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Vurdering av materialer for brønnsementering

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Geofag og petroleumsteknologi
Innlevert: Juni 2012
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HOVEDOPPGAVE/DIPLOMA THESIS/MASTER OF SCIENCE THESIS

Kandidatens navn/The candidate's name:	*Phi Long Nguyen*
Oppgavens tittel, norsk/Title of Thesis, Norwegian:	*Vurdering av materialer for brønnsementering*
Oppgavens tittel, engelsk/Title of Thesis, English	*Assessment of materials for primary cementing*

Utfyllende tekst/Extended text:
Background:
Primary cementing is one of the most important and critical operations during well construction, and the objective of primary cementing is to provide zonal isolation as well as to support the casing.
Portland Type G cement is normally used as isolation material, but other cement systems such as foamed cement and alternative materials (i.e. ThermaSet and Sandaband), may also be used.
Task:

1) Provide an overview of primary cementing challenges and considerations such as mud displacement, casing eccentricity, mud cake removal etc. . . .
2) Describe properties of materials suitable for primary cementing, such as cement systems (Portland Type G, foamed cement) and alternative materials (ThermaSet, Sandaband).
3) Assess these materials as primary cementing materials, with an emphasis on applicability, placement and zonal isolation. Include suggestions on possible operational procedures, if suitable.

Supervisor	*Sigbjørn Sangesland*
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Studieretning/Area of specialization:	*Petroleum Engineering, Drilling Technology*
Fagområde/Combination of subject:	*Drilling*
Tidsrom/Time interval:	*January 16 – June 11, 2012*

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Sigbjørn Sangesland *Torbjørn Vrålstad*

I. SUMMARY (NORSK)

En av de viktigste operasjonene i en brønnkonstruksjon er primærsementering. En dårlig utført primærsementering kan være en fare for både mennesker og miljøet rundt. En reduksjon i produktivitet, dyre sementering løsninger for å reparere skader og tap av brønnen kan komme av en dårlig primærsementering. Migrering av olje og gas grunnet mangel på isolasjon kan føre til forurensninger, i verste fall kan mangel på isolasjon føre til en farlig utblåsning.

I dag er det slik etterspørselen etter olje og gass økes mens oljen og gassen som er "lett tilgjengelig" minkes fort. Dette fører til at operatører blir tvunget ut mot dypere vann, arktiske områder, reservoarer med høytrykk og høytemperaturer og andre ukonvensjonelle resurser blir oppsøkt. Konsekvensen av dette er at de ulike operasjonene som er involvert blir mer komplisert, spesielt primærsementeringen. Dagens sementeringsteknologi gir ikke tilstrekkelig isolasjon over lenger tid.

For å forbedre på primærsementering har alternative materialer med egenskaper som gir bedre langtidsisolering blitt evaluert. En vurdering av ThermaSet og Sandaband som primærsementerings materiale ble gjennomført, forslag til plassering av materialet og evaluering metoder ble også diskutert. Materialene ble sammenlignet opp mot konvensjonell sement.

Vurderingen av materialene viste at det kan være mulig å bruke både Sandaband og ThermaSet som erstatning for sement i en primærsementerings operasjon. Begge materialene hadde egenskaper som gjorde dem passende for en langtidsvarende primærsementering, men sement vil fortsatt være det eneste materialet for primærsementering i nær fremtid. Dette er på grunn av den overlegne evne til å støtte foringsrøret, mangfoldet av sement å velge mellom, og de lave kostnader av sement. Bruken av Sandaband vil være begrenset til enklere brønnløsninger, et eksempel på bruk av Sandaband kan være vertikale brønner i grunne gassreservoarer. Når det gjelder ThermaSet så er det fortsatt en del tester som per dags ikke er blitt utført.

Et forslag til å redusere svakheten av sement og best mulig forbedre på primærsementeringen er å benytte seg av forebyggende tiltak, et eksempel på et forebyggende tiltak er "swellable elastomer packers". SEP i bruk sammen med sement kan styrke sementen. En vurdering av muligheter til å kombinere ulike sement systemer sammen for å oppnå en bedre og langvarig sement design kan også være en løsning til å styrke svakheten med sement.

II. SUMMARY

Primary cementing is a critical part of a well construction. A poor primary cementing operation can lead to huge economic losses and be a danger to the environment and the people involved. A reduction in productivity, expensive remedial cementing jobs and possible loss of the well bore can occur. Cross flow due to lack of isolation can contaminate freshwater aquifers and in worst case result in an uncontrolled blowout.

During a primary cementing operation there are cementing challenges and considerations that needs to be dealt with for a successful operation. As the “easy to reach” oil and gas are running low, operators are moving into more challenging environments, resulting in more advance cementing challenges.

Traditionally the industry has been concentrating on properties of the cement slurry to ensure an effective slurry mixing and placement. It has been common practice to assume that high compressive strength is sufficient and an indication of long term integrity. However, present cementing technology does not provide satisfactory zonal isolation over long periods.

In order to improve the primary cementing, alternative materials to cement was evaluated. An assessment of ThermaSet and Sandaband was conducted with the emphasis on applicability, placement and zonal isolation.

The assessment of the materials showed potential in both Sandaband and ThermaSet. Even though both materials had properties which made them good for long lasting isolation, cement will still be the only material for cementing in the near future. This is because of the superior ability to support the casing, the diversity of cement, low cost of the material and due to the state of the industry.

A proposal to deal with the weakness of cement is using preventive measures such as swellable elastomer packers to enhance the cement, evaluate and combine different cement systems together to achieve a better and long lasting cement design.

III. PREFACE

The Master of Science thesis concludes the undersigned candidates five year long education at Norwegian University of Science and Technology in Trondheim, Norway. The Master thesis has been performed by the candidate in collaboration with Department for Petroleum Engineering and Applied Geophysics at NTNU.

The author acknowledges with thanks to the assistance given by his supervisors Torbjørn Vrålstad, SINTEF Petroleum Researcher and Sigbjørn Sangesland, Professor at Norwegian University of Science and Technology (NTNU).

During the last semester many people have involved with their help, guidance and opinions, especially Brede Thorkildsen, Senior Research & Development Engineer at FMC Kongsberg Subsea AS and Vidar Rygg, Project Manager at Sandaband Well Plugging AS.

The undersigned candidate hereby declares that this Master of Science thesis has been performed by him and according to NTNU regulations.

11.06.2011 NTNU, Trondheim

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VI. ABBREVIATIONS

TABLE 1 : TABLE OF ABBREVIATIONS

Abbreviations	Definition
API	American Petroleum Insistute
C-S-H	Calsium Silicate Hydrate
DEG	Diethylene glycol
ECD	Equivalent Circulation Density
EIA	Energy Information Administration
FEA	Finite Element Analysis
HDR	Hot Dry Rock
HGS	Hollow Glass Sphere
HPHT	High Pressure High Temperature
O&G	Oil and Gas
P&A	Plug and Abandonment
PC	Portland Cement
RCC	Reversible Circulation Cementing
SAGD	Steam-Assisted Gravity Drainage
SEP	Swellable Elastomer Packer
SG	Specific Gravity
WOC	Wait on Cement

1 Introduction

Oil and gas constitutes more than 57% of the global energy consumption. The Energy Information Administration (EIA) projects that by 2030 the world will demand 27% more oil and gas than it does today. Currently the fields that are providing the hydrocarbons are maturing and the production rates of these wells are declining. Additionally, the discoveries of new reservoirs are emerging primarily in areas representing complicated challenges. These challenges include ultra-deep water, extreme downhole conditions of pressure and temperature, and unconventional source rock (1).

As operators are moving into the direction of more complicated reservoirs, the well operation gets more difficult. One of the most important and critical operations during well construction is primary cementing. The main objective of a primary cementing is to provide casing support and zonal isolation for the life of the well. A good primary cementing job is critical for the well integrity throughout the lifetime of the well.

1.1 WELL INTEGRITY

NORSOK D-010 defines well integrity as the "application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the lifecycle of a well (2). This is a widely accepted definition throughout the industry.

During the recent years there has been an increased focus on well integrity and there has been conducted many studies to get an overview of the current situation. One of the projects was conducted in 2006 by the Petroleum Safety Authority Norway to evaluate the integrity problems with wells in the Norwegian Continental Shelf (3). The study that was done included input data from 12 pre-selected offshore facilities that were operated by 7 different oil companies. From these offshore facilities 406 development wells were selected representing a collection of injection and production wells with a varying age and development category. The study showed that 18% of the wells in the survey had well integrity issues, and 7% of these wells were shut in due to integrity issues.

The results from the survey highlighted that most of the integrity issues occur in wells from early 1990s and onwards. With regards to cement, there were 8 wells where cement had failed as a well barrier element. One of the risk related to primary cementing are well integrity problems that may result in shut in. Although these 8 wells only account for 2% of the total 406 wells, there could be many more wells where the problem has yet been discovered or developed.

1.2 ZONAL ISOLATION

Cement has always been the material used for a primary cementing job to create zonal isolation and to support the casing. Portland type G cement is the most common cement system, and in order to improve the chance of effective zonal isolation the American Petroleum Institute developed a classification system widely used in the petroleum business. There are eight classes of PC, designated A to H. They are arranged according to the depth of placement and the temperatures and pressured which they are exposed to. For other well conditions, there is special cement systems designed to face the challenges, such as:

- Weak Formations
- Corrosive Environments
- Arctic Conditions
- Deepwater wells
- High Pressure High Temperature

Even without the upcoming challenges, the usage of cement has shown failures, there are limitations to cement. Traditionally, the industry has concentrated on the properties that are applicable during the cement slurry stage. This is necessary to ensure an effective slurry mixing and placement. It has been common practice so assume that high compressive strength is adequate and an indication of long term integrity. However, the long term integrity depends on other properties such as: Shrinkage and expansion characteristics, mechanical properties such as Young's modulus, tensile strength and resistance to temperature and chemicals are important properties (56). Present cementing technology does not provide sufficient zonal isolation for long periods. Inadequate zonal isolation result in cross-flow between different formation, this can lead to environmental risks if the freshwater aquifers are being contaminated. A failure in primary cementing can cause environmental risk and large economical damage. The development of new technology and methods to improve cement is still happening. But is it sufficient?

Plug and Abandonment (P&A) is another important well operation where cement is being used for isolation. P&A is the well operation where the well is being secured with one or more plugs for temporarily or permanently abandonment. The plugs used to secure the well are normally cement plugs, but there are other materials that may be better suited due to the long term integrity properties; two alternative materials for P&A operations are Sandaband and ThermaSet.

Swellable elastomer packer (SEP) technology may be relatively new, but the usage of the swellable technology in the oil and gas industry has proven to be a great success. The range of applications for swellable elastomer packers continues to grow and the SEP has been used to replace cement to in horizontal sections to isolate multiple zones in openhole wells, is it possible to use swellable elastomers to somehow replace cement in primary cementing?

Improving the conventional isolating methods will help increase the total recovery and support the worlds increasing demand of oil and gas. In order to improve the primary cementing an assessment of materials for primary cementing was done.

1.3 OBJECTIVE

The objective of this thesis is to assess materials to see if there are any materials, beside cement which can be used in a primary cementing operation. The evaluation is being carried out to see if there are possibilities to improve the primary cementing.

The first part of the thesis will be an overview of the oilfield cement, including a description of the cement properties, followed up with a classification of the conventional cement and an outline of cement additives.

Further on, procedure of the primary cementing, challenges and considerations which must be dealt with for a successful zonal isolation is described. The special environments and the cementing challenges which come with the new challenges will be explained. Also, special cementing systems designed for different well environment are enlightened.

Swellable elastomer technology is a technology being used as a packer solution for zonal isolation in oil industry. The concept will be described and the two other alternative cement solutions, Sandaband and ThermaSet are also described.

A short section to explain the methods used to place cement in a primary cementing operation is the done, before the main part of the thesis, the discussion.

The discussion will contain a small introduction part to explain where the industry is heading in terms of well design and challenges. A recommendation of placement method and verifications methods for the alternative materials will be evaluated. A cost analyze will also be in the discussion, comparing conventional cementing cost with the alternative materials. What type of well scenarios and environments that will best fit the materials will and the current best way to improve the primary cementing is also an objective of this thesis.

A conclusion at the end will enclose the thesis.

2 Oilfield Cement

Oilfield cements can vary in complexity and properties, but are usually based on Portland cement (PC) (4). PC is artificial cement made by burning a blend of limestone and clay. PC sets and develops strength due to hydration when mixed with water. A chemical exothermic reaction between the water and the compounds present in the cement occurs. The development of strength is predictable, uniform and relatively rapid. After hydration, the set cement will harden into a solid impermeable mass, well suited for primary cementing.

2.1 CEMENT PROPERTIES

The oilfield cement has important properties that need to be controlled both as cement slurry and when it's hydrated to set cement. The most important ones are listed and described below (5).

Slurry:

- Density
- Filtration Rate
- Viscosity and Yield Point
- Thickening Rate

Set Cement:

- Permeability
- Tensile and Compressive Strength
- Soundness
- Fineness

2.1.1 DENSITY

Cement density is one of the most important properties that need to be controlled. If the cement slurry density is to low there is a chance of influx from the highest pressured formation, and to high density could result in fracturing weak formations. In most cases the slurry needs to be adjusted to the downhole by adding either weight increasing solids or weight reducing solids. The most common ones are listed below.

Weight-reducing solids:

- Bentonite
- Diatomaceous earth
- Solid hydrocarbons
- Expanded perlite
- Pozzolan

Weight-Increasing solids:

- Hematite
- Ilmenite
- Barite
- Sand

2.1.2 FLUID LOSS

Fluid loss is when the liquid in the cement is lost to a permeable formation. Losing a large amount of the liquid will affect the cement properties, and it's important to keep the cement properties stable. As the liquid part is lost to the formation, a filter cake is created on the formation wall which seals and stops the loss of liquid. The cement should have the ability to seal leaks too keep the fluid loss as low as possible. This parameter can be measured using a filter press.

2.1.3 VISCOSITY AND YIELD POINT

Viscosity is defined as the liquid resistance to shear forces, which is the resistance to flow, and the yield point is the liquid initial resistance to flow. These two properties are important during pumping and placement of the cement. High viscosity cement that is pumped through the well at high rate creates high friction loss which can cause formation to break.

2.1.4 THICKENING TIME

Thickening time is the time it takes for the cement to gain consistency, more accurate the time it takes for the slurry to reach consistency of $100B_c$. This value represents the upper limit of pumpability. The thickening time of cement slurry is dependent on several parameters; the parameters that are not controllable are the pressure and temperature downhole. When the cement is in place it has to develop sufficient strength to support the casing and to seal off any fluid movement behind the casing before drilling operations can be assumed. Depending on the well depth and the temperature this waiting time can be long and expensive; many additives can be added to control this setting time.

2.1.5 PERMEABILITY

The desired permeability for the cement is zero. No flow should be able to pass through the cement sheath after it has been set. The permeability of cement can be measured with a permeameter and usually water as the flowing fluid, then using Darcy's law to compute.

2.1.6 TENSILE AND COMPRESSIVE STRENGTH

The compressive strength of cement is the force needed to crush the cement divided by the cross sectional area of the structure. The tensile strength is a lot weaker than the compressive strength, usually about 12 times smaller.

2.1.7 SOUNDNESS

When referring to portland cement, "soundness" refers to the ability of a hardened cement slurry to retain its volume after setting without delayed destructive expansion. This destructive expansion is caused by excessive amounts of free lime (CaO) or magnesia (MgO). If this change is to too great it will cause disruption of the set cement and create serious problems for the intended cement operation.

2.1.8 FINENESS

Fineness of cement describes the size of the cement particles, this property determines the hydration rate and on the rate in which the cement gains strength once it starts settling. The fineness of the cement can be measured with a turbidimeter.

The cement properties are normally not tested on the drill site but normally it's tested in a laboratory during planning of the upcoming cementing operation. The cement is tested according to the standards which have been developed by standardization organs like API and ISO.

2.2 API CEMENT CLASSIFICATION SYSTEM

Because of the variation of PC being used in different depth and conditions, the American Petroleum Institute developed a classification system widely used in the petroleum business. There are eight classes of PC, designated A to H. They are arranged according to the depth of placement and the temperatures and pressured which they are exposed to.

TABLE 2 : API CLASSIFICATION SYSTEM (4)

API Class	Description
Class A	Intended for use from surface to depth of 6000 feet, when special properties are not required
Class B	Intended for use from surface to depth of 6000 feet, when conditions require use of moderate to high sulfate resistance. Has a lower C_3A content
Class C	Intended for use from surface to depth of 6000 feet, when conditions require high early strength. Available in all three degrees of sulfate resist
Class D	Intended for use at depth from 6000ft. to 10 000 ft. under conditions of moderately high temperatures and pressures.
Class E	Intended for use at depth from 10000ft. to 14.000 ft. under conditions of high temperatures and pressures.
Class F	Intended for use at depths from 10000ft. to 16,000 ft. under conditions of extremely high temperatures and pressures
Class G	Intended for use as a basic well cement
Class H	Intended for use from surface to depth of 8000 ft. as manufactured, but can be used with accelerators and retarders to cover a wide range of well depths and temperatures.

2.3 CEMENT ADDITIVES

Cement is specially designed by additives to provide slurry characteristics for almost any subsurface environment. Essentially additives are free flowing dry powder, the additives can be blended in with the cement before transporting or it can be dispersed into the water. Considerations must be given to the contaminating fluids which the cement slurry will be exposed to. Today, there exist over 100 additives for well cementing, and we can divide them into eight major categories used in well cementing (6).

Listed are the eight categories:

- Accelerators: Chemical that shorten the settling time of the cement slurry
- Retarders: Chemicals that increase the settling time of the cement
- Extenders: Materials that lower density if the cement and may reduce the quantity of cement per unit volume of set product
- Weighting Agents: Materials used to increase slurry density
- Dispersants: Chemicals that reduce the viscosity of a cement slurry
- Fluid Loss Control Agents: Materials used to control leakage of the aqueous phase of a cement system to the formation
- Lost Circulation Control Agents: Materials that control loss of the cement slurry to weak formations
- Specialty Additives: Miscellaneous additives, such as antifoam agents, fibres, etc

2.4 PRIMARY CEMENTING

The main objective of primary cementing is to provide zonal isolation to prevent fluid from migrating in the annulus. The cement job will provide support to the casing and liners, the cement will also protect the casing string from corrosive fluids. The primary cement is considered as the most important operations in constructions of gas, water, injector or oil well. The cement sheath provides the critical hydraulic seal between the casing and the formation, isolating the individual zones and preventing annular flow.

Primary cement jobs are usually performed by pumping cement slurry down through the casing and up the annulus. It can be performed by a single stage cementing job, or a multi-stage cementing job. Multi-stage cementing jobs are being executed due to high hydrostatic pressure created by the cement column in deeper wells.

Single stage job is performed by pumping a bottom plug down in the hole inside the casing, and then pump cement on top of the bottom plug as illustrated in Figure 1. The bottom plug cleans the hole, and prevents the cements from mixing with lighter drilling fluids. When the bottom plug reaches the float collar and stops, the pumping pressure opens a one-way valve for the cement to pass through the calculated cement volume is finished pumping, a plug is then placed on top of the cement and displacement fluid on top of the plug. The top plug is pumped down towards the bottom plug and the pumps are shut off for the cement to set. The plugs and the cement inside the casing can be drilled out and further drilling operations can proceed. Depending on the specific well conditions, sometimes it requires chemical washing fluid in front of the bottom plug is required, and a spacer fluid between the bottom plug and the cement is needed(6).

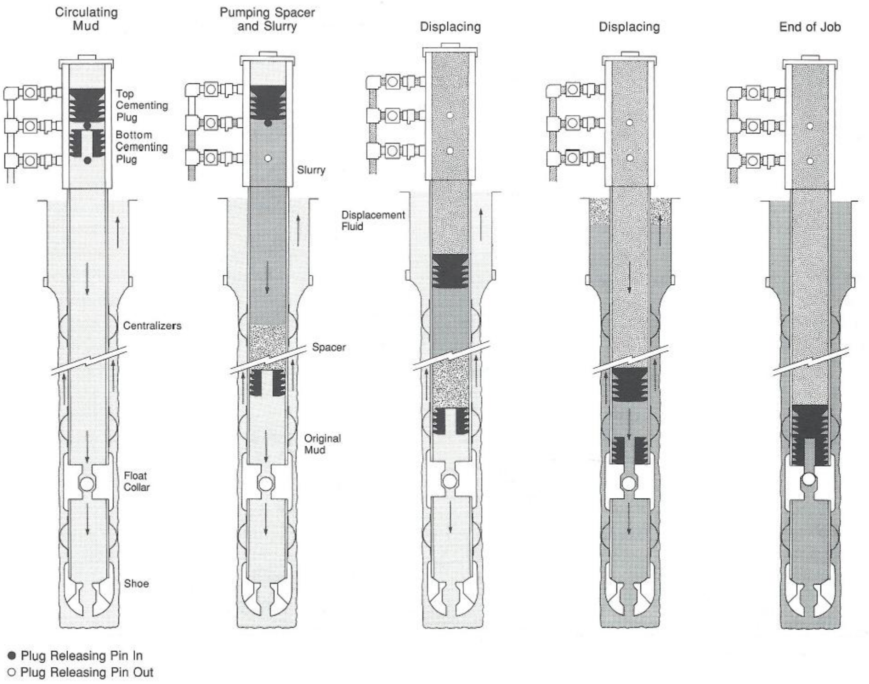

FIGURE 1 : TYPICAL SINGLE STAGE PRIMARY CEMENT JOB IN A SURFACE CASING STRING (6)

2.5 CHALLENGES AND CONSIDERATIONS RELATED TO PRIMARY CEMENTING

2.5.1 MUD DISPLACEMENT AND CEMENT PLACEMENT

During a primary cementing job there are many considerations and challenges that need to be dealt with for a successful operating. The first challenge that needs to be dealt with is regarding too displacing the mud in the annulus. Primary cementing failures often occur when channels of mud is avoided by the cement in the annulus. Through the years research has been done on the subject of mud displacement (7). The results of this is to use spacer, spacer or spacer fluid is any liquid used to physically separate one special liquid from another one. The most common spacer is water, which leave the casing and formation water-wet, water is compatible with both cement and mud.

Cement placement is another challenge important to the primary cementing. The successful cement placement requires the mud gel to be broken down throughout the annulus during mud circulation prior to the cementing (8). Two other conditions are needed for a great cement placement. The yield stress of each fluid must overcome to allow fluid to flow in or out of the narrow side of the annulus. The last condition is regards to channeling, the interface between two fluids on the narrow side of the annulus should move as quickly as possible. If it moves far slower than on the side communication channel will result. The degree of channeling is strongly depended on the rheology and the density of the contrast between the fluids. This can be greatly reduced by careful control spacer density and rheology. Turbulent flow also aid greatly in minimizing mud channels.

An important factor which may affect the mud removal and the placement of cement is the wellbore geometry (9). Incorrect interpretation of the borehole geometry can lead to underestimated or overestimated cement volume. If the cement volume is underestimated the top of the cement will be lower than desired. The wellbore geometry is mistakenly calculated due to large variations in radius and by misunderstanding how round or oval the well is. A wrong calculation of the geometry can be caused due to a changing hole geometry as a well is drilled through different cross sections. The larger diameter sections are often referred as washouts. If the flow velocity is too low, it may cause problems with cuttings and drilling fluid, if the cuttings and mud gel up, further problems with cement placement could be encountered.

2.5.2 CENTRALIZERS

During a primary cementing, centralizers are being used to achieve a better cement placement. Since cement flows better through large space, rather than narrow openings, poorly centralized casing may risk that cement bypasses some of the narrow side, leaving a mud-filled channel. To make sure that casing is spaced out from the borehole wall, centralizers are placed at certain intervals along the casing. The intervals should be long enough to allow free passage of the flowing fluid, but short enough to prevent the casing from contacting the low side of the hole (10). More centralizers are usually being placed in porous formations where it is crucial to get a good amount of cement all around the pipe.

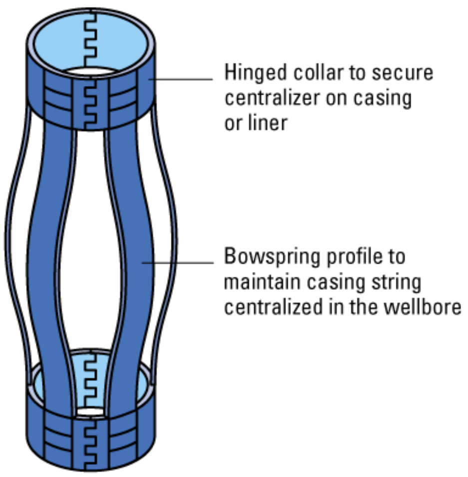

FIGURE 2 : BOW SPRING CEMENT CENTRALIZER (11)

2.5.3 PIPE MOVEMENT

Pipe movement can be done by rotation, reciprocation, or both during a cementing operation. Reciprocation is done with full length casing string, while rotation is more often done with liners alone. Many studies have shown that the displacement efficiency is greater in both laminar and turbulent flow regimes when the pipe was put in motion (12). Wellbore irregularities and poor centralization of the casing are two main causes for poor mud displacement. Since it's not possible to centralize in the exact centre of a borehole it will normally be eccentric and lay close to one side. The closer the casing is to the wall, the more difficult it is to displace the mud into the annulus. By rotating the casing, the gel structure of the mud can be broken up enhancing mud displacement.

Reciprocation is also beneficial to mud displacement. Reciprocation provides a linear drag force constantly pushing or pulling the cement. When the casing string is pulled, the drag forces will tend to pull the cement in the same direction. Although rotation and reciprocation is beneficial in mud displacement, certain safety issues needs to be accounted for. The reciprocation could cause lost circulation problems in pressure sensitive formation due to surge pressure.

2.5.4 MUD CAKE REMOVAL

When drilling through a permeable formation, drilling fluid may invade the formation leaving behind a filter cake. The filter cake can be a problem during a cementing operation. To achieve good bonding between the cement and the formation, it is necessary to properly remove the filter cake. A pre-flush fluid and the spacer fluid are usually used to clean out the well. In some areas, a mechanical wall-cleaning device that scrapes off the filter cake is used.

2.5.5 GAS MIGRATION

Even if the mud is properly displaced and the cement is placed correctly, the location and quality of the cement can fail in several ways over time. There is a number of ways in which the casing cement can fail; gas migration is one of the main problems. Natural gas is often present in formations exposed to the wellbore at the time of cementing. This gas must be prevented from migrating through the cement column during the wait on cement (WOC) time. A failure to prevent this can result in problem such as high annular pressures at the surface, blowouts, poor zonal isolation, loss of gas to non-productive zones, low producing rates, etc. All these factors will affect the ultimate hydrocarbon recovery and requires expensive operations for remedial. Before the cement begins to hydrate, cementing slurry in the annulus will provide a necessary hydrostatic head preventing gas invasion into the slurry. However, during the early stages of hydration the slurry develops gel strength and tends to become load bearing, once the hydrostatic pressure exerted by the fluid column decreases below the pore pressure exerted by the fluid column, there is a risk of fluid influx from the formation into the annulus. During this period there is also a reduction of the volume due to the hydration process, and a potential fluid loss to the formation. The decrease of the hydrostatic pressure and with a potential decrease of volume can lead to gas invasion of the cement matrix. This can be prevented by adding migration preventing additives in the cement slurry.

2.5.6 FORMATION FRACTURE PRESSURE

The formations fracture pressure gradient needs to be considered during a primary cementing job. The fracture pressure gradient is used to determine the formation fracturing pressure at a well depth. During the planning stage for drilling a well, decisions must be made regarding casing seats, mud weight and cementing requirements. Sufficient knowledge of formation fracture pressure, pore pressure, and lithology is required to optimize the casing and drilling plan, and to provide a successful primary cementing. Knowing the total hydrostatic pressure at which the exposed formation will fracture is critical. For safe operations, formation fracture pressure is defined for cementing purposes as the fracture extension pressure. The fracture initiation pressure is higher because of the tensile strength of the exposed rocks. The safety measures is done because it seems that during normal drilling operations the formation could be broken unintentionally without it being indicated at the surface. Designing for maximum slurry density in the bases of initiation pressure could easily lead to lost circulation during the cementing job. Including the fracture pressure gradient, the pressure in the well also has a great impact on the cement sheath. Increase in pressure within the well cause the casing to expand along the cement sheath; however the casing will only deform elastically, but the cement sheath may deform plastically. This difference between the casing and cement sheath could create pathways in which formation fluids could migrate. There are different operations that may affect the cement sheath. It's very important to identify all the operations which the well may require, in order to design a primary cementing to withstand the pressure increase and other exposures which may affect the cement sheath (13).

2.5.7 WELL TEMPERATURE

Another important consideration that needs to be accounted for is the temperature gradient and the well temperature. The well temperature is an important parameter because it affects all the properties of cement, especially the settling time of cement and the strength development. The downhole cementing temperature can vary widely, and it's very important to determine the temperature accurately, a small increase in the temperature can affect many properties. In order to obtain the temperature, temperature logs are being run in the hole, if less than 24 hours has elapsed, another temperature log or bottomhole circulation survey should be run. Once a static temperature is determined, the appropriate temperature schedule for a slurry design purposes can be obtained from API tables. High temperature wells, as seen in steam-assisted gravity drainage (SAGD) fields, can present a unique challenge to the sealant system. One thing is to design a cementing operation for high temperature wells, but in some cases there is a cycling in temperature. Long-term exposure to high temperature can lead to brittle failure of the cement sheath, resulting in cracks and possible channels through the cement back to the surface. This affect is magnified in a well with cycling temperature. As the wellbore heats up, the casing expands and may crack the cement sheath (14).

2.5.8 CEMENT FAILURE

Casing cement has two interfaces, one between the formation and the cement, the other is between the cement and the casing (15). Numbers from the EIA states that there are 15% of failures in either of the interfaces in the primary cementing jobs in the US. In order to maintain well integrity, both these interfaces need to have a good and undamaged mechanical bond. If one interface is debonded, the results would be an annular opening that could fail to seal the intended zone. The debonding can result in cement shrinkage due to hydration or casing expansion/contraction.

Another type of failure is when the cement sheath fractures caused by tensile stresses that exceed the tensile strength of the cement. Since cross sectional cracking does not influence sealing capacity significantly, and hoop cracking is assumed unlikely since interface bonds are considered the weak point, radial cracking is usually the only type of fracture that is reported (15). Radial cracks may allow fluid communication both in radial and in vertical direction. Furthermore the cement can lose its sealing and mechanical properties if it's exposed to a combination of a compressive and shear stresses. When this happens, the cement can crumble and this is referred to as shear deterioration. There are many ways that shear deterioration can occur, including micro-cracking, crushing or shear bands.

Also, the casing can be permanently deformed if the load exceeds the yield point. Small deformations of the casing can cause larger loads being applied to the cement, which may in turn lead to cement failure.

A failure in primary cementing can result in:

- ☐ Loss of productivity due to cross flow of fluids along the cement sheath, or influx of fluids from adjoining formations
- ☐ Injection of fluids into unintended zones in injection wells
- ☐ Incomplete stimulation of intended zones, or the escape of fluids along the annulus in either matrix or hydraulic fractured operations
- ☐ Failed Leak off or Formation Integrity tests
- ☐ Sand production due to early water encroachment
- ☐ Gas migration through the cement sheath, resulting in sustained casing pressure both at surface and in the intermediate strings
- ☐ Expensive remedial operations

2.6 CHALLENGES IN SPECIAL ENVIRONMENTS

The oil and gas industry is moving in a direction of more challenging environments. As the world demand of energy is increasing, renewable energy and other alternative energy needs to be improved. The geothermal energy is similar to the O&G industry in many ways, primary cementing is one of the similarities, and developments and technologies within the O&G industry can be applied to the geothermal energy. Because the energy demand is increasing, unconventional oil such as heavy oil is being produced in a larger scale. Other challenging environments include the arctic conditions, as more and larger projects are being developed in colder environments, new challenges for primary cementing is included. New wells are moving in a direction of longer horizontal sections and more complicated branched completions which also yields problems for the primary operations and the cement. This section covers the extra challenges and considerations on primary cementing, focusing on the effect on the cement.

2.6.1 GEOTHERMAL WELLS

The completion of geothermal well presents cementing problem that are unique. Cementing is the next most important operation after drilling when it comes to development of a geothermal well. The life of the well and the potential production of the reservoir are depended on the quality of the cementing of the casing. The cost of cementing is usually a very small proportion of the total cost of the well, yet a lot depends on the success of the cementing operation. The cement job should last for the service lifetime of the well, which can be a period of twenty to thirty years (16).

There are two types of geothermal wells where primary cementing is critical, hydrothermal wells and hot dry rock wells. Hydrothermal wells consist of reservoirs that transfer heat upwards by vertical circulations of fluids driven by differences in fluid density corresponding to differences in temperature; this geothermal resource is the most common.

Hot Dry Rock (HDR), consists of pumping high pressured water into the high temperature rock found up to thousands of meter below the surface. The injected water travels through fractures in the rock, gets heated up and travels through a second well back to the surface. The heat is converted into electricity; the water is cooled down and injected back to into the formation.

Conventional hydrothermal wells usually have three main problem areas that differ from oil and gas wells:

- Bottom hole temperature ranging from 140° C to 400°C
- Flashing brine
- Larger lost circulation to fractured formations

Although flashing brine will probably not occur in hot dry rock geothermal wells, these systems will have several additional problems that need to overcome:

- Hydrostatic pressures from deep wells
- Temperature cycling from 40°C - 350°'C
- Special completion technique may involve stage cementing and cementing of liners or openhole isolation packers, for flow control

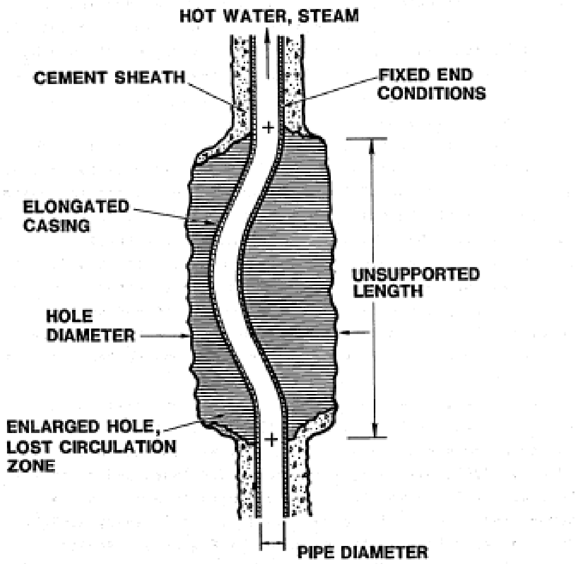

FIGURE 3: A CASE OF UNSUPPORTED CASING CONDITION CAUSING CASING BUCKLING WITH TEMPERATURE EXCURSION (17)

2.6.1.1 MECHANICAL FAILURE OF CONVENTIONAL CEMENT UNDER THERMALLY INDUCED LOADING

The thermally induced loads on the cement sheath in the well can be extreme in geothermal wells, from the time the casing is cemented in place to the time at which it is first produced; the casing can be subjected to a temperature increase of up to 300°C. The well may be cycled through such temperature increases and decreases many times. Under these conditions, the cement sheath may fail (18).

2.6.1.2 CEMENTING CORROSION

Aggressive formation and injection fluids may lead to corrosive attack of the cement sheath. The cement-sheath corrosion failures will result in many of the problems already mentioned. The loss of zonal isolation are the biggest concerns, because they affect the wellbore integrity and so the life of the well (19).

The economic consequences from corrosive attacks:

- Decline in production rates
- Loss of production times for remedial cementing
- Complete well failure/collapse

There are many factors affecting cementing corrosion:

- High temperatures
- Poor cement quality or incompatible cement additives
- Expansive attack
- Dissolving attack
- Presence of CO_2

2.6.1.3 EXPANSIVE ATTACK

Generally, there are two categories of cement corrosion induced by chemical attacks, corrosion by expansive attack and by dissolving attack. During the expansive (expanding) attack, the corrosive fluid penetrates the cement pores and forms voluminous water-insoluble products. As their crystal size increases, these products create high pressure inside the set cement, resulting in cracks, fractures and fragments. The most well-known expansive attack is the sulphate attack. Sulphate attack containing formation fluids penetrate into pores of the cement sheath and react with $3CaO * Al_2O_3$ phase of the cement and its hydration products to form secondary or delayed ettringite crystals, which fill the cement pores. Different types of expanding attack yield various problems; the formation of expending $Mg(OH)_2$ induces mechanical stresses in the set cement, resulting in destruction (19).

2.6.1.4 DISSOLVING ATTACK

When cement exposure to corrosive fluids creates-soluble products, the set cement is leached from the surface. In the oil and gas industry where reservoir stimulation is common after the well is drilled, the stimulation job may expose the cement sheath to strong acids. Conventional set API cements do not withstand acidic conditions and will dissolve over time with decreasing pH. The portlandite becomes unstable at a pH below 12.6 and will leach out first (19).

$$2H^+ + Ca(OH)_2 \rightarrow Ca^{2+} + 2H_2O$$

2.6.1.5 PRESENCE OF $\boldsymbol{CO_2}$

Cement corrosion in the presence of $CO_2$is a special case of dissolving attack because it consists of three sequential: The first step is the formation of carbonic acid in the presence of moisture. The second step is the carbonation of the cement components: The carbonic acid penetrates reacts with the portlandite, converting it into calcium carbonate and water. The final step is leaching and deposition process, further carbonic acid reacts with the formed calcium bicarbonate, which is highly water soluble and can be leached out of the cement matrix easily (19).

2.6.2 LONG STEAM INJECTION WELLS

Operators involved in the heavy-oil recovery often face the problem of maintaining well integrity in steam-injection wells. A significant portion of these wells suffer various forms of leaks and in the most severe case complete steam breakthrough to surface (20). Throughout the life of heavy oil wells, cement material degradation and stresses in the cement sheath induced by extreme temperature cycling result in severe mechanical damage and ultimate failure of the cement sheath. The main challenge for operators is to design thermally stable cement with mechanical properties sufficient to withstand, stresses induced by the large temperature. Extreme conditions of these stimulations processes impose stringent requirement on the performance of the cement sheath to maintain the wellbore integrity. Cement mechanical properties play one of the key roles in providing reliable and durable zonal isolation through the life of the well. However, the task to design strong, flexible and durable zonal isolation is somewhat ambiguous. The problems related to stem injection wells are similar to the mentioned problems already discussed from the geothermal well section. Problems such as expansion and contracting of casing can cause crack in the already set cement.

2.6.3 ARCTIC CEMENTING CHALLENGES

Well cementing in Arctic environments is particularly challenging, because of generally low temperatures, sometimes permafrost and sometimes the possibility of gas-hydrates in the formation. Permafrost thickness can be up to 1500 m and could cause enormous problems if not cemented right. Some of the cementing problems in such conditions could be freezing of mix-water before the cement sets, development of cracks due to the freezing of water in the capillaries of the cement, thawing of the permafrost due to the heat released during the exothermic process of cement hydration. This thawing of the permafrost can lead to cavities, low level of cement slurry in the annulus, unsatisfactory adhesion with the formation and gas migration problems. Generally low temperatures can also increase the setting time and permafrost zones may change the physical properties of the cement (21).

Under some arctic conditions, freeze temperature depressants are required to lower the freezing temperature of water so that cement hydration and placement can take place below freezing temperatures. The commonly used freeze point depressants are salts, alcohols and polymers. Sodium Chloride (NaCl) is the most common freeze temperature depressant salt used for permafrost cement formulation along with fly ash in "Ciment Fondu". The problem with NaCl is the increasing corrosion risk. Non-ionic additives like Methanol and Diethylene glycol (DEG) can also work as freeze point depressants (22).

Cement setting is usually accompanied by heat release in hydration reactions of cement components. This property may be ignored in many other areas, but it becomes a significant problem in Arctic permafrost environments because the heat release causes permafrost to thaw. The formation, previously firm and strong, becomes unconsolidated and unstable as liquid water forms around the borehole. If the permafrost contains gas hydrates, they can decompose to release methane in dangerous quantities.

Regarding the cement in arctic permafrost regions, extra focus on the following properties is needed to ensure a good cementing job:

- Low free-water content – to avoid freezing of the water during cement setting.
- Heat insulating properties – to be able to withstand higher temperature differences during well life.
- Low hydration heat release – to avoid permafrost thawing during setting.
- Expanding cement – to compensate for shrinkage to avoid influx of gas/water during setting time.

2.6.4 CEMENTING HORIZONTALLY

Cementing of horizontal wells in any formation is often challenging, especially the problems related to slurry properties. Two of the most important properties of cement slurry are the stability and fluid loss (6).

The slurry stability depends on free water content and sedimentation. During the process where the cement sets, the free water can migrate to the upper side of the wellbore and create a channel where fluids can flow. Sedimentation can result in low strength, highly porous cement in the upper part of the hole. This can result in fluid migration and loss of zonal isolation. To avoid this, free water should be maintained at zero, adding of thickening agents should be considered.

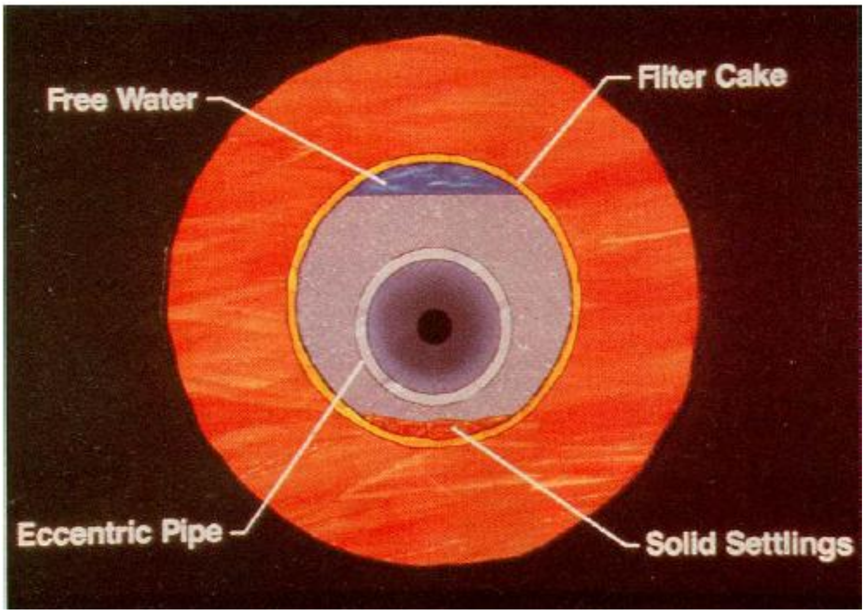

FIGURE 4 : PARAMETERS THAT AFFECT CEMENTING OF HORIZONTAL WELLS (23)

Fluid-loss control is important because the horizontal sections if often exposed to a longer range of permeable formations compared to vertical sections. Low fluid loss is very important for maintaining the desired slurry properties.

Another major problem related to cementing in horizontal wells is to be able to correctly place the casing and keep it centralized. Higher well-deviation generally makes removal of drilling fluid and thus requires greater attention to ensure that mechanical cementing aid function properly. The most common problem associated with centralizers is the insufficient numbers of them are used. Another problem is that centralizers cause an excessive amount of drag.

The major problems associated with obtaining a good cement job in horizontal wells can be categorized into four areas: hole cleaning and drilling-fluid displacement, centralization of pipe, optimizing cement slurry designs, and evaluation with acoustic tools. Each area has specific problem that must be addressed if a horizontal well is to be cemented correctly and evaluated properly.

3 Cementing Systems

3.1 CEMENTING SYSTEM FOR CORROSIVE WELL ENVIRONMENTS

In many well situations where CO_2 are involved or other aggressive formation fluids, corrosive attack can be a major problem for the cement sheath. Synthetic and epoxy-resin based binder provide high chemical resistance and good mechanical properties in the well. Epoxy cement is prepared by mixing an epoxy resin with a hardening agent. A solid filler such silica flour is often used to build density, and to act as a heat sink for the exothermal reaction which occurs during the cure. Epoxy cements are characterized by their corrosion resistance, and high compressive and shear bond strength. Epoxies are also resistant to hydrocarbons and alcohols, but not chlorinated organic or acetone. The biggest problem with synthetic and epoxy-resin binders is the high costs which limit their use to special applications (24). Calcium aluminate or phosphate-based cement also proved to be more highly corrosion resistant than Portland cements.

Cementing deep and sour wells present a number of challenges. A new and more advance cementing system was tested for this application, both laboratory and field experiences proved that this advance system worked better than conventional cementing. This advanced cementing technique consists of multifunctional fluid migration control systems together with engineering particle sizing technique improved the performance of cementing jobs, including: superior fluid migration control, predictable, thickening time, stable API properties at high slurry densities, and great resistance to H_2s, CO_2 and salt corrosion. Many chemical and mechanical techniques was involved in this cementing system, using expansive and flexible cement, and with a low permeability cement system, gas migration and sour gas corrosion on oil well cement was avoided (25).

3.2 FLEXIBLE, EXPANDABLE SEALANT SYSTEMS

Expansive cement systems are being used to address the issue of failed cement sheaths and tailor mechanical properties of a set-cement system by ensuring a contact and good bonding between cement and casing or cement and formation. During the production life of a well, the cement sheath is exposed to varying stress fields with pressure and temperature fluctuate in the wellbore (26). These stresses can affect the cement sheath reducing the ability to maintain hydraulic isolation.

Studies has shown that cement with low Young's modulus and good expansion properties during the hardening phase is best for mechanical durability and resistance to stresses. The flexible and expandable sealant system is adaptable to pressure and temperature changes, and the ability to expand improves the sealing at the casing to formation interface. The application of this cement system is good in wells with large temperature and pressure variation, gas wells, HPHT wells, multilateral wells, plugging and abandon applications and for wells with high tectonically activities.

Although set-cement properties are improved, other factors should be considered before designing flexible slurry. An increase in flexibility will decrease the compressible strength. Expanding cements exhibit the best properties against hard formations and decrease the risk of creating an inner annulus between the casing and the cement.

The concentration of expansion additives required for a certain value depends on several factors. These include bottomhole static temperature, nature of the surrounding formation, cement type and slurry additives. The amount of expansion can only be measured by testing in annular –expansion molds under downhole conditions.

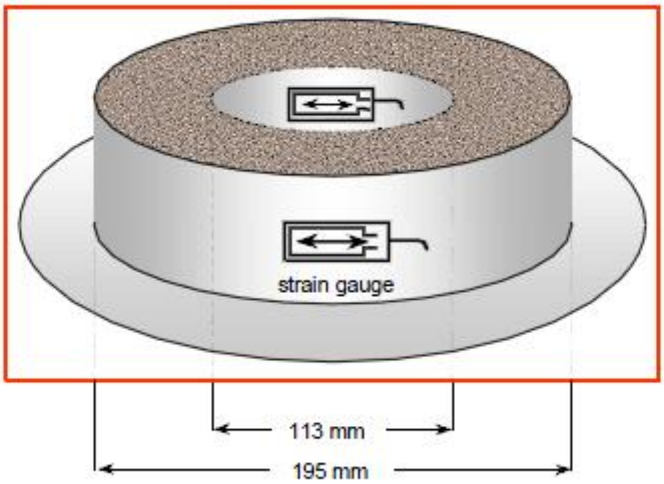

FIGURE 5 : ANNULAR EXPANSION MOLD UNDER DOWNHOLE CONDITION (26)

3.3 THIXOTROPIC CEMENT SYSTEMS

Thixotropy is a term used to describe the property exhibited by a system that is fluid under shear, but which immediately begins to gel when the shear stops. A more thorough and accurate definition is that a good thixotropic slurry is a slurry that mixed easily, but which rapidly increases in viscosity both at surface temperature and bottomhole temperature as the shear rate approaches zero (27).

Thixotropic cement is often used in wells with weak zones, which fracture under low hydrostatic pressure, because of the rapid gel strength abilities. Another important application of thixotropic cement is treatment of lost circulation during drilling. When thixotropic slurry enters the thief zone, the velocity of the leading edge decreases and gel structure begins to develop. Eventually, the zone becomes plugged because of the increased flow resistance. Thixotropic systems can be clay-based, calcium-sulfate based, aluminum sulfate, iron-sulfate, or cross-linked cellulose polymer systems.

3.4 SALT CEMENT SYSTEMS

Cement systems containing significant quantities of sodium chloride have been used in oil wells since completion of wells through salt domes in the Gulf Coast in the 1940's. Another application for the salt cement system is when salt-water is the mixing water or in water-sensitive zones (28). Another application of brines for mixing cement occurred when early cementers found that certain shale formations could be more effectively squeezed when using water from the producing zones. NaCl is most frequently used, but KCL has been reported better for sensitive clay formations.

One thing that is important to notice is that the salt cement systems can cause confusion in cement calculations, because salt can be dissolved in basedfluid and the volume of salt in solid state is not the same salt as in solution phase. Therefore, density of solid salt is not the same as the dissolved salt in liquid (29).

3.5 THERMAL CEMENT DESIGN

For many years, Class G cement with silica flour has been used for thermal oil and gas well cementing. The conventional Portland cement with the tricalcium silicate and dicalsium silicate mixed with water will both hydrate to Calcium Silicate Hydrate (C-S-H) gel. This gel structure can provide good compressive strength for the cement at temperature up to 230 ° F. However, at the temperature increase above this, the (C-S-H) gel will convert to an alpha dicalcium silicate hydrate, which is a weak and permeable binder (6).

The advancement in technology makes it easier to design best-fit cement slurries for different well conditions today. It is now possible to design for specific mechanical properties and appropriate particle size distribution of the cement slurry systems using computer modeling for finite element analysis (FEA), hydraulics and temperature simulations. Physical and/or mechanical factors, as well as chemical reactions and placement environments, such as cycling temperatures and pressure, are considered during the design process. The cementing engineer will match the actual job requirements to the design as closely as possible to achieve the life for the sealant system at the designated conditions (30).

3.6 ARCTIC CEMENTING

The challenges of the arctic provide unique cementing challenges. Conventional cement systems are not satisfactory in these conditions, because they freeze before developing sufficient compressive strength. It is possible to add freezing temperature depressants like salts, alcohols and polymers, but this has been shown to have effect upon the quality of the cement. Instead, two special systems have been developed to perform a better primary cementing in these conditions. The two special systems are the Calcium-aluminate cement and gypsum cement blends.

The calcium aluminate cements are special use cements of limited production and premium price. Their compositions are predominately monocalcium aluminate as opposed to the tricalcium aluminate used in Portland cement. The high alumniate cements will set and gain strength rapidly at low temperatures, reaching about 95% of the ultimate strength in 24 hours (31). These cements however, exhibit a high heat of hydration and since the hydration reactions occur rapidly, high cement-column temperatures may result. Fly ash is often added to reduce the heat of hydration. Two high-alumina cements are marketed under trade names of Lumnite and Climent Fondu.

Gypsum-cement blends, with a mixing water freezing temperatures depressant, have unique properties that make them attractive for low and subsurface freezing temperatures environments. The gypsum phase sets and gains strength rapidly at these temperatures, and provides adequate strength for continuing well operations. Protected from freezing, the more slowly setting Portland phase will be able to hydrate, providing the cement with high ultimate strength and durability. By controlling the concentration of retarder, the fluid or thickening time of these blends can be controlled from a short as 20 to 30 minutes to more than 4 hours, with good strength developing in 12 to 24 hours.

To obtain the cement systems of the required properties, we need to apply complex multi component cement blends, which have to include a number of functional components - base cement, lightweight additives, accelerators, stabilizers and expanding additives.

3.7 LIGHTWEIGHT CEMENT

Cementing across depleted zones, high pressure zones and narrow pressure and fracture pressure margin zones requires more sophisticated methods and materials than conventional cement. A method that has been used when facing these types of challenges is lighter cement. There are typically three ways to achieve lighter cement.

- ❑ Water Extended
- ❑ Foam Cement
- ❑ Hollow Microspheres

Water extended is to done by increasing the water ratio in the cement slurry. Water is mixed into the slurry together with extender and water absorbing additives such as bentonite, fly ashes and silicates gels to control the free water while lightening the slurry. The most common lightweight cements are only blended to a density of around 1500 $\frac{kg}{m^3}$. (32)

If cement lighter than 1500 $\frac{kg}{m^3}$ is desired, usually called ultra-light cement, hollow microspheres or foam cement must be utilized. All the mentioned methods to create lightweight cement have their weakness and benefits. In the most challenging conditions a combination of all the methods could be used (33).

3.7.1 FOAMED CEMENT

Foam cementing technology has been used for over two decades in the O&G industry. Virtually any hydrocarbon well cementing situation can be considered a candidate for foam cementing. Foam is applicable for supporting primary and remedial cementing in vertical and horizontal, offshore and onshore. Such cements produce a low-density matrix with low permeability and relatively high strength. This unique technology of zonal isolation has evolved a lot through a better design model, perfect job executive and excellent post job evaluation. Foamed cement's tensile strength ductility and displacement properties have made it especially useful in several zonal-isolation scenarios.

3.7.1.1 FOAM CEMENT CHEMISTRY

Foam cement is made by properly combining three elements: cement slurry, foaming agents, and a gas (usually nitrogen). Creating foamed cement is an easy process. When discussing foamed cement the term foam quality is often being discussed. This term refers to the volume ratio of the gas compared to the total foam volume. An example of this is, "60 quality" foam is when the gas volume makes up 60% of the total volume. This concept is easy to understand under normal and static conditions, but as temperature and pressure increases the nitrogen volume changes, hence the quality. The higher the quality of foam slurry, the "thicker" or more viscous it will act. In practical terms, this means that you will not be able to achieve turbulent flow with foam cement. When the pressure increases, the foam quality will decrease. Changing the temperature also has an effect on volume/foam quality. When performing a foamed cement job, managing these variables and the resulting dynamic volume change is the only really difficult aspect. Nitrogen is the preferred gas for a foamed cement job, but for certain low-pressure or shallow applications, compressed air could be used. In certain circumstances, compressed air may be cheaper than nitrogen and related pumping equipment. (34) Figure 7 shows a typical equipment layout for a foam cement job.

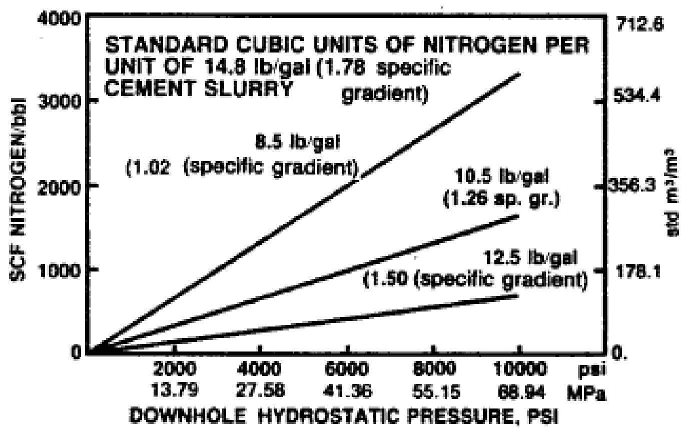

FIGURE 6 : NITROGEN REQUIREMENTS TO PREPARE FOAM CEMENT (35)

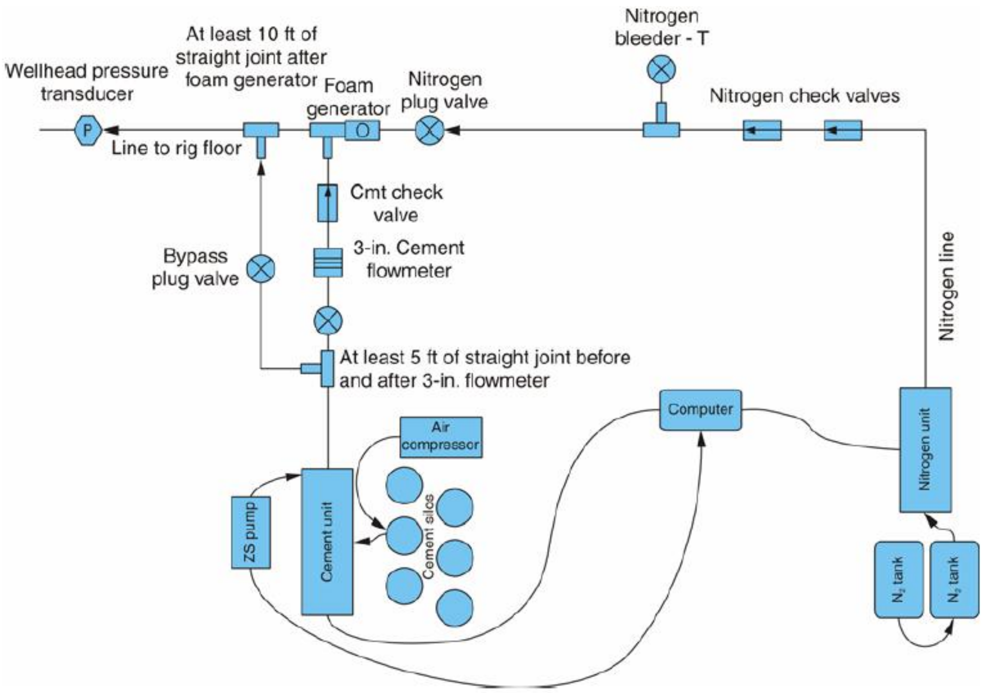

FIGURE 7 : EQUIPMENT LAYOUT – FOAM CEMENT (36)

3.7.1.2 FOAM CEMENT DESIGN

In general, foam cement does not require many additives. Neat cement can be foamed down to 0.4 g/cc density, so lightweight additives are not necessary. Foam cement has very low water content and there is almost no settling, so high water-ratio stabilizing additives are usually not necessary. Foam cement has inherently low fluid loss, so fluid loss additives are often not necessary either. Because foamed cement is used to face low fracture pressure gradients, heavyweight additives are typically not necessary.

3.7.1.3 FOAMED CEMENT BENEFITS

Foamed cement is introduced here because of its benefits to improve primary cementing, and it exhibits several properties that make them suitable in well construction. The various advantages associated with the usage of foamed cement for enhanced properties and in weak/critical formations include:

- Lost Circulation Control
- Ductility and Tensile Strength
- Improved Displacement
- Density/Compressive Strength Improvement
- Migration Control
- Lower Environmental Impact

Loss circulation control is a common problem in weak formation. Conventional cement used in such wells need to be lightweight and low-strength, and stage tools are often necessary in order to cement the casing string all the way back to the surface. Foamed cement can be designed for high strength and low density, eliminating the need for stage tools. Because of the low weight of foamed cement, they are less likely to exceed the formation fracture gradient and cause lost circulation (14).

The two most crucial properties of a cement ductility and tensile strength are the most important properties for long-term zonal isolation. Foamed cement, however, is at least one order of magnitude more ductile than other cement and can produce a cement sheath capable of withstanding higher internal casing pressures, allowing the cement sheath to yield while the casing expands. This ductility allows the cement sheath to withstand higher hoop stresses from casing pressure and temperature cycling (14).

Because of the low viscosity, displacement of foamed cement is improved compared to conventional cementing. The base slurry for a foamed-cement job typically has relatively high rheological properties. When surfactant and nitrogen are used to foam the base slurry, the viscosity of the slurry increases proportionally to the amount of gas phase of the foamed slurry. This high viscosity makes foamed cement slurry ideal for mud removal and achieving excellent mud displacement during a cement job. More effective mud removal will improve the zonal isolation (14).

Foamed cement provides lighter density slurry capable of achieving compressive strength equivalent to those of the conventional slurry, eliminating the need for using a two stage cement job to bring cement return all the way to the surface. By eliminating the two stage cement job, the overall costs are reduced. In addition, the low slurry density eliminates the need for increasing formation strength with lost-circulation plugs, which also reduces cost associated with materials and rig time.

Gas migration is a problem already mentioned. The compressed gas bubbles in foam cement shrink or expand, but they don't move around or merge. Instead, they maintain pressure while the cement hydrates. This ensures that there is virtually no gas migration into the cement while cement is being placed or while setting. Because nitrogen gas constitutes a large portion of the slurry pumped into the well, using foamed cement typically decreases the amount of materials that must be brought to the job location. In addition, foamed cement base slurries are composed of a bare minimum of raw materials and chemical additives. Nitrogen is noncorrosive, nonreactive and inert. All of these factors contribute to make foamed cement more environmental friendly compared to conventional cementing.

3.7.1.4 CHALLENGES RELATED TO FOAMED CEMENT

Using foamed cement has lots of benefits, but it also presents two main challenges. The main challenge is likely to occur during applications in deep water uses. The challenge of using foamed cement is related to the equipment needed in the operation. Using a nitrogen pumping unit on the location increases the complexity of the operation. The complexity comes from the need of synchronization between the cement pump and the nitrogen pump. Large variation can produce foamed cement that is either too light or too heavy. Because the foamed cement is compressible makes the design stage more complex in the simulation of a foamed cement job. The other problem is related to interpretation. The acoustic impedance of conventional high-strength is significantly higher than drilling mud, making it easier for operators to distinguish between it with a conventional acoustic impedance tool. The acoustic impedance of foamed cement is often equal to that of drilling fluid, making it nearly impossible to distinguish between them (14).

3.7.2 LOW DENSITY SPHERE CEMENT

Low density spheres, hollow microspheres have been available to the industry for some time, but their use has not been widely applied (37). The spheres that are currently being applied to the industry are the pozzolanic (also known as the ceramic spheres) and the borosilicate type spheres (glass spheres).

The majorities of produced pozzolanic sphere materials are waste by product; generated by coal burning power plants. As coal is burned to generate electricity, it releases fly ash. Around 20% of the released fly ash is ceramic particles made out of silica and alumina. The ceramic particles, also known as cenosphere are hollow. Gas filling spheres consist of air, nitrogen or carbon dioxide, and the specific gravity of the particle ranges from 0.6 to 0.9.

Hollow glass sphere (HGS) also called microspheres are microscopic bubbles of glass that are manufactured for a wide variety of uses in many different industries. The most common usage of this material is a lightweight filler material in paint, metals and concrete. In addition to the ability to reduce the weight, the glass sphere has a low thermal conductivity and a high compressive strength making them suitable lightweight additive to oil well cements. The specific gravity of the spheres ranges from 0.32 to 0.6.

Choosing between the two types of spheres is a function of cost versus performance along with, overall risk. In non-critical applications, the use of ceramic spheres may provide good and cost effective solutions. By contrast, in critical applications requiring performance predictability, the glass spheres provide a better alternative.

3.7.2.1 PROPERTIES OF HGS CEMENT

In order to achieve wanted density, a wide range of hollow glass bubbles is available. High pressured bubbles typically have a higher density which results in heavier cement slurry. Low pressure rated bubbles are usually lighter and will give a bigger difference in density as a larger portion of the original cement is replaced with HGS, but they are weaker. In other words, there are a wide range of density which can be reached dependant on the desired strength, the glass bubbles starts to break if the crush strength is exceeded. Table 3 shows the variation is HGS glass bubbles from 3M.

TABLE 3 : 3M™ GLASS BUBBLES HGS SERIES AND CRUSH STRENGTH OVERVIEW (38)

Product	Density [g /cc]	Crush Strength [psi]
3M™ Glass Bubbles HGS2000	0.32	2000
3M™ Glass Bubbles HGS3000	0.35	3000
3M™ Glass Bubbles HGS4000	0.38	4000
3M™ Glass Bubbles HGS5000	0.38	5500
3M™ Glass Bubbles HGS6000	0.46	6000
3M™ Glass Bubbles HGS8000X	0.42	8000
3M™ Glass Bubbles HGS10000	0.60	10000
3M™ Glass Bubbles HGS18000	0.60	18000

The slurry from HGS is incompressible until the glass bubbles start to break. Breaking of the bubbles will increase the density of the slurry, because crushing of spheres is expected the cement mixture must be lighter at the surface than the target density.

3.7.2.2 HGS CEMENT DESIGN

Crushing of the spheres is expected, and when this happened, the density will increase and the volume decrease. Based on the spheres pressure rating and expected downhole conditions the amount of crushed spheres can be predicted. Based on the spheres pressure rating, and the downhole conditions, a correct mixture can be determined with simple volume and density calculations.

3.7.2.3 ADVANTAGES AND LIMITATIONS OF LIGHTWEIGHT CEMENTS

The advantages of the foamed cement have already been listed earlier; this section will discuss the advantages of lightweight cements in general and a comparison between the foamed cement and the low density sphere cement.

The lightweight cement usually contains less cement and more water, low density spheres, foam or other additives which lowers the final compressive strength. Permeability of the set cements is also typically higher, than of conventional cement.

As mentioned earlier the spheres in HGS cements crush as the pressure increases, leaving cement slurry with and increased density slurry. This can be prevented by using a higher strength sphere, but this is more expensive and will give a higher density, which is not desired in lightweight cement, too get the desired density now, a larger amount of HGS cement needs to be used, making it more expensive. HGS is the most expensive alternative for lightweight cements, but it will have the highest compressive strength and the lowest permeability if the lightweight oilfield cements alternatives (33).

4 Swellable Elastomers

As operators are facing harsher environments and greater challenges, alternative to cement needs be explored. The deepwater environments present numerous of challenges when it comes to casing cementing. Many deepwater wells contain high wellbore deviations at intervals in the trajectory. It is also believed that in future deepwater developments, there will be more focus on complicated well operations such as extended reach wells and branched completions. Swellable elastomer is a technology with a huge potential within zonal isolation, and can be used to overcome future challenges in primary cementing by improving and in some case replace the primary cementing.

4.1 SWELLING ELASTOMER PACKER

Swellable packer can be divided into two main categories depending on the swelling mechanism. The two main categories are hydrocarbon swellable and water swellable packers. With these packers the operators can achieve critical downhole zonal isolation and at the same time overcome various difficulties associated with cement placement and annular isolation. The packers rely on the expansion mechanism of the bonded elastomer to provide the annular seal when the rubber is exposed to hydrocarbon or water, depending on the packer type. The packers have no moving parts and require no service tools or surface operations to be activated or set. The packers make it a lot easier for the operators and it can significantly cut cost in rig time and materials (39).

4.2 PACKER CONSTRUCTION AND SWELLING THEORY

The packer consists of a standard oilfield grade tubular layered rubber bonded along the length of the tubular. The swelling of the rubber is a thermodynamic absorption process. All liquids have a solubility parameter. The solubility parameter is defined by the energy required to vaporize the liquid. When a polymer is in contact with a liquid or gas with a solubility parameter close to itself, there will be a strong affinity between the fluid and the polymer. A combination with the flexible polymer network in a rubber causes the swelling effect. The swelling can increase the size with several 100% in rubber volume, but the typically expansion is between 200 – 300 %.

Swelling is homogenous along the element length. The hydrocarbon does not degrade the rubber structure but it will change the mechanical property effects. The swelling generally causes a reduction in the mechanical properties; hardness, tensile strength and Young's Modulus. While some mechanical properties will be reduced others may be improved, like the resilience, low temperature properties and sealing pressure. The change of the properties is a function of the volume change in the rubber element.

A positive swelling pressure is developed which exceeds the surrounding pressure by a few psi. The swelling pressure is very different from the sealing pressure of the packer. The sealing pressure is the maximum estimated pressure differential across the element. The sealing ability depends on the absolute swelling (hole size versus packer dimensions), not the swelling fluid.

4.3 PACKER TYPES

Different packer types are used depending on the downhole conditions. In cases where water-based mud is used at a temperature of 220˚ F, a packer with a single layer bonded elastomer is used. At a temperature higher than 220˚ F require the use of a high temperature packer, specially designed to prevent deboning of the elastomer from the base tubular. The high temperature packers can be used on environments up to 400 ˚ F.

When dealing with oil-based mud, a multi-layered construction on the packer is being used to delay the onset of the swelling while the packers is run from the surface and down into the well. The packer is designed with high-swelling inner core surrounded by a low-swelling outer layer and a diffusion barrier, as shown in Figure 8. The outer layer can delay the swelling onset with 72 hours

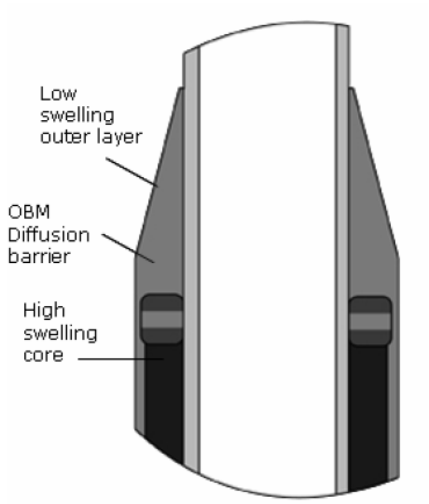

FIGURE 8 : PACKER USED IN OIL BASED MUD SHOWING THE LOW SWELLING OUTLAYER USED TO DELAY THE SWELLING OF THE HIGH SWELLING CORE (40)

4.4 FIELD INSTALLABLE SWELLING PACKERS

There are several types of swelling packers that instead of being mounted on a joint pipe can be applied directly to the completion or liner pipes. The two main categories of these field installable swelling packets are clamp on and slide on packers. Due to the lower differential pressure across the set packer, these packers are often called barriers instead of packers, so they are mainly used as mean of annular barrier in multi-segmented completions. The typical clamp-on swelling packer is built with a rigid steel cage surrounded with a swelling compound. The tool can be installed to an existing pipe using hardened steel pin.

FIGURE 9 : TYPICAL CLAMP-ON PACKER WITH A RIGID STEEL CAGE (39)

The other field installable swelling packer is the slide on packer. The typical slide-on packer is a fixed on the costumers casing or screens with set of fixed screws as shown in the figure above. The seal on the OD on the casing/screen is designed with the use of swellable O-ring that will absorb water/oil depending on the design to seal of the flow. This tool is strictly used for debris management and annular barrier and is not rated or tested to hold differential pressures due to the large variation of existing pipe ends.

FIGURE 10: TYPICAL SLIDE-ON PACKER (39)

4.5 DESIGN AND DEPLOYMENT

The Application of the swelling packers and the design is based on three different key variables: The size of the open space that needs to be isolated, the required differential pressure across the packer, and the required time to swell and set.

Through continuously testing of the expansion properties of the elastomer, simulators has been developed to accurately predict the expansion ratio of the elastomer, the pressure capability of the packers and the time to seal for a given base pipe and an outer element diameter. The simulators are being used to design and size a packer for a given application. The final hole size must be considered carefully in the design phase to make sure the packer is sized correctly to fill the annular space and to sustain the required differential pressure.

Since the packer has no moving parts and requires no surface or downhole activation, deployment is very straightforward: The packer is simply set together with as a part of the completion or casing string, and deployed with the assembly in a single trip.

While it may seem that the swell packers may be ideal, it's not suitable for all well conditions, due to its dependence of factors such as temperature, fluid and openhole size. In cases where swellable packers are not applicable, the use of a standard inflatable of a mechanical open hole packer can be run instead.

4.6 USE OF SWELLABLE ELASTOMERS TO ENHANCE PRIMARY CEMENTING

Many of the problems related to primary cementing can be overcome by including swellable packers in the casing program. Too often the challenges and considerations related to primary cementing are not dealt with properly, which will result in new challenges and problems. Even though it may seem like the well was properly cemented, failures in the cement sheath or microannulus leads to loss of annular isolation. For many cases in the deepwater environments, the slurries are designed to be fit-for purpose. However, the test run in the laboratory on the cement properties are done with an estimation of the well condition, it's not possible to predict a number of real conditions that leads to cement sheath failure. A simple approach to protect the cement sheath from failure is to utilize the swellable elastomers (41).

There is a simple approach to protect the cement sheath in critical areas. With a swellable packer completely surrounding the cement, excessive stresses formed by pressure and temperature fluctuations are absorbed by compression of the elastomer. Figure 11 illustrates how an elastomer seal assure 20 feet of undamaged cement, which is adequate to provide hydraulic isolation.

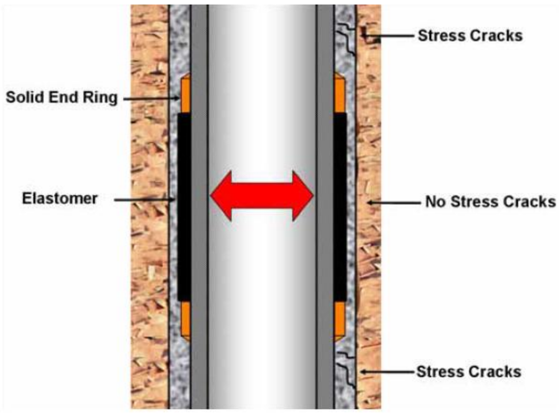

FIGURE 11 : SWELLABLE PACKER PROTECTING THE CEMENT SHEATH (41)

Not only will the elastomer protect the cement sheath, while the end caps constrain the amount of displacement, it has the ability to compress to accommodate casing diametric displacement. The end caps also contribute with reduction of casing radial displacement. This effectively increases the thickness of metal over the interval of elastomer seal length, which decreases potential diametric displacement.

The packer can be placed in critical areas such as but not limited to;

- Surface or intermediate casing to protect against sustained casing pressure
- Between known water and production zones
- Between depleted zones
- Intervals where production zone are expected to deplete at various rate

The cost of remedial intervention is often large compared to the cost of including swellable packers in the initial well completion design. Including this material and the packer solution in a primary cementing can be a good solution in developments wells through voids left by microannulus or mud channels.

5 Alternative Materials

5.1 PLUGGING AND ABANDONMENT MATERIALS

Plug and Abandonment is the well operation where the well is being secured with one or more plugs and abandon the well temporarily or permanently. A temporarily abandonment is defined as the well status where the well is abandoned and the well control equipment is removed, with the attention that the well will be put back to use at a later time frame, from days to several years. A permanent abandonment is defined as the well status where the well or part of the well will be plugged and abandoned permanently, and with the intention never re-enter the well again.

Conventionally, cement has been the material for plugging of the wells both permanently and for temporarily plugging. A complete isolation prevents gas, oil or water from migrating to surface or flowing from one subsurface formation to another, an operation that is very similar to a primary cementing operation.

The idea here is to evaluate the alternative materials used in well plugging to improve primary cementing jobs. Alternative materials for cement for in P&A operations are ThermaSet and Sandaband.

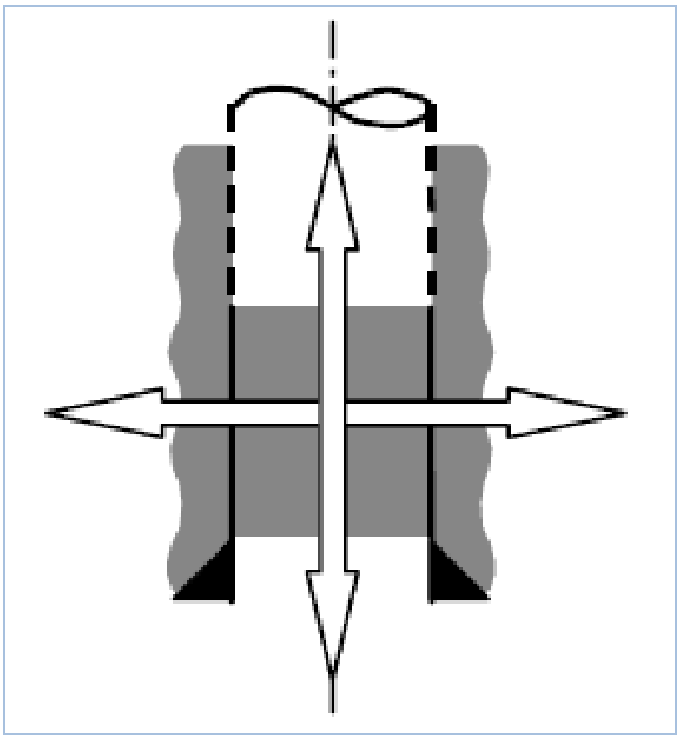

FIGURE 12 : BARRIER ILLUSTRATION SHOWING THE NEED OF HORIZONTAL AND VERTICAL ISOLATION (42)

5.2 THERMASET

The development of ThermaSet started around 1990, using SINTEF, the largest research group in Scandinavia. A systematic study was conducted, where many types of materials were investigated. From a total evaluation of the exposure, the material had to sustain and endure a variation of temperature and pressure, a specific thermosetting material was eventually chosen.

Thermaset is a resin-based sealant, a penetrating liquid with low viscosity. In its liquid form, Thermaset can easily be pumped and also be injected into small openings because its 100% particle free. The unfilled Thermaset has a density of 1.03 SG, by using either lightweight or heavy filler, the density can be adjusted to fit for purpose (43).

As mentioned, the Thermaset starts with a low density and it possible to regulate the density with particles. The liquid is the binding material and it also has an accurate setting time. Thermaset also has the advantages of right angle set and the property to reinforce weak formations. The viscosity of the material is also very low, figure shows the viscosity and how it’s changed with temperature (44).

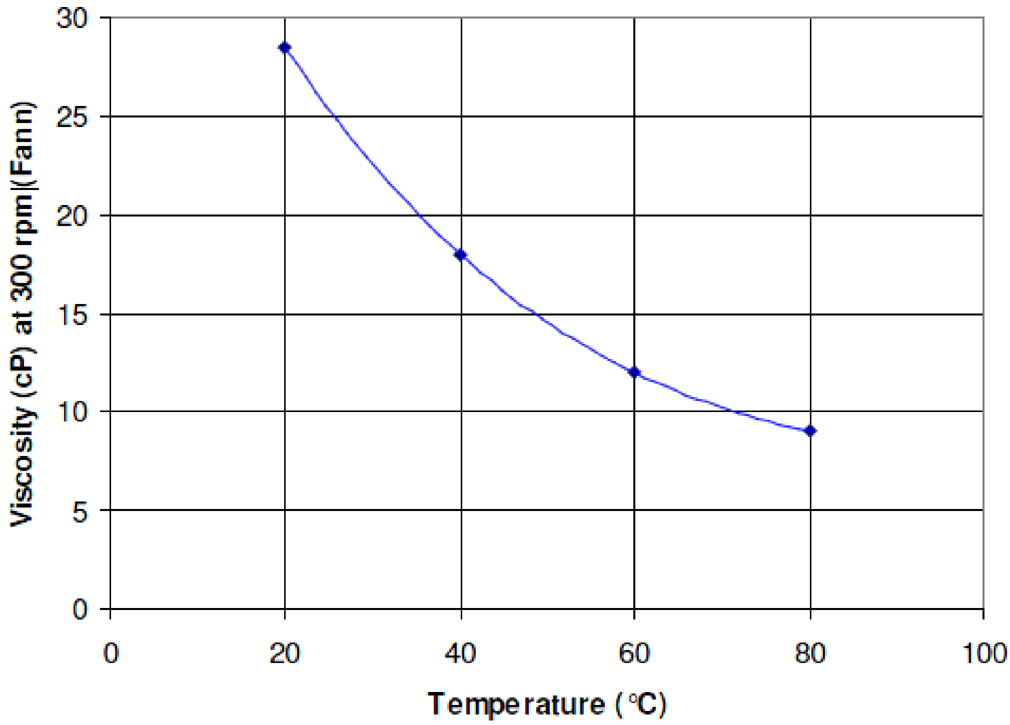

FIGURE 13 : VISCOSITY OF THERMASET DUE TO CHANGE OF TEMPERATURE (43)

5.2.1 ADVANTAGES OF THERMASET COMPARED TO CEMENT

An Ageing Test of ThermaSet was performed by SINTET. Wellcem claims that the test results from ThermaSet can withstand approximately 6 times the flexural Strain. E-modulus shows a far superior elasticity, and a highly increased Compressive Strength was tested and the rupture elongation is 6 times higher in ThermaSet. Table 4 shows a comparison between ThermaSet and Portland G Cement.

TABLE 4 : THERMASET VS. CEMENT (43)

Properties	ThermaSet	Portland G Cement
Compresive Strength (MPa)	77 ± 5	58 ± 4
Flexural Strength (MPa)	45 ± 3	10 ± 1
E-modulus(Mpa)	2240 ± 70	3700 ± 600
Rupture Elongation %	3.5 ± 0	0.01
Tensile Strength(MPa)	60	1
Feilure Flexural Strain (%)	1.9 ± 0.2	0.32 ± 0.04

Laboratory test shows that ThermaSet is a lot stronger than cement from different perspectives, and it has been used in different operations to replace cement.

Listed are the operations where ThermaSet has been including well therapy for all areas.

- Loss Circulation
- Zonal Isolation
- Depleted Zones
- Rock Stability
- Junction Isolation
- Water/Gas Shut off
- Leaking Annulus
- Plug & Abandonment
- Plugging of Control/Transmittal Lines

When a well has been set to production, the well starts to heats up due to the flow of warm oil. As a result, the casing will expand and cause tangential tensile stresses in the cement. ThermaSet can withstand such stresses. Figure 14 shows the two-dimensional situation, how a radial crack pattern occurs in the cement due to up heating.

FIGURE 14 : RADICAL CRACK CAUSED BY OIL HEATING (43)

Thermaset is initially a product for P&A, to repair failed cement and fix loss circulation. The advantages of Thermaset are good compared to cement. The company Wellcem As, based on tests, claim that they are just about there to be able to challenge cement in the operation of primary cementing (43).

5.3 SANDABAND

The idea behind Sandaband was based on the fact that poorly sorted sand has low permeability, and that a certain particle distribution can form sand slurry with high solids content that is possible to pump (45). Hence a low permeability material could be placed in the well that does not require chemical reaction to develop hydraulic sealing properties. Sandaband consist of 70-85 % quartz with a grain size diameter varying from less than a micron to a couple of millimeters. The rest of the volume consists of water and chemicals controlling the liquid properties such as viscosity and freezing temperature.

Compared to the desired properties of a permanent well barrier element described in the NORSOK, cement does not fulfill two properties; it's neither non-shrinking nor is it ductile. Sandaband is incompressible, non-shrinking, ductile, non-fracturing, none segregating, thermodynamically stable and chemically inert.

As mentioned, Sandaband does not set up following a chemical reaction, and therefore requires no setting time. Instead, Sandaband has properties like a Bingham Plastic material (45). A Bingham Plastic fluid are characterized by the fact that they need a certain minimum shear stress to start flowing, but have a linear relationship between shear stress and shear strain, shown in Figure 15.

This process is not time-dependent; meaning that the slurry will rapidly form a rigid body when pumping is stopped.

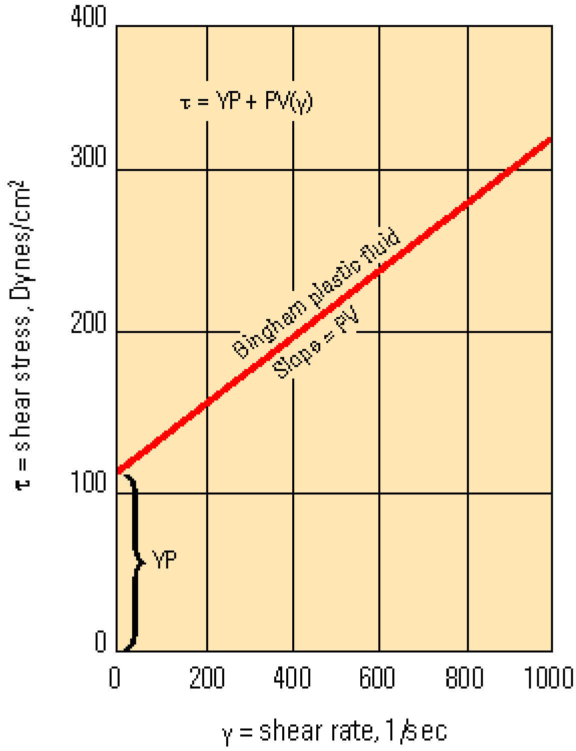

FIGURE 15 : RHEOLOGICAL MODEL FOR BINGHAM PLASTIC (11)

One of the main disadvantages of Sandaband is the fact that it needs to be premixed onshore. This could cause problems regarding uncertainties in the volume. The advantage though, is that Sandaband experiences almost zero losses to the formation, due to its behavior of Bingham Plastic material, making it easy to predict the volume needed.

As a replacement for cement in P&A operations Sandaband is a good alternative, but Sandaband has never been used in a commercial primary cementing operation. Although Sandaband works well by being thermodynamically stable, chemical inert and reduces the time spend by eliminating the wait on cement time, it lacks the ability to bond to the casing and formation, and therefore requires a solid fundament to rest on.

In 2007, Sandaband was considered as a material for primary cementing in the Peon field in well 35/2-2 by Statoil. The Peon field is a shallow gas deposit with unconsolidated overburden; it represented a number of new and technical challenges. The Peon field is still under development and the final installation won't be ready before 2016.

The operation plan for peon well 35/2-2 involved an external casing packer (ECP) filled with cement, the ECP together with a 10 meter gas tight cement column worked as fundament for the Sandaband (46) . Figure 16 illustrates the well design.

In order to inject cement behind the casing, the operation included port collars, casing with holes that can be opened and closed by means of an instrument (9 5/8 combo tools) that runs on the drill string. Figure 17 illustrates the tool setup.

The well barrier schematic, using Sandaband as barrier behind casing is attached as an appendix.

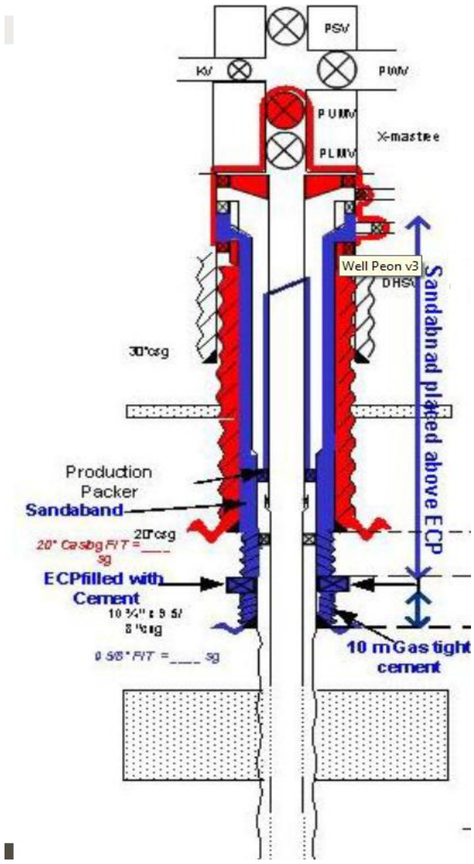

FIGURE 16 : WELL DESIGN IN PEON WELL 35/2-2 (46)

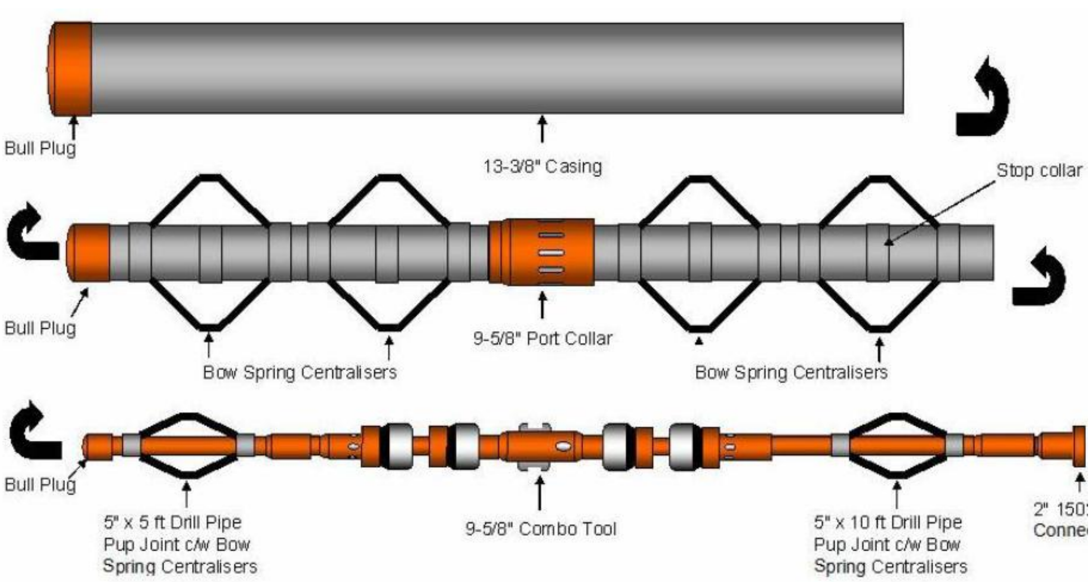

FIGURE 17 : DOWNHOLE SOLUTION SHOWING THE PORT COLLAR AND THE 9 5/8 COMBO TOOL ATTACHED TO THE DRILLPIPE. (46)

6 Cement Placement Methods

When it comes to placing cement slurry in the well, there are three methods being used in the O&G industry.

Listed are the methods:

- Conventional Cement Circulation
- Reversible Cement Circulation
- Coiled Tubing Cementing

The conventional method is already described in the section of primary cementing 2.4.

6.1 CEMENTING THROUGH COILED TUBING

Cementing through coiled tubing is not a new service line. However, it remains one that has received little technical attention. Cementing through coiled tubing is a much smaller business compared to conventional cementing of steel casings and liners, but it is still conducted daily. The typical cementing through coiled tubing is not one of placing large volumes of cement behind casing strings; it is one of placing a relatively small volume of cement in a well for remedial purposes (47).

Typical applications are:

- Curing channelling behind tubular
- Blocking off perforations
- Squeezing off perforations
- Placing, in conjunctions with packers, for wellbore isolation or abandonment
- Placing through holes in completion strings to produce "cement packets"
- Curing lost circulation zones during drilling
- Forming plugs for drilling sidetracks, "cement whipstocks".

6.2 REVERSIBLE CIRCULATION CEMENTING

Conventional cementing involves displacing cement slurry through the bore of the casing and out to the annulus between the casing and the wellbore to the desired level. Conventional cementing techniques have been used for many years, but it can be some shortcomings related to the technique. The conventional cementing placement method can be time-consuming because the cement has to be pumped all the way to the bottom and then back up into the annulus. Conventional circulation can cause excessive cement waste and cost associated with the cement volume used, and expensive additives such as retarders to slow down the hydration process of cement. These conditions get aggravated by high temperatures in the borehole and during lost circulation. In extreme conditions, the cement can be set before reaching the desired destination. These factors can potentially make conventional cementing more costly.

In reverse-circulation cementing, cement is being pumped directly into the annulus between the casing and the wellbore. Figure 18 illustrates the two cementing placement methods, and by doing this, the RCC avoids the higher pressure necessary to lift the cement slurry up the annulus. (51) In order to perform the RCC technique, a few changes are necessary. Conventional float equipment is not suitable for RCC jobs; the float equipment needs to be specially ordered.

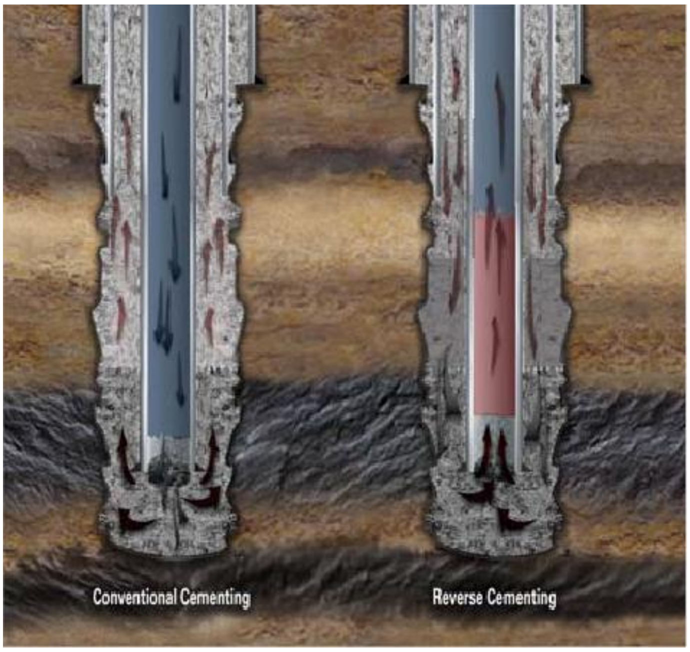

FIGURE 18 : CONVENTIONAL CEMENTING VS. REVERSE CEMENTING (51)

The main advantage of the RCC technique is the reduction in equivalent circulation density, the ECD is the effective density exerted by a circulating fluid against the formation taken into account the pressure drop in the annulus (52). By placing the cement directly in the annulus, the amount of retarders and the total amount of cement can be reduced. Another advantage of RCC is the improved productivity due to less risk of cement invasion into the producing zone.

The reverse circulation technique has some disadvantages; the one problem with RCC is the need of an indicator in order to know when the cement turns the corner. And as mentioned earlier, some equipment is not suitable for the RCC jobs, more iron and special kit are required to rig up for a RCC job. As the cement reaches the bottom and starts to flow up, the system may require pressure to be held on the casing as the casing backpressures.

All the previous applications of the RCC jobs confirmed a significantly reduced ECD at the casing shoe compared conventional circulation cement (52). A hydraulic design calculation was done and the result showed that RCC is advantageous over conventional method when the zone of interest was not at the bottom of the well. Using RCC is favorable; however risk of fluid loss is greater if a weak zone is located far away from the casing shoe

7 Discussion

The world demand for oil and gas is increasing, and the production rate on the largest producers is declining. We know that 57% of global energy consumption comes from oil and gas, by 2030 the EIA projects that the demand for oil and gas will increase by 27%. Even though the oil demand will increase, the world will not run short of oil in the next few decades, but there is a limit on supply of the oil that is easy to reach. This forces oil companies to go deeper in search for oil and gas. By 2030 the production of oil from water deeper than 600 meter will double up from five million to 10 million barrels per day. The disaster with the Macondo well in the Gulf of Mexico at a depth of 1500 meters shows the challenge, the risk and the importance of primary cementing.

Going deeper is a factor; there will also be an increase in unconventional sources such as extra heavy oil and oil sand. Deposits in Canada and Venezuela combined are believed to exceed the total world resources held in conventional oil field (47). In order to meet the oil demand the production of unconventional sources will increase in the future, a forecast is shown in Figure 19.

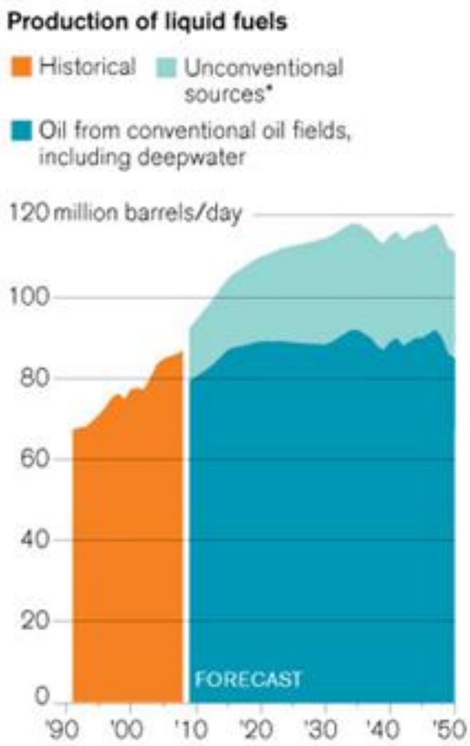

FIGURE 19 : PRODUCTION FORECAST OF LIQUID FUELS SHOWING AN INCREASE ON UNCONVENTIONAL SOURCES WHICH INCLUDE: COAL- AND GAS TO LIQUIDS, BIO FUELS, LIQUID NATURAL GAS AND TAR SANDS. (47)

Another unconventional source is shale oil and shale gas. A newer shale oilfield, Eagleford in Texas, is one of about 20 new onshore oil fields so far that combined could increase the oil output of the United States by 25 percent within 10 years (48). During the recent years, the shale liquid production has increase exponentially, as shown in Figure 20. In order to recover the resources from the shale play, it's necessary to drill long horizontal sections and use hydraulic fracturing to enable the production.

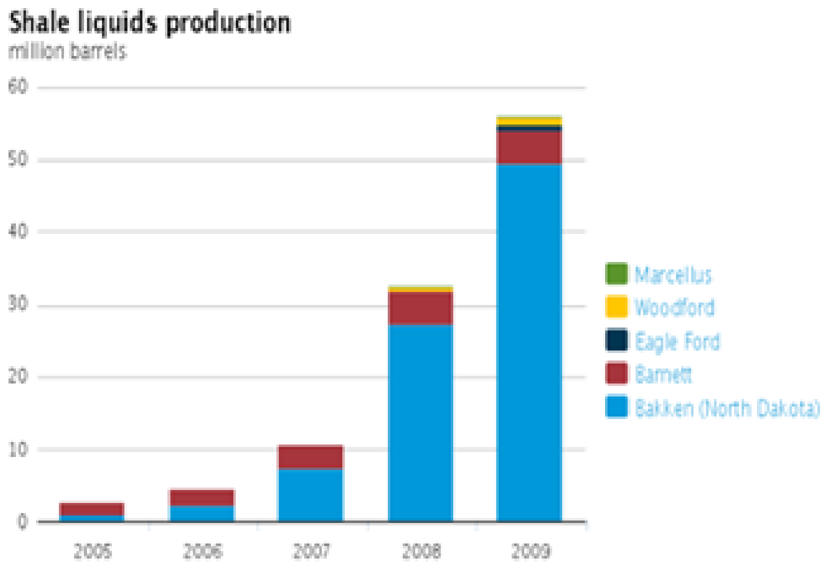

FIGURE 20 : SHALE LIQUIDS PRODUCTION IN MILLION BARRELS SHOWS THE LARGE INCREASE IN SHALE OIL PRODUCTION IN THE RECENT YEARS (48)

Further development of oil and gas resources in the petroleum industry today include looking into remote areas such as harsh environments as the Arctic. The low temperatures and high pressure reservoirs can pose serious challenges for the primary cementing, and needs to be solved. In the Arctic, surface issues and challenges such as the extreme harsh environment and low temperature, ice, transportation and infrastructure logistics, as well as down-hole problems as permafrost, must be addressed and solved.

Because we are moving in the direction of deepwater and unconventional source for petroleum, we need to work with well challenges in those types of wells, especially primary cementing challenges. In the heavy oil industry, commercial production of heavy oil and bitumen uses steam injection to increase production. Injecting steam into a heavy-hydrocarbon deposit can be effective in two ways.

The viscosity of all hydrocarbons is greatly reduced as the temperature of increases. Injecting steam raises the temperature of a reservoir and makes the hydrocarbon liquid within the reservoir flow more easily. If the injected temperature heats a reservoir to a sufficiently high temperature, the heavy components can break down into lighter hydrocarbons. This process is called in situ conversion, and the produced hydrocarbons can be similar to crude oil.

The most advanced production technology systems using steam is steam-assisted gravity drainage, SAGD (49). In its most complicated configuration, SAGD utilizes multilateral horizontal wells, as shown in Figure 21.

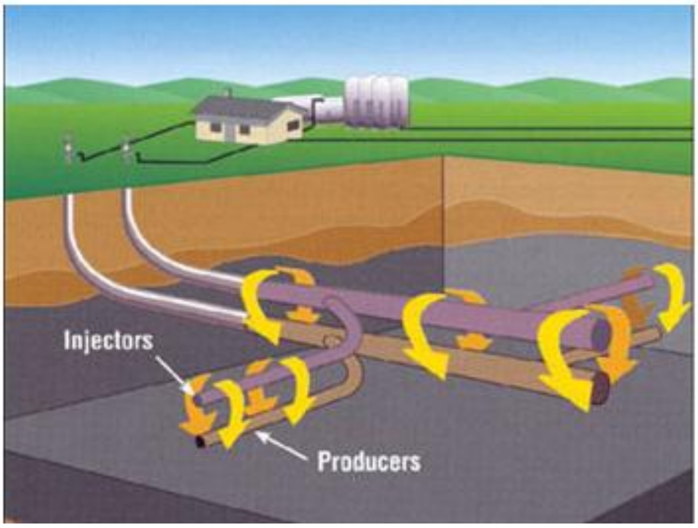

FIGURE 21 : ILLUSTRATION OF SAGD PRODUCTION OF HEAVY OIL USING MULTILATERAL HORIZONTAL WELLS (49)

Because we are running low on "easy oil", operations such as primary cementing will be more challenging. Results from horizontal well technology has proven it to be cost effective in optimizing hydrocarbon recovery, in many cases, long horizontal sections is the only solution. Multilateral-well technology has revolutionized the way to access the reservoir with wells. The ability to create wells with multiple branches can target widely spaced reservoir, this can be done with both new wells and by side tracking older wells to improve the access to the reservoir. The challenges with primary cementing will be related to both environmental and complications from well design. If a new material where to be used in a primary cementing job, it should be both applicable under both types of challenges.

Listed are factors that can lead to primary cementing challenges:

- The Arctic Challenges
- Shale-Gas and Shale-Oil Challenges
- Extra Heavy Oil and Oil Sand Challenges
- Deepwater Challenges
- Long Horizontal Sections Challenges
- Steam Injection Well Challenges
- Side Tracking Challenges
- Multilateral Well Challenges

What does an increase in energy consumption has to do with primary cementing? In order to access the future oil resources it's economically necessary to have good well integrity starting with a solid primary cementing.

Listed are problem that arises from a bad primary cementing

- The well will never reach its full production potential
- Efforts to repair the cementing job may actually end up causing irreparable damage to the formation
- Lost reserves
- Lower production rates
- Stimulation treatments may not be able to be confined to the producing formation
- Aquifer and reservoir damage from cross-flow

7.1 OILFIELD CEMENT

Since the first use of cement in wells in 1903, cement has been used for primary cementing. Because of that, experience related to cement is plenty. The use of cement is the only current means of establishing zonal isolation within wellbores.

The reason why cement is the only material being used for primary cementing is based on 3 main factors:

- The experience related to cement
- The large variation of cement
- The low initial cost

Cement is a very complex material with a large variation of properties that can be modified using additives. With different techniques and additives, cement can be modified to fit the well environments. The additives can be divided into 8 main groups for the different properties.

TABLE 5 : SIMPLE OVERVIEW OF ADDITIVES FOR OILFIELD CEMENT

Additives Overview	
Accelerators	Chemical that shorten the settling time of the cement slurry
Retarders	Chemicals that increase the settling time of the cement
Extenders	Materials that lower density if the cement and may reduce the quantity of cement per unit volume of set product
Weighting Agents	Materials used to increase slurry density
Dispersants	Chemicals that reduce the viscosity of a cement slurry
Fluid Loss Control Agents	Materials used to control leakage of the aqueous phase of a cement system to the formation
Lost Circulation Control Agents	Materials that control loss of the cement slurry to weak formations
Specialty Additives:	Miscellaneous additives, such as antifoam agents, fibres, etc

The additives can be chemicals and materials added to the cement slurry to modify the characteristics of the slurry or the set cement. The cement additives are commonly available in powder or liquid form, enabling some flexibility in how the cement slurry is prepared. Including the additives there are other techniques to totally change the structure of the cement. An example is to add foaming agents and nitrogen to the cement slurry to create foamed cement. By modifying the cement, it's possible to make cement more suited for harsher well conditions. Table 2 is an overview of different cement types; some are dry blend of API cement with a few additives, while others are cements containing other chemicals characteristics. The compositions of the cements is controlled and often kept confidential by the suppliers.

The table is created to show the diversity of cement and how it can be modified to fit the purposes:

TABLE 6 : **BRIEF DESCRIPTION OF SPECIAL CEMENTS**

Cement Classification	Cement Name	Description
Conventional Cement	Portland Cement	Portland cement is artificial cement made by burning a blend of limestone and clay. PC sets and develops strength due to hydration when mixed with water. A chemical exothermic reaction between the water and the compounds present in the cement occurs
Conventional Cement	Gypsum Cement	Gypsum cements are commonly used in low temperature applications because gypsum cement set rapidly, has early high strength, and has positive expansion (approximately 2.0%).
Lightweight Cement	Pozzolanic- Portland Cement	Pozzolanic materials are often dry blended with Portland cements to produce lightweight (low density) slurries for well cementing applications
Lightweight Cement	Water Extended-Cement	Water extended is done by increasing the water ratio in the cement slurry. Water is mixed into the slurry together with extender and water absorbing additives such as bentonite, fly ashes and silicates gels to control the free water while lightening the slurry.
Lightweight Cement	Foamed Cement	Foam cement is made by properly combining three elements: cement slurry, foaming agents, and a gas (usually nitrogen). Foam is applicable for supporting primary and remedial cementing in vertical and horizontal, offshore and onshore.

Lightweight Cement	Hollow Glass Spheres	Hollow glass sphere (HGS) also called microspheres are microscopic bubbles of glass that are manufactured for a wide variety of uses in many different industries. In addition to the ability to reduce the weight, the glass sphere has a low thermal conductivity and a high compressive strength making them suitable lightweight additive to oil well cements. The specific gravity of the spheres ranges from 0.32 to 0.6.
Lightweight	Hollow Ceramic Spheres	The ceramic particles, also known as cenosphere are hollow. Hollow Ceramic Gas filling spheres consist of air, nitrogen or carbon dioxide, and the specific gravity of the particle ranges from 0.6 to 0.9.
Remidial Cement	Microfine Cement	Microfine cements are composed of very finely ground cements of either sulfate-resisting Portland cements, Portland cement blends with ground granulated blast furnace slag, or alkali-activated ground granulated blast furnace slag. Harden fast and can penetrate small fractures.
Flexible, Expandable Sealant Systems	Expanding Cements	Expansive cements are available primarily for improving the bond of cement to pipe and formation. Expansion can also be used to compensate for shrinkage in neat Portland cement.
Thermal Cement	Calcium Aluminate Cement	High-alumina cement (HAC) or calcium aluminate cements (CAC) are used for very low and very high temperature ranges. These cements can be accelerated or retarded to fit individual well conditions, however, the retardation characteristics differ from those of Portland cements.

Thermal, Corrosion Resistant	ThermaLock™	ThermaLock cement is specially formulated calcium phosphate cement that is both CO2 and acid resistant. This cement is well suited for high temperature geothermal wells. ThermaLock has been laboratory tested and proven at temperatures as low as 60°C and as high as 371°C.
Corrosion Resistant Cement	Latex Cement	A well distributed latex film may protect the cement from chemical attack in some corrosive conditions, such as formation waters containing carbonic acid. Latex also makes the hardened cement elasticity and improves the bonding strength and filtration control of the cement slurry.
Corrosion Resistant Cement	Resin or Plastic Cements	Resin and plastic cements are specialty materials used for selectively plugging open holes, squeezing perforations, and the primary cement for waste disposal wells, especially in highly aggressive acidic environments
Thermal Cement	Sorel Cement	The cement is made by mixing powdered magnesium oxide with a concentrated solution of magnesium chloride. Sorel cements have been used to cement wells at very high temperatures (up to 750°C)
Corrosion Resistant Cement	EverCRETE™ CO2	EverCRETE CO2 is marketed as CO2-resistant cement that can be applied for carbon capture and storage, as well as CO2 enhanced oil recovery projects It can be used both for standard primary cementing operations, as well as plugging and abandoning existing wells.

7.2 LIMITATIONS OF CEMENT

Experience has shown that after operations such as completions, pressure testing, hydraulic stimulation, and production, can cause the cement sheath too lose its ability to provide zonal isolation.

Listed are factors that can cause cement to fail

- High temperature
- Corrosion heavy environments
- Cement shrinkage
- Formation damage
- High cement permeability
- Cement carbonation
- Casing expansion/contraction

Because cement has many ways it can fail, the petroleum industry is constantly trying to improve all operations involving cement. The primary cementing operations is a complicated operation with many challenges and considerations. During the earlier stages of the cement operation, it's important to displace the mud to avoid contamination with the cement. As mentioned earlier, the cement is a complex material, and if it gets mixed with the drilling fluids it can lose important properties leading to failures in the cementing operation. Other challenges and considerations involve placing the cement correctly and keeping the casing centralized in the hole. Listed are challenges and considerations during a primary cementing operation.

- Mud displacement
- Mud cake removal
- Cement placement
- Centralizers
- Gas migration
- Formation fracture pressure
- Well temperature

One important thing to be aware of is, if cement were to be replaced by an alternative material, the challenges and considerations for primary cementing will also be applied to those materials.

7.3 ALTERNATIVE MATERIAL

In theory, there are materials with better properties than cement, but no alternative material has yet been used in a primary cementing job. The various environment and different types of well will need different properties and solutions for a primary cementing job, and an alternative material may be used depending on the well.

7.3.1 SANDABAND

Sandaband is the other alternative material which is being assess in a primary cementing operation. While ThermaSet is a particle free resin-based sealant, Sandaband is based on specially sorted sand. Compared to the desired properties of a permanent well barrier element described in the NORSOK, cement does not fulfill two properties; it's neither non-shrinking nor is it ductile. Sandaband has properties that surpass cement.

Listed are the properties that make Sandaband better than cement for primary cementing purposes:

- Incompressible
- Non-shrinking
- Ductile
- Non-fracturing
- None segregating
- Thermodynamically stable
- Chemically inert

Being ductile makes it adaptable to changes in the wellbore, a property ideal for a long lasting primary cementing. The problem with Sandaband is that it lacks the ability to bond to the casing and the formation, and therefore requires a solid fundament to rest on.

Challenges and considerations during a primary cementing when cement is being used will also be important for Sandaband. One of the most important challenges is keeping the casing centralized. It's critical to have the casing centralized when placing Sandaband behind the casing, it has to do with the Bingham Plastic properties and the fact that the flow area is a lot smaller when injecting Sandaband compared to conventional cement placement, because of the solid fundament Sandaband cannot be placed behind the casing conventionally. A challenge that we can ignore is gas migration, Sandaband does not settle and its gas tight during the pumping stage. Because it's thermodynamically stable, well temperature has no effect on Sandaband.

7.3.1.1 SANDABAND PLACEMENT

A solution to place Sandaband as barrier behind casing will involve an external casing packer (ECP) filled with cement; the ECP together with gas tight cement column will work as fundament for the Sandaband to rest on. The plan in the Peon filed was to use port collars in order to pump the Sandaband conventional behind the casing after the ECP and the cement column was set. Instead of forcing Sandaband behind the casing by circulating Sandaband conventionally, applying the method of reverse circulation cementing might be a better solution. If RCC where to be used with Sandaband it can reduce the time of the operation because the isolating material is being displaced directly into the annulus. Another positive effect achieved from pumping Sandaband directly into the annulus is a reduction in the equivalent circulation density (ECD); this will reduce the chance of Sandaband invading the formation which can lead to lost circulation. Even though an opening is not required for Sandaband to be injected in, the drilling fluid needs an exit to be circulated back to the surface. Using RCC will still require an opening to be created above the solid fundament where the Sandaband will rest on; this is because the material shall not be placed on top of a fluid column allowing gravitational settling. After Sandaband is successful placed behind the casing, it's necessary to have a detection tool to know when all the mud is displaced out and when Sandaband has been placed properly. This is required to know when to activate the combo tool to close the opening in the port collar.

If we look at the negative side of using the RCC, there is the fluid loss challenge when RCC is being used over intervals of weak formations. Since Sandaband has Bingham Plastic properties. The Bingham Plastic properties will reduce the fluid loss problems because it requires a certain minimum shear stress for the Sandaband to start flowing. Another problem with RCC is that it will require some extra equipment compared to the conventional circulation. Using Sandaband requires many changes to the standard setup, more iron and special kit that is necessary won't make any difference for the operation. If Sandaband where to be used, I would recommend to use the RCC as the placement method for it.

7.3.1.2 VERIFICATION OF SANDABAND

A good primary cementing job needs to provide adequate zonal isolation in order to prevent cross flow, it also needs to support the casing and protect it from corrosion. With the design purpose stated, it's possible to perform testing on the isolating material. Verification of the Sandaband column is stated in the Well Barrier Element Acceptance Criteria Table (WBEAT) attached in the appendix:

The verification requirements for having obtained the minimum Sandaband height shall be described which can be:

- ❑ Verifications by logs (gravel pack evaluation, bond log), and/or
- ❑ Estimation on the basis of records from the pumping operation (volumes pumped, returns during pumping, etc.).

Usually when a cement evaluation is being conducted, a sonic or ultra sonic logging tool is being used. When it comes to Sandaband, there may be some other verification methods which can be used. Gravel packing is a process usually undertaken to prevent production of sand and other formation materials to be produced with oil and gas. This is done by placing gravel of a specific size in the annulus. There is a great similarity between gravel packs and Sandaband, where both are composed of unconsolidated rock fragments. Verification of gravel packs may be used for Sandaband.

In the WBEAT it is also stated that measurement on the volumes being pumped and the volumes returning can be used to estimated height of the Sandaband column.

Logging Sandaband is basically the same as for cement logging; with the difference that Sandaband has less compressive strength than cement. This means that the difference in the measurements above and below Sandaband column will be smaller than a standard cement column. A solution to this is to log 2-3 passes over the interval before and after placement and then compare the data. This may seem troublesome; but it's a method which is often used when dealing with foamed cement. Because the acoustic impedance of foamed cement being similar to the mud/completion fluids, the effect on the logs when using foamed cement is low.

The method mentioned earlier which is being conducted to evaluate gravel packs is the pulsed neutron tool. To describe the method simply, this technique provides a measure of the amount of quartz (SiO_2) behind the casing, the result can be used to determine the top of the Sandaband column because Sandaband consists mainly of quartz.

Other methods that can be used is to add a radioactive tracer to the mass, typically a cobalt or iodine isotope with a relatively short half-life (a few days / weeks), then log it with a standard gamma-ray tool. It is also possible to log with a density tool. Again, this should be done both before and after placement and then compare values.

The methods mentioned, including sonic tools will only give an average of the entire circumference, not all the channels behind the casing will be identified. Over important and critical parts of the well, the best way to evaluate the primary cementing job would be to use ultra sonic bond log tools.

Listed are some Ultrasonic logging tools from various service companies:

TABLE 7 : ULTRASONIC TOOLS AND THE COMPANIES

Ultrasonic Tool	Company
Ultrasonic Imager Tool [USIT]	Schlumberger
Segmented Bond Tool™ [SBT™]	Baker Hughes
Circumferential Acoustic Scanning Tool-Visualization [Cast-V]	Halliburton

7.3.2 THERMASET

The development of ThermaSet started around 1980 and it has gone through a variety of systematic testing. ThermaSet is initially a product for P&A, repair failed cement and used to fix loss circulation, but it has the potential to be an alternative material for cement in primary cementing because of the improved mechanical properties. Thermaset is originally particle free, and placing of ThermaSet won't be any problem. Information from Wellcem shows that vital strength of Thermaset is much stronger than of Portland G cement, and Thermaset can withstand stresses caused by casing expansion when the casing it heated by warm reservoir fluids. Thermaset is superior to cement in terms of strength and it can be used in corrosion heavy environments. Just like cement, ThermaSet has challenges and considerations that need to be accounted for. Most of the challenges related to cement will also apply to ThermaSet. ThermaSet is particle free, and to remove the mud in the annulus and the mud cake is important to avoid contamination. Keeping the casing centralized also necessary, because it's easier to displace compared to cement, it's will not be as critical for ThermaSet as it would be when using cement to have a casing centralized. Reservoir temperature will not affect ThermaSet either, the same way as it affect cement. ThermaSet can be designed to settle quite accurately when the temperature is known, according the Wellcem. Casing expansion due to heating can cause tangential tensile stresses in the cement; ThermaSet has proven to withstand tangential tensile stresses.

7.3.2.1 THERMASET PLACEMENT

ThermaSet is originally a particle free substance which can easily be placed. Depending on well structure and down hole environments, the conventional and RCC are both good solutions for ThermaSet. ThermaSet has only been used as remedial cementing and for well integrity solutions, in these cases ThermaSet was placed reversible. If ThermaSet was to be used as a replacement for cement, I would recommend a conventional placement method. Keeping the operation as simple as a possible is the key for using ThermaSet.

7.3.2.2 VERIFICATION OF THERMASET

Verification of ThermaSet is normally done by pressure tests except casing cementing. For casing cementing the quality verification is still under developing. Because ThermaSet is particle free, it's hard to say how it's going to response to the acoustic logging tools. Testing and evaluating how ThermaSet will respond to verification methods is critical if Thermaset is to be used as a material for isolation behind the casing. Adding radioactive tracers in the mixture can also be a solution, it's necessary to test if tracers, such as cobalt and iodine isotope have any effect on the properties of ThermaSet. Wellcem could confirm that testing of verification methods were soon to be conducted.

7.4 STATE OF THE INDUSTRY

Sandaband and ThermaSet have properties which makes them better than cement when it comes to a long lasting primary cementing. Why are they not being used in replacement of cement? I believe one of the reasons why this is not happening is related to the state of the industry. I pointed out earlier in the discussion that cement has been used since 1903 and the knowledge around cement is plenty, both positive and negative. The petroleum industry has the tendency to be conservative in some aspects. One of the reasons is related to economy. The petroleum industry is a high risk industry where large investments is locked in equipment and on services around the usage of cement, the usage of an alternative material to replace cement will impact both operators and service companies. The fact that cement has always been the only material being used may yield another problem. The people sitting in the decision making positions are probably cement experts, choosing cement is something that comes naturally; it's understandable that they don't want to choose another material they have no familiarity with for such an important operation. Even though they know that cement can fail in several ways, at least they know about the problems and they know what to do when the problem occur, even though it's expensive. Nobody wants to be the first to test a new material for such an important and expensive operation. At the same time, because the materials have not been tested out for such an important operation, the reason for testing them out is even greater.

7.5 APPLICABILITY OF SANDABAND AND THERMASET

Because of the large variation in challenges, both Sandaband and ThermaSet may be used in some primary cementing operation. In environments with high temperatures and in presence of CO_2 or other aggressive formation fluids, corrosive attack can be a major problem for the cement sheath. Both Sandaband and ThermaSet are chemically inert and will be resistant to any corrosion attacks, making both potential candidates for future solutions in high corrosion wells. Many wells with corrosion are caused by high temperature, and a high temperature fluctuation makes the casing expand and contract. The high thermal induced stresses will affect both the casing and the cement sheath, Sandaband with its ductile properties can be good solutions for temperature fluctuating wells. Test data from Wellcem shows that ThermaSet can withstand large temperature induces stresses. Example of wells with high temperature and large changes in temperature are HDR wells, hydrothermal wells, steam injection wells, arctic wells and HPHT wells.

The well type that might suit the usage of Sandaband best as isolation behind the casing are shallow gas fields, such as the Peon field. The water depth to the sea bed in the Peon field is around 350 meters and the reservoir is 165 meter under the sea bed. The reservoir covers 250 km^2 and the gas column thickness ranges from 0-25 meters (55). This is a very narrow gas column and should normally be developed with horizontal wells. Since the reservoir is just 165 meters beneath sea depth, it's currently not possible to build up a horizontal section. The reason why Sandaband is a good solution in shallow gas fields is because it's a simple well design and due to subsidence and cracking. Subsidence and cracking of the formation will occur when the field has been produced over a certain time; because water from the cap rock is drained into the gas reservoir. Sandaband will serve as barriers element if the cement fails because of subsidence and cracking. Sandaband is a fluid with Bingham plastic properties and can maintain integrity with the cracking and subsidence. Although Peon is a shallow and low pressure gas well, blowout is still a great issue. A vertical well is short and almost frictionless; a blowout can be very costly. Sandaband fills the space between the formation and the casing so that gas cannot flow past and to the surface.

The usage of Sandaband has certain limitation; it's complicated to use Sandaband. By evaluating future usage of the materials for primary cementing, we need to look at what type of wells we might see an increase of. Unconventional oil and gas, thin reservoirs and complex formations are increasing challenges. Long sections of horizontal wells, branched completions and side tracking are well designs to overcome in the future. Solutions involving Sandaband in these types of well designs is not an option, the usage of Sandaband is already complicated without the extra challenges.

While well design such as long sections horizontal section with narrow spacing, side tracing and other complicated well scenarios is not suited for Sandaband. Using ThermaSet can be a much easier in a complicated well design, if ThermaSet is able to support the casing. The test results from Wellcem confirm that the Young's Modulus of ThermaSet is lower than classical Type G cement. It's uncertain how long sections of casing ThermaSet can support, in cases where ThermaSet can't support the casing; cement needs to be used together with ThermaSet. The solution of combining cement and ThermaSet will be too time consuming and too expensive.

7.5.1 COST ANALYSIS

Oil well cementing cost can be broken down into 3 major categories;

- Cost of rig time
- Cost of services
- Cost of material

Table 8 shows a relative cost comparison between the alternative materials with conventional cement.

TABLE 8 : COST COMPARISON BETWEEN THE ALTERNATIVE MATERIAL AND CONVENTIONAL CEMENT

Primary Cementing Material	Rig Time	Cost of Services	Cost of Material
Conventional	High	Low	Low
Sandaband	Low	High	Medium
ThermaSet	Medium	Medium	High

The price of conventional cement without special cements additives is low. The cost of services is also low and we can use the conventional rig time as a standard to compare with the two other materials.

The cost of Sandaband is more expensive compared to conventional cement, when it comes to more sophisticated cement mixture it is probably more similar, or perhaps even lower. A cost increase will come from the extra services needed to deal with a more complicated operation. A reduction in rig time will account for the extra cost from material and extra services. Even though the usage of Sandaband will require a fundament of cement, the rest of the material does not need time to settle. This is the factor where time and money can be saved in the operation. Depending on the well, a reduction of 10-20 hours can be achieved if executed properly. Using a material that does not settle has other positive side with it also. Reduced risk of pumping is not straight forward to quantify, cementing into a drill string is one of the critical risk when dealing with cement, days and up to weeks of rig time can be lost, reduced risk of wrong cement settling or wrong cement placement is clearly an advantage of using a non-hardening material.

If conventional cementing procedure were to be used for ThermaSet, a reduction in rig time can be achieved. Even though ThermaSet will require time to settle, the settling time is very low compared to cement. The cost of services will be increased due to dealing with an unconventional material; I assume that there will be some extra services when using ThermaSet. The main problem with

ThermaSet is the cost of the material. ThermaSet is at least 5 times more expensive than cement, and it's not clear if is this is conventional cement or special cement. Even though material cost is a small part of the cost of a well construction, it can be determine factor for a material trying to compete with the cheaper conventional cement.

The last factors which can be discussed are cost savings related to a reduced number remedial cementing job. Because cement has some issues when it comes to long lasting zonal isolation, both the alternative material has better properties for a longer lasting primary cementing, which will reduce the number of intervention needed. This cost saving regarding to a reduced number of remedial operations are very hard to quantify, the number of remedial cementing operation needed is impossible to predict, the cost and the time used to fix a well vary a lot, and the cost of shutting a well down for maintenance depends on the value of a well.

7.6 SWELLABLE TECHNOLOGY

Another technology that is becoming more increasingly used in the oil and gas industry is swellable elastomers, the uptake and usage of swellable technology is quite rapid but the application of swellable packer as an alternative to cementing is still in the earlier stage of development. Downhole swellable elastomer technology is essentially very simple. A swellable compound is applied on the outside of the casing. When the swellable element comes in contact with the downhole fluids it will swell to fill the annulus and to create a high pressure seal.

Reason why swellable elastomer packers are becoming more popular compared to cement in completion jobs:

- Less time-consuming
- Cheaper
- No special personnel required
- No extra equipments required
- Tested at high pressures

The main problem when it comes to replacing cement in a primary cementing job is that the packers do not provide the necessary casing support. In a primary cementing job, supporting and keeping the casing centralized is critical. But as the ability to drill very long horizontal section has improved, the demand placed on cement has also been increased. In many cases, the demand that is put on cement cannot be met due to downhole space restriction; such wells have often been left "bare foot". These types of solutions can be very risky, especially if there are concerns about water breakthrough or formation damage. The swellable elastomer packers can be used to achieve an isolation job as fast and simple as an open hole completions with the zonal isolation solution usually associated with cement.

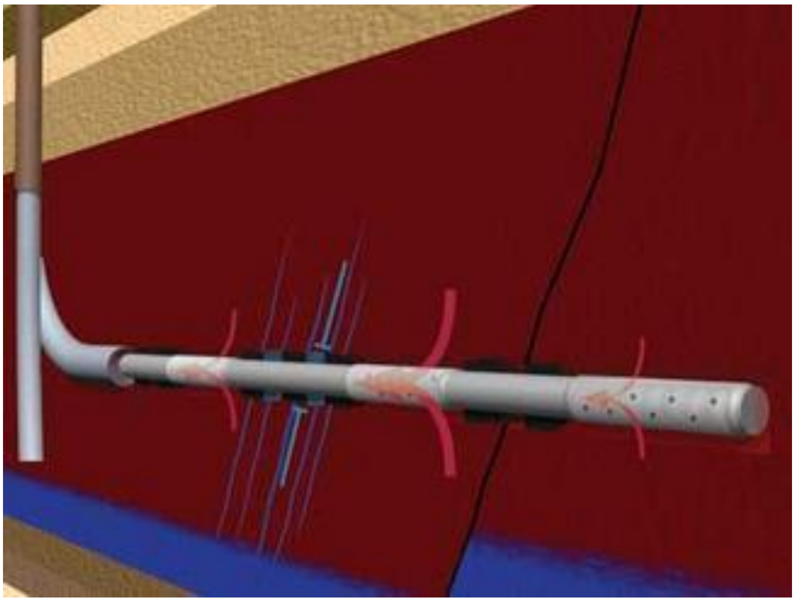

FIGURE 22 : ILLUSTRATION OF SWELLABLE ELASTOMER PACKERS USED IN A HORIZONTAL WELL APPLICATION TO PROVIDE ZONAL ISOLATION FOR THE WATER PRODUCTION (53)

7.6.1 USE OF SWELLABLE ELASTOMERS TO ENHANCE PRIMARY CEMENTING

As mentioned earlier in the discussion, cement has some many ways to fail; damage from pressure and temperature as well as minor geological movement can cause formation of micro annuli. The swellable packers may not be able to replace cement in a primary cementing job, but it can be used in some applications where the usage of cement is not convenient and it can be used together with cement to improve the primary cementing.

The failure of cement often occurs between the cement and the casing, rather than between the cement and the formation. This is because the casing has the tendency to expand and contract due to temperature variation, which conventional cement cannot respond to, leading to gas or fluid migration that can get worse over time.

If the swellable elastomer is designed to react to the formation fluids, it can be used to enhance the primary cementing. By using thin layers of swelling rubber bonded onto the casing, the swellable elements can respond to the expansion of the casing by absorbing with compression of the elastomer. In case of contractions and a void is created, the swellable elements can react to the formation fluids and swell to fill in the area left behind.

A good thing about this reinforcing solution is once at depth, the elastomer packer simply waits. Should the well's cement fail at any time, there is a remedial solution already in place. The elastomer can also be designed to swell sufficiently to bridge the gap between the casing and the cement, an illustration is shown in Figure 23.

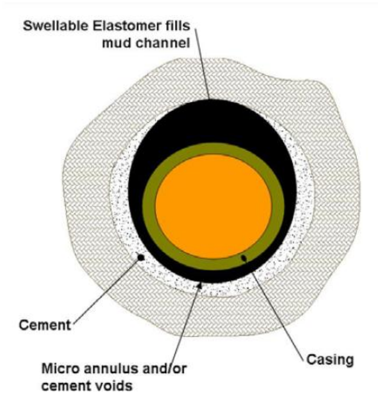

FIGURE 23 : SWELLABLE PACKER EXPANDED AND FILLING VOID AND MUD CHANNEL (41)

It's not possible to predict a number of real conditions that leads to cement sheath failure, even though it's expensive to include the swellable packers in primary cementing, the cost of remedial interventions is much larger. Including swellable elastomer packers in a primary cementing will be cost effective over time, especially in fields where microannulus and mud channels are a problem.

7.6.2 THE SITUATION TODAY

As the situation is today, ThermaSet and Sandaband cannot compete with cement in a primary cementing operation. Cement will still be the first and only choice for a primary cementing material for now. Currently, Sandaband and ThermaSet are still at a testing stage and both alternatives seem to have limitations.

In order to make Sandaband more competitive as a primary cementing material, it needs to be used as a primary cementing material. Experience needs to be gained in order to develop method and improve equipments to best suit Sandaband. Data to prove that Sandaband is a trustworthy option for cement is needed. If we look at the properties of Sandaband again, the properties are ideal for long lasting isolation purposes.

Listed are the properties that make Sandaband better than cement for primary cementing purposes:

- Incompressible
- Non-shrinking
- Ductile
- Non-fracturing
- None segregating
- Thermodynamically stable

How did swellable elastomer packers manage to replace cement in completion jobs while the usage of Sandaband in primary cementing has not been tested? One of the reasons for using the SEP was because cement could not be used in those applications. An argument to use Sandaband instead of cement is based on the long lasting limitations of cement. But in order to place Sandaband behind the casing as isolation, it's necessary to include cement. This is one of the reasons why it can be an issue.

Another reason why SEP managed to enter the market is because the SEP is easy to deploy. It will automatically swell once placed downhole, the procedure of placing Sandaband is even more complex than cement.

The usage of horizontal wells is becoming a standard in the oil and gas industry, and the primary cementing challenges are becoming harder to overcome. Listen are the challenges that makes it hard to get a good cement job in horizontal wells.

- Hole cleaning and drilling-fluid displacement
- Centralization of pipe
- Optimizing cement slurry designs
- Evaluation with acoustic tools

In cases where the challenge is to great, using cement may not be an option, and it will be impossible to use Sandaband. If we look at the possibility to sidetrack a well at a later stage, using Sandaband can be a problem. Sandaband does not act like cement, it is ductile and movable. When sidetracking through the Sandaband, the material will start to circulate out from where it was placed originally and back to the surface. To stop this, a window is needed to be drilled through the Sandaband and a cement pillar needs to be placed to create isolation and a new fundament for the Sandaband to rest on. This needs to be done in order to drill further on. Not only is it a very complex procedure, but it can be an issue for the well integrity.

Earlier in the discussion I listed up challenges that will be more common today and in the future. We have already ruled out horizontal wells and wells with sidetracking. Other application which were it may be too complicated to use Sandaband is in the Arctic. I mentioned that it might be applicable in the Arctic because Sandaband is good in temperature fluctuating environments. But in the Arctic, all operations get more difficult, a complicated operation such as Sandaband is not recommended. Most of the steam injection wells are horizontal or the most complex SAGD wells are multilateral, the usage of Sandaband in these wells is also limited. Currently, the only type of well where I believe we can utilize and benefit from Sandaband today is shallow gas wells.

ThermaSet bonds to steel very well and has a higher mechanical strength than any well cement. The people from Wellcem also claims it resist temperature up to 320 degree Celsius. If we compare ThermaSet with Sandaband, ThermaSet does not have the issue of a complicated placement method. The largest issues with ThermaSet are the cost and uncertainty of supporting the casing. ThermaSet will bond to steel, but there are not data available showing the capability to support the casing. The other issue is related to verification, no test has yet been conducted to see how well ThermaSet will respond to the sonic and ultra sonic logging.

Currently the best way to improve primary cementing is not to replace cement with other materials, but specially design a cementing program best suited for the well operation. Table 6 is a cement system overview created to show the diversity of cement in this discussion.

Regarding to the lack of ductility which has been identified as a major reason for cement failure; flexible and expandable cement systems was developed to prevent cement sheath cracking. The use of vulcanized rubber a very good solution, but is also very costly. The diversity of the cement systems gives another alternative for ductile cement; foamed cement. Foamed cement exhibit improved ductility over conventional cement, at least a magnitude more ductile than conventional cement. Foamed cement is often chosen for primary cementing because it shows great displacement properties and its has a low density, which makes it great for problem such as depleted zones, high pressure zones and formations with a narrow pressure, it’s also useful when there are concerns over reservoir compaction or salt-formation flow.

If there were a cheaper solution for ductile cement, why did they have to develop flexible and expandable cement systems?

This has to do with the limitations of foam cement; Listed are some limitations with foamed cement:

- ☐ Fracture and pore pressure profile
- ☐ Permeability of formation
- ☐ Density of the lead slurry
- ☐ Safety factors
- ☐ The length of a foam column

Because foamed cement slurry is permeable, there must me a limitation on the permeability. And the limitation is often less than one-tenth of the formations permeability. Although the density of foamed cement should be low, it has to be able to contain the pore pressure of the formation; this creates a lower limit on the density. When designing the foamed cement, it also important to remember that a purpose of primary cementing is to support the casing. Depending on the regulations, the compressive strength of the cement should be in excess of 100 psi, even above 500 if it's required by regulations.

If we take a short comparison between these two ductile solutions of cement systems; even though foamed cement is more expensive than conventional cement it is cheaper than flexible cement, but flexible cement is one of the most durable cement that can be used.

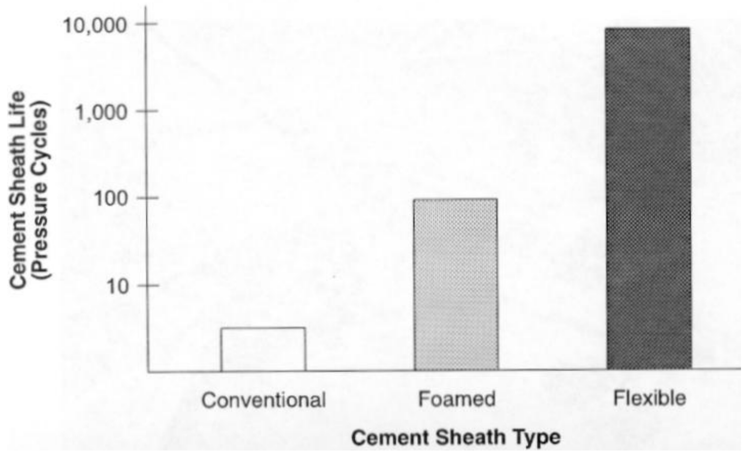

FIGURE 24 : THIS FIGURE SHOWS THE NUMBER OF PRESSURE CYCLES THE GIVEN CEMENT CAN ENDURE, A WAY TO CLASSIFY THE DURABILITY OF THE CEMENT (14)

The flexible cement is not as ductile and as long lasting as Sandaband, but it has a longer life than foamed cement and it can offer a longer well life in sour(H_2S)/sweet(CO_2) well applications. In search for a long lasting primary cementing, flexible cement can be a decent solution. But the cost of flexible cement is high, and I don't think it will be used as a standard well solution.

Another way to improve primary cementing with regards to the materials, combining cement can be solution, especially if they have properties that work well together. An example that might work is combining HGS and foamed cement.

Foam cement is somewhat opposite from the HGS in regards of price, since nitrogen is cheaper than the base slurry it will become cheaper as more nitrogen is added to the mix. However, as more foam is increased the compressive strength is decreases and permeability, compressibility and elasticity will increase. A decrease of compressive strength and increase of permeability is not beneficial for primary cementing, but an increase of compressibility and elasticity is often helpful. Compressibility will help counter losses in hydrostatic pressure and a higher elasticity helps maintaining a long term seal.

In order to face the challenges in the large variation of primary cementing operations, these two lightweight solutions are not good enough by themselves. By combining them together, it’s possible to create solutions to new challenges. High strength low permeability slurries can be designed by using high quality hollow glass spheres and then using foam to achieve the required density. A mixture between these two low density solutions can result in high strength slurry with low perm, good elastic and compressible strength.

Designing a cement program by combining different cement systems and use SEP to support and protect the cement sheath is in my opinion the best way to achieve a long lasting primary cementing.

8 Conclusion

In order to improve the primary cementing operation, alternative materials to replace cement have been evaluated. The alternative material Sandaband and ThermaSet has been evaluated. A conclusion that can be drawn from the evaluation is:

- Cement will still be the only material for primary cementing in the near future. This is because of the superior ability to support the casing, the diversity of cement, low cost and due to the state of the industry.

- The property of the alternative materials makes them possible candidates for future corrosion heavy and temperature fluctuating wells. Sandaband can also be used as isolation behind the casing in shallow gas wells. The usage of Sandaband will be limited to simple well solution because of the complex of the operation. ThermaSet is currently too expensive, and there are too many untested issues related to it as a primary cementing material.

- Instead of replacing the materials, challenges and considerations related to the usage of cement needs to be dealt with. A better primary cementing design involving different cementing systems and preventive measures such a swellable packers can strengthen the cement and making it more viable for long lasting zonal isolation.

9 Bibliography

1. **Halliburton.** Zonal Isolation for the future. *Oilfield Technologies.* 2009.

2. **Norway, Standard.** NORSOK D-010: Well Integrity in Drilling and Well Operations. 2004.

3. **Vignes. B and B.S Aadnøy.** Well-Integrity Issues Offshore Norway. *IADC/SPE Drilling Conference, 4-6 March 2008, Orlando, Florida, USA.* 2008.

4. **Energy, Serene.** Techincal Oveview on Oil and Gas Industri. [Online] http://www.sereneenergy.org/Cementation.php.

5. **Stensrud, Magnus.** Analysis of System and Methods for Improved Cementing of Oil - and Gas Wells. *Masterthesis - NTNU IPT.* 2011.

6. **Nelsen, Erik B.** *Well Cementing.* 1990.

7. **Haut, R.C and R.J Xrook.** Primary Cementing: The Mud Displacement Process. *SPE Annual Technical Conference and Exhibition, 23-26 September 1979, Las Vegas, Nevada.* SPE 8253, 1979, Vols. 8253-MS.

8. **D.F. Ryan D.S. Kellingray, and C.F. Lockyear.** Improved Cement Placement on North Sea Wells Using. *SPE 24977.* 1992, European Petroleum Conference held in Cannes, France. 16-18 November 1992.

9. **Sauer, C.W.** Mud Displacement During Ceenting State of the Art. *Journal of Petroleum Technology.* SPE 14197, 1987.

10. **Heathman and H. Rogers** Cementing Casing Equipment: Proper Selection Vital to Success. *OTC 17083.* 2005.

11. **Schlumberger.** http://www.glossary.oilfield.slb.com. *Oilfield Glossary.* [Online]

12. **Works, C.R Hyatt and M.H Partin Jr..** Liner Rotation and Proper Planning Improve Primary Cementing Success. *SPE Deep Drilling and Production Symposium, 1-3 April 1984, Amarillo, Texas.* SPE 12607, 1984.

13. **M. Laws, A. Riyami, H. Soek Edwards, Y.Elmarsafawi, S. Abdenour, and D. Valstar, M. Misran and A. Hassan.** Special Cement System and Cementing Techniqures Improve Zonal Isolation in South Oman. 2006, Vol. SPE 102414.

14. **Kevin Kopp, Shawn Reed, Jay Foreman, Brian Carty, and James Grifith.** Foamed Cement vs. Conventional Cement for Zonal Isolation. 2000, SPE 62895.

15. **Tahmourpour, F., M. Exner, and Khallad.** Design and Operational Factors for the Life of the Well and Abondonment. 2008, SPE 114866.

16. **Roland A. Pettitt, Los Alamos Scientific Laboratory.** Completion Of Hot Dry Rock Geothermal Well Systems. SPE 8267.

17. **Robert P. Rechard, Karl W. Schuler.** Euler Buckling of Geothermal Well Casing. 1983.

18. **K.ravi, M.Fukuzawa, W.J.Hunter and Noerdin, A.Isvan.** Advanced Cement Systems Used To Improve Geothermal Well Reliability Java. 2008, Vol. SPE 115638.

19. **K.Ravi.** Improve the Economics of Oil and Gas Wells by Reducing the Risk of Cement Failure. *IADC/SPE Drilling Conference, 26-28 February 2002, Dallas, Texas.* 2002, Vol. SPE 74497.

20. **G. Debrujin, A. Loiseau, A. CHougnet-Sirapian, B. Piot, E, Pershikova, and W.Khater and K.evoy and G. Wilson,.** Innovative Cementing Solution for Long-Term Steam Injection Well Integrity. *SPE EUROPEC/EAGE Annual Conference and Exhibition, 14-17 June 2010, Barcelona, Spain.* SPE 131324, 2010.

21. **Korostelev, A. S. , TyumenNIIgiprogas.** Design and Field Practice of Arctic Cement Systems Applied for Well Construction in Permafrost Zones. *SPE Arctic and Extreme Environments Conference and Exhibition, 18-20 October 2011, Moscow, Russia.* 2011, Vol. SPE 149928.

22. **Dead Radojevic, Yelena Shafeyeva, Tyummenniigiprogas.** Primary Cementing in Permfrost Conditions. *SPE Russian Oil and Gas Technical Conference and Exhibition, 3-6 October 2006, Moscow, Russia.* SPE 100816, 2006.

23. **Fred L. Sabins.** *Problems in Cementing Horizontal Wells. 20005.PA 1990*

24. **A. Brandl, J. Cutler, A.Sansil, and G. Braun.** Environments, Cementing Solutions for Corrosive Well. *International Oil and Gas Conference and Exhibition in China, 8-10 June 2010, Beijing, China.* 2011, Vol. SPE 132228.

25. **Z. Liu, J.sun, H.A Nasr-El-Din, H. Shan, Z. Xiao.** Advanced Cement System for Deep and Sour Wells. *SPE/DGS Saudi Arabia Section Technical Symposium and Exhibition, 15-18 May 2011, Al-Khobar, Saudi Arabia.* 2011, Vol. SPE 149063.

26. **H. El- Hassan, M. Sultan, and A. Saeed, and C. Johnson.** Using a Flexible, Expandable Sealant System to Prevent Microannulus Formation in a Gas Well. *SPE Middle East Oil and Gas Show and Conference, 12-15 March 2005, Kingdom of Bahrain.* SPE 92361, 2005.

27. **Clement, C. Clark.** A Scienticfic Approach to the Use of Thixotropic Cement. *Journal of Petroleum Technology.* SPE 6011, 1970.

28. **Knox A. Slagle, Dwight K. Smith.** Salt Cement for Shale and Bentonitic Sands. *Journal of Petroleum Technology.* 1963, SPE 411.

29. **http://www.drillingformulas.com.** Drilling formulas. [Online] 2011.

30. **C. Witt, F. Tahmourpour.** Thermal Sealant Improve Cementing in SAGD areas. *2009. Petroleum Society of Canada .* 2009, Vols. Document ID 09-06-39-TN.

31. **Maier, L.F.Carter, M.A.Cunningham, W.C.,Bosley, T.G.** *Cementing Materials for Cold Environments.* Journal of Petroleum Technology : s.n., 1971, Vols. SPE 2825-PA.

32. **J.Collins, K.S Chan R. Cox D. Wakelam.** Alternative Cementing System For Low Pressure Formation in Canada. *Annual Technical Meeting, Apr 21 - 24, 1991 , Banff.* 1991, Vol. SPE 9148.

33. **D.Kulakofsky, S. Snyder, R. Smith,, and K.Mork and D. Coors,.** Case Study of Ultralightweight Slurry Design Providing with the required Properties for Zonal Isolation in Devonian and Mississipi Central Appalachian Reservoirs. *SPE Eastern Regional Meeting, 14-16 September 2005, Morgantown, West Virginia.* 2005, Vol. SPE 97847.

34. **Ogbonna, Oyetade Taiwo and Joel.** Foam Cementing Design and Application: A cure for Low gradient Associted Problems in Deepwater Operations in the Gulf of Guinea. *Nigeria Annual International Conference and Exhibition, 30 July - 3 August 2011, Abuja, Nigeria.* SPE 150767, 2011.

35. **Febus, W.M Harms and J.S.** Cementing Fragile-Formation Wells With Foamed Cement Slurries. *Journal of Petroleum Technology.* 1985, Vol. SPE 12755.

36. **Atta, Ahmed El- Seginy and bdel Azim.** Improving Deep-Well Economics with Foamed-Cementing Solutions. *North Africa Technical Conference and Exhibition, 14-17 February 2010, Cairo, Egypt.* 2010, Vol. SPE 128239.

37. **M El Shaari, Scott H. Myers, Ragib Dajani,and Dle Roberty Doherty.** Applications of Ultra Low Density, Operationally simple, Non-Foamed Cement Slurries. *SPE Western Regional and Pacific Section AAPG Joint Meeting, 29 March-2 April 2008, Bakersfield, California, USA.* 2008, Vol. SPE 114143.

38. **3M.** 3M TM. [Online] 19 Februrary 2012.

39. **G. Kennedy, Easywell, A.lawlwss, and T.Alab, K. Shaikh.** The Use of Swell Packers as a Replacement and Alternative to Cementing. *SPE Annual Technical Conference and Exhibition, 9-12 October 2005, Dallas, Texas.* SPE 95713, 2005.

40. **Paolo Gavioli and Robert Vicario.** The Evolution of the Role of Openhole Packers in Advanced Horizontal Completions: From Optional Accessory to Critical Key of Success. *SPE Asia Pacific Oil & Gas Conference and Exhibition, 18-20 October 2010, Brisbane, Queensland, Australia.* 2010, Vol. SPE 132846.

41. **Bob Brooks, Tim Davis, Frank DeLucia.** Use of Swellable Elastomers to Enhance. *the Deep Offshore.* 2008.

42. **Norway, The Standards Organisation in.** *NORSOK, Standard D-010, Well integrity in drilling and well operations (Rev 3 Aug 2004), http://www.standard.no/imaker.exe?id=5738.* 2011.

43. **AS, WellCem.** WellCem As. *Corporation Web Site.* [Online] http://www.wellcem.no/page/Front_page_id10.html.

44. **ThermaSet.** Oil Well Therapy : Zonal Isolation in Subsea Wells Using Multi-Purpose Field Vessels and Thermaset Isolation Materials. 2008.

45. **Plugging, Sandaband Well.** Summary of Testing and Qualifying Sandaband . 2010.

46. **Nyhammer, Øyvind.** Peon Drilling - Sandaband Verification. 2008.

47. **Review, Technology.** Technology Review By MIT Magazine. *Technology Review .* [Online] 2010. http://www.technologyreview.com/energy/26048/.

48. **IER.** Institute for Energy Research - Shale Oil May Mirror the Shale Gas Boom. *Institute for Energy Research.* [Online] http://www.instituteforenergyresearch.org/2011/06/30/shale-oil-may-mirror-the-shale-gas-boom/.

49. **E. Hunter Herron.** Petroleum Equities Inc : Heavy Oil: A solution to Dwindling Domestic Oil Supplies. *Petroleum Equities Inc.* [Online] 2000. www.petroleumequities.com/HeavyOilReport.htm.

50. **Portman, Lance.** Cementing Through Coiled Tubing: Common Errors and Correct Procedures. 2004.

51. **Hernandez, Rafael.** Reverse-Circulation Method and Durable Cements Provide Effective Well Constructions: A Proven Technology. 2010.

52. **Schlumberger.** Oil field glossary. [Online] http://www.glossary.oilfield.slb.com/DisplayImage.cfm?ID=638.

53. **Magazine, Offshore.** Offshore Magazine - More Drilling & Completion News, Swelling elastomers. *Offshore Magazine.* [Online] http://www.offshore-mag.com/articles/print/volume-68/issue-10/drilling-completion/swelling-elastomers-set-to-supersede-cement-in-well-completions.html.

54. **Jeff Hibbeler, Phil Rae and Todd Gilmore and Lawrence Weber.** Using Alternative Sources of Oilwell Cement. 2000, Vol. SPE 62746.

55. **Hydro, Statoil.** *Peon Discovery .* Bergen : s.n., 2008.

56.**Kris Ravi, D.G.** *Procedures to Optimize Cement Systems for Specific Well Conditions . AADE Drilling fluids Technical Conferenc 2006*. AADE-06-DF-HO35.

10 Appendices

TABELL 9 : WBEAT - WELL BARRIER ELEMENT ACCEPTANCE CRITERIA TABLE

Features	Acceptance Criteria
A. Description	This element consists of impermeable Sandaband material in solid state with Bingham plastic behaviour located in the annulus between the concentric casing strong, or the casing/liner and the formation.
B. Function	The purpose of the element is to provide a continuous, permanent, flexible and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids and resist pressures from above or below. It will reshape to changes in geometry from e.g. faults, subsidence and temperature etc.
C. Design, construction and selection	1. A design and installation specification (pumping program) shall be issued for each Sandaband pumping job. 2. The Sandaband material shall be capable to provide lasting zonal isolation. 3. The Sandaband plug shall be prevented from longitudinal movement by either having sufficient height and length such that its combined weight and yield point overcome initial (non-depleted) reservoir pressure; or: being anchored with a permanent solid material on the top and bottom. 4. The material shall not be placed on top of a fluid column allowing gravitational settling. 5. Temperature exposure, cyclic or development over time, shall not lead to reduction in strength or isolation capability.
D. Initial verification	The combined element consisting of Sandaband and foundation shall be verified through formation strength test when the casing shoe is drilled out. Alternatively the verification may be through exposing the Sandaband column for differential pressure from fluid column above Sandaband in annulus. In the latter case the pressure acceptance criteria and verification requirements shall be defined. 2. The verification requirements for having obtained the minimum Sandaband height shall be described, which can be verifications by logs (gravel pack evaluation, bond log), and/or estimation on the basis of records from the pumping operation (volumes pumped, returns during pumping, etc.). 3. Properties of each batch of Sandaband produced shall be verified by laboratory testing to be within accepted values for density and water content to ensure sealing capability. This shall be documented in batch certificate issued by the manufacturing plant.
E. Use	None
F. Monitoring	1. The annuli pressure above the Sandaband well barrier shall be monitored regularly when access to this annulus exists. 2. Surface casing by conductor annulus outlet to be visually observed regularly.
G. Failure modes	Non-fulfilment of the above requirements (shall) and the following: 1. Pressure build-up in annulus as a result of e.g. insufficient volumes placed in the well, excessive contamination of the material during placement, etc.