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Cement Formula to Prevent Gas Migration Problems in HT/HP Wells

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Abstract— Gas Migration through cement columns has been an industry problem for many years. The most problematic areas for gas migrations are in deep gas wells. To control gas migration, cement densities required to successfully cement the zone could be as high as 170 pcf (Pounds per Cubic Foot). As cement slurry sets, hydrostatic pressure is reduced on the formation. During this transition, gas can leave the reservoir and travel up through the cement column resulting in gas being present at the surface. The permeable channels, from which gas flows, cause operational and safety problems at the well site.

Current high density cement formulations do not provide good gas migration prevention due to settling and increase in permeability. To solve the settling problem and reduce permeability, Saudi ARAMCO had developed a formula that resulted in great gas prevention.

A gas migration model helped in testing and optimizing cement formulations to measure gas flow through cement columns. The gas migration model consists of the following systems: computer, data acquisition, full-length permeability determination, two partial length permeability determinations, cement volume change measurement, gas flow meter, and electronic filtrate weight determination. The pressure and temperature limitations are 2,000 psi maximum and 350 °F. Different chemicals for gas migration prevention were evaluated. Special types of cements were designed and evaluated for possible use for cementing gas wells. Addition of inert particles to cement and their effect on gas migration prevention were investigated.

In this paper, a new cement system was developed and results in great gas prevention. The performance of this system outstand any known existing gas cement formulations and has great potential to improve wellbore isolation in gas wells in Saudi Arabia.

Index Terms— cement, compressive strength, directional drilling, inert particles, multilateral wells, rate of penetration, sidetracks.

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1 INTRODUCTION

Jennings et al. (2003) mentioned that gas migration through cement columns has been an industry problem for many years. Approximately 80% of wells in the Gulf of Mexico have gas transmitted to surface to surface through cemented casings. The most problematic area in Saudi Aramco operations for gas migration is in deep gas wells (Khuff/pre-Khuff) in the Ghawar field.

The most problematic gas migration problems occur in deep gas wells when drilling through the base of Jilh Dolomite. Drilling fluid densities as high as 163 pcf are needed to control gas or formation fluid influx, Ezzat et al. (2000).

Soran et al. (1993) mentioned that gas channeling reasons can be categorized as follows:

- Bad mud/spacer/cement design that results in a passage of the water and gas, resulting to failures in cementing operations,
- High fluid loss from cement slurries which cause water accumulation, resulting in micro-fracture within the cement body, and
- Cements not providing enough hydrostatic to control the high pressure formation.

Good displacement practices with the use of stable, fast-setting, low-fluid-loss slurries are important in solving gas zonal isolation problems in many but not all cementing operations failures, Stewart and Schouten (1988). The resulting slurry properties are affected by the slurry composition and the well conditions. The slurry composition effects include the dehydration of the liquid phase, gelation of the slurry, settling of the solid particles, and packing of the solid particles. The setting of cement starts when water is first in contact with the cement. At the beginning, the whole cement slurry column behaves as pure fluid and fully transmits the hydrostatic pressure. As the cement starts to set, settling and packing of the slurry continue. Once the cement structure starts to gel, the pore pressure inside the cement columns starts to decrease until it becomes equal to the pressure of the formation. Then as the cement pore pressure decrease more this will allow the gas to invade the cement pore spaces. If the cement permeability to gas is high and gas invasion occurs, the gas can permeate the whole cement matrix, charging it with enough gas (and pore pressure) to inhibit the hydration process from closing the pore spaces. When gas pressure is higher than the hydrostatic pressure after the cement initially set, a channel would form and gas would continue to migrate even after decreasing the formation gas pressure. There is a strong relationship between water separation in cement slurry and the loss of hydrostatic head of the cement columns. A good way to improve gas migration control is by using fluid loss additives and expansion additives. Fluid loss additives keep the water required for hydration of cement and slowly release it during the complete hydration process. In addition, fluid loss additives minimize the ability of fluids to flow thought the cement porosity. Using expansion additives improve bonding at the casing/cement and cement/formation area (Cheung and Beirute, 1985).

Gas can migrate when the cement is in the slurry form, if densities are not well designed. Slurry setting will prevent hydrostatic pressure transmission, and consequently, reduce pressure facing the gas zone. Slurries that minimize this transition time are desirable. At the end, the cement will solidify completely. In this case, the hardened cement should be resistant to mechanical and thermal stresses, if not a fracture may become an easy path for the gas. Optimizing slurry design is important to have zero free water and minimum fluid loss. Adjusting cementing properties based on conventional testing is not enough to confirm that the slurry will be gas migration resistant. Testing slurries on a gas flow simulator is an important tool for the optimizing process, Martins et al. (1997).

The use of latex additives help control gas migration in cement because cement pore pressure drop is delayed and the transition time between the liquid and set state is shorten. As long as the cement behaves as a true liquid, gas can channel up in the annulus when gas pressure is higher than cement hydrostatic pressure. Then density must be designed according to the formation pressure and the fracture gradient and must be controlled during the whole cementing operations (Drecq and Parcevaux, 1988).

Slurry density can be increased either by the reduction of slurry porosity (i.e., low water content) or the addition of inert high specific gravity materials (i.e., weighting materials). As the slurry density increases, controlling the desired properties becomes more and more difficult. A concrete slurry system based on optimizing the packing volume fraction (PVF) of the dry blend using sized inert particles (Pokhriyal et al., 2001) was used in Saudi Arabia fields with some success. Although we were able to have good cement slurries in the lab, the cement did not set in the field even after waiting on cement for 1 week. The collected samples showed solids settling. The density of the top of the tested cement sample was lower in density by more than 5 pcf than the bottom one.

The basic dry blend formulation is: Class G Cement + 35% BWOC silica sand + up to 185% BWOC hematite + 5% BWOC expansion additive at cement densities up to 170 pcf. As cement slurry sets, the hydrostatic pressure is reduced on the formation. During this transition, gas can leave the reservoir and travel up through the cement column resulting in gas being present at the surface. The permeable channels, from which gas flow, cause operational and safety problems at the well site. Current high density cement formulations do not provide good gas migration prevention due to settling and increase in permeability. To solve the settling problem and reduce permeability, a new formula is needed to prevent gas migration problems in cementing high pressure formations. The objective of this study is to develop a new cement formula that can prevent gas migration problems and show low settling problems compared to conventional formulations by utilizing different ratios of silica sand, flour, hematite and manganese tetraoxide.

2 FIELD EXPERIENCE WITH CONVENTIONAL CEMENT FORMULATIONS

The following additives were mixed in water at location with the biocide always being mixed first, then a retarder, a fluid loss additive, a dispersant, a defoamer, and a biocide.

In Khuff/Pre-Khuff wells latex additives may be required to reduce or prevent gas/fluid migration during the setting of cement. For wells that have considerable fluid or gas flow, latex is required. For wells that have the Khuff and pre-Khuff open together latex is required. On wells with mud weights equal to or greater than 135 pcf, latex is required. For wells with drilling fluid densities that are less than 120 pcf, conventional dry fluid loss additives are recommended. These wells with high mud density usually have had considerable flow from the formation. These muds have been gas and/or well fluid cut. The time, which is required to build the required mud volumes to obtain the proper mud weight, is usually more than a day. Expanding cement additives are required for wells that will be drilled with mud densities that are less than 15 pcf from the previous hole section. The reduction of pressure from reducing the mud density can cause the casing to shrink. This shrinkage can cause the casing to shrink. This shrinkage can cause the cement-casing bond to break and allow gas flow. This situation is more likely to occur as the depth increases. Expanding additives are also recommended for cement jobs where a gas producing formation is being cemented and the depth is greater than 10,000 ft, Jennings et al. (2003).

The most common problem associated with heavy weight cement slurries using hematite is settling. Some times, settling can be controlled by anti settling chemicals in the lab. However, controlling hematite settling in the field is not ensured even with the presence of a cementing specialist. Several wells experienced bad cementing job at the lower section of the well. Pressure testing showed a leak at the bottom of the cemented casings. In addition, cement settling is observed in the mixing tanks used to pump the slurries. The high weight cement slurry problem was due to hematite settling in the lower section. This explains the good upper cemented section and the bad job at the bottom, which caused fluid immigration through the lower section.

3 EXPERIMENTAL STUDIES

3.1 SLURRY PREPARATION PROCEDURE

The main requirement in the tested cement formula is to have density equal to 170 pcf. The formula is prepared in the lab using the standard API blender. The maximum rotational speed used during slurry preparation is 12,000 rotations per minute (rpm). The slurry was mixed for 15 seconds at 4,000 rpm and 35 seconds at 12,000 rpm, Nelson, 1990.

3.2 SLURRY RHEOLOGY

The slurry was conditioned in the atmospheric consistometer before obtaining the rheological readings. A Fann viscometer (Model-35) was used to evaluate the slurry rheology, Nelson, 1990.

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3.3 THICKENING TIME TEST

The prepared slurry was then poured into API standard HP/HT consistometer slurry cup for thickening time to evaluate the pumpability of the cement slurry, Nelson, 1990.

3.4 FREE WATER AND SLURRY SEDIMENTATION TESTS

When cement slurry is allowed to stand for a period of time prior to set, water may separate from the slurry migrating upwards. This separation can result in zone isolation problems. The free water test is designed to measure water separation using 250 ml graduated cylinder. The duration of the test is 2 hours according to API 10A procedure. Settling can be measured by comparing densities of different sections of the cement column cured, Nelson, 1990. Cylindrical shaped cell, used to cure the cement formula for settling test, has a diameter of 1.4″ and length of 12″. Sections of 2″ long were taken from the top, middle and bottom of the LDC column sample. The cement formula was cured at 3,000 psi and 280ºF for 24 hours. The density of each section of the LDC was measured using Model-1330 gas pycnometer.

3.6 GAS MIGRATION MODEL

The gas migration model consists of the following systems: computer, data acquisition, full-length permeability determination, two partial length permeability determinations, cement volume change measurement, gas flow meter, and electronic filtrate weight determination. The pressure and temperature limitations are 2,000 psi maximum and 350oF. Differential pressure must be used in the system when testing for deep gas migration with a maximum limit of 350oF. The schematic of the cement gas migration system is shown in Fig. 1.

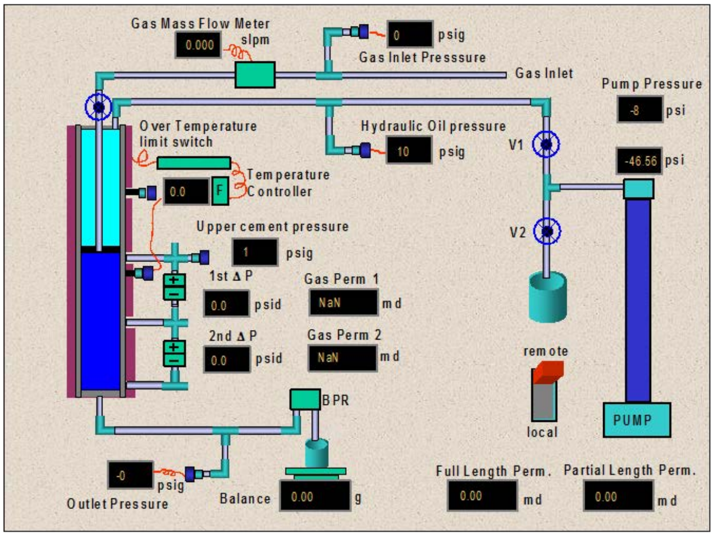

Fig. 1 A schematic diagram for the cement gas migration system

Cement slurry is mixed according to the current API 10B-2 procedure. The sample is then stirred in an atmospheric consistometer for the TRB (time to reach bottom). The cement slurry is then transferred to the pre-heated CGMS slurry cell and filled to the 900 cm3 mark using a depth gauge. All connections are made up, the data acquisition system is started and the gas injection begins. Nitrogen gas is injected through the rodded accumulator at the test pressure. A gas mass flow meter records the flow rate during the test. Gas injection pressure and flow rate are stored in a data set for later evaluation. The test is terminated sometime after five hours if no gas has migrated through the cement. An increase of gas flow rate is a good indication of gas migration for most tests.

3.7 MATERIALS USED IN THE NEW FORMULA

Silica Material

Portland cement has tricalcium silicate (C_3S) and dicalcium silicate (C_2S). When mixed with water both hydrate to form calcium silicate hydrate (C-S-H) gel. The C-S-H gel can provide good compressive strength for the cement at temperature up to 230 ºF. However, at higher temperature, C-S-H gel becomes under metamorphosis condition forming a phase called alpha dicalcium silicate hydrate (α-C_2SH) which cause decrease in compressive strength and permeability of set cement. To prevent the formation of α-C_2SH, the lime-silica ratio (C/S) should be reduced by addition of silica materials. The addition of silica material with cement, when hydrated, will form a phase known as tobermorite (C_5S_6H) at 230ºF instead of α-C2SH phase and high strength cement is resulted. Silica sand with an average particle size of 100 microns is used intensively in high density cementing operations, Nelson, 1990. Silica flour was used in the new formula in combination with silica sand for the first time to formulate the high density cement required to resist gas migration problems. The idea behind this combination is to increase the solids packing density of the cement blend and thus reduce the permeability of set cement to gads flow.

Expansion Additives

Adding expansion additive is important in cementing casings and liners. Magnesium oxides which were burned at 1200 °C were used as expansion additives, Rudi (2000).

Manganese Tetraoxide

Manganese tetraoxide (Mn3O4) was used in oil-based drill-in fluid. The properties of small particle size, spherical shape and high specific gravity of Mn3O4 make it good weighting material to reduce solids loading and settling compared to CaCO3 and BaSO4. Mn3O4 was used in oil-based drill-in fluid and due to its fine size it showed minimum settling profile. Low plastic value of 50% less was observed when using Mn3O4 compared to barite. The low plastic viscosity associated with Mn3O4 was a result of lower friction in particle to particle interaction due to their spherical shape, Franks and Marshall (2004). Manganese oxide was used with hematite and conventional cement to formulate sidetrack cement plugs, but not for high pressure formations, Al-Yami et al. (2006).

4 RESULTS AND DISCUSSION

All cement formulations were designed to have the required properties listed in **Table 1**. Low and high temperature retarders were used to slow down the setting of the cement and fluid loss additives to maintain the water within the cement slurry. Gas block (latex) was used to coat the cement and aid in gas migration prevention.

4.1 EFFECT OF MANGANESE TETRAOXIDE

Table 2 (Tests 1-14) shows detailed concentrations of manganese tetraoxide, silica sand, expansion additives and gas Block Additives. The table shows the duration of the test, fluid loss collected, and gas permeability of the cement slurry. The first parameter that we should consider is the test duration which should be around 5 hours without any sudden gas breakthrough. The test is terminated after 5 hours in order to clean the cell before cement slurry sets. Fluid loss and gas permeability are also important parameters to evaluate a certain formulation. In order to have a good cement formulation we should have minimum or zero fluid loss and gas permeability. Using manganese tetraoxide (Mn3O4) by itself as a weight material did not result in good fluid loss control. The main problem with all of these tests was the fluid loss control and the sudden gas break through. Gas block additives were varied from 1 to 2.5 GPS without any success in solving this problem. The lowest fluid loss was 42 ml with using 90% BWOC Mn3O4; however, we had a sudden gas break through after 223 minutes. As mentioned above, high fluid loss from cement slurries will lead to gas migration through the cement column.

4.2 EFFECT OF MANGANESE TETRAOXIDE & HEMATITE

Table 3 (Tests 15-27) shows detailed formulations for different weight ratios of manganese tetraoxide and hematite. The best combination was using 45% BWOC of Mn3O4 and 45% BWOC Hematite. The fluid loss control was improved greatly to only 3.7 ml but with using high concentration of gas block additives (latex) up to 3.5 GPS. Also, the test was terminated because of the sudden gas breakthrough after 231 minutes.

4.3 EFFECT OF MANGANESE TETRAOXIDE, HEMATITE, SILICA FLOUR AND SAND

Table 4 (Tests 28-30) shows detailed formulations for 45% BWOC of Mn3O4 and 45% BWOC hematite with different ratios of silica sand and silica flour. All three tests showed outstanding results in terms of zero gas permeability, long test period with no gas breakthrough and minimum fluid loss. The best formulation was obtained when 25% BWOC silica flour and 10% BWOC silica sand were used. The results showed zero gas permeability, zero fluid loss control and test duration time of 324 minutes.

4.4 SETTLING TEST

There are not standards set to show the minimum density difference between the top and bottom of cured cement samples tested for settling. It depends mainly on the cement density and field experience. Samples collected from successful cement jobs at this high density (more than 150 pcf) showed results up to 3 pcf difference. Samples collected from failure jobs showed more than 5 pcf difference. Since there is less than 5 pcf (pounds per cubic foot) difference in density from the top compared to bottom sections, then there is no settling problem with the formula to be used in deep gas wells, Table 5.

5 CONCLUSIONS

Different cement blends were tested to develop the best cement formula to resist gas migration commonly noted in deep gas wells:

1. Hematite, expansion additives and silica sand with cement at high densities, temperature, and pressure settled down and caused several operational problems in the field.
2. Manganese tetraoxide by itself does not provide good cement blend to control gas migration.
3. Adding hematite to manganese tetraoxide improved the gas migration resistance but did not stop the flow completely even when using high concentration of latex.
4. Using silica sand, silica flour, hematite, manganese tetraoxide with expansion additive showed the best performance in terms of gas migration problems, fluid loss control and minimum settling.

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Abbreviations

API : American petroleum institute
Bc : berden consistency
BHCT : bottom hole circulating temperature, ^{o}F
BHST : bottom hole static temperature, ^{o}F
BP : British Petroleum
BV : bulk volume, inch3
BWOC : by weight of cement
GPS : gallons per sack
TD : total depth, ft

Table 1: Required properties for all tested formulations to prevent gas migration at 280 °F and 3,000 psi

Cementing Requirement	Range
Thickening Time, hrs	7-9
Fluid Loss (ml/30 min.)	< 50
Free Fluid, %	0
Rheology, YP	>1
Sonic Strength (50-500 psi)	< 1 hour
Settling Density Difference	< 5 pcf
Fluid Migration (time for gas break through)	> 5 hours

Table 2: Lab results from cement formulations showing effects of Mn3O4

Test #	Test duration, min	Fluid loss, ml	Gas permea-bility, md	Formulation
1	223	42	0	CL-G cement+25% BWOC S.S.+5%BWOC E. +90% BWOC Mn3O4+1.5 GPS G.B.+0.25 GPS G.B.S.+1.15% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
2	240	64	0	CL-G cement+25% BWOC S.S.+5%BWOC E. +70% BWOC Mn3O4+1.5 GPS G.B.+0.25 GPS G.B.S.+1.15% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
3	301	52	0.1	CL-G cement+25% BWOC S.S.+5%BWOC E. +80% BWOC Mn3O4+1.5 GPS G.B.+0.25 GPS G.B.S.+1.15% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
4	350	75	0.2	CL-G cement+25% BWOC S.S.+5%BWOC E. +60% BWOC Mn3O4+1.5 GPS G.B.+0.25 GPS G.B.S.+1.15% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
5	122	44	1.5	CL-G cement+25% BWOC S.S.+5%BWOC E. +90% BWOC Mn3O4+1.0 GPS G.B.+0.25 GPS G.B.S.+1.15% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
6	102	66	7.1	CL-G cement+25% BWOC S.S.+5%BWOC E. +90% BWOC Mn3O4+1.5 GPS G.B.+0.2 GPS G.B.S.+1.35% BWOC H.T.R.+ 0.7% BWOC D. +0.50% BWOC L.T.R.
7	116	69	7.62	CL-G cement+25% BWOC S.S.+5%BWOC E. +90% BWOC Mn3O4+1.0 GPS G.B.+0.2 GPS G.B.S.+1.35% BWOC H.T.R.+ 0.7% BWOC D. +0.50% BWOC L.T.R.
8	296	117	0	CL-G cement+25% BWOC S.S.+5%BWOC E. +90% BWOC Mn3O4+2.0 GPS G.B.+0.25 GPS G.B.S.+1.2% BWOC H.T.R.+ 0.7% BWOC D. +0.55% BWOC L.T.R.
9	301	82	0	CL-G cement+25% BWOC S.S.+5%BWOC E. +90% BWOC Mn3O4+2.5 GPS G.B.+0.25 GPS G.B.S.+0.8% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
10	300	134	0.1	CL-G cement+25% BWOC S.S.+5%BWOC E. +70% BWOC Mn3O44+2.0 GPS G.B.+0.25 GPS G.B.S.+0.8% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
11	153	73	10	CL-G cement+25% BWOC S.S.+5%BWOC E. +70% BWOC Mn3O4+2.5 GPS G.B.+0.25 GPS G.B.S.+0.75% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
12	243	150	7	CL-G cement+25% BWOC S.S.+5%BWOC E. +60% BWOC Mn3O4+2.0 GPS G.B.+0.25 GPS G.B.S.+0.75% BWOC H.T.R.+ 0.7% BWOC D. +0.45% BWOC L.T.R.
13	64	86	1.1	CL-G Cement+25% BWOC S.S.+5% BWOC E.+90% BWOC Mn3O4+1.2% BWOC H.T.R. +0.7% BWOC D.+0.45% BWOC L.T.R.

14	45	57	7	CL-G Cement+25% BWOC S.S.+5% BWOC E.+110% BWOC Mn3O4+1.2% BWOC H.T.R. +0.8% BWOC D.+0.45% BWOC L.T.R.

S.S.: Silica Sand, E.: Expansion additive, H.T.R.: High Temperature Retarder, L.T.R.: Low Temperature Retarder, FL.: Fluid Loss additive, GL-G: Class G, S.F: Silica Flour, G.B: Gas Block Additive, G.B.S.: Gas Block Stabilizer, D.: Dispersant.

Table 3: Lab results from cement formulations showing Effect of Manganese Tetraoxide & Hematite

Test #	Test duration, min	Fluid loss, ml	Gas permeability, md	Formulation
15	283	188	5.5	CL-G Cement+60% BWOC H.+5% BWOC E.+30% BWOC Mn3O4+1.0 GPS GB+0.1 GPS G.B.S+1.2% BWOC H.T.R.+0.7% BWOC D.+0.45% BWOC L.T.R.
16	300	173	0.1	CL-G Cement+75% BWOC H.+5% BWOC E.+25% BWOC S.S+15% BWOC Mn3O4+1.5 GPS G.B.+0.15 GPS G.B.S.+1.2% BWOC H.T.R+0.45% BWOC L.T.R.
17	300	215	0	CL-G Cement+75% BWOC H.+5% BWOC E.+25% BWOC S.S.+15% BWOC Mn3O4+1.0 GPS G.B.+0.1 GPS G.B.S.+1.2% BWOC H.T.R.+ 0.7% BWOC D.+0.45% BWOC L.T.R.
18	104	82	5.4	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+1.0 GPS G.B.+0.2 GPS G.B.S.+1.2% BWOC H.T.R.+ 0.7% BWOC D.+0.45% BWOC L.T.R.
19	167	77	1.1	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+1.0 GPS G.B.+0.2 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.+0.3% BWOC F.L.
20	143	57	1.1	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+1.0 GPS G.B.+0.2 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.+0.6% BWOC F.L.
21	164	63	1.1	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+1.5 GPS G.B.+0.2 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.
22	186	57	1.2	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+1.5 GPS G.B.+0.2 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.+0.3% BWOC F.L.
23	109	50	1.1	CL-G Cement+30% BWOC H.+5% BWOC E.+25% BWOC S.S.+60% BWOC Mn3O4+1.5 GPS G.B.+0.2 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.
24	123	40	1.1	CL-G Cement+30% BWOC H.+5% BWOC E.+25% BWOC S.S.+60% BWOC Mn3O4+1.5 GPS G.B.+0.2 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.+0.3% BWOC F.L.

25	22	34	0.8	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+2.5 GPS G.B.+0.3 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.+0.2% BWOC F.L.
26	143	23	0.1	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+3.0 GPS G.B.+0.45 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.+0.3% BWOC F.L.
27	231	3.7	0	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+45% BWOC Mn3O4+3.5 GPS G.B.+0.5 GPS G.B.S.+1.2% BWOC H.T.R.+0.45% BWOC L.T.R.+0.3% BWOC F.L.

S.S.: Silica Sand, E.: Expansion additive, H.T.R.: High Temperature Retarder, L.T.R.: Low Temperature Retarder, FL.: Fluid Loss additive, GL-G: Class G, S.F: Silica Flour, G.B: Gas Block Additive, G.B.S.: Gas Block Stabilizer, D.: Dispersant.

Table 4: Lab results form cement formulations showing Effect of Manganese Tetraoxide, Hematite, Silica Flour and Sand

Test #	Test duration, min	Fluid loss, ml	Gas permeability, md	Formulation
28	290	0	0	CL-G Cement+45% BWOC H.+5% BWOC E.+10% BWOC S.S.+25% BWOC S.F.+45% BWOC Mn3O4+3.5 GPS G.B.+0.5 GPS G.B.S. +1.2% BWOC H.T.R. +0.45% BWOC L.T.R.+0.3% BWOC F.L.
29	316	1.6	0	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+10% BWOC S.F.+45% BWOC Mn3O4+2.5 GPS G.B.+0.35 GPS G.B.S. +1.2% BWOC H.T.R. +0.45% BWOC L.T.R.+0.3% BWOC F.L.
30	324	22	0	CL-G Cement+45% BWOC H.+5% BWOC E.+25% BWOC S.S.+10% BWOC S.F.+45% BWOC Mn3O4+1.5 GPS G.B.+0.30 GPS G.B.S. +1.2% BWOC H.T.R. +0.45% BWOC L.T.R.+0.3% BWOC F.L.

S.S.: Silica Sand, E.: Expansion additive, H.T.R.: High Temperature Retarder, L.T.R.: Low Temperature Retarder, FL.: Fluid Loss additive, GL-G: Class G, S.F: Silica Flour, G.B: Gas Block Additive, G.B.S.: Gas Block Stabilizer, D.: Dispersant.

Table 5: Settling results for cement formula # 28

Section	Measurements # 1, Density (pcf)	Measurements # 2, Density (pcf)
Top	150.11	150.38
Middle	151.35	151.58
Bottom	152.44	152.58