TITLE : Review of Macondo #1
7" x 9-7/8" Production Casing Cementation

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DATE : 7 April 2011

5004
Exhibit No. ______
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Contents

Abbreviations Used		
bbl - barrel	gps - gallons per sack (94 lb sack of cement)	SG- specific gravity
BHCT - bottom hole circulating temperature	mL - milliliter	sk - sack (94 lb sack of cement)
BHST - bottom hole static temperature	N2 - nitrogen	SOBM - synthetic oil based mud
bpm - barrels per minute	ppg - pounds per gallon (lb/gal)	TOC - top-of-cement
BWOC - by weight of cement	psi - pounds per square inch	TS - tuned spacer
cP - centipoise	PV - plastic viscosity	UCA - ultrasonic cement analyser
FQ - foam quality	QC - quality control	WOC - waiting-on-cement
FS - foam stability	scf - standard cubic feet	

Review of Macondo #1 7" x 9-7/8" Production Casing Cementation

1. Report Objectives

The issues that Transocean requested to be addressed in this report include:

- Examining the cement design utilized.
- Reviewing and commenting on the lab test results for the slurries.
- Considering whether the design application was fit for purpose.
- Reviewing the job execution.
- Suggesting recommendations for future cementing operations in similar situations.
- Evaluating wellbore preparation prior to cementing (evaluation of what was done and recommended best practices).
- Assessing any other areas not addressed above.

2. Report Summary

2.1. Laboratory Testing

- Some basic laboratory testing of slurry properties were omitted by the service provider, Halliburton. These include:
  - Fluid loss test.
  - Free fluid test.
  - Stability test of base-slurry.
  - Compatibility test of cement and spacer.
  - Rheology tests of all fluids at predicted BHCT (135°F).
  - Crush strength test of foamed cement at 180°F with retarder concentration used.
- Compatibility test of mud/spacer was not performed with representative samples of mud and spacer.
- The sole foam mix and stability test run with the proposed slurry formulation indicated that there were possible issues concerning the foam stability. Earlier foam stability tests with a higher retarder concentration further highlighted the instability issue.
- Operator failed to demand a full suite of laboratory tests with rig samples prior to job in order to assess product suitability.
- Halliburton wrongly stated in all their pre-job proposals that the BHST of the well was 210°F, when in fact it was considerably higher - above 240°F. The lower temperature may have been used in a temperature simulator to determine the BHCT for laboratory testing, but there was no evidence seen to confirm this.

2.2. Float Collar

- The auto-fill float collar probably failed to convert. The nine attempts to convert the float collar suggest that it may have been damaged and subsequently failed to function correctly.
- The flow-back test at the end of the job, indicating zero flow-back, was possibly misinterpreted to mean that the float collar check valves were holding back-pressure. In fact it seems more likely that the inside and outside pressures of the casing were almost equal. Calculated end-of-job lift pressure indicated that any flow would be from casing to annulus.
- Since the negative differential pressure between casing and annulus made it impossible to verify whether the float check valve could hold pressure, a viable option would have been to wait a sufficient time to ensure the cement was set, prior to proceeding with the negative test.

2.3. Cement Properties, Mixing, Density Control & Foamed Stability

- Anti-foaming agent and potassium chloride in the cement recipe are not believed to be compatible with stable foamed cement.
- No fluid loss agent was added to the slurry to provide adequate fluid loss control and to help prevent gas migration
- The base-slurry density control $\pm$0.25 lb/gal was too great for a critical cementation (density varied from 16.5 to 17.1 lb/gal), together with the down-hole density being controlled by the addition of nitrogen (N2). Once placed, foamed cement does not remain at a constant density; the density decreases as it heats up prior to setting. This particular characteristic of foamed cement makes it a questionable choice when well-control margins are tight. For critical cementations, a density variation of not more than $\pm$0.1 lb/gal is usually preferred.
- The yield point (YP) of the base-slurry was well below 5 lbf/100ft^2, which is the recommended minimum YP for creating a stable foamed cement. Chevron's subsequent laboratory testing with Halliburton additives confirmed that there was a foam stability issue.
- A nitrogen ratio of 584 scf/bbl appeared too high for foaming cement from 16.74 lb/gal to a target density of 14.5 lb/gal with a mud density of 14.17 lb/gal. At the BHCT of 135°F, the average density would have been ~14.36 lb/gal, decreasing to ~14.23 lb/gal at 180°F.
- Halliburton's design proposal HAL_0010988 of 18 April 2010 reported the length of the foamed cement column as 1,952.1 ft, HAL_0010988/06, with the top being at 16,352.9 ft. This put the top more than 1,000 ft above the theoretical top of cement. Thus the OptiCem program was predicting significant channelling.
- Last 4 bbl of shoe track cement (nominally 16.74 lb/gal) averaged ~0.2 lb/gal less than the rest of the cement mixed, and was thus slightly more retarded.

- From Halliburton's job report, it was not verifiable whether the correct volume of retarder SCR-100L was added during mixing, or that its SG was checked against the product specification sheet at the wellsite.

2.4. Unset Cement

- Cement was most probably not set at the time the well erupted due to one or more of the following reasons: over-retarded slurry; cement contamination with mud during placement; an exchange of fluids between the shoe track and rat-hole after placement; waiting-on-cement (WOC) for an insufficient time to allow the cement to set.
- There was no evidence from any of the testing done that gave a clear indication as to the earliest time after the job that the cement would have been set.
- It is very probable that the cement slurry – even in an uncontaminated state - would not have set prior to attempting the negative test ~18 hours after cement placement. The available evidence – no cement set in 24 hours at 180°F (crush test), and cement fully set in 12 hours at 210°F (UCA test).
- The result of the UCA test at 210°F, after only a 4-hour heat-up time to temperature, would have given the Operator false confidence that the cement was set. Ideally, this test should also have been run with the temperature and pressure at the top-of-cement, under conditions prevailing at the anticipated time of the negative test, with the temperature and heat-up rate derived from a temperature history simulation.
- The common effect of an inverted thickening time, from ~140°F up to the 180°F to 200°F range with certain cements, may have been responsible for the slow set. In other words, the thickening time increases with increasing temperature until a threshold temperature is reached, and then the transition is rapid from liquid to solid.

2.5. Centralization

- Poor casing centralization over the top half of the cemented interval (above ~17,882 ft), increased the risk of poor mud removal and cement channeling, and negated the prospect of a good hydraulic seal across the whole of the cemented interval.
- Where casing stand-off was anticipated to be good in the lower section of the annulus, i.e. from casing shoe to ~17,882 ft, there should have been good cement coverage assuming that uncontaminated cement was reaching the shoe.

2.6. Well Security

- The OptiCem Circulating Pressure and Density Plot showed that the fracture pressure at 18,189 ft was exceeded by over 400 psi, indicating that the displacement rate of 4 bpm should have been reduced for the last ~50 bbl of displacement to avoid possible losses.
- The reduction in the average returns flow rate after the cement rounded the shoe indicates that some losses may have occurred.
- Pumping 7 bbl of 6.7 lb/gal base oil flush ahead of the spacer further lowered the pressure from annulus to casing by 42 psi, which could have compromised well control

should an unplanned stoppage have occurred at the wrong moment during the displacement. It further lessened the annulus pressure to produce flow-back to confirm whether or not the float collar could hold back-pressure.

- For future similar cementations, whenever the annulus and casing pressures at the float collar are close to equal, a sufficient volume of a low density fluid should be pumped at the end of the displacement to apply 300 to 500 psi back-pressure at the float collar, to verify with more certainty that it is holding.

2.7. Foamed Cement Risks

- For critical cementations with foamed cement, particularly those requiring relatively small volumes of slurry and precise density control, the risks are significant. First, the issue of obtaining the correct base-slurry density when mixing on-the-fly (as was the case here), second to control accurately the nitrogen delivery system, third to maintain foam stability throughout the FQ range (from surface mixing to down-hole placement), and fourth to achieve target density after foaming.
- The added complexity of a computer model simulating the placement pressures and displacement efficiency of a compressible fluid, with its inherent continuously changing density and rheology, makes the predictive outcome from any simulator even more questionable.
- The preferred cement slurry option in this case would be batch mixing a low density, high strength, particle-matched slurry at 14.5 lb/gal - without the need of nitrogen addition. This was a feasible option considering the relatively small volume of cement being mixed. Such a slurry system can have its main properties verified during the design stage, and again after mixing and before pumping down-hole.

3. Introduction

3.1. Source Data Reviewed

The following data was reviewed when compiling this report:

- 3 - Halliburton's 9 7/8" x 7" Production Casing Design Reports (OptiCem) (HAL_0010592, HAL_0010699, HAL_0010988) of April 15 at 3.30 pm and 6.12 pm, and of April 18, 2010.
- Halliburton 9 7/8" Liner Design (HAL_008253), March 30, 2010.
- 5 - Halliburton 9 7/8" x 7" Production Casing of: April 2, 2010 (Version 2 / HAL_0009306), April 12, 2010 (Version 3 / HAL_0010241), April 15, 2010 (Version 4 / HAL_0010722), April 16, 2010 (Version 5 / HAL_0010827), April 18, 2010 (Version 6 / HAL_0011047)
- An interoffice correspondence (Subject: Cement Procedure) from Brian Morel to Jesse Gagliano, April 16, 2010 (reference HAL_0010815).

- An interoffice correspondence, subject "OptiCem Report", to Mark Hafle et al, (no date) giving the results of an OptiCem Centralizer Calculation Report created on April 15, 2010 with 10 centralizers (reference HAL_0010650), and a second interoffice of April 15 with 6 centralizers (reference HAL_0010648).
- Halliburton Lab Results Report (Request/Slurry 739092/1, HAL_0010868) dated April 12th 2010 of the proposed slurry (SCR-100L retarder concentration 0.08 gps – 70Bc 5:30) for the cementation, including thickening time of base-slurry, rheology of base and foamed slurry, compressive strength of foamed slurry.
- Halliburton Lab Results Report (Request/Slurry 739092/2) dated April 12th 2010 of the proposed slurry (SCR-100L retarder concentration 0.09 gps – 70Bc 7:37) for the cementation, including thickening time of base-slurry, rheology of base and foamed slurry, compressive strength of foamed slurry.
- Halliburton 9.875" x 7" Foamed Production Casing Post Job Report, April 20, 2010 (Reference HAL_0011210)
- Halliburton Energy and Commerce Committee Staff Briefing of June 3rd 2010.
- BP Operating Procedure (BP-HZN-CEC017621) for 7" x 9-7/8" Interval.
- Five BP Daily Operation Reports for Well OCS-G 32306 MC252 #1/01 dated from 15 to 19 April 2010.
- Five Transocean Daily Drilling Reports dated from 16 to 20 April 2010.
- Weatherford Centralizer Drawing, Dwg No. D000401160.
- Excel File: Macondo Casing Data Package Rev 1.xls.
- Excel File: MC252_001_ST00BP01_long string Cementing Raw Data.xlsx (5-second data).
- M-I SWACO Synthetic-Based Report No. 79 of 4/19/2010.
- Recommended Practice on Preparation and Testing of Foamed Cement Slurries at Atmospheric Pressure, API Recommended Practice 10B-4, July 2004.
- CSI Laboratory Analysis of Cementing Operations on the Deepwater Horizon – CLS0733 –August 11, 2010.
- Analysis of Cementing Operations on the Deepwater Horizon and Possible Contributing Factors to Loss of Well Control, BP-HZN-BLY00139698.
- Excel File: HAL Cement Data 18 April 20 April 2010 Converted to Excel.xlsx (1-second data).
- OptiCem Wellbore Simulator Report, BP-HZN-MBI00136477.
- Chevron Letter to Deputy Chief Counsel of October 26, 2010 regarding Cement Testing Results.
- Cement Lab Weigh-Up Sheet, April 7, 2010 – Req/Slurry: US-72908/2.
- Rheology of Foamed Cement by R.M Ahmed et al. published by Cement and Concrete Research 39 (2009).
- SPE 39315 Determination of Temperatures for Cementing in Wells Drilled in Deep Water by D. G. Calvert and T. J. Griffin, Jr.
- SPE 23073 Retardation of Cement Slurries to 250°F by J. Bensted.

- Cement Lab Weigh-Up Sheet, Feb 16, 2010 - Req/Slurry: US-65112/3.

3.2. Job Objectives & Evaluation

In order to evaluate a cement job it is necessary to know the objectives of the Operator. It is assumed that these were:

- Minimum length of the cement column (top of cement (TOC) to a certain depth ~17,300 ft) to support and protect casing in the long term; and in the short term, to maintain well control during placement and WOC.
- Good seal at the casing shoe, and good mechanical support to casing above TOC.
- Good zonal isolation across the pay and high pressure zones.

Placing cement between the 7" casing and the previous casing was not an objective.

Issues to be addressed during an evaluation of any cement job require certain information before, during, and after the execution of the cement job. These include:

- Were there any drilling anomalies?
- Was a caliper run? Which type? Degree hole over gauge?
- Were the number, size and location of centralizers properly designed and run?
- Did mud conditioning and mud rheologies prior to the cement job differ from design?
- How long was the well circulated prior to the job?
- Was the pipe moved (rotated or reciprocated) during mud conditioning and during cementing?
- Were all preflushes pumped as per design?
- Were all preflushes prepared to the design characteristics?
- Were there any losses or any inflow during the cement job?
- Did any unexpected event occur during or before the job?
- Were the slurry and preflush properties fit for purpose?
- Were the slurry volumes and densities as per design?
- Was the BHCT assumed for the slurry design correct?
- Were the plugs launched properly? Did they work?
- Was the displacement carried out at the design rate?
- Were the fluid returns (liners and plugs) circulated to surface after placement as expected?
- Did the post-laboratory tests with actual job samples tally with design?
- Were any logs run after cementing, temperature and/or acoustic (CBL/VDL/CET/USI)?
- Were postmortem laboratory thickening time tests run with actual heat-up rates to a simulated BHCT?

- Did postmortem laboratory compressive strength tests take into account the heat-up rate to simulated bottom-hole temperatures at the time of first hydrocarbon flow into the casing?

Answers to these questions can provide valuable information to identify the possible cause of an unsuccessful cement job.

3.3. Well Schematic

The well schematic (Figure 1) shows the tops of cement, spacer and base oil, assuming 100% mud displacement efficiency, after the well was cemented and before sea water was circulated to 8,637 ft to apply a negative pressure of ~2,500 psi at the casing shoe.

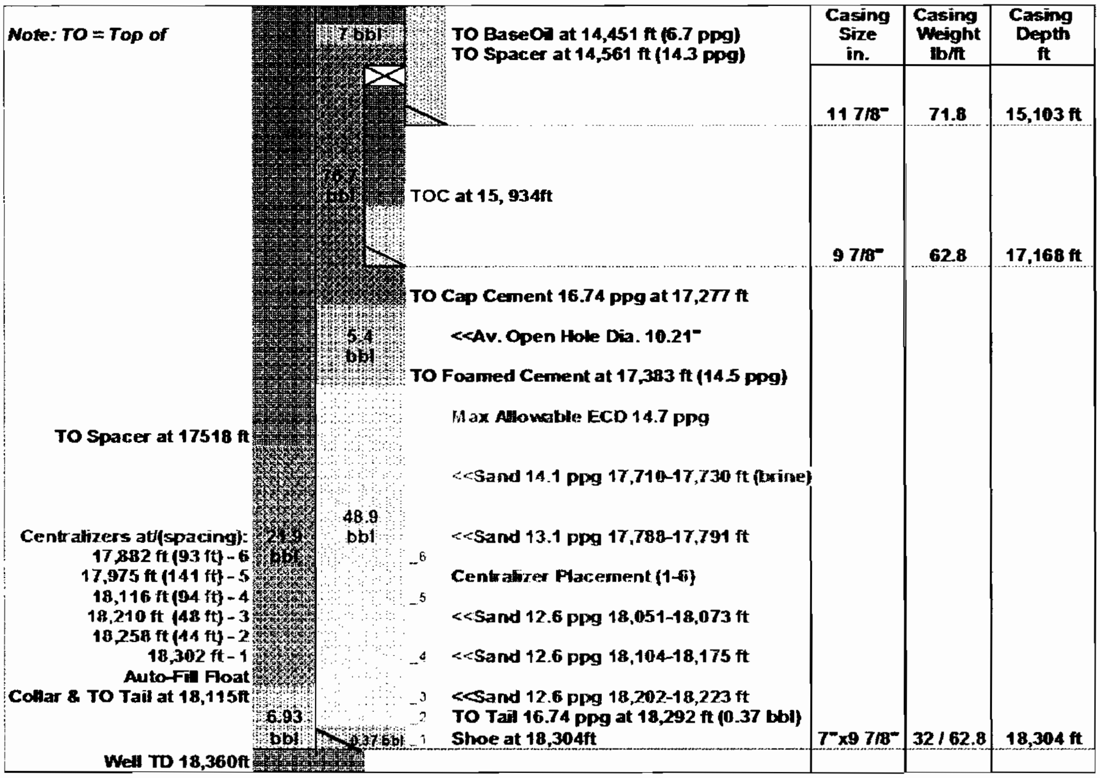

Figure 1: Well Schematic – Est. Fluid Levels after Cementing 7" x 9-7/8" Casing

Note 1: Centralizer depths, reference Tally Sheet HAL_0010818.
Note 2: Open hole geometry/volume, reference BP-HZN-MBI00136477).
Note 3: Actual volume of fluids pumped from real-time one-second cement unit data.

4. Halliburton OptiCem Cementing Design

4.1. Fluids to be Mixed & Pumped

The Halliburton OptiCem cementing design (HAL_0010988/95) recommended the following sequence of fluids to be pumped:

- 7 bbl of 6.7 lb/gal Base Oil, pumped at 4 bpm, to provide a compatible spacer between the synthetic based mud 14 lb/gal and the following Tuned Spacer III.
- 72 bbl of Tuned Spacer III (TS III) mixed at 14.3 lb/gal, pumped at 4 bpm.
- 5.26 bbl of 16.74 lb/gal unfoamed cap slurry, pumped at 2 bpm.
- 39.1 bbl of 16.74 lb/gal base-slurry, pumped at a constant 2 bpm, at the same time foamed by adding 0.6 gpm Foaming Agent and 583 scf N2/bbl, thus increasing the yield at down-hole pressure to ~48 bbl of foamed slurry, at a density of 14.5 lb/gal.
- 7.2 bbl of 16.74 lb/gal unfoamed cap slurry, pumped at 4 bpm.
- Drop Top Plug.
- Displace 20 bbl of Tuned Spacer III (TS III) mixed at 14.3 lb/gal with cement unit pumps at 4 bpm.
- Displace 857 bbl of 14.0 lb/gal Synthetic OBM with rig pumps at 4 bpm.

4.2. Cement Base-Slurry Formulation

The base-slurry formulation, designed to be mixed at 16.74 lb/gal, was formulated as follows (see Lab Results R/S 73909/1 and 73909/2):

100 %BWOC	Lafarge Class H Cement
0.07 %BWOC	EZ-FL (dry-blending flow additive)
0.25 %BWOC	D-Air 3000 (antifoam agent)
1.88 lb/sk	Potassium Chloride Salt (prevents swelling in water sensitive shales/clays)
20 %BWOC	SSA-1 Silica Flour – PB (prevents strength retrogression over 230 °F)
15 %BWOC	SSA-2 (100-mesh) – PB (prevents strength retrogression over 230 °F)
0.20 %BWOC	SA-541 (over 150°F material yields to improve suspension of solids in slurry)
0.11 gps	ZoneSealant 2000 (foam stabilizer)
0.08 gps*	SCR-100L (cement retarder - non-lignosulfonate type) (R/S 73909/1)
0.09 gps**	SCR-100L (cement retarder - non-lignosulfonate type) (R/S 73909/2)
4.93 gps	Fresh Water

* Several lab tests (see R/S 73909/1) crush compressive strength and rheology, used this concentration of retarder. These same test results were repeated in R/S 73909/2 where only the thickening time and UCA tests had the higher 0.09 gps retarder concentration.

** Concentration used for the cementation.

Antifoam agents such as D-Air 3000 are normally not compatible with foamed cement (possible destabilizing agent). The use of D-Air products is not recommended by Halliburton and this fact is clearly stated in Halliburton's Foamed Cementing Manual (ref. HAL_0046635/50). Thus D-Air 3000 (antifoam agent) should not have been included in the slurry unless rigorous laboratory testing had dictated otherwise. Additionally, potassium chloride (KCl) was included, which is also believed to be incompatible with stable foamed cement. As early as February 16, 2010, stability tests (with 0.2 gps SCR-100L) indicated that the system was unstable when foamed, reference Req/Slurry: US-65112/3.

Omitted from the recipe was a fluid loss agent, which would have provided adequate fluid loss control and helped prevent gas migration.

Both SSA-1 (silica flour) and SSA-2 (100-mesh silica sand), pre-blended in the cement (aka PB), were included in the slurry formulation. Initially it was not clear why this was done, since all of Halliburton's proposals (e.g. HAL_0011047/50 & HAL_0010827/31, and Lab Report HAL_0010868) stated that the BHST was no higher than 210°F. Silica flour/sand at a combined concentration of 35% BWOC is not generally used at BHSTs below 230°F. Other documentation seen subsequently (Halliburton, OptiCem Report, May 12, 2010) showed it to be considerably higher, around 241°F at 18,304 ft, which justified the need for silica flour/sand.

It is important when using silica flour/sand to ensure that it is evenly distributed throughout the cement/silica dry blend. Although it is not an issue when batch mixing the slurry, it can be a factor when mixing on-the-fly. Changes in the cement/silica ratio of dry blended cement can occur, which will alter the retarder to cement concentration, and consequently modify the thickening time and compressive strength development. There was some evidence (HAL_DOJ_0000035 & HAL_DOJ_0000049) that the pycnometer test was run to determine the percent of silica flour/sand in the blend. The result shown is 35.000%. Normally a field sample would be expected to be close to 35%, but to be that exact to three decimal places is quite exceptional. It is also good practice to vary the retarder concentration by +/-5% to check that the slurry design is robust. This is based on field errors not exceeding +/-2.5%.

For laboratory testing, a foaming agent was added to the slurry at a concentration of 1.5% BWOW and the slurry was foamed with air to 14.5 lb/gal.

Although not mentioned in the lab tests (R/S 73909/1 and 73909/2) and OptiCem proposal (HAL_0010988), WellLife-734 was included in the field mixed slurry at a concentration of 1 lb/bbl. WellLife-734 is a glass fiber material developed to improve the tensile strength of set cement and to act when needed as a lost circulation material. It is essentially an inert material and can either be dry-blended with the cement or batch mixed. It should have no effect on the thickening time or compressive strength development. This material was added "by hand to down-hole side", reference HAL_0011047/52.

4.3. Temperature Anomalies – Bottomhole Static (BHST) & Bottomhole Circulating (BHCT)

BHST of this well is understood to be around 242°F at 18,360 ft. Consequently, a BHST of 242°F would normally be the starting point for estimating the BHCT. However rather confusingly, there is some ambiguity in all the pre-job Halliburton documents examined.

Three of Halliburton's 9-7/8" x 7" Production Casing Proposals note that the BHST and BHCT are both 210°F (ref. HAL_0011047/50, HAL_0010827/31, HAL_0010722/26), which are obviously incorrect.

A fourth proposal (ref. HAL_0010241/45) states that the BHST is 210°F and BHCT is 135°F.

Two Lab Results-Primary (ref. HAL_0010868, R/S 73909/1 and R/S 73909/2) give the BHST as 210°F and BHCT as 135°F. Thus, it is assumed that a BHCT of 135°F was used for the thickening time tests.

For a critical cementation such as this one, there should have been a temperature simulation run to determine the BHCT. There was no evidence or mention of this in any of the reports, but it is assumed that one must have been run to determine a BHCT of 135°F. However, if a BHST of 210°F was used in the simulation, then the resulting BHCT would probably have been 15°F to 30°F lower than if the correct BHST temperature had been used. This would certainly have affected the required retarder concentration. In the case of a slurry system exhibiting an inverse temperature effect, taking a lower BHCT for the thickening time test would effectively extend the thickening time, due to more retarder being required, see Figure 3.

In temperature simulations to determine the BHCT (see Figure 4), a volume of mud (corresponding to the conditioning mud phase prior to the cementation) would be "pumped" ahead of the cementing system to cool the well. There was no evidence that this volume was determined, and if so, that BP was advised of it.

Subsequent data seen, reference OptiCem Wellbore Simulator Report BP-HZN-MBI00136477 Section5.8.4 (12 May 2010), shows the casing and annulus temperature profile, but the temperature from surface to 135°F (BHCT) and back to surface is completely linear. There is no cooling effect over the first and last 5,000 ft as would be expected from a temperature simulation run in a deepwater well, where the water temperature is ~40°F from a depth of ~2,000 ft to sea bed.

4.4. Rheology & Mud Removal

Inconsistencies in the testing temperatures were noted for the Fann-35 laboratory tests (HAL_0010988/96-97).

Test temperatures were for: a) mud - 40°F, 100°F, 150°F; b) base oil - 75°F, 120°F, 150°F; c) base-slurry of 16.74 lb/gal - 80°F and 135°F; and d) foamed cement at 14.5 lb/gal - 80°F.

Rheology of Tuned Spacer III (TS III) was given as PV 51.98 cP and YP 30 lbf/100ft^2, **at both 80°F** (HAL_0010988/97) **and 190°F** (HAL_0010988/99-00). This cannot be correct, as the viscosity decreases with increasing temperature, and begs the question as to whether the correct rheology was used in their OptiCem mud displacement program.

The OptiCem program assumed a BHCT of 135°F (i.e. temperature of the cement thickening time tests), thus the rheology readings for all fluids should have been made at this temperature for the OptiCem displacement program to be valid.

For the base oil, a Newtonian fluid, its rheology was calculated using the Herschel-Bulkley model with 6 readings (HAL_0010988/96). It should also be noted that the last four readings 200, 100, 6, and 3 were near identical, due to an inappropriate rotor-bob-spring configuration being used.

On the Macondo Foamed (Base) Slurry – 16.74 lb/gal (Class H) at 80°F, the 60 rpm reading of 26 could have been recorded in error (HAL_0010988/97). To fit the rheological model, the reading should be nearer 18. The 600 readings at 80°F and 135°F also appear to be in turbulent flow and as such should be discarded from the rheological calculation.

The mud rheology was given as PV 23.83 cP and YP 6.27 lbf/100ft^2 (HAL_0010988/99-00, but no temperature was stated at which the readings were taken. The mud rheology at the time of cementing was PV 28 cP and YP 15 lbf/100ft^2 at 150°F (reference M-I SWACO Mud Report #79, HAL_0011194).

At 4 bpm, the rate at which the job was designed and executed, the mud (14.17 lb/gal), TSIII spacer (14.3 lb/gal) and base-slurry (16.74 lb/gal) would have been in laminar flow, thus the displacing fluid should always be more viscous and have a higher density than the displaced fluid. This was the case in respect of the spacer displacing mud, but not for the base-slurry displacing spacer.

Fann-35 readings are reported (HAL_0010988/99-00) for mud, base oil, base-slurry 16.74 lb/gal, and foamed cement 14.5 lb/gal. No readings are reported for Tuned Spacer III (TS III) and it is not clear why such data was missing on this important fluid in the displacement process.

Based on the rheologies given, the TS III spacer should have been effective in removing the mud where the casing was properly centralized (standoff >80%); the base-slurry viscosity was less than that of the spacer, but its density was considerably higher, so quite probably it also should have been effective. The base oil (6.7 lb/gal) should have been in turbulent flow due to its low viscosity so again, where the pipe was properly centralized, displacement efficiency should have been good. However, the possibility of the base oil intermixing with spacer would thin its rheology and possibly increase the potential for the spacer channeling through mud.

One of the difficulties with foamed cements is laboratory testing in field cementing labs. Rheology tests can only be conducted at atmospheric pressure and temperatures up to 180°F, due to higher levels of water evaporation above this temperature compromising the result. API states that the rheological readings may be suspect for a foamed cement slurry tested with a rotational viscometer, as separation of gas from the slurry can cause erroneous results, reference API RP 10B-4 Section 10.4.

For testing foamed cements, Halliburton uses an adaptor on the Fann-35 known as the Fann Yield Stress Adaptor (FYSA) which permits a direct measurement of the yield point. It is claimed that this device shows that the viscosity of foamed cement is higher than that of the base-slurry, thus helping to improve displacement efficiency. However, the increase in viscosity for foam qualities below 30% is disputed in the study of the rheology of foamed cements generated under different pressures.

Published tests conducted under pressure (Rheology of Foamed Cement by R.M Ahmed et al. (2009)) indicate:

- Low foam quality (<30%) cement slurries have less viscosity than the base-slurry. This brings into doubt the general belief that foam cements provide better drilling fluid displacement than non-foamed cements, unless the foams have different extensional viscosity properties than conventional cement slurries.
- Cement foam viscosity increases as the quality increases from 10% to 30%.
- Rheology data of the base-slurry best fits the Power Law rheological model. However, the rheological measurements of the cement foams at low shear rates indicate the presence of a yield stress.

In conclusion, for mud removal and effective displacement of fluids under laminar flow conditions (4 bpm):

- The rheological properties of Tuned Spacer III were well matched to effectively displace the SOBM (Mud).
- The base-slurry's (16.74 lb/gal) viscosity was less than that of Tuned Spacer III, so channeling and cement spacer contamination was probable, though the base-slurry's

higher density would have helped stabilize the interface. Contamination of the cement slurry with spacer would probably further lengthen the setting time of the cement. *(Note: This could be confirmed by thickening tests of the base cement slurry contaminated with varying percentages of spacer).*

- The lower viscosity of foamed cement and its lower density than the base-slurry ahead of it, create the conditions for channeling and mixing to occur, even in well centralized sections. However as mentioned above, there is a belief among advocates of foamed cement that it has better displacement properties than non-foamed cements.

4.5. Rheology of Base-Slurry

The rheology of the base-slurry (PV 54.7 cP and YP 2 $lbf/100ft^2$) was possibly too low on two fronts. For laminar flow displacement, the displacing fluid (base-slurry) should be more viscous than the displaced fluid (spacer). This was not the case, and could lead to the displacing fluid bypassing the displaced fluid on the wide side of the annulus. Secondly, a yield point (YP) of 2 $lbf/100ft^2$ is probably too low for generating a stable foam slurry. Higher YPs, over 5 $lbf/100ft^2$ are preferred, reference BP's Deepwater Horizon Accident Investigation Report of September 10, 2010 - Appendix K. Laboratory Analysis of Cementing Operations on the Deepwater Horizon (from CSI Technologies) – page 3. Post-job laboratory testing by Chevron indicated that foamed cement stability was an issue.

4.6. Foamed Cement Density Change after Placement and Nitrogen Ratio

A particular issue with foamed cement is the uncertainty of its final density immediately prior to setting, as this can have an effect on well control in a critical cementation where there is only a small safety margin between well control and losses. The density of foamed cement will decrease after placement.

Figure 2 shows that after placement at the BHCT of 135°F there will be 0.2 lb/gal decrease in density (if slurry still liquid) as the cement heats up to Halliburton's "BHST" of 210°F. The density decreases due to gas expansion as the temperature increases at a constant pressure. These calculations are based on a 16.74 lb/gal base-slurry and a nitrogen ratio of 584 scf/bbl, and Nitrogen Tables giving SCF (standard cubic feet) of Nitrogen per Barrel of Space, reference DS Field Data Handbook, TSL-0538. The pressure at the top and base of the foamed cement column after placement is estimated to be ~12,800 psi and ~13,500 psi respectively.

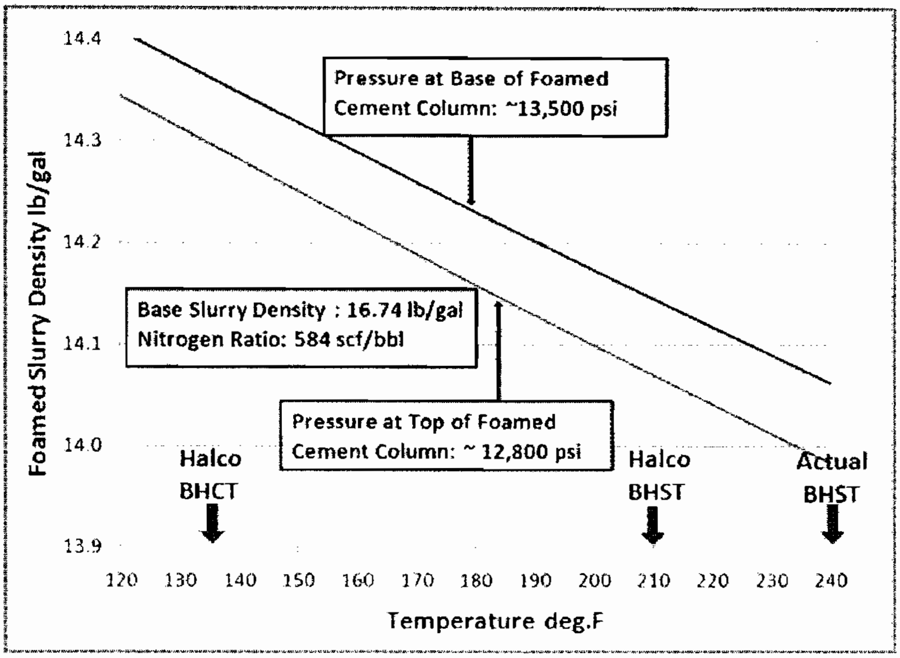

Figure 2: Foamed Cement Slurry after Placement – Density Change with Temperature and Pressure (at 13,500 and 12,800 psi), at a Nitrogen Ratio of 584 scf/bbl

This graph highlights the importance of running temperature simulations prior to the job, to estimate both the BHCT (for thickening time testing to determine the correct retarder concentration) and for the temperature ramp-up after placement. The ramp-up temperature rate can then be used in conjunction with a UCA to help determine the temperature at which the slurry will initially set. From this result, a better estimate can be made of the foamed cement setting temperature in order to calculate the correct ratio of N2 to add per barrel of base-slurry. There is no evidence in the Halliburton pre-job reports that this was done.

To achieve a foamed cement density of 14.5 lb/gal, with a 16.74 lb/gal base-slurry at a down-hole pressure of 13,500 psi at 160°F, the nitrogen requirement would be 523 scf/bbl, and at 200°F it would be 494 scf/bbl. Knowing the setting temperature of the base-slurry is therefore critical in deep wells with a high BHST, in this case around 240°F.

Halliburton's Lab Results (R/S 73902/2) state that the foamed cement density is 14.5 lb/gal as does their Post Job report (HAL_0011210/11-12). However, when examining their Casing Design Report (HAL_0010988/08-09) it indicates that the density varies from 14.29 lb/gal at the top of foamed cement column to 14.44 lb/gal at base. Furthermore, it is not stated what temperature is used for the calculation. From Figure 2, it appears that the temperature would have to be below 120°F to achieve a foamed cement density of 14.5 lb/gal (with a N2 ratio of 584 scf/bbl).

Note: Generally, when designing a foamed cement job, a target value of 14.5 lb/gal would indicate the average density of the foamed cement column, i.e. the column would be lighter at the top and heavier at the bottom.

Further examination of the data highlights a number of inconsistencies with respect to nitrogen concentration in several Halliburton reports:

(A) Production Casing HAL_0011047 (18 April 2010)

(B) Production Casing Design Report HAL_0010988 (18 April 2010)

(A) states that the N2 ratio should be 521.1 scf/bbl (HAL_0011047/54) to give a down-hole slurry density of 14.5 lb/gal, with a mud density of 14 lb/gal.

(B) states that the N2 ratio should be 583.4 scf/bbl (HAL_0010988/02) to give a down-hole slurry density of between 14.29 lb/gal (foamed cement top) and 14.44 lb/gal (bottom) (HAL_00 10988/08-09 respectively), with a mud density of 14.17 lb/gal *(Note 1).*

Thus, it appears that the N2 concentration used on the job (584 scf/bbl) may have been too high to achieve an average slurry density of ~14.5 lb/gal. The density would have been somewhat lower, 14.29 lb/gal to 14.44 lb/gal as predicted in (B), *Note 2.*

Note 1: Effective mud density of 14.17 lb/gal was derived from PWD (Pressure (monitoring) While Drilling).

Note 2: OptiCem is understood to predict higher foamed densities due to the program using dynamic pressures for compressibility calculations and allowing for mud compressibility. This difference can lead to foam cement density predictions in this particular case being up to 0.2 lb/gal heavier than by conventional calculation.

4.7. Foamed Cement Depth & Volume in Production Casing Design Report HAL_0010988 of April 18, 2010

Based on the hole diameters tabled in Well Geometry (HAL_0010988/94) and 38.98 bbl of base-slurry (HAL_0010988/95), producing 48 bbl of foamed slurry (down-hole volume), the annular length will be just over 900 ft based on 100% displacement efficiency.

However, Halliburton (HAL_0010988/06) reported the length of the foamed cement column as 1,952.1 ft with the top being at 16,352.9 ft. Whilst this might appear incorrect by a factor of two, it is understood that OptiCem makes this prediction based on the displacement efficiency being less than 100%, with some of the cement by-passing the mud due to poor centralization and washouts in the open-hole section, reference BP-HZN-BLY00139698/703.

BPs document entitled "Deepwater Horizon Accident Investigation Report" of 8 September 2010 gave the depth of top of cement column at 17,260 ft (page 14), i.e. a column length of 1,044 ft (100% displacement efficiency).

Based on Wellbore Geometry, BP-HZN-MBI00136477, our own calculation gives a total cement column length of 1027.1 ft; 11.9 ft for 0.37 bbl "shoe" cement, 909.4 ft for 48.7 bbl of foamed cement and 105.8 ft for 5.4 bbl of cap slurry.

4.8. Thickening Time

The thickening time test of the base-slurry (retarder concentration SCR-100L of 0.09 gps), at BHCT 135°F and 14,458 psi, shows an excellent (i.e. very short) transition from fluid to solid (right-angle set) between 7:30 and 7:40 (Lab Results R/S 73909/2).

An earlier thickening time test with a retarder concentration of 0.08 gps gave a thickening time of 5:30 (to 70 Bc) (Lab Results R/S 73909/1).

The job was executed with SCR-100L at 0.09 gps. Placement time was 4:30, indicating a safety factor of 3 hours.

Note: Lab Results (R/S 73909/2) with retarder SCR-100L concentration 0.09 gps includes:

- *Test ID's 806075 and 806076 giving rheology of base-slurry at 80°F, and 135°F. Both these tests are with 0.08 gps SCR-100 retarder.*
- *Test ID 806069 for crush compressive strength of foamed cement (with 0.08 gps SCR-100 retarder).*
- *These Test ID's are identical to those reported earlier in Lab Results R/S 73909/1 with 0.08 gps SCR-100 retarder. Though one would expect only a small change in the rheology results, there would be a significant increase in the time for the foamed cement to set and develop compressive strength. This lower retarder concentration should have been noted on the report by Halliburton, particularly with respect to the crushed strength test.*

Note: It is unclear why Halliburton used a pressure of 14,458 psi for their thickening time (and UCA) tests, as the maximum circulating pressure did not exceed ~14,100 psi during placement, see OptiCem graph, **Figure 6**. *The static pressure after placement was ~13,500 psi.*

4.9. Compressive Strength – Foamed Cement

At 180°F the 24-hour compressive strength was ZERO. Only at the 48-hour test did it show significant compressive strength, 1590 psi (Table 1).

This test was run with a lower retarder concentration (0.08 gps) than that used on the job (0.09 gps), thus the compressive strength development will be even slower than indicated.

Crush Compressive Strength Request Test ID 806069

Curing Temp (°F)	Time 1 (hrs)	Strength 1	Time 2 (hrs)	Strength 2	Time 3 (hrs)	Strength 3	Foam quality
180	12	0	24	0	48	1,590	0

Condition for 1.5 hrs, Foamed to 14.5 ppg

Table 1: Crush Compressive Strength Development of Foamed Cement (Test ID 806069)

Note 1: Table 1 states foam quality is 0, when it should read ~13.4%. However, down-hole at ~13,500 psi the foam quality will be ~19% for a 14.5 lb/gal density. Thus, for an equivalent compressive strength test at atmospheric pressure, the foamed slurry density should be ~13.6 lb/gal.

Note 2: Crush compressive strength testing was not performed by Chevron due to foam instability.

Moreover, without any other evidence to the contrary, the time waiting-on-cement to set (WOC) should have been considerably longer than it was before putting any confidence in the cement seal. The negative test took place 17 hours and 50 minutes after the cement was in place. The explosion on surface occurred around 21 hours and 25 minutes after the cement was in place. This indicates that the cement was probably not set.

The extended setting time, in excess of 24 hours at 180°F, might appear odd compared to thickening time of 7:40 at 135°F BHCT. However, in the low temperature range below 200°F, it is often observed that many cements exhibit an inverse temperature effect with respect to thickening time (i.e. shorter thickening time at a lower temperature), when a retarder is present in the slurry.

The severity of the phenomenon and peak temperature when the maximum thickening time is reached is also cement brand related, and peaks in roughly the 180°F to 200°F range.

An unpublished study in 1994 with different brands and batches of cement showed this inverse temperature effect. One of the brands of Class G cement tested, mixed at 16 lb/gal with 0.05 gps of retarder, demonstrated this effect and showed that there was some batch-to-batch variation, see Figure 3. During this study with another brand of cement, the peak temperature reached was 200°F.

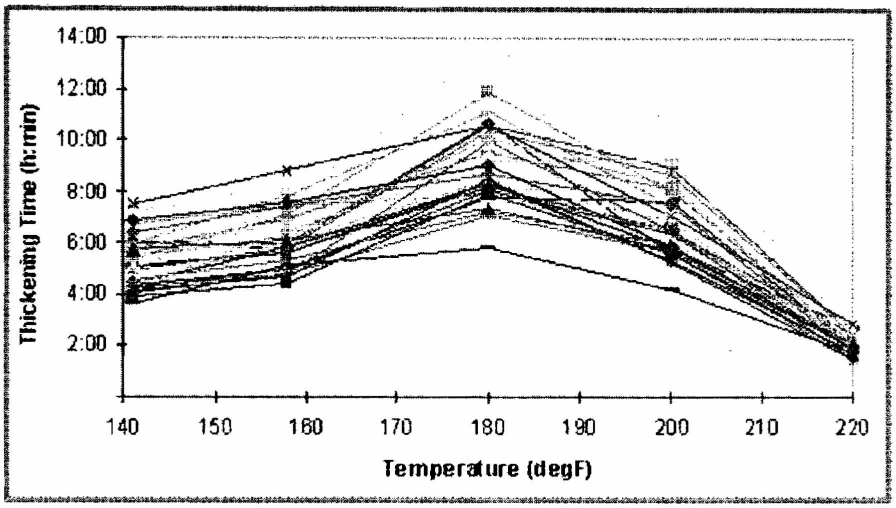

Figure 3: Thickening Times with Different Batches of Same Brand of Class G Cement with 0.05 gps Retarder Mixed at 16 lb/gal, demonstrating an inverse temperature effect with respect to thickening time.

These unexpectedly long thickening times in the range ~160°F to ~190°F have been noted and fully analyzed in SPE 23073 – Retardation of Cement Slurries to 250°F by J. Bensted. He explains that "the cause of the threshold effect has been found to be a surge in the hydraulic reactivity of the ferrite (C4AF) phase from the Class G cement. The hydration products thus formed, mostly AFt phase or ettringite C3(A,F).3CaS04.31-32H20, are deposited on the hydrating clinker surfaces, and in particular impede the hydration of the main cementitious alite (C3S) to calcium silicate hydrate (C-S-H), the initiation of which is the prime cause of cement thickening. As a result, thickening time is extended and not diminished. However, as the temperature rises above ca. 190°F, the increased hydraulic potential of the cement manifests itself. There is no longer an increased surge in ferrite phase hydration to obstruct C-S-H formation, so the C3S hydration rate rises again, culminating in lower thickening times once more".

Note: There are no chemical differences between Class G and Class H cements; Class H cement was used in Macondo #1. Class H cement is simply more coarsely ground and requires less water; 38% for Class H and 44% for Class G.

The thickening time tests should be re-run at say 150°F and 170°F to investigate whether this was the cause of the extended time taken for the foamed cement to set.

4.10. Compressive Strength – Un-Foamed Cement

An Ultrasonic Cement Analyzer (UCA) was used to evaluate the compressive strength of Lead and Shoe Track slurry (un-foamed cement). The test (ID: 811522) was conducted with 0.09 gps SCR-100L retarder at 14,458 psi and with a 4-hour heat-up time from 135°F to 210°F. Results indicated that 500 psi compressive strength was reached in 8:40 (h:min) and 2,300 psi in 12 hours (see Table 2).

UCA Comp. Strength, Request Test ID:811522

End Temp (°F)	Pressure (psi)	50 psi (hh:mm)	500 psi (hh:mm)	12 hr CS (psi)	24 hr CS (psi)	48 hr CS (psi)
210	14,458	08:12	08:40	2,301	2,966	3,099

Circulate before pouring C.S. for 3 Hrs

Table 2: Compressive Strength Development of Un-Foamed Cement

Ideally this test should also be run at the temperature and pressure at the top of cement, under conditions prevailing at the anticipated time of the negative test.

A temperature simulation of the well heat-up after cementing would have been a useful guide for selecting a more appropriate temperature for the UCA test. The insulating properties of gas will also increase the bounce-back time to static conditions. Figure 4 illustrates that there will be a certain time delay between the temperature at the end of the cementation (i.e. the BHCT) and the temperature at which the cement sets.

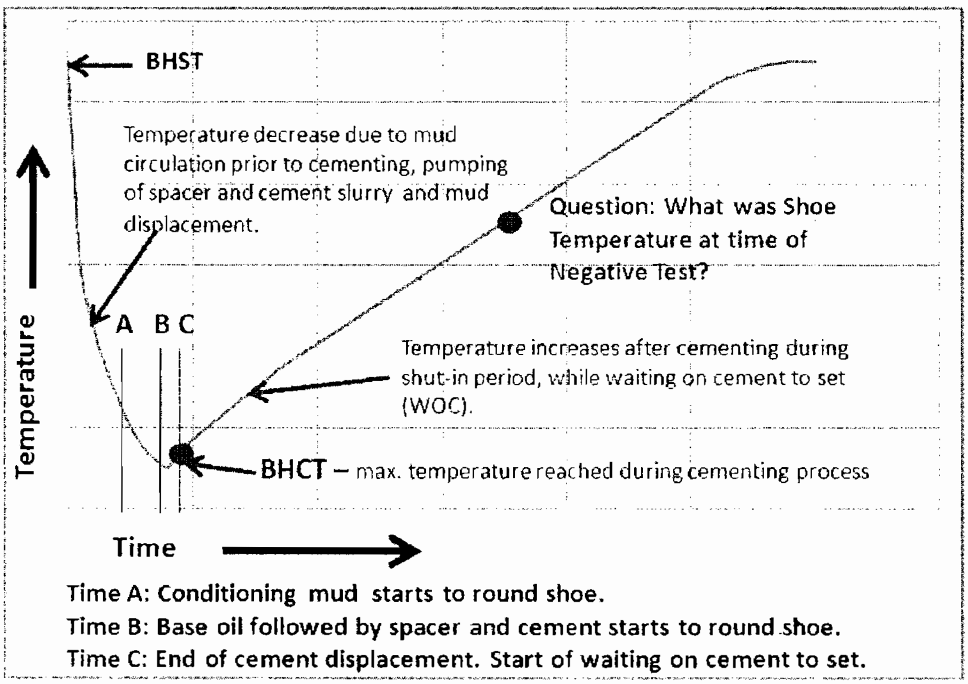

Figure 4: Example Graph of Temperature History at Shoe showing Prediction of BHCT and Temperature Increase after Mud Circulation & Cementing

Based on the temperature history simulation, a better estimate of the temperature ramp can be obtained to run UCA compressive strengths. Tests should be re-run as it appears very likely that the cement was still un-set at the time of the negative test.

The UCA tests carried out by Chevron, to confirm Halliburton's laboratory test data, replicated the 4-hour heat-up rate to temperature, rather than follow a heat prediction and a final temperature derived from a temperature simulator. This would have ascertained more accurately the true state of the cement at the time of the negative test.

Similar graphs showing the temperature history at the shoe are depicted in SPE 39315 - Determination of Wells Drilled in Deep Water by D.G. Calvert and T.J. Griffin, Jr. They are also referenced in Well Cementing (Erik Nelson).

Had this been done ahead of the job, the cementing service engineer would have been in a better position to advise the Operator (BP) when it would be safe to run a negative well test. Additionally, the same set time and temperature would have allowed a more accurate calculation to be made of the nitrogen ratio required to achieve the down-hole target density, and verify that any reduction in density of the foamed cement after placement was safe from a well control stand-point.

4.11. Spacer/Mud and Cement/Spacer Compatibility Tests (Test Partially Performed)

When two fluids (e.g. spacer and mud) are mixed together in different ratios, the resulting viscosity of the mixture must be somewhere between the two initial viscosities for the fluids to be judged compatible. The procedure for these tests is documented in Section 16 of API 10B; the fluid ratios being prepared according to Table 14 in said API document.

This test is particularly important with oil-based-muds as they can destabilize foamed cement. Similarly, the surfactants used in spacers to enhance their compatibility with oil-based-mud can also have a detrimental effect on foamed stability.

From the documentation seen to date, compatibility tests were run only between mud and spacer (using unrepresentative samples), reference Cement Lab Weigh-Up Sheet, April 7, 2010 – Req/Slurry: US-72908/2. There is no evidence that compatibility tests were run between spacer and cement.

From the sole test run, the following observations are made:

- Mud density given as 14.4 lb/gal was denser than the mud in the well during the cementation, 14.0 lb/gal. M-I SWACO's Mud Report (19 April 2010) of their 14 lb/gal mud gave Fann-35 readings (600 / 300 / 200 / 100 / 6 / 3) at 150°F of: 70 / 43 / 32 / 20

/10 / 9. Halliburton's Weigh-Up Sheet US-72908/2 of 14.4 lb/gal mud gave Fann-35 readings (600 / 300 / 200 / 100 / 6 / 3) at 140°F of 120/ 76 / 60 / 40 / 10 / 9. Therefore, the mud densities and rheologies were quite different – the mud tested was more viscous than the one at the wellsite. Normally, a rig (wellsite) sample would be used for the test. It was not stated on the Weigh-Up Sheet whether the mud sample was a wellsite sample or a lab mixed sample.

- The spacer was mixed at 15 lb/gal for this compatibility test; for the job it was 14.3 lb/gal.
- For the mud and spacers tested, it would appear that they were reasonably compatible, except for the Mud/Spacer ratio of 25/75 at 80°F when the readings of 600 rpm and 300 rpm were outside the compatibility envelope.
- At 140°F, the fluids tested are fully compatible.
- Missing from this compatibility report are the readings for 95%Mud/5%Spacer and 5%Mud/95%Spacer. These ratios are recommended by API and should be standard procedure for most cementing laboratories; see API RP 10B, Table 15 on page 119. Often a small percentage of contamination can create incompatibility.

Note: Again there seems to be some confusion concerning the BHST in this well. Report (Req/Slurry: US-72908/2) states under Test Conditions that the BHST is "-18°C / 0°F"! The stated MD of 19,650 ft may have been anticipating the expected final depth of the well, hence the heavier mud and spacer fluids tested.

Normally, one would have expected Halliburton to have re-run the tests prior to the job with a wellsite sample of 14 lb/gal mud and their recommended 14.3 lb/gal spacer, at the predicted BHCT of 135°F.

4.12. Base Oil 6.7 lb/gal (Flush)

A low density (6.7 lb/gal) 7 bbl base oil flush was proposed and pumped between the mud and spacer. This is an inexpensive way of ensuring good compatibility between mud and spacer. However, it can compromise the design when there is only a small window between pore and frac pressures (ECDs), and in such cases it should be avoided.

If pumping is stopped for any reason just as the base oil is pumped across the 14.1 lb/gal brine sand (17,710-17,730 ft), the hydrostatic pressure will drop below the pore pressure, allowing the well to flow. It should be noted, however, that this condition is rectified as soon as the following denser fluids, spacer and cement slurry, cross this sand. Nevertheless, it is an unsafe feature in the overall job design, and in this case could have been avoided by pumping a spacer fully compatible with the mud.

An additional drawback of including the base oil (and quite detrimental to the outcome) was that it reduced the end-of-job hydrostatic pressure by 42 psi, further ensuring that there was less annulus pressure to produce back-flow, to confirm whether the float collar had converted.

4.13. Foamed and Base-Slurry Stability

API RP Spec 10B-4 recommends stability testing for both **unset foamed cement** after leaving the samples for 2 hours at room temperature, ~80°F, and for **set foamed cement** after curing the samples at 180°F until they are set.

In addition to above API test, BP developed the BP Settling Tester, a simple but effective piece of equipment developed some years ago at their Engineering and Research Centre (Sunbury, UK). To pass the test, the density variation, of the set sample, from top to bottom should not be greater than 0.4 lb/gal, and overall shrinkage less than 5 mm.

From the evidence available, the sole foam mix and stability test run (Table 3) indicates that there were issues concerning the foam stability of the slurry. The slurry foamed in 8 seconds, which is within API requirements of 15 seconds or less for slurry to foam. However, it appears that the slurry foamed to 14.5 lb/gal was measured top and bottom at SG 1.8 (15 lb/gal). If the test had been mixed in error at 15 lb/gal, a repeat test should have been performed at the correct density. Obviously, the denser the slurry, the more likely it will be stable.

Note: It is assumed that this test is with unset foamed cement as the curing temperature is not stated.

Foam Mix and Stability, Request Test ID:813603

Time to Foam (Sec)	SG top	SG bot.	Conditioning time (hrs.min)
8	1.8	1.8	03:00

Table 3: Stability Test of 14.5 lb/gal Foamed Cement

There is no evidence that an API recommended test was run with foamed cement, cured at 180°F until set.

Various tests also run by Chevron using the same design parameters as the Halliburton production casing slurry, were unable to obtain a stable foamed cement.

There is no evidence that a stability test was run for the base-slurry.

Note: Earlier laboratory testing in February (reference US-65112/3) with 0.2 gps SCR-100L retarder indicated that serious foam stability issues existed. Foam Mix & Stability Tests of a 14.5 lb/gal foamed slurry gave top and bottom SG readings of 1.91 (15.9 lb/gal) and 1.9 (15.8 lb/gal) in one test and 2.02 (16.8 lb/gal) and 2.11 (17.6 lb/gal) in another. Base-slurry rheologies at a) 80°F, b) 130°F and c) 190°F were a) PV 61 cP and YP -3.5 lbf/100ft^2, b) PV 29 cP and YP -1.5 lbf/100ft^2, and c) PV 107 cP and YP -1.8 lbf/100ft^2 respectively; a negative YP is also indicative of an unstable slurry.

One of the difficulties of this system may have been the addition of 15% BWOC SSA-2 (100-mesh sand) to the cement dry blend, making it difficult to produce a stable system. Generally, SSA-2 (100-mesh sand) is substituted for SSA-1 silica flour only to give better rheological properties to higher density slurries (17 to 20 lb/gal, weighted with barite or hematite), thereby giving the slurry more fluidity.

4.14. Fluid Loss (Test Not Performed)

No fluid loss test seems to have been run. For a critical cementation such as this one, a fluid loss of <50 mL/30 min would be expected in the base-slurry, particularly when a severe gas flow problem has been identified, HAL_0010988/05.

Although foamed cement exhibits relatively good fluid loss properties (supposedly around 300 mL/30 min – impossible to measure with standard cement laboratory equipment), the base-slurry itself does not exhibit even these properties unless it contains a fluid loss additive.

Thus a fluid loss additive should be included in the base-slurry design to provide fluid loss control in the lead cement, and to any additional un-foamed slurry resulting from foam destabilization.

Alternatively, the preferred option: a batch-mixed low density, high strength, particle-matched slurry, without the need of nitrogen addition to achieve a density of 14.5 lb/gal, would exhibit a very low fluid loss, <50 mL/30 min. Such a slurry could have been designed with a more viscous rheology than that of the spacer, thereby preventing the 14.5 lb/gal cement channeling through the spacer.

Note: Two fluid loss tests, subsequently carried out by Chevron with Halliburton additives, showed that the fluid loss of the base-slurry was in one case 456 mL/30 min and in another 578 mL/30 min, which are significantly above 50 mL/30 min.

4.15. Free Fluid (Test Not Performed)

None reported. The purpose of this test is to determine the static stability of a cement slurry, reference API RP 10B, Section 15. Both the free fluid result and the sedimentation result are required to understand the static stability of the slurry under downhole conditions. Free fluid can be formed with minimal sedimentation and sedimentation can take place without free fluid forming. Therefore, both results must be evaluated to determine slurry stability.

Note: Subsequent Chevron tests after HPHT conditioning gave results of 1.6% and zero free fluid in two separate 90°-vertical tests, and 2% and "channel present" in two separate free fluid 45°-angle tests, indicating that there are issues with the slurry stability. Normally, the reading to pass the 90°-vertical test should be either "zero" or a "trace"; 1.6% is too high, thus the test should have been repeated to determine which was the rogue result.

4.16. Centralizers

Halliburton's original program called for running 21 centralizers, but after consultation with BP this was reduced to 6. The Daily Operations Report and Drilling Report did not state at what depths they were run. However, correspondence from Brian Morel to Jesse Gagliano dated of April 15, 2010 indicated depths should have been circa 18,300 ft, 18,253 ft (47 ft above), 18,160ft (93 ft), 18,113 ft (47 ft), 17,974 ft (139 ft), 17,835 ft (139 ft).

Halliburton's Section 4 of their OptiCem Report on Centralizers was not consistent on the size of centralizer proposed:

- Report April 18 (page16 / HAL_0010988/03): 7 centralizers of 8.5 (section 4.4).
- Report April 15 (page 15 / HAL_0010699/13): 6 centralizers of 8.5 and 15 of "Macondo") (section 4.4)
- Report April 15 (page 13 / HAL_0010592/04): 4 centralizers of 8.5 and 6 of 9.875 (section 4.4)

As the hole size was 10 to 11 inches at depths shallower than 18,107 ft (ref. HAL_0010988/94), it is surprising that a larger sized centralizer was not proposed. The 8.5 centralizer size would have been unsuitable.

In fact, the Weatherford 7" 541R Centralizer was used. It has a large bow size of 10-3/4" OD. Thus, it is very probable that the centralization was good, around 80% or better below 17,882 ft. This would be expected in a near vertical hole, with this number of centralizers and spacing - six in all, at the depths given in Tally Sheet HAL_0010818, Figure 5. This should have ensured good mud removal over the lower centralized interval, and good cement coverage with minimal channeling (i.e. an effective hydraulic seal), assuming uncontaminated cement was reaching the shoe.

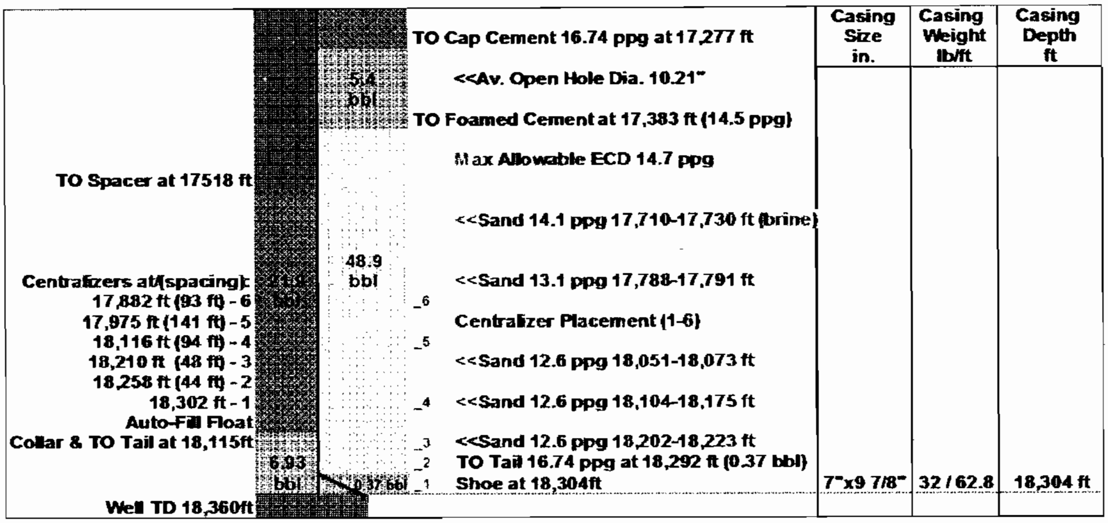

Figure 5: Centralization Depths - Centralizer Depths, reference Tally Sheet HAL_0010818

However, above 17,882 ft to top of cement, the casing would be resting largely on the bore-hole wall and as a result, there will be channeling, cement contamination, and practically no hydraulic seal after the cement is set.

A post-job simulation report (reference BP-HZN-MBI00133443) with Weatherford centralizers shows that over the centralized interval, stand-off is generally very good and mostly above 80%. However, the centralizer depths given are not the same as per their Tally Sheet. Instead the centralizers are positioned at 18,279.0, 18,233.2, 18,187.4, 18,139.9, 18,044.1, 17,904.8 ft. See Table 4.

Part No.	Type	Spacing Between Centralizers (ft)	Measured Depth (ft)	Hole Deviation (°)	Hole Azimuth (°)	Actual Standoff (%)	Static Tension (lbf)
1366204	Bow Spring	45.8	18,279.0	0.50	37.43	87.14	0.0
1366204	Bow Spring	45.8	18,233.2	0.56	39.93	86.85	1,146.9
1366204	Bow Spring	47.6	18,187.4	0.66	36.42	92.37	2,293.7
1366204	Bow Spring	95.7	18,139.9	0.74	35.89	66.10	3,456.4
1366204	Bow Spring	139.3	18,044.1	0.64	24.38	66.31	5,885.4
1366204	Bow Spring	0.0	17,904.8	0.45	23.00	70.00	9,070.4
			17,857.0			70.00	
			17,837.0			40.00	
			0.0			40.00	

Table 4: Data from OptiCem Wellbore Simulator Report of 5/11/2010 – BP-HZN-MBI00133443

4.17. Exceeding Fracture Pressure

The OptiCem Circulating Pressure and Density Plot (HAL_0010988/12) indicated that the Fracture Pressure at 18,189 ft was exceeded by over 400 psi, indicating that the displacement rate of 4 bpm should have been reduced for the last ~50 bbl of displacement to avoid possible losses (see Figure 6).

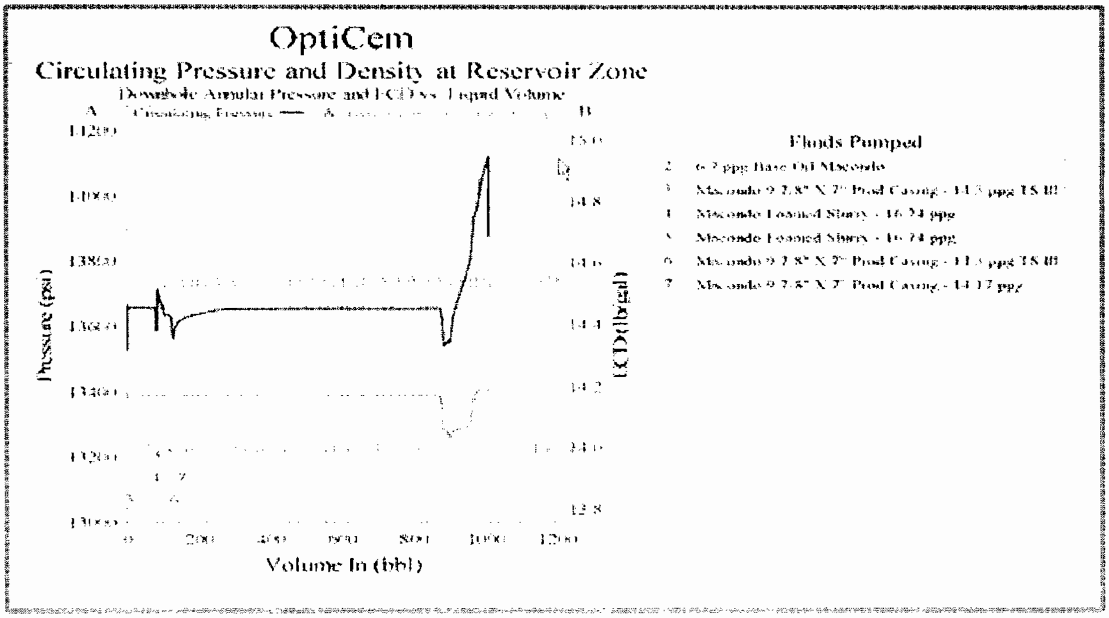

Figure 6: Fracture Pressure Exceeded at 18,189 ft

A reduction in the pump rate from 4 bpm to 2 bpm would have reduced the ECD by around 0.2 lb/gal in the annulus. Lowering the pump rate towards the end of displacement is considered good practice, being particularly relevant in this case where the OptiCem simulation indicates the likelihood of fracturing.

5. Actual Job Execution – as per BP's Daily Operations Report

As per the Daily Operations Report, the actual execution including the pre-cementing mud circulation was reported as follows:

- Break circulation and stage pump up to 4 bpm and circulate 211 bbl mud (*Note – see below*).
- Pause of 27 minutes.

- Break circulation again and stage pump up to 4 bpm and circulate 111 bbl mud.
- Pause of 22 minutes to hold pre-job cement meeting.
- Pressure tested Halliburton N2 lines to 5000 psi.
- Halliburton pumped 7 bbl of 6.7 lb/gal base oil, and 10 bbl of 14.3 lb/gal spacer (Tuned Spacer III), tested lines to 5000 psi (good test).
- Pumped 62 bbl spacer (Tuned Spacer III) at 4 bpm.
- Monitor well on trip tank, well static.
- Performed cement job as follows;
    - Pumped 4 bbl 16.74 lb/gal Class H cement, at 2 bpm.
    - Drop Dart #1 on the run.
    - Pumped 4 bbl cement at <2 bpm.
    - Started pumping N2- pumped 39 bbl cement – foamed volume 48 bbl.
    - Pumped 4 bbl cement.
    - Pumped 3 bbl 14.3 lb/gal (Tuned Spacer III).
    - Drop dart #2 on the run.
    - Pumped 17 bbl spacer (Tuned Spacer III) at 4 bpm.
    - Pumped 133 bbl of 14 lb/gal mud with cement unit at 4 bpm.
    - Bottom dart to diverter; 3,500 psi sheared at 43 bbl mud pumped.
    - Bottom dart to DTD: 3,250 psi, DTD sheared – 150 bbl mud pumped, bottom dart to plug: no indication of plug shear, top dart to diverter: 3,200 psi top plug shear at 100 bbl mud pumped, top dart to DTD: 3,400 psi DTD shear 109 bbl mud pumped, top dart to plug 3,300 psi shear at 119 bbl mud pumped.
    - Switched to rig pumps.
    - Displaced cement with 14 lb/gal mud with rig pump at 4 bpm at 530 psi. Indication bottom plug through crossover with 800 psi and 469 bbl.
    - Monitored active system for gains and losses.
    - Continued displacing cement with 727 bbl of 14 lb/gal mud.
    - With 4,155 stks/523 bbl, top plug went through x-over with 590 psi.
    - Bottom plug landed with 673 bbl pumped at 2,932 psi.
    - With 727 bbl pumped, bumped top plug with 740 psi over circulating pressure.
    - Bled pressure off, bled back 5 bbl, floats holding, cement in place at 12:35 am (4/20/2010).

Note: Up to this point, the well had not been circulated for around 77 hours. All the cement thickening tests assumed a BHCT of 135°F. There was no evidence that a temperature simulation was run to ascertain what the circulation temperature would be after pumping just 346 bbl of mud (volume of mud pumped between float collar conversion and start of cementation), and what minimum volume of mud needed to be pumped at 4 bpm to lower the BHCT to 135°F. It should also be noted that circulating bottoms up (in this case ~2,750 bbl), or at least a casing volume plus 20% (~1,000 bbl), is considered good practice prior to cementing.

More recently, API RP 65 Part 2 (May 2010) recommends that "at a minimum, the hole should be conditioned for cementing by circulating 1.5 annular volumes or one casing volume, whichever is greater." In any event, a sufficient volume of mud should be pumped ahead of the cement to ensure that the bottomhole circulation temperature will not exceed the design BHCT used for conducting laboratory thickening time tests.

6. Actual Job Execution – as per Halliburton's Post Job Report (HAL_0011210)

This report noted that the following fluids were pumped:

1. **Spacer: 72 bbl of Tuned Spacer III** mixed at 14.3 lb/gal with 0.6 gal/bbl Surfactant A + 0.6 gal/bbl Surfactant B + 0.6 gal/bbl SEM-8 + 1 lb/bbl WellLife 734 + Fresh Water.

2. **Lead Cement (*see Note A below*): 5.26 bbl / 22 sk** Premium H cement + 0.07% BWOC EZ-Flo + 0.25% BWOC D-Air 3000 + 1.88 lb/sk KCl + 20% BWOC SSA-1 (silica flour) + 15% BWOC SSA-2 (100-mesh silica) + 0.2% BWOC SA-541 + 0.11 gps ZoneSealant 2000 + **0.09 gps SCR-100L** + 1 lb/bbl WellLife 734 mixed with fresh water at 16.74 lb/gal.

3. **Foamed Tail Cement: 38.9 bbl / 159 sk (47.75 bbl foamed volume** – *see Note B below*) Premium H cement + 0.07% BWOC EZ-Flo + 0.25% BWOC D-Air 3000 + 1.88 lb/sk KCl + 20% BWOC SSA-1 (silica flour) + 15% BWOC SSA-2 (100-mesh silica) + 0.2% BWOC SA-541 + 0.11 gps ZoneSealant 2000 + **0.09 gps SCR-100L** + 1 lb/bbl WellLife 734 mixed with fresh water at 16.74 lb/gal and foamed to 14.5 lb/gal with a 1.69 cuft/sk foamed yield (N2 conc. of 584 scf/bbl).

4. **Shoe Track Cement (*see Note C below*): 6.93 bbl / 28 sk** Premium H cement + 0.07% BWOC EZ-Flo + 0.25% BWOC D-Air 3000 + 1.88 lb/sk KCl + 20% BWOC SSA-1 (silica flour) + 15% BWOC SSA-2 (100-mesh silica) + 0.2% BWOC SA-541 + 0.11 gps ZoneSealant 2000 + **0.09 gps SCR-100L** + 1 lb/bbl WellLife 734 mixed with fresh water at 16.74 lb/gal.

5. **Spacer: 20 bbl of Tuned Spacer III** mixed at 14.3 lb/gal with 0.6 gal/bbl Surfactant A + 0.6 gal/bbl Surfactant B + 0.6 gal/bbl SEM-8 + 1 lb/bbl WellLife 734 + Fresh Water.

6. **Displacement: 133 bbl** 14 lb/gal SOBM w/Halliburton pumps.

7. **Displacement: 728.5 bbl** 14 lb/gal SOBM w/Rig pumps, leaving 189 ft of cement in shoe track.

Note A: This states that 5.26 bbl of lead cement were pumped. Halliburton's 1-second job data suggests that it was 5.4 bbl, thus this volume is used for placement calculations.

Note B: This states that 38.9 bbl un-foamed / 47.75 bbl foamed slurry were pumped. Halliburton's 1-second job data suggests that it was 39.7 bbl un-foamed / 48.7 bbl foamed slurry, thus the slightly larger volume is used for placement calculations.

Note C: This states that 6.93 bbl of shoe track cement were pumped. Halliburton's 1-second job data gave it as 7.3 bbl. Thus, the extra volume of 0.37 bbl of shoe track cement rounded the shoe.

Comment: A 3-bbl treating line volume is assumed between the cement unit and the rig floor, and also for calculating base-slurry and foamed cement volumes, and fluid volumes between plugs. Nitrogen injection into the base-slurry occurred through a foam generator at the rig floor. This accounts for the 3-bbl shift in calculating volumes pumped, e.g. cap volume (unfoamed lead) reads ~8.4 bbl on Fig. A3 when it is actually ~5.4 bbl. Similarly, the shoe cement volume is ~7.3 bbl and not ~4.3 bbl.

Halliburton's job log (HAL_0011210/12-13) noted the following times and events:

04-19-10

19:00 Pre-job safety meeting with rig crew reviewing detailed pumping procedure.
19:29 Blow nitrogen (N2) through choke to assure line is cleared. Nitrogen line plugged.
19:38 Nitrogen line cleared.
19:39 Test nitrogen lines to 5000 psi. Leak found. Leak repaired.
19:45 Test N2 lines 56000 psi *(typo, should have read 5000 psi)* – bleed off, no leaks noticed.
19:47 Pump 7 bbl of 6.7 lb/gal base oil. Had 5 bbl of mud ahead of base oil.
19:53 Pump 10 bbl 14.3 lb/gal Tuned Spacer III to break circulation.
19:54 Returns seen at well head.
19:57 Test cement lines to 5000 psi – bleed off, no leaks noticed.
19:59 Pump 62 bbl of Tuned Spacer III at 14.3 lb/gal – Sem-8 online.
20:17 Finished pumping spacer. Wash out measuring tanks.
20:28 Start weighing up cement.
20:37 Started pumping 16.74 lb/gal Unfoamed Lead Cement – ZoneSealant 2000 online. Pumped 4 bbl of Unfoamed Lead Cement (1 downhole / 3 in Lines).
20:39 Drop dart to release bottom plug.
20:41 Completed Unfoamed Lead Cement. Total of 5 bbl.
20:42 Started pumping Tail Cement to 14.5 lb/gal – Nitrogen online.
21:00 Completed Foamed Tail Cement. Total 39 surface bbl – Nitrogen offline.
21:01 Started pumping 16.74 lb/gal Unfoamed Shoe Cement.
21:03 Completed Unfoamed Shoe Cement. Total of 7 bbl.
21:04 Pump 3 bbl of 14.3 lb/gal Tuned Spacer III to clear lines of cement.
21:05 Drop dart to release top plug.
21:06 Pump 17 bbl of 14.3 lb/gal Tuned Spacer III – Sem-8 online.
21:11 All spacer pumped.

21:12 Start displacing cement with 14.0 lb/gal SOBM using HES pumps.
21:21 Dart#1 through diverter at 3500 psi with 43 bbl of SOBM pumped using HES pumps.
21:23 Dart #1 through DTD at 3200 psi with 50 bbl of SOBM pumped using HES pumps.
21:35 Dart #2 through diverter at 3150 psi with 101 bbl of SOBM pumped using HES pumps.
21:37 Dart #2 through DTD at 3350 psi with 109 bbl of SOBM pumped using HES pumps.
21:39 Dart #2 launched top plug at 3300 psi with 117 bbl of SOBM pumped using HES pumps.
21:43 Finished pumping 133 bbl of SOBM & turn over to rig pumps to complete displacement.
23:39 Bottom plug through x-over at 830 psi with 469.5 bbl of SOBM pumped with rig pumps.
23:53 Top plug through x-over at 500 psi with 525 bbl of SOBM pumped with rig pumps.

04-20-10
00:29 Bottom plug bumped at 2900 psi with 673 bbl of SOBM pumped with rig pumps.
00:40 Top plugs bumped at 1150 psi (1000 psi over circulating) with 728.5 bbl of SOBM pumped with rig pumps.
00:43 Check floats .... Bled back 5 bbl. Floats held.

Halliburton's "Significant Points" (HAL_0011210/14) noted:

Cement job pumped as planned.
Chemical straps determined that additives were pumped at planned volumes.
Rig completed displacement and both plugs were bumped.
Full returns seen throughout entire job.
Estimated 100 psi of lift pressure (350 psi circulating to 450 psi circulating), before bumping top plug.
Floats held after job (*see Note below*).

Note: A simple hydrostatic calculation of the different fluid heights in the annulus and casing would have shown that there was no back pressure from annulus to casing to test the float check valves (see Table 6 & Table 7)

6.1. Cement Density Control

The base-slurry was mixed on-the-fly at a reported average density of 16.74 lb/gal. The density plot Figure **7** (see also Fig. A1 and Fig. A3 in Appendix) indicates that the density during the foamed cement stage varied from about 16.6 to 17.1 lb/gal, a fluctuation of $\pm$0.25 lb/gal. Sensor noise may also be responsible for exaggerating the maximum and minimum readings once target density was reached. However, the average density appeared to be almost 0.2 lb/gal heavier than programmed.

From the 1-second data provided by Halliburton, spreadsheet HAL Cement Data 18 April 20 April 2010 Converted to Excel.xlsx, the average density, minimum and maximum densities and standard deviation were calculated for the cap (lead) slurry, foamed base-slurry and tail (shoe track) slurry, and standard deviation. These results are given in Table 5.

Slurry	Volume bbl	Average Density lb/gal	Target Density lb/gal	Min Density lb/gal	Max Density lb/gal	Std Deviation lb/gal
Cap	5.4	16.02	16.74	9.6	16.9	1.57
Foamed (Base)	39.7	16.93	16.74	16.7	17.1	0.08
Shoe	7.3	16.81	16.74	16.5	17.1	0.15

Table 5: Slurry Density Fluctuation During Mixing

Note: Cap slurry average density was on the light side, as expected from on-the-fly mixing; the slurry rapidly increased in density from a low of 9.6 ppg to a high of 16.9 ppg, averaging 16.02 ppg.

The average density given in the job report of 16.74 lb/gal was lower than recorded, except for the cap slurry. Presumably the average recorded density (for all three stages) was adjusted downwards based on the average reading of the pressurized mud balance, but this was not confirmed in the Post Job Report, HAL_0011210. In most cementing operations, it is customary to confirm the recorded density with a Pressurized Mud Balance, and note the difference.

Normally, a density fluctuation during mixing of not more than ±0.2 lb/gal would be preferred. This keeps the retarder concentration (liquid type) variation just below ±2.5%, the slurry being slightly less retarded when the density is higher than the target density and slightly more retarded when the density is lower. For ±0.3 lb/gal, this is equivalent to ±3.6% retarder variation.

The last 4 bbl of the shoe track cement density averaged around 0.2 lb/gal less than the rest of the cement mixed (thus was slightly more retarded). This was contrary to common field practice where the last few barrels of cement slurry are intentionally mixed at a slightly higher density to reduce thickening time and ensure competent shoe track cement. However, the density variation observed during mixing was fairly typical of a good mixed on-the-fly cementation. Overall, the cement mixing operation appeared well executed and density control was good.

Nevertheless, since the total volume of the base-slurry was only ~52 bbl, practically it would have been feasible to batch mix the slurry to a density of 16.74 lb/gal within limits of less than ±0.1lb/gal.

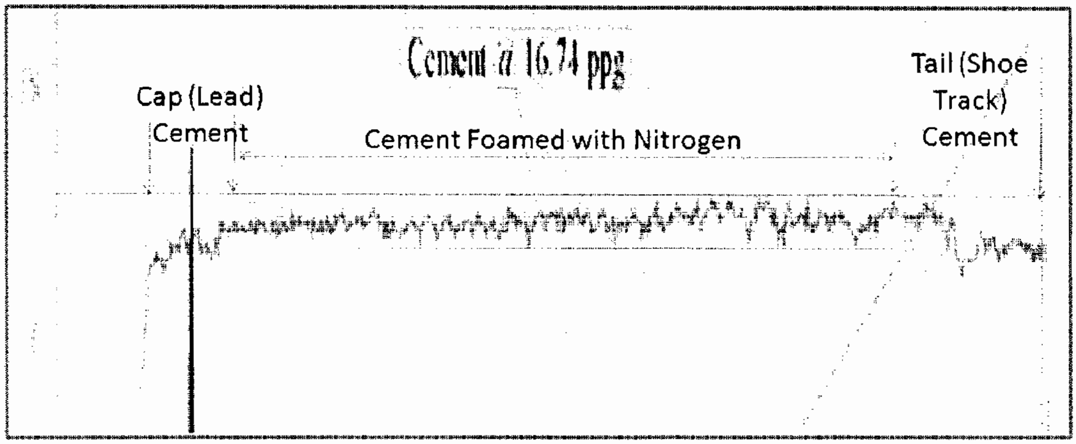

Figure 7: Graph Indicating Some Variation in Cement Slurry Density

6.2. Nitrogen Addition to Foam the Cement

The Nitrogen target rate was 584 scf/bbl. Nitrogen was added to the 16.74 lb/gal base cement slurry on-the-fly, while pumping the base-slurry at 2.05 bpm (see Figure 8 below, and Fig. A3 and Fig. A4 in Appendix).

Nitrogen was injected downstream through a foam generator into the base-slurry stream at a rate of ~1190 scf/min. This is equivalent to a N2 ratio of 580 scf/bbl which is extremely close to the target rate.

The Post Job Report did not provide a graph joining up the pumping parameters measured at the cementing unit and N2 unit. To overcome this, two separate graphs over the same time period (Appendix, Figs A3 and A4) are shown next to each other in Figure 8 to illustrate how the pressure was increasing in the treating line to the well head, as nitrogen was injected through a foam generator to foam the base-slurry.

The pressure drop across the foam generator was well above the minimum requirement of ~800 psi for generating foamed cement. It ranged from around 1,450 psi at the start of foamed cement generation, down to just over 950 psi at the end of N2 injection.

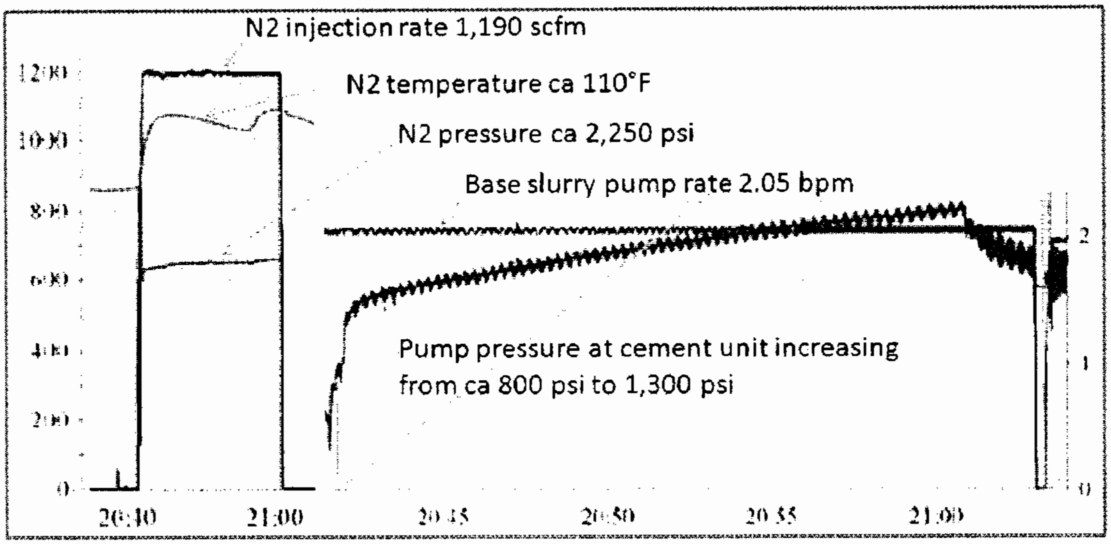

Figure 8: Graph shows N2 Injection Rate on Left and Base-Slurry Pump Rate on Right (for time period 20:40 to 21:01)

As noted above, the "16.74 lb/gal" base-slurry was mixed between 16.5lb/gal and 17.1 lb/gal which would have affected the downhole foamed cement density accordingly. In addition, the temperature at which the foamed cement initially set would have slightly reduced the density, reference Figure 2.

6.3. Additives Added On-the-Fly Downstream of the Cement Unit

These were ZoneSealant 2000 added to the cement slurry and SEM-8 to the Spacer (see Figure 9 and Fig. A1 and Fig. A5 in Appendix).

Target rate for ZoneSealant 2000 was 0.11 gps. This is equivalent to metering the additive at 0.974 gal/min when pumping the base-slurry at 2.05 bpm. The plot indicated that the rate was correct at ca. 0.972 gal/min, again acceptably very close to the target rate.

Target rate for SEM-8 was 0.6 gal/bbl of Tuned Spacer III. Actual rates were all very close to design:

- Spacer Ahead – 2.22 gal/min / 3.87 bpm = 0.57 gal/bbl
- Spacer Behind 1 – 2.49 gal/min / 4.16 bpm = 0.6 gal/bbl
- Spacer Behind 2 – 2.44 gal/min / 4.06 bpm = 0.6 gal/bbl
- Spacer Behind 3 – 1.99 gal/min / 3.35 bpm = 0.59 gal/bbl

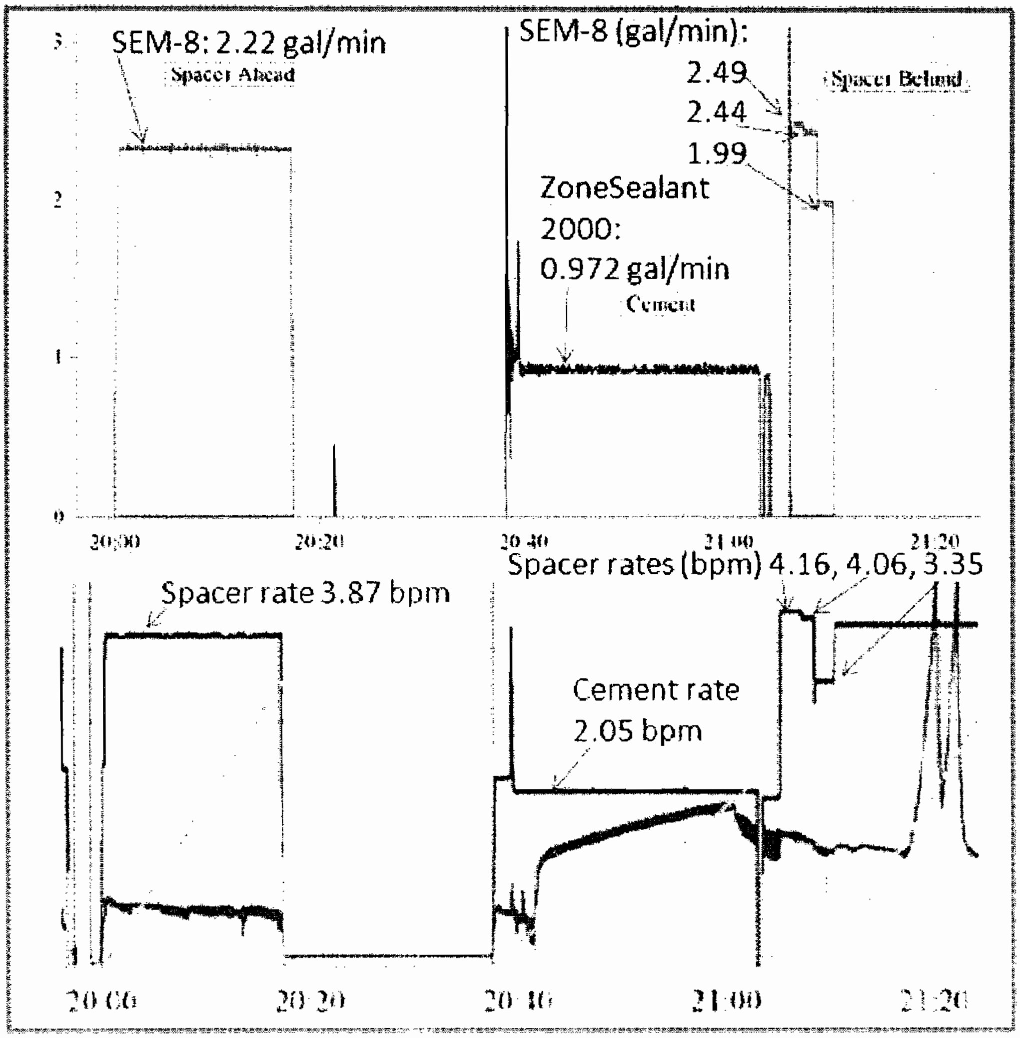

Figure 9: Graph of Additives (ZoneSealant 2000 & SEM-8) Injected Downstream of the Cement Unit

6.4. Retarder SCR-100L - Liquid Additive for Cement

Whilst this additive could have been added on-the-fly during mixing to the mix water in the displacement tanks through a Liquid Additive System, no mention is made of this in the report. Alternatively it could have been added to the mix water prior to the job, if a separate tank was provided for this purpose.

Thus there is no way of verifying whether the correct volume of this key additive was added to the slurry. Normally, the Operator (BP) or a nominated third party should have been monitoring the addition of this additive and the cementation overall.

6.5. Liquid Additives and Product QC Program

There was no mention in Halliburton's Post Job Report, HAL_ 0011210 that the SG of each liquid additive was checked against the product specification sheet, a basic requirement of a credible QC program. This requirement is also mandated by BP Exploration, reference Drilling Manual Section 3000/Gen, Rev. 2 (8/91), Page 2 of 4, which states that "All cement additives to be used in a forthcoming cementing operation must be physically checked using a hydrometer". This is widely recognized as being good practice, particularly to avoid contamination mishaps from reused drums/containers. It is not unknown for even factory sealed containers to house an off-specification product.

Additionally, an effective QC program would inventory all materials before and after the job, and then compare actual usage with expected usage. Halliburton's Post Job Report, HAL_ 0011210/14, noted that "chemical straps determined that additives were pumped at planned volumes" indicating that this was done, but no strap figures have been seen to indicate how closely execution followed design.

7. Post Job Evaluation

7.1. Lift Pressure - End of Displacement

Halliburton's post job report estimated 100 psi of lift pressure (350 psi circulating to 450 psi circulating), before bumping top plug (HAL_0011214).

Halliburton's OptiCem report (HAL_0010988) stated that "Annulus fluid is heavier than the casing fluid by 38 psi". However, this report gave a cement column length in the annulus of 2,164.9 ft (from 16,139.6 ft to 18,304.5 ft) that far exceeded the cement annulus fill as executed, which was less than 1,100 ft; thus, making this already very small positive number even smaller.

The pressure curve (Figure 10) derived from 5-second data (Rig Data) indicates that the pressure declines to a minimum just before the Bottom Plug bumps, then the pressure increases and appears to plateau just before the Top Plug bumps.

From Halliburton's 1-second data set, the pressures are slightly different from the 5-second data as pressures can change quite considerably in 4 seconds (also the respective pressure sensors (if more than one?) may not be giving identical readings). Here, the pressure is shown to decline to a minimum of 228 psi just before the Bottom Plug bumps, then the pressure increases from 299 psi to ~342 psi when the Top Plug bumps.

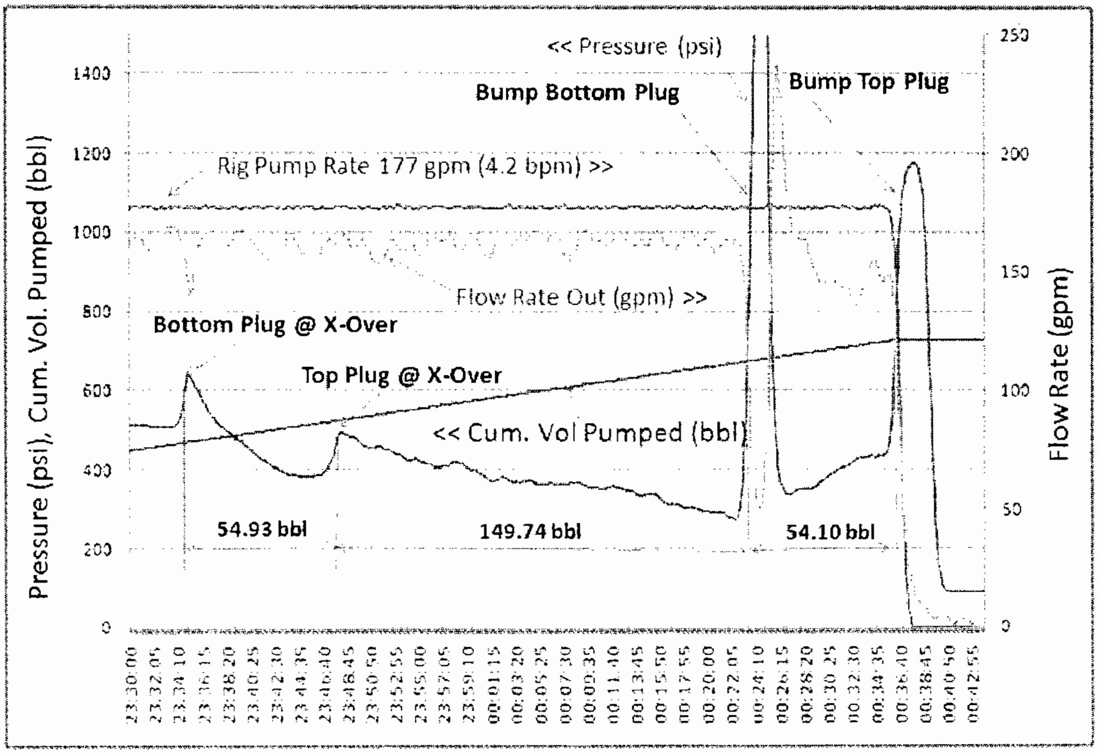

Figure 10: Rig (Pump Rate, Pressure, Flow Rate Out and Cum. Volume Pumped) versus Time (ref Excel File MC252_001_ST00BP01_long string Cementing Raw Data.xlsx)

The decrease in surface pump pressure reading between the X-over and Plug Bump is probably due to a reduction in friction pressure, as the viscosity of each fluid pumped decreases with increasing temperature. Moreover, the viscosity of foamed cement will also decrease as its foam quality decreases, (ref: Rheology of Foamed Cement by R.M Ahmed et al. published by Cement and Concrete Research 39 (2009)).

As the foamed cement rounds the shoe and ascends the annulus, its foam quality will increase together with its viscosity (and friction pressure). Similarly, as the other fluids (spacer, base-slurry 16.74 lb/gal, and base oil) rise in the annulus they will also cool slightly, resulting in a slight increase in viscosity and friction pressure. However, it is suggested that the main increase in friction pressure, between the bottom and top plugs bumping, comes from the viscous spacer passing through the more restricted or "tighter" 7" x 8.625" annulus (9-7/8 casing at 17,168 ft). The slight drop in pressure before the plug bumps was probably due to the spacer front entering the larger 7" x 10.711" annulus above 14,803 ft; the friction pressure in this annulus being lower than in the open-hole annulus. It is therefore contended that this "100 psi" pressure increase is due mainly to an increase in spacer friction pressure.

In fact, the lift pressure at the end of displacement was more likely to have been negative, between -80 psi and -53 psi. The negative pressure indicated that flow would be from the casing to the annulus and not vice-versa, as is usually the case. The volumes and heights of the well fluids at the end of the cementation are shown in Table 6 and Table 7 for two cases. The pipe tally (HAL_0010818) indicated that the drill pipe fluid level was around 71 ft above the rig floor immediately after displacement, and around 35 ft when checking the float collar for flow-back, hence the difference of -27 psi.

Note: Based on the slightly reduced volumes given in Halliburton's Post Job Report (HAL_0011210/11), the calculated lift pressures would have been -82 psi and -55 psi, reference Appendix, Table A1 and Table A2, assuming 100% displacement efficiency. Even assuming less than 100% displacement efficiency, as per Halliburton's final job design HAL_0010988 where the length of the cement column was 2,165 ft, the end of job lift pressure was calculated to be -10.2 psi; annulus pressure being 13,506.5 psi (18,304.5 x 14.19 x 0.052 – HAL_0010988/09) and casing pressure 13,516.7 psi (189 x 16.74 x 0.052 (cement) + 545.6 x 14.3 x 0.052 (spacer) + 17,570.4 x 14.17 x 0.052 (mud) - HAL_0010988/06). In the several cases examined, it indicates that any flow as a result of u-tubing will be from casing to annulus.

The float collar valves, therefore, could not be tested to see if they were holding pressure by the usual flow-back technique. Thus, Halliburton's note in their Post Job Report "check floats....bled back 5 bbl....floats held" was most probably incorrect.

Fluid	Volume bbl	Density lb/gal	Fluid Top ft	Length ft	Pressure psi
Annulus					
SBM to Flowline (6.37 ft)		14.17	6.37	14445	10644
Base Oil	7.00	6.70	14451	110	38
Spacer	76.70	14.30	14561	2716	2020
Base Slurry	5 40	16.74	17277	106	92
Foamed Cement	48.70	14.50	17383	909	686
Base Slurry	0.37	16.74	18292	12	10
				18298	**13489**
Casing					
SBM to Surface (-71.35 ft)		14.17	-71.35	17589	12960
Spacer	21 90	14.30	17518	597	444
Base Slurry	6 93	16.74	18115	189	165
				18375	**13569**
				Lift Pressure - psi	-80

Table 6: Theoretical Lift Pressure immediately after displacement with cementing assembly 71.35 ft above rotary table (-80 psi).

Fluid	Volume bbl	Density lb/gal	Fluid Top ft	Length ft	Pressure psi
Annulus					
SBM to Flowline (6.37 ft)		14.17	6.37	14445	10644
Base Oil	7.00	6.70	14451	110	38
Spacer	76 70	14.30	14561	2716	2020
Base Slurry	5 40	16.74	17277	106	92
Foamed Cement	48 70	14.50	17383	909	686
Base Slurry	0 37	16 74	18292	12	10
				18298	**13489**
Casing					
SBM to Surface (-34.91 ft)		14.17	-41.38	17553	12933
Spacer	21 90	14.30	17518	597	444
Base Slurry	6 93	16.74	18115	189	165
				18339	**13542**
				Lift Pressure - psi	-53

Table 7: Theoretical Lift Pressure when checking for back flow with bleed-off valve 34.91 ft above rotary table (-53 psi).

Note (re Table 6 & Table 7):

- *Casing internal hydrostatic pressure greater than annulus hydrostatic.*
- *Additional hydrostatic pressure due to pipe elevation above rotary table:*
    - *Using 9-7/8" x 7" casing tally, extension above rotary head immediately after cementing = 71.35 ft (Table 6).*
    - *Using 9-7/8" x 7" casing tally, bleed-off valve above rotary head, while checking float equipment = 34.91 ft (Table 7).*
- *Fluid heights calculated from Section 1.5 Wellbore Geometry, BP-HZN-MBI00136477.*
- *Fluid volumes derived from Halliburton's 1-sec Job Data Acquisition, reference spreadsheet HAL Cement Data 18 April 20 April 2010 Converted to ExcelVer2.0.xlsx.*

Furthermore, in Halliburton's OptiCem Wellbore Simulator Report (Section 5.5 Pressure to Break Circulation), reference BP-HZN-MBI00133550, it states that if the gel strength of the fluid in the well is 25 lbf/100ft^2, a surface pressure of 643 psi is required to break circulation. The mud in the Macondo #1 well had a 10-sec gel strength of ~15 lbf/100ft^2. This would imply that the pressure differential on the annulus side should have been in excess of 370 psi for flow-back to occur.

Thus to test the float collar integrity, this issue should have been resolved by running a simple calculation to check the final casing and annulus hydrostatic pressures, and compensating the negative pressure by tailing in the displacement with a sufficient amount of base oil to ensure a back pressure of ~400 psi.

7.2. Flow-Out Reduction after Bottom Plug Bump (see Figure 10)

On examining the raw data (ref Excel File MC252_001_ST00BP01_long string Cementing Raw Data.xlsx) of Flow-Out from the well over the following times, before and after the cement rounds the shoe:

- 00:11:40 to 00:23:30, the average flow rate out is 161.9 gpm (3.85 bpm) (*see Note*)
- 00:23:35 to 00:36:00, the average flow rate out is 145.4 gpm (3.46 bpm)

Note: Although these rates are below the mud displacement rate of ~4.22 bpm, they are most probably an artifact of the flow-rate-out measuring device, as no losses were reported.

Normally, foamed cement would increase slightly in volume as it ascends the annulus, so if anything, a small increase in flow rate would be expected.

The relative decrease would appear to indicate that slight losses may have occurred during the final phase of placing the cement behind the casing, as predicted by Halliburton's OptiCem program, Figure 6. The loss in volume over the 12.5 minute period would be ~5 bbl, i.e. (161.9 – 145.4) x 12.5/42.

However, there was no mention in the Drilling Report of the fluid level in the annulus dropping after the Top Plug bumped.

7.3. Reduction in Foamed Cement Volume as Indicator of Foamed Stability

Halliburton job log (HAL_0011210/12-13) reports that between plugs there should have been a "downhole" total of 58.94 bbl (4.26 bbl cap cement 16.74 lb/gal + 47.75 bbl of foamed cement (when placed downhole) + 6.93 bbl shoe track cement 16.74 lb/gal). BP's Daily Operations Report gave the total volume between plugs as 59 bbl (4 bbl cap + 48 bbl foamed cement + 7 bbl shoe track cement).

A revised calculation based on the 1-second data suggests that the "downhole" volume was closer to 60.4 bbl (4.4 bbl cap + 48.7 bbl foamed cement + 7.3 bbl shoe track).

The volume of cement between Top and Bottom Plugs at the X-over was calculated to be 54.93 bbl and at Plug Bump 54.10 bbl (*Note 1*), see Figure 10, a difference of 0.83 bbl. This was from examining the 1-second data to determine the exact times the bottom and top plugs reached the X-over and at plug bump. The average flow rate during these periods was derived from flow in pumping rates (~4.22 bpm) given in Excel File MC252_001_ST00BP01_long string Cementing Raw Data.xlsx.

The contraction in volume of 0.83 bbl between the plugs at the X-over (54.93 bbl) and at plug bump (54.10 bbl) is half the expected contraction of 1.62 bbl, due to the foamed cement compression as the pressure increases between the X-over and plug bump. This tends to suggest that the foamed cement was unstable, due to some of the nitrogen separating from the slurry and by-passing the top plug as it moved down the casing.

For calculating foamed slurry volume reduction, the pressure and temperature at X-over and plug bump were estimated at 9,235psi/117°F (*see Note 2*) and 13,420 psi/135°F respectively.

Note 1: The volume of ~60.4 bbl should have been the volume computed between plugs at Plug Bump. The fact that it was 6.3 bbl short (60.4 – 54.1) is concerning. Possible explanations include: N2 breakout (as described above); top plug by-passing fluid; and/or bottom dart dropped late and top dart early (at 2 bpm this would imply a 3- to 4-minute recording error, which seems unlikely). At a pump rate of 2bpm, a ±2 bbl error would be the most expected.

Note 2: Temperature of 117°F estimated from Well Bore Temperature Profile, BP-HZN-MBI00136561.

7.4. Auto-Fill Float Collar Operation

It took nine attempts after RIH with the casing to convert the auto-fill float collar and establish circulation. It finally appeared to convert at 3,142 psi versus the 500 to 700 psi design pressure and pump rate of 5 to 8 bpm. The circulation pressure after conversion was also reported to be lower than expected, 350 psi versus expected 570 psi at 4 bpm. Circulation was then initiated with Pump 3, but the pressure was still low at 390 psi. Concerns were discussed with the onshore well management, but it was decided to proceed with the cementing.

Subsequent testing of this equipment, contracted by Transocean, suggests that the ball could have ejected without converting the float collar, thus providing a clear flow path from the well. Hence, the flow-back test at the end of the job, judged to be zero flow-back (i.e. float check valves working), was misinterpreted.

Instead the zero flow-back was due to the casing and annulus pressures being almost the same. As explained in Section 7.1, the calculated lift pressure was around -53 psi when checking for flow-back, see Table 7. A negative number indicates that any flow would be from casing to annulus.

7.5. Shoe Track Cement Contamination

Once the pressure on the plugs was released, some seepage may have occurred around the plugs since the positive differential pressure was now from casing to annulus. This may have accounted for some further contamination of the shoe track cement with spacer. Another possible cause of contamination is mixing between the cement and drilling mud left in the rat hole. Frequently, before pulling out of hole to run casing, a heavier mud pill is placed in the rat hole to prevent this from occurring. However, the BP Well Team chose not to do this due to lost circulation concerns.

7.6. Acoustic Logs

Non-destructive testing of the cement sheath, using sonic and ultrasonic logging tools, can provide valuable information about the position and condition of the cement behind the casing.

However, it should be noted that acoustic logs are normally only run if sufficient doubt exists on the success of the cementation execution and/or well conditions at the time of the job. In fact, many operators do not run them until the well completion phase.

It may not be essential in cases where all the cementing fluids are batch mixed to the correct target densities and rheologies, and the fluids are pumped at the prescribed rates across a well centralized interval.

For a cementing job where a relatively small volume of slurry has been mixed on-the-fly, with poor centralization over the top section of the cemented interval, very large displacement volumes, and a foamed slurry of variable density setting in more than 24 hours, it would have been prudent to confirm the state of the cementation with a log.

In this case the minimum time WOC before running acoustic logs would have been around 48 hours, based on the compressive strength test of zero strength after 24 hours at 180°F, and 1590 psi after 48 hours (page 2 of Halliburton's Lab Results Report of April 12th 2010 (R/S 73909/1 & HAL_0010869)).

One major operator suggests that the theoretical minimum WOC time before logging is 4 to 5 times the UCA initial set-time of the cement slurry at the TOC static temperature. Sufficient time must be allowed for the acoustic impedance of the set cement to increase to above 70% of its final value.

M.E. Jordan et al. in SPE 14200 Cement Bond Log: Determining Waiting-on-Cement Time presents a graph (Figure 11) that gives the required compressive strength to log based on the ultimate compressive strength. This graph is used in conjunction with a UCA to determine the ultimate compressive strength at the estimated static temperature at the TOC; appropriately, simulating temperature history conditions of the slurry at surface, pumping and displacement time to BHCT, and heat-up time to curing temperature.

Though acoustic logs of lightweight foamed cement jobs are difficult to interpret, this should not have been the case here where the density was ~14.5 lb/gal. This cement would have had a relatively high acoustic impedance of ~4.7 MRayl and correspondingly lowish CBL amplitude, where there is good zonal isolation.

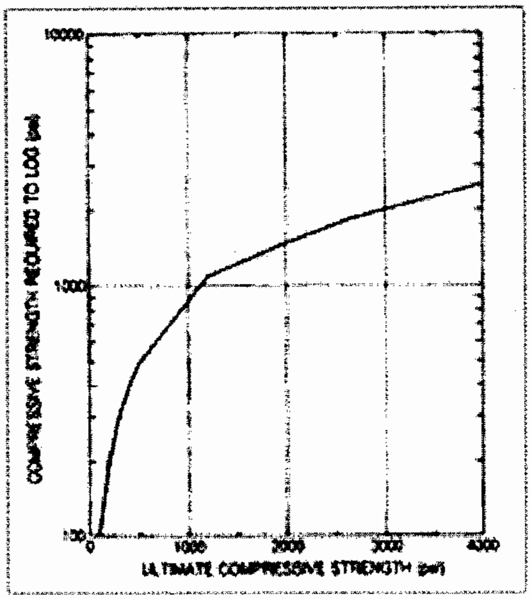

Figure 11: Compressive strength required to run a CBL, as a function of the ultimate compressive strength.

7.7. Temperature Log

Whilst a wait-on-cement time of 48 hours is quite a normal delay before running an acoustic log, a temperature survey could have been run much sooner, usually within ~10-15 hours, to verify that the cement had set. Because of the exothermic character of cement hydration, the heat generated by the cement raises the temperature of the wellbore, and induces a deviation from the normal temperature gradient, see Figure 12. A temperature survey would detect the top of cement, in this case the top of the cap cement. Once this is confirmed, it would be reasonable to assume that the shoe track cement is also set. Knowing the top-of-cement depth and volumes of cement pumped would also have given a good indication of the degree of channeling that may have occurred, and alerted the Well Team to take other precautionary measures.

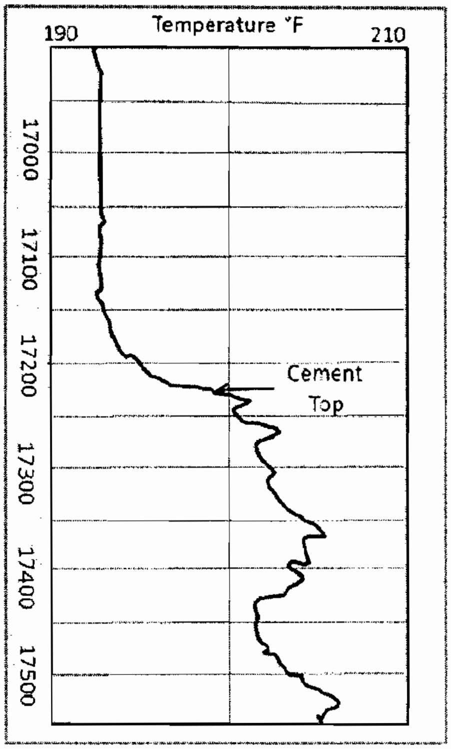

Figure 12: Example of a temperature survey log

7.8. Post Job Laboratory Testing

Normally wellsite samples would have been kept for this purpose but owing to the catastrophic circumstances this was obviously not possible, thus laboratory samples would have to be substituted.

That said, laboratory testing to date seems to be verifying the correctness of the limited testing performed by Halliburton, rather than ascertaining the possible causes of the cement slurry not setting and sealing the well bore. Though the aspect of verification is important, further tests should be run to confirm whether the cement formulation used would have set in the well, had the temperature been lower than 210°F. Temperature simulations would estimate the downhole temperature at the time of the negative test, and enable the correct heat-up rate to be used in UCA and crush strength tests. There has been no evidence of such tests to date.

8. Foamed Cement - Pros and Cons

While foamed cement may offer several advantages over conventional (water extended) slurries:

- Easily tailored density for cementing across non-critical pore and frac pressure zones.
- The base-slurry has a lower water-to-solids ratio than conventional extended slurries, therefore has better compressive strength.
- Greater resistance to stress cracking caused by cyclic activity.
- Foamed matrix provides space for crystalline growth associated with temperature retrogression at temperatures in excess of 230°F.
- Some control of fluid loss, gas migration, and water flow.

Foamed cement also has a number of drawbacks:

- Accurate estimation of temperature in deep wells to calculate nitrogen ratio for projected down-hole density. This is an important issue in wells having a very narrow window between pore and fracture pressure. In this case, it is important to allow for a decrease in density as the foamed cement heats up prior to setting.
- Foam cements are not reproducible because it is almost impossible to produce two samples with the same initial bubble-size distribution.
- Added complexity for computer simulators due to compressible nature of fluid, constantly changing rheology and density, makes predictions of placement ECDs, displacement efficiency and final bottomhole hydrostatic pressure more questionable.
- Unstable slurries result in a pore structure that is non-spherical and interconnected, resulting in a sponge-like structure with lower compressive strength, higher permeability, and inferior bonding.
- More costly than conventional extended cement systems and are more demanding operationally.
- Can be destabilized by contamination with oil based muds.
- Batch mixing is not an option, thus density control can be an issue.
- Concerns over accurately controlling the nitrogen and foaming agent delivery system when mixing on-the-fly can cause unstable or even vugular foam cement.
- Good caliper data is required for precise placement of different stages over a long interval.
- Rheology is not generally tested at temperatures above room temperature thus it is impossible to accurately determine ECDs and displacement efficiency.
- Controlling foamed returns to the surface can also be a concern for rig crews.

In cases where the volume is manageable, generally less than 100 to 150 bbl of slurry (in this particular case 48 bbl), batch mixing of the base-slurry is preferred.

Alternatively, today's technologies allow relatively lightweight slurries, where some of the cement is replaced with precisely sized particles resulting in reduced porosity and reduced water content, capable of rapid strength development. Unlike foamed cement, its properties can be measured in a laboratory at pressure and temperature: thickening time, rheology, fluid loss, density, free water, and stability. Its properties can be checked at the wellsite after batch mixing and before pumping, to ensure a high degree of confidence in the slurry being pumped. Such a system can be fully engineered.

As with all batch mixing operations, sufficient stock should be on hand to "dump" and remix any slurry not mixed within agreed specifications.

9. Liner Cementing

The large 7" x 9-7/8" casing and landing string volume of near a 900 bbl, against the relatively small slurry volume of ~62 bbl, implies that there will be some slurry-mud contamination during displacement due to the very large casing wall surface being wiped. This creates the risk of having contaminated cement in the shoe track.

Thus cementing a well through a 7" liner instead of a 7" x 9-7/8" combination string would have considerably reduced the displacement volume of fluid pumped, and also reduced the potential for cement-spacer contamination and spacer-mud contamination. Top and bottom wiper plugs have a smaller area to wipe, and due to their more compact size are more robust than combination plugs.

Running a liner also has an added advantage in that it enables pipe movement (rotation and reciprocation) during cementing, which helps to improve mud removal and slurry placement.

A possible drawback might be increased circulating pressures due to the restriction between the liner hanger and casing, which would necessitate a reduced pump rate to prevent fluid losses. This factor would be easily quantified by a computer simulator such as OptiCem.

10.Recommendations for Future Cementing Operations in Similar Situations

10.1. Classification of Cementing Jobs

In order to determine the degree of laboratory testing, sampling, and on-site supervision necessary for a particular cementation, all cementing jobs programmed for a well should be classified by the Well Team into different categories.

These categories could be under headings such as:

- Routine – jobs comprising any conductor, surface casing, intermediate casing, abandonment plug, production casing or liner in a well with a BHST less than say 300°F (or BHCT under say 250°F), and mud density less than say 15.5 lb/gal.
- Critical – jobs within the Routine pressure and temperature range that the Well Team view as Critical. These include: casing in long reach wells, liner cementations, cement plugs set in reservoir, and deep sub-sea cementations.
- High Pressure High Temperature (HPHT) – jobs where the BHST is greater than 300°F (or BHCT over 250°F) and mud density greater than 15.5 lb/gal.

10.2. Guidelines for Job Design & Execution, Laboratory Testing & Wellsite Checks

A Guideline should be provided for handling the different job categories, engaging not only the Cementing Contractor but everyone directly involved in the operation, including the Well Operator and Drilling Contractor. Such a document would define the roles and responsibilities for the Well Operator, Drilling Contractor and Cementing Contractor and outline the kind of quality control procedures that should be followed when providing computer-aided job design programs, laboratory tests and well-site checks.

10.3. Points to Consider

The following suggestions could help to improve the outcome of future operations:

- Develop a temperature simulation matrix from given data on BHST of expected maximum and minimum BHCT:
    - Expected BHCT (result of the planned circulation rate and time).
    - Maximum BHCT (result of the minimum circulating rate and time).
    - Minimum BHCT (result of the maximum circulating rate and time).
- Design the cement slurry based on expected BHCT (from temperature simulation). Use the temperature matrix to determine the sensitivity of the slurry.
- Avoid if possible slurry formulations that exhibit an inverse temperature effect (i.e. a lower thickening time at a lower temperature). If unavoidable, ensure an adequate thickening time safety margin at the lowest temperature, and WOC a sufficient time for it to set.
- Minimize displacement volumes and possible contamination issues by cementing a liner rather than a mixed casing string.
- Circulate the well and condition the mud with at least one hole volume prior to cementing, or in a case where this is not practical, at least calculate (thermal simulator) the volume necessary to be pumped to reduce the BHCT to the design value (in this case 135°F), or to a minimum value at the given rate.
- Lower the YP of the mud as much as possible to improve efficiency of pre-flushes (wash/spacer).

- Ensure that the critical interval to be cemented is centralized to at least to an 80% stand-off or better.
- Move the pipe (liner rotation – if feasible) during spacer and cement placement to improve mud removal.
- Formulate a cementing system that can be batch mixed at the required density, fluid loss, rheology and strength, whenever practical for critical and HPHT cementations.
- Ensure all the displacing fluids - spacer and cement - have the correct density and rheology for effective displacement in laminar flow.
- Ensure that an active QC procedure is in place on location, to confirm SG of all liquid additives to be used on location, to facilitate proper sampling of cement and additives, before and during the job.
- Have cementing contractor's laboratory technician on location to QC the fluids before mixing, and to check the fluids when mixed for density and rheology, prior to pumping.
- Have cementing contractor's job design engineer on location for Critical and HPHT jobs to assist and provide technical support to Well Operator's representative regarding any changes in the program.
- Collect well-site samples of all materials to be used, and store for a period defined by Well Team.
- Collect at least one "live" sample of foamed cement in high-pressure sampler during mixing and under pressure and cure until set. Then disassemble cell, core out and measure the density at top, middle and bottom to quantify foam stability.
- Have back-up materials on hand in case a spacer or cement slurry has to be remixed.
- Verify plugs launched correctly and pressure indicators confirm effectiveness.
- Record any losses occurring during placement.
- Ensure job displaced at the correct pump rate. Near the end of the displacement, ensure the displacement rate is reduced as necessary, thus preventing the increasing BHP from cement placement exceeding the fracture ECD.
- End displacement by pumping a sufficient volume of base oil or water depending on mud type to apply sufficient back-pressure on float collar to verify that it is holding, whenever the annulus and casing pressures at the float collar are close to equal.
- Allow sufficient time for the cement to be set – attaining 70% of final strength - before subjecting well to high negative differential pressures.
- Determine accurate waiting-on-cement (WOC) time based on heat-up rate, and alert operator of the time to wait before attempting any test of cement integrity. These temperatures can be estimated by the cementing contractor's cementing design software program.

Appendix

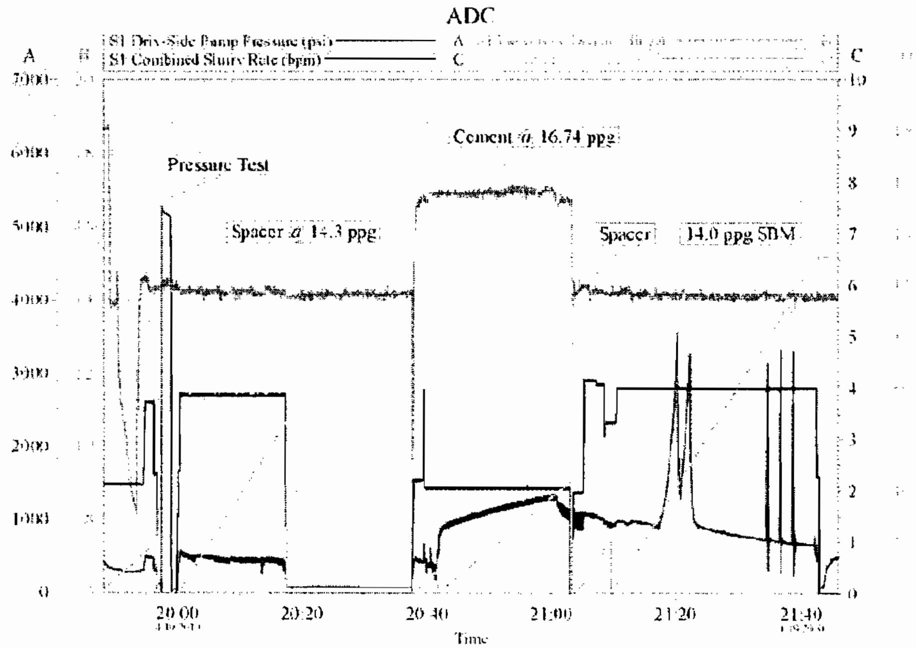

Fig. A1: Recorded at Cement Unit (Pump Pressure, Density, Pump Rate, Stage Slurry Volume) – HAL_0011210/15.

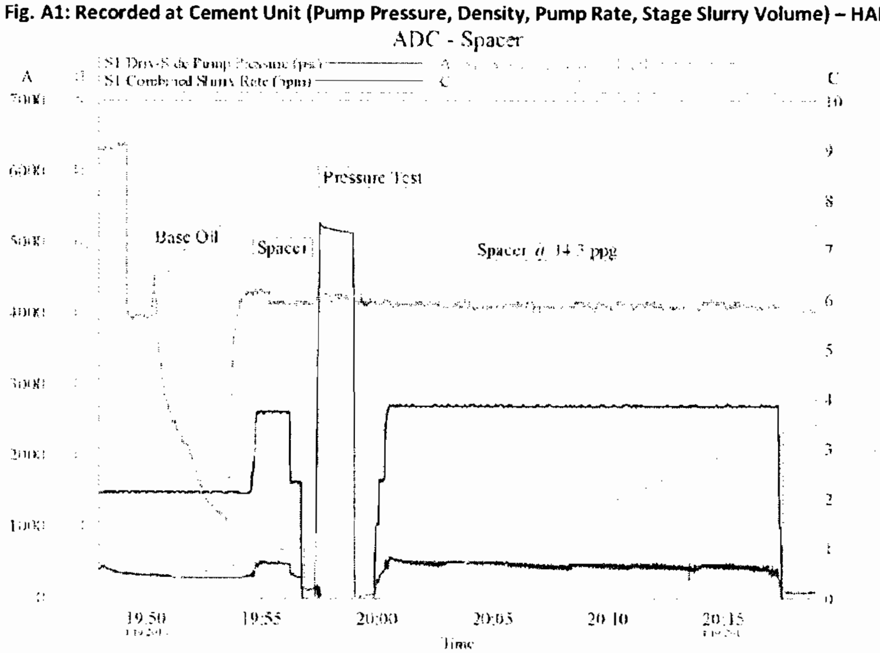

Fig. A2: Recorded at Cement Unit (Pump Pressure, Density, Pump Rate, Stage Slurry Volume) – HAL_0011210/16.

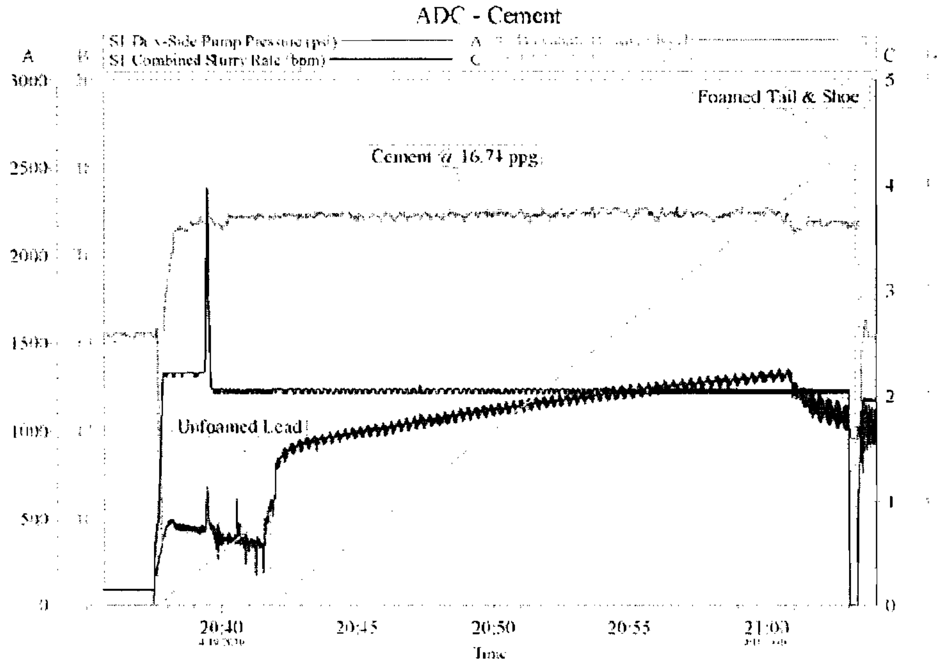

Fig. A3: Recorded at Cement Unit (Pump Pressure, Density, Pump Rate, Stage Slurry Volume) – HAL_0011210/17.

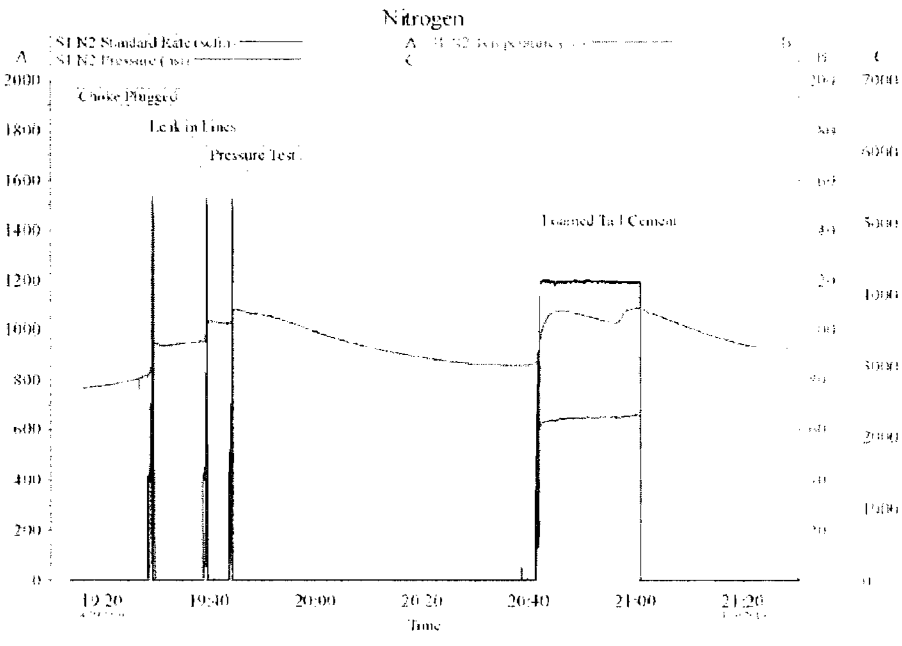

Fig. A4: Recorded at N2 Unit (N2 rate automates from combined pump rate read by N2 unit) – HAL_0011210/21

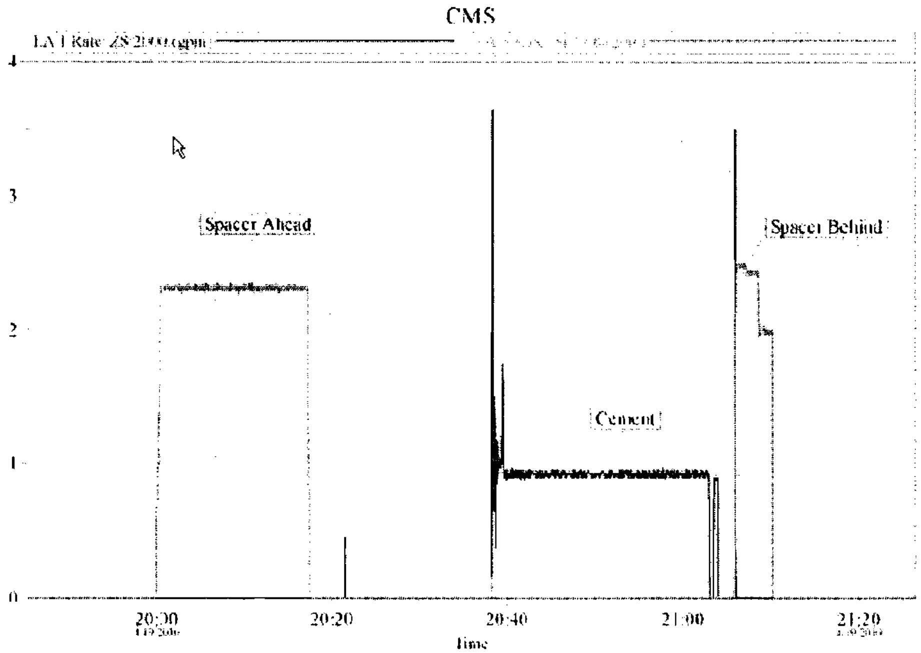

Fig. A5: Recorded at Cement Unit (CMS rate – ZoneSealant 2000 automates with combined pump rate) –HAL_0011210/20

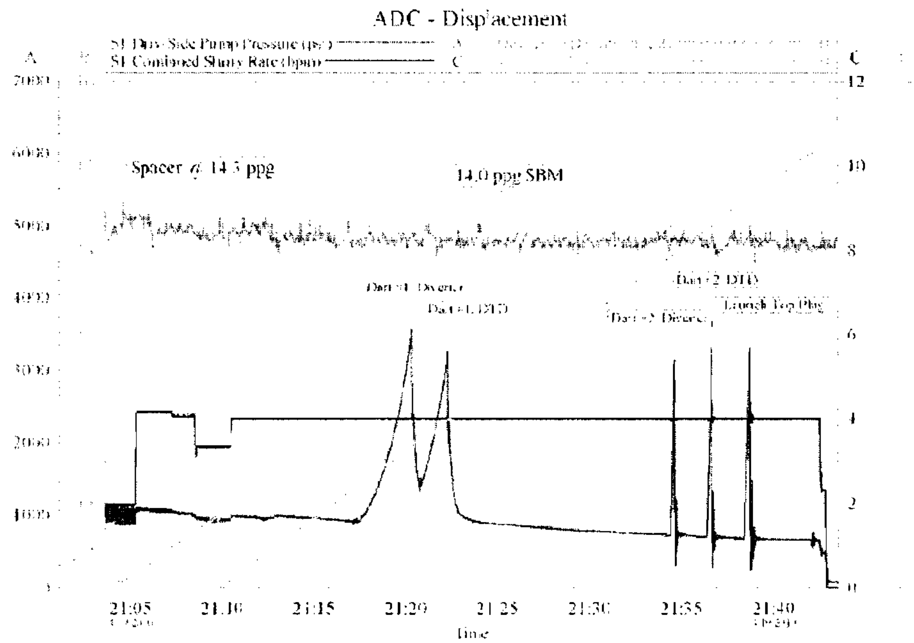

Fig. A6: Recorded at Cement Unit (Pump Pressure, Density, Pump Rate, Stage Slurry Volume) – HAL_0011210/18

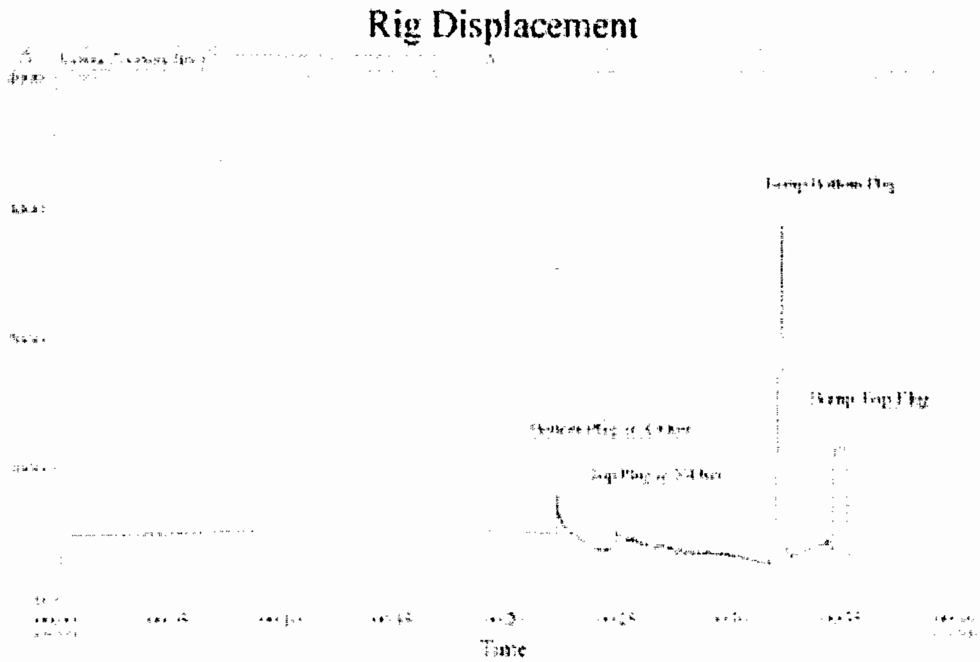

Fig. A7: Recorded at Sperry's Unit (Pressure, Stage Slurry Volume) – HAL_0011210/19

Note 1: Event times are incorrect. Correct times from Halliburton Job Log are:

23:39 Bottom plug at x-over
23:53 Top plug at x-over
00:29 Bump bottom plug
00:40 Bump top plug.

Note2: Job Volume should read bbl, not gal.

Fluid	Volume bbl	Density lb/gal	Fluid Top ft	Length ft	Pressure psi
Annulus					
SBM to Flowline (6.37 ft)		14.17	6.37	14541	10715
Base Oil	7.00	6.70	14548	110	38
Spacer	72.00	14.30	14657	2652	1972
Base Slurry	5.26	16.74	17309	98	86
Foamed Cement	47.75	14.50	17407	897	676
Base Slurry					
				18298	13486
Casing					
SBM to Surface (-71.35 ft)		14.17	-71.35	17641	12998
Spacer	20.00	14.30	17569	546	406
Base Slurry	6.93	16.74	18115	189	165
				18375	13569
				Lift Pressure - psi	-82

Table A1: Theoretical Lift Pressure immediately after displacement with cementing assembly 71.35 ft above rotary table (-82 psi) – Halliburton Data.

Fluid	Volume bbl	Density lb/gal	Fluid Top ft	Length ft	Pressure psi
Annulus					
SBM to Flowline (6.37 ft)		14.17	6.37	14541	10715
Base Oil	7.00	6.70	14548	110	38
Spacer	72.00	14.30	14657	2652	1972
Base Slurry	5.26	16.74	17309	98	86
Foamed Cement	47.75	14.50	17407	897	676
Base Slurry					
				18298	13486
Casing					
SBM to Surface (-34.91 ft)		14.17	-41.28	17604	12972
Spacer	20.00	14.30	17569	546	406
Base Slurry	6.93	16.74	18115	189	165
				18339	13542
				Lift Pressure - psi	-55

Table A2: Theoretical Lift Pressure when checking for back flow with bleed-off valve 34.91 ft above rotary table (-55 psi) – Halliburton Data.

Note: Fluid volumes are as given in Halliburton's Post Job Report (HAL_0011210/11). Fluid heights are calculated from open-hole data given in Section 1.5 Wellbore Geometry, BP-HZN-MBI00136477, assuming 100% displacement efficiency.