IBP1025_06

NEW APPLICATION OF TECHNOLOGY ASSISTS IN PETROBRAS DEEPWATER SUCCESSES

David S. Kulakofsky[1], Paulo Souza[2], Marcelo Sledz[3]

Abstract

With today's ever-increasing demand for energy, operators are forced to drill more and more difficult wells. This quest for new oil means operators will be forced to drill in deeper water, through depleted zones, into over-pressured zones, through highly fractured zones, with longer intervals to be cemented in one stage and through younger, weaker formations. To successfully complete these wells, the cementing operation should yield long-term zonal isolation under this varying array of challenges. Over the years, the industry has developed many different solutions for cementing problems. Research has shown that no single cementing solution is the correct answer for every well problem. The subject paper will use deepwater case histories to illustrate how this new application of technology makes it easier for the operator to choose the right solution for their current problem. Pros and cons for the various solutions will be tabulated, along with guidelines for pairing job and well conditions with the most appropriate solutions.

Com o aumento da demanda de energia visto hoje, as companhias petroleiras são forçadas a perfurar cada vez mais e em poços com muitos desafios. Isso leva às operadoras a perfurar em águas profundas, em zonas depletadas, em zonas de altas pressões, em zonas altamentas fraturadas, com longos intervalos a serem cimentados em apenas um estágio e em formações debilitadas. Para que tenhamos sucesso na perfuração desses poços, a operação de cimentação do poço deve ser tal que tenhamos um isolamento ou selo de longa duração, sob as condições de poço existentes. Ao longo dos anos, a indústria desenvolveu diferentes soluções para os problemas de cimentação. A experiência tem mostrado que uma única solução não é a resposta para todo tipo de problema. Este trabalho, usará casos históricos de poços em águas profundas para ilustrar como essa nova aplicação de tecnologia faz as companhias petroleiras escolherem a solução correta para seus problemas. Prós e contras para várias soluçções serão apresentadas, com recomendações e condições de poço com soluções apropriadas.

1. Introduction

The standard water requirements for oilfield cements typically yield densities in the 15.6 to 16.4 lb/gal range. When wellbores encounter weak and/or depleted zones, standard cement often cannot be used because the high densities cause bottomhole circulating pressure (BHCP) that may exceed the rock strength, open fractures in the rock, and create flow paths for the cement to be lost to the formation. If a portion of the cement is lost to the formation, top of cement (TOC) will be reduced.

If the TOC is significantly lower than designed, remedial cement jobs may be required, wasting valuable drilling days and driving up the well construction costs. To avoid losing bulk cement slurry to the formation, the cement slurry density can be reduced to a level where the hydrostatic pressure plus the frictional forces are less than the fracture gradient. In less difficult drilling conditions, adding extra water (and necessary water-extending additives that will tie up the extra water) can reduce the slurry density sufficiently to allow the cement to be circulated, reaching the desired or required TOC.

As additional water is added, above the standard 4 to 6 gal/sk water nominally required to mix cement, the cement becomes more dilute, strength declines, and permeability increases. As the density decrease approaches

[1] Chemical and Ocean Engineer, Sr. Product Champion - HALLIBURTON
[2] Engineer, Cementing Sales Leader – HALLIBURTON
[3] Engineer – PETROBRAS

11 lb/gal, the dilution affect becomes so great that compressive strength development is too slow or so low that it becomes impractical for use in oil or gas wells.

Kulakofsky et al. (2003, 2005a) reported that wells requiring densities <11 lb/gal or a higher-quality cement than one gets from water-extended designs at densities >11 lb/gal, the industry has turned to using lightweight microspheres (LMS) or stable foam for density reduction. Both of these alternative systems have advantages compared to water-extended systems and when compared to each other.

In the LMS method, lightweight microspheres composed of relatively inert materials are added to the cement slurry. The key advantages of the LMS systems include:

- Can create competent cement down to 6.5 lb/gal.
- Can create a set cement sheath with near normal cement properties at much lower densities.
- Can provide the fastest strength development of any system at a given density (meaning a reduced waiting on cement (WOC) time).
- Can provide the lowest permeabilities at a given density.
- Can use conventional mixing equipment.

The second premium method to provide cement slurry density reduction involves delivery of a stable foam. The preferred technology calls for the injection of nitrogen through a properly sized choke and injection of special chemicals to stabilize the foam. Advantages from placing a foamed cement in oil and gas wells include:

- Can create a high-quality, low-density cement slurry.
- Can increase set cement elasticity.
- Can increase liquid-state compressibility.
- Can be very cost effective.

If the nitrogen concentration becomes too high, a permeable cement matrix can result. Various references (Ravi et al., 2002; Pine et al., 2003; Benge et al., 1982; Sweatman, 2003) indicate that to prevent a substantial increase in the set cement permeability (when compared to conventional cement), it is critical to keep porosity below 40%, but ideally below 30%. Cement can be foamed down to any density by simply adjusting the nitrogen concentration. Kulakofsky et al. (2005b, 2006a) determined that since the ideal gas volume concentration (i.e. meaning a balance of increased elasticity, increased compressibility, good strengths, and low permeabilitiy maintenance) is 10 to 30%, the resulting downhole densities typically only are reduced to between 70 and 90% of the base fluid density. Thus, typical downhole foam density ranges upward from 10 lb/gal.

2. The Problem

The Campos Basin (**Figure 1**) contains many of Brazil's most productive reservoirs (**Figure 2**). Typically deepwater equates to younger formations. Young formations commonly have lower fracture gradients. Thus, the difficulties associated with drilling in deepwater are magnified by lost-circulation concerns. To avoid lost-circulation problems, lightweight cement slurry designs are required. Traditionally, lightweight cement has relied on water extended designs to provide the required density reduction. Since reducing cement slurry density with extra water yields the least expensive slurries, operators have shown some reluctance to switch to the newer and more expensive technologies that, while more expensive, provide far superior set cement sheath properties and/or drastically reduced WOC times. Reduced WOC times mean the rig can begin the next phase of the well plan quicker, minimizing non-productive time (NPT).

Another problem facing operators in the Campos Basin (as well as many other parts of the world) is how to achieve an effective annular cement seal with typical water-based cement when the well is being drilled with an oil-based mud (OBM) or a synthetic-based mud (SBM) as the external phase. Recent advances in spacer design are required to address the issue of effective mud removal and re-water wetting the formation and pipe.

A final problem faced in these and other similar deepwater wells around the world is effective usage of cementing plugs. Cementing plug technology has advanced substantially from the original wooden plugs. Current technological advances include non-rotating inserts and higher efficiency wiper blades on the outside. Cementing plugs are used to:

- Separate the mud from the spacer
- Separate the spacer form the cement
- Separate the cement from the mud
- Wipe the inside of the pipe clean
- Provide a positive indication of when the cement has been properly displaced into the annulus.

Traditionally one or more plugs are loaded into a plug container, which is affixed to the top of the casing, and through the operation of a set of valves, in which the plug or plugs are dropped (or pumped) into the casing string.

With deepwater wells, subsea wellheads have become the norm. Standard plug sets and plug containers do not work in these scenarios.

Figure 1. Location of the Campos Basin

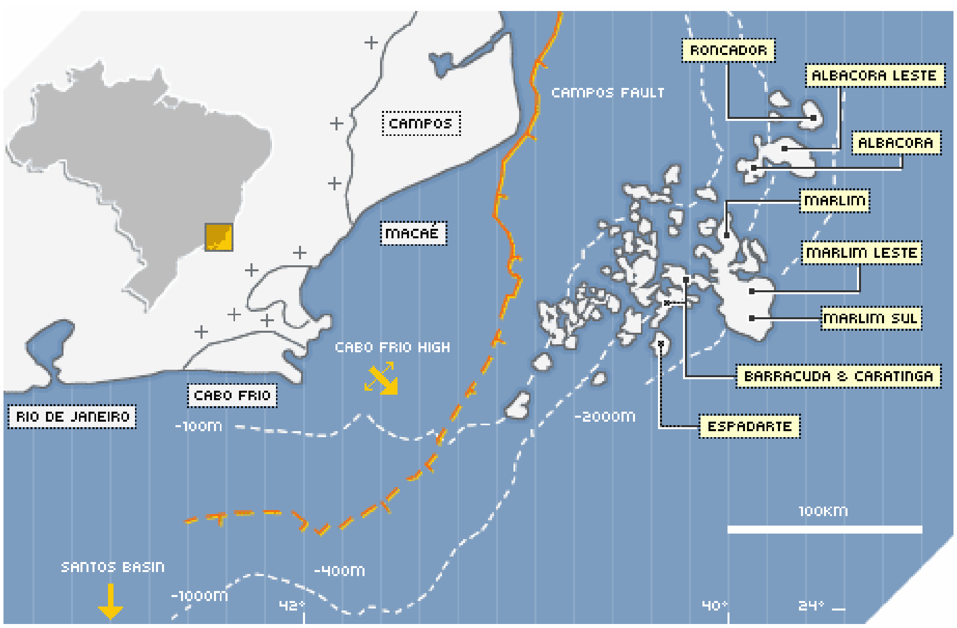

Figure 2. Major Fields of the Campos Basin

2. New Technology Solutions

In the Campos Basin it is common for the cement slurry densities to be reduced from the standard density of 15.6 lb/gal down to a range from 11 to 12.5 lb/gal. In **Figures 3 and 4** we see compressive strength development curves for typical water extended designs used previously in offshore Brazilian wells. From these curves two things become readily apparent. First, compressive strength development with this class of cement slurry designs is slow, and second, even after several days, the maximum strength is very low as well. In **Figure 5** we can see how microsphere technology has allowed us to address both of these issues. Notice how the initial set time, which was 19 and 27 hours (**Figures 3 and 4**), is now only 7 hours, and the compressive strength, which was barely useable, now exceeds 700 psi after only 18 hours. Not only does the microsphere slurry exhibit superior strength in this example, but it does so at 11 lb/gal. Imagine how much better it would look at the higher 12.5 lb/gal density at which our two water-extended designs were tested or the 13.5 lb/gal jobs listed in **Table 1**. The addition of the traditional pozzolanic based microspheres to a slurry will not increase strength or decrease set time by themselves. The benefit is derived from the fact that the same reduced density can be achieved without having to add as much water to the system. It is this reduction in the cement-to-mix water ratio that the benefits from microspheres are realized.

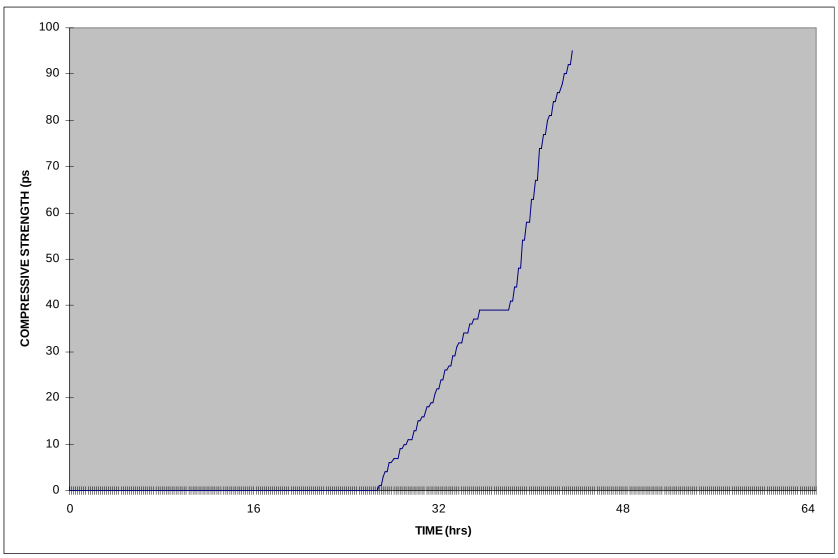

Figure 3. 12.5 lb/gal sodium silicate water-extended design

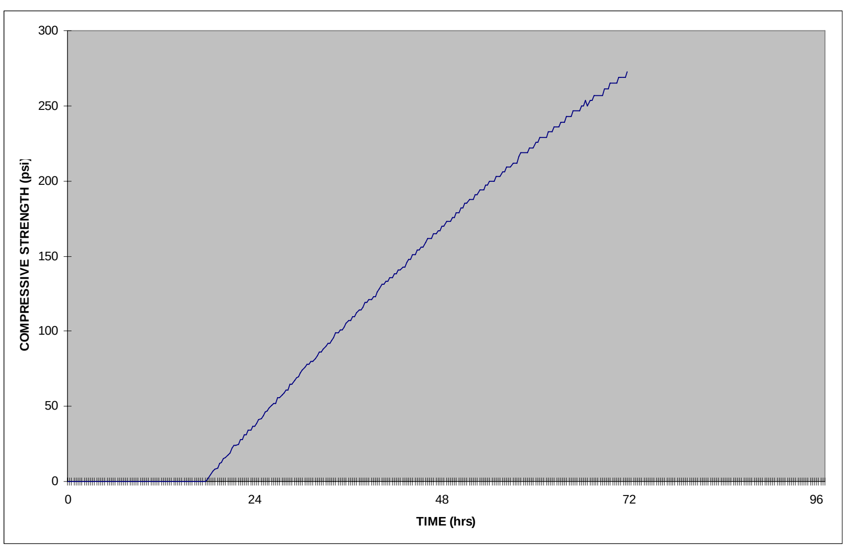

Figure 4. 12.5 lb/gal sodium silicate water-extended design

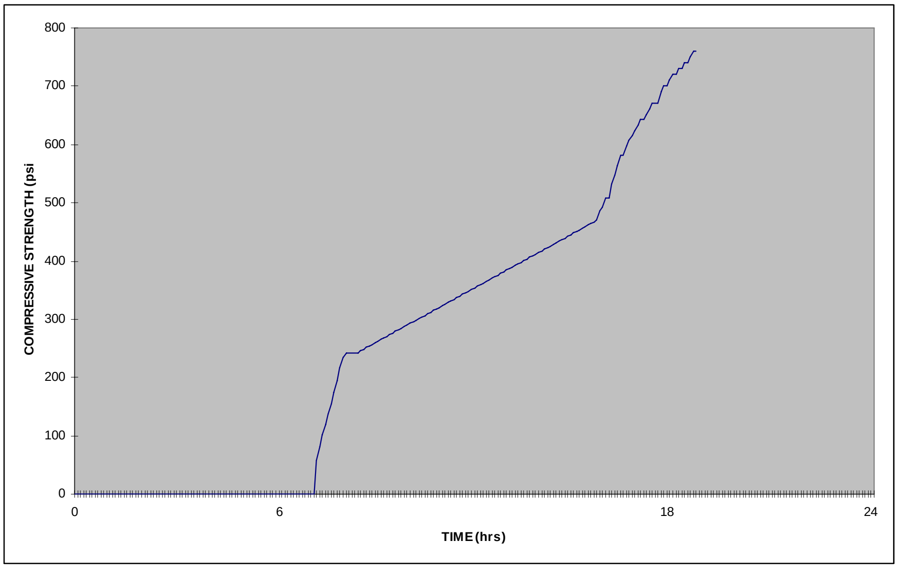

Figure 5. 11.5 lb/gal pozzalanic microsphere design

Table 1. Recent Microsphere Jobs in the Campos Basin

CUSTOMER	PROJECT NAME	WATER DEPTH	JOB TYPE	CSG SIZE	LEAD CMT TYPE	COMMENTS
PETROBRAS	-	-	-	9 5/8"	12.50 lb/gal	Cement circulated
PETROBRAS	RJS-551	1,489 M	Production Casing @ 3,890 M	9 5/8"	12.00 lb/gal	Cement circulated
PETROBRAS	RJS-558A	2,483 M	Production Casing @ 4,950 M	9 5/8"	11.50 lb/gal	Cement circulated
PETROBRAS	RJS-561	2352 M	Production Casing @ 3,514 M	9 5/8"	11.50 lb/gal	Cement circulated
PETROBRAS	1-RJS-566	1207 M	Production Casing @ 4,256 M	9 5/8"	11.50 lb/gal	Cement circulated
PETROBRAS	1-RJS-568	1629 M	Production casing @ 3,734 M	9 5/8"	11.50 lb/gal	Cement circulated
PETROBRAS	7-CRT-21HP-RJS	888 M	9 5/8" Production Casing @ 3,083 M	9 5/8"	12.00 lb/gal	Cement circulated
PETROBRAS	9-ESP-14D-RJS	923 M	9 5/8" Production Casing @ 3,508 M	9 5/8"	12.50 lb/gal	Cement circulated
PETROBRAS	7-BO-22H-RJS	216 M	7" Production Liner @ 2,576 M	7"	12.50 lb/gal	Cement circulated
PETROBRAS	7-ESP-13H-RJS	948 M	9 5/8" Production Casing @ X,XXX M	9 5/8"	12.50 lb/gal	Cement circulated
PETROBRAS	7-ESP-15H-RJS	864 M	9 5/8" Production Casing @ 3,721 M	9 5/8"	12.50 lb/gal	Cement circulated
PETROBRAS	1-RJS-582	1493 M	9 5/8" Casing job @ 4,801 M	9 5/8"	11.50 lb/gal	Cement circulated
PETROBRAS	7-ESP-17-RJS	837 M	9 5/8" Casing job @ M	9 5/8"	13.50 lb/gal	Cement circulated
PETROBRAS	7-BR-56H-RJS	741M	9 5/8" Casing Job @ 3379,59 M	9 5/8"	13.50 lb/gal	Cement circulated
PETROBRAS	1-RJS-587	1391 m	9 5/8" Casing Job @ 5,187 m	9 5/8"	11.50 lb/gal	Cement circulated
PETROBRAS	3-ESS-135	1316 m	9 5/8" Casing Job @ 3,315 m	9 5/8"	12.80 lb/gal	Cement circulated
PETROBRAS	9-JUB-5-ESS	-	9 5/8" Casing Job at	9 5/8"	12.20 lb/gal	Cement circulated
PETROBRAS	6-ESS-139	1402 m	9 5/8" Casing Job at 3,020 m	9 5/8"	12.20 lb/gal	Cement circulated
IOC	Curio	2,500 M	Surface Casing	20"	12.50 lb/gal	Cement circulated
IOC	Curio	2,500 M	Surface Casing	13 3/8"	12.50 lb/gal	Cement circulated
IOC	Grimpeiro	2,100 M	Surface Casing	20"	12.50 lb/gal	Cement circulated
IOC	Grimpeiro	2,100 M	Surface Casing	13 3/8"	12.50 lb/gal	Cement circulated
IOC	Simao	1,639 M	Conductor Casing	20"	12.50 lb/gal	Cement circulated
IOC	1-KGMB-2-SPS	1520 M	13 3/8" Casing Job @ 2905 M	13 3/8"	12.00 lb/gal	Cement circulated
IOC	3-ELPS-15-SPS	168 m	Recementing 13 3/8" x 30"	Annular ID 30"x 13 3/8"	12.50 lb/gal	Cement circulated

During the last few years, world-wide usage of alternative microspheres has been increasing. Some types of alternative microspheres are used to modify the mechanical properties of the set cement sheath. In some instances modifying the mechanical properties can be very beneficial to the resulting lightweight sheath if it is required to provide long-term zonal isolation in a high-stress environment. Because these plastic materials usually have a specific gravity around unity, the minimum slurry density often is limited to 10 to 11 lb/gal., which meets the current Brazilian requirements, but cannot deliver ultra-lightweight cementing densities unless combined with other techniques. A second superior type of microspheres, when compared to pozzolan-based materials, are hollow glass bubbles. The key advantages of this material are superior quality control and a reduced specific gravity. The specific gravity varies from 0.28 to 0.61, depending on collapse pressure requirements. The primary advantage of using a bubble with a reduced specific gravity is that less of the material will be required to achieve the same water ratio reduction at any given density. Since these lightweight particles have such a large bulk volume, as the required mass goes up, the volume percent of cement decreases. If the cement volume concentration becomes too low, the set properties start to degrade. Thus at a given density, less material is required, or for a given volume or mass percentage of material, a lower slurry density can be achieved when using lighter microspheres. An example of this can be seen when comparing **Figures 5 and 6.** The decrease in set time, increased rate of strength development, and higher short term strength are all due to the reduction in filler volume (less microspheres). The ability to use less microspheres and still yield the same density reduction in our cement slurry is directly related to the glass microspheres being lower in specific gravity than the material used in **Figure 4.**

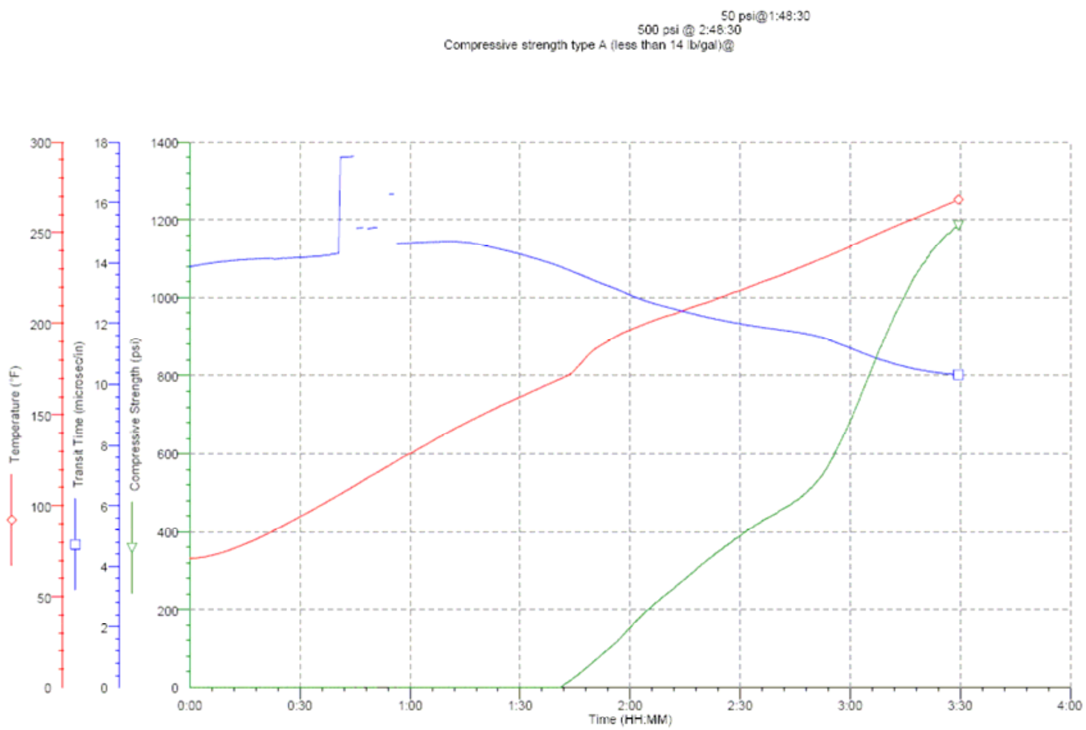

Figure 6. 11.5 lb/gal glass bubble design

While decreased WOC times and increased compressive strength numbers are nice, the real benefit of these microsphere cementing solutions stems from the fact that they can be delivered at densities previously unavailable. As well section lengths increase and annular clearances decrease, frictional pressure increases. Since the effective circulating pressure is the sum of frictional and hydraulic forces, the hydrostatic must decrease if the friction increases and the resulting circulating pressure maximums remain fixed. With lower circulating pressures, the chance of losing circulation is reduced. If circulation can be maintained throughout the cement job, TOC is more likely to be as planned. If the TOC is less than planned, the required zonal isolation may not be achieved. As long as the hydrostatic pressure stays above the formation pressure, reduced slurry density can be a useful tool in fighting lost circulation problems. From Table 1 we can see that a number of these reduced slurry weight jobs have been pumped in the Campos Basin. Cement was successfully circulated in all 25 of these jobs. Kulakofsky et al. (2005b, 2006a,b) reported that when hydrostatic limitations require it, these microsphere cement slurries can be designed all the way down 7.5 lb/gal. By then foaming the ultra-lightweight slurry, downhole densities have been achieved behind offshore liners as low as 5.4 lb/gal.

Two recent advances in spacer technology have aided operators in their quest to achieve good bonding with water-based cements in hole sections that have been drilled with OBM or SBM systems. The first advance is made possible because of cheap computational power with the advent of the personal computer. For a given annular geometry and a set of mud properties including ultimate gel strength **(Figure 7**), a computer can be programmed to calculate the amount of force required to remove the gelled up mud. With planned pump rate and desired spacer density, the same computer software then can calculate how viscous the spacer must be to provide the required levels of wall shear stress to remove the gelled mud at the planned rate in the given wellbore geometry. If a spacer then is created with the calculated rheological properties, the mud should be removed from the annulus, allowing effective placement of the cement slurry into the annular space formed by the insertion of a casing or liner string into the wellbore. Often spacers are designed to be thicker than the dynamic mud properties. These spacer properties can be inadequate if the mud has gelling properties. A second common mistake is to only measure the mud's short term gel profile. The common mud gel properties are collected after 10 seconds and 10 minutes. Occasionally a value will be reported after 30 or 60 minutes. Closer examination of **Figure 7** shows that with this mud system there is a very large increase in gel strength between 2 and 4 hours. It is very common for mud systems to develop higher gels after long static periods. A mud with a gel strength of 47 would require a spacer with different rheological properties than a spacer designed based off the 10-minute time gel strength of 12 lb/100 ft^2. While running casing, the mud system in the wellbore will remain static for a long period of time. Knowing this long term gel strength value can aid in the mud displacement process.

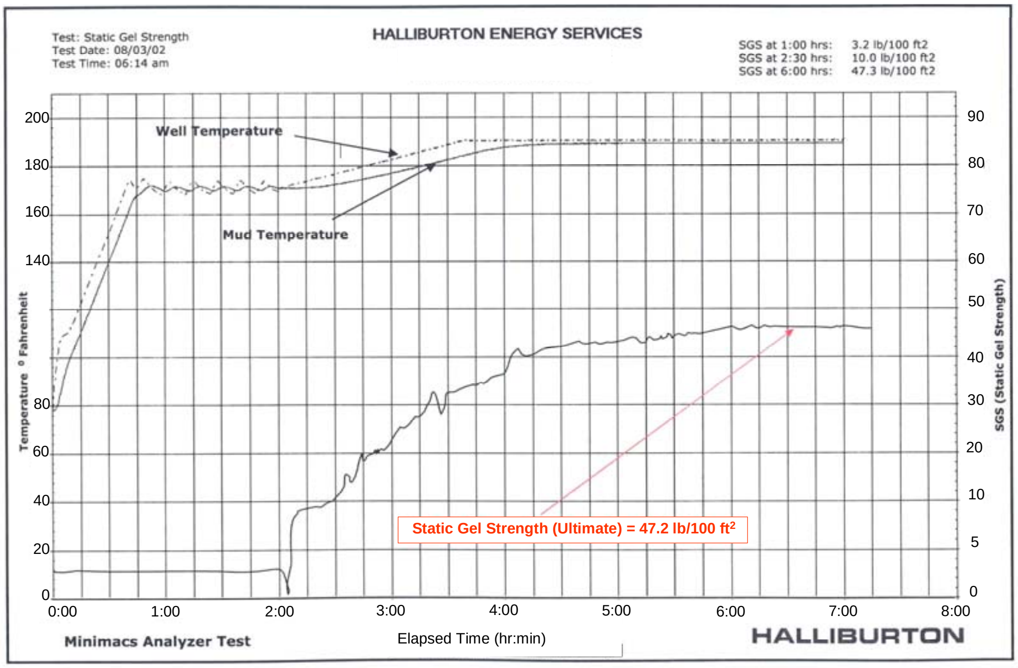

Figure 7. Ultimate gel-strength curve

The second half of the spacer design equation is providing water-wet surfaces to which the cement slurry can bond. To accomplish this task, the spacer must contain the proper mix of surfactants and solvents. Previously, numerous qualitative techniques have been employed. With the development of the wetability meter, a quantitative test is now available. If two electrical probes are placed in a nonconductive fluid such as OBM or SBM, current will not pass easily between the probes. If those same probes, still coated with the nonconductive mud, are placed in a conductive fluid, such as a standard water based spacer, current will still not pass easily between the probes. Different quantities and types of surfactants and solvents can be tested in the planned spacer on the mud coated probes until a recipe is found that will break the coating down and allow the current to flow. If the pipe and formation are water-wet, effective bonding can occur only if the mud also is removed effectively from the annulus.

Recent technological advances have allowed subsea release plug set systems to incorporate most of the advances developed for conventional cementing plug systems. Obviously when cementing critical wells, we want to use the best technology available. The following are a few of the latest features to look for when selecting subsea release plug systems.

- Multiple bottom plugs offer several advantages. Sometimes the bottom plug is used to separate the spacer and the mud. Other times they are released between the spacer and the cement. Both have advantages. With two bottom plugs, you can choose to separate all three fluids. Additionally, by monitoring the fluid volume pumped between when the bottom plug is released and lands on the float collar or shoe, a improved displacement volume can be determined.
- Pump-down foam wiping darts are now available. The foam wiping darts can pass through various geometries and IDs, eliminating the need to have multiple configurations of dart sizes as is required with rubber wiper type darts. The foam darts allow for more accurate displacements as they tend not to wrinkle or fold when passing through restrictions, thus minimizing bypass.
- Composite plugs also now are available. Composite construction provides greatly improved drillability and can be drilled easily with PDC type bits.
- High wiper blade efficiency designs from land-based plugs also now are available. Obviously better wiping efficiency is important because it equates to better separation of the fluids and will leave less cement stuck to the inside of the pipe.

- The final advance made to these subsea release plugs sets that operators may want to look for when planning future wells is increased flow area. Some of the newer systems are offering nearly twice the flow area as the older systems. This additional flow area allows improved circulation prior to cementing and provides for quicker fill-up while running pipe to help minimize pipe running times.

3. Conclusions

- Microsphere cements have been used successfully offshore Brazil.
- Cement slurries designed with microspheres can develop initial set much quicker than water extended cements at the same density.
- Cement slurries designed with microspheres can develop more compressive strength than water extended cements at the same density.
- Microsphere-based slurries can be designed at lower densities than are possible with water-extended slurry designs.
- New technology is available to tune a spacer's rheology to planned cementing conditions.
- Mud systems can become gelled during the static period before a cement job.
- New technology is available to help ensure that the pipe and formation are water-wet before placing cement in hole sections that were drilled with OBM or SBM.
- Adoption of recent advances in subsea release cement plug sets can make a big difference in cementing effectiveness.

4. Acknowlegements

The authors wish to thank the management of Petrobras and Halliburton for their permission to publish this paper, the laboratory personnel for their support, and operations employees whose assistance was vital to the outcome of the project.

5. References

BENGE, G. et al. Foamed Cement: Solving Old Problems with a New Technique. Paper SPE 11204 presented at: *SPE AIME FallTechnical Conference and Exhibition*, New Orleans, Louisiana, USA: Society of Petroleum Engineers, 26-29 September 1982.

KULAKOFSKY, D. S. et al. Lightweight Cementing Solutions: A Novel Concept Utilizes Field Case Histories. Presented at: *Subsea Houston Conference,* Houston, Texas, USA : 18 September 2003.

KULAKOFSKY, D. S. New Technology Provides Cementing Solutions in Problem Areas. Presented at: *Petrotech Conference*, Delhi, India : 15-19 January 2005.

KULAKOFSKY, D. S. et al. New Ultra-lightweight Cementing Technology Proven with Case Studies, Combines Benefits of Current Leading Technologies. Paper SPE 92970 presented at *Middle East Oil and Gas Show and Conference*, Bahrain : Society of Petroleum Engineers : 12-15 March 2005.

KULAKOFSKY, D. S. et al. Ultra-Lightweight Cementing Technology Sets World's Record for Liner Cementing with a 5.4 lb/gal Slurry Density. Paper IADC/SPE 89124 presented at *IADC/SPE Drilling Conference*, Miami, Florida, USA : 21–23 February 2006.

KULAKOFSKY, D. S. et al. Superior Zonal Isolation Provided by Ultra-Lightweight Cementing Technology Increases Profitability of Wells in Difficult to Cement Areas. Paper SPE 104066 presented at the *First International Oil Conference and Exhibition in Mexico*, Cancun, Mexico : 31 August - 2 September 2006.

PINE et al. Selection of Foamed Cement for HPHT Gas Well Proves Effective for Zonal Isolation–Case History. Paper SPE 79909 presented at *SPE/AIDC Drilling Conference*, Amsterdam, The Netherlands : 19-21 February 2003.

RAVI, K. et al. Safe and Economic Gas Wells through Cement Design for Life of the Well. Paper SPE 75700 presented at *SPE Gas Technology Symposium*, Calgary, Alberta, Canada : 30 April - 2 May 2002.

SWEATMAN, R. Well Design, Drilling, and Cementing Practices to help prevent Annular Flows. *DEA Workshop – "Deepwater Drilling: Where Are We Headed?"*, Galveston, Texas, USA : 17-18 June 2003.