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Cementing Deepwater, Low-Temperature Gulf of Mexico Formations Prone to Shallow Flows

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Abstract

Shallow gas and water flows are a major concern when cementing deepwater wells in many Gulf of Mexico fields, often requiring expensive remedial work, premature well abandonment and respudding. Entire templates can be compromised if a single cement job on surface pipe fails to provide zonal isolation from the shoe up to the mud line.

Traditionally, compressible fluids (mainly foamed cements containing nitrogen) have been used to mitigate shallow-flow hazards in the Gulf of Mexico[1]. The disadvantages of these systems include safety concerns, complicated logistics, lack of reliability, placement problems, and lack of confidence in long-term cement integrity.

As an alternative to standard energized fluids, special cementing systems based on packing volume fraction and ratios of sized particles (particle-size distribution or PSD systems) have been used with success in water depths exceeding 6,000 ft in the Gulf of Mexico. This paper provides case histories and discusses the use of these innovative systems for deepwater situations. These systems are specially designed to provide optimized gel and compressive-strength development in low-temperature environments while allowing the thickening time to be tailored to any wellbore geometry. Slurry volumes from 1,500 to 2,500 bbl have been pumped without incident. The intrinsically low permeability and porosity of these systems at both the slurry and set-cement stages provide resistance to external attacks and influx of water or gas. In addition, these systems are tested and pumped using standard equipment, completely avoiding the complications of energized fluids; extra personnel are not required.

Introduction

Cementing operations through low-temperature formations prone to shallow flows are increasingly common in the deepwater Gulf of Mexico. Near freezing temperatures, flowing sands and lost circulation constitute key challenges in deepwater wells during critical surface pipe running and cementing operations. Low temperatures during cementing slow the hydration process considerably, compromising gel and compressive-strength development, which are essential to preventing fluid migration and providing structural support for the well.

Different operators and service companies have jointly agreed that several slurry and set-cement properties are instrumental in addressing shallow flow phenomena:

- Strict slurry density control at surface and downhole conditions.
- Adequate rheology for optimal mud displacement.
- Fast gel and compressive-strength development.
- Minimal shrinkage and low permeability.
- Engineered set-cement mechanical properties to ensure long-term hydraulic isolation.

PSD systems possess all these properties. In addition, they offer key advantages in safety and logistics at the wellsite.

Background

Shallow water flows have been identified by the oil industry in the Gulf of Mexico as one of the top challenges in deepwater drilling. More than 60% of all deepwater wells in the Gulf have experienced shallow water flows[2]. Overpressured sands may result from both slumping and rotating faults or from reworked cut-and-fill channels sealed by impermeable mud or clay.

Abnormally pressured sands have been found in water depths up to 6,000 feet below the mudline **(Fig.1)**. The pore pressure in these areas ranges from 9.0 to 9.6 lbm/gal equivalent mud weight reference rotary table according to pressure while drilling sensors and static flow checks of pilot holes. Shallow water flows rates might go from 10,000 to 100,000 B/D, often creating massive washouts and loss of the well or template.

Slurry Properties for Shallow Flow Mitigation

When cementing a surface casing in a deepwater environment, the challenge is to obtain the desired slurry characteristics coupled with the optimal set-cement properties. In deepwater wells, the temperature at the sea floor is usually 35° to 45°F, and the bottom hole static temperature (BHST) may be as low as 50°F. The density of the cement system has to be light enough to be placed without losses and heavy enough to keep the well under control. The required hydraulic and mechanical properties are often difficult to achieve under these conditions. Additionally, the cement system must meet logistical, economical and environmental requirements.

Free Fluid. The slurry should exhibit no free fluid. If the slurry has free fluid, channels will form that may impair zonal isolation. Free fluid will also lead to a slurry volume reduction. As water is removed from the slurry, the pressure in the cement column will drop, possibly leading to an influx of reservoir fluids into the annulus and compromising zonal isolation.

Stability. Slurry settling or sedimentation is undesirable. When continuous mixing systems are used and settling problems occur, sumps and c-pumps in the field become plugged, leading to costly downtime. Once the slurry is placed in the annulus, slurry settling might cause density differentials throughout the cement column that may result in insufficient hydrostatic pressure to maintain well control. Slurry settling also significantly alters the properties of the set cement, often leading to reduced mechanical strength and permeability increase.

Fluid-Loss Control. When excessive amounts of fluid are lost during placement (i.e., dynamic fluid loss), an increase in slurry density may occur, leading to a lost-circulation situation; at the same time, the rheology and thickening time will change. If static fluid loss (i.e., loss of fluid from the slurry after placement) is not carefully controlled, a slurry volume reduction and the associated drop in interstitial pressure can allow reservoir fluids to enter the slurry. API fluid loss values between 20 and 50 mL/30 min. are recommended.

Rheology. The rheological parameters should be specifically designed for effective annular displacement. Care must be taken that the slurry rheology allows for easy mixing in the field, especially when large volumes are needed. Adequate rheology is also important to prevent high equivalent circulating densities and minimize the chances of incurring lost circulation.

Thickening Time. Long thickening times (often in the range of 7-10 hr) are needed to place the large volumes of slurry required for surface casings in deepwater wells. Since API formulas and tables are not adapted to deepwater conditions, computerized-temperature simulators are used. These bottom hole circulating temperature (BHCT) models (**Fig. 2**) have to be closely followed by the cementing lab technicians during the thickening time (TT) tests. Additionally, TT tests for surface casings need to be shut down up to 45 to 60 min to verify the slurry is still pumpable should unexpected events halt the cementing process (for example, equipment failure or well control issues).

Gel-Strength Development. The gel-strength development of the slurry affects the hydrostatic pressure distribution and the flow of either gas or water into the cement filled annulus, a phenomenon known as fluid or gas migration.

The risk of invasion or inflows into the cement matrix is greatest during the critical hydration period (CHP) that begins when the hydrostatic column no longer balances the pore pressure[3,4] (**Fig. 3**).

The point where the CHP begins is defined as critical wall shear stress (CWSS). This is the gel strength value in which the cohesive forces between the cement slurry, the wellbore walls and the casing become strong enough to cause the hydrostatic pressure to decline to a pressure equivalent or lower than the formation pore pressure. The value of the CWSS can be calculated based upon the geometry of the cemented portion of the wellbore, the pressure at the top of the cement column, and the height and density of the cement column. CWSS calculations are best achieved through the use of computer simulators.

The upper value of the CHP marks the latest stage of the hydration period, which ends when the slurry has developed enough strength to prevent the entry and flow of reservoir fluids into the annulus. The end of the CHP relies upon the properties of the cement slurry and the formation fluids. This value is not easily calculated and has to be determined experimentally by using an apparatus called the Cement Hydration Analyzer (CHA) (**Fig 4**).

The various static gel-strength development stages can be measured with a specialized apparatus, such as the Vane Rheometer among others.

The shorter the measured CHP, the better the chances for controlling fluid migration. CWSS, decrease in the gel strength value, and slope of the gel strength versus time curve are three factors that can be changed to minimize the CHP.

The industry had so far recognized that the time that it takes for a slurry to go from a gel strength value of 100 lbf/100sqft to 500 lbf/100sqft can be used as a default CHP for practical purposes (Fig. 5).

Mechanical Properties. The loss of zonal isolation with time due to changing downhole conditions is often observed on surface casings, even in situations where the cement had an adequate compressive strength, was properly placed and initially provided a good hydraulic seal. This isolation failure is revealed, for example, by an annular pressure increase due to gas or water inflows. Cracks in the cemented annulus, along with bonding problems at the casing-cement and cement-formation interfaces might lead to catastrophic zonal isolation problems.

A methodology to design a cement for surface casings that withstands constant changes in downhole conditions is complemented by a set-cement stress analyzer simulator. The input data to the software include the well geometry, casing, cement and formation thermo-elastic properties and the expected variation of downhole conditions. Once the required values of the cement elastic parameters have been determined, correlations are used to estimate the concentration of flexibility-inducing additives to be added to the slurry. The slurry-design process aimed at obtaining durable set cement typically follows the standard methodology used for PSD systems.

Compressible Cements

Compressible systems are usually created by dispersing gas (nitrogen or air) into a cement slurry containing foaming agents and stabilizers. These systems are usually known as foamed cements. Foamed cement density is determined by the characteristics of the base (unfoamed) slurry, the amount of gas injected, and the downhole temperatures and pressures encountered during the slurry placement.

A key factor when executing a foamed cement job is to keep the density constant throughout the cement column. This operation is relatively complex since the gas rate must be continually increased in stages throughout the slurry mixing operation in an attempt to match continuously changing downhole conditions. Practically, the interval to be cemented must be divided into shorter sections and the gas/cement ratio adjusted throughout the job. This results in a foamed cement column that has a varying density for each short section.

The use of automated systems to monitor and control the process of steadily adding gas to the slurry has improved the design and quality of foamed cement jobs somewhat, but it is unclear whether the measured slurry properties are representative of the entire cement column. This is due to the fact that most cementing laboratory tests are performed on base slurries and not on the actual fluids to be pumped downhole. Besides, downhole foamed cement densities depend on hydrostatic pressures that might be substantially different from the simulated ones due to actual mud weight variations and complexities of the wellbore geometry not taken into account during the design process. Only static or pseudo-dynamic well security can be determined for foamed cement since its rheologies cannot be easily measured.

The logistics of foamed cementing systems are complicated. Specialized personnel are required to execute a foamed cement job. Extra personnel are required to run the gas (nitrogen or air) equipment, and safety concerns related to energized fluids are always present **(Fig. 6)**. Foamed cement slurry requires specialized process-control because the slurry properties (density, gas ratio) are constantly changing due to varying downhole pressures during pumping operations. Complex laboratory equipment, often unavailable at field level, is necessary to test foamed cement properties.

PSD Systems

A cement design methodology based on PSD systems **(Fig. 7)** has been recently introduced for the design of deepwater slurries that prevent inflows during the setting process. These systems allow for the optimization of the set cement mechanical properties, improving long-term zonal isolation prospects in comparison with standard compressible systems.

Once the dry blend has been optimized by the addition of particles that improve the mechanical properties of the set cement, the slurry design can be formulated with conventional additives.

The main advantages of PSD systems are:

- Slurry and set cement properties are independent of the solids/liquid ratio (density).
- A wide range of densities can be achieved with minor changes in the dry blend composition.
- Intrinsic fluid loss control is provided by the characteristics of the blend, reducing the need for high concentrations of fluid loss additives.
- Fast gelling and compressive-strength development.
- Low slurry and set-cement permeability and porosity, which improve the resistance to shallow water or gas influx.
- Set-cement elastic properties can be controlled and engineered to match casing and formation mechanical properties
- Density variations have minimal effect on slurry stability and set cement properties.
- Minimal additional training is required for cementing personnel.
- No additional personnel are necessary for the cement job.
- No additional safety procedures are required; no energized fluids are used at the wellsite.

Case Histories

Surface casings in deepwater areas play a vital role in the life of the well, providing wellhead structural support and often serving as a barrier against plastic formations (Fig. 8). These casings are frequently set in unconsolidated, washed-out zones where the prevailing low temperatures are not conducive to a rapid cement gel- and compressive-strength development, which are key factors in shallow flow prevention and casing support. Commonly, the correct design and execution of surface casing cement jobs in deepwater wells are more crucial to well integrity and productivity than the equivalent processes for production casing or liner strings. A poor surface casing job has the potential to endanger entire templates, which might require well abandonment and the loss of millions of dollars[5].

In order to mitigate the risks associated with loss of isolation across surface casings in deepwater, PSD systems have been successfully utilized for annular flow prevention during and after cementing. Two case histories in water depths in excess of 6,000 ft in the Gulf of Mexico (GoM) demonstrate how PSD systems successfully cemented 20" surface casings in open hole diameters ranging from 24" to 40" **(Fig. 9)**. In both jobs, more than 2,000 bbls of slurry were pumped to ensure cement returns at the mud line. PSD cementing systems achieved the objectives for these casings while minimizing the amount of cementing equipment and personnel at the location. Reducing the exposure of personnel and rig equipment to high pressure and eliminating the use of energized fluids (nitrogen) were a common goal for both Operator and Service Company.

Comprehensive cement placement simulations were performed during the design phase, including centralizer optimization, circulating temperature prediction and mud removal efficiency. A state-of-the-art simulator, handling heat transfer effects and multiple temperature gradients, accounting for well deviation, annular geometry, type of formations, fluid rheologies and flow regime was essential in predicting the outcome of these jobs. Special attention was placed on effective casing centralization design, even though both wells were practically vertical. Casing standoffs on wells presenting deviations of less than 3 degrees have been proved to be detrimental to the successful outcome of surface jobs. Actual measured deepwater temperature data have been collected in many offshore areas in order to validate the computer models utilized during the cementing design process. The output of the temperature simulator was used by the cementing laboratory personnel to optimize all the cementing fluid properties.

Additionally, the cement sheath mechanical response under worst-scenario downhole conditions (extreme temperature differentials) was analyzed and determined. Cement placed in the annulus between the casing and the formation provides long-term isolation between the different formations penetrated by the wellbore. But even if the slurry was properly placed during the cementing job, and initially fulfills its isolation role as pointed out above, changes in downhole conditions can induce sufficient stresses to destroy the integrity of the cement sheath. To quantify stresses caused by temperature changes on the order of 200°F (roughly equivalent to the difference between mud line and downhole temperatures at the producing horizons of these wells) and to determine the required properties the cement would need to avoid loss of integrity throughout the life of the well, numerical modeling was carried out as a function of well geometry, cement and formation mechanical properties. This analysis demonstrated that due to their improved elastic properties once set, the PSD set cement offers improved mechanical resistance to changes in downhole conditions compared with conventional systems **(Fig. 10)**.

Both 20" jobs were successfully executed as per design and the pumping process made available to personnel in the office in real-time through a dedicated service company web site **(Fig. 11a & 11b)**.

Conclusions

PSD slurries based on multicomponent, engineered blends are relatively simple to design and are mixed the same way as standard cementing systems. No additional training, equipment, or personnel are required. The yield of the PSD blends depends entirely on the water/cement ratio and amount of blend relative to hole size. Slurry formulations can be optimized for deepwater applications, where low bottomhole static and circulating temperatures are common. The low water content of these systems enhances the early gel and compressive strength development, while low densities minimize the risk of losses associated with the low fracture gradient encountered in many deepwater wells in shallow-flow prone areas. The resulting set cement displays an extremely low permeability and engineered elastic properties that ensure superior zonal isolation throughout the productive life of the well and after its eventual abandonment. In contrast, foamed cements frequently involve different gas ratios in several stages to meet slurry and set-cement design requirements. Due to compressibility of gas, annular fill depends on good knowledge of hole size and proper design, mixing and placement of various foamed stages.

Examples from the deepwater Gulf of Mexico demonstrate the ease of job designs and the efficiency of PSD operations. Complemented by laboratory testing and computer simulations, PSD systems offer previously unattained similarity between cementing plans and cementing results.

Acknowledgements

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Conversion Factors SI METRIC

bbl x 0.1589 = m^3

ft x 0.3048 = m

in x 25.4 = mm

gal x 3.7854 = ltlb/gal

lb/gal x 0.12 = kg/lt

lbf/100 ft^2 x 0.48 = Pa

(degF – 32) x (5/9) = degC

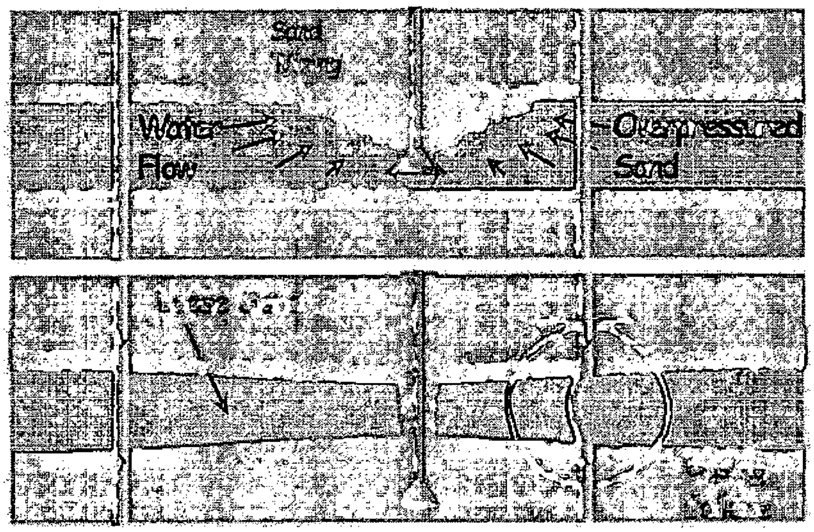

Fig 1. Loose sands (bottom) and shallow water flow (top) could lead to a primary cement job failure.

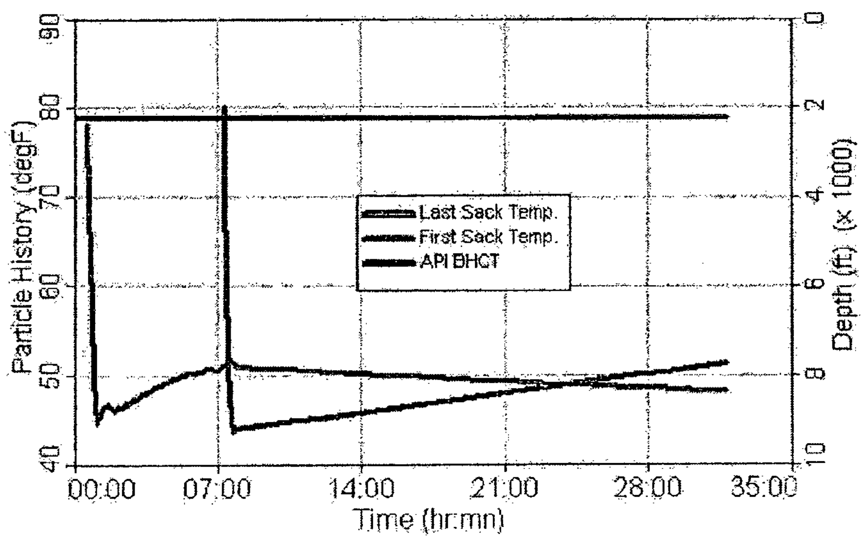

Fig. 2 – Temperature simulation: BHCT while pumping for first 7:20 hr:min and BHST for the last 24:00 hr:min

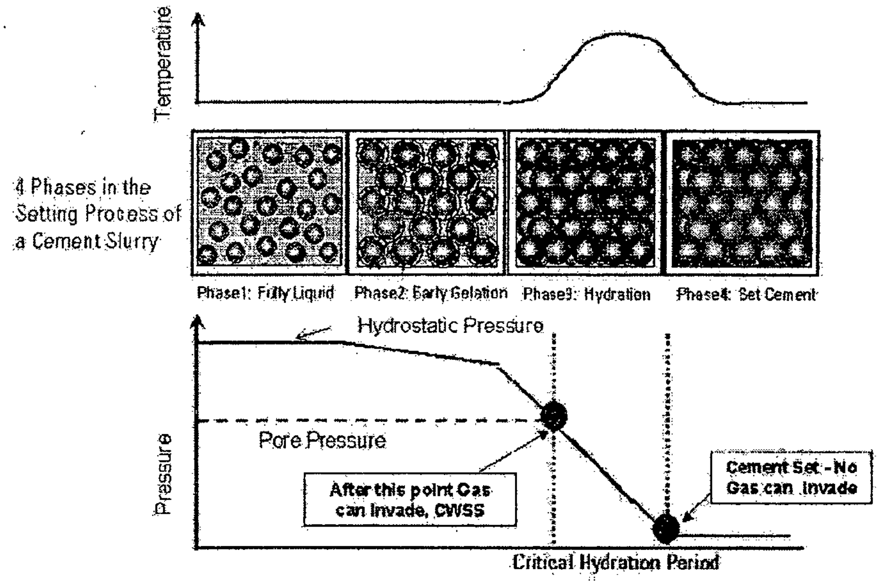

Fig. 3 – The Critical Hydration Period occurs during the Hydration Period of the slurry.

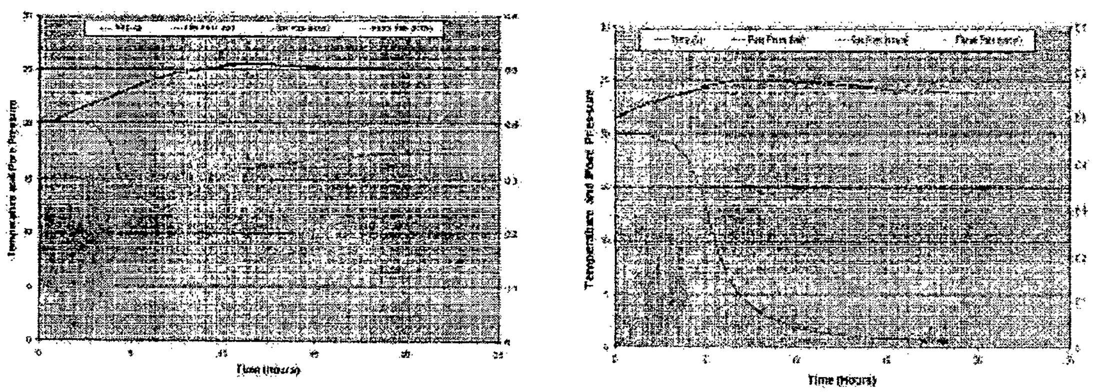

Fig 4. Cement Hydration Analyzer graphs. (Left graph shows gas invading cement; right graph shows no flow through cement).

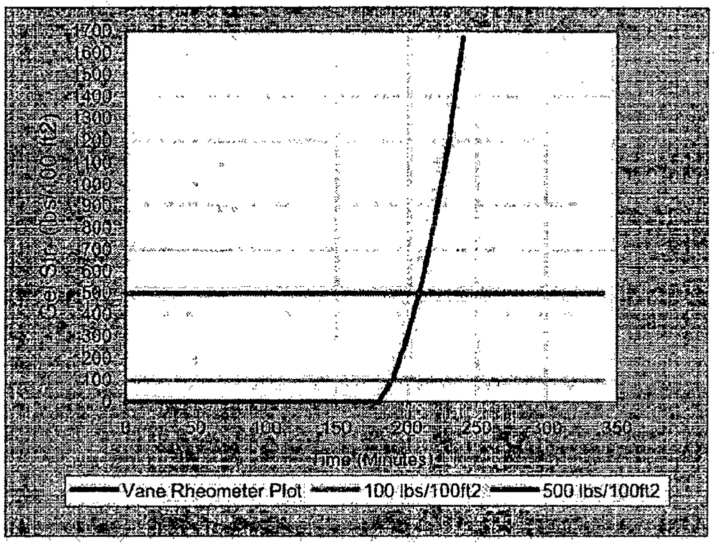

Fig 5. Static Gel Strength vs Time from Vane Rheometer

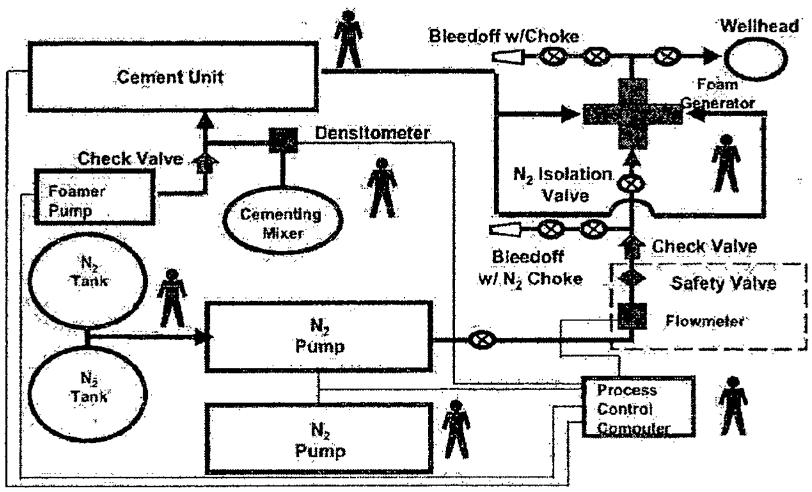

Fig. 6. Typical Foamed Cement Setup

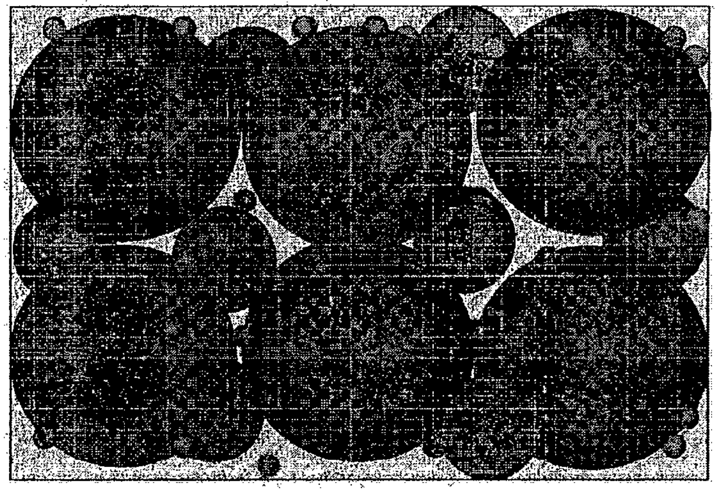

Fig. 7 –Set cements based on Particle Size Distribution blends display very low permeability, improving long-term zonal isolation.

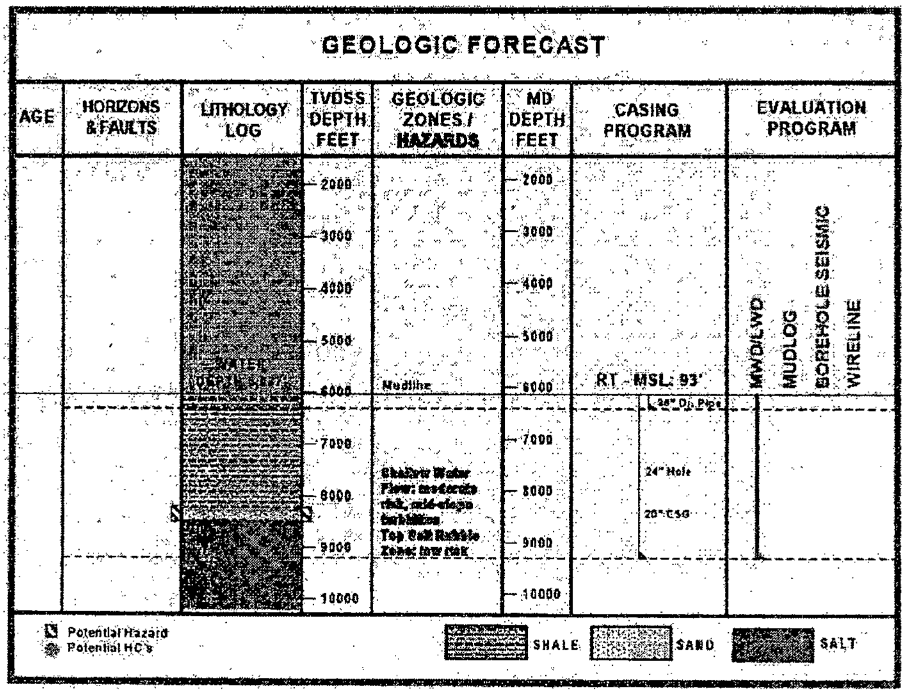

Fig. 8 Geological forecast for conductor casing.

Basic surface casing cementing programs			
Cement type:	PSD blend		
Top of Cement length	Mud Line		
Fill length:	3,230 ft		
Open hole excess:	> 150%		
Volume:	2,300 bbls & 1,995 bbls		
BHST:	80 degF		
BHCT:	50 degF		
Formulation & Basic Properties			
Density:	13.20	PSD blend	1.00 sack
Yield:	1.46	Brine (9 ppg)	4.17 gps
Mix Fluid:	4.91	Antifoam	0.02 gps
Thickening Time:		Fluid Loss	0.50 gps
70 Bc:	9:08	Dispersant	0.12 gps
100 Bc:	9:28	Set Enhancer	0.10 gps
Gel Strength			
100 lbf/ft2:	3:10		
500 lbf/ft2:	3:29		
Compressive Strength			
12 hrs:	175		
24 hrs:	700		

Fig. 9 – Cementing job summary.

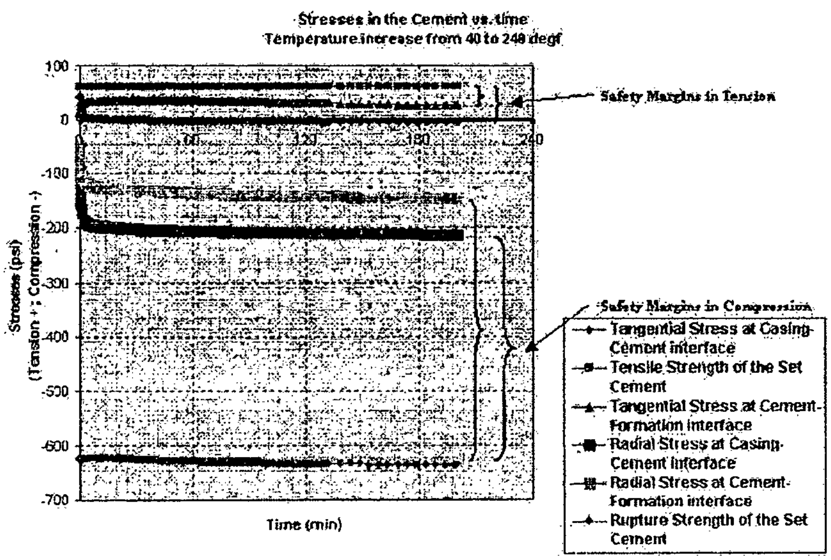

Fig 10. Stress analysis under extreme temperature change for a PSD system.

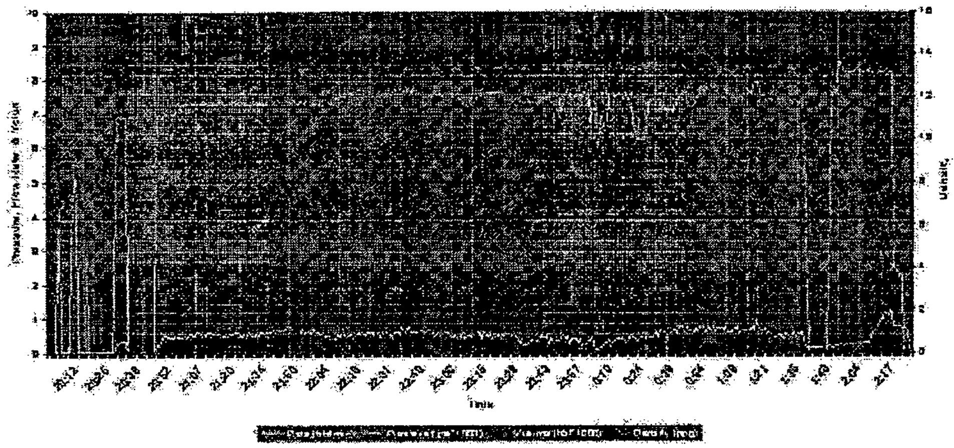

Fig. 11a – Execution of a 20" job in the GoM, where 2350 bbls of 13.2 ppg PSD slurry were pumped.

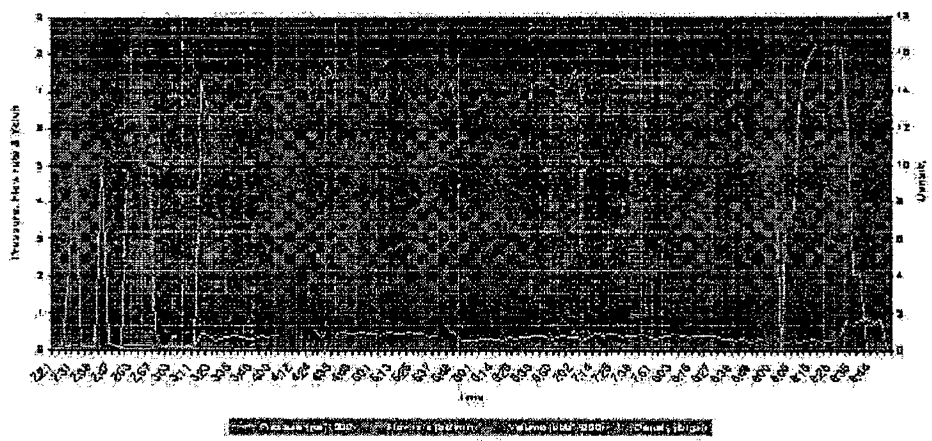

Fig. 11b – Execution of a 20" job in the GoM, where more than 1900 bbls of 13.2 ppg PSD were pumped.