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SPECIAL CONSIDERATIONS IN CEMENTING HIGH PRESSURE HIGH TEMPERATURE WELLS.

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Abstract

Growing demand to drill High Pressure High Temperature (HPHT) wells requires improved technology to overcome the HPHT challenges. The case studies of the Montara well blowout 2009 and Gulf of Mexico 2010 showed that one of the main contributing factors to the failure was the substandard cement job. During the 2012 HPHT Wells Summit, HPHT professionals were surveyed about the most critical technology gaps in the HPHT operations. Cement Design was reported to be the third most concerning technology gap for the HPHT operations (15%). Other areas of their concerns are shown in Figure 1. A similar survey of the HPHT professionals that had been conducted two years earlier in the 2010 HPHT Wells Summit reported that the Cement Design as the biggest technology gaps for HPHT operations (Figure 2).

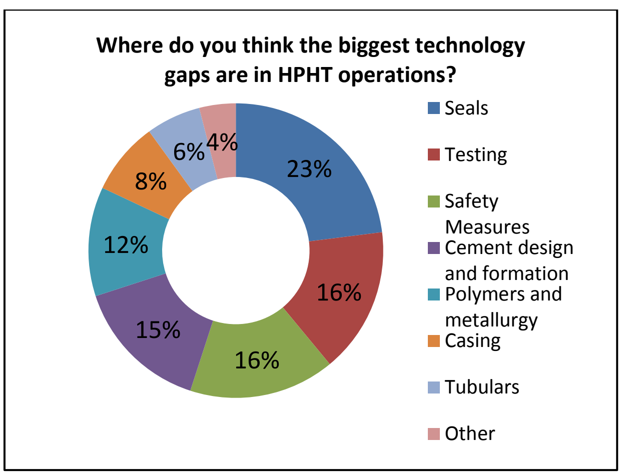

Figure 1. HPHT Technology Gaps (2012 HPHT Well Summit)

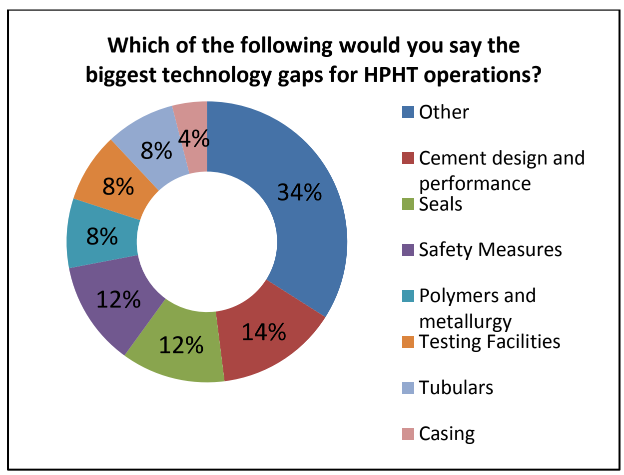

Figure 2. HPHT Technology Gaps (2010 HPHT Well Summit)

This paper provides a review of some of the best practices and case studies in the area of HPHT cementing. It elaborates on the design, execution and evaluation of the cementing operations. It also examines some crucial problems in HPHT cementing and provides some Recommendations and Conclusion.

Keywords: High Pressure high Temperature, cement design, MWD/LWD tools temperature limitation, and seismic resolution

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Introduction

During the past decade, the number of HPHT projects has increased. The main HPHT areas are found in the United States (Gulf of Mexico), Indonesia, North Sea, Norwegian Sea and Thailand. Some of the thermal recovery projects are located in Canada, California, Venezuela and Eastern Europe (Figure 3).

Figure 3. HPHT Projects around the world (Schlumberger)

Many of the oil and gas resources are located in deeper formations. This provides a wide range of difficult challenges and mechanical issues. One of these issues is the negative impact on cement's rheological properties when exposed to high pressure high temperature conditions, which are common in deep drilling. The most common HPHT definition is when bottomhole temperature exceeds 300°F (150°C) or the bottomhole pressure exceeds 10,000 psi.

High temperature gives a sensitive effect to the cement slurry, especially to the thickening time. It reduces the thickening time which could set the cement quicker compared to average temperature wells.

High temperature could also affect the cement rheology. The Plastic Viscosity and Yield Point will decrease with an increase of temperature (Ravi and Sutton 1990).

High pressure requires the drilling engineer to be very selective in determining a correct weight to overcome small equivalent circulation density window. Cement weight should withstand the formation pressure by creating minimum overbalance. As increasing curing pressure, an earlier compressive strength development and higher ultimate compressive strength are observed to result from the high pressure.

As the well depth increases, hydrostatic pressure and the ECD (Equivalent Circulating Density) will increase. Conversely, the rise of temperature will

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reduce the ECD due to thermal expansion. In HPHT wellbore, it's suspected to have high-temperature variation that affect the expansion and contraction of casing and plastic formation and may lead to cracking set cement (Elzeghaty et al. 2007). Cement physical and chemical behavior changes significantly at elevated temperatures. Cementing in high-temperature environment is encountered in three principal types of wells; deep oil and gas well, geothermal wells, and thermal recovery wells (Nelson 2006).

Design

Drilling a high temperature high pressure well means that we will be dealing with a narrower annulus and, sometimes, corrosive fluids. Therefore, the cement design should consider a combination of silica, retarders, weighting agent, extender, expanding additive, fluid loss agent, casing eccentricity, mud removal, and laboratory tests, which lead to the original objective to provide complete isolation in the proper zone over the life of the well. For the time being, silica stabilized Portland cement is still in use for HPHT oil and gas wells.

Class	Depth (ft.)	Temperature (°F)	Purpose	Properties
A	0 – 6,000	80 - 170	Use when special properties are not required.	**O**
B	0 – 6,000	80 - 170	Moderate or high sulfate resistance.	**MSR and HSR**
C	0 – 6,000	80 - 170	High early strength.	**O, MSR, HSR**
D	6,000 – 10,000	170 – 290	Retarder for use in deeper well (High temperatures & high pressure).	**MSR and HSR**
E	10,000 – 14,000	170 – 290	For high pressure and temperature	
F	10,000 – 14,000	230 – 320	For extremely high pressure and high temperature.	
G	All depths		Basic well cement (improved slurry acceleration and retardation).	
H	All depths			
J	All depths	>230	For extremely high pressure and high temperature.	**HSR**

O: Ordinary, M: Medium, H: High, O: Ordinary, S: Sulfate, R: Resistance, E: Early, TT: Thickening Time

Table 1. Cement class standard specification

Cement type for high temperature or high pressure well

For the last 50 years, the most commonly used cements for thermal wells have been Portland cement, Silica-Lime system, and High-Alumina cement. Table 1 presents Cement class standard specification; some information were taken from Nelson 2006.

Portland cement chemistry

Portland cement is a calcium silicate material; most of its components are tricalcium silicate (C_3S) and dicalcium silicate (C_2S). With the addition of water, tricalcium and dicalcium silicate hydrate to form a gelatinous calcium silicate hydrate called "CSH phase" which is an early hydration product and excellent binding material at well temperatures less than 230°F (110°C). In high temperature, "CHS phase" decreases the compressive strength and increases the permeability of the set cement. Swayze (1954) describes this phenomenon as *Strength Retrogression*. At temperatures above 230°F, conventional Portland cement system results in a significant loss of compressive strength within one month.

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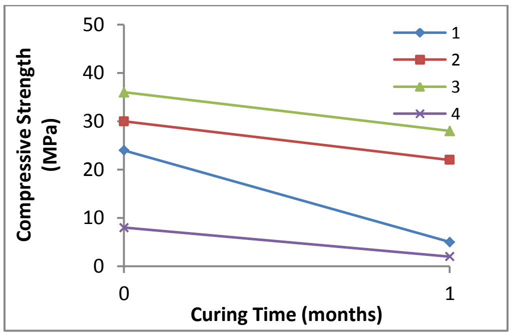
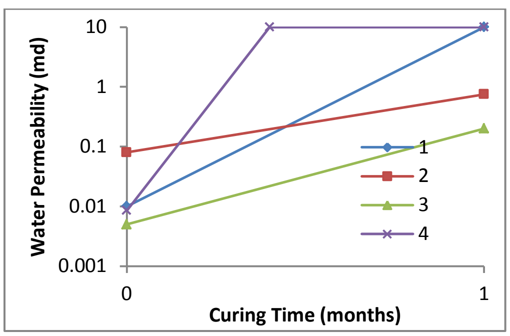
The main problem is a serious permeability increase; within one month, the water permeabilities of the normal density class G cement were 10-100 times higher than the recommended limit (0.1 mD). High-density Class H permeability was barely acceptable. The Compressive strength and permeability behavior of Portland cement at an elevated temperature are presented in Figure 4.





1 = normal density Class G
2 = normal density Class G
3 = high density Class H
4 = lower density extended cement

Figure 4. Compressive strength and permeability behavior of Portland cement at elevated temperature (Nelson and Eliers 1985)

Strength retrogression can be prevented by reducing the bulk lime with a silica ratio (Menzel 1935, Kalousek 1952, Carter and Smith 1958). Portland cement could be replaced partially by fine silica sand or silica flour. At 230°F, adding 35-40% silica BWOC (By Weight of Cement) will reduce cement silica ratio and at this level, tobermorite, which preserves high compressive strength and low permeability is formed. As the curing temperature increase to 300°F, tubermorite normally converts to xonotile and gyrolite which lower cement deterioration of cement performance. Normal density class G cement which stabilizes with silica is cured at 446°F and 608°F.

At 480°F, truscottie begins to appear. Curing temperatures of 750°F or higher will result in disintegration of cement set. Cements containing significant amounts of truscottite are usually characterized by low permeability (Gallus et al. 1978). In general, set cements that consist of cement silica ratio less than or equal to 1.0 tend to have higher compressive strengths and lower water permeabilities. Nevertheless, cement set not only depends on downhole temperature, but also on the presence of other minerals; its composition can evolve as downhole conditions change.

Well cements are permanently exposed to downhole conditions. Above 230°F, commonly used Portland cement may shrink, lose strength, and gain permeability. This deterioration can be minimized or even prevented by adding at least 35% silica by utilizing cements engineered for the HPHT environment. Even if zonal isolation is initially adequate, changes in downhole temperature and pressure can crack or even shatter the cement sheath; radial pressure/temperature fluctuations can create a microannulus. These concerns are particularly significant in deep, hot wells and thermal-recovery wells. HT high-temperature flexible cement has a lower Young's modulus for improved flexibility and a significantly higher expansion after setting to ensure firm contact with the casing and formation. High temperature cementing jobs are generally performed with API Class G or Class H cement. In Northern Italy case history, HPHT slurries used a combination of Class G cement with 40% silica flour which provided excellent oilfield retarders and prevented mechanical strength retrogression (Frittella, Babbo and Muffo 2009).

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High Alumina Cement

High Alumina cement is used because it can withstand wide ranging temperature fluctuations. Figure 5 shows the effect of curing temperature at high alumina cement extended to 70% crushed firebrick (Heindl and Post 1954). From 1,022°F to 1,742°F, recrystallization occurs. The strength and durability of high alumina cement between 440°F to 1830°F are controlled by the initial water to cement ratio. The amount of added water to prepare slurry should be minimum; at least 50% of the solids should be cement. Dispersant is helpful for pumpability of the slurry.

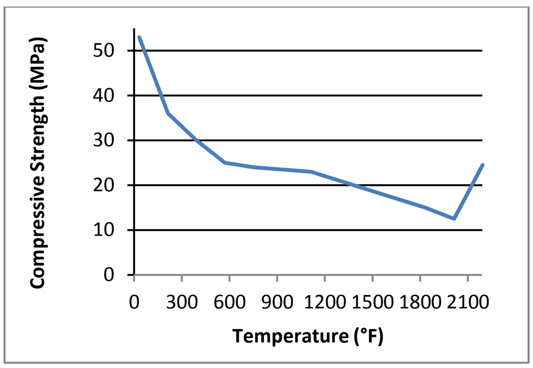

Figure 5. Compressive Strength of High Alumina Cement crushed firebrick concrete after 4 months exposure from 68° F to 2,190°F (Heindl and Post 1954)

Silica sand should not be used for temperatures exceeding 572°F because of the change in the crystalline structure; thermal expansion is relatively high at these temperatures and thermal cycling could eventually disrupt the cement. The most commonly used extender for high alumina cement is crushed aluminosilicate firebrick. Other suitable materials include calcined bauxite, certain fly ashes, diatomaceous earth, and perlite.

Class J Cement

Class J cements was developed in the early 1970s for cementing wells with static temperatures above 260°F (Maravilla 1974, Degouy and Martin 1993, Bensted 1995). Class J cements is like Portland cement; it's a calcium silicate material but with no aluminate phase. Since it is not widely used, currently class J cement is not in the API cement list, however, it's still used mainly for geothermal well applications. Similar cement known as belite silica cement has been used in high temperature wells cementing (Bulatov 1985). It's very useful because addition of silica is not required and retarder is not necessary for circulating temperatures less than 300°F. Cement silica ratio of class J cement is adjusted and obtained upon curing.

Retarder (Thickening Time)

HPHT wells are wells with pressure exceeding 15,000 psi, temperature exceeding 300°F, and usually located at depth greater than 15,000 ft. Commonly, cement slurries pumping time is designed to last at least 3 to 4 hours. Since it's a deep well, differential static temperature between top and bottom of cement column can exceed 100°F. Small temperature difference of even only 10°F can cause significant changes in thickening time. Retarder has varying sensitivity levels, especially to the temperature. Proper amount of retarders must be blended into the cement system, if it's too much, it will cause long waiting on cement and in high pressure wells may lead the entry of gas into the cement. It's important to have good relation between additives and cement and to have a good result a lignosulphonate high temperature retarder or synthetic high temperature retarder is usually used (Frittella, Babbo and Muffo 2009). On the extreme temperature, thickening time was measured initially with ± 10% of the retarder concentration (North, Brangetto and Gray 2000).

In high pressure well, as curing pressure increases, a significant accelerating effect is observed (Beardne 1959); earlier compressive strength development and higher ultimate compressive strength are also seen (Handin 1965, Metcaf and Dresher 1978). Figure 6 shows that a significant accelerating effect is observed upon rising pressure.

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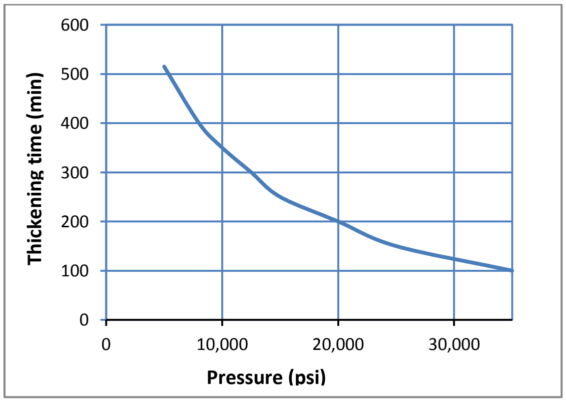

Figure 6. Effect of pressure on pumpability of cement API class H with 0.3% retarder, 200°F BHCT (Smith 1976)

Weighting Agent

It's crucial to maintain hydrostatic pressure balance or exceed the formation pressure. For deep wells, mud weight ranging from 15 lbm/gal to 27 lbm/gal (Nelson & Guillot 2006) are typically required to overcome this matter, cement slurry with density over 16.5 lbm/gal requires a weighting agent. White powdery *Barite* is available in most oilfield location; it has 4.33 specific gravity and additional water is required to wet its particle. Slurry with density up to 19.0 lbm/gal can be prepared with Barite. Red crystalline granules *Hematite* is very efficient weighting agent; it has 4.95 specific gravity and could overcome many of the shortcomings of barite. Dispersant is often used to prevent excessive hematite slurry viscosity. Hematite is used for preparing slurries with density as high as 22 lbm/gal.

Reddish-brown powder *Manganese Tetraoxide* has very small sized particles (average 5µm) with 4.84 specific gravity. With significantly greater particle surface area than other weighting agent, it provides a better mix, especially when well control is one of the issues. It has fewer tendencies to settle than hematite and can be added directly to the mixing water (Johnston and Sense 1992) without severe settling. Combination between hematite and manganese tetraoxide can be prepared to have slurries densities as high as 22 lbm/gal. Slurries containing manganese tetraoxide typically develop higher compressive strength than other weighting materials and sometimes shorten thickening time. Physical Properties of weighting agents are presented in Table 2 (Nelson and Guillot 2006).

Material	Specific Gravity	Absolute Volume (gal/lbm)	Color	Additional Water Requirement (gal/lbm)
Ilmentie	4.45	0.027	Black	0.00
Hematite	4.95	0.024	Red	0.0023
Barite	4.33	0.028	White	0.024
Manganese tetraoxide	4.84	0.025	Reddish brown	0.0011

Table 2. Weighting agents physical properties for cement slurries

Large quantities of weighting materials can lead to slurry sedimentation. Using multi particle size distribution or dry blended weighting agent to cement bulk will minimize the concern. On the other hand, dry blended weighting agent in cement bulk can vary the dry blend mixture, also the mixture powder should be sent to the cement unit which will make the density of cement slurry inconsistent. Too much weighting material can lead to viscous slurry properties, which can cause a decrease in cement compressive strength.

Extender

In HPHT condition, preventing a lost circulation or avoiding a formation breaking is a common practice. Sometimes, low density slurries or raising slurry yield are required to prevent these problems. Extenders such as flyash, bentonite, and prelite are commonly used to overcome these matters. In experiments at temperatures of 450°F and 600°F, *Fly Ash* was the heaviest 15.6 lbm/gal, and had the highest density and initial compressive strength; however, over 24 months, its compressive strength starts to degrade. *Bentonite* and *Perlite* have adequate compressive strength performance at both curing temperature 450°F and 600°F but the permeabilities were too high. Today Perlite is rarely used, since it is compressible and could increase hydrostatic pressure. With 16 lbm/gal, class J cement has adequate

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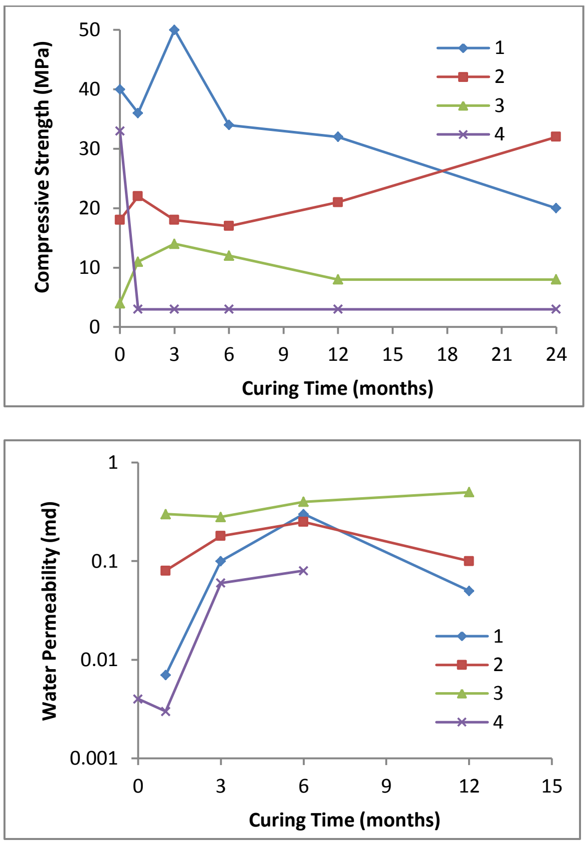
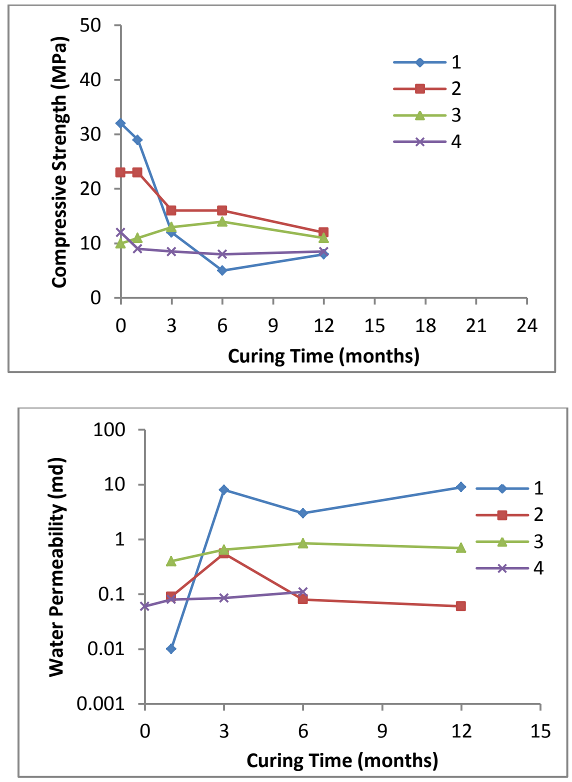
compressive strength at temperature 450°F and has low water permeability. The behavior of these examples illustrates that assumption that high compressive strength is linked to low permeability is not true. Figure 7 and 8 illustrate the long term performances of conventional system cured at 450°F and 600°F.



1 = Fly Ash, 15.6 lbm/gal
2 = Perlite/Bentonite, 12.9 lbm/gal
3 = Perlite/Bentonite, 11.9 lbm/gal
4 = Diatomaceous earth, 13.8 lbm/gal

Figure 7. Compressive strength and permeability performance of conventionally extended Portland cement slurries 450°F (Nelson and Eliers 1985)



1 = Fly Ash, 15.6 lbm/gal
2 = Perlite/Bentonite, 12.9 lbm/gal
3 = Perlite/Bentonite, 11.9 lbm/gal
4 = Diatomaceous earth, 13.8 lbm/gal

Figure 8. Compressive strength and permeability performance of conventionally extended Portland cement slurries 600°F (Nelson and Eliers 1985)

The conventional extended Portland cement with density below 12.5 lbm/gal may not be able to perform suitably in high temperature wells. Cement with density bellow 12.5 lbm/gal may need microsphere-extension, multimodal particle size, or foamed cement. Glass microspheres with hydrostatic crush strengths could hold 10,000 psi but ceramic microspheres can only withstand up to 3,000 psi (Nelson 2006); however, both could be used in thermal well since they stabilize in high temperatures. Ceramic system appears to perform better at higher temperatures up to 600°F. For geothermal and steamflood wells, it is common to use foamed cement which can occasionally be used in deep high temperature wells.

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Expanding Additive

Besides proper cement placement in the annulus, strong cement-casing support and right zonal isolation are most important. One way to achieve strong cement bond between casing cement and formation is by adding expanding additive. Cement containing Manganese Oxide (MgO) provides excellent expansive performance at curing temperatures as high as 550°F and at temperature below 140°F the hydration proceeds very slowly (Saidin at el. 2008). The presence of the expanding additives MgO would increase the number of matrix in cement and, with hydration process, could cause better expending in cement. *Burning temperature* is the temperature at which MgO is burnt and *conditioning temperature* is the temperature at which it is conditioned, like temperatures in the wellbore (Rubiandin 2000). Figure 9 shows class G cement containing 1% BWOC MgO. It shows that amount of the expansion increases with increasing in temperature.

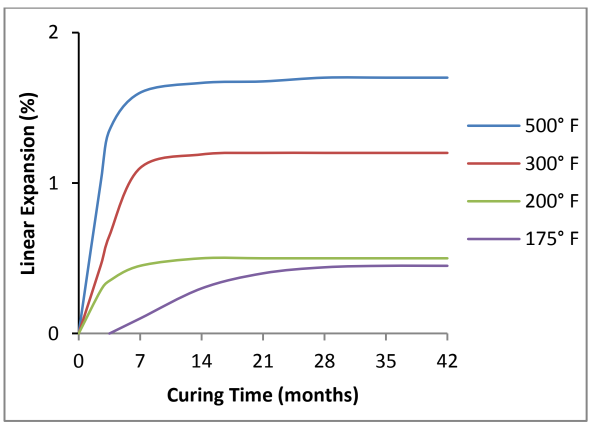

Figure 9. Expansion of cement containing 1% BWOC calcined Manganese Oxide (Guillot and Nelson 2006)

Base on Rubiandini (2000) adding burnt MgO will increase shear bond stress but will reduce the compressive strength, even if it is still higher than the minimum value. High burning temperature hardens the MgO and will make it difficult for MgO to react with cement. With the same conditioning temperature, the value of shear bond strength and compressive strength decrease in accordance with the rise of burning temperature. High conditioning temperature increases the reaction velocity of MgO (for the same burning temperature, the value shear bond strength and compressive strength increased in accordance with the rise of conditioning temperature). Pure MgO which is burnt at 1,832°F to 2,552°F are capable of increasing shear bond strength up to 300%. For high conditioning temperature of 300°F to 400°F, using 2200°F burnt MgO is convenient. At conditioning temperature higher than 300°F, better performance is shown. On the other hand, burnt pure MgO at 2,552°F shows dissatisfying results. The effective expanding additive concentration for increasing shear bond strength ranges from 5 to 10 %.

Fluid Loss Agent

Maintaining constant fluid loss in the deep well is necessary to preserve the chemical and physical characteristic of the cement slurry, especially due to differential pressure on top and bottomhole in a long or deep well. Also, fluid loss agents need to prevent the development of filter cake that may cause bridging in the annulus. It would likely occur in long string casing, especially in deep well cement. Narrow clearance between wellbore and liner causes a fluid loss to be significant. Effect of temperature and fluid sequence to fluid loss is presented in Figure 10.

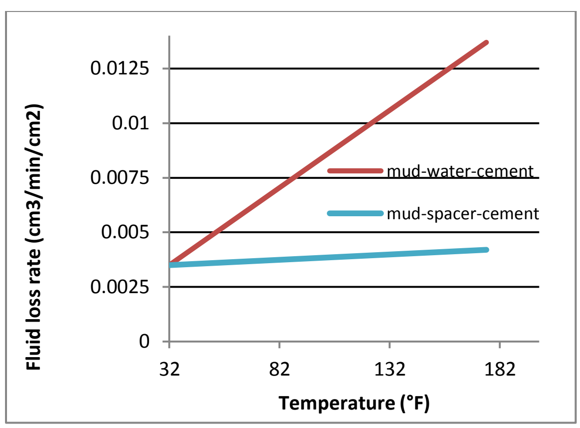

Figure 10. Effect of temperature and fluid sequence upon dynamic fluid loss rates (Nelson, 2006)

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Too much fluid loss may provide space for the gas to get into the cement slurry in the annulus. Fluid Loss agent are used to prevent early slurry dehydration for HPHT cementing operation. The design criteria for fluid loss control are linked to dynamic filtration rather than static filtration. Maximum fluid loss rates for oil wells are 200 ml per 30 minutes and 50 ml per 30 minutes for gas wells (Hartig et al. 1983). Christian et al. 1976 and Frittella, Babbo and Muffo 2009 mentioned that the limit for fluid loss is 50 ml per 30 minutes. Another study by Dillenbeck and Smith (1997) showed that, for specific gas field, no fluid-loss is necessary to get a good cement job. Thixotropic cement slurries can give high fluid loss rates, though dehydration and bridging must be considered (Pour and Moghadasi 2007).

Casing Eccentricity

Generally, 70% standoff is considered as the minimum requirement to have good cement bond; casing need to be kept at the center of the wellbore. For centralizer near the shoe, 75% standoff is too high. The ideal wellbore is free or at least 1.5in wide washout; a result of imperfect borehole making, the casing would not be in the center of the open hole. Fluids will naturally flow more readily on the wider side of the annulus. Maintaining above 67 % standoff casing centralization as per API standard was an early guideline to facilitate the displacement process. Good survey and four arms caliper are recommended to determine a proper centralizer placement in critical wells.

Increasing the degree of casing eccentricity does not significantly increase the max von Mises stress in cemented wellbore casing when using high-thermal property cements. However, increasing the degree of casing eccentricity will increase the maximum von Mises stress in cemented wellbore casing when using low-thermal property cements. At casing eccentricity lower than 40%, eccentricity has minor effect on the casing von Mises stress. When casing eccentricity approach 90%, at wellbore angle between 30° to 50°, it causes a maximum von Mises stress of 7.5E4 psi, which is 67% larger than the stress developed at the concentric condition (Yuan, Schubert, Teodoriu 2012). Casing eccentricity leads to reducing cement shear stress and tensile stress, but on the other hand, it increases cement compressive stress.

Mud Removal

Mud removal planning in quantity and sequence is crucial in achieving strong cement bond and proper cement placement in HPHT wells. The plans include the conditioning of drilling fluid, preflush, spacer, and mud removal tools such as scratchers. Drilling fluid conditioning is circulated before cementing to remove gas and cuttings, break the muds gel strength, and lower the mud viscosity. For chemical wash and spacer pump ahead of the slurry to act as a buffer between possibly incompatible mud and cement, around 10 minutes contact time is recommended. Difference between spacer and mud densities and cement and spacer densities should be around 10%. In Northern Italy, minimum of 262 ft/min annular velocity should be considered to get effective turbulent flow. Maintain separation from displacement to avoid slurry contamination. We need at least 650 ft of spacer ahead and 170 ft behind cement slurry (Frittella and Muffo 2009).

Improving pipe stand-off, increasing μ_p / τ_y, decreasing mud gel strength, and increasing flow rate are important factors to achieve a good mud removal. For Bingham Plastic fluids, the higher the dimensionless shear rate, the better circulation efficiency will be (Table 3). Base on Yetunde and Ogbonna (2011) having a minimal gel strength development, a low plastic viscosity to yield viscosity ratio PV/YP, and design compatibility of drilling fluid and displacement is important in cementing. Pipe rotation and reciprocation can help to get planned flow models and recommend starting the movement during mud conditioning. Top and bottom plugs should pump ahead and behind the slurry to separate from the mud. Another thing that must be ensured is the minimum and maximum allowable flow rates to pump different fluids.

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Stand Off (%)	Minimum Flow Rate (bbl/min)	
	Laminar Flow Around the Annulus	Mixed-flow Regime (Laminar & Turbulent) Around the Annulus
80	2	2
60	11	11
40	38	19
20	> 100	33

Table 3. Minimum flow rates required to achieve complete flow around the annulus. Calculated for Bingham Plastic fluid (Guillot and Nelson 2006)

Laboratory Test

Cement slurry system, preflush, and spacer should be designed and tested at the laboratory to fit the objectives to be achieved. When mixing slurry, extensive laboratory testing needs to be run to ensure that the slurry displays the right properties at surface and downhole conditions (Wray, Bedford, Leotaud and Hunter 2009). Mixing technique also need to be done since some of the additives are sensitive to shear. Laboratory tests must be simulated at an appropriate period of ambient pressure and temperature to provide proper mixing energy. Base on North (2000) the slurry was tested ± 50°F from targeted BHCT (Bottom Hole Circulation Temperature). Slurry and spacer test guidelines are described in Table 4.

LABORATORY TEST		
Slurry Test	Temperature	- Highest Simulated BHCT - Variation of retarder and temperature
	Pressure	Actual BHP (for thickening time)
	Compressive Strength	At Top of Liner condition: - Simulated temperature and pressure - Lowest simulated BHCT (with longest thermal recovery) - UCA set for simulated temperature and actual BHCT
	Mixing	- Order of addition - Time taken to add - Holding of mix water - Time to mix at surface - Surface mixing temperature / shear effect
	Slurry Stability	- Sedimentation test - HPHT rheology
	Fluid Loss	- Reduce chance of dehydration - Synergistically shorten the transition time for improved resistance of gas migration.
Spacer Test	Compatibility	Between drilling fluid and cement slurry
	Water wet ability	Surfactant addition
	Stability	- High temperatures - Variable rheology (to allow efficient mud removal without raising ECD)

Table 4. Slurry and spacer test guidelines (North, Brangetto and Gray 2000)

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Faster thickening time or the inability achieve the desired compressive strength can be caused by cement contamination. To avoid these problems, compatibility test of drilling fluid and cement slurries should be done before the cement job. The required elasticity, tensile, compressive strength, and compressibility depend on downhole condition and need to be to determined carefully by engineering analysis (Ravi, Bosma and Hunter 2003).

Cementing Computer Program

Cementing operation could be optimized by simulating it first in cementing computer program. It will give an overview of the proper flow pump sequence, pumping schedule (include stage timing, flow rate, volume for each fluid, worse depth scenario regarding collapse and burst), and centralizer placement. Some of the program could give ECD predictions and the efficient displacement rate. The program can give illustrations of pore and fracture pressure window, which help in deciding the best slurry density, drilling fluid conditioning, spacer, lead or tail slurry etc.

After proper cement placement, we need to make sure of the cement sheath. There is software to analyze cement sheath stress which quantifies the risk of wellbore cement sheath failure by applying stress analysis and sensitization criteria. It can model up to 10 strings simultaneously, analyzing the stress imposed on each string by a well event, such as pressure testing. The software analysis of radial and tangential stresses can determine cement sheath performance in compression, tension or both, enabling the design of the set cement behind the casing. Figure 11 shows some of the examples of non-optimized cement system and an optimized cement system done by Cement Sheath Analysis Software can be seen in Figure 12 (http://www.slb.com/~/media/Files/cementing/product_sheets/ cemstress.pdf).

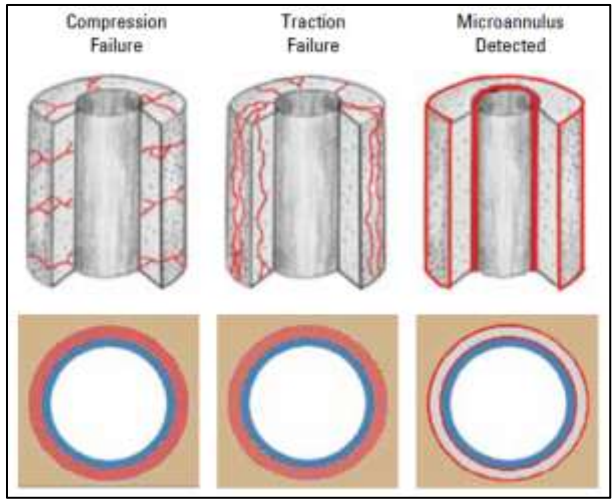

Figure 11. Non-optimized 16 lbm/gal cement system with Young's modulus of 8,000 MPa

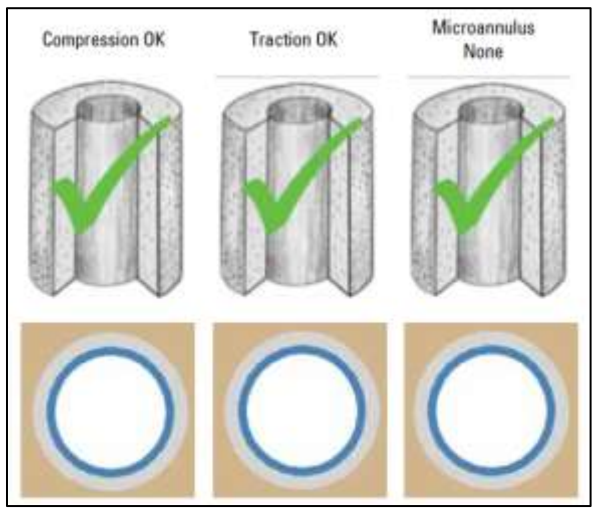

Figure 12. Optimized 16 lbm/gal cement system with Young's modulus of 2,500 MPa and expansion properties

Execution

Quality Analysis (QA) & Quality Control (QC)

OA / QC of cement bulk that is used and a good record, such as documenting the batch number for each additive, are essential. Sensitivity of chemical behavior should be tested in laboratory using the actual mixing water and temperature. Additional chemicals that are tested in the lab must be similar to

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the mixing materials in the field; a good sample from the rig is one way to do it. Also, the levels of chloride in the mix water must be checked.

Real Time Data Accuracy

Bottom Hole Circulating Temperature (BHCT) is the temperature of the cement slurry when it's being pumped into the well and Bottom Hole Static Temperature (BHST) is the temperature of the cement slurry when the pump is being stopped for a period of time. In high temperature wells, slurry becomes sensitive to thickening time, causing the cement to set faster. BHCT is the bottomhole temperature that must be considered since it will give influence to the thickening time. As the temperature rise, Plastic Viscosity and Yield Viscosity will decrease. Precise temperature (BHCT and BHST) readings are essential for cementing HPHT wells; an error as small as 10° F can significantly affect cement rheology and reduce the thickening time. Using a cementing simulator program could give an estimation of HPHT bottom hole temperature. Utilizing Pressure While Drilling (PWD) will give a real-time data to record accurate BHCT and BHST. Other parameters, such as ECD, flow rate and fluid density, can be monitored by real time data acquisition software in rigsite (Wray, Bedford, Leotaud and Hunter 2009).

Evaluation

CBL and VDL

CBL (Cement Bond Log) or VDL (Variable Density Log) are one of the ways to see if the cement job that has been done is in accordance with the primary cement objective. The analysis of full display gives only qualitative information about the cement job. If the cement-casing bond is good, most of the sonic energy will leave the casing and pass into the cement, thereby the casing waves will have a low amplitude. Acoustic impedance of the material in the annulus is one of many parameters that influence acoustic measurement. Figure 13 shows that higher temperature and pressure will affect pipe, cement, formation, velocity, and attenuation of sound through wellbore fluids (Nelson and Eliers 1985). Nayfeh et al. (1984) published pressure and temperature corrections for the transducers used in CBL tools.

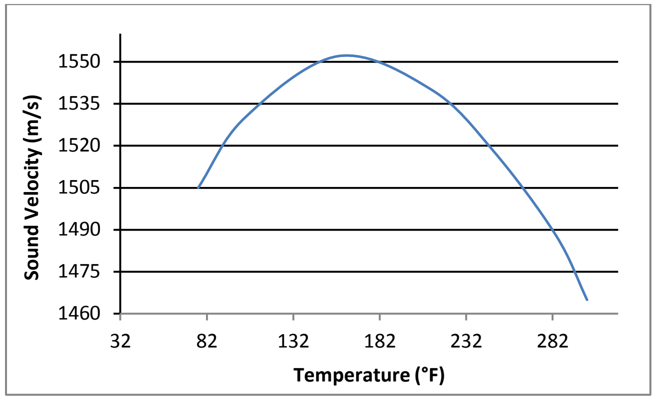

Figure 13. Effect of temperature on velocity of sound through water at 3,200 psi

Foamed cement should have poor acoustic properties, a Cement Bond Log will only indicate marginal zonal isolation when 100% mud displacement is achieved (Harlan, Foreman, Reed and Griffith 2001). On the other hand, at Norwegian, North Sea wells field experience showed that certain foamed-cement slurries can be effectively logged using conventional CBL, it showed bonding quality varying between good and excellent through cemented interval (Griffith, Lende, Ravi 2004). The Ultrasonic logging tools have been developed to evaluate the impedance variation produce by the foamed cement than measuring magnitude of cement impedance.

Ultrasonic Imager Logs

Ultrasonic Imager Logs use a single rotating transducer to achieve full coverage of the pipe wall. Measurements are made at 36 points around the circumference. The basic idea is to make a small area of the casing resonate through its thickness. The transducer sends a short pulse of ultrasound and listens to the echo containing the resonance. If behind the casing is fluid, it will resonate, but if it's a solid, resonance will be damped. Sonic and ultrasonic tools are sensitive to the bond between the material and the

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pipe. Ultrasonic logs are generally easier to interpret than sonic logs, but combination between the two logs provides more information. Supporting well information, cement job sequence (pre and post job well detail), circulation pressure and temperature data, and procedure for preparing spacer or slurry are needed.

HPHT Crucial Problems

High Angle Well

Due to high cost associated with HPHT wells, it is a high priority to eliminate any cementing failure and keep wellbore life. There is a significant difference in von Mises stress distribution in the casing between cement having high thermal properties with thermal conductivity of 2.4 Wm-1K-1 and cement having low thermal properties with a thermal conductivity of 0.66 /Wm-1K-1 (Manoochehr at al. 2010).

Size of cement channel is shown by cement channel angle β (Figure 14) which could range from 0° to 360°. In this paper we used 2-in height of cement channel. Figure 15 presents casing eccentricity (e) calculated using this equation (Yuan, Schubert and Teodoriu 2012):

$$e = \frac{2\,\varepsilon}{Welbore\ ID - Casing\ OD}$$

Equation 1. Casing eccentricity

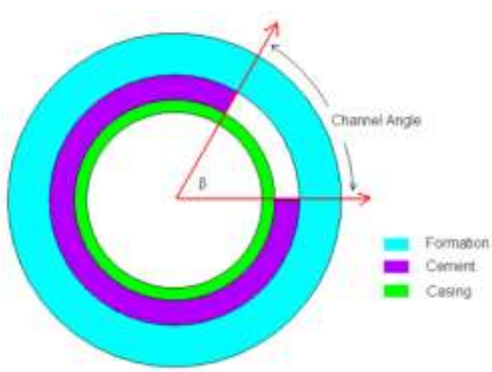

Figure 14. Cement Channel

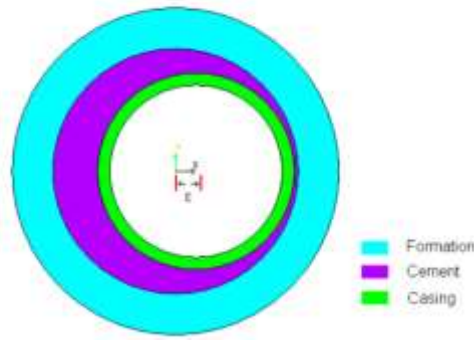

Figure 15. Casing Eccentricity

For high angles wells, effects of cement channel give the maximum casing von Mises stress between 80° to 120° cement channel angle at a wellbore angle of 90°. Cement maximum shear stress, tensile stress and radial stress happen between 40° to 50° cement channel angle. Above 50° channel angle, maximum shear, tensile, and radial stresses tend to be constant. Maximum shear stress happens between 40° to 50° wellbore angle. Cement maximum von Mises stress reaches 2.7E4 psi and happens at a wellbore angle of 40°. It's 440% larger than stress developed at the concentric condition without cement channel (Yuan, Schubert and Teodoriu 2012). The effect of cement channel angle and wellbore angle on casing von Mises stress, cement shear stress, cement tensile stress, and cement radial stress are shown in Figure 16, 17, 18 and 19.

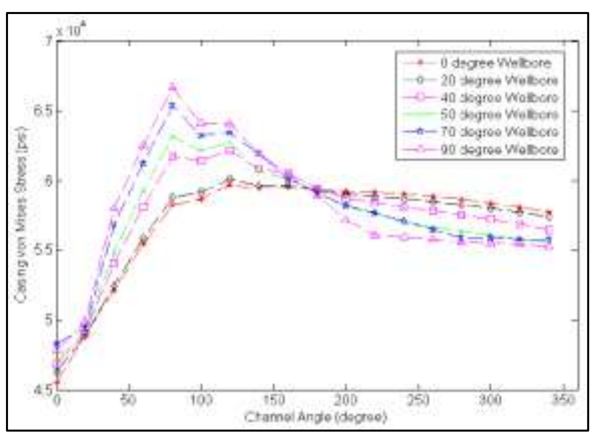

Figure 16. Effects of cement channel angle & wellbore angle on casing von Mises stress

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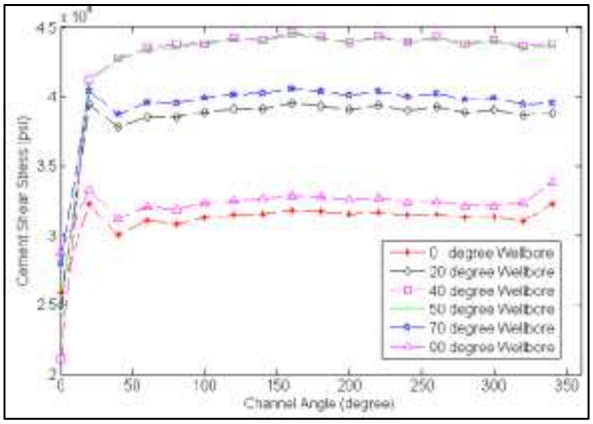

Figure 17. Effects of cement channel angle & wellbore angle on cement shear stress

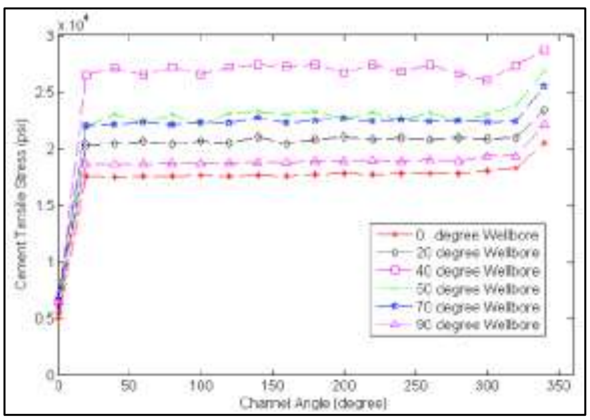

Figure 18. Effects of cement channel angle & wellbore angle on cement tensile stress

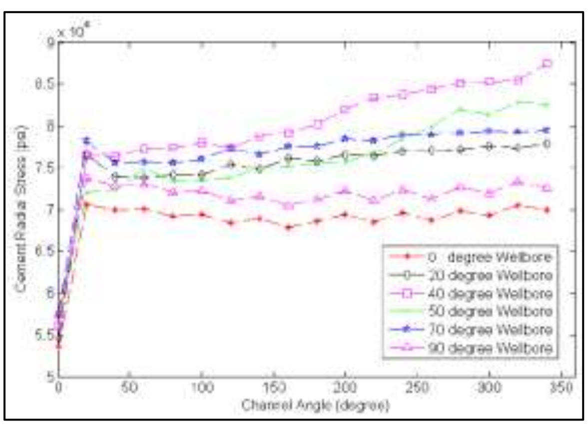

Figure 19. Effects of cement channel angle & wellbore angle on cement radial stress

Casing eccentricity has slight effect on the casing von Mises stress at casing eccentricity lower than 40% at different angle wells. Von Mises stress reaches a maximum when casing eccentricity approach 90% between 30° and 50° wellbore angle. Cement has the highest tensile failure in cement channeling condition and highest compressive failure in casing eccentricity condition (Yuan, Schubert and Teodoriu 2012). The effect of cement eccentricity and wellbore angle on casing von Mises stress, cement shear stress, cement tensile stress and cement radial stress are shown in Figure 20, 21, 22 and 23.

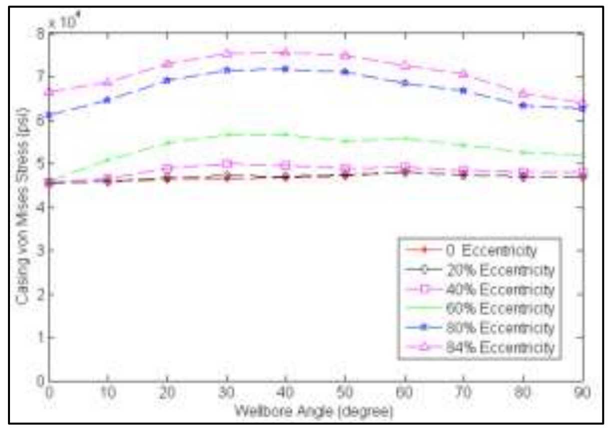

Figure 20. Effects of cement eccentricity & wellbore angle on casing von Mises stress

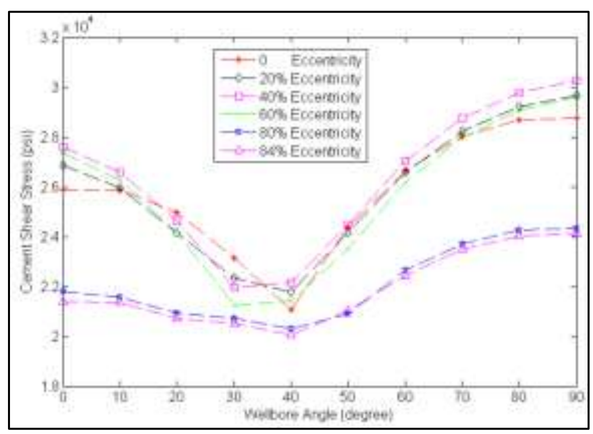

Figure 21. Effects of cement eccentricity & wellbore angle on cement shear stress

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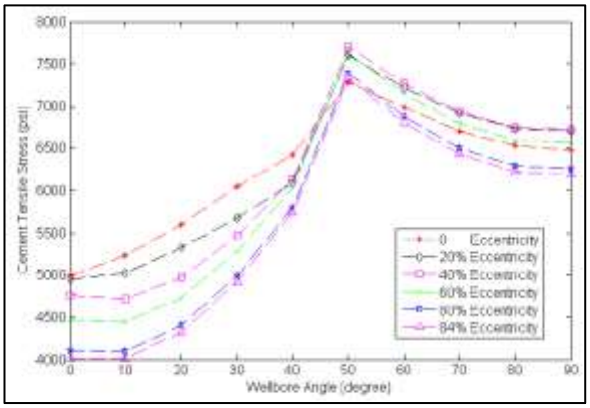

Figure 22. Effects of cement eccentricity & wellbore angle on cement tensile stress

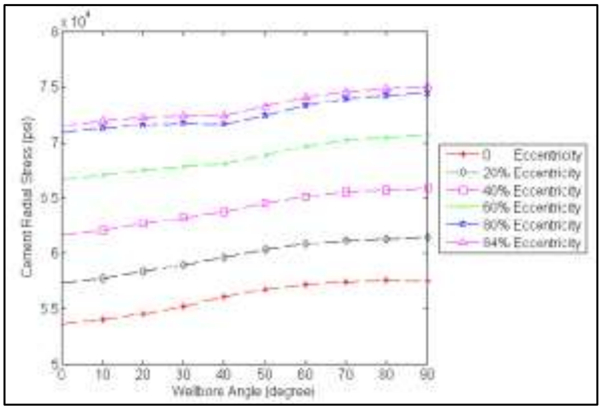

Figure 23. Effects of cement eccentricity & wellbore angle on cement radial stress

Gas migration

Worldwide, gas migration is a common problem for the oil industry, especially in deep gas wells. In Gulf of Mexico, more than 80% of the wells encounter a gas transmitted to surface at trough cemented casing (Yetunde and Ogbonna, 2011). It is very important to control the flow after cementing for deeper high pressure oil and gas wells; gas could invade and migrate through the cement matrix during waiting on cement time (Pour and Monghadasi 2007). Flowing hydrocarbons from tight formation or casing contraction during switchover from displacement fluid to sea completion fluid could create micro annuli. In Shearwater field, Central North Sea, Central Graben, during switchover operation, internal casing pressure was reduced by 7,800 psi. Gas migration can lead to poor zonal isolation, high water and gas cuts, low production rates, high surface annular pressure, or even blowout.

Gas migration could invade in different stages:

- Stage one, when it's dense fluid: based on Pour and Monghadasi (2007), if the slurry is higher than formation pressure, gas can't invade. But, almost immediately, annulus pressure begins to fall because of gelation, fluid loss and bulk shrinkage. Premature gelation leads to loss hydrostatic pressure control. Mud filter cake between formation and cement could make pressure differential (even less than 1 may allow gas to enter the annulus). Incorrect cement density can result in hydrostatic imbalance. If it's assumed that wall shear stress equals the static gel strength, following equation can be used to describe hydrostatic pressure reduction during gelation:

$$\Delta P = SGS\ \frac{4\ L}{Dh - Dc}$$

Equation 2. Hydrostatic pressure reduction

Where:
ΔP = hydrostatic pressure changes on column
SGS = static gel strength
L = cement column length
Dh = hole diameter
Dc = casing outside diameter

- Stage two, when it's a two-phase material: when the cement solid particles are interconnected with the liquid phase, hardening and drying continues to accelerate. Hydration takes shrinkage of an internal cement matrix up to 6% of cement volume. High cement shrinkage can lead to initiation of fractures and interfere in cement and casing bond. High loads encountered in deep wells compress sets in and destroy the cement sheath by compaction of matrix porosity (Elzeghaty et al. 2007). This destruction is caused by mechanical failure, which creates cracks in the cement matrix. These cracks create a pathway for gas migration

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from formation to surface at the same time, thereby shortening the life of the well.

- Stage three, when cement is set: cement becomes an elastic and brittle material (gas no longer migrates). It can flow only through microannulus more likely results from thermal stresses (cement hydration, steam), hydraulic pressure stresses (casing pressure test, squeeze pressure) and mechanical stresses (pipe or tubular banging in the casing), and mechanical failure (shrinkage induced stresses, thermal expansion).

Since cementing an unbalanced wellbore in high pressure formation can cause cement migration in the cement column, killing the well using mud and cementing could be one of the best procedures. Most of the gas channeling in a cement column occurs during a transition period from liquid to solid, latex additives help to delay cement pore pressure drop and shorten transition time between liquid and solid stage (Al-Yami, Nasr-El-Din and Al-Humaidi 2009).

Base on Al-Yami, Nasr-El-Din, and Al-Humaidi (2009) experiment; *Hematite*, expansion additive, and silica sand in high density cement and under high temperature high pressure conditions caused significant settling in mixing tanks. *Manganese tetraoxide* by itself does not control gas migration, but adding hematite to a manganese tetraoxide improved the gas migration resistance. As the depth increase, sometimes reducing the mud density will reduce the pressure which can cause the casing to shrink, leading to micro annulus or cement-casing bond breakage, which will allow gas to flow. Expanding additives are recommended for cement jobs for a gas producing formation and at greater depth. Tests using the combination of 45% BWOC Manganese Tetraoxide, 45% BWOC Hematite, 10% BWOC silica sand, and 25% BWOC silica flour showed an outstanding result of zero gas permeability with no gas breakthrough and zero fluid loss. Class G Cement + 35% BWOC Silica sand + 185% BWOC Hematite + 5% BWOC expansion additive at cement densities up to 22.7 lbm/gal are used to cement high pressure formations in terms of minimizing gas migration, fluid loss and settling (Al-Yami, El-Din and Al-Humaidi 2009; AL-Yami, Schubert, Cetina, and Yu 2010).

Pour and Moghadasi (2007) discussed that in gas migration phenomenon, high gel strength development may help resist gas percolation and, therefore, suggested to use thixotropic and high-gel-strength cements. Thixotropic systems are unlikely to be effective in situations where the gas zone pressure exceeds the water gradient, unless additional backpressure is held in the annulus.

Lost Circulation / Weak Formation

Prevention

Low density slurry, or foam cement, is chosen for certain advantages in tight mud window HPHT well encountered in deepwater applications. Lightweight cement is a special formulation composed of interground Portland cement clinker and lightweight siliceous aggregates. Consequently, some pozzolanic activity occurs. The particle size distribution is finer than Portland cement which could give slurry density range between 11.9 lbm/gal to 13.7 lbm/gal. Nowadays, there is 7.5 lbm/gal slurry system that can provide the high strength and low permeability which can provide equal compressive strength and permeability to 15.8 lbm/gal cement.

To get lighter cement density besides water, gas can also be used as a slurry base. Foams have lower thermal conductivity due to the presence of gas voids and lower amount of solid (Short et al. 1961). Thermal conductivity of a cement system is roughly proportional to slurry density regardless of whether the cement was foam or not (Nelson 1986). Nitrogen is incorporated directly into the cement slurry to obtain low-density foamed cement. Formulated base cement slurries are needed for preparing a homogeneous system with high compressive strength and low permeability. Foamer concentrations are constant and nitrogen rates are driven to control

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downhole density during lead and tail cementing work (Harlan, Foreman, Reed and Griffith 2001).

Foam cement is more ductile than non-nitrified cements and more resistant to both temperature and pressure-cycling-induced sheath stresses (Marriott, Griffith, Fyten, Mallett and Szutiak 2005), which allow the cement sheath to yield while the casing expands and then rebound when the casing returns to its original conditions (Griffith et al 2004). The test shows that above 35-quality foamed cement is generally too porous to provide isolation, and below 20-quality foamed cement is generally too brittle to provide the minimum ductility (Harlan, Foreman, Reed and Griffith 2001). Foam sealant slurry could be a compressible fluid that is less sensitive to loss of hydrostatic pressure due to slurry gel strength development (Biezen and Ravi 1999).

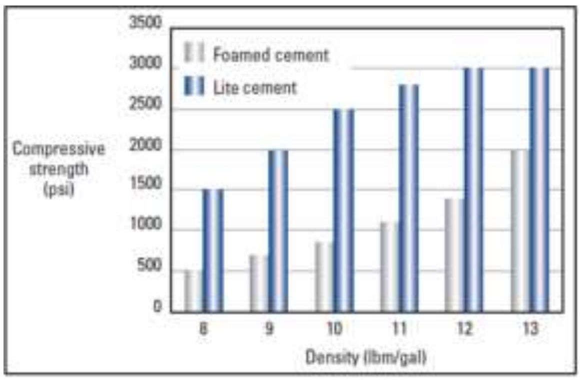

Figure 24. Compressive strength lightweight slurries vs foamed cement

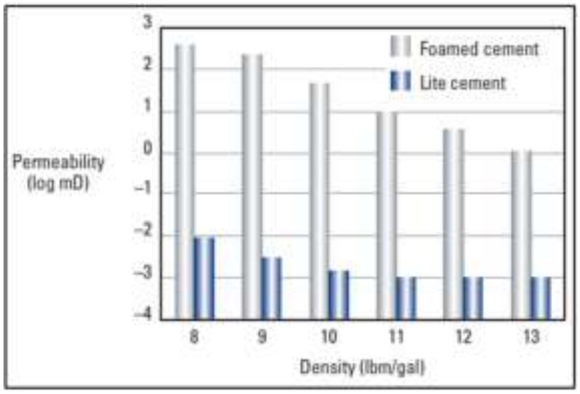

Figure 25. Permeability lightweight slurries vs foamed cement

Wells that we drill have an irregular shape, with foam cement, however, the slurry could expand and fill the gap in the annulus. This feature has stable rheological properties, which lead to efficient displacement; the density could be from 7 to 15 lbm/gal. After setting, it could be a long term sealing and can bond well casing and formation. Foam slurry is considered to have superior mud removal properties, and the capability of filling lost circulation voids (Pine et al. 2003) eliminate free water development, expansion properties, controlling gas migration or formation influx, increase ductility, and higher tensile strength. Comparison between lightweight slurries and foamed cement can be seen in Figure 24 and Figure 25 (Cementing Services and Products, page 41).

Treatment

Lost circulation problems can occur while drilling or cementing in HPHT wells and it can be expensive and time consuming. Lost circulation occurs by natural or induced mechanisms. Lost Circulation is divided into several categories: unconsolidated formations, high permeable or low pressure formations (depleted zones), natural fractures, induce vertical or horizontal fractures, and cavernous and vugular formations (limestone or dolomite formations). Severity classification for lost circulation is shown in Table 5. Losses location should be determined accurately; lost circulation materials and techniques must match the type and severity of the loss zone. Data records from previous lost circulation history often point out the way to an effective solution.

Type of Losses	Severity (bbl/hr)
Seepage – minor	< 10
Partial – medium	10 to 100
Severe – massive	100 to 500
Total - complete	Unable to keep the hole full

Table 5. Severity classification for lost circulation (Nelson 2006)

If lost circulations during cementing are anticipated, there are two methods to be used. *First*, decrease

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downhole pressure by reducing slurry density below ECD, minimizing the height of cement column, and limiting casing and annular friction pressure during the placement of cement slurry. *Second*, pump plugging material as a spacer in front of the slurry that contains lost circulation material or other additives that have thixotropic properties to the slurry (Nayberg and Linafelter 1984).

The most common LCM is the granular type. Since *Gilsonite* has a low melting point 220°F, this makes it unsuitable for high temperature wells. *Crush coal* in mesh range 14-22, which has a melting point of approximately 1,000°F can be used in high temperature wells. Shells from *walnuts*, pecan and nuts can be used as well. *Cellophane flakes* at concentration above 2lbm/sk make mixing with cement slurry extremely difficult. *Nylon* and *polypropylene* have a tendency to plug pump plungers and float equipment. Recently, *silica base fiber* has been developed; it is very flexible and readily mixes into cement slurries and disperses in an aqueous medium (Messier et al. 2002, Low et al. 2003 and El-Hasan et al. 2003).

Thixotropic cement is used to overcome severe lost circulation problems. Thixotropic cement is slurry that remains liquid when sheared (pumped) and begins to turn into a gel when the shear stops. Another way to solve lost circulation problems is lowering the density by using a foam cement system (Nayberg and Petty 1986).

HPHT Sidetrack

In HPHT deep wells, multilateral wells root from one wellbore to reach different reservoir zone. Sidetrack operations have been used to overcome the HPHT challenges. Al-Yami, et al. (2006) mentioned that the maximum formation compressive strength can reach up to 22,500 psi and the maximum cement compressive strength is 5,000 to 9,000 psi. To provide good isolation, 100 psi cement compressive strength is required. The compressive strength of regular cement is much lower than that of the formation which leads to a fast cement rate of penetration. Increasing cement compressive strength will minimize the difference in rate of penetration between the cement plug and the formation.

For sidetrack drilling, using weighting material such as hematite or manganese oxide with conventional cement is more effective compared to special high density blend. Since increasing cement density is more effective, silica solid is recommended to be used to reduce the rate of penetration. Expansion additives and manganese oxide with silica material showed no improvement in rate of penetration. 24 hours waiting on cement is recommended for most cases before drilling. Slow rate of penetration formulation is a combination of mixed cements cured at 290°F resulted from a strong cement core. It ensures that the thickening time and settling test are acceptable, which makes slow rate of penetration (SROP) formulation the best solution to achieve good sidetrack drilling (Al-Yami, Jennings, Nasr-El-Din, Khafaji and Al-humaidi 2006; A-Yami et al 2008).

Casing Collapse

In HPHT wells casing collapse probability is present. Cement sheath not only provides zonal isolation but also supports casing and increase casing collapse resistance. In HPHT gas wells, the differential pressure between the formation and the casing is larger than that in normal wells, which introduces greater challenges to casing integrity. Reducing cement Young's modulus will reduce cement maximum von Mises stress and increase cement maximum shear stress. Modified cement Young's modulus could prevent cement shear failure. Maximum von Mises stress difference is only 0.27% for 0.3 inch casing eccentricity; it doesn't have much effect on casing and cement. Stress in a casing under elastic cement is 12% lower than the stress in a casing under brittle cement (Yuan and Schubert 2012).

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Environmental Restrictions

UK sector of the North Sea complies with governmental regulations that characterize materials by their volumes to be discharged to the sea. Cementing materials are categorized from A to E. Discharge of category A materials is strictly limited while category E discharge is not restricted. Most of the materials that fall under category E could achieve high performance while complying with the environmental regulation (North and Gray 2000).

Some regions have restricted environmental regulations that dictate using biodegradable chemical materials. Such regulations limit the desired properties of HPHT chemical. Hence, development of new chemicals that meet environmental regulations while performing effectively under high temperature / high pressure conditions should be sought.

Technology Solutions

Nowadays, cementing technology allows cementing to last in higher pressure or higher temperature. Technology to reduce WOC (Waiting On Cement), would be very meaningful for wells that require substantial operational cost such as deepwater wells or deep HPHT multilateral wells. Technology solutions have been made and continue to be developed to provide long life cementing zonal isolation.

High Angle Well – In high angle well, over stress in casing or cement can be overcome by providing proper casing centralizer or reducing cement channel. If those ways can't help, changing the well or cementing design should be implemented.

Gas Migration – Most of the gas channeling in cement column occurs during a transition period from liquid to solid. Adding latex additives helps delaying cement pore pressure drop and shortening transition time between liquid and solid stage (Al-Yami, Nasr-El-Din and Al-Humaidi 2009). To prevent gas migration, slurry modification could be done by decreasing volume losses, extending zero gel time, reducing transition time, adding gas influx preventing material, and increasing slurry compressibility. Job design changes could be done by decreasing effective column height, increasing overbalance pressure, interfering in the gelation process, and drilling a larger diameter hole (Wray, Bedford, Leotaud and Hunter 2009).

Across weak formation – Lightweight slurry system that has high compressive strength and low permeability should be used to cement a weak formation. The lightweight system could give 7.5 lbm/gal slurry densities which could even be comparable to 15.8 lbm/gal cement properties. Using foamed cement (by adding gas and surfactant) also can be considered in very weak formation; it mixes immediately prior to the job, unlike preblended cement. If there has been a lost circulation, downhole pressure should be decreased and plugging material LCM (lost circulation material) should be pumped.

High-Pressure well / kickoff plug – High density cements (up to 24 lbm/gal) could be used for kickoff plug or to handle well control issues specially to provide high pressure zonal isolation.

Isolation problems (Microannulus) – Expanding agents can be selected to prevent microannulus in cement set and squeeze cement material could be used to handle microannulus cement by filling the empty space without dehydrating or bridging during placement.

Changes in pressure and temperature throughout well's life – Flexible cement additives are fabricated to provide flexibility to overcome stress changes in the wellbore and give higher compressive strength and lower permeability.

Interrupt cement sheath – Durable cement additives provide a high quality cement sheath even against disturbing by vibration or impact mechanical shock stress.

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Summary & Conclusions

1. Based on the survey in HPHT Summit, cement design is one of the HPHT technology gaps that should be given high attention. In the design phase, increase of temperature will decrease plastic viscosity and yield viscosity (Ravi and Sutton 1990). To overcome the strength retrogression problem, when the static temperature exceeds 230°F, 35 % - 40 % silica by weight of cement should be added to Portland cement. For temperatures exceeding 750°F, High Alumina cement is more suitable than Portland cement. Silica in High Alumina cement should not be used as an extender for temperatures exceeding 570°F; fly ash or aluminosilicate firebrick is more suitable. If the static temperature exceeds 450°F, fly ash should not be used in Portland or Class J cement, however bentonite and perlite are suitable.

2. Glass microspheres with hydrostatic crush strengths could hold 10,000 psi but ceramic microspheres can only withstand up to 3,000 psi, however, both could be used in thermal wells since they stabilize in high temperatures (Nelson 2006). The assumption that high compressive strength is linked to low permeability is false. In general, set cements that consist of a cement silica ratio less than or equal to 1.0 tend to have higher compressive strengths and lower water permeability. Cement set not only depends on downhole temperature, but also on the presence of other minerals. Its composition can evolve as downhole conditions change. Proper amount of retarders must be blended into the cement system. Too much retarders can cause long wait on cement and, in high pressure wells, may lead to the entry of gas into the cement.

3. Combination of silica sand, silica flour, hematite, manganese tetraoxide with expansion additives showed the best performance in terms of minimizing gas migration, fluid loss, and settling. Hematite, expansion additives and silica sand, in high density cement caused significant settling in mixing tanks. Manganese tetraoxide by itself does not control gas migration, but adding a hematite to manganese tetraoxide improved the gas migration resistance (Al-Yami, Nasr-El-Din and Al-Humaidi 2009).

4. In high temperatures of 300°F to 400°F using burnt MgO is more preferable. The effective expanding additive concentration for increasing shear bond strength is ranging from 5 to 10 % (Rubiandini 2000). General guidelines such as fluid loss should be in range of 50 ml per 30 minutes. Generally, 70% standoff is considered as minimum requirement to have good cement bond; casing needs to be kept at the center of the wellbore. Improving pipe stand-off, increasing μ_p / τ_y, decreasing mud gel strength and increasing flow rate are important factors to achieve a good mud removal. Cement slurry system, preflushed and spacer should be designed and tested at the laboratory to fit the objectives to be achieved. Cementing operation could be optimized by cementing simulator program, real time data accuracy, quality analysis and quality control of materials.

5. For deep and hot wells, an accurate static and circulating temperature to obtain efficient thickening time and optimal compressive strength should be considered. In high pressure wells, we must consider an anticipated bottomhole pressure to obtain good well control or avoid fluid invasion. To control gas migration, the "zero gel" time can be long but the transition time should be as short as possible. Cement evaluation could be done with CBL, VDL, Ultrasonic Imager Logs or combination of them.

6. For high angle wells, effects of cement channels give the maximum casing von Mises stress between 80° to 120°, and at the wellbore angle of 90°. Cement maximum shear stress, tensile stress and radial stress happen between 40° to 50° cement channel angle. Above 50° channel angle, max shear, tensile and radial stress tends to be constant. Maximum shear stress happens between 40° to 50° wellbore angle. Casing

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eccentricity has minor effect on the casing von Mises stress at casing eccentricity lower than 40% at different angle wells. Von Mises stress reaches a maximum when casing eccentricity approaches 90% between 30° and 50° wellbore angle. The maximum von Mises stress difference is only 0.27% for 0.3 in eccentricity and the casing centered in the hole (Yuan, Schubert and Teodoriu 2012).

7. When cement additives are not dry blended with the bulk cement, liquid additives are preferable to allow accurate addition and reduced mixing time. To provide greater control and consistency in HPHT operations or long liner sections, cementing requires large fluid volumes and batch tanks for crucial jobs (North, Brangetto and Gray 2000).

Acknowledgment

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