a lower Young's modulus than the surrounding formation, otherwise, will not expand in the direction of the casing and a development of microannulus will be formed. Most expanding cement systems use the principle of development of ettringite, where ettringite crystals have a greater bulk volume from which they are formed.

Polymer Based Cementing Systems

These cementing systems are also referred to as latex-cement modified. The adding of different thermosetting polymers to the conventional portland cement base will enhance some of its characteristics. By that, increasing its tensile strength and elasticity, decreasing its shrinkage and improving bonding to other materials [8]. By adding thermoset polymers to the slurry can give the ability of right angle set (depending on the polymer type), that is an instant strength development when setting. In contrast to conventional cementing systems which has an inconsistent strength development during the hydration reaction [42].

These types of systems are especially useful in challenging well conditions, such as thermal and injection wells, where the need for flexural plugging materials are evident. But also in regular conditions, as added polymers will give better bonding to oil-wet and water-wet surfaces and has increased resistance to contamination by well fluids [8].

Cement Placement Considerations

There are several different considerations, best practices, and methods used for performing a successful cementing operation, some of the industry recognized ones are listed below.

- Drilling practices
- Proper mud removal
- Casing centralization
- Casing movement

The drilling practices that especially affect the final hole size, all contribute to a successful zonal isolation. That includes avoiding lost circulation that needs remedial work, washouts, and cavings which are vulnerable for cutting accumulation that will contaminate the cement and lower the compressive strength and sealing capability. Optimal pump rates for proper cleaning and transport of cuttings is essential, especially in horizontal sections where can accumulate on the low side, wiper trips also need to be considered. Proper mud removal is key for performing a successful primary cementing operation, incomplete mud displacement and conditioning can leave mud layers on the formation or pipe interfaces, which will significantly reduce bonding of cement. Drilling mud and cement slurry are incompatible and may form a highly viscous and unpumpable mixture [29]. Preventing these two from mixing, a spacer is pumped in-between, which also clears remaining mud from pipe and formation, in addition, water-wets the different surfaces.

It is important to achieve the highest possible stand-off, thereby increasing the success rate for proper mud displacement. Proper casing centralization is key for avoiding mud-channeling, as fluids always flow the easiest path, which is in the wider channel. Good centralization is achieved with a combination of centralizers and minimizing hole size [15]. The main reasons for casing movement while cementing is to improve mud removal and modify the cement transition time. While rotating, a thin water film develops around it and when stopped, this layer heals quickly and bond is attained between the cement and the pipe. The transition time from liquid to solid state for the cement is much shorter when applying this method [10].

2.3.2 Diagnostic Methods

The objective of diagnostic testing is finding the root cause(s) for fluid migration due to a defect or problems in a well. By eliminating the root cause, the problem (SCP) will also be eliminated. Some of the main diagnostic methods used by the industry today are listed below.

- Fluid sampling and analysis
- Pressure bleed-down and pressure build-up performance
- Temperature and noise logging
- Cement evaluation tools

Fluid Sampling and Analysis

By analyzing the weight and composition of the fluid(s) causing pressure buildup, may give valuable information about its origin and potential leak-off point(s). All potential migrating fluids (e.g. water, oil, and gas) may have different probable formations which they are leaking from.

Water is most likely from shallow water zones, or aquifers, or if an injection well finding its way back to surface through migration paths. The characteristics of sampled hydrocarbons can be analyzed in comparison to those produced.

Pressure Bleed-Down and Pressure Build-Up Performance

These performance tests can give valuable information of the annular volume of gas and channel/microannulus flow capacity. The different pressure versus time patterns observed will depend on several factors, among them; the size of the needle valve and opening (only for bleed-down), type of fluids (the main issue is gas), formation pressure, cement properties (such as porosity and permeability) and if mud is present above TOC [25]. The difference between the two lies in the name, for a bleed-off the pressure is decreased by opening the needle valve and after the valve is closed, the pressure will start to increase, hence build-up, the responses for each test can be evaluated.

These performance tests are also known as positive and negative pressure tests conducted for evaluating the integrity of a well barrier. For a cemented annulus, the integrity regarding hydraulic isolation can only be directly assessed by a negative pressure test, by observing the potential build-up of pressure in the annulus over a period of time.

Temperature and Noise Logging

Both temperature and noise logging can provide information about fluid entry points behind casing when the flow is significant. The temperature survey main application (aside from production services) is verifying TOC. This can be done as a result of cement hydration is an exothermic reaction, therefore will generate heat and this can be detected. In addition, temperature logs can locate fluid movement downhole. When the well is left static (no flow), the temperature will eventually approach the formation temperature. When gas is under high pressures, it becomes cooled, while liquids stay warm. If producing from an oil zone and observe a gas build-up (from a gas cap or shallow zone) in B-annulus, one method for detecting leak point is running a temperature survey. Which will indicate deviations in borehole temperature from the normal gradient.

When running a noise log, this cannot be done in a continuous fashion, but rather a set of stationary readings [8]. Detecting leaking pipes and potentially migration through the cement, the sound from leaking gas will be become higher closer to the source, as the velocity increase so will the sound.

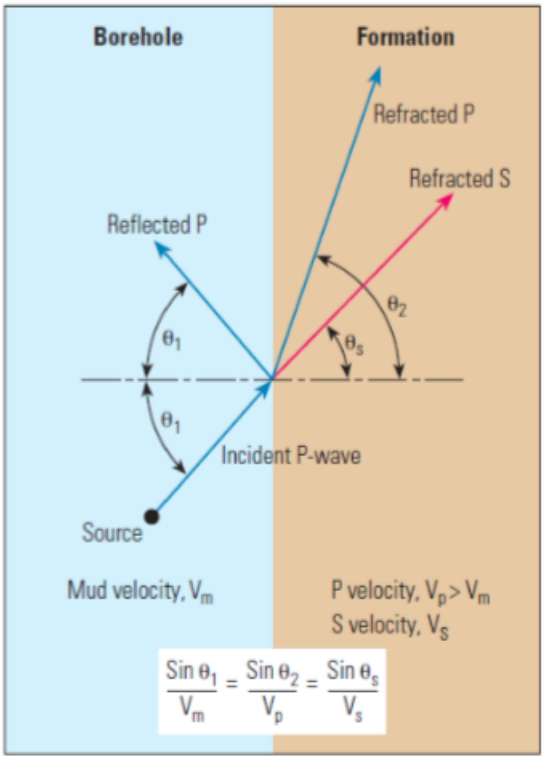
Cement Evaluation Tools

Cement evaluation tools are the most widely used diagnostic tools, providing information about the general health of the annulus. There has been a lot of research done within this field, both on developing new technology and within log-interpretation. The industry has moved from the traditional Cement Bond Log (CBL) to the ultrasonic tools (high-frequency sound waves). This has made it possible not only to interpret if something is in contact with the casing, but also what mediums are present (i.e. solid, liquid or gas). Ultrasonic tests have been performed on different types of epoxy resins in the annulus for verification, this is discussed in Subsection 2.4.2 with the associated achieved results. Below, the acoustic tools will be reviewed briefly, the author recommends readers with little experience with such tools, reading Appendix B for additional information.

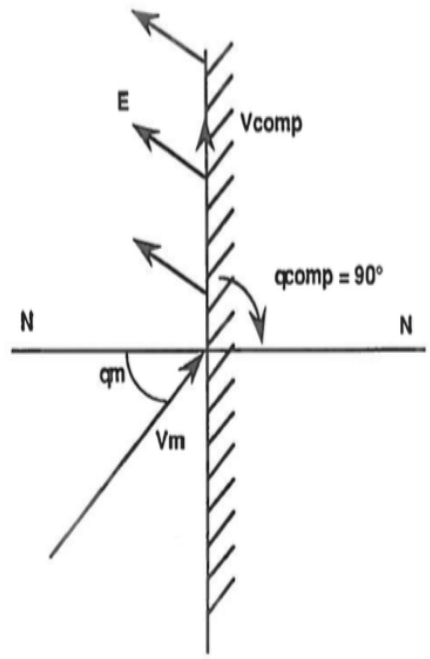
Acoustic logging tools use the principle of emitted sound waves which will propagate with certain velocities through different mediums. Different mediums, such as formation, cement, casing and fluids all have different acoustic properties, which are dependent on their elastic properties (e.g. Young's modulus (E), shear modulus (G) and Poisson's ratio (ν)). The emitted sound wave will be critically refracted when in contact with the casing (between two different materials) if the velocity in the entering medium (V_2) is larger than the abandoned one (V_1). The angle at which is refracted along the interface is called the critical angle (θ_c), it can be quantified by application of Snell's law, when $\theta_2 = 90°$ and $\sin\theta_2 = 1$, the angle of incident (θ_1) is then referred as to the critical angle θ_c given in equation 2.5. See figure 2.10a for graphical descriptions.

$$\sin\theta_c = \frac{V_1}{V_2} \ (where \ V_2 > V_1) \tag{2.5}$$

This refracted wave called the head wave will then travel along the casing radiating energy back to receivers at the tool which can be used for quantitative interpretation about the state of the annulus (e.g. solids present). The basic measurement principle is that the head wave will dissipate energy into the surroundings (both sides of the casing). The measured signal back at the tool will consequently be a function of the elastic properties of the medium(s) in contact with the casing.



(a) Wavefront reflection and refraction at interfaces (same principle when borehole and casing).



(b) The refracted angle (θ_2) reaches 90°.

Figure 2.10: Creating a head wave in the borehole [43].

The following three acoustic tools/principles used by the industry today are listed below.

- Cement Bond Log (CBL) and Variable Density Log (VDL)
- Ultrasonic Measurements
- Flexural Wave (Isolation Scanner from Schlumberger)

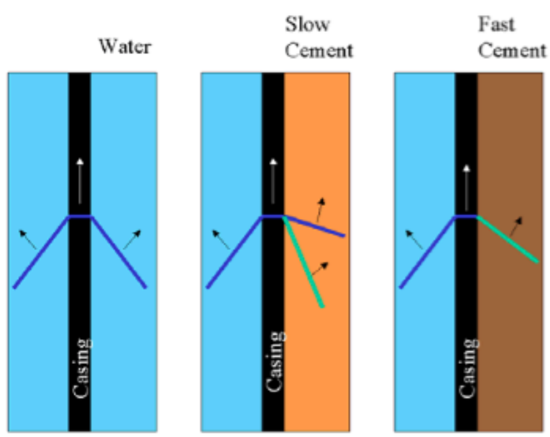
The CBL is run in combination with the VDL to give quantitative information about the state of the annulus. The CBL records the amplitude of the refracted casing wave if there is a low amplitude recorded this is an indication of the casing to cement contact, as much energy will dissipate into the surroundings. However, if the casing is "ringing", meaning high amplitude on receiving signal, less energy is dissipating into the surroundings, which can be a result of fluid present at the interface of the casing. The CBL can only give information about what is in direct contact with the casing, no information about potential hydraulic isolation of the cement can be obtained or discrimination between solids. The VDL can help discriminate between casing and formation arrivals, this principle can be used to give information about the acoustic coupling between the cement-formation given that good coupling between the cement and the casing.

The ultrasonic tools in comparison to the CBL emits sound waves with much higher frequency (200 - 700 kHz compared to 20 - 30 kHz) [8]. The differences in measurements is that while the CBL measures the amplitude or attenuation of a wave traveling along the casing, the ultrasonic tools measures the acoustic impedance of the medium(s) in contact with the casing. The acoustic impedance (Z) can be obtained using equation 2.6, where ρ is the density of the medium and the unit is Mega-Rayleigh (MRayl).

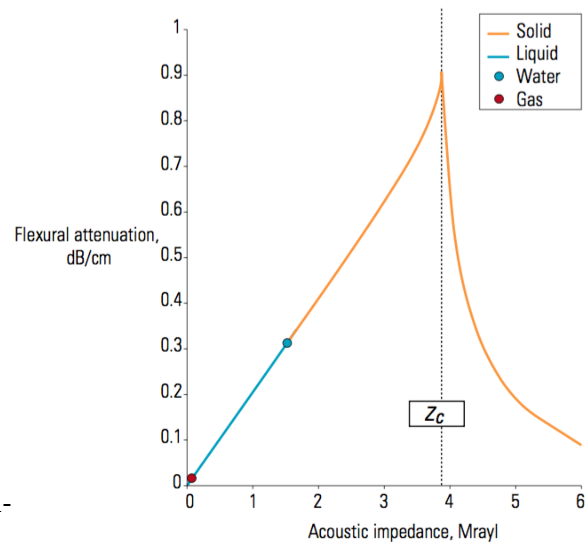
$$Z = \rho v_p \tag{2.6}$$

The emitted sound signal traveling along the casing will have an exponential decay in the reflected echo, which is controlled by the acoustic impedance of the cement (or other mediums present) and the mud in the wellbore. Knowing the mud impedance (obtained real-time from separate measurement) enables the extraction of the cement impedance [48]. Gas has an impedance value below 0.1 MRayl, liquids between 1 to 3 MRayl while conventional and lightweight cements have 6 MRayl and 2.4 MRayl (approximate values) respectively. The USI log-intepretation can, therefore, distinguish between conventional cement, gas and liquid, however lightweight cement does impose interpretations challenges. One of the main limitations of the USI-tools are the shallow depth of investigation in the radial direction, where cannot image defects within the cement sheath itself or at the cement-formation interface, where migration of fluids frequently occurs.

The previously mentioned interpretation challenges when solids have approximate the same impedance values as liquid, a new technology from Schlumberger with the Isolation Scanner has aimed to resolve this issue. The Isolation Scanner combines the conventional pulse-echo (USI) technique with a second mode, the flexural attenuation, a flexural wave created by a dipole source. For a flexural wave to radiate into the cement as a compressional and shear wave, the cement compressional or shear velocity must be less than the flexural phase velocity (at 200 kHz have velocity around 2650 $\frac{m}{s}$) [48]. The shear wave velocity of a cement will always be smaller than emitted phase velocity of a flexural wave, this is not always the case for a compressional wave such as with "fast cements" (see table B.2). When a compressive wave cannot be radiated into the cement annulus this will decrease the overall flexural attenuation, which is dependent on radiated compressive and shear waves attenuation in the annulus, shown in figure 2.11a.



(a) Radiation of flexural wave into different surroundings.



(b) Flexural attenuation vs. acoustic impedance.

Figure 2.11: First illustration showing how a head wave induced flexural wave radiates into different surroundings, such as water, slow and fast cement. The blue and green lines represent the compressional and shear waves respectively. Second, relationship between flexural attenuation and acoustic impedance [48] and [38].

As a result of this drop in flexural attenuation, one attenuation value corresponds to two impedance values shown in figure 2.11b. Hence, this measurement cannot distinguish between a liquid and a solid as a stand-alone measurement. But when deploying USI thresholds of impedance values for differentiating between solid, liquid and gas together with that there is a distinct flexural attenuation of low-impedance cement. Such as light-weight cement, this can be used to differentiate them from liquids [38]. Same principle can be used when logging resins, a low-impedance medium. Another important application of the Isolation Scanner is the third interface reflection, this can give information about casing position(s) within the borehole, that also gives second -hand information about potential channeling issues due to fluid traveling the way of easiest resistance path.

2.3.3 Remedial Methods

The main remedial methods used for elimination of SCP are listed below. All of the which will be briefly discussed, for the interested reader Appendix C gives a more thorough introduction including the operation and challenges of each method.

- Squeeze cementing
- Perforate, Wash and Cement (PWC)
- Section milling

For repairing a leaking cemented annulus, first, need to access the region causing the migration. Section milling actually removes/mills away the casing while squeeze cementing and PWC perforates before cementing. Squeeze cementing has been the primary method for repairing an improper cement job, leading to a poor zonal isolation. However, with a success rate of only 50 % [34], the PWC technology was developed and performance enhancement has been recorded.

Squeeze Cementing

Squeeze cementing forces the cement slurry under pressure through perforated holes in the casing or the liner, into holes, gaps or channels in the annular space. This method has several different applications, some of these are listed below.

- Repairing improper zonal isolation (due to mud-channeling, insufficient cement height in annulus)
- Repair casing leaks caused by corroded or split pipe
- Abandon a nonproductive or depleted zone
- Seal lost-circulation zones
- Plug one or more zones in a multizone injection well to direct the injection into desired intervals

[7] & [30]

The perforations prior to cementing will penetrate a short distance into the formation. The cement slurry consists of both an aqueous phase and solid particles. The particles will form a filtercake at the interface between the permeable formation and the perforations. This will eventually enable the water from migrating into the formation and the dehydrated cement can settle, shown in figure 2.12. The fundamental concept of squeeze cementing is that the initial seal is formed by the cement filter cake [47].

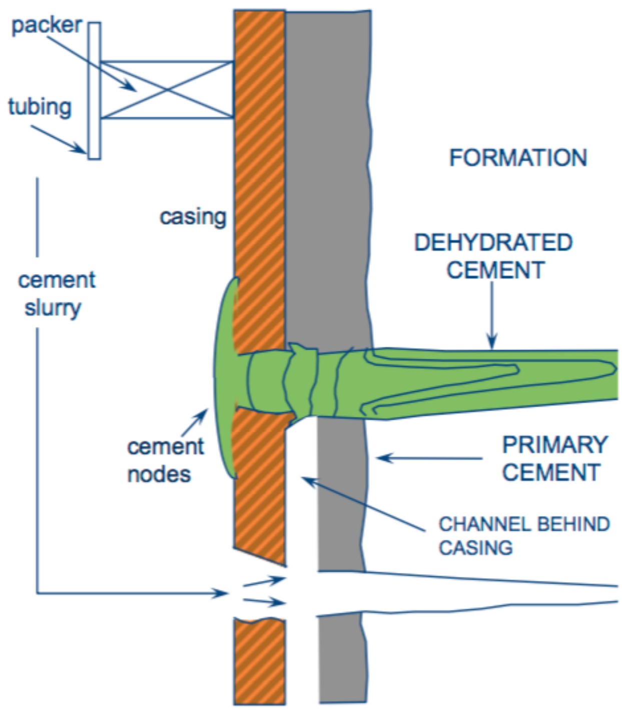


Figure 2.12: Showing injection of cement slurry into perforation in a squeeze cementing operation [30].

Selecting the optimum slurry is very important for performing a successful squeeze operation (as with all cementing operations). An injection test is performed prior to the slurry is mixed and pumped, and it is not uncommon that the cementing engineer has different slurry candidates for selection of the final slurry [8]. The slurry used in a squeeze cementing operations normally has the following characteristics; low viscosity (so can penetrate small cracks), fluid-loss control (ensure optimal filling of cracks and perforations), appropriate cement particle size (regarding filtercake generation) and proper thickening time [8].

Squeeze cementing techniques can be divided into different methods, such as high or low pressure squeeze, different pumping techniques (running or hesitation) and applications (bradenhead or squeeze tools). Which technique that is used will depend on, among others things, what type of operation and under which conditions, this is further discussed in Section C.1 in Appendix C. The main positive and negative characteristics associated with squeeze cementing are listed in table 2.1.

Perforate, Wash and Cement (PWC)

HydraWells PWC system will be the only technology described in this document.

This is a further development of the traditional squeeze cementing operation, involving perforating, washing and cleaning the annular space then mechanically placing cement. This system has been widely used on specially NCS, HydraWell has set 205 PWC plugs to date worldwide [27]. The main application has been for P&A, but also the elimination of SCP of wells that has been set back in production or injection.

The first commercial tool from HydraWell was the HydraWash, this was a one trip system to perforate the casing, then wash and finally cement. However, due to the difficulties controlling the induced washing pressure while cleaning the annulus, the HydraHemera system is now primarily used by HydraWell. The difference lies in how the annulus is cleaned of old mud, debris and poor cement. The one trip HydraHemera system are illustrated in figure 2.13 with associated tools.

From bottom to top, the Tubing Conveyed Perforation (TCP) guns are dropped automatically after firing gaining communication to the annulus. This given that the rathole is long enough, if not a two trip system can be used. The HydraWash tool piece is set below the perforated interval to act as an internal cement foundation. Then the washing sequence using the jetting tool is performed, cleaning with high energy jets of mud (illustration provided in figure C.6a in Appendix C). Finally, a ball is dropped diverting the flow through the spray cementing tool, enabling setting a balanced cement plug while rotating the pipe. The HydraArchimedes helps to circulate and force cement in place through the perforations (before had to apply squeeze pressure). NORSOK D-010 requires each plug (primary and secondary) to be 50 m which the sealing ability needs to be assessed in a P&A scenario. HydraWell can set both 50 and 100 meters plugs in a single run.

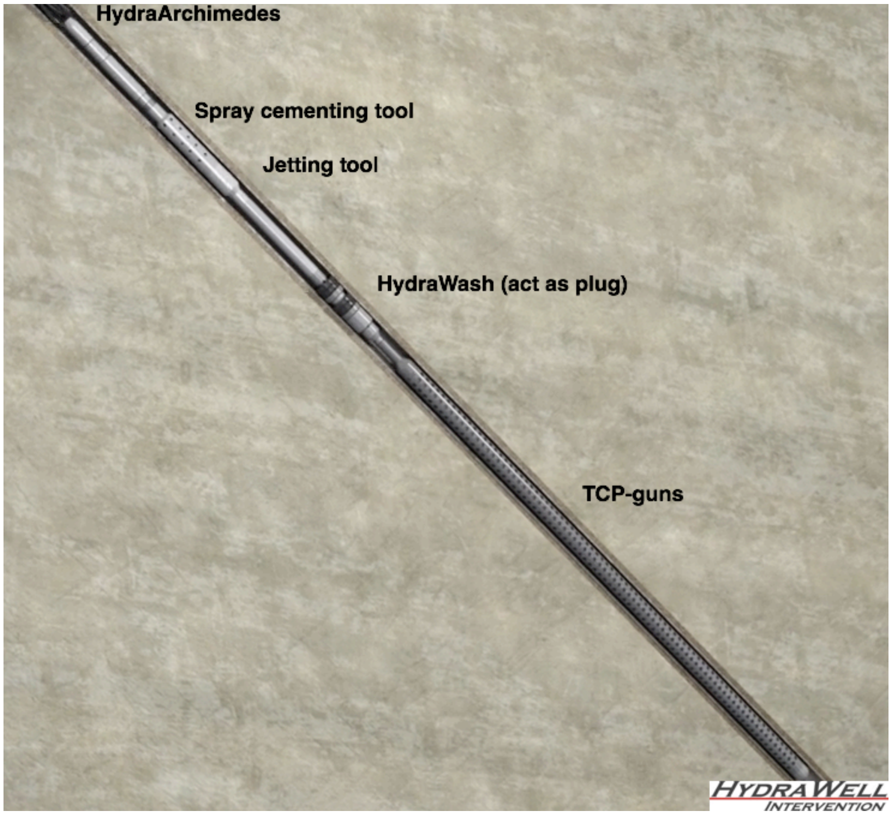


Figure 2.13: HydraWell intervention tools [26].

The USI-tool can be used for evaluation of the set cement after it has been drilled out. Appropriate times of PWC operations are given in figure 2.15, with and without verification. The different associated positive and negative characteristics are listed in table 2.1. The technology is also further discussed in Section C.2 in Appendix C for the interested reader.

Section Milling

The main goal with section milling is grinding away the casing and removing whatever old cement, cuttings or debris are present in the annulus. This is done in order to set a new cement plug and achieve a proper zonal isolation. Section milling can be utilized for the elimination of SCP in well abandonment, but also in wells that are meant to set back in production. This method is primarily a last resort for the operator companies, due to the complexity, cost and associated HSE view of the operation.

The operational steps will slightly differ if the well is to be P&A or set back in production, where a casing (or liner) needs to be run and cemented in place. The general operational steps are listed below.

1. Set a bridge plug below planned milled window
2. Section mill away the unwanted casing
3. Underream to fresh formation ("Scrape" away old cement, debris and cuttings)
4. Set cement plug over the entire cross-section of the well (or run casing/liner after bridge plug is pulled)

The "K-Master" section mill from Schlumberger is shown in figure 2.14, performing operation 2. listed above. To reduce the number of trips and enhance performance the ProMILL system has been developed, executing operations 1., 2. and 3 in a single run, potential time savings are given in figure 2.15.

Figure 2.14: K-Master Section Mill from Schlumberger [39].

The section mill removes the steel by use of multiple knives, which extends out of the tool when applied additional pumping pressure. An important part of the operation is achieving small and consistent swarf that is transported out the wellbore with correct chosen milling fluid. The milling fluid most be viscous enough for transporting the swarf out of hole, while avoiding fracturing the formation. After the casing is milled away, the underreamer scrapes away old cement, debris and cuttings, proper removal of the settled materials is crucial prior to performing a successful cementing operation. The associated positive and negative characteristics are listed in table 2.1. The operation and challenges with the technology are further discussed in Section C.3 in Appendix C.

Comparison of the Different Remedial Methods

The three discussed remedial methods all have their positive and negative characteristics, some of these are listed in table 2.1. These methods have been widely used worldwide for restoring zonal isolation integrity. They all involve larger intervention workover and uses cement as plugging material.

Table 2.1: Listed positive and negative characteristics of different remedial methods.

Method	Plugging Material	Positive	Negative
Squeeze Cementing	Cement	• Simple design and operation • Method been used for decades • Wide range of applications	• The annulus is not cleaned • Loss of casing integrity • Pressurize wellbore, closing small channels present (will not be cemented) • Locating channels present • General low success rate • Some cases not possible apply squeeze pressure due to casing integrity
PWC	Cement	• The annulus is cleaned • Field proven technology • Simple design and operation • Possible re-entry into well • Compared to section milling, no swarf generation • Verified time and cost savings in comparison to section milling	• Locating channels present • Additional time spent on verification (drill out and re-log) • Old cement and casing part of plug design • Improper cleaning of annular, will lead to contaminated cement • Pressurize wellbore, closing smaller channels present (will not be cemented)
Section Milling	Cement	• Barrier extending over entire cross-section • Improvements regarding knife longevity and combining several tools (saving time and cost) • Still method of last resort	• Swarf generation leading to pack-offs tendencies, topside handling and HSE issues • Time consuming and costly operation • Problems related to re-entry into well

Time comparison for conventional section milling, ProMILL by Schlumberger and PWC operations for one and two trips system, with and without verification for single casing are given in figure 2.15. For full information about the different operational times, see Appendix E. These times are for performed P&A operation, but the approximate same times can be expected to perform remedial repair of SCP in regards to producing or injecting well. No times has been given by Schlumberger or HydraWell creating this table, all times are approximate and deviations in positive and negative regard can be expected.

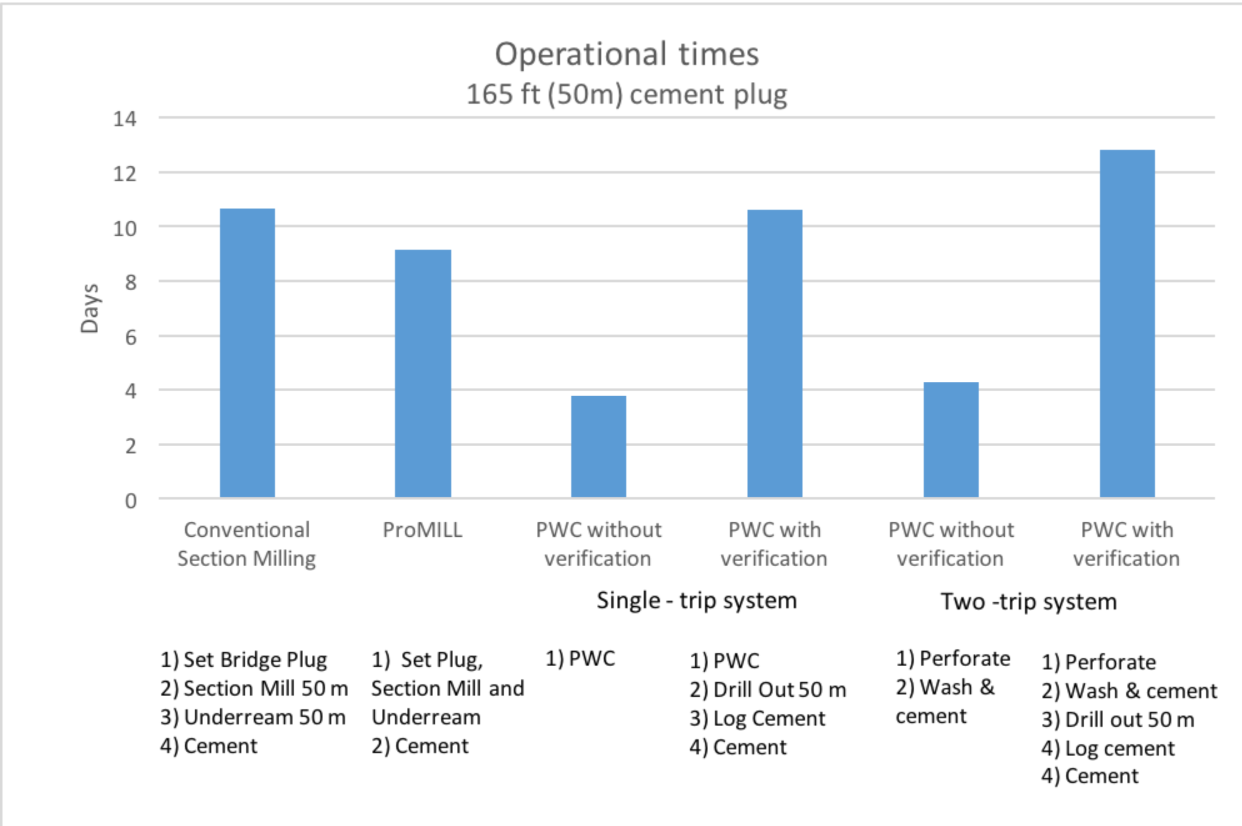


Figure 2.15: Operational times conventional section milling, ProMILL and PWC. See Appendix E for gathered operational data.

2.4 Alternative Annular Plugging Materials

The conventional Portland cement is by far the most used plugging material for achieving long term zonal isolation in petroleum wells. The use of cement is both cheap and the industry has extensive experience with the material. The system does present a challenge achieving long-term zonal isolation, due to the several causes leading to cement failure discussed in Section 2.1. There is no direct alternative competing with cement both on price and its mechanical properties. A thermosetting polymer system does address many of the limitations experienced with the cementing system. Therefore, the success rate for achieving long-term integrity in regards to fluid migration could be enhanced by either used as a standalone plugging material or in combination with the cementing system.

2.4.1 Thermoset Polymer

The remedial plugging material that is being used in tests for the elimination of fluid migration in this thesis is a two component epoxy resin, one type of thermoset polymer. In contrast to cement which transforms from a liquid to solid through a hydration process, a thermoset phase change is due polymerization. Polymerization is a chemical reaction binding single molecules together forming long chains (e.g. a polymer).

The advantage related to the curing process of a thermoset polymer compared to cement is that curing is thermally activated and thereby the curing time can be controlled. The rate of curing can be controlled by temperature, proper choice of curing agent and for selected systems by optimizing the concentration of curing agent.

The epoxy resin can operate under different stress and environmental conditions. Various additives can be added to the resin for achieving certain mechanical properties, such as flexibiliers and fillers. The resin system can be designed having higher compressive and tensile strength and lower Young's modulus and are therefore better suited for higher stress conditions than conventional cement. In addition, having higher adhesion to other materials (oil- or water-wet surfaces), lower permeability and porosity, reduced shrinkage while curing and increased resistance against contamination than cement.

2.4.2 Isolation Scanner Test with CannSeal Resin

The following tests were performed by Schlumberger on behalf of Mærsk. The test was part of a qualification project between Mærsk and CannSeal and the report was provided by Mærsk so it could be included into this thesis.

Isolation Scanner tests have been performed on three different resins system under surface conditions. The main objective was to evaluate the verification potential of placed resin in the open annulus with the newest technology within acoustic tools. Three resin systems was tested, all having the same resin base but mixed with different degree of gravel (0%, 20% and 40%). The mixed gravel had as objective to increase the density thereby the acoustic impedance, for easier distinguishing from liquid (water). The Isolation Scanner gives a 360° coverage with ultrasonic and flexural waves, enabling acoustic impedance measurements and cross-plot of flexural attenuation versus acoustic impedance to separate liquids from solids. Lab tests with ultrasonic transducer was also performed for comparing the acoustic impedance to the Isolation Scanner results.

Test Set-Up

The three different resin systems were placed between a 7" (29#) casing and 8.75" ID PVC tube, shown in figure 2.16. The annulus was filled with 75% resin and 25% water, this in order to have a measurement of both for comparison (if could be distinguished). The Isolation Scanner was then placed inside the test set-up for performing measurements.

Lab acoustic measurements of the resin were also conducted, for comparison to the Isolation Scanner measurements. This experimental set-up is given in figure 2.17a, showing all the components used. The samples had a transducer placed on both sides, for emitting and receiving ultrasonic waves. The measurements obtained from this test was the compressional (v_p) and shear (v_s) velocity, density and the acoustic impedance. The resin samples are shown in figure 2.17b.

Pure resin (no gravel) Resin mixed with 20% gravel Resin mixed with 40% gravel. Resin not filled all the way up

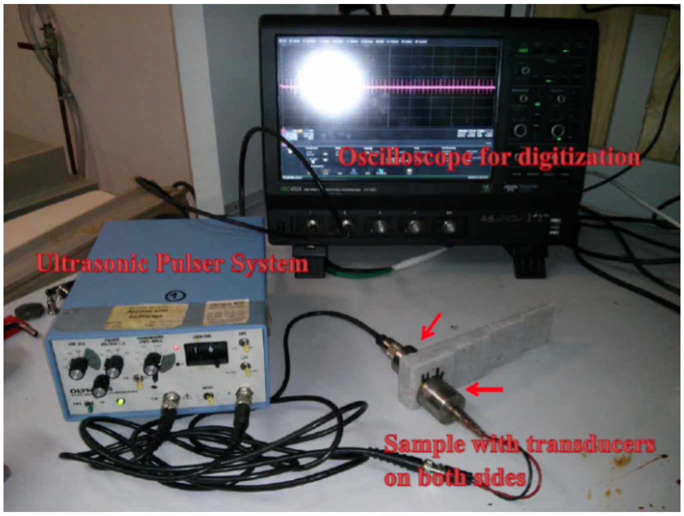
Figure 2.16: Showing the three different annular filled with different resin systems. Courtesy of Schlumberger.

Results Isolation Scanner

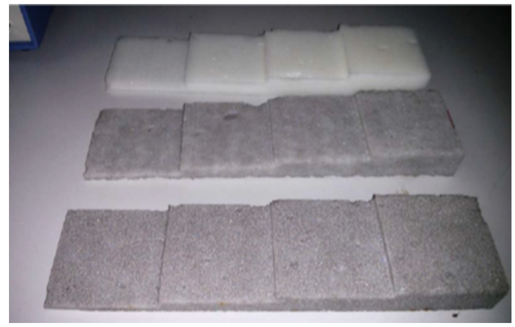
The results from the Isolation Scanner are provided in figure 2.18, of main interest, are the SLG map and cross-plot between flexural attenuation and acoustic impedance. As this can be used to separate between the water and the low-density resins.

The tool provides a 360° coverage of the casing-resin interface, this can be seen on the evaluation results in figure 2.18. As 75% of the cross-section was filled with resin (higher impedance) and 25% with water (lower impedance), this corresponds on all logs for the different resins. Figure 2.18a gives the result for the pure resin (no gravel). The SLG shows a distinct separation between the water and resin present in the annulus. The cross-plot also provides two distinct clouds. On the lower left is the water present and upper right is the resin, which has both higher flexural attenuation and acoustic impedance than the water. Interpreting the logs clearly shows the Isolation Scanner can give a bond evaluation of the placed low-density resin.

Same trends are also observed on the resin mixed with 20% and 40% gravel. The clouds on the cross-plot for the resin moves a little further to the right (higher acoustic impedance), which match that are higher density mediums than the pure resin. The logs provided in figure 2.18c, shows that for the 40% mixed gravel with resin, the responses are poorer than for the other two tests. This can be a result of poorer distribution of the resin in annulus, that not properly in contact with the casing.

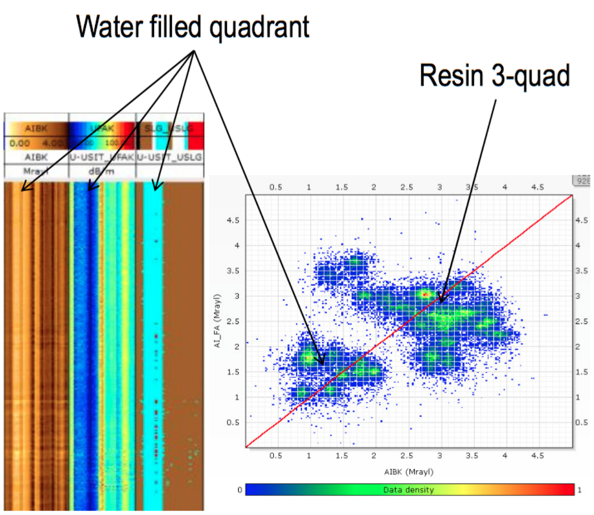


(a) Experimental set-up for lab-testing.

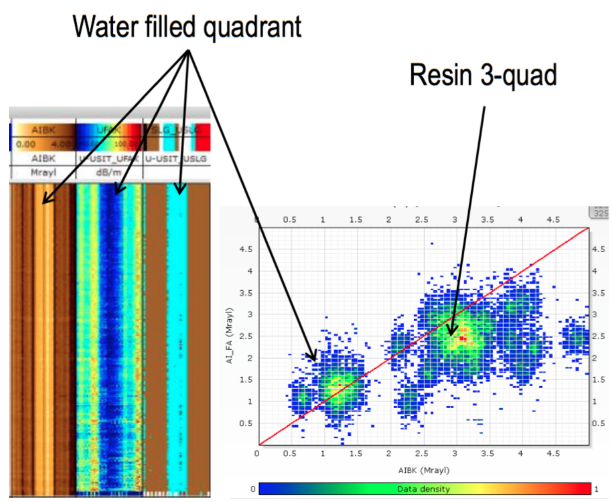


(b) Resin samples.

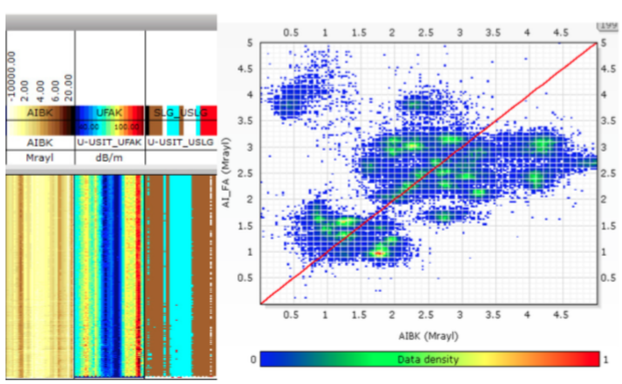
Figure 2.17: Lab acoustic measurement set-up. Courtesy of Schlumberger.



(a) Pure resin sample



(b) Resin mixed with 20% gravel.



(c) Resin mixed with 40% gravel.

Figure 2.18: The Isolation Scanner test results for the three different resin systems. The logs are showing the measured acoustic impedance, SLG map and cross-plot between flexural attenuation and acoustic impedance. Courtesy of Schlumberger.

Lab Acoustic Measurements Results

The lab acoustic measurements results and those obtained from the Isolation Scanner for comparison are provided in table 2.2.

Table 2.2: Lab acoustic measurements results and Isolation Scanner results on the different resins. Courtesy of Schlumberger.

Resin type	Lab results				Log results
	Vp [m/s]	Vs [m/s]	Dens, [kg/m3]	Zp, [MRayl]	Zp, [MRayl]
Pure resin	2212	1140	1012	2.3	~2.5
Mixed w. 20% gravel	2226	1170	1152	2.6	~2.5
Mixed w. 40% gravel	1146	1196	1336	3	~2.8

Conclusions

These in-house tests confirmed the feasibility of utilizing the Isolation Scanner for CannSeal resin bond evaluation under surface conditions. Is should be noted that these tests do not exactly represent downhole well conditions (different temperature and pressure). The resin in these tests was also carefully placed around the casing, for placement in a real well scenario this would be with the CannSeal tool.

The potential for utilizing acoustic tools for verification of injected resin into a cemented annulus will be discussed in Section 5.4.

2.5 The CannSeal Deployment System

CannSeal is a new technology run on electrical wireline that can inject a thermoset polymer into the annulus for zonal isolation purposes. This is done a one trip system, where the resin is brought downhole in a sealed canister, tool schematic is provided in figure 2.20. When at well-target, the tool perforates the casing, the seal around the perforated area for then to inject the resin (sealant) into the annulus. The resin can be tailored to fit different purposes, for example a high viscosity resin for sealing in an open annulus or an Ultra Low Viscous (ULV) resin for injection into a cemented region.

The previous sections has discussed among other things the available technologies for remedial repair in relations to SCP. The following chapters will describe the functions of the CannSeal technology and how it potentially can be used to seal off a poorly cemented annulus.

The main applications of the CannSeal technology related to P&A activities are listed below.

- Mitigating SCP in cemented annulus
- Annular support for circulating in cement, ThermaSet or similar placement.
- Place annulus plugs on top of reservoir.

[12]

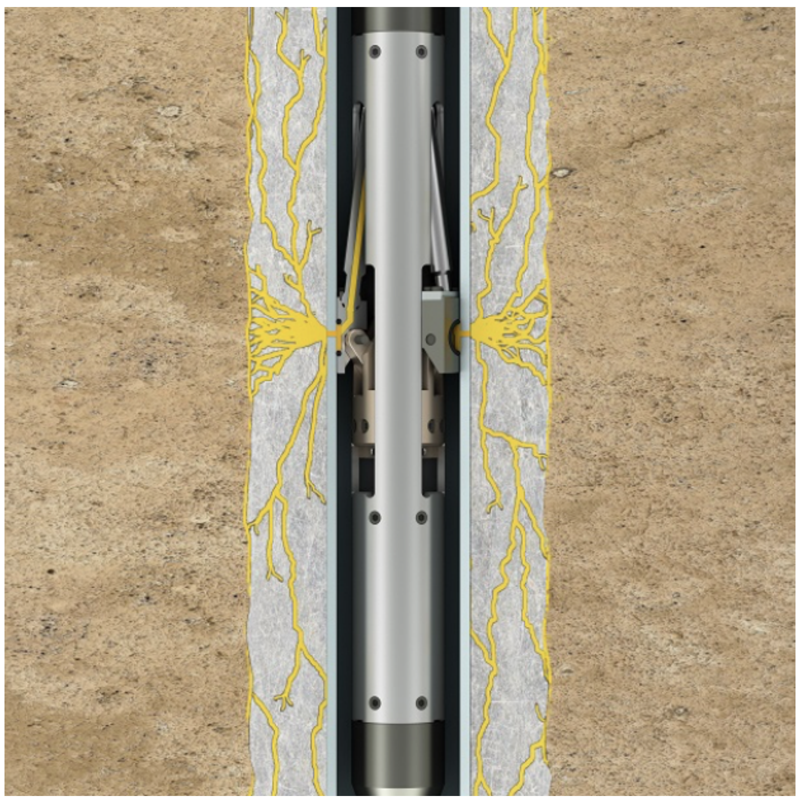


Figure 2.19: CannSeal remedial microannuli repair [12].

An illustrative sketch of microannulus repair with the CannSeal technology using a ULV-epoxy resin is shown in figure 2.19.

2.5.1 Operation Steps for Performing Remedial Repair of Cement

The main operational steps for placing a resin into the annulus using the CannSeal tool are listed below, with a full tool-schematic illustrated in figure 2.20.

1. Set the anchor against the inner pipe
2. Stroke up for placing the perforation assembly over desired shooting interval
3. Perforate
4. Stroke down to place the injection tool over the perforations
5. Inject resin into the annulus

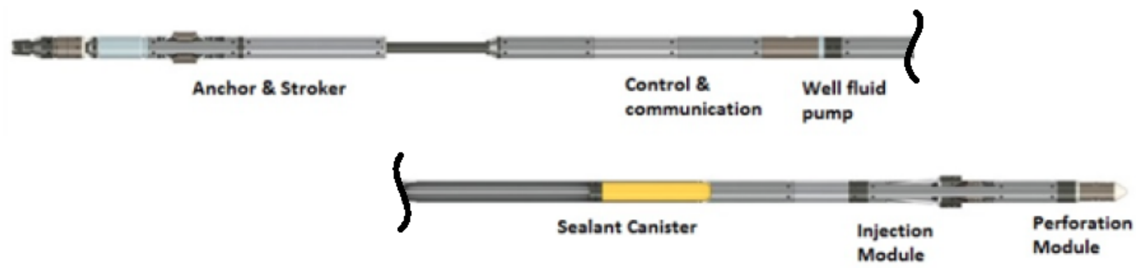
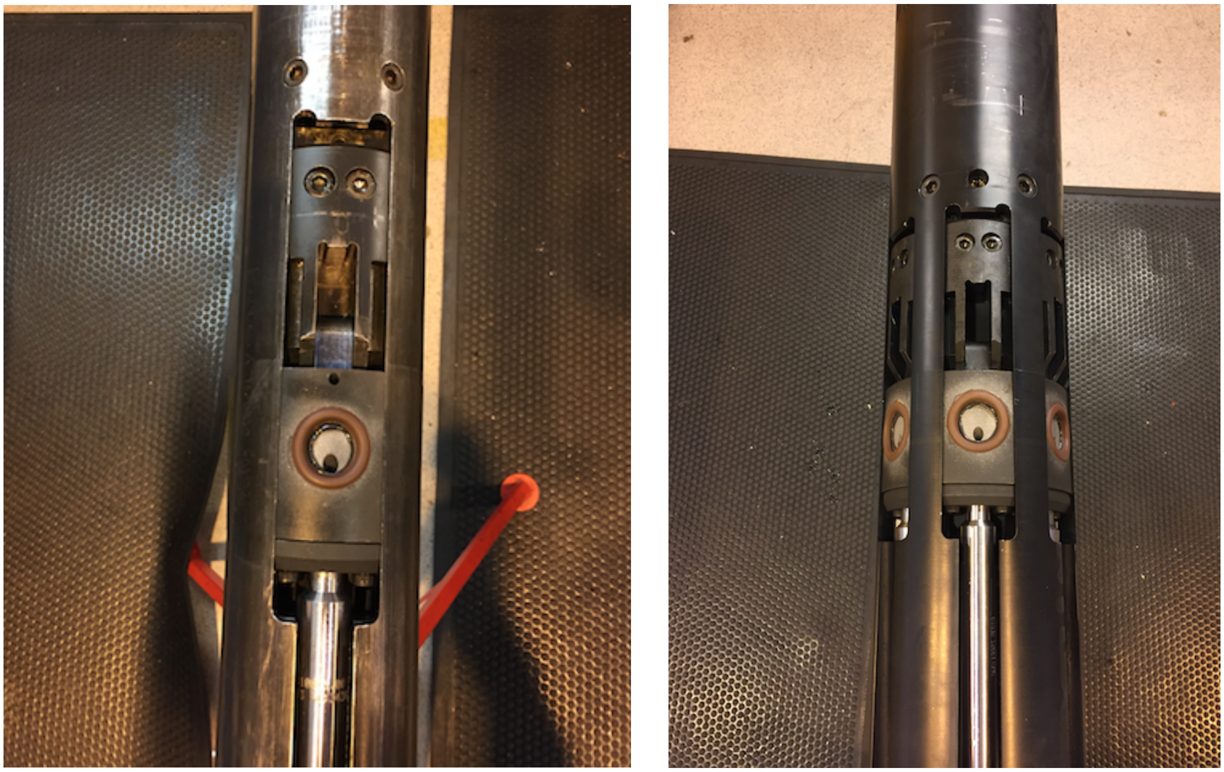


Figure 2.20: The CannSeal tool [13].

The CannSeal tool can either be run with a three or six shot perforation and injection modules, depending on what type of operation will be performed.

Both the three- and six pads injection module can be used for pumping epoxy resin into the annulus, shown in figure 2.21. For the three pads system, there is one pad every 120 °, which is the traditional module for injection epoxy resin into an open annulus. However, when the annulus is cemented, having more pads gives greater access to the cross-section and increases the chance for locating all channels, voids or microannulus(es) that may be present. The newly developed six pads system is developed to resolve this issue, having one pad every 60 °.



(a) Three pads injection module. (b) Six pads injection module.

Figure 2.21: Showing the two different pads systems, one pad every 120° or 60° respectively.

Figure 2.22 is provided to give a better view of a perforated annulus between two well-cemented pipes. This is a 4-1/2" pipe cemented concentrically in a 7" pipe, where a three shot perforation module was deployed. Figure 2.21a clearly shows that perforations penetrated the inner pipe and cement, while figure 2.21b shows that stopped in the outer pipe. When injecting the resin, based on visual interpretation of these photos, there should be good communication the potential migration paths present against the outer pipe.

(a) Showing perforation through the cement.

(b) Perforated 4-1/2" pipe and cement interface.

Figure 2.22: Perforated cemented annulus between 4-1/2" and 7" pipe.

Chapter 3

Method and Experimental Details

This chapter addresses the choice of method for evaluating the injecting and sealing ability of an Ultra Low Viscosity (ULV)-epoxy resin into a "leaking" cement annulus. Each main constitute of the experimental details will be discussed, including technical drawings, illustrations and photos with associated descriptions for giving an understanding of each aspect of the tests.

3.1 Method

There are several steps which need to be performed when qualifying a product to do a specific operation downhole. The CannSeal technology has been qualified and performed operations with regards to injecting a resin for sealing in an open annulus. The overall aim of this master thesis is to test the potential for sealing off microannulus (or smaller channels) by a resin type sealant using the CannSeal tool in a large scale testing scenario.

The alternative sealing material used in all of the following tests is a ULV-epoxy resin developed specifically for injection into narrow channels by CannSeal, which for simplicity reason will be referred to as a resin (or simply sealant). The resin characteristics and rheological properties will be discussed.

Both the choice of design and test procedure does to a certain extent overlap each other, but in order to have a neat overview, they have been separated.

3.1.1 Choice of Test Set-Up

There are several factors that can lead to cement losing its integrity, the main constitutes were covered in Section 2.1. The state of the annulus will to some extent be unknown, even after evaluation with diagnostic methods such as acoustic tools. Migration can occur through smaller or larger channels, present at formation (or casing)-cement-casing interfaces or within the cement sheath itself. All of these factors (and many others) cannot be taken into account when performing testing for remedial repair with sealing materials and placement methods.

The following choice of set-up for the cemented annulus is to have the annulus cement condition as similar as possible for the different cells, illustrated in figure 3.1. Therefore, all cells need to be cemented following the same procedure, both regarding cement composition (Class G) and placement method (full procedure described in Section 3.3). In order to have comparable results of gas leak rates prior and after resin injection for sealing. There will always be both physical and human factors that prevent the set cement to be identical, this needs to be accounted for. In comparison to an actually cemented annulus in a petroleum well, the test-cells will have a "perfect" cement condition (will be referred to as "well-cemented"). By that, no other fluids than air were present while cementing, cells were concentrically orientated, the cement was properly displaced around the tubular and was set to cure over an appropriate time to develop sufficient strength.

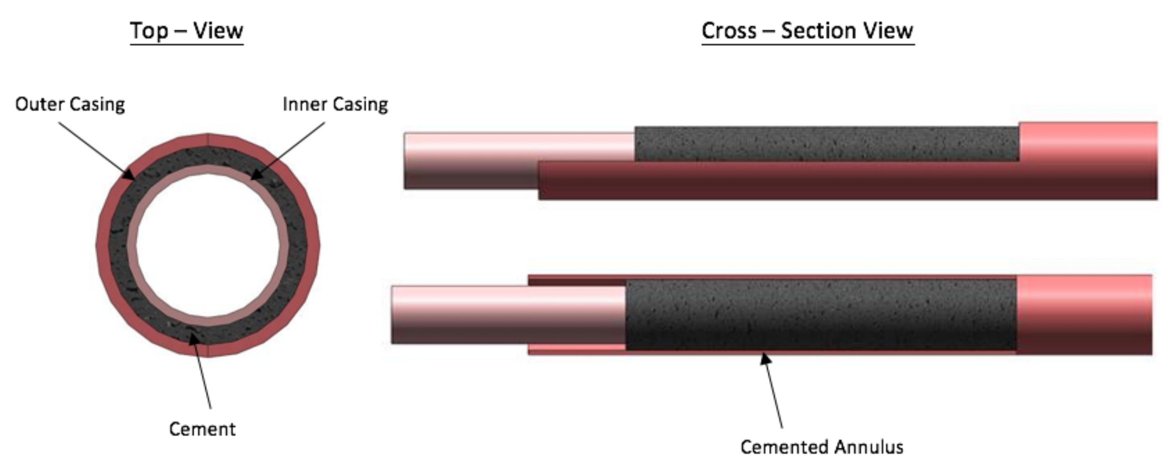


Figure 3.1: Illustrating a top and cross-sectional view of a cemented annulus.

The main objective with the designed dimensions is listed below, and overview is given in table 3.1.

- Perform large scale testing, e.g. bigger casing sizes and lengths to replicate injection and sealing area to downhole dimensions.

For cells one and two, these are not geometrically downscaled to fit any general case, but designed to get an understanding and knowledge when injecting a resin for sealing into a "well-cemented" annulus. The chosen design for cells three and four are to best replica downhole dimensions.

Table 3.1: Overview of the four tests, including size, injection points and injection method.

Cell Number	Size	Injection Points	Injection Method
1	4.5" – 7"	3	Manifold
2	4.5" – 7"	3	CannSeal Tool
3	7" – 9.625"	6	Manifold
4	7" – 9.625"	6	CannSeal Tool

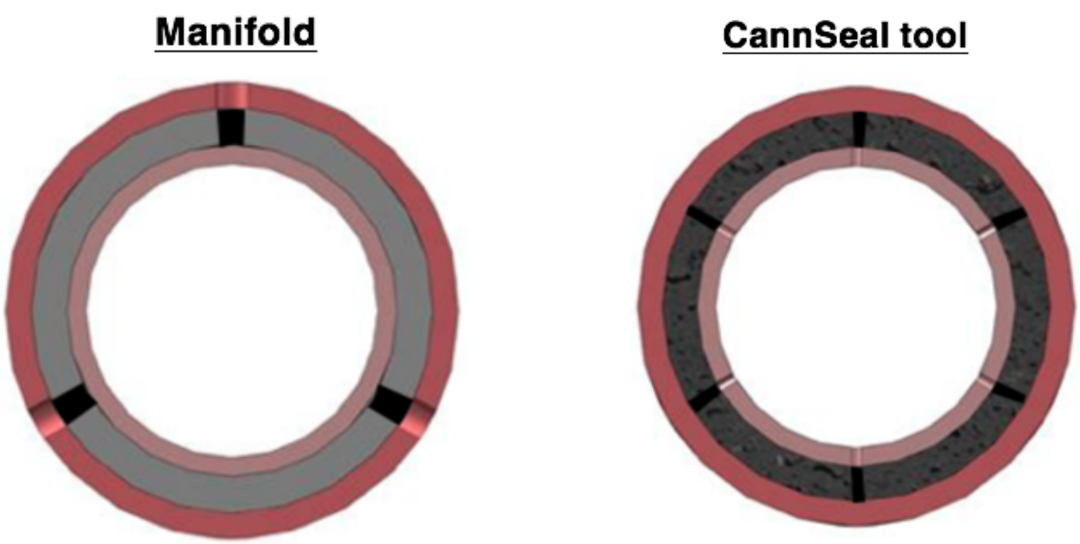
These large-scale cells will be constructed to understand the wide range of factors coming into play when injecting a resin for sealing into a "well-cemented" annulus. Among them, the cross-sectional area and cement lengths the resin needs to "cover" in order to access whatever microannulus, channels or voids that are present. Considering the main factors contributing to leak-paths, for this case, this will most likely be due to cement debonding between cement-casing interfaces as a result of bulk shrinkage of the cement and/or poor shear bonding to the casing. What needs to be taken into consideration when pressure testing with both gas and water, is that ballooning of the pipe will occur and this will affect the recorded leak rates. Extensive pressure-cycling will provoke additional debonding of the cement and lead to a poorer cement integrity.

3.1.2 Choice of Test Procedure

The main objectives behind the choice of test-procedure are listed below.

- Compare injection of the resin with the outside manifold versus CannSeal tool with three and six injection points.
- Test the injectivity of the resin into a "well-cemented" annulus and its potential sealing of microannulus (or smaller channels) in regards to fluid migration (specially gas).
- Perform pressure tests with both gas and water prior and after injection of the resin.

When injecting from the manifold, the resin has direct access to the annulus, while the CannSeal tool first need to perforate the inner pipe and place pads for injecting,both methods are illustrated in 3.2.This difference needs to be accessed and comparison of results will be performed, in order to establish if oppose any challenges. There will also be conducted injection from three and six points. With additional injection points, the resin will have greater access to the cross-section of the annulus which should give better distribution of the resin. However, when injecting with six points the cross-sectional area of cells three and four are also larger.



(a) Three pre-drilled holes.

(b) Six perforations.

Figure 3.2: Showing the schematic for injection from the outside manifold and with the CannSeal tool, same principle for six pre-drilled holes and three perforations.

The resin will be injected into very narrow gaps, this will set a restriction of the viscosity (μ) before the resin is un-pumpable (viscosity versus time for this resin, see figure 3.13). The CannSeal tool can deliver a maximum pumping pressure of 200 bar. The moment the hardener and accelerator are added, the epoxy resin will start to build viscosity as a result of polymerization until gel point is reached. This puts a limited time window for injection, but this development is favorable in-comparison to a thermoset polymer which sets radically (builds viscosity almost instantly at a given temperature) for injection into narrow channels for this application. For a known range of operating temperatures, the curing and development of viscosity has been identified by previously measurements. Therefore, as the viscosity builds under isothermal conditions, the injection rate can be controlled by monitoring the injection pressure. Letting the resin cure under elevated pressures will most likely increase its sealing ability. For these tests, its expected that will lead to small local ballooning effects of the casing when high pressure are applied. When the resin transitions from liquid to a solid, the casing may contract against the cured resin and expectantly creating a competent seal. The resin also has a great adhesion to both casing and cement, enabling good shear bonding.

The cells needs to be pressure tested both prior and after injection of the resin, in order to evaluate the sealing ability. The main issue regarding SCP and loss of cement integrity is the migration of gas, which can lead to extensive pressure build-up. Consequently, the main objective is to minimize this gas flow/migration through the annulus by placing the resin in the previously discussed preferred leak-paths. Pressure sensors will be placed in the bottom, middle and top of the cells in order to monitor the pressure regimes when testing and injecting the resin.

3.1.3 Validation of Chosen Method

The state of the annulus for each petroleum well will to some extent be unique, because of the many previously mentioned factors contributing to damage of the cement sheath. One should be very careful to generalize results, that applies to all research/testing, generalizing is therefore not an objective with the following tests. As four tests is not sufficient to provide a sample that statistically represents the whole population in question. Since the exact same method used is not systematically repeated, meaning some variables will be changed for each test, it would not be economically viable performing several tests for each method to get a statistically basis.

Nevertheless, by the following tests performed, these should get a good idea of the potential using a resin for sealing against gas migration with an alternative placement method for a "well-cemented" annulus.

The resin (ULV-epoxy) used in these tests is specifically tailored to enter very narrow channels for sealing. The resin can also be tailored to applications involving larger channels, using higher viscosities, and the appropriate curing rate can be increased by adding accelerators if necessary. Different additives such as flexibilisers or fibers can be used to adjust flexibility and strength respectively. In addition, strength of the resin can be increased by post-curing. That is, subjecting the resin to higher temperatures for achieving higher conversion rates (number of cross-links). For isothermal curing around 40-70% conversion is reached, with post-curing about 70-90% is accomplished (CannSeal has developed such a heating tool). This could be used in specific cases where additional mechanical strength are required.

Even though testing is performed for a specific case, which could be viewed as a "worst case", sealing and attaining improved results for "well-cemented" annulus is harder than for a poorly cemented one. The tests is planned and will be performed in such a way that results will contain viable information about the potential for success of the CannSeal tool and the resin system for a well-scenario. This including answering questions about the movement of resin in the cells (both radial and axially), if able to perforate and inject with CannSeal tool, sealing ability of the resin for the different injection methods.

3.2 Design of Set-Up

The design of the set-up will be presented in greater detail, including technical drawings and descriptions.

3.2.1 Cell 1

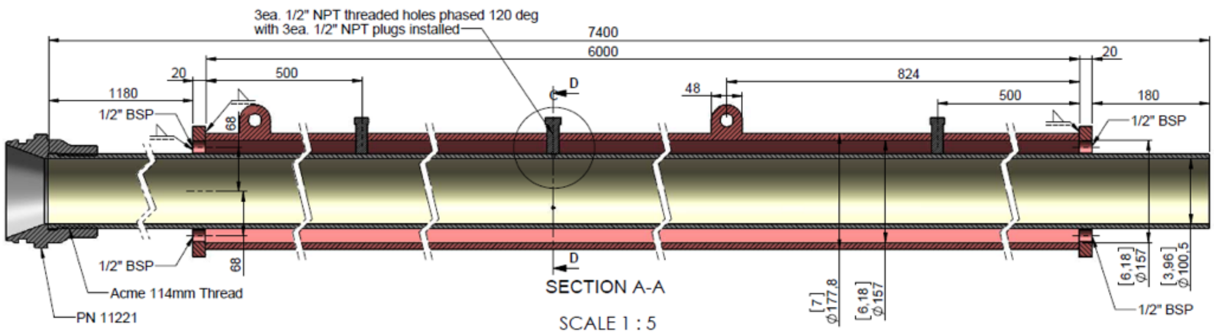
The cell consist of a 4-1/2" pipe cemented concentrically in a 7" pipe. The pipes were welded together in the bottom and top, in order to have an isolated system. A single hole was drilled in the welded part in the bottom and top, in order to install valves and pressure gauges. In the center of the cell, three holes were drilled, technical drawings for cell one are provided in figures 3.3a and 3.3b. Figure 3.3b illustrates the center of the cell, clearly showing the previously discussed injection points. Here the bolts was removed after cementing, in order to inject the resin from the outside manifold. Set-screws was also installed in the center of the inner pipe, in retrospect this should not been part of the original design, the pre-drilled holes created leak-paths and needed to be isolated. Two drilled holes in outer pipe was made for pumping in cement, also shown in figure 3.3a. Table 3.2 gives the dimensions of cells one and two. The 7" and 4-1/2" pipes has weights 29 $\frac{lbm}{ft}$ and 12.6 $\frac{lbm}{ft}$ respectively. The casing grade used for all test cells were L-80.

Table 3.2: Dimensions of cells one and two.

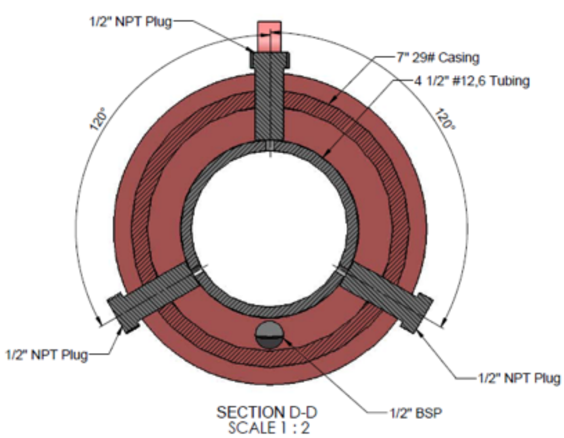
Outer Pipe OD and ID [Inches]	**Inner Pipe OD** [Inches]	**Annular Thickness of Cement** [Inches / meter]	**Lengths Outer and Inner pipe** [meter]
7 / 6.184	4.5	0.842 / 0.0214	7.4 / 6

3.2.2 Cell 2

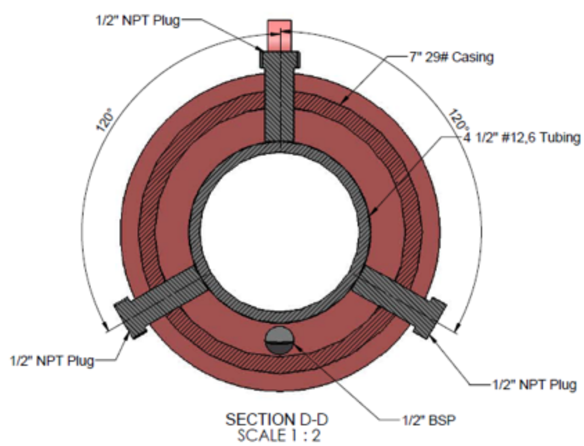
Cell two has the same dimensions as cell one, the difference between the two is illustrated in figure 3.3c. There was not pre-drilled any holes in the inner-pipe for cell two. Injection of the resin was done with the CannSeal tool. In order to best understand the distribution when injecting the resin throughout the cross-section and length, three pre-drilled holes in the outer pipe was part of the design. The pre-drilled holes had bolts installed that was removed after the cementing operation, in order to monitor the pressure.



(a) Horizontal view of both test-cells.



(b) Cell one with installed set-screws.



(c) Cell two without set-screws.

Figure 3.3: Technical drawings of cells one and two. Courtesy of CannSeal.

3.2.3 Cell 3

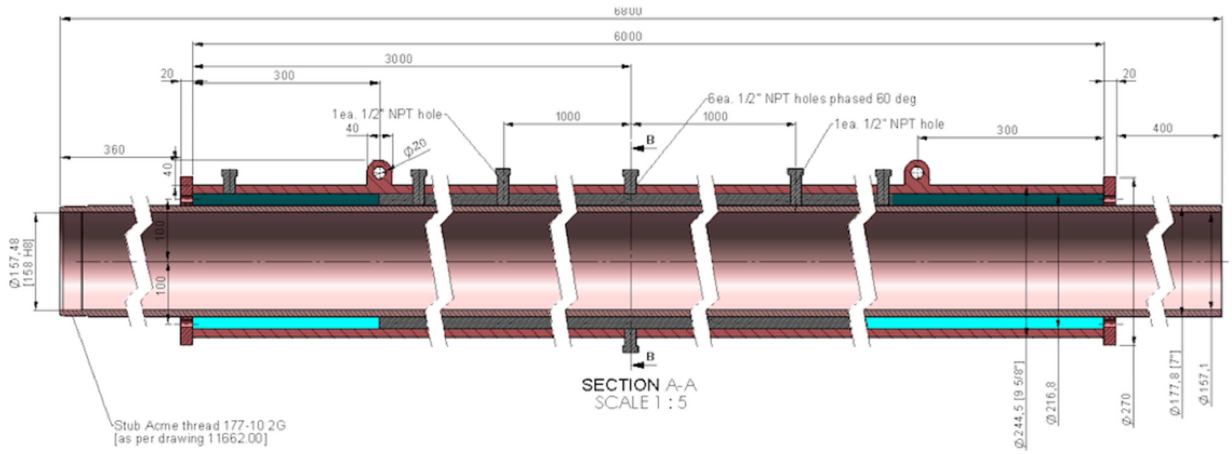
The main difference compared to cells one and two was summarized in table 3.1, which is the different dimensions and number of injection points. Cell three consist of a 7" pipe cemented concentrically in a 9-5/8" pipe. Having six injection points in the center, illustrated in figure 3.4b, the plugs in the center was removed after cementing in order to have pressure communication between the outer and inner pipe. For injection an outside manifold was installed, photo given in figure F.1b. This cell had no set-screws as cell one, but had the two drilled holes enabling pumping of cement in the annulus. Table 3.3 gives the dimensions of cell three and four. The 9-5/8" and 7" pipes had weights of 53.5 $\frac{lbm}{ft}$ and 29 $\frac{lbm}{ft}$ respectively.

Table 3.3: Dimensions of cells three and four.

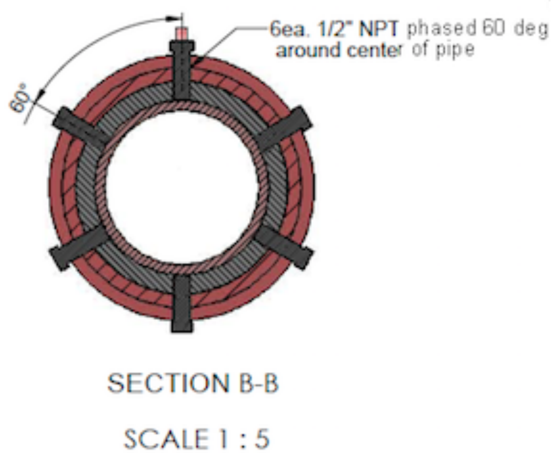
Outer Pipe OD and ID [Inches]	**Inner Pipe OD** [Inches]	**Annular Thickness of Cement** [Inches / meter]	**Lengths Outer and Inner pipe** [meter]
9.625 / 8.535	7	0.7675 / 0.0195	6.8 / 6

3.2.4 Cell 4

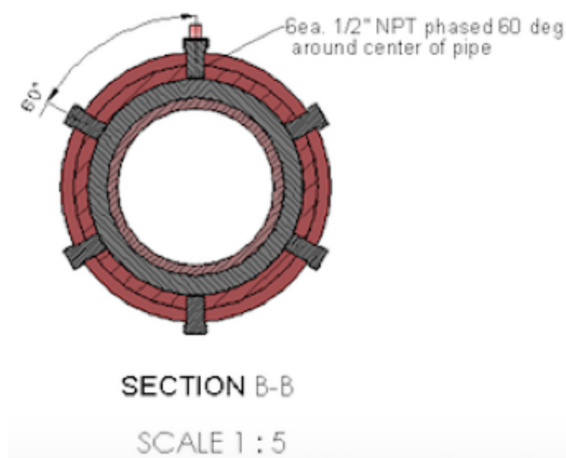
Has the same dimensions as cell three, the difference is that resin was injected from the CannSeal tool. Hence, was not installed plugs in the center of the cell, this is illustrated in figure 3.4c.



(a) Horizontal view of both test-cells.



(b) Cross-section in center for cell three.



(c) Cross-section in center for cell four.

Figure 3.4: Technical drawings of cells three and four. Courtesy of CannSeal.

3.3 Cementing Procedure

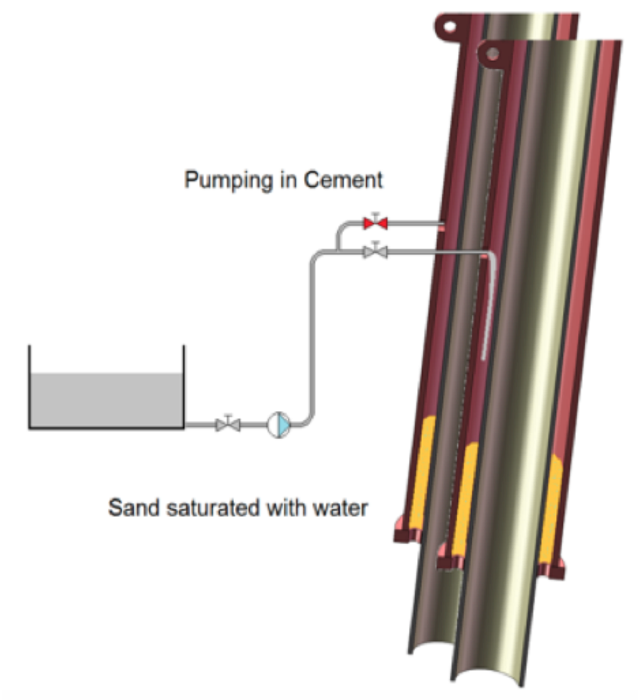
All cells were cemented with API Class G cement from Norcem. The cementing procedure followed is listed below.

1. For avoiding cementing the whole bottom of the cell, the cells were first filled with some water-saturated sand and a small amount of cement was placed above the sand. This little amount of cement was cured prior to filling the remaining cement slurry.
2. The cement was mixed together with a 0.44 water/cement ratio using a paddle-mixer in a

container.

3. The cement slurry was then pumped into the cells using a diaphram pump, illustrated in figure 5.1a.
4. The cells were lifted vertically before the cement was pumped, the pressure was increased from the top to 7 bar (with water) and cured for a minimum five days.

Before any of these activities were carried out, the safety data sheet provided by Norcem [4] was carefully reviewed and followed by involved personnel.



(a) Illustration of set up for filling of cement slurry.

(b) Photo of cells 1 and 2 prior to filling.

Figure 3.5: Filling cells with cement slurry.

As previously discussed in Subsection 3.1.1, this cementing operation does not replica down-hole conditions. This cementing operation is referred to as "dry", meaning only air was present during placement of the slurry. This gives maximum density difference to the slurry, providing good distribution and bonding to the tubulars. The cement was cured under 7 bar applied from the top with water, compressing air present and minimizing air-pockets/voids in the cement sheath.

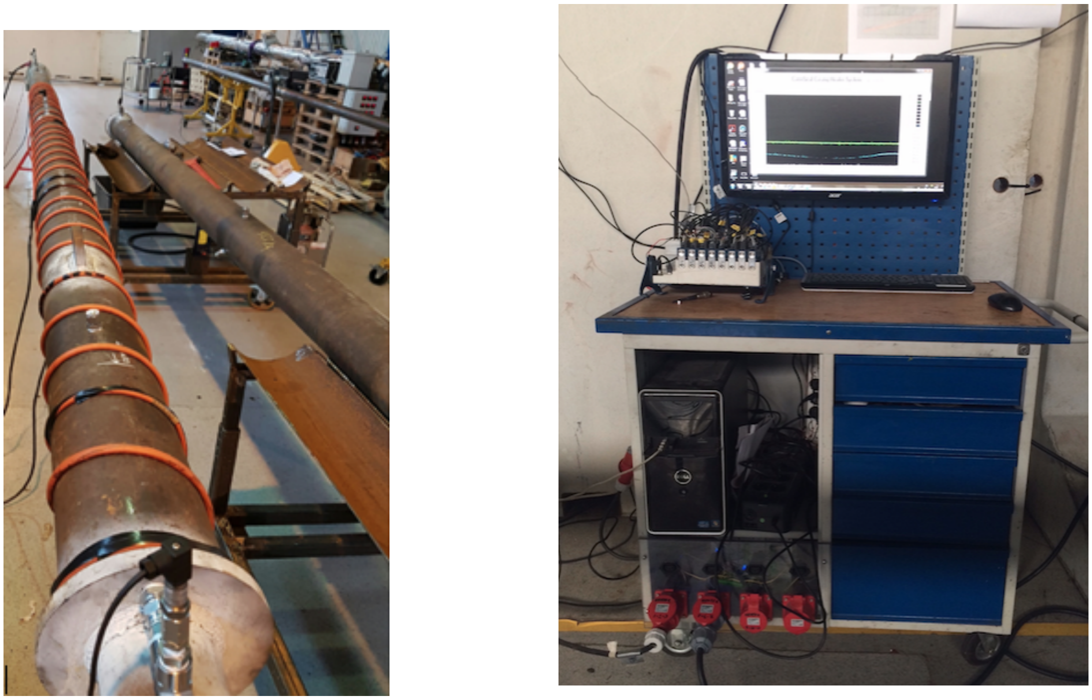
Table 3.4: Calculation of Non-Cemented Lengths.

Cell number	Bottom of cell (From bottom of cement to end flange) Volume/length (Theoretical/Calculated)	Top of Cell (From top of cement to end flange) Volume/length (Measured)	Effective Annular Cement Length
1	1.8 L / 0.197 m	3.47 L / 0,38 m	5.42 m
2	1.8 L / 0.197 m	4.29 L / 0.47 m	5.33 m
3	3.23 L / 0.3 m	10 L / 0.83 m	4.87 m
4	3.23 L / 0.3 m	10 L / 0.83 m	4.87 m

3.4 Instrumentation

The cells were instrumented with heating cables from bottom to top shown in figure 3.6a. This enables heating the specimens (casings and cement) to a predetermined temperature, which were 30 °C for all cells. The temperature and pressure data was monitored and controlled from the panel shown in figure 3.6b. After heating cables were installed, isolation and protective foil was wrapped around the cells for reducing heat loss to the cooler surroundings, shown in figure 3.7.

For cells one and three an outside manifold was installed for injection of the resin, photos are provided in Appendix F in figure F.1. Pressure sensors were installed for all cells, this in order to take proper build-up rates when pressurizing and monitor injection pressures. For cells two and four, additional sensors was added to better monitor distribution of the resin when using the CannSeal tool.



(a) Instrumenting cells with heating cables.

(b) Panel used for monitoring and controlling pressure and temperature data.

Figure 3.6: Instrumentation of testing cells.

Figure 3.7: Photo of cell one.

3.5 Pressure and Leak Testing

Pressure and leak tests was be performed prior and after injection of the resin. The basic set-up is almost identical for all cells, illustration given in figure 3.8. The main difference is that cell four was not able to pressurize from the center (see figure 3.4c). Pressure manifolds and sensors were mainly installed in the bottom, middle and top (P_B, P_M and P_T). These notations are used to refer to a position on the cell. For example, applying pressure on P_B, implies pressurizing from the bottom.

For the tests, a 50 liter nitrogen tank was used with initial pressure of 250 bar for the gas tests. The water was pumped and pressurized using a conventional piston pump from a tank which the water was pre-heated to 30°C.

General Pressure and Leak Test Procedure

1. Apply gas pressure at P_B. Note breakthrough pressures for observed gas at P_T.
2. Take leak tests at P_T (under ambient conditions) for different applied pressures at P_B.
3. Perform same tests above, when testing from P_M. That is, apply pressures at P_M and observe, monitor and perform leak tests at P_B and P_T.
4. Perform the same steps when pressurizing and testing with water.

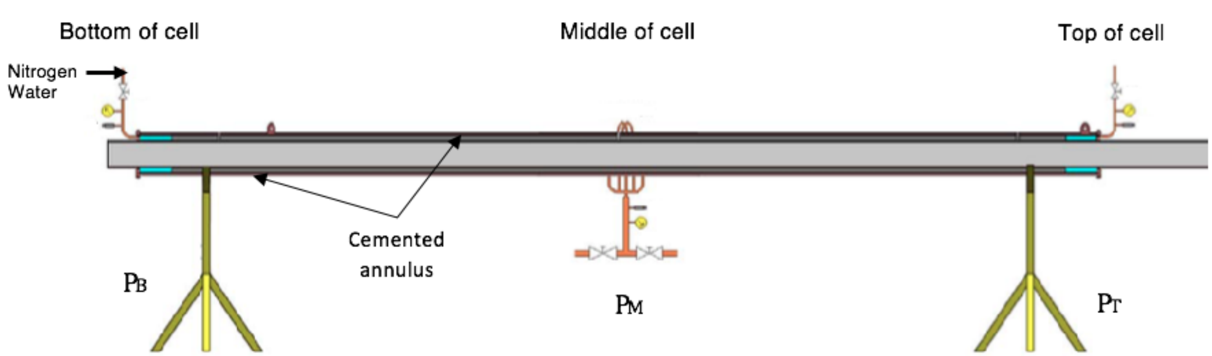


Figure 3.8: Generalized illustration showing the placement of pressure sensors and valves.

The general testing procedure after injection is the same with only a few minor exceptions. For the two cells injecting with the manifold, the injection was done from the center. Hence after the sealant had cured could not pressurize or observe pressures at P_M. The leak tests was then only performed at P_T while pressurizing from P_B. Cell four did not have preinstalled plugs in the center enabling monitoring of pressure while leak testing. This lead to only pressurizing from P_B and record leak rates at P_T.

All testing was performed in a safe area, protected with concrete blocks and non-involved personnel were not allowed to enter. Before initial testing, the whole system was pressure tested to 250 bar, which was not exceeded during the later testing stages.

3.5.1 Measurement of Leak Rates

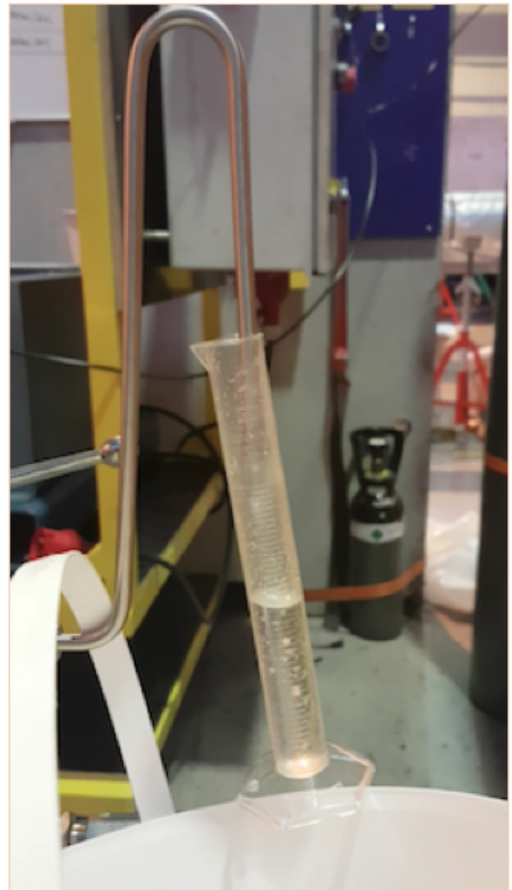
The basic measurement set-up for estimating leak rates of gas and water are shown in figure 3.9. Different measuring cups can be selected to estimate the amount of fluids that are able to flow through the cell at different applied differential pressures.

To measure the leak rate of gas, the measuring cup was initially filled with water and turned upside down in the basin, as shown in figure 3.9a. When the timer starts the hose from the outlet of the cell was led into the cup, then the gas replaces the water and the rate could be estimated. There are several uncertainties related to these measurements, the objective is to detect and monitor trend differences before and after injection of the resin, exact accuracy is therefore not essential.

3.5.2 Monitoring of Pressure

The pressure sensors installed on the cells could be monitored and recorded, a screenshot of the software is given in figure 3.10. The recorded data could be saved as an Excel file, enabling easier processing of the collected data. The same sotfware controlled the temperature of the heating cables.

(a) Gas leaking measurement.



(b) Water leaking measurement.

Figure 3.9: Measurement set-up of leak rates.

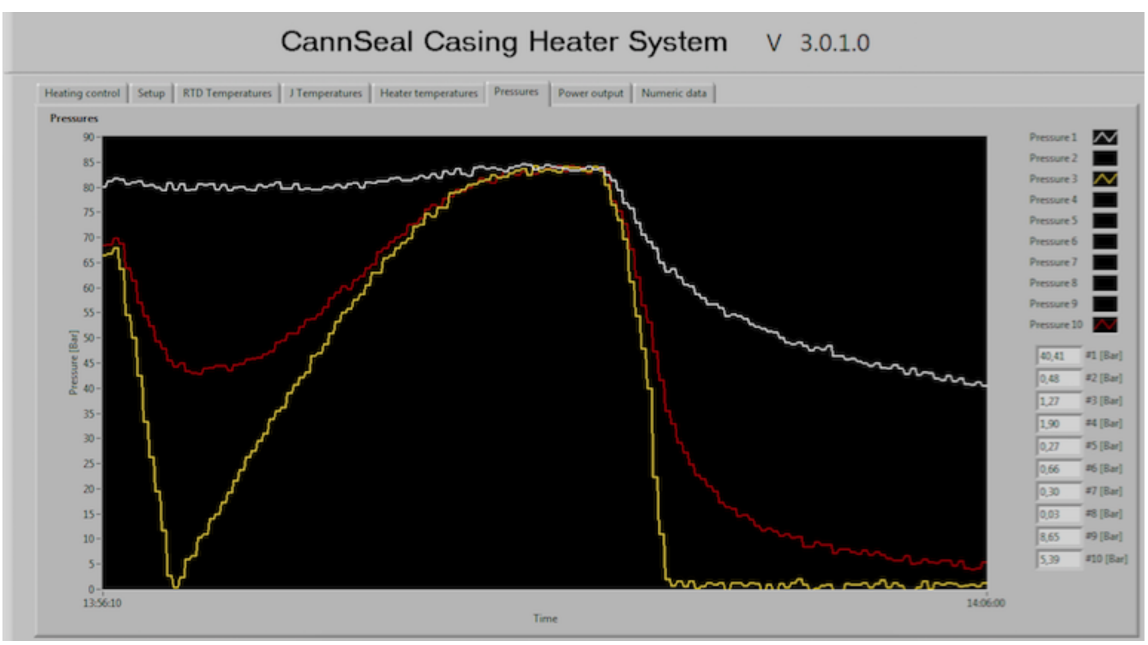


Figure 3.10: Screenshot of the "CannSeal Casing Heater System" that enables monitoring pressures and controlling temperature of the cells.

3.6 Mixing of the Resin

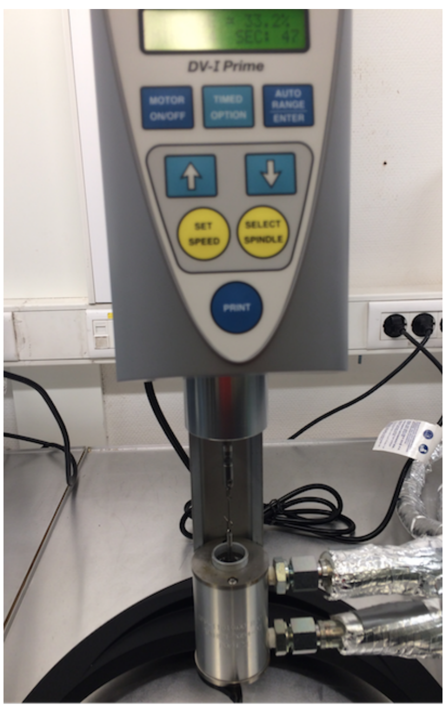
The resin needed careful handling and only absolute necessary personnel with appropriate personal protective equipment was involved in the mixing process. The mixing of the resin was done in the same manner for all cells, approximately the same volumes for all tests was prepared, each sample-cell could hold a volume of 3 L. The resin was mixed manually, then transferred to sample-cells before injection started. Approximately 100 mL of resin was taken for viscosity measurements, this will be discussed in section below. For injection using the outside manifold (cells one and three), the sample-cells containing the resin was kept at 30 °C prior and during injection. This was not possible when using the CannSeal tool (cells two and four), hence the water inside the tubing was heated to 30 °C throughout the operation.

Figure 3.11: Mixing of the resin. Picture shows the addition of hardener system.

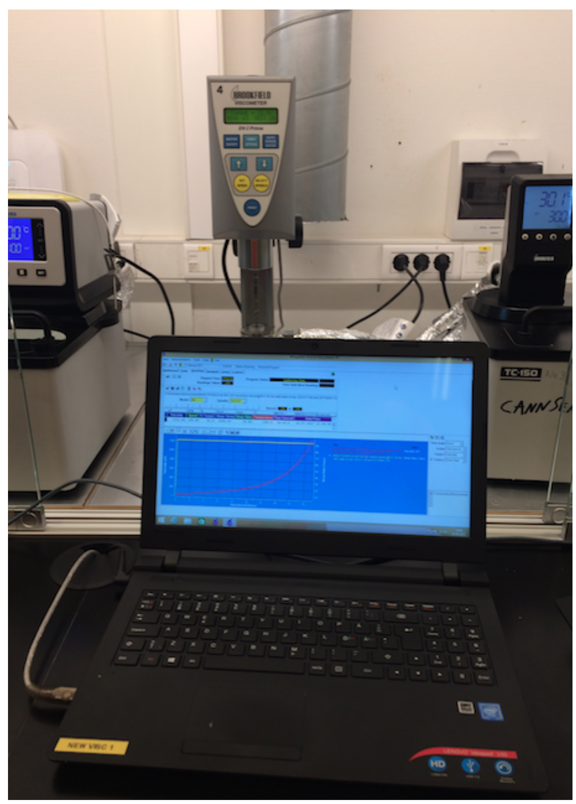
3.6.1 Resin Characteristics

The resin had a very low initial viscosity (~ 20 centipoise (cP)) and no filler materials were added. These characteristics was chosen so that it could penetrate the small gaps present in the cemented annulus.

Prior and during injection of the resin, the viscosity was measured with a digital viscometer shown in figure 3.12a. Gaining knowledge about the resins rheological characteristics such as the viscosity is valuable in predicting its pumpability over time and curing period. The basic principle of measurement of the viscometer is recording the torque required to turn the spindle in the fluid, which is a function of the viscosity of that fluid. The rotating viscometer measures this torque while rotating in the resin at a constant velocity. The output and calculated viscosities with time are then digital displayed in the "Brookfield Engineering Labs" software, full set-up shown in figure 3.12b.



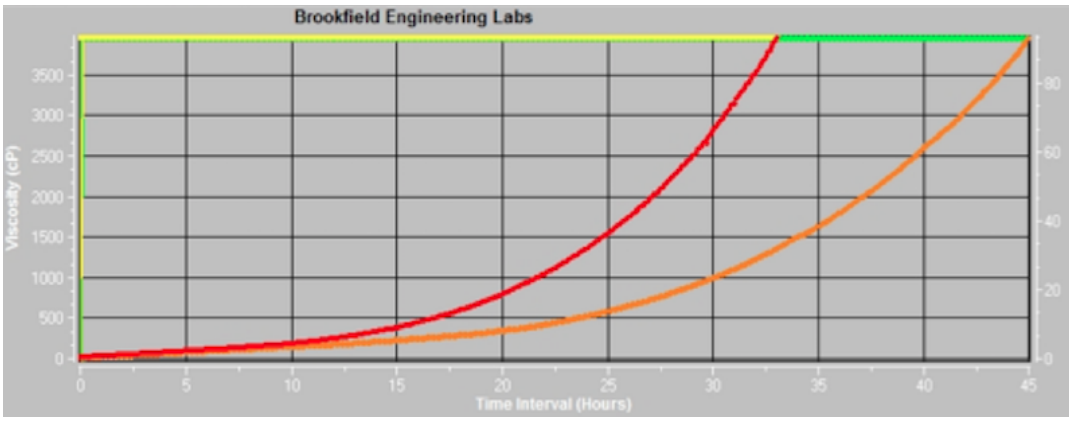
(a) Digital viscometer from Brookfield Engineering.



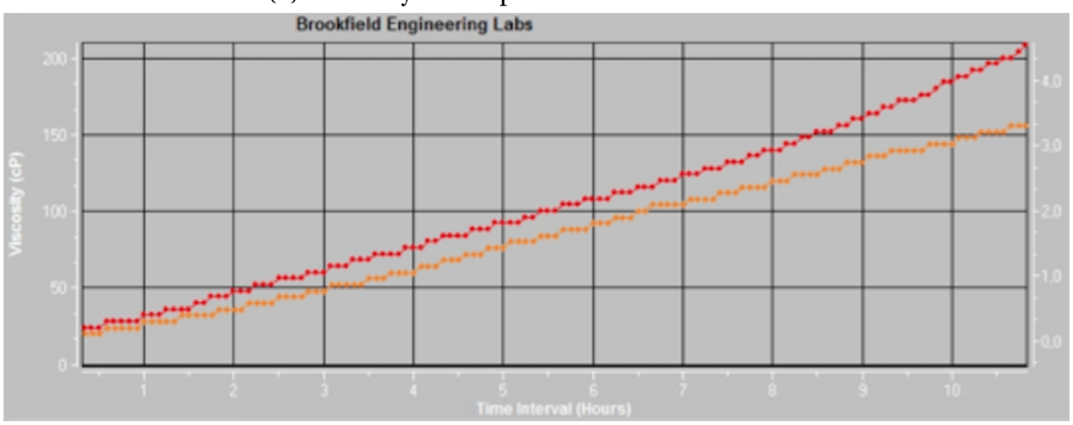
(b) Full viscosity measurement set-up.

Figure 3.12: Measurement of the resin viscosity while curing.

Graphs provided in figure 3.13 the resin development of viscosity with time while curing. These are actual measurements performed prior to injection and gives information about expected time window when resin is pumpable. The resin is designed to be used at a temperature of 30 °C, however also performed measurements of viscosity building at 25°C due to uncertainty of temperature in the canisters and in the cells.



(a) Viscosity development from 0 to 45 hours



(b) Viscosity development from 0 to 11 hours

Figure 3.13: Viscosity development during curing at 30 °C (red graph) and 25 °C (orange graph). Both graphs showing the viscosity development with time, just at different time scales.

3.7 Injection of the Resin

The injection of the resin was done either from the manifold or with the CannSeal tool, the overview was given in table 3.1 for each cell.

The final leak testing was with water, the cells was therefore water filled prior to resin injection.

This was preferred as water is an incompressible fluid in comparison to gas. If no gas pockets are present, injection of resin will lead to almost pressure build-up when P_B and P_T are closed. This is a verification of resin entering the cell and displacing the water. If the cells were gas-filled (highly compressive fluid), large volumes of resin would have to be injected before same verification. The resin will be set to cure under high injection pressures, this is due to the previously discussed ballooning effect.

3.7.1 Cells 1 and 3

Figure 3.14 illustrates the test setup. Injection of the resin was from the middle of the cells through the injection module. The general procedure described below is after the cells were preheated to the reference temperature of 30 °C and the mixed resin was transferred to sample-cell and connected to the injection module.

1. Open valves at bottom and top (V_3 and V_4) to ambient conditions.
2. Start to inject the resin carefully and observe if any return of water on either ends (bottom or top). If leak is only from one side, close either V_3 or V_4 to displace the resin over the entire length. There will most likely be poorer cement from middle to top than middle to bottom as result of gravity settling and shrinkage, therefore V_4 is expected to be closed first.
3. Evaluate pressures and leak rates. The goal is letting the resin cure at a high pressure ($\sim$ 150 - 200 bar). Let the resin gain the appropriate viscosity so this can be achieved without filling the end flends full of resin. Some small volumes of resin is however expected.
4. Continue monitoring and injection until the resin has set and cured at this predetermined pressure, should cure while V_3 and V_4 are closed.
5. Perform same leak tests (discussed in Section 3.5) to evaluate the seal of the resin after it has cured.

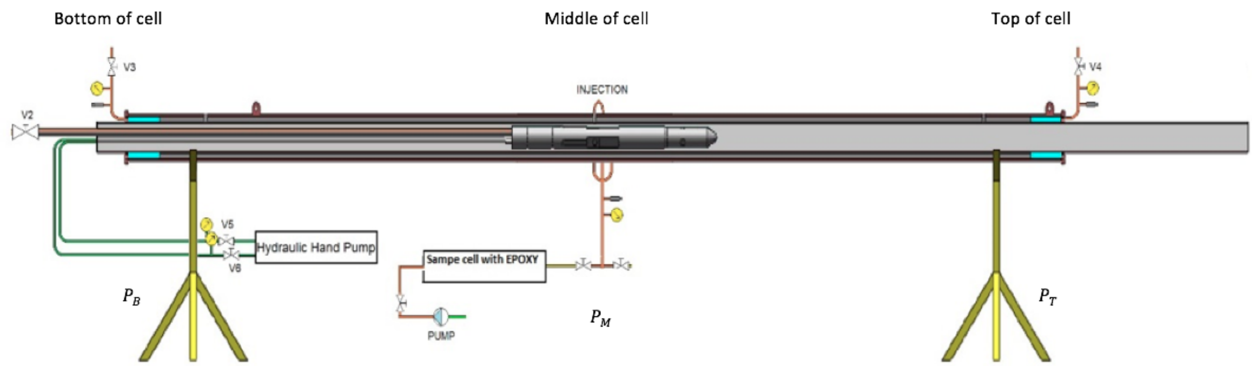


Figure 3.14: Injection of the resin using the outside manifold for cells one and three. Illustration showing the injection module which was used only for cell one, due to had to seal leak as a result of installed set-screw in the inner pipe.

3.7.2 Cells 2 and 4

For cells two and four, the full operational sequence using the CannSeal tool was performed, including in-house perforation. The difference between the two tests and set-up, are the use of three and six point perforation and injection module. This was the first time using this six shot and six arm injection module. The sequence for performing both the perforation and injection were the same for both tests.

Handling of explosives needs among other things, professional and experienced personnel. The internal procedures were followed throughout the operation, without going further into details about these. No personnel except absolutely necessary were present during this operation.

The general procedure for injection described below is after the resin has been mixed. The same notations used for describing valves placement above, will be used here.

1. Rig-up CannSeal assemblies with perforation module.
2. Install tool in the cell set-up, illustrated in figure 3.15. Fill the tubing with water that is preheated to 30 °C, continue heating the cell holding the temperature stabile.
3. Set anchor against inner pipe.
4. Pressure test the pads against the casing to ensure no leak.
5. Retract pads and stroke up.
6. Perform in-house perforation (perforation points are located 3.4 m and 0.3 m from the left

stub for cell two and four respectively).

7. Stroke down placing pads again perforated interval. Prepare for resin injection.
8. Start to inject the resin by slowly increasing the pump pressure and monitor pressure and leak rates at the bottom and top end.
   - If leak is only from one side, close either V_3 or V_4 to displace the resin over the entire length.
   - If a high leak is observed for both directions, wait until the resin has gained viscosity due to curing and continue injection.
   - Need to be careful not filling the ends with resin, small amounts is however expected.

   The goal is still letting the resin set at a high pressure (~ 150 - 200 bar).
9. Evaluate and monitor the pressure and leak rates while pumping.
10. Continue monitoring and injection until the resin has set and cured at this predetermined pressure, should cure while V_3 and V_4 are closed for cell two.
11. Perform the same leak tests with nitrogen and water prior to injection (discussed in Section 3.5) to evaluate the seal of the resin.

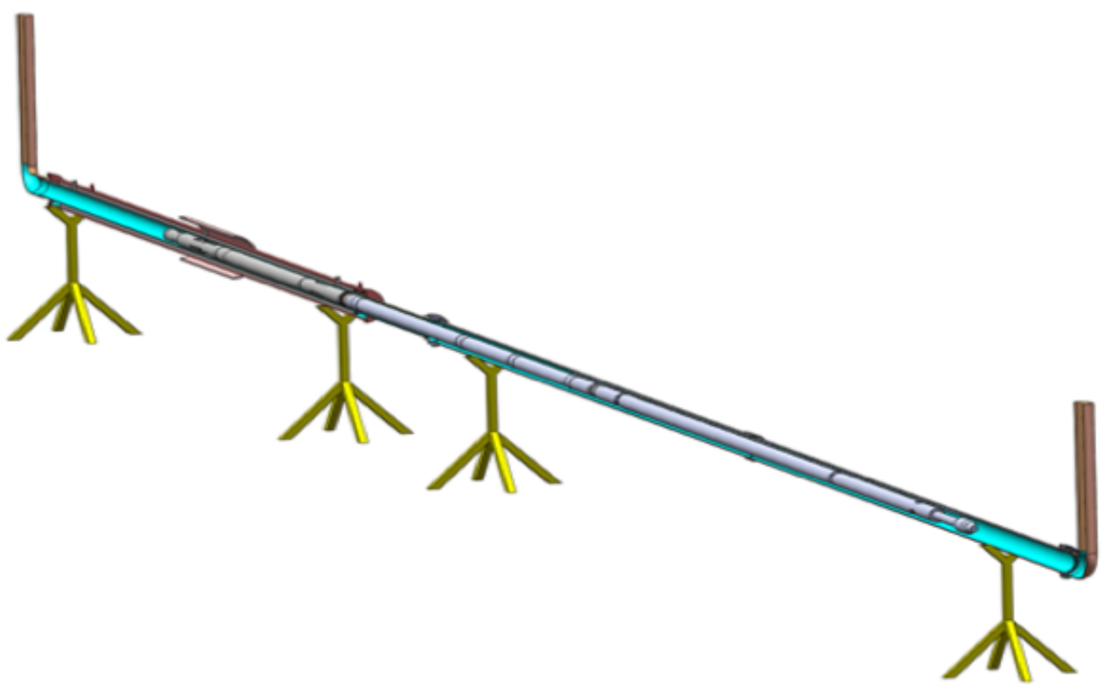


Figure 3.15: The CannSeal tool installed in the cell for perforation and injection of the resin. Courtesy of CannSeal.

Chapter 4

Results

The main motivations behind the experimental work have been to establish that can inject a ULV-epoxy resin into a well-cemented annulus for improved sealing with the CannSeal tool. The results from injection pressures for cells two and three are presented in this chapter, hence injecting with the manifold and with the tool. The gas leak results prior and after injection and curing of the resin are also included.

4.1 Injection Results

The learnings from injection results of the resin arre important for understanding how it behaves when injected into a "well-cemented" annulus as it cures (builds viscosity). The injection from both the manifold and CannSeal tool will be presented. Graphs giving the injection pressures and associated readings at the different pressure sensors will be provided. The viscosity development from separate parallel readings from the digital viscometer and volumes of injected resin will be listed. Furthermore, short descriptions of the applied injection pressures and observed responses on the sensors are itemized.

4.1.1 Injection from Manifold

The injection pressure versus time for cell three is provided in in figure 4.1. These graphs give the collected pressure data from 19 to 39 hours and 68 to 85 hours from the time the operation started. These intervals were chosen to best show the behavior of the injected resin with time, the whole dataset is provided in Appendix A. The resin had cured approximately for two hours before injection started resulting, hence viscosity had already started building from initial 20 cP.

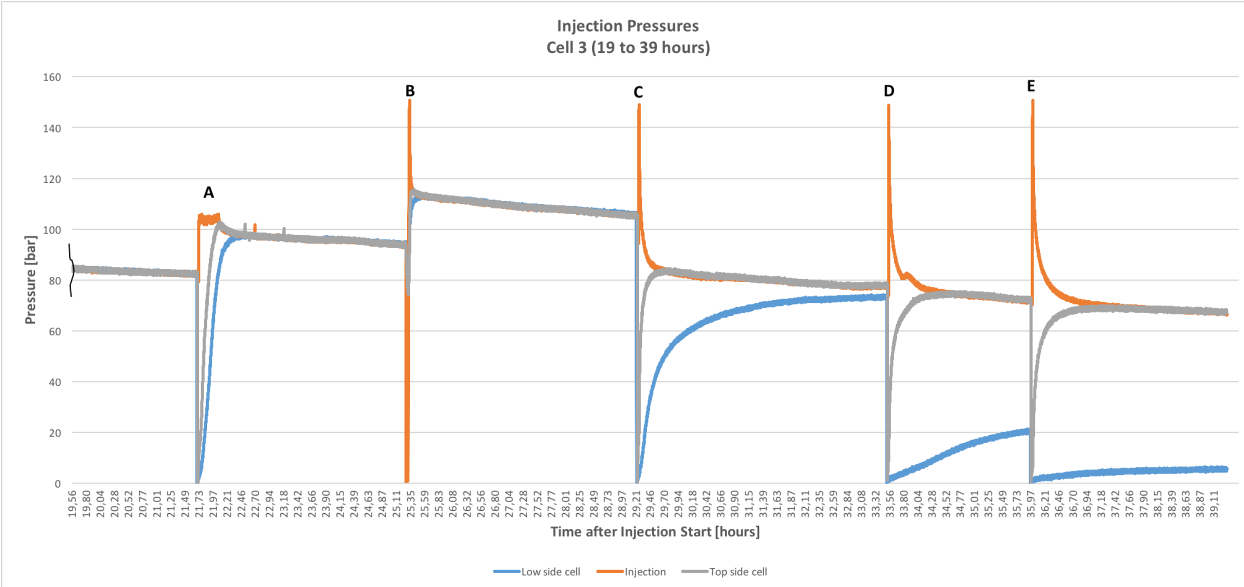
Two "sample-cells" with resin was used for this test, a total of 2.5 L was pumped. The first cell needed to be changed out (was empty) after 55.5 hours into the operation. The sample taken for viscosity measurements was from the original mix that was transferred to both sample-cells, the second from sample-cell two after 50 hours. These did show a difference in viscosity (see table A.1), the reason was that the heating jacket did not apply a uniform heat giving 30 °C along the whole sample-cell. Therefore, when changed to sample-cell 2 there was a difference in viscosity for the already injected resin and the one now being injected.

A short listed description for figure 4.1 is given on the next page, with viscosity measurements provided in table 4.1.

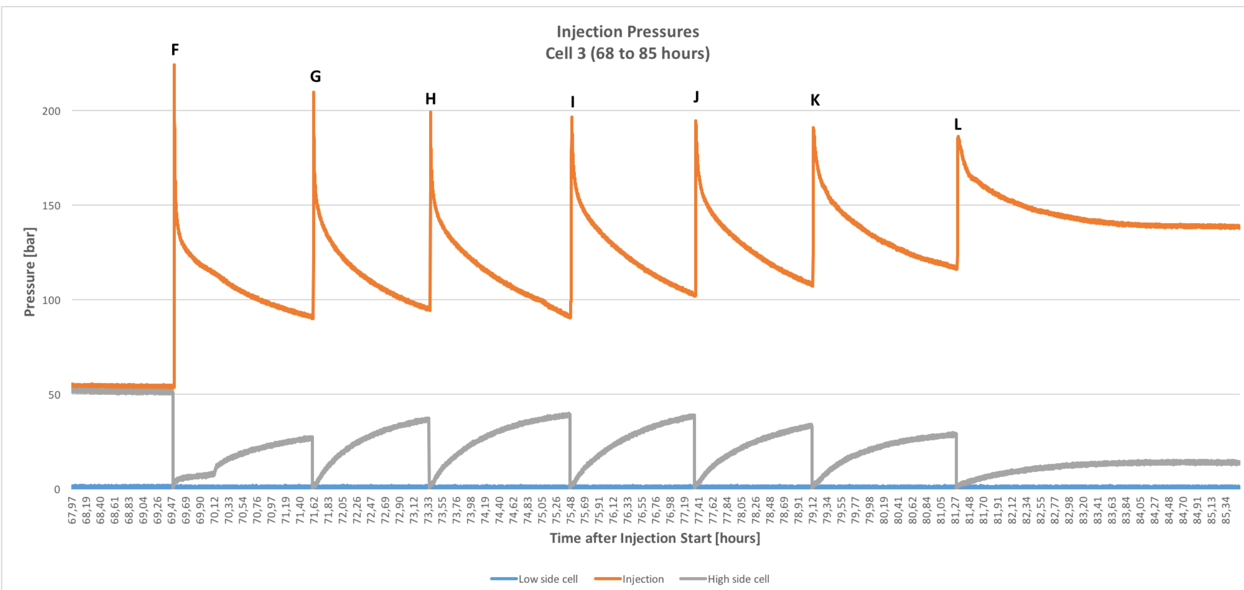
Table 4.1: Descriptions associated to figure 4.1.

Time after injection start [hours]	Letter on graph	Viscosity Sample – Cell 1 [cP]	Viscosity Sample – Cell 2 [cP]	Cumulative volume of resin pumped [L]
22	A	1244	-	1.16
25.3	B	1964	-	1.34
29.2	C	3204	-	1.41
33.6	D	4000	-	1.488
36	E	8000	-	1.564
------------	------------	------------	------------	------------
69	F	EE	120 000	2.277
71.6	G	EE	740 000	2.317
73.3	H	EE	2096 000	2.353
75.5 – 81	I – L	EE	EE	2.485*

EE: The high viscosity spindle on the Brookfield viscometer cannot quantify numbers over 4000 Pa*s (4 000 000 cP).
*: The volume pumped at 83.5 hours.



(a) From 19 to 39 hours after injection start.



(b) From 68 to 85 hours after injection start.

Figure 4.1: Graphs giving applied injection pressure (at manifold) and corresponding pressure readings at the bottom and top of cell three, for two different chosen time intervals.

A - B There is a quick pressure response between applied pumping pressure and subsequent bleed-off for all sensors, this was done with closed valves on both ends. This implies that the resin with this low viscosity has founds paths both to higher and lower parts of the cell, most likely as a result of the ballooning effect in combination of the high applied injection pressure and low viscosity. Between each equalization (stop off pumping) a high injection pressure is applied. While equalization there is a decreasing trend in pressure for all sensors. In this period, the resin is filling up the channels and voids present in the cemented annulus. After each equalization the pressure is bleed off at each end, this is done throughout the test.

C - E The pressure response changes as a result of the increasing viscosity. The resin is less and less able to penetrate down the lower section of the cell, this can be seen by the delayed pressure responses after applied pumping pressures. The local area around injection points are now being filled with the resin. This is also favorable, creating a 360° distribution of the resin. Point E shows an almost absent pressure response on the low side when applied 150 bar injection pressure. This side of the cell is now being sealed off, the limit between applied pressure and viscosity for the resin to penetrate down to the lower side is being reached, due to the high friction losses. This pressure response is desirable, when the operation is done the casing will contract against resin creating a competent seal.

F - L The trends observed for all applied pumping pressures are similar. The lower side has been completely sealed off, allowing no flow of the resin. With applied injection pressure of 200 bar, there is a slow response at the top. For equalization periods of 2 hours (points F - K) the build-up does not reach the center pressure. This can be explained by the high pressure losses due to the significant viscosities. Not long after point L, there will be a phase transition of the resin. A final injection is performed (see figure A.2c) up to 200 bar, showing no response at the upper sensor.

4.1.2 Injection from CannSeal tool

The following injection operation was performed on cell two, with the three-pad injection and perforation system, replica a full operational sequence. The injection pressure versus time and associated pressure readings are provided in figure 4.3. A total of five pressure sensors were installed, one on each end and three in the center. Figure 4.2 gives the names corresponding to the pressure curves. The three sensors installed in the center gave valuable information about the distribution of the resin throughout the cross-section. The orientation of the three perforations were in the same manner as seen in figure 4.2. The curve "Injection Pressure" is the pressure recorded at the pads while "WFP Outlet" is the piston pressure applied from the pump.

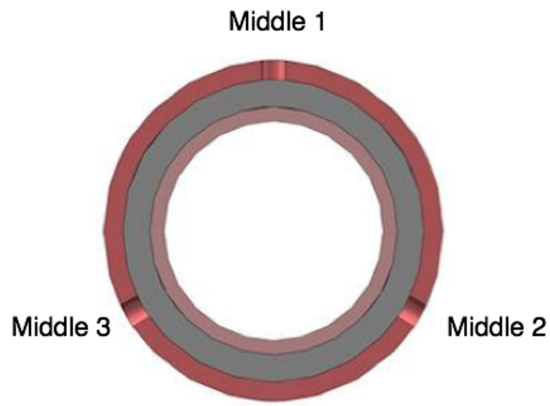
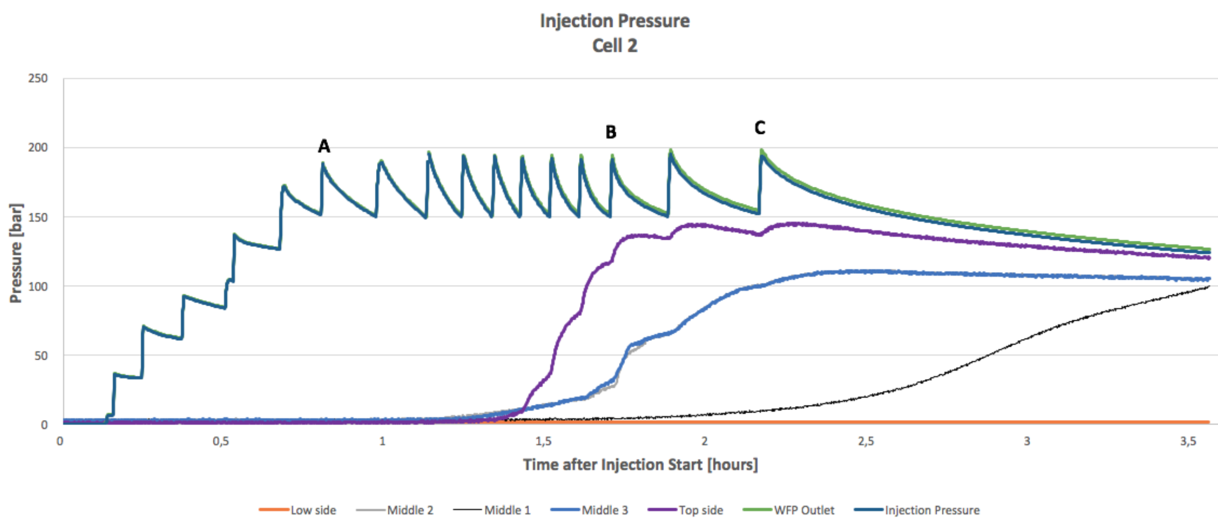


Figure 4.2: Names of pressure sensors corresponding to the curves in figure 4.3.

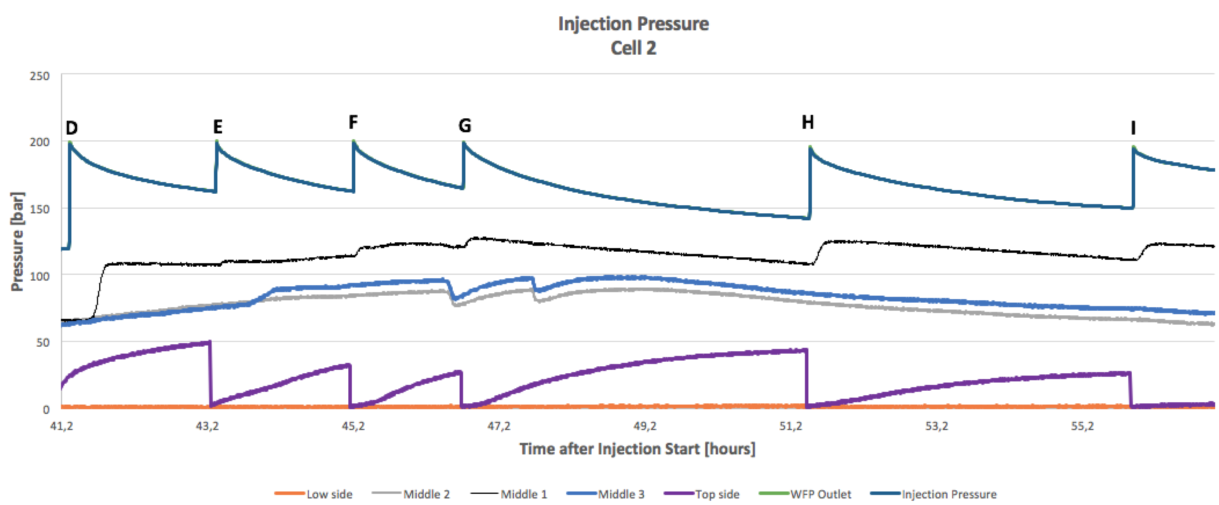
The graphs in figures 4.3 gives the recorded pressure data from 0 to 3.5 hours and 40 to 55 hours respectively. A listed description for the observations in figure 4.3 is given below and table 4.2 provides the measured viscosities and amount of resin injected.

Table 4.2: Descriptions associated to figure 4.3.

Time after injection start [hours]	Letter on graph	Viscosity [cP]	Cumulative volume of resin pumped [L]
1	A	104	0.96
1.75	B	120	1.27
2.4	C	-	1.35
------------	------------	------------	------------
41	D	28 000	1.88
43 and 45	E - F	32 000 and 36 000	1.92 and 1.92
48 and 52	D – H	44 000 and 624 000	1.96 and 2.00
56	I	EE	2.04



(a) From 0 to 3.5 hours after injection start.



(b) From 40 to 55 hours after injection start.

Figure 4.3: Graphs giving the applied injection pressure (by the CannSeal tool) and corresponding pressure readings at the five pressure sensors.

A An injection pressure of 200 bar is reached after a stepwise pressurization, no observed increase on either of the sensors. To a certain degree unknown why did not observe instant pressure build-up as both valves on either ends was closed. One theory is that gas was present in the cemented annulus itself or in the end flends.

B - C All sensors expect the lower one has gotten a response. The resin is being injected through the perforations, which is placed 0.4 m from the center of the cell towards the top. A combination of volume injected and pressure applied gives enough ballooning of the casing for the resin to migrate in both directions. The top sensor has a larger response than the sensors in the center, since the lowest restriction is in that direction. There is a delayed response on sensor "Middle 1" compared to the other two, most likely this is due to the resin being pumped through the two perforation holes with the same orientation. When the two curves stabilize however, the easiest direction of flow becomes in the direction where "Middle 1" is. This can be explained by that the pressure difference (or force) is now sufficient for the resin to flow there. No pressure observed on lower end, most likely as a result of perforations points was close to the top and the pressure losses were to large for the fluid to reach that side.

D - F In this section, there was bleed-off liquid at the top between each equalization. The build-up rate decreased as a function of time as a result of the increasing viscosity. There was a slow increasing trend on the sensors in the center, because of the high injection pressures and short equalization periods. No response on the lower side, also expected at this stage of injection.

G - I The same procedure regarding bleed-off was continued, though much longer intervals. The resin was now at such high viscosities that are starting to seal off the top end of the cell. There is a decreasing trend in the middle sensors because of the long equalization periods, allowing movement of the resin towards the top.

4.2 Leak Testing with Gas

The following gas leak tests was performed in the manner presented in Section 3.5. After injection and curing of the resin, the cells could not be pressurized from the center (P_M). Therefore, the tests below gives leak rates when pressurized from the bottom (P_B) and measured gas leaks at the top of the cells (P_T). Data collected from leak tests from the center and with water are attached in Appendix A. The main challenge in the industry regarding SCP is gas migration, sealing off or minimizing gas flow is thus the main focus.

The phenomena of the cement plug not being homogeneous over its entire length were seen on the injection results above. As the resin tended to flow towards the top due to lowest restriction (smallest ΔP). This can be seen even more clearly in figure 4.4, which is the leak test with gas performed for cell two prior to injection (cells one and three showed similar results, see Appendix A).

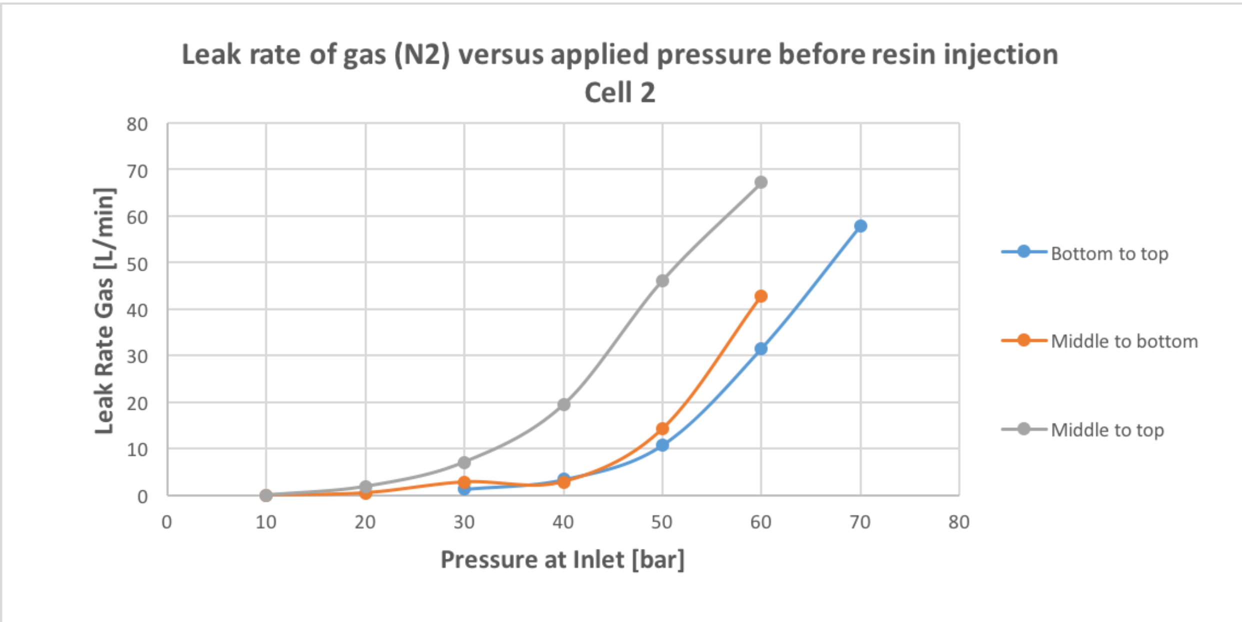


Figure 4.4: Leak rate of gas before resin injection for cell two.

This data is important for understanding the previously discussed preferred flow paths within the annulus. Figure 4.4 shows that for the same applied pressure at the center, the leak rate is much larger at the top than the bottom. This comes most likely as a result of gravity settling and bulk shrinkage of the cement, in the transition phase between being a liquid and a solid. Since the "Bottom to top" and "Middle to bottom" curves is almost identical, this means that after the fluid has reached the center of the cell, there is almost no restriction towards the top. This can be partly due to the high pressures that are already expanding the casing in a more poorly cemented region (middle to top), allowing even easier flow off the fluid.

4.2.1 Cell 1

The gas leak tests from bottom to top performed prior and after injection of the resin are given in figure 4.5. The breakthrough gas pressures, meaning the applied pressures at the bottom before observed leak at the top were 30 bar and 100 bar, before and after resin injection respectively.

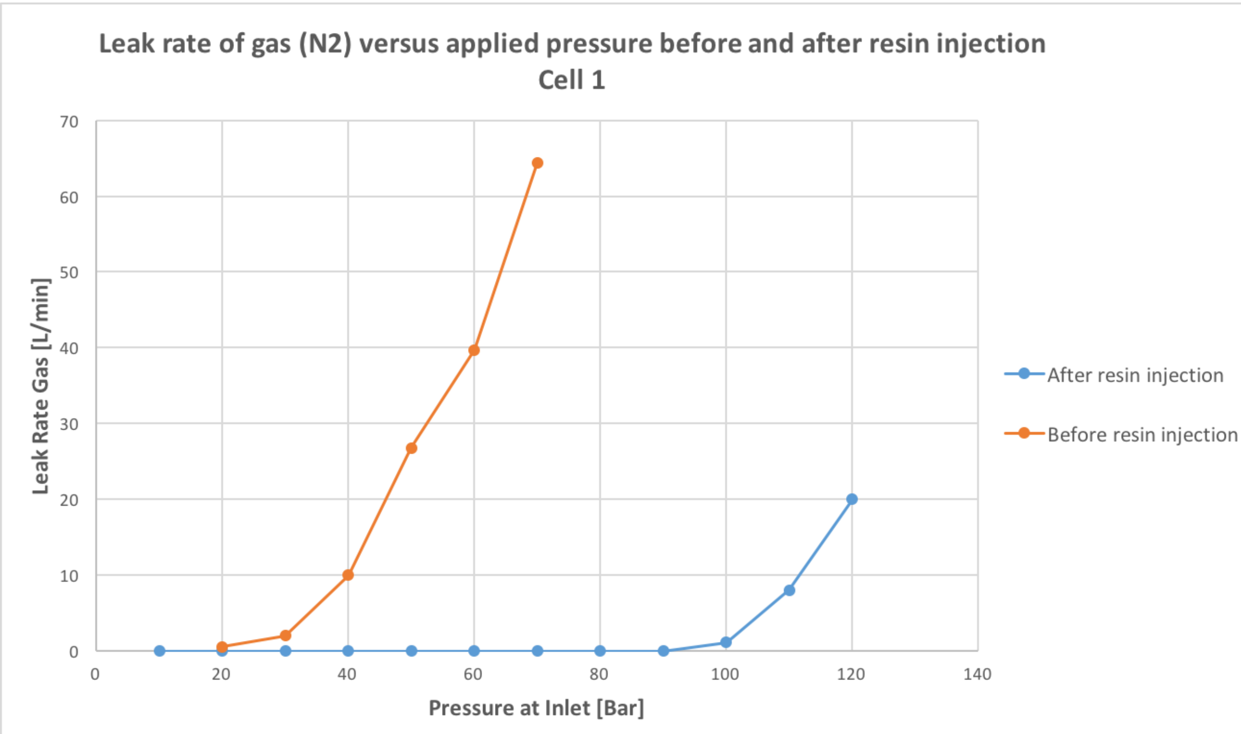


Figure 4.5: Leak testing with gas for cell one before and after resin injection.

The results obtained for cell one clearly shows a significant decrease in leak rates after injection of the resin. The injection from the outside manifold seems to have properly distributed the resin in the preferred leak paths where gas migrated. The leak rates prior and after injection will most definitively be a function of ballooning of the casing, which is difficult to account for when interpreting a singe leak curve. The effect of ballooning, however, will affect the casing the same for both tests, and it is evident that after injection the seal is much better when having resin and cement present than just cement. The resin was set under 70 bar injection pressure at the manifold.

4.2.2 Cell 2

The results for cell two when leak testing with gas both prior and after injection are given in figure 4.6. The gas breakthrough pressures were 30 bar and 150 bar before and after injection respectively.

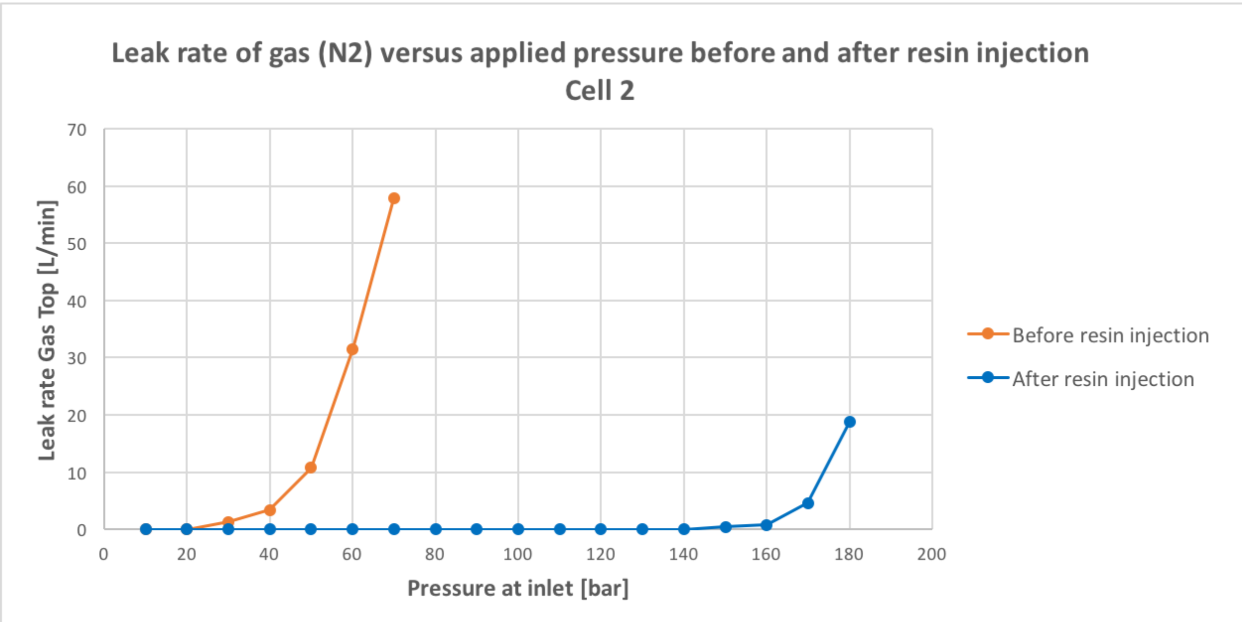


Figure 4.6: Leak testing with gas for cell two before and after resin injection.

The injection was with the CannSeal tool using the three-arm system after perforation. The resin did distribute over the entire cross-section, which was seen in figure 4.3. The placement method together with mechanical properties of the resin, lead to a significant decrease in leak pressures. The resin was set under 150 bar injection pressure for this test. This is higher than for cell one, therefore could be one explanation for holding greater gas pressures.

4.2.3 Cell 3

Figure 4.7 displays the results from the gas testing for cell three. The gas breakthrough pressures before and after resin injection were 20 bar and 140 bar respectively.

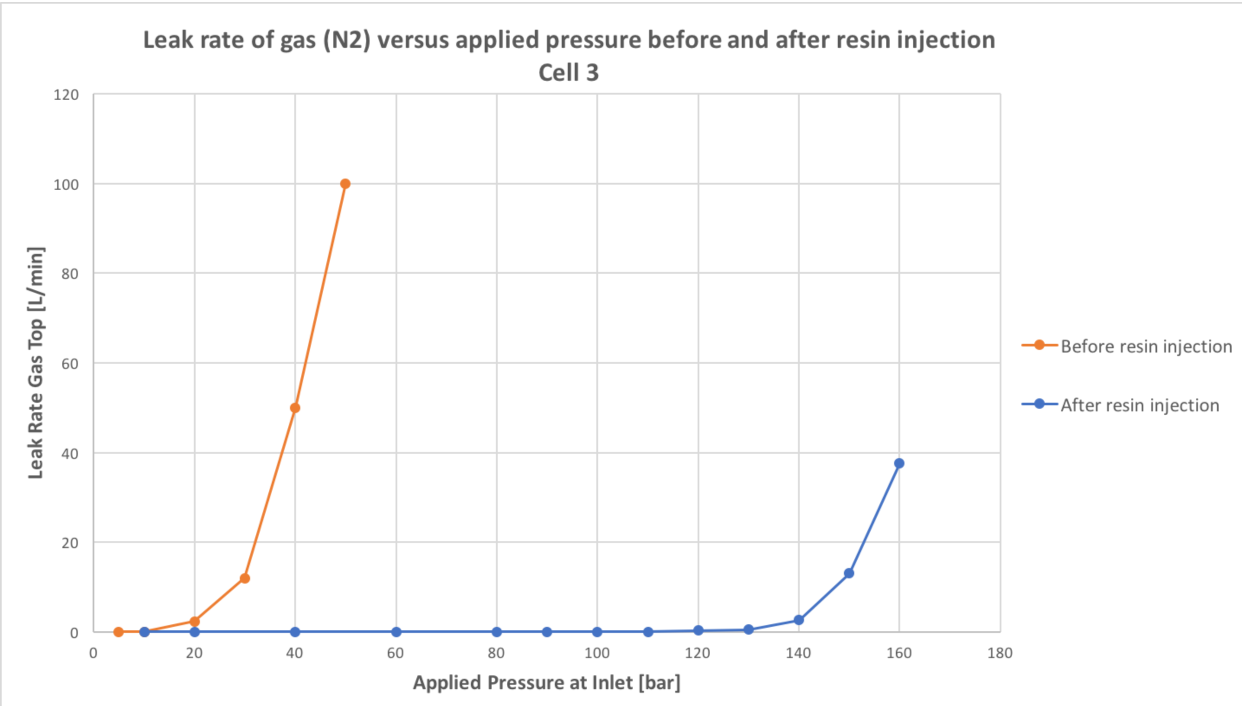


Figure 4.7: Leak testing with gas for cell three before and after resin injection.

This graph shows the same trends as the previous tests with a significant decrease in leak rates after injection. This decrease suggests that the resin was properly distributed over the entire cross-section of the cemented annulus for the larger cell using a six point injection from the manifold. The resin was set to cure under 200 bar injection pressure.

4.2.4 Cell 4

The leak testing with gas results is given in figure 4.8. The gas breakthrough pressures were 20 and 130 bar before and after injection respectively.

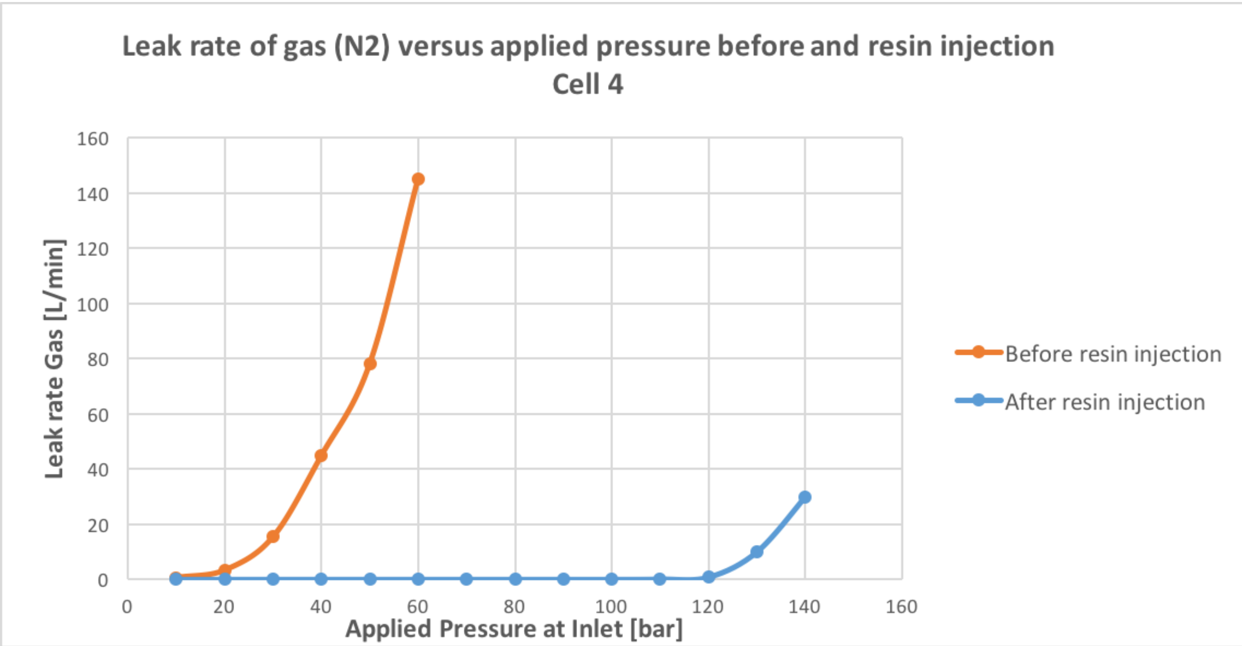


Figure 4.8: Leak testing with gas for cell four before and after resin injection.

The resin was set to cure under 160 bar injection pressure applied from the CannSeal tool. The injection results (not provided), showed a properly distribution of the resin both radially and axially throughout the cell. This test was performed with the six point perforation and injection module.

Chapter 5

Discussion

The results obtained in regards to gas leak testing and sealant injection pressure will be further discussed. In regards to gas leak testing, the results for different cells will be discussed in relation to injection method, casing ballooning effect and other potential factors affecting the results. The section discussing sealant injection pressure will focus on the monitored resin distribution throughout the cells, the importance of maintaining high curing pressures and the resins favorable elastic properties in regards to sealing. Then, learnings from the experimental tests in regards to well-application will be evaluated. Finally, suggestions for future work will be listed.

5.1 Discussion of Gas Leaks Results

The largest restriction in the cemented annulus for all cells was from the bottom to middle. The cement was pumped into the test cells while in a vertical position, hence the gravity made the cement seal better at the bottom than at the top. When applying a gas differential pressure across the cell, the primary sealing against flow was therefore in the lower region.

All cells, that includes injecting via the manifold or the CannSeal tool, with both three and six injection points and for different dimensions of the annulus test cells showed a significant sealing improvement after the resin was injected and cured. This verifies that a resin can be injected via the CannSeal tool through perforations into a well-cemented annulus and create a competent distributed resin seal against high differential gas pressures. Water leak testing results are provided in Appendix A, these will not be further discussed as they showed consistent trend differences prior and after injection as gas leak testing. The ballooning effect that expands the annulus as a function of applied pressure, has an impact on the recorded leak rates. To what degree is hard to determine, but most likely the recorded leak rates for high applied differential pressures was primary a function of this phenomena. Cement has a low shear bond in comparison to an epoxy resin, this could also be one of the explanations of the significant improvement of sealing after resin injection and curing. The resin is cured under a high pressure together with its flexible properties, gives a much better resistance against casing expansion and thereby improved sealing.

To check the ballooning effect theory on measured leak rates, high differential pressures was applied to all cells to steady leak rate was observed. Then, the pressure was reduced holding approximately 100 bar of gas differential pressure for nearly 24 hours. The pressure was then increased for comparing leak results, these did show consistent results for all cells. This proved that high differential test pressure did not damage the sealing ability of the resin, but the casing to casing gap generated the gas leak.

There are several potential factors that can have affected the variations in recorded leak rates for the different cells, some of these factors are listed below.

- Under what injection pressure the resin was set to cure.
- The physical and human factors that prevent each cement plug being identical.
- The different casing dimensions leads to larger cross-section area for the fluid to flow, leading to greater recorded leak rates.
- The uncertainties related to measuring methods.
- Different injection method could lead to different displacement of the resin.

When comparing the different results obtained, the above factors should be considered. For example, comparing the injection methods for cells one and two (manifold and tool respectively). The leak testing in both cells prior to injection did show a similar cement condition (same for cells three and four). However, after solidifying of the injected resin in the annulus the gas breakthrough pressure for cell one was 100 bar, while 160 bar for cell two. This is a noteworthy difference, but curing pressures were 70 bar and 150 bar for cells one and two respectively. This difference in applied pressure while curing will have a significant impact on the sealing ability of the resin in the cemented annulus. These learnings (which also was expected) was also applied for the last two tests. In comparison to the first two, these tests were conducted in a larger annulus (7" x 9-5/8") with six injection points. The applied pressure while curing was approximately the same, and there were only minor differences in gas breakthrough pressures.

The results from leak testing are evident, the annular sealing ability of the injected resin gave very positive results compared to testing prior to injection.

5.2 Discussion of Injection Pressure Results

The injection results from cells two and three gave necessary information for clarifying the thesis questions regarding injection of the resin into a well-cemented annulus. Therefore, the injection versus time for cells one and four are not provided, however, learnings from these tests are a part of the whole evaluation.

The distribution of the resin radially in cells two and four showed a 360° placement in the center of the cells. This concludes that both with three and six injection points one were able to properly inject the resin throughout the cross-section. For cells one and three the same distribution around the center for a certain length are expected (could not be monitored as pressure sensors were not installed). This is based on the gas leak testing results showing similar results for each injection method.

The results obtained from gas leak testing evidently showed the importance of letting the resin cure under high pressures. The reason why will be elaborated briefly. When the resin is injected into the annulus, it will flow the path of least pressure loss or resistance. After enough resin has been injected, filling whatever gaps are present and sufficient viscosity has been build, injection pressure will start to increase. The pressure will start to build and equalize over the cell, thereby causing incremental ballooning of the casing. Equation 5.1 (provided also in Subsection 2.1.5) gives the relationship between applied pressure and radius change of the casing, assuming 360° of equal applied pressure.

$$\Delta r_{casing} = \frac{r_{casing}^2 \Delta p}{h_{casing} E} \tag{5.1}$$

If the resin is cured under these high pressures this will enable better resistance against the ballooning effect. Because, while the resin is solidifying the casing will "push" the resin against the cement. The flexible properties of the resin will, however, allow it to follow both the contraction and expansion of the casing, thereby mitigating fluid flow. The higher the curing pressure, the higher differential pressures likely to withstand. If the injection is stopped and the CannSeal tool retracted prior to proper curing of the epoxy, the contraction of the casing may force it to either side. The voids and/or microannulus(es) will be filled, but the plug will hold poorly against high differential pressures as a result of the ballooning effect.

After the resin is well into the curing process, there will be a deviation between the curves "Injection Pressure" and "WFP Outlet" in the CannSeal tool (see figure A.4c). The "Injection Pressure" is the observed pressure at the pads while "WFP Outlet" is the piston pressure. The deviations between them imply that the piston cannot fully translate its pressure to the pads. This is a result of the high degree of cross-linking of the resin leading to high viscosities, thereby restricting flow and this is an indication that the injection operation can be stopped.

5.3 Discussion of Well-Application

There are several considerations that needs to be assessed in regards to results obtained from testing a specific case (well-cemented annulus) to what can be expected in a well-scenario. Some of the main points of focus in this thesis in that regard are listed below.

- Uncertainties related to the state of the cemented annulus. That includes the size of channels, voids or microannulus(es) present. And where the migration paths are present, such interface (i.e. formation (or casing)-cement or cement-casing).
- If able to attain high injection pressures while curing.

- The presence of old mud, cuttings and debris and at which degree this will influence the total sealability of the plug in the annulus.
- Casing integrity after the pipe has been perforated and operation is finished.
- Verification of the set resin in the annulus.
- The resins sealing ability in the longer term perspective.

There will be uncertainties of where the preferred migration paths are present in the annulus and if these can be fully sealed off. With the newest technology within acoustic tools, they provide relative good information about potential migration paths in the interface between cement-casing. However, very limited information can be obtained about cement voids or channels present against the formation. This means that limited information prior to injection (pre-job analysis) can be obtained about where the resin will be injected and if there will be communication allowing resin accessing the different migrations path for sealing. As previously mentioned, the condition of a petroleum well annulus can to some extent be unique.

Achieving a high injection pressure while curing will enable holding higher differential pressures over the resin plug. If this is possible for a well-scenario will depend on the resin volume filled and its distribution in the annulus, and if sufficient pressure drop can be achieved.

The scope of this thesis was not to test the resin in regards to long-term sealing ability under different conditions and environments. This is, however, something that needs to be conducted together with the operator companies following the regulatory framework.

The casing integrity after the pipe has been perforated is something that needs to be further tested in regards to remedial repair of SCP. After injection is performed and the tool is retracted, there will be either three or six points where potential fluid migration can occur if not properly sealed. CannSeal has performed extensive testing on the matter regarding injection of a high viscous resin into an open annulus. The tests concluded that the resin was able to properly seal off the perforations. If the sealing capability in the perforated area are questioned a mitigating factor could be to install a casing patch (as are done in regular cement squeeze operations involving perforation).

The presence of old mud, cuttings and debris can be present in the annulus. How this will affect the total sealing ability needs to be assessed. The tests discussed in this thesis there was no contamination of the cemented annulus. However, the literature states that a polymer resin has great adhesion to other materials, oil- and water-wet surfaces and more resistant to contamination than conventional cements. Thereby, these properties could lead to proper sealing under such conditions. For well-application one should consider include as many injection points through the CannSeal tool as possible, this could increase the success rate of filling all channels, voids or microannulus(es) present.

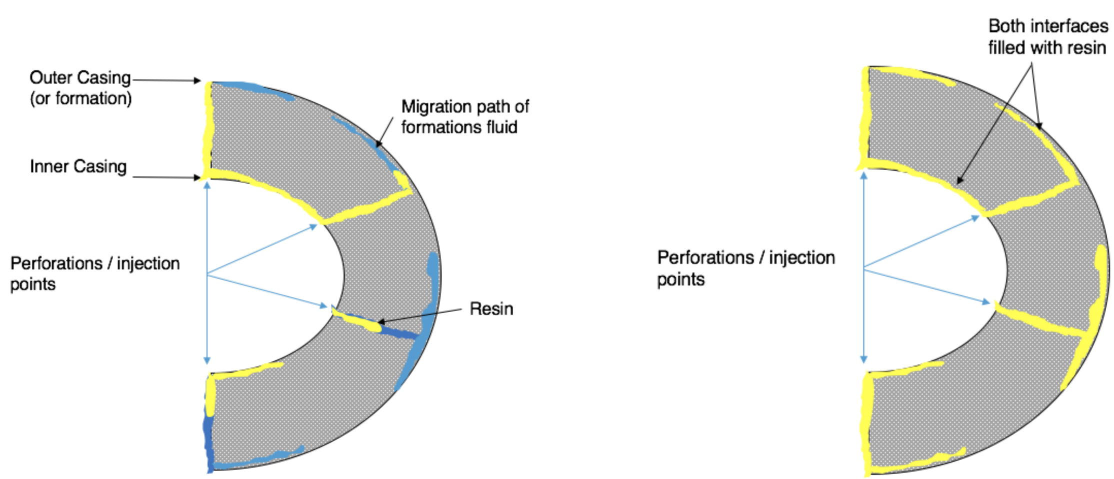
5.4 Discussion of Verification Results from Isolation Scanner

The tests performed with the Isolation Scanner on injected resin in open annulus was presented in Subsection 2.4.2. These results will be discussed on the basis of verification of injected resin into an already cemented region and what responses could be expected. When injected a resin for sealing in an already cemented region, the verification with acoustic tools becomes much more challenging compared to when only one solid present (i.e. cement or resin). The main reasons are listed below.

- Acoustic tools cannot distinguish between which solids are present, only between fluids and solids.
- Primary measurement is what is in contact with the casing (i.e. solid, liquid or gas). If the resin is injected outside of this interface would be very difficult (if even possible) to verify the placement in the annulus.
- A resin used for sealing in a cemented region has different mechanical properties then the cement. Its low density might lead to an acoustic impedance in the liquid region.

The reasons listed above suggests that new verification tests should be conducted for this application. However, some important learnings can be drawn, such as that a resin based system can be identified and be distinguished from well liquids with the Isolation Scanner.

The cemented interval to be repaired should be logged and evaluated prior to injection of the resin. Figure 5.1 shows an injected resin present at different interfaces between the outer and inner boundary of the annulus. If the well has been logged prior to injection and showing a very poor bond (contact) between the cement and casing. Thereafter, the resin is injected between the cement and inner casing (if this is preferred flow path). It is fair to say that the post-evaluation could give information about the potentially improved bonding, as a result of the injected resin. The resin characteristics, such as the density and acoustic impedance could be found in advance, helping with log-interpretation (known acoustic impedance). The acoustic tools (not taken into account the limited information from third interface eco) only gives information about the interface between the casing and the medium behind. The post-evaluation would then be very dependent on what flow-paths the resin has taken in the annulus. Anywhere outside this interface, it would be very hard to evaluate the potential improvements by the injected resin due to the cement evaluation tools measurement limitations.



(a) Resin filling primarily first interface.

(b) Resin filled both interfaces.

Figure 5.1: Illustrations showing filling of resin at different interfaces with time.

The ultrasonic maps do give information about potential gas, liquid or solid in contact with the casing. However, after discussions with professionals in the industry, tools such as the Isolation Scanner can identify solids in the annulus, but to determine a specific solid (i.e. resin or cement) could be problematic.

A tracer in the resin would probably ease the identification of resin distribution in the annulus, this and another potential verifications method are discussed in Appendix D.

5.5 Recommendations for Further Work

The described test project is an ongoing JIP between Shell, Mærsk and CannSeal, and further testing and field trials are planned later this year. Some recommendations for further work are listed below.

- Perform tests with different conditions of the cemented annulus. This could include larger channels and voids, or parts of the annulus missing cement altogether. This would require testing different types of higher viscosity resins in relations to injection and sealing.
- Test the possibility of a two-run operation for remedial repair of a poorly cemented annulus. First, run inject a high viscous resin taking care of the larger gaps, then in the second run perform a low viscous injection while holding a high injection pressure.
- Perform tests in regards to qualifying the epoxy resin as permanent plugging material on NCS.
- Execute additional tests and verifications methods of the injected resin into a cemented annulus. This could include acoustic tools, tracers and other methods.

Chapter 6

Conclusion

Four annular test cells were built and filled with cement in order to investigate the potential of remedial treatment sealing of fluid leaks. The plugging material injected for sealing was a thermoset polymer, more specifically a ULV-epoxy resin. The injection was done both with a manifold (direct access to the annular) and with the CannSeal tool. Lastly, the inner casing was perforated prior to injecting the resin into the well-cemented annulus. Three and six injection points for both methods was tested for comparison.

- Conventional cementing systems present a significant challenge regarding achieving long-term integrity. Mainly as a result of its brittleness, limited strength, low flexibility and poor adhesion to other materials. Alternative plugging materials such as thermoset polymers overcomes many of these challenges, by exhibiting higher strength and lower modulus thereby more flexible, and its much higher adhesion to other materials.
- The available remedial methods for repairing a poor cement requires a large intervention workover, which can be both time-consuming and costly. All methods uses cement as plugging material.
- Testing showed that one where able to inject the resin using the manifold and later the CannSeal tool into the well-cemented annulus.
- The resin was set under high injection pressures while curing, and test results showed a significant decrease in gas leak rates. The recorded leak rates was after all certain primary

a function of the ballooning effect. All smaller gaps (microannlunus) present seemed to be properly filled and sealed by the resin.

- On all four cells the measured average gas breakthrough differential pressure including all cells were 25 bar prior to injection, and 130 bar after injection and curing of the resin.
- Both three and six point injection distributed the resin properly both radially and axially throughout the cells. For well-application, six point injection would be preferred for assurance of this displacement in the annulus. Larger injection cross-section will increase the success rate for filling the channels, voids or microannulus(es) present.
- As far as the author is aware, the CannSeal tool is the only available technology on the market run on electrical wireline which can perform a remedial repair of a leaking cemented annulus.
- The resin can be tailored in regards to reactivity (curing time), viscosity and mechanical properties for different annulus conditions.
- Verification of the set and cured resin can potentially under the right circumstances by verified with the newest technology within acoustic tools. Further testing has to be performed.

Chapter 7

Acronyms

BOP Blow Out Preventer

BHA Bottom Hole Assembly

CBL Cement Bong Log

CHFR Cased Hole Formation Resistivity

cP Centipoise

CT Computed Tomography

ECD Equivalent Circulation Density

EOR Enhanced Oil Recovery

HSE Health Safety Environment

JIP Joint Venture Project

LCM Lost Circulation Material

LSU Louisiana State University

MAASP Maximum Allowable Annulus Surface Pressure

MD Measured Depth

MRayl Mega-Rayleigh

NCS Norwegian Continental Shelf

P&A Plug and Abandonment

PP&A Permanently Plug and Abandonment

RIH Run In Hole

RPM Revolutions Per Minute

TCP Tubing Conveyed Perforation

ULV Ultra Low Viscosity

PWC Perforate, Wash and Cement

POOH Pull Out of Hole

SCP Sustained Casing Pressure

TOC Top Of Cement

USIT UltraSonic Imager Tool

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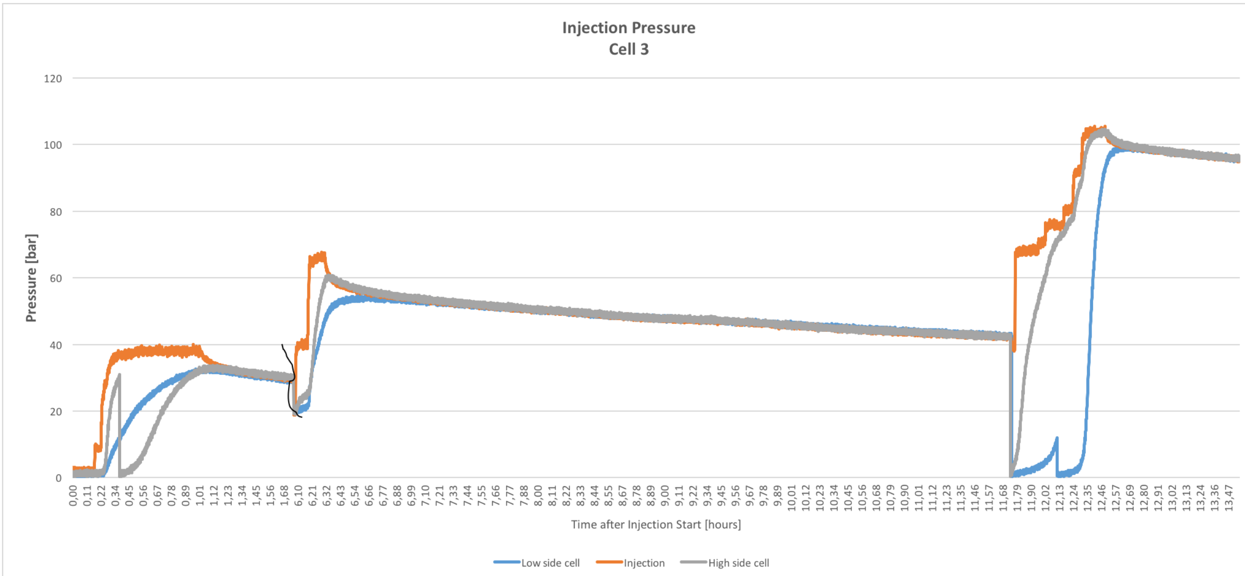
Appendix A

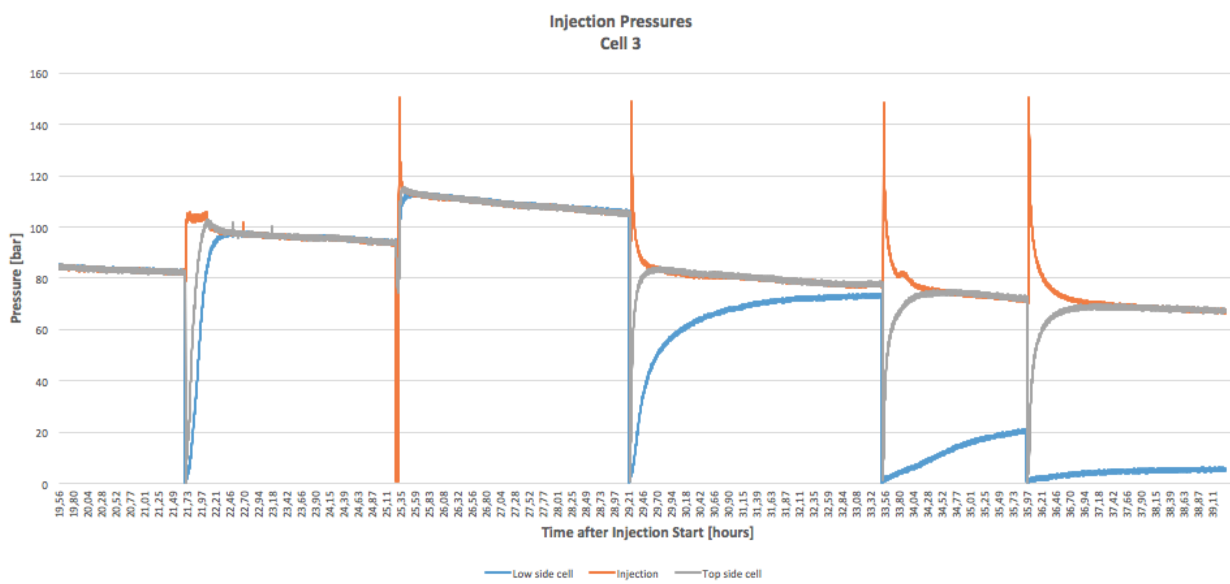
Additional Results

A.1 Injection Pressures

A.2 Leak Testing

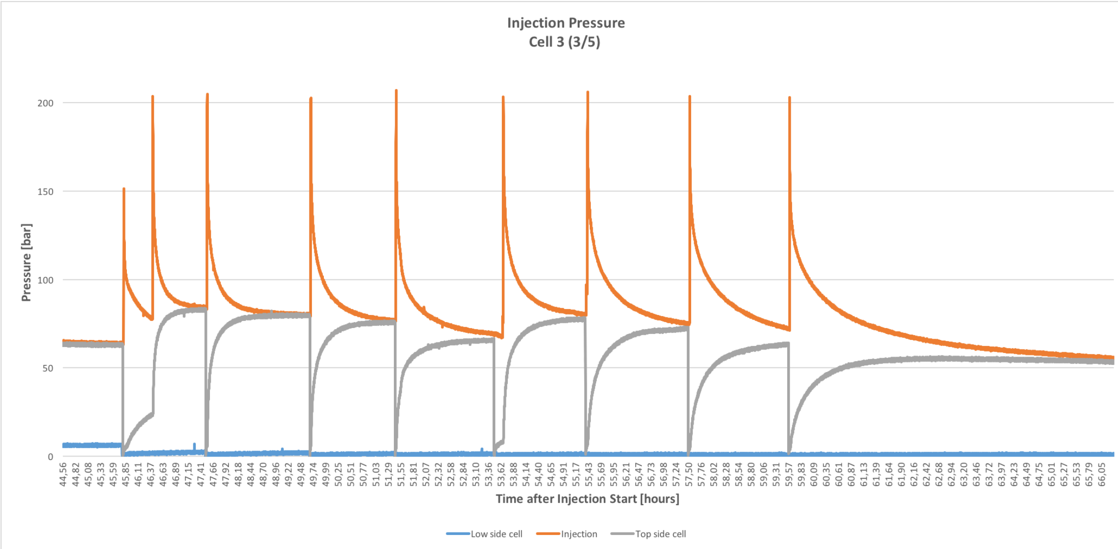


(a) 0 to 13.5 hours.

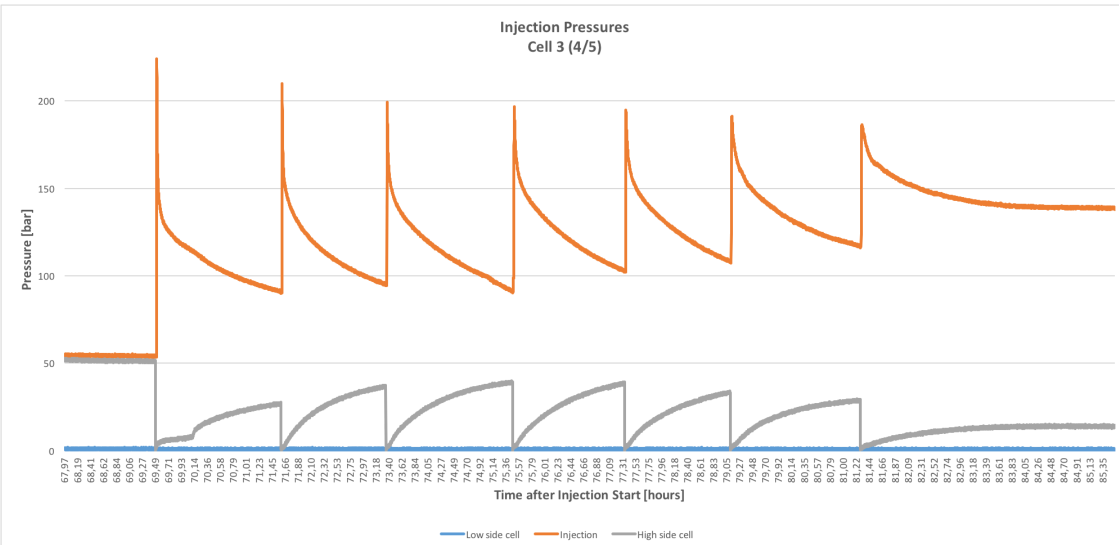


(b) 19.5 to 39 hours.

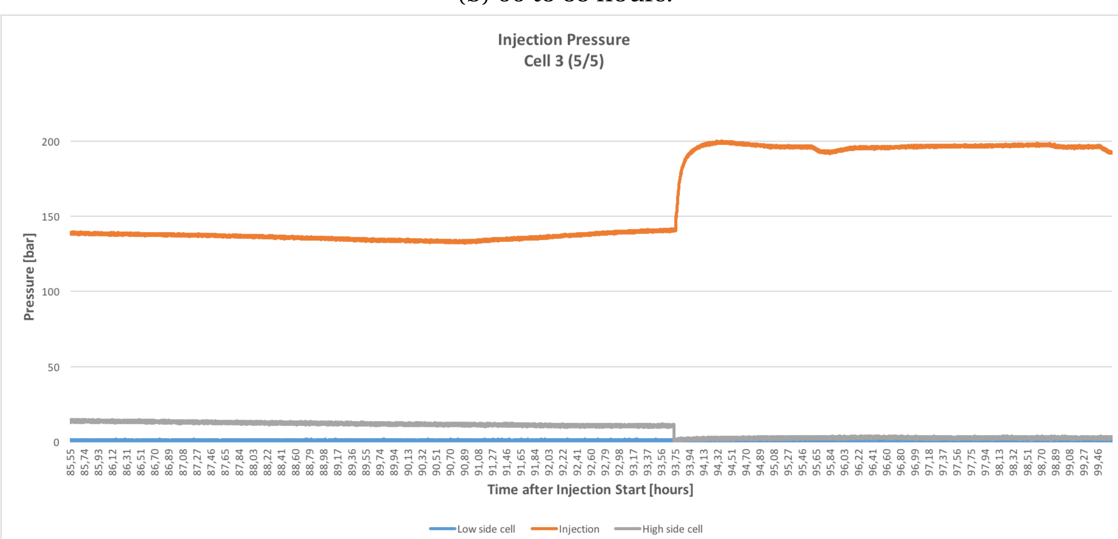
Figure A.1: Injection pressure for cell three from 0 to 39 hours.



(a) 44.5 to 66 hours.



(b) 66 to 85 hours.



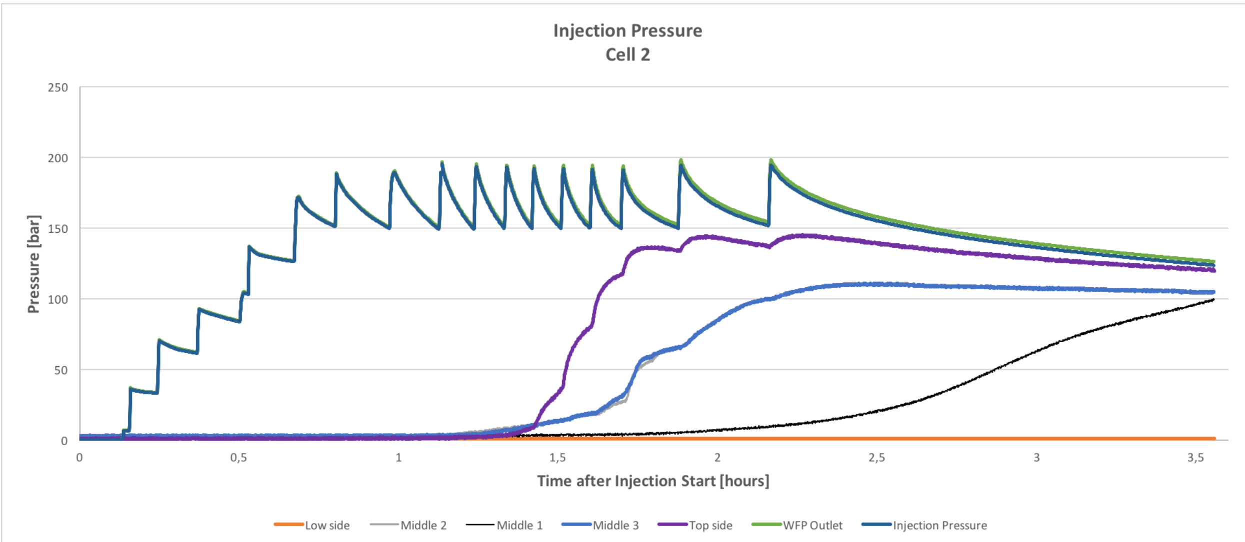
(c) 85 to 99.5 hours.

Figure A.2: Injection pressure for cell three from 44.5 to 99.5 hours.

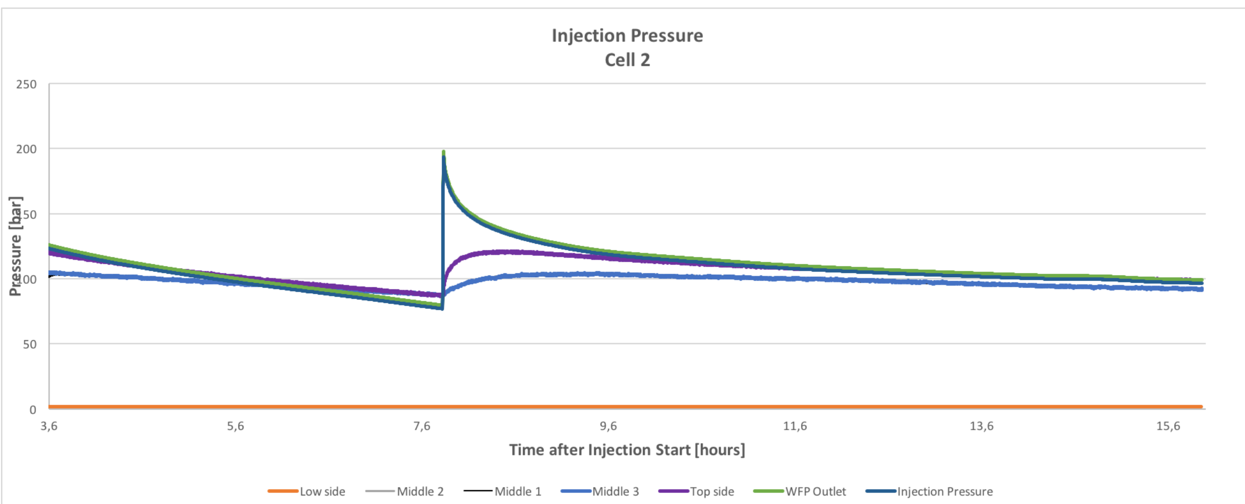
Table A.1: Viscosity measurements for injected resin in cell three and volumes injected. Start of injection was approximately 2 hours after mixing of resin was finished (resin had cured for 2 hours prior to injection).

Time after injection start [hours]	Viscosity Sample – Cell 1 [cP]	Viscosity Sample – Cell 2 [cP]	Resin pumped [L]	Cumulative resin pumped [L]
0.22	32	-	0.3	0.3
0.89	44	-	0.22	0.5
6.32	116	-	0.13	0.63
11.8	280	-	0.38	1.01
22	1244	-	0.15	1.16
25.3	1964	-	0.18	1.34
29.2	3204	-	0.07	1.41
33.6	4000	-	0.078	1.488
36	8000	-	0.076	1.564
45.8	16 000	-	0.026	1.59
46.4	16 000	-	0.096	1.686
47,4	20 000	-	0.09	1.776
49.7	24 000	-	0.086	1.862
51.3	28 000	-	0.086	1.948
53.4	40 000	-	0.098	2.046
55.4	60 000	8 000	0.071	2.117
57.5	112 000	12 000	0.066	2.183
59.57	368 000	16 000	0.05	2.233
69.5	EE	120 000	0.044	2.277
71.5	EE	740 000	0.04	2.317
73.5		2096 000	0.036	2.353
75.5		EE	0.042	2.395
77.5		EE	0.034	2.429
79			0.03	2.459
81.2			0.026	2.485
94			0.018	2.503

EE: The high viscosity spindle on the Brookfield viscometer cannot quantify numbers over 4000 Pa*s (4 000 000 cP).

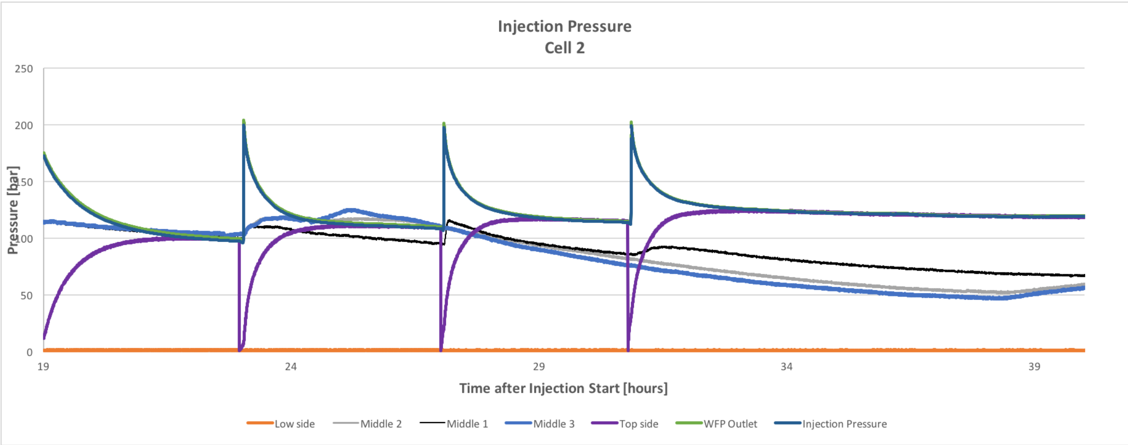


(a) 0 to 3.5 hours.

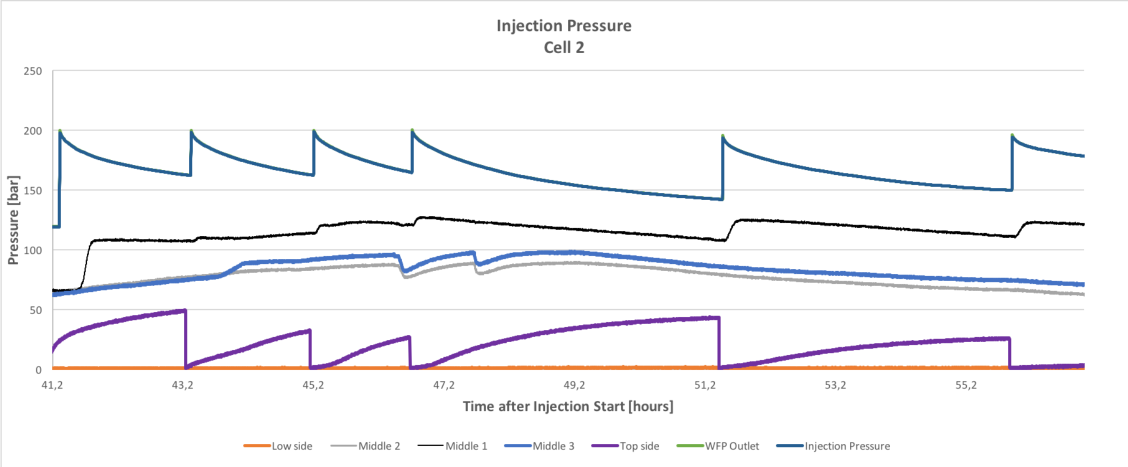


(b) 3.5 to 15.6 hours.

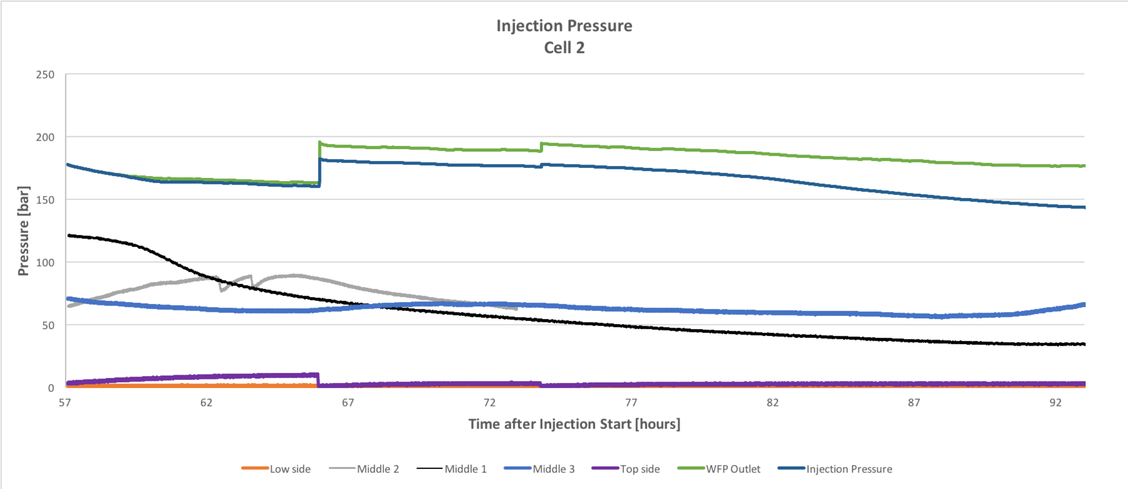
Figure A.3: Injection pressure for cell two from 0 to 15.6 hours.



(a) 19 to 40 hours.



(b) 41 to 57 hours.



(c) 57 to 92.5 hours.

Figure A.4: Injection pressure for cell three from 19 to 92.5 hours.

Table A.2: Viscosity measurements for injected resin in cell two and volumes injected.

Time after injection start [hours]	Viscosity [cP]	Cumulative resin pumped [L]
Start (0)	96	0.46
1	104	0.96
1.75	120	1.27
7.6	310	1.35
19	1512	1.58
22	2492	1.65
27	4000	1.73
31	5867	1.81
41	28 000	1.88
43	32 000	1.92
45	36 000	1.92
48	44 000	1.96
52	624 000	2
56	EE	2.04
72	EE	2.08
77	EE	2.08

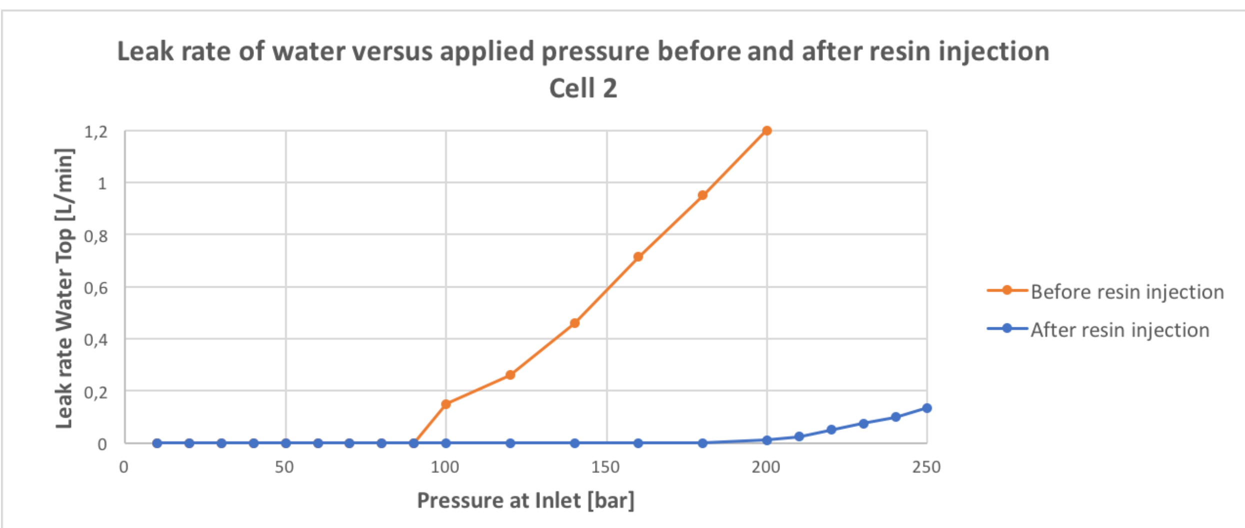


Figure A.5: Leak test with water before and after resin injection for cell two.

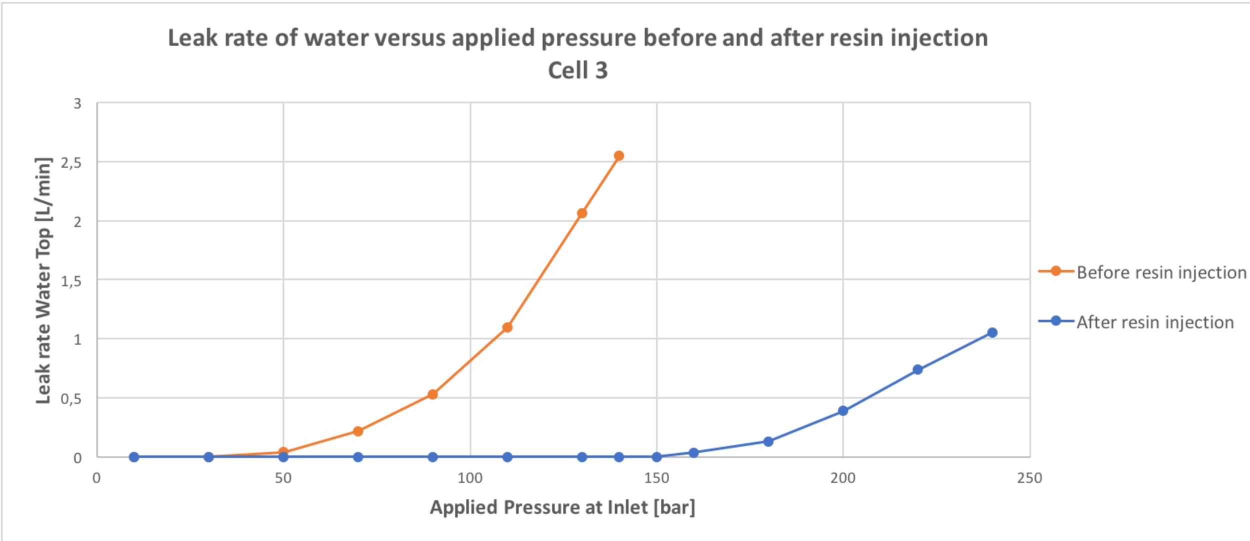


Figure A.6: Leak test with water before and after resin injection for cell three.

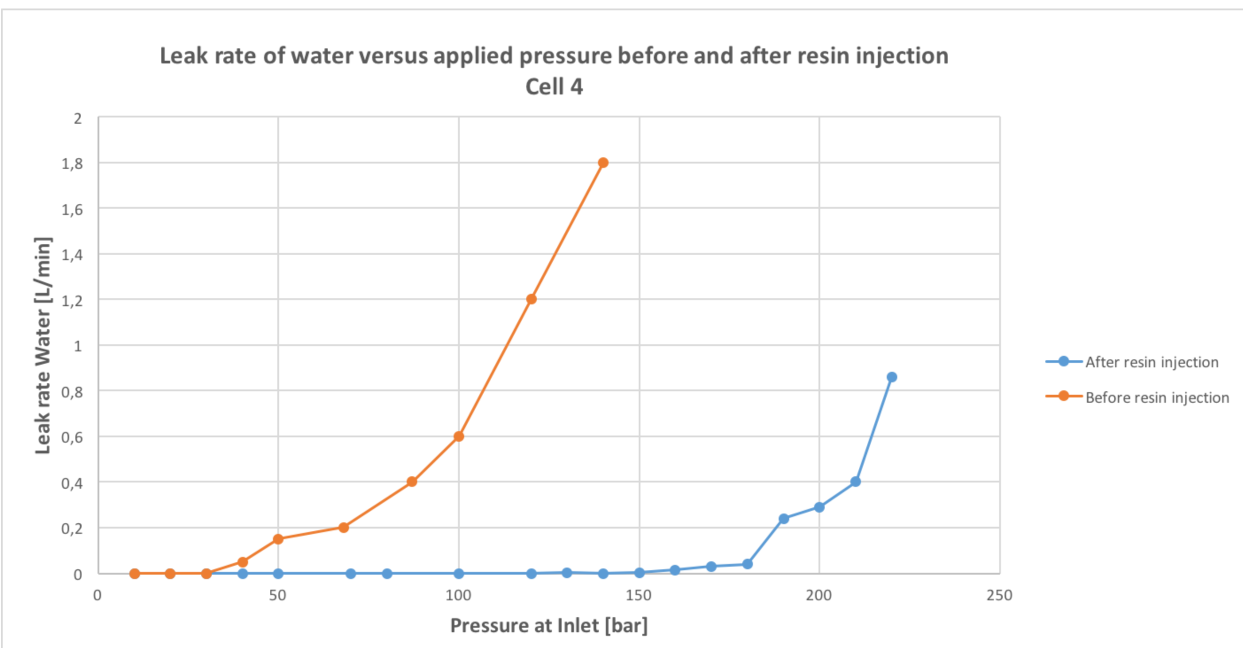


Figure A.7: Leak test with water before and after resin injection for cell four.

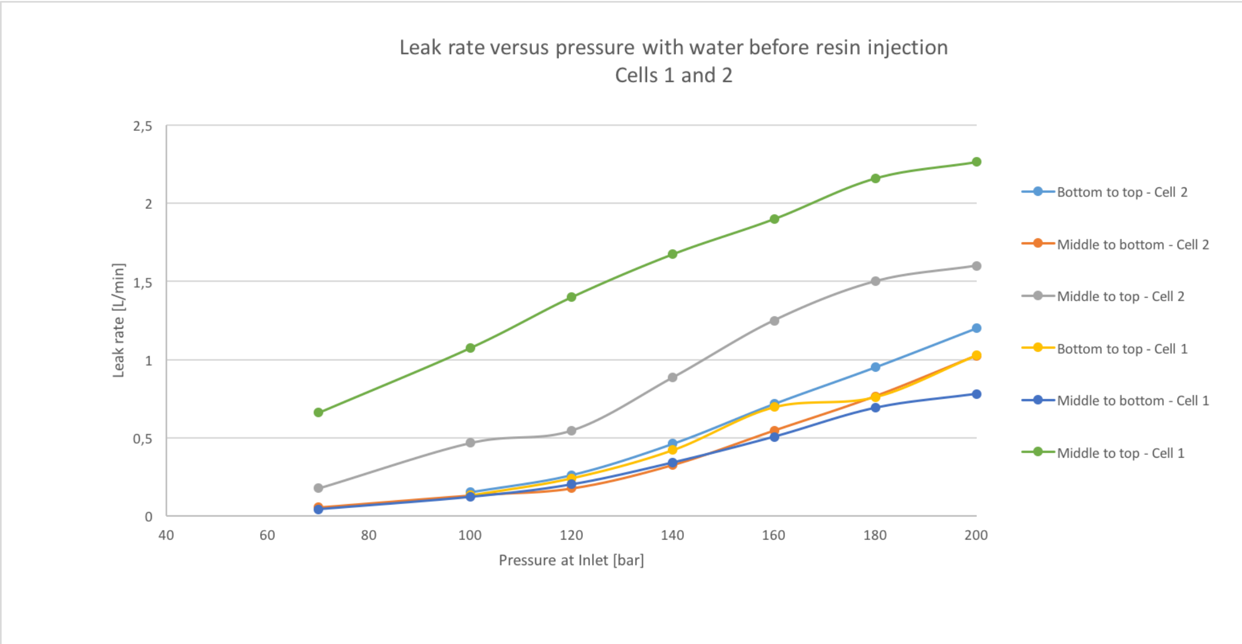


Figure A.8: Leak test with water before resin injection for cells one and two.

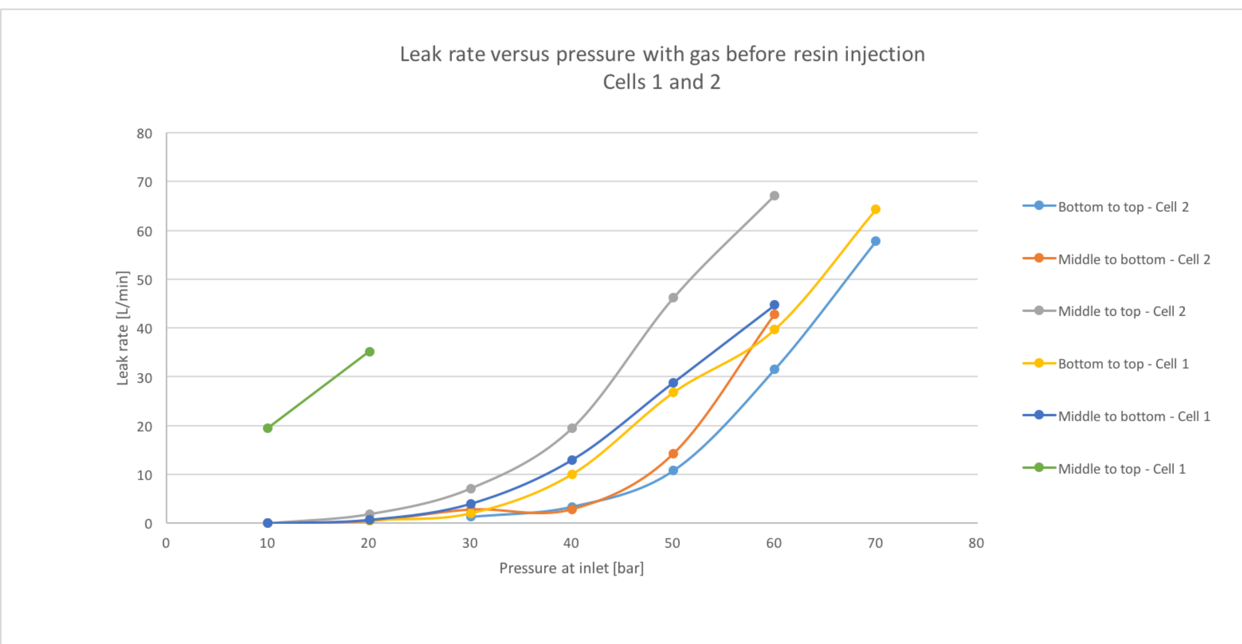


Figure A.9: Leak test with gas before resin injection for cells one and two.

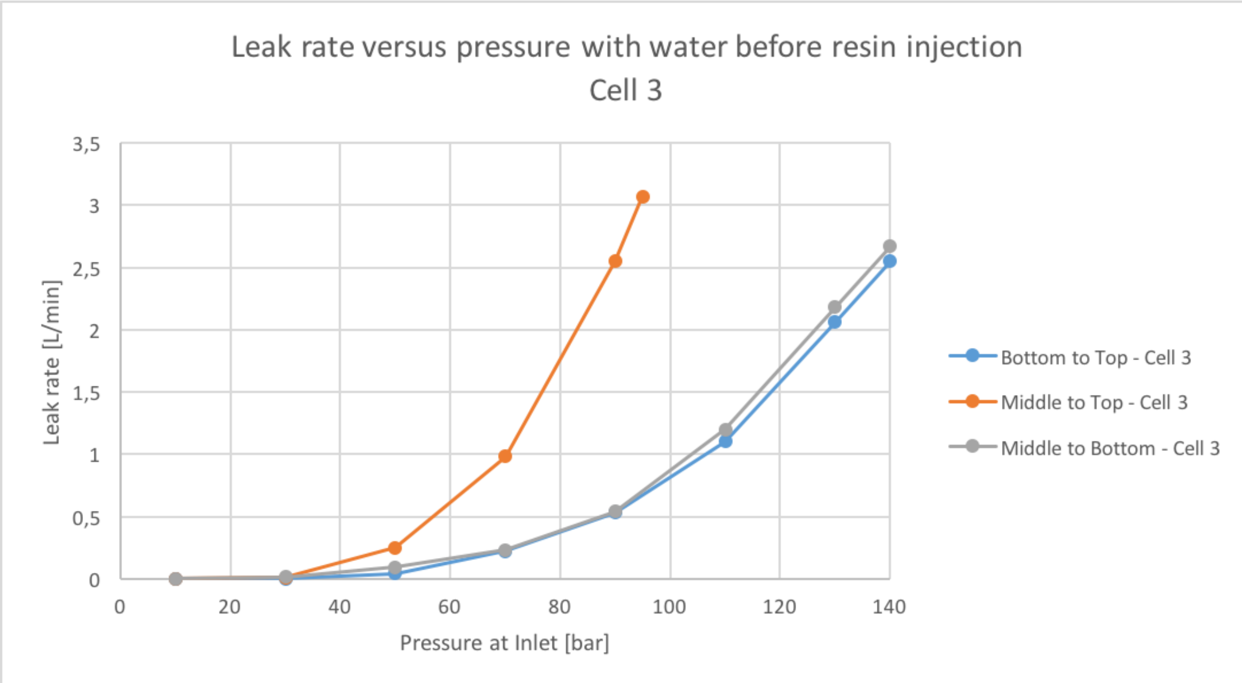


Figure A.10: Leak test with water before resin injection for cell three.

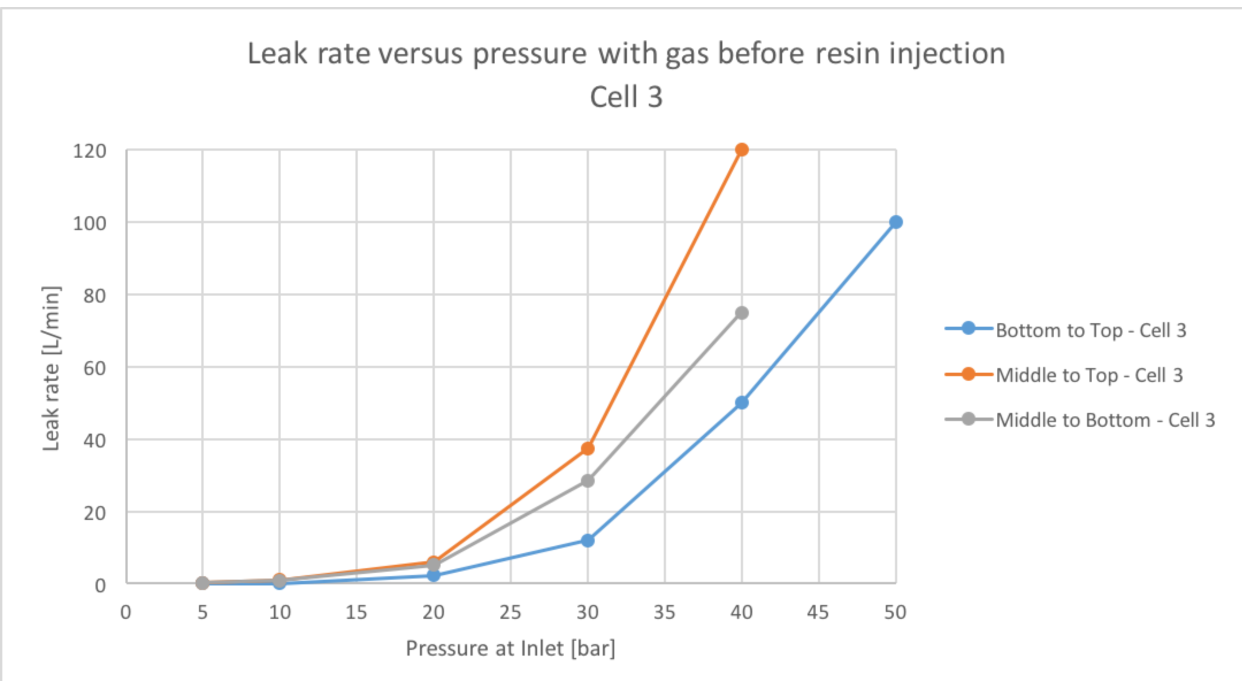


Figure A.11: Leak test with gas before resin injection for cell three.

Appendix B

Cement Evaluation Tools

This appendix is provided as additional information for the interested reader. Giving an introduction to acoustic logging/measurement principles, log-examples and the different technologies available on the market.

Acoustic logging tools use the principle of emitted sound waves which will propagate with certain velocities through different mediums. Different mediums, such as formation, cement, casing and fluids all have different acoustic properties, which is dependent on their elastic properties (e.g Young's modulus (E), shear modulus (G) and Poisson's ratio (ν)).

The two different waves of interest traveling through the cement are compressional and shear waves. The compressional wave propagates faster, it also travels though both solids and fluids, while shear waves don't exist in a fluid. For a linear elastic material, the compressional and shear wave velocities (v_p, v_s) are given by equations B.1 and B.2 respectively [8].

$$v_p = [\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}]^{0.5} \tag{B.1}$$

$$v_s = [\frac{E}{2\rho(1+\nu)}]^{0.5} \tag{B.2}$$

The acoustic impedance of a medium can be obtained by the compressional wave velocity and the mediums density (ρ), given in B.3 [8]. The unit is called mega-Rayleigh (MRayl), equation B.3 is for a homogeneous and nondissipating medium.

$$Z = \rho v_p \tag{B.3}$$

The primary measurements of these acoustic logging tools are the travel time of an elastic wave through the surroundings to yield the velocities or slowness (v^{-1}) of the medium. In tables B.1 and B.2 are different sound velocities and associated acoustic impedance given for different homogeneous fluids and cement formulations respectively. When logging cement, the physical properties will change over time in regards to hydration and/or damage to the cement.

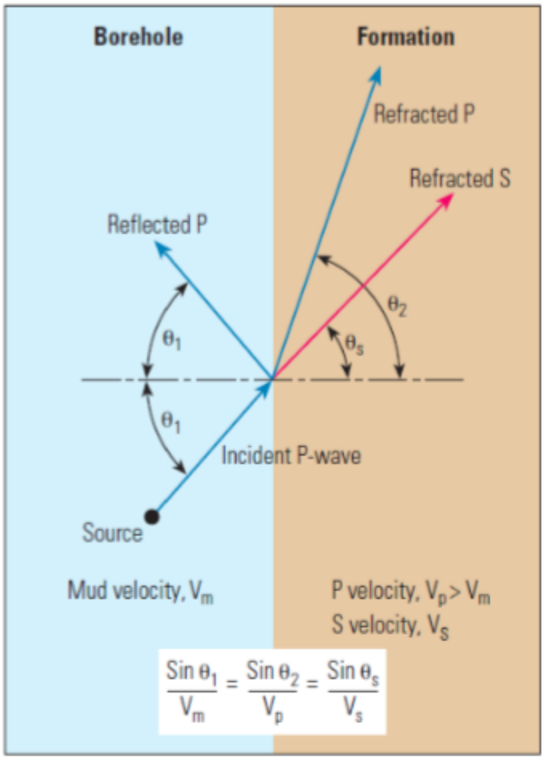
B.1 Head Wave

This wave is critically refracted and will travel along the borehole, radiating energy back to the tool in the wellbore. A head wave can be created along any boundary (between two different materials) if the velocity in the entering medium (V_2) is larger than the abandoned one (V_1). The angle at which is refracted along the interface is called the critical angle (θ_c), it can be quantified by application of Snell's law given in equation B.4 with associated graphical description in figure B.1a.

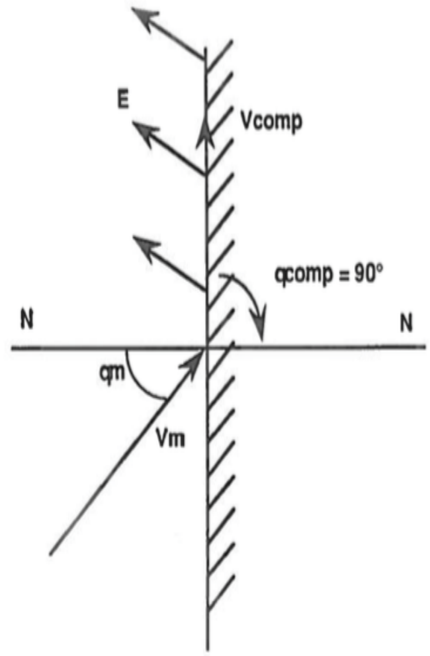
$$\frac{\sin\theta_1}{V_1} = \frac{\sin\theta_2}{V_2} \tag{B.4}$$

When the wave is refracted along the interface between two materials, $\theta_2 = 90°$ and $\sin\theta_2 = 1$. The angle of incident (θ_1) is then referred as to the critical angle θ_c given in equation B.5.

$$\sin\theta_c = \frac{V_1}{V_2} \ (where \ V_2 > V_1) \tag{B.5}$$



(a) Wavefront reflection and refraction at interfaces (same principle when borehole and casing).



(b) The refracted angle (θ_2) reaches 90°.

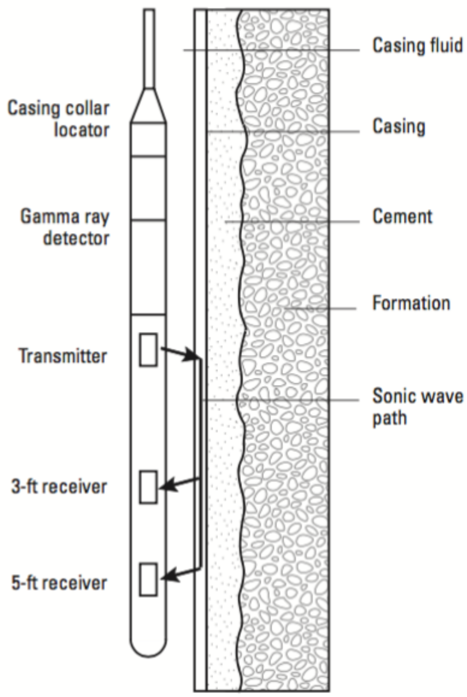
Figure B.1: Creating a head wave in the borehole [43].

The head wave enables the cement evaluation tools gathering information about the state of the annulus.

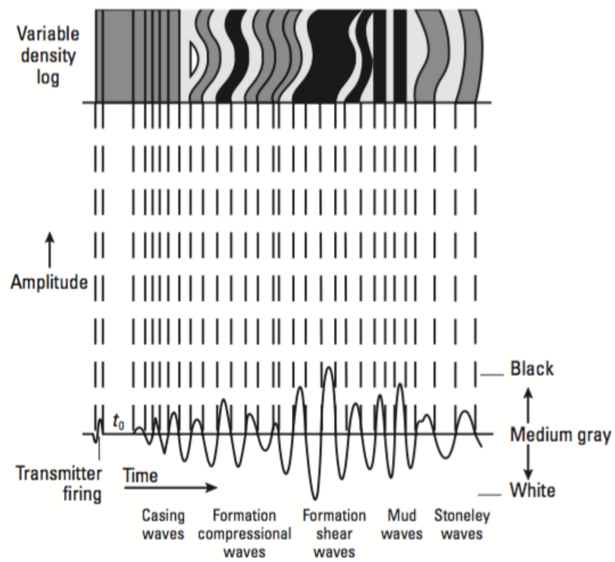
B.2 Cement Bond Log (CBL)

The CBL is combined with a Variable Density Log (VDL), to asses the quality of the cement behind the casing. The tool consists of one transmitter that emits bursts of sound and two receivers at different spacings, shown in figure B.2a. In-between transmitting each burst, the receiver picks up the signal and make the bond-log measurement [8]. The emitted sound wave will propagate in 360°, the different arrivals (normally seen) are given in figure B.2b.

Figure B.2b shows that the first arrival will be from the casing string, secondly refractions from the formation, then the mud-waves and the Stoneley waves (fracture detection). Each wave has



(a) CBL-VDL tool.



(b) Complete waveform signa.l

Figure B.2: Showing the CBL-VDL tool configuration and received waveform signal [8].

a specific amplitude (as a result of attenuation) depending on the properties of the medium, the VDL displays this as a function of time, recorded from the furthest spacing (5-ft receiver). The CBL is the amplitude of the first casing arrival measured at the first receiver (3-ft).

The casing to cement bond is indicated by low amplitude on the refracted casing wave, as much energy will dissipate into the cement. If a microannulus containing a fluid is present at the casing-cement interface, this will have a strong effect on the signal as much less energy will dissipate into the surroundings. If the CBL shows a high amplitude (the casing is "ringing"), this is an indication that the cement is not in contact with the casing. The VDL can in combination with the CBL give quantitative information about the state of the annulus. The recorded amplitude of the casing wave is a function of shear coupling between the interfaces of casing and cement (or fluid) [40]. The greater the shear coupling, the greater is also the loss of energy into the adjacent materials. For fluids, there is no shear coupling, so minimal attenuation of the casing signal.

The VDL can help discriminate between casing and formation arrivals [8]. A casing arrival would be indicated with high amplitude with early arrival (at transit time) at the VDL log (see figure B.2b). The absence of this arrival together with seen formation arrival (wavy patterns, due to different acoustic properties in the formation) are both good indicators of good acoustic coupling between the cement-casing and cement-formation. This given that good coupling between cement and the casing.

The CBL can give information about the Bond Index (BI) of cement to the casing, by the principal of attenuation rate which has been identified to have a close linear relationship to the cement bonding. This relationship is given equation B.6 below.

$$BI(\%) = \frac{E_{fp} - E_{meas}}{E_{fp} - E_{100\%cem}} \tag{B.6}$$

[8]

where

E_{fp} is the CBL amplitude corresponding to 100 %

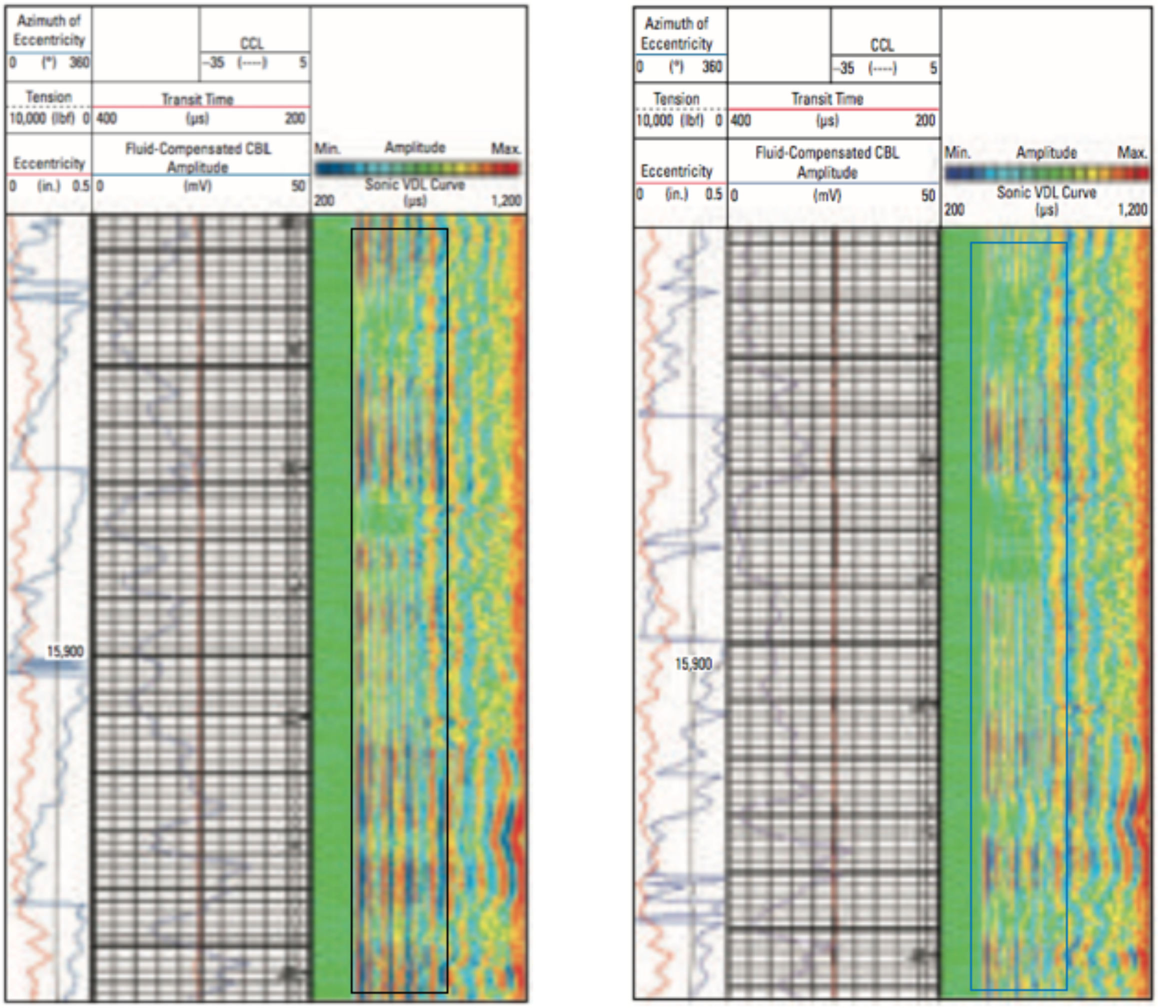
$E_{100\%cem}$ CBL amplitude with free pipe

E_{meas} is the measured CBL amplitude

The BI is not directly related to hydraulic isolation, so even a BI = 100 % does not mean that fluid migration does not occur. The CBL only gives information about bonding and state of the cement against the casing, not deeper into the annulus.

A microannulus present between the casing and cement can be detected by a CBL-VDL, by running two separate passes of the zone of interest, with and without applied borehole pressure. Figure B.3a shows the effect of a microannulus by weak to moderate casing arrivals (market in black), implying that little energy is lost to the adjacent cement. After the internal pressure of the casing is increased, another pass is performed given in figure B.3b. Here the casing arrivals are either disappeared or reduced significantly (marked in blue), the CBL before and after also shows to be significantly reduced.

When channeling, pressurizing the casing will produce little or no change in the CBL amplitude



(a) Before applied pressure.

(b) Pressurized casing.

Figure B.3: CBL-VDL showing the effect of microannulus between the casing and cement [8].

or VDL [21]. Thereby, can be differentiated if have microannulus present or channeling.

Some of the main factors affecting the bond quality are centralization of the casing, borehole fluid, fast or slow formations and the properties of casing and cement.The CBL-VDL gives general information about the "health" of the cement in the annulus, however smaller channels or microannulus are not easily identifiable. As a result of the general averaging of values and the cement composition itself not being truly homogenous, creating density differences that can obscure the logs.

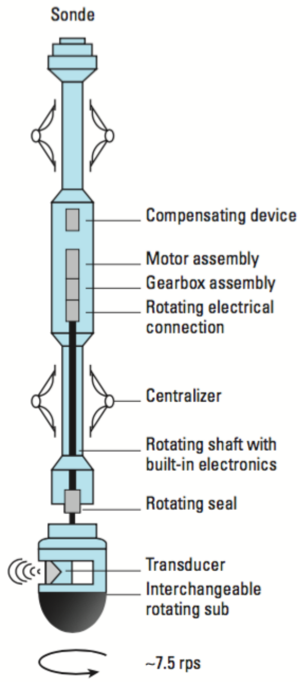
One of the main limitations of the CBL-VDL (including the other available cement evaluation tools) is the inability to provide information about the cement's hydraulic bond quality (sealing ability) in the annulus.

B.3 Ultrasonic

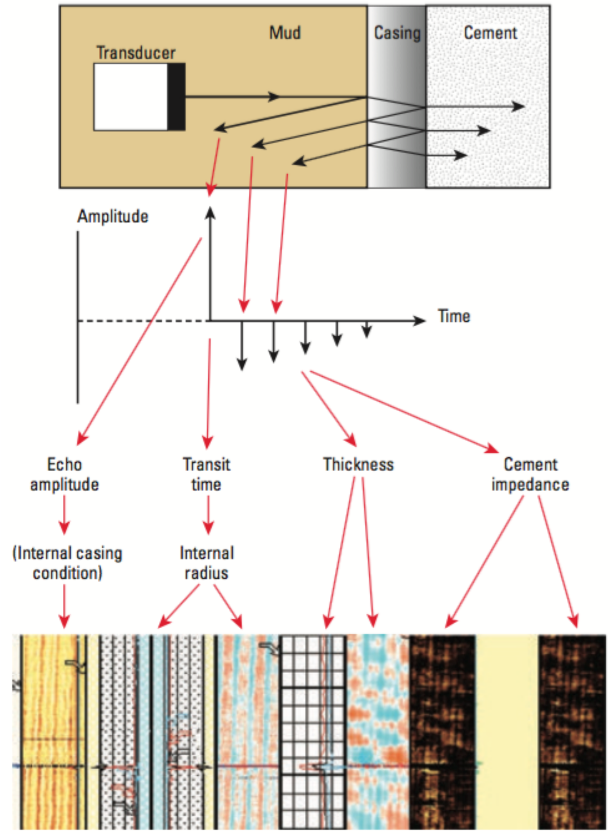
The ultrasonic tools in comparison to the CBL emits pulses of much higher frequency (200 - 700 kHz compared to 20 - 30 kHz) [8]. The new generation of these tools are USIT (Ultrasonic Imager Tool) and Isolation Scanner from Schlumberger [41] and CAST-V from Halliburton [23]. Both using the principle of a single rotating transducer to achieve full coverage of the pipe wall. The USIT from Schlumberger is shown in figure B.4a. The difference in the measurements itself between a CBL and USI tool is that CBL measures the amplitude or attenuation of a wave traveling along the casing, while ultrasonic tools measure the acoustic impedance of the mediums in contact with the casing.

The basic principles of ultrasonic cement evaluation are emitting these high energy pulses (ultrasonic echo pulses) against a small area of the casing, making if resonate through its thickness [8]. The pulse will have an exponential decay in the reflected echo, which is controlled the acoustic impedance of the cement (or medium behind the casing) and the mud in the wellbore. Knowing the mud impedance (obtained real-time from separate measurement), enables the extraction of the cement impedance [48]. Figure B.4b shows the ultrasonic transducer and the different travel paths, interfaces and resulting information.

The transducer emits a high-frequency pulse, shown in figure B.4b. First ultrasound travels through the fluid in the wellbore to the casing wall. When comes into contact with the casing, the majority of energy is reflected back to the transducer, while some are refracted through the casing. The first signal back to the transducer arrives at the transit time and gives information about the internal diameter of the pipe (and general condition of the casing surfaces) [24]. The amount of energy reflected versus refracted depends on the acoustic impedance contrast between the two mediums, given in equation B.7. Where Z_2 and Z_1 are the acoustic impedances for outer and inner medium respectively, obtained from equation B.3. Due to the high contrast of acoustic impedance between the borehole fluid and the casing, much is reflected. The energy refracted through the casing, will again meet the interface between casing-cement where again



(a) Schematic of the USIT.



(b) Ultrasonic principle and measurement.

Figure B.4: Showing a general tool schematic of the USIT from Schlumberger with the basic principles and measurements [8].

some energy is reflected or refracted. This continues until the returning signal is to low to detect.

$$K_{ref} = \frac{Z_2 - Z_1}{Z_2 + Z1} \tag{B.7}$$

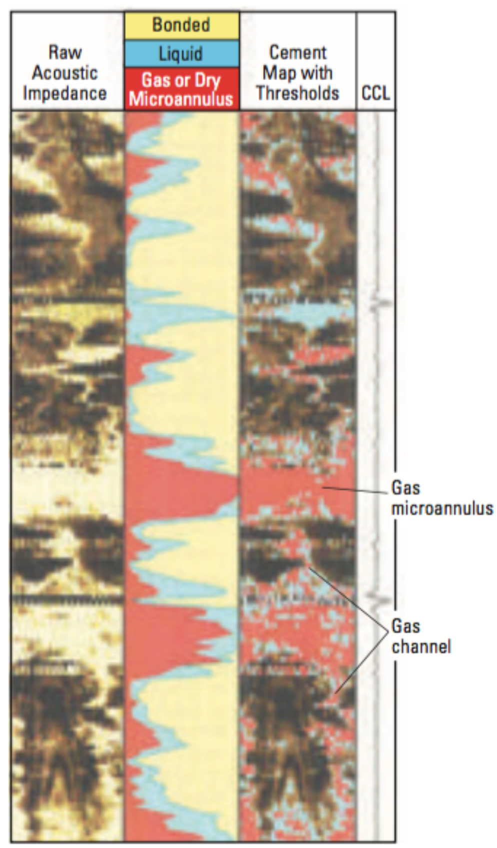
[8]

Figure B.5b shows a USI-log with microannulus and channels of gas. Gas can be distinguished from cement as a result of having different acoustic impedances, the threshold is given in figure B.5a for the Schlumberger USIT. By knowing the different impedance values for cement, liquid and gas the ultrasonic log - interpretation differentiates between them. Gas have a impedance value below 0.1 MRayl, liquids has impedance values between 1 to 3 MRayl. Neat cement has approximately a value of 6 MRayl, while light-weight cement can have as low as 2.5 MRayl, therefore crossing the liquid range [8]. Such cement do impose interpretation difficulties, however, new technology introduced by Schlumberger with Isolation Scanner has aimed to resolve this issue.

One of the main limitations of the USI-tools is the shallow depth of investigation in the radial direction, where cannot image defects within the cement sheath itself or at the cement - formation interface, where migration of fluids frequently occurs. The set limits (thresholds) of acoustic impedances to distinguish between solid, liquid and gas can result in interpretation challenges. Especially regarding light-weight cement (densities around or lower than water) and contaminated cement (with mud lowering the acoustic impedance). The accuracy of acoustic impedance measurements is approximately 0.5 MRayls, so to differentiate between fluid and cement impedances need at least 1.0 MRayls difference [48].

Material	Color	Impedance Image Range (MRayl)
Gas	Red	0–0.38
Gas-cut liquid	Light blue	0.38–1.15
Liquid	Blue	1.15–2.30
Solid-liquid transition	Yellow	2.30–2.70
Low-impedance cement	Light brown	2.70–3.85
Medium-impedance cement	Dark brown	3.85–5.00
High-impedance cement	Black	>5.00

(a) USIT impedance image ranges.



(b) USI logging showing presence of gas microannulus and channel.

Figure B.5: The different thresholds for acoustic impedance and USI log with these applied[8].

B.4 Flexural Wave - Isolation Scanner

A flexural wave is created by a dipole source (instead of monopole which creates compressional wave), this is essentially an alternating sound signal that creates a relative higher shear wave once it reaches the casing. When the flexural wave reaches the casing and creates a head wave, it will "leak" a wave into mediums present on both sides, just as the compressional wave does. This causes attenuation of the signal, that is sensitive to the mechanical properties of the inner and outer mediums. The overall flexural attenuation is the sum of attenuation of the borehole fluid and of the material present in the annuli [48].

The flexural wave will create a faster shear wave into the material than a compressional wave. For a flexural wave to radiate into the cement as a compressional and shear wave, the cement compressional or shear velocity must be less than the flexural phase velocity [48]. Radiation of flexural wave into annulus containing water, slow and fast cements are shown in figure B.6.

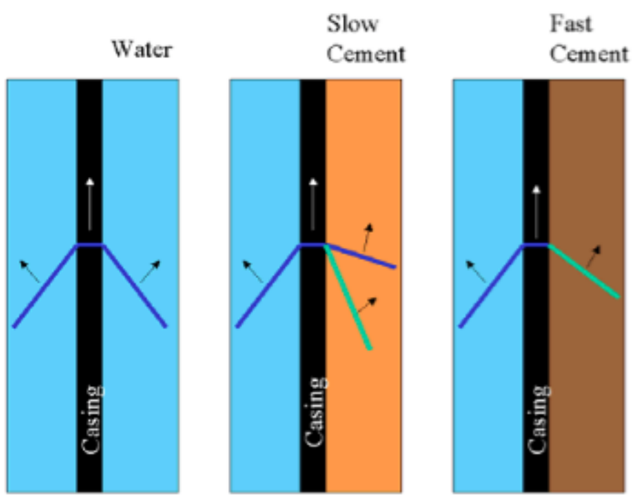
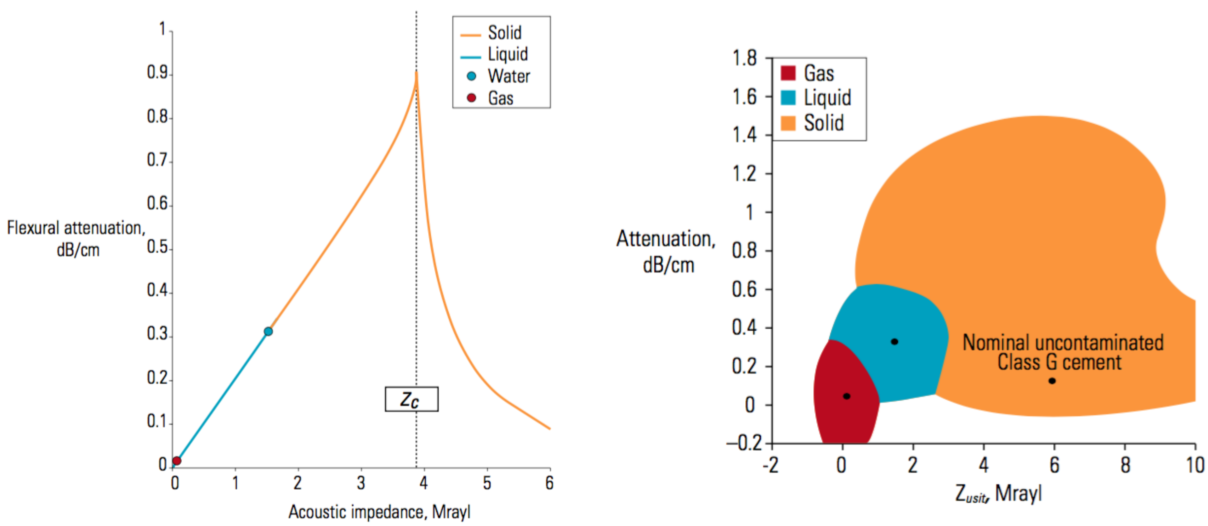


Figure B.6: Radiation of flexural wave into water, slow and fast cements. For "slow cement", both the compressional and shear velocity are smaller the flexural phase velocity. For "fast cement" only shear wave velocity is smaller than the flexural phase velocity [48].

For a dipole transmitter creating a flexural wave with 200 kHz, it will have approximately the velocity of 2650 $\frac{m}{s}$ [48]. For creating a compressional and shear wave in the cement, the V_p and V_s in the cement needs to be smaller than this (which will depend on its elastic properties, see equations B.1 and B.2). The shear wave in cement are always smaller than 2650 $\frac{m}{s}$, this is however not always the case for compressional wave velocity, such as with "fast cements" or cements with high elastic moduli (see table B.2). When a compressive wave cannot be radiated into the cement annulus this will decrease the flexural attenuation, which is dependent on radiated compressive and shear waves attenuation in the annulus.

The Isolation Scanner from Schlumberger [38] combines the conventional pulse-echo (USI) technique with a second mode, the flexural wave attenuation. The fluid in the borehole exhibits an approximately linear trend between flexural attenuation and the acoustic impedance. For cement bonded to the casing, the attenuation exhibits a more complex behavior as a function of the velocities at which the compressional and shear waves propagate in the cement [38]. The relationship between flexural attenuation and acoustic impedance is given in figure B.7a.



(a) Flexural attenuation vs. acoustic impedance

(b) SLG mapping

Figure B.7: Data processing of flexural attenuation and acoustic impedance for cement evaluation purposes [38]

Below approximately 3.9 MRayl, the flexural attenuation increases linearly with the impedance (whether liquid or solid). However, above this acoustic impedance value, only shear waves propagate in the cement, the reason being that compressional wave velocity of the cement is larger than the flexural phase velocity ($\sim 2650 \frac{m}{s}$). This results in a significant drop in the flexural attenuation, resulting in an attenuation value corresponding to two impedance values (for example liquid and a high-impedance cement), therefore this measurement cannot distinguish between liquid and solid as a stand-alone measurement.

The USI-tools set thresholds of impedance values for differentiating between solid, liquid and gas. This is especially problematic for light-weight cements and liquids, where impedances can be very similar. However, by utilizing a flexural attenuation, there is a distinct flexural attenuation of a low-impedance cement, such as lightweight or contaminated cements, is used to differentiate them from fluids [38].

The flexural attenuation gives information about the medium in contact with the casing and does not probe information about cement sheath deeper in the annulus. However, the pulse being radiated into the annulus will travel through the annulus media and be reflected by the third interface, the cement-formation interface. This can provide information about casing position(s) within the borehole, that also gives second-hand information about potential channeling issues due to fluid traveling the way of easiest resistance path.

Solid-liquid-gas (SLG) map is computed before logging commences, such a map is given in figure B.7b. This is done by using previous knowledge about acoustic impedance values of different mediums and requires a model for the flexural attenuation. The measured flexural attenuation and impedance values are then mapped according to the pre-computed SLG map, providing information about which medium is present in the annulus.

The main limitation with today's cement evaluation tools (including the Isolation Scanner) is the inability to provide information about cracks in the cement sheath itself, or mud-channels and microannulus present at the cement-formation interface. However, by combing conventional USI and flexural wave attenuation gives a much more robust method for distinguishing between light-weight cement and fluids. therefore also low-density materials such as thermoset polymers.

B.5 Acoustic Properties of Different Fluids and Cementing Systems

Below are tables B.1 and B.2 provided giving among other things the slowness and acoustic impedances of different fluids and cementing systems.

Table B.1: Acoustic properties of various homogeneous fluids [8].

Material	Density (lbm/gal [kg/m^3])	Slowness (μs/ft)	Velocity ft/sec [m/sec])	Acoustic Impedance (MRayl)
Water	8.33 [998]	206	4,860 [1,482]	1.48
Water + 10% NaCl	8.98 [1,075]	193	5,180 [1,580]	1.70
Water + 25% NaCl	9.90 [1,186]	175	5,710 [1,740]	2.06
Water + 36% $CaCl_2$	11.3 [1,350]	170	5,870 [1,790]	2.42
Water + KCl	9.18 [1,100]	189	5,280 [1,610]	1.77
Water + 58% $CaBr_2$	15.2 [1,824]	179	5,580 [1,700]	3.10
Sea water	8.56 [1,025]	199	5,020 [1,531]	1.57
Kerosene	6.74 [808]	230	4,340 [1,324]	1.07
Diesel	7.09 [850]	221	4,530 [1,380]	1.17
Air at 15 psi, 32°F [0°C]	0.01 [1.3]	920	1,090 [331]	0.0004
Air at 3,000 psi, 212°F [100°C]	1.59 [190]	780	1,280 [390]	0.1

Table B.2: Acoustic properties of various cement formulation [8].

Slurry Type	Density (lbm/gal [kg/m^3])	Time (days)	Sound Velocity in Cement (m/s)	Acoustic Impedence (MRayl)	Change in Acoustic Impedence Over 1 Day (%)
Neat Class G	15.8 [1.89]	1 2 7	3,000 3,250 3,400	5.68 6.16 6.44	0 8 13
Class G + latex + hollow silica microspheres	11.2 [1.34]	1 2 7	1,650 2,200 2,500	2.21 2.95 3.36	0 33 52
Class G + soluble silicate extender	12.0 [1.44]	1 2 7	1,600 1,750 2,000	2.30 2.52 2.88	0 9 25
Class G + hollow silica microspheres + 4% $CaCl_2$ (BWOC†)	12.0 [1.44]	1 2 7	2,600 2,800 3,000	3.74 4.03 4.32	0 8 16
Class G + soluble silicate extender	13.3 [1.59]	1 2 7	1,750 2,200 2,500	2.79 3.51 3.99	0 26 43
Class G + latex	15.8 [1.89]	1 2 7	2,900 3,150 3,350	5.49 5.97 6.35	0 9 16
Class G + 18% NaCl (BWOW‡)	16.1 [1.93]	1 2 7	2,850 3,200 3,375	5.50 6.18 6.51	0 12 18
Class G + hematite weighting agent	19.0 [2.28]	1 2 7	3,300 3,400 3,530	7.59 7.74 8.04	0 2 6
36% quality foam	10.0 [1.20]	7	2,300	2.76	–§
Conventional low-density system	12.51 [1.50]	7	2,000	3	–
Engineered-particle-size low-density system	10.0 [1.20]	7	2,900	3.48	–
Engineered-particle-size ultralow-density system	8.61 [1.03]	7	2,790	2.87	–

† By weight of cement
‡ By weight of water
§ Not available.

Appendix C

Remedial Methods

This appendix is meant as a supplement for Subsection 2.3.3 in Chapter 2. For the attentive reader, there will be parts that have already been discussed, however, this part is provided to give a more thorough overview of the different methods.

C.1 Squeeze Cementing

Squeeze cementing forces the cement slurry under pressure through perforated holes in the casing or the liner into holes, gaps or channels in the annular space. This method has several different applications, some of these are listed below.

- Repairing improper zonal isolation (due to mud-channeling, insufficient cement height in annulus etc)
- Eliminate intrusion of unwanted fluids
- Repair casing leaks caused by corroded or split pipe
- Abandon a nonproductive or depleted zone
- Seal lost-circulation zones
- Plug one or more zones in a multizone injection well to direct the injection into desired intervals

[7] & [30]

The perforations prior to cementing will penetrate a short distance into the formation. The cement slurry consists of both an aqueous phase and solid particles. The particles will form a filtercake at the interface between the permeable formation and the perforations. This will eventually enable the water from migrating into the formation and the dehydrated cement can settle, shown in figure C.1. The fundamental concept of squeeze cementing is that the initial seal is formed by the cement filter cake [47].

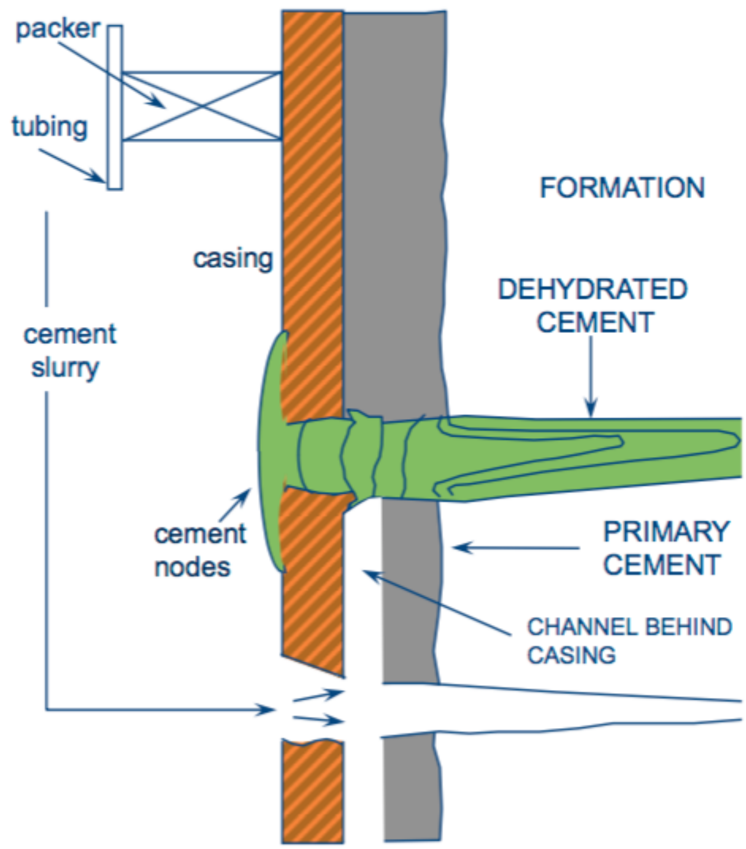


Figure C.1: Showing injection of cement slurry into perforation in a squeeze cementing operation [30].

Selecting the optimum slurry is very important for performing a successful squeeze operation (as with all cementing operations). An injection test is performed prior to the slurry is mixed and pumped, and it is not uncommon that the cementing engineer has different slurry candidates for selection of final slurry [8]. In brief notes, an injection test involves pumping a fluid (typically water) into the well for obtaining information about if the perforations are open, estimates of cement slurry injection rates and expected pressure that should be pumped with. As well as estimates of slurry volume and which kind of cement characteristics should be used.

The slurry used in a squeeze cementing operations normally has the following characteristics; low viscosity (so can penetrate small cracks), fluid-loss control (ensure optimal filling of cracks and perforations), appropriate cement particle size (regarding filtercake generation) and proper thickening time [8].

The different squeezing techniques can be divided into the following shown in figure C.2.

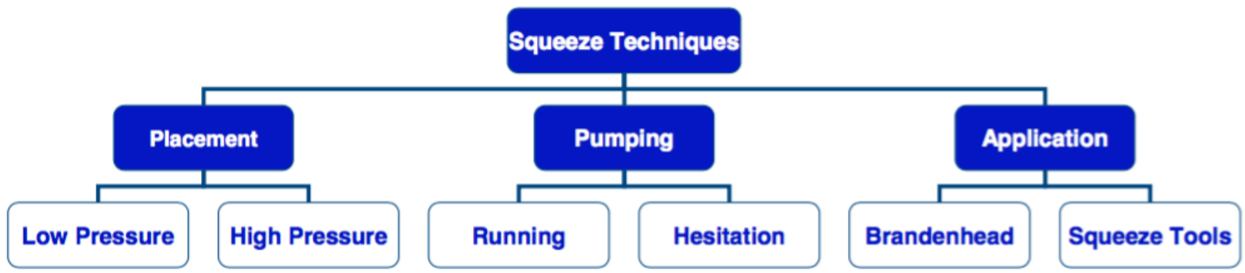


Figure C.2: General overview of squeeze cementing techniques [30].

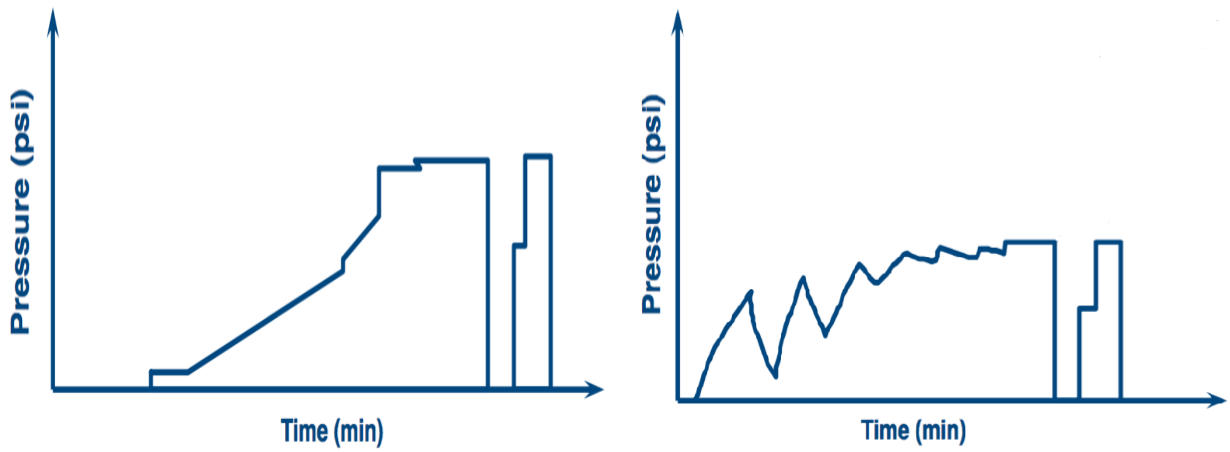
C.1.1 Low-or High-Pressure Squeezes

The difference lies in whether fracturing the formation or not. For the low-pressure squeeze, the formation is not fractured. Use of this method relies on if the perforations and channels are cleared of mud or other solids, if not proper zonal isolation will most likely not be achieved. If "dirty" wellbore fluids or old mud needs to be displaced, or channels are not interconnected with the perforations, a high-pressure squeeze needs to be conducted. Here both the formation and cement close to perforations are fractured, allowing for displacement of fluids and opening up to small cracks present in cement sheath.

C.1.2 Running or Hesitation Squeeze Method

For the running squeeze method pumping is commenced until reaching a pre-determined squeeze pressure, which can be above or below the fracture gradient. After this pressure is reached, pumping stops. If a declining pressure is observed, pumping is maintained until stabilized desired pressure is observed, this sequence is shown in figure C.3a.

For the hesitation squeeze method pumping is performed in intervals. Because during a squeeze operation it can be difficult having control of pressure downhole, especially regarding not exceeding the fracture gradient. The main reason is that filtrate fluid loss is lower than minimum pumping rate [8]. Therefore, a solution is observing the pressure and stopping when appropriate for letting fluid migrate into the formation until a sufficient filtercake allows cement to settle at a pre-determined pressure, shown in figure C.3b.



(a) Running squeeze method.

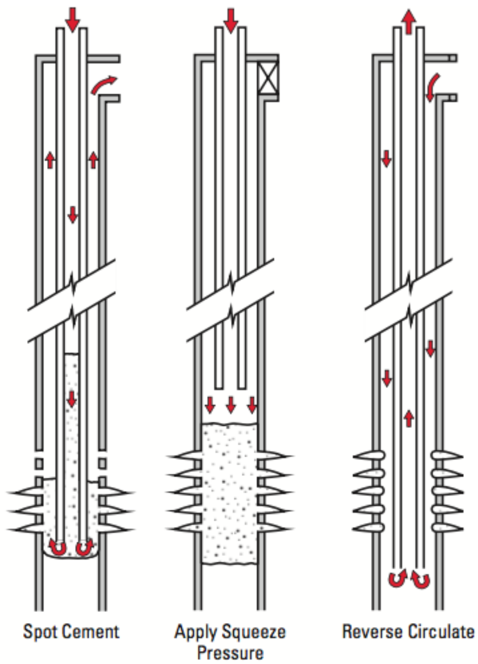
(b) Hesitation squeeze method.

Figure C.3: Graphical representation of pressure versus time [30].

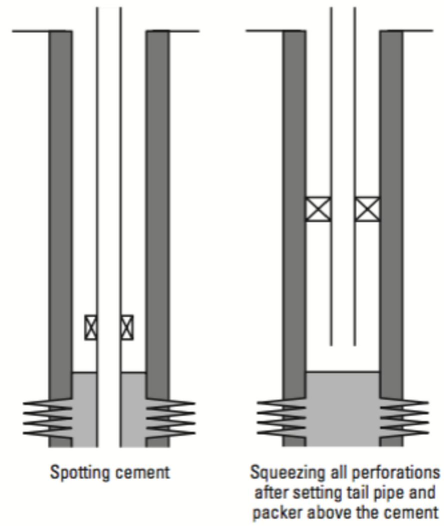
C.1.3 Bradenhead (no packer) Squeeze or Application of Squeeze Tools

The bradenhead squeeze is a low-pressure squeeze method, with where no packer is used. The casing if first perforated, then an open-ended pipe is run down to perforation depth and the injection test is performed while the BOP rams are closed. Thereafter, the cement slurry is spotted shown in figure C.4a. Afterward, the pipe is pulled above TOC and squeeze pressure is applied. Lastly, the cement slurry remaining in the pipe is circulated back to surface.

The two principal squeeze tools are the retrievable-squeeze and drillable-casing packers. Both packers can be set in either compression or tension. The retrievable packer has a bypass valve which enables circulation while RIH but also when packer has set, a squeeze job with this tool is shown figure C.4b. The main advantage with a retrievable over drillable is its ability to set and release several times. The drillable packer is best suited where cement has a tendency to flow back after the job while reverse circulating or pulling out of hole [47].



(a) Bradenhead squeeze.



(b) Retrievable-squeeze packer.

Figure C.4: Two different techniques of performing a squeeze job operation [8].

C.1.4 Challenges

Some of the main challenges associated with squeeze cementing are listed below.

- Filtration rate control
- Improper washing of perforations
- No cleaning of annuli of old mud and debris
- Locating leaking channel (migration path)
- Loss of casing integrity

Most squeeze cementing operations depend upon the control of the deposition of the filter cake in order to immobilize the cement solids in the desired location [47]. When there is a high filtrate loss from the slurry (e.g. water), the cement filter cake may form in the casing. Therefore, observed final pressure at the surface may indicate a successful operation, but the cement has not properly filled voids in the poorly cemented annulus. However, with a too low filtration rate, a sufficient filter cake will not be produced for immobilization of the cement solids.

Washing the perforations prior to cementing will most likely increase the success potential, by removal the contaminations or blocking materials. For the high-pressure placement methods, fluids present will be displaced into the formation. However, the annular space is not cleaned in a sense where removal of debris and cuttings. This could prevent hydraulic bond for being achieved, by blocking for filling of the cement slurry and/or contamination leading to lowering of the cement strength.

Locating channels were fluids are migrating to surface may be an issue. A problem when pressurizing the wellbore while squeeze cementing, the pipe will expand and potentially close the small cracks which should be cemented.

When perforating the integrity of the casing is lost, a potential leak path from the permeable formation into the wellbore is created if the cement fails. This could be solved with the installation of a casing patch.

C.2 Perforate, Wash and Cementing

HydraWells PWC system will be the only technology described in this document.

This is a further development of the traditional squeeze cementing operation, involving perforating, washing and cleaning the annular space then mechanically placing cement. This system has been widely used on specially NCS, HydraWell has set 205 PWC plugs to date worldwide [27]. The main application has been for P&A, but also the elimination of SCP of wells that has been set back in production or injection.

C.2.1 Operation

The first runs performed by HydraWell was a three trip system. First perforate, then two runs for washing and cementing. As the technology was further developed, two trip system were introduced. Where the perforations guns are run in hole on a separate run from the washing and cementing tools. Lastly, the single trip system were all operations are combined. However, due to difficulties controlling induced washing pressure for the HydraWash system, the HydraHemera is primarily used by HydraWell. Hence, this will be only the system discussed.

From bottom to top, for the single trip PWC system consist of 50 m TCP-guns which are dropped after firing if the rathole is long enough. Above the TCP-guns is the jetting and spray cementing tool. Lastly, the HydraArchimedes can be part of the BHA, all tools are shown in figure C.5. This is a typical BHA for a P&A operation, where the HydraWash tool will be used to act as a base for the upcoming cement job. For remedial repair of cement in B-annulus for restoring well integrity, the first run will typically be a bridge plug set an appropriate depth below planned perforation interval. A second run will be performed for perforation and a third for washing and cementing. Then the cement plug needs to be drilled out.

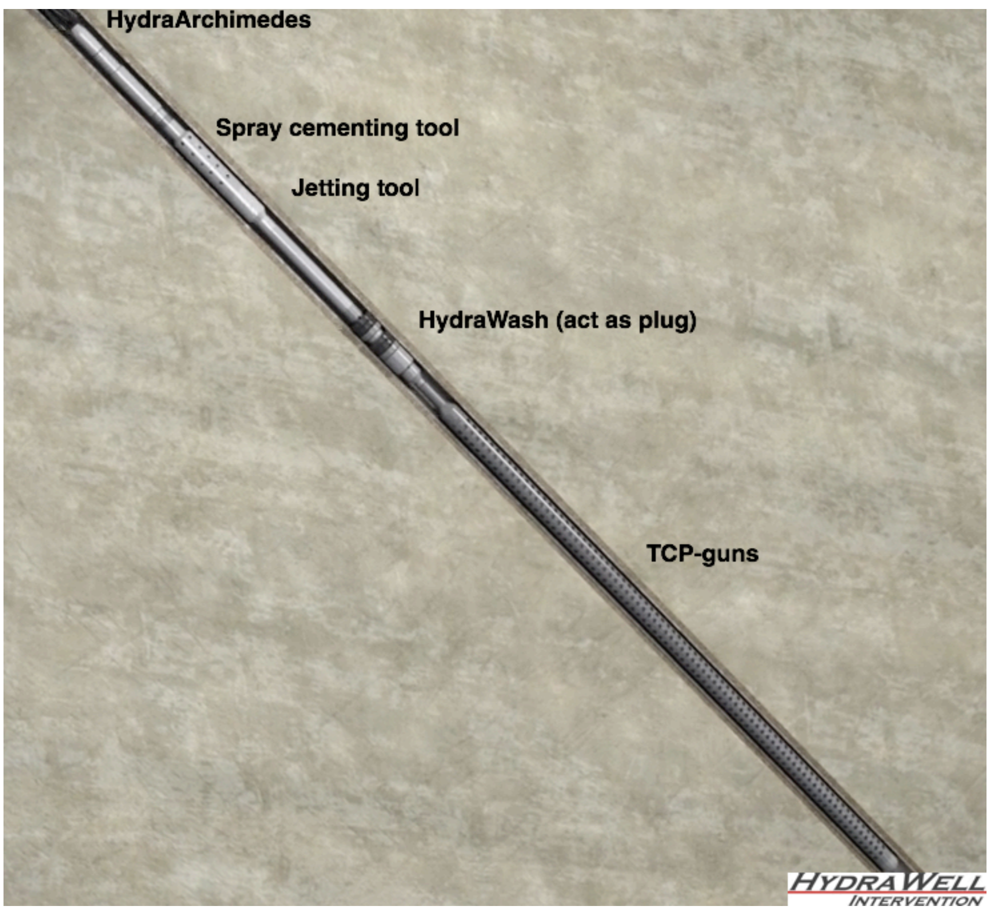
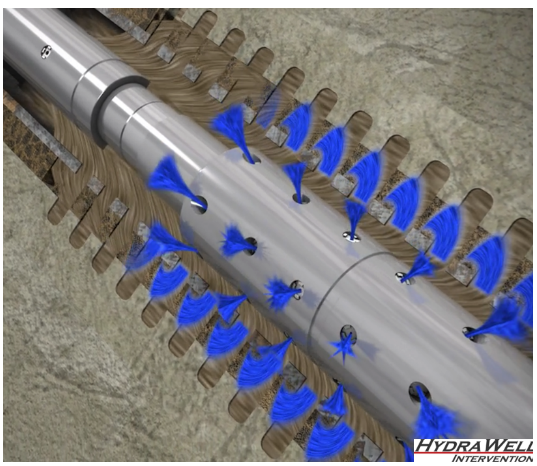


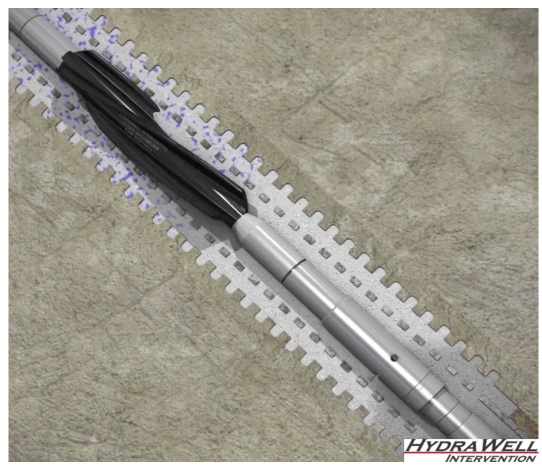
Figure C.5: HydraWell intervention tools [26].

In order to evaluate the annular space, a cement evaluation should be conducted prior to PWC operations. This in order to determine the condition of the cement and whether the formation has collapsed around the wellbore [20]. The chosen interval should be according to requirements from NORSOK D-010 and where free pipe is indicated. The system can also be used in the annulus which is cemented, according to HydraWell only the poor cement will be washed and cleaned away and good cement will still be intact. Diagnostic methods can be conducted for indicating where the leak is coming from.

The first step is to position the TCP-guns over the predetermined interval, these can be dropped after firing or be run in a separate run. The perforated interval consists of 12 shots per foot [20]. Next step is washing the annulus using the jetting tool, shown in figure C.6a. Which properly cleans the annulus of old mud, debris and cuttings by high energy jets of mud. Then a spacer fluid is pumped prior to the cementing operations, ensuring bonding to the formation and the casing (making surfaces water-wet).



(a) Jetting tool.



(b) Spray cementing tool and the Archimedes tool.

Figure C.6: Animation showing washing and cementing of single casing [26].

A ball is dropped for diverting flow through the spray cementing tool shown in figure C.6b, while placing the balanced cement plug the pipe is rotated with HydraArchimedes tool. Which has been developed by HydraWell to help circulate and force the wet cement in place through the perforations. Prior to commencement, when setting the balanced plug this had to be done by applying additional pressure to squeeze the cement in place and this squeeze pressure is held until the cement has set sufficiently [20]. This creates in most cases delays in the operation and for some wells not possible due to casing integrity. Use of the HydraArchimedes tool, applying squeezing pressure is not necessary.

After the cement plug has been placed for a well that is to be P&A, verification of the external WBE is required from NORSOK D-010. This involves drilling out the set cement and performing a cement evaluation. For wells to be set back in production or start injecting, the cement plug needs to be drilled out and bridge plug retrieved.

This system has been successfully deployed for annulus-B remediation repair for restoring the integrity of the well. After performed PWC of the production casing, a scab liner over the interval was set and cemented in place. By monitoring and comparing pressure build-up in the B-annulus before and after commencement, showed improvements [3].

C.2.2 Challenges

Some of the main challenges associated with the PWC-technology are listed below:

- Proper cleaning of the annulus
- Loss of casing integrity when perforating
- Locating leaking channel (migration path)
- Verification of external WBE

The annulus can be difficult to clean properly of old mud, cuttings and debris. Specially settled weighting material (e.g. barite sag) can be challenging to remove in the washing process. Therefore, the cement slurry may get contaminated and lose some of its compressive strength and bonding of cement to formation or casing may not be achieved.

When perforating the casing, the integrity of the pipe is lost. This is not an issue for a well that is to be P&A, however, can oppose great challenges for a well set back in production. If remedial cementing is not successful, the fluids may migrate through the perforations. This could create pressure build-up in the annulus between for example the scab liner and production casing that cannot be monitored. The same challenge applies as with squeeze cementing, is locating the leaking channel(s).

Perforating the casing does oppose verification issues regarding the use of cement evaluation tools. A CBL-VDL which takes an average measurement over the entire cross-section of a casing, cannot be normally utilized due to the perforations present. The USI-log however which gives a 360° coverage due to the rotating transducer. This enables the signal of the decayed head wave traveling along the non-perforated interval and giving information about the state of the cement behind the casing.

C.3 Section Milling

The main goal with section milling is grinding away the casing and removing whatever old cement, cuttings or debris are present in the annulus. This is done in order to set a new cement plug and achieve a proper zonal isolation. Section milling can be utilized for the elimination of SCP in well abandonment, but also in wells that are meant to set back in production. This method is primarily a last resort for the operator companies, due to the complexity, cost and associated HSE view of the operation.

C.3.1 Operation

One of the main reasons why the operation are both complex and costly is that large amounts of steel need to be milled and transported out of the hole. The knives used will wear down while milling, leading in many cases to several runs for milling one section. This seems reasonable considering that removing 50 m of 9-5/8" (42 #) casing gives approximately 3.1 tons of steel. Creating additional problems such as stuck pipe, swarf in the Blow Out Preventer (BOP), topside handling and disposal.

The operational steps will slightly differ if the well is to be P&A or set back in production, where a casing (or liner) needs to be run and cemented in place. The general operational steps are listed below.

1. Set a bridge plug below planned milled window
2. Section mill away the unwanted casing
3. Underream to fresh formation ("Scrape" away old cement, debris and cuttings)

4. Set cement plug over the entire cross-section of the well (or run casing/liner after bridge plug is pulled)

The "K-Master" section mill from Schlumberger is shown in figure 2.14, performing operation 2. listed above.

Figure C.7: K-Master Section Mill [39].

The taper mill on the bottom of the tool-assembly in figure C.7 main function is helping with the centralization of the string, as well as having nozzles milling fluid can be pumped through, lifting cuttings out of hole. The "undergauge stabilizer" above the taper mill helps with active stabilization, this reduces vibration, improves milling performance and knife longevity, reducing the number of trips to mill the casing section [22].

The section mill consists of multiple knives, they extend out of the tool by applying additional pump pressure. The force from the circulation pressure and rotation on the drillpipe, makes it possible to cut through and mill down the casing [45]. The jar on top of the Bottom Hole

Assembly (BHA), is very important in situations where get stuck.

Underreaming to the fresh formation is done by reaming away old cement, debris and cuttings. So the cement can settle against the fresh formation. It is crucial for a proper cement job, that the cement does not get contaminated, this will lower its strength.

The great advantage with use of the technology is that in a P&A scenario able to set a "fresh" cement plug over the entire cross-section of the well. This in comparison to squeeze cementing and PWC, where the old cement and casing is part of the plug design.

C.3.2 Challenges

Some of the main challenges and problems associated with section milling are the large time consumption and HSE view of the operation. A few of the operational problems causing these consequences are listed, these will also be discussed.

- Stuck pipe due to swarf pack-offs
- Need for several milling runs
- Fracturing of formation due to too high Equivalent Circulation Density (ECD)
- Swarf BOP and rig equipment
- Problem running casing after milled away section (re-entry issues)
- Loss of casing integrity milling dual casings

Stuck pipe are one of the main reasons for additional time spent on section milling. This can be caused by swarf pack-offs around the BHA and drillpipe, due to generation of to large cuttings that is not transported out of hole. The need for several milling runs can be caused by worn knives or damage to the BHA. The knives will of course be worn down while milling, the problem is big inconsistency in meters milled before knives are completely worn down and needing to POOH. Milling is a violent operation when considering downhole equipment leading to BHA failure. To remove big amounts of steel when milling down the casing, the need for weight on mill and rotating with relative high RPM puts big amount of stresses on the BHA, which can lead to failure.

To lift steel cuttings out of hole requires a high viscosity milling fluid pumped with a sufficient velocity. This can lead to fracturing of the exposed formation behind the casing, if the ECD is higher than the formation strength. Creating problems such as lost time due to need for pumping Lost Circulation Material (LCM) and mud pills to core the losses [37]. Swarf in the BOP is caused by when milling fluid transports the steel cuttings across the rams, it can settle due to lowering of the velocity. This can in worst case scenario, lead to problems closing the rams and maintaining control of the well. Another problem is swarf in the rig equipment, that can lead to damage to the processing system and associated downtime.

For wells that is not to be P&A but set back in production after casing is milled away, problems running casing or liner through open hole milled section in horizontal wells can be problem. The pipe will be on the low side due to gravity forces, therefore going from open hole to a smaller diameter casing can oppose great challenges.

Loss of casing integrity while milling inner casing when dual casings present is especially an issue in horizontal sections. The outer casing can be damaged as a result of the knives on the low side can worn down the steel.

Appendix D

Verification of External Set Resin

This appendix is provided giving two other potential methods of how to detect axial displacement of resin in the annular. The following is only a literature study, this has not been any testing of the matter, only thoughts from the author.

D.1 Radioactive Tracers

The use of radioactive in a squeeze cementing operation for indicating whether the cement is placed in the desired interval is a well-known method. The same principles could be applied for giving information about where the injected resin has been placed in the annulus. Some of the radioactive tracers that have been used in the industry in squeeze cementing operations are the isotopes ^{131}I (Iodine-131), ^{192}Ir (Iridium-192) and ^{46}Sc (Scandium-46). They have half-lives of 8 days, 75 days and 85 days respectively [8]. Each isotope will emit gamma-rays with a specific count rate (number of gamma-rays emitted per unit time) and their energy level (in mega electronvolt (MeV)). The gamma-ray spectroscopy can measure/detect both the quantity and energy of these gamma-rays, enabling distinguishing between each isotope and the natural gamma-rays from the formation. The gamma-ray spectroscopy tools are quite sensitive, and injection off too much tracer can cause more problems than injecting too little. This needs to be taken into account when mixing, as well as choosing the tracers with appropriate energy levels to best distinguish from natural gamma-rays. The basic principle of interpretation when using a radioactive tracer is illustrated in figure D.1. A logging run should be run prior and after injection. The gamma-ray spectrometer cannot pinpoint the radial displacement of the injected tracer, it will only give an overall average at that depth.

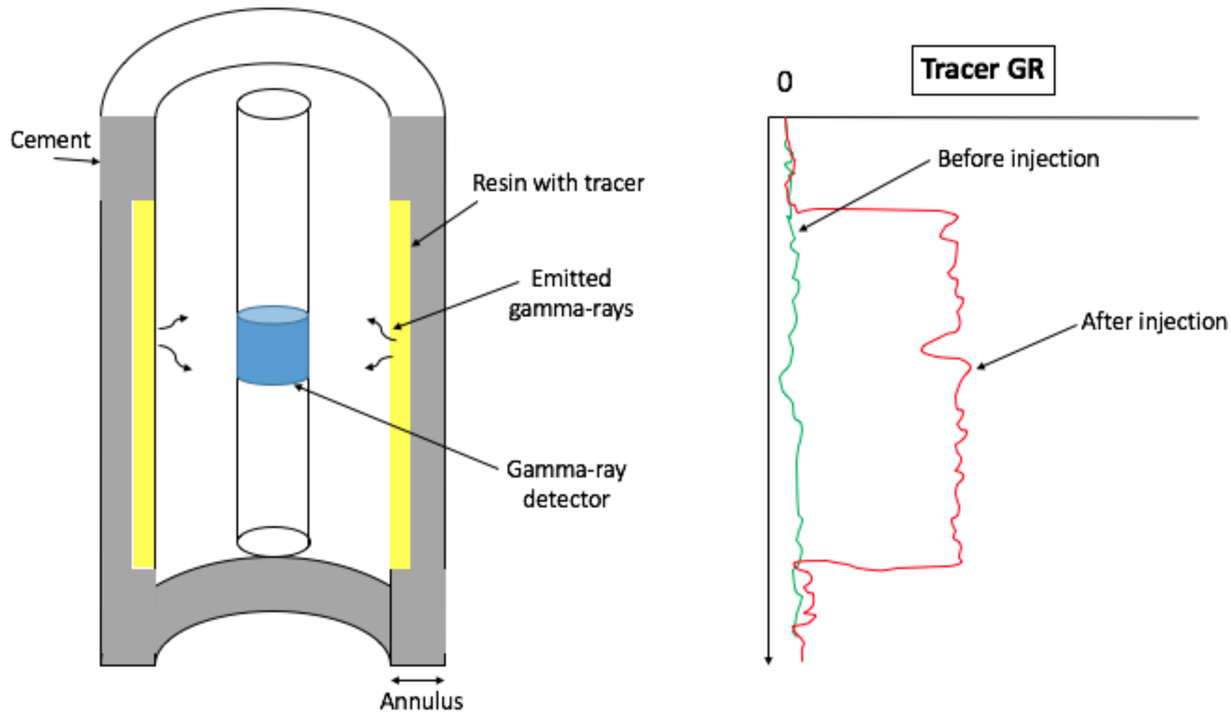


Figure D.1: Illustrative view showing verification of injected resin interval using radioactive tracers.

The choosing of tracer should for injection into small channels be soluble with the pumped resin. Small particles could potentially plug the channels and restrict flow, which would not be desirable. In addition, tracer should be uniformly mixed and not fall out of suspension, which could lead to interpretation challenges.

D.2 Resistivity Measurements

The use of resistivity measurements to determine the formation resistivity (commonly known as R_t) in order to evaluate reservoirs saturations and establish fluid contacts, such as gas-oil and oil-water contacts are widely used within the petrophysical analysis. Such resistivity measurements have primarily been part of the open hole logging evaluation, meaning logging directly against the formation. However, Schlumberger has introduced the Cased Hole Formation Resistivity (CHFR) tool which enables measuring R_t through the casing, which previously only been possible for open hole [28]. This makes it possible monitoring change of the reservoir saturations and fluid contacts after the well has been set in production.

The basic principle of measurement for laterolog resistivity tools (such as the CHFR), is an electrode emitting a current (I) and measuring the voltage (V) difference created when this applied current travels into the surroundings around the borehole. The resistivity is the measurement of how strongly a material opposes an electrical current traveling through it, given in equation D.1 for resistors in series.

$$R_{eq} = \frac{V}{I} = \sum_{i=1}^{n} R_i = R_1 + R_2 + .. + R_n \tag{D.1}$$

For determination of the formation resistivity, need to take into account the resistivity of the casing and cement in the annulus. The main difference for a resistivity measurement taken open hole compared to a cased hole, is that the steel casing serves as a giant electrode directing current away from the wellbore [28]. The current will follow the path of easiest resistance, which is the steel casing as a result of having a much lower resistivity than the surroundings. Different resistivity values for casing, cement and epoxy resin are provided in table D.1, should be noted that these will vary, the provided values are examples.

In regards to verification of set epoxy resin in the annulus, the principle of resistivity measurement could be an option. Considering that epoxy is an isolating medium, which means that has a very high resistivity, the resistivity given in table D.1 was at 25 °C (will be lower for higher temperatures). This is a factor over a billion times bigger than the resistivity of cement. Although

Table D.1: Resistivity values for steel casing, cement and epoxy resin [28], [31] and [19]

Material	Resistivity [ohm-m]
Casing	~ 1 to 10×10^{-7}
Cement	$\sim 0.1 - 10$
Epoxy resin	$\sim 10^{12}$

the measurement objective of a resistivity tool is to obtain the formation resistivity, it could be possible obtaining information about the injected interval of epoxy resin. If logging the desired interval before and after injection, the measured R_t should be much higher after the epoxy resin is placed in the annulus. As a result of the pre-job logging run for obtaining R_t would require a set value for the resistivity of cement. The post-job log, when the epoxy resin is present in the annulus, this would yield much higher R_t values, which would be an indication of the isolating medium is present and obscuring the logs.

Appendix E

Operational Times

The operational times gathered for creating figure 2.15 will be listed.

The conventional section milling operational times was taken from daily reports [36]. Table E.1 gives the times extracted. Service and operator company are unknown.

Description of Operation	Duration (hours)	Duration (days)
Install Reservoir Barrier (total time)	**255,75**	**10,65625**
Set Bridge plug above Tubing Cut	62	2,58
Section mill 165 ft (50m)	128,5	5,35
Underream Open Hole	28,25	1,18
Set Balanced Cement Plug	37	1,54

Figure E.1: Conventional section milling times [36].

For the ProMILL times, no information about times were given by Schlumberger. So these might not be representative. To generate approximate operational times, know that with the ProMILL system saves two runs. By assuming 16 hour round trips and M/U and M/D time for BHA a total of 8 hours. The total time savings comes to 40 hours. Important to address that these section milling times were based on one operation taken from [36], each milling operation is unique. For the ProMILL times just subtracted the approximately time that could be saved.

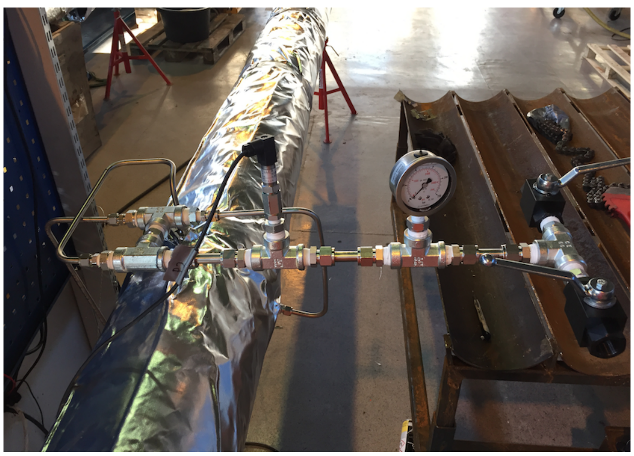
The PWC times in figure E.2 were taken from table 16 in [18]. The table is from PWC operations on Snorre.

	Comment	With verification [days]	Verification [days]	Without verification [days]
Primary plug	Two-trip system	12,8	8,5	4,3
Secondary plug	One-trip system	10,6	6,8	3,8

Figure E.2: Single- and two-trip system for PWC operations on Snorre [18].

Appendix F

Photos



(a) Cell one with three point injection manifold

(b) Cell three with six point injection manifold

Figure F.1: Injection manifolds for cells one and three

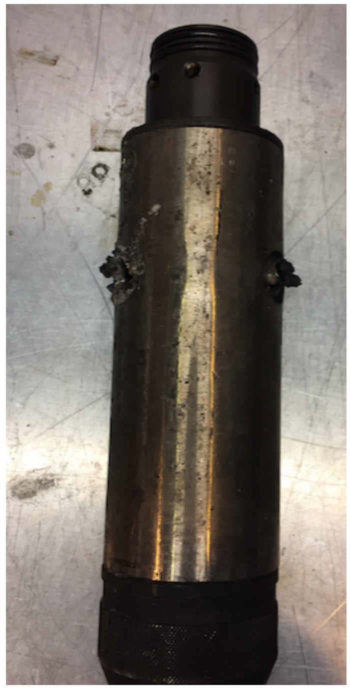


Figure F.2: Photo of perforation module after firing (3 shots)

Figure F.3: Photo of sample-cell used for storing and pumping of resin for cells one and three. The sample-cell is installed with heating cables.