Foamed cement successfully applied in shallow water environment in Caspian Sea

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To combat shallow water flows post cementing on the Azeri-Chirag-Gunashli field, located 100 km east of Baku, Azerbaijan, the drilling team for the Central Azeri Platform applied foam cement on surface casing operations.

THE GIANT Azeri-Chirag-Gunashli (ACG) field, located 100 km east of Baku, Azerbaijan, has potential reserves greater than 5 billion bbls of oil and is planned as a 30-year development project. Due to geohazards in tophole sections and previous unsuccessful attempts to combat Shallow Water Flows post cementing, the Central Azeri Platform drilling team reviewed the feasibility of using foamed cement on the surface casing operations. This article describes the pre-planning, field trial and successful application of foamed cement in a shallow water environment and lessons learned.

BACKGROUND

Discovered in the 1970s in relatively shallow waters of the Caspian Sea (100-300m), the ACG field has been in development since September 1994 after the "Contract of the Century" was signed between a consortium of foreign oil companies and the **State Oil Company** (SOCAR). Operated by **British Petroleum**, full-scale development drilling operations began from the initial Chirag platform in September 1997 as part of the Early Oil Project, and now full field development is under way. The 48 slot Central Azeri (CA) platform was installed in September 2004 and is producing approximately 250,000 bpd.

The Caspian basin depositional environment was formed with a sedimentation rate of 1,000 m/million years. This high rate combined with tectonic uplifts and mud volcanoes in the area contribute to the formation of high-pressure water zones. Shallow water flows (SWF) of varied strength and duration are a common occurrence in the ACG field, typically at depths of 480-570m TVDBRT in the Apsheron formation.

Typical well design includes a 30-in. conductor pipe driven to 190-200m below the seafloor (361-371m TVDBRT) and a 20-in. surface string set at 550-600m TVDBRT. Low fracture gradients in the shallow sections have in many cases resulted in partial or no returns during drilling and cementing operations. A fracture gradient of approximately 1.2sg is estimated at the 30-in. conductor shoe. A combination of lightweight lead and conventional tail cement slurries have been used historically to combat losses with slurries densities as light as 1.38sg.

Average ambient temperatures in the area range between 35ºC in the summer and 6ºC during winter. However, the seafloor temperature remains steady year-round at around 5ºC. The water depth across the field is approximately 130m.

The combination of all of these factors produces an environment similar to deep water and the associated problems of cementing in the top-hole sections. It was for this reason that foam cementing was considered. Although new to the Caspian region, foam cementing was considered a viable option to ensure integrity of the sea floor adjacent to the platform.

CEMENTING CHALLENGES

When water depths are less than 300m, foamed cement slurries are typically shunned as the hydrostatic pressure above the slurry is considered too low to prevent gas breakout. As per the ideal gas law, as gas travels up hole and the hydrostatic pressure is decreased, the increase in gas volume is volumetrically very large at shallow depths. With the constant density method of foam cementing, the amount of nitrogen added to the slurry is dependent on the hydrostatic pressure where the slurry will be placed in situ. Foamed slurry that was intended for a deeper depth may end up very near the surface, and as this gas volume expands, slurry density is reduced below the intended target density. If slurry density is reduced too much, it may fail to maintain the proper hydrostatic pressure on the flow zone and initiate the shallow water flow.

Additionally, a reduction in hydrostatic pressure requires less gas to be placed in the slurry. This can present a problem with the currently available nitrogen pumping units. Typically nitrogen pumping units used for foaming cement can not pump efficiently at rates less than 200 scf/bbl for a sustained time.

The CA platform is located in 128m of water with 30-in. drive pipe as the initial conduit to surface and 20-in. surface casing planned to be set below the potential SWF zones. The hydrostatic pressure realized while foam cementing the 20-in. surface casing with this well design would be less than 500 psi. This would require precise placement when foaming the slurry to prevent nitrogen breakout to surface.

The planning and testing phase would include measures to ensure that:

- Foamed cement returns could be handled at the surface;
- The nitrogen and foaming agent delivery must be accurate to maintain a stable slurry density and stability in order to maintain pore pressure over the potential SWF zones and below the 30-in. conductor fracture gradient;
- Precise slurry placement;
- Control of free nitrogen, caused by mud contamination and the resultant destabilization of the foamed slurry;
- Slurry must exhibit short transition time.

EARLY CEMENT FORMULATIONS

Traditionally the lightweight lead slurries for the shallow casing strings in the area were extended using sodium silicate. This material is an excellent and inexpensive extender for normal applications. However, for the low seafloor temperatures observed in the area and due to the large water-to-solids ratio in the slurry, the silicate formulations display slow setting time and delayed strength development. Water extended slurries at low temperatures may even remain in a gelled state indefinitely, leading to the loss of hydrostatic transmission and promoting SWF.

Applying the hydrostatic pressure loss model introduced by Sabins[1] and later employed by Mueller[2] to quantify the annular pressure loss in SWF scenarios, the critical static gel strength (CGS) for a slurry placed in front of a high pressure aquifer can be calculated using the following equation:

CGS = (MPR * 300) ÷ (L/D)

Where:

MPR = Maximum pressure restriction, psi

300 = Conversion factor

L = Length of cement column, ft

D = Effective diameter of the cement column, in.

For a typical 20-in. casing, the hydrostatic pressure at 430m below mud line, with 1.44sg cement in the annulus is 1,116 psi (936 psi corresponding to the cement head and the remainder to the column of 1.01sg seawater). The formation pressure equivalent of 1.2sg at the SWF results in a pore pressure of 993 psi as compared with the hydrostatic of 1,116 psi equates to a difference of 193 psi. SWFs can occur once this pressure reduction is exceeded due to slurry gelation.

Considering a 28-in. hole with wash out, the static gel strength capable of producing this pressure reduction is calculated as follows:

CGS = (193 psi * 300) ÷ (1500 ft /8 in)

CGS = 309 lbf/100 sq ft

The CGS marks the beginning of the period when the slurry is susceptible to formation water inflow, and the time elapsed between the CGS and gel strength of 500 lbf/100 sq ft is known as the transition time. The slurry design criteria for SWF requires a formulation that exhibits a transition time of 45 min or less. Laboratory measurements of the transition time for the silicate extended slurries show that these slurries are unacceptable for controlling flow.

MODIFIED CEMENT DESIGN

Despite the relatively shallow water depth in the ACG field, the weak and unstable nature of the top soil units, the occurrence of overpressured water aquifers, and low seafloor temperatures assimilate deepwater conditions and cementing systems. Lightweight slurries used in deepwater areas with potential geohazards are typically water reduced systems with short transition times, either foamed or extended with hollow microspheres.

In addition to the cement requirements for SWF control, the potential top casing scenarios and the uncertainty on the pore and fracture pressure profiles demanded a cement formulation capable of last-minute density adjustment. The cement system selected had to allow density change without major alteration of the key properties required for SWF control and setting in low temperature environment. The hollow sphere lightweight systems, used in the earlier designs, are typically dry blended and formulated for a specific slurry density. Deviation from the design density in this case would result in alteration of critical slurry properties. Foamed slurries, on the other hand, are obtained by the addition of gaseous nitrogen to a base cement mix, and since nitrogen is chemically inert, the slurry density can be altered varying the ratio of gas to liquid in the mix, without major effect in the slurry properties

The slurry selected for foaming consisted of Class "G" cement, a reactive mineral clay used for early strength development, a non-retarding bonding/fluid loss package and sodium metasilicate to adjust the thickening time. The blend was designed to obtain base slurry with a density of 1.89sg. To prevent a set cement with interconnected porosity, the slurries are typically foamed to a maximum of 0.46-0.72sg below the density of the base cement. Hence, the base slurry designed for these jobs would allow for a reduction in density to 1.2sg. For the specific well conditions, this resulted in foam slurry with a maximum foam quality of 29.6% just inside the 30-in. shoe.

LOGISTICAL PLANNING

After foamed cement slurries was accepted, it was determined that a feasibility test would be required to prove foamed cementing technology could be assimilated into the local infrastructure in a timely fashion as well as meet accuracy expectations. A yard test at the local base and a simulated foam cement job on the CA platform were performed. The introduction of the Automated Foam Cementing System (AFCS) into a new area requires a coordinated effort from experienced AFCS support personnel and logistical experts.

Planning began in late 2004, and several mechanical and installation challenges emerged:

- Personnel requirements and bed space constraints;
- Platform layout and deck space limitations;
- Potential for foamed cement and/or nitrogen breakout at surface
- Yard test statement of requirements and objectives.

A detailed logistical plan was created that included personnel and equipment requirements to meet the various program deliverables.

The basic AFCS package is modular, and the rig-up configuration varies, the distance that each component may be placed from another is limited only by the amount of wiring, hydraulic hoses, and treating iron that is available. Additionally each component must have an electronic connection back to either the Central Processing Unit (CPU) or the Mixing Control Module (MCM) for the system to operate as a unit. This meant that if the equipment were spread out, it would require a great deal of exposed wiring. The solution was to identify the location of each piece of equipment in advance and install explosion-proof junction boxes at each location. Equipment would then be shipped out to the platform and placed, requiring only short jumper cables to be installed just prior to the job.

The drilling schedule demanded that the permanent electrical installations and the equipment test on the platform be completed by June 2005. The actual foam cement job would coincide with the drilling of the B-013 well and was scheduled for October 2005. A survey of the CA platform was conducted to determine the required materials and locations of the permanent electrical installations. The equipment needed for the job requiring an electrical junction box include:

- Foam manifold;
- Nitrogen unit;
- Foaming agent injection pump;
- MCM and CPU.

Another safety concern was the possibility of foamed cement returning to the surface caused by severe channeling. The diverter system would need to be modified to defoam any foamed cement that made it to the surface. The equipment required to handle the defoaming operation included:

- Chemical injection pump to defoam nitrogen slurry at the surface;
- Connections on diverter system to inject defoamer.

The full foam cement equipment package was rigged up and yard-tested successfully in May 2005. All of the equipment and installation requirements were ready on location by June 2005.

FIELD TRIAL

A test of the AFCS was scheduled to take place on location designed with actual job parameters. The anticipated volume of casing cement slurry was to be pumped twice during the test, which would be split into 2 phases.

Phase 1 was designed to demonstrate the AFCS' accuracy and flexibility while slurry rate varied. Phase 2 was to be identical to the planned job and would be pumped at a constant rate of 5 bpm. However, prior to attempting to mix the cement slurry, the equivalent amount of water was to be pumped at 3, 5 and 7 bbl/min. while injecting the foaming agent and nitrogen to test equipment functionality. Since slurry rate is the parameter used in determining nitrogen and foaming agent addition, the rate changes would be added to demonstrate the system's accuracy and flexibility. The test revealed no areas of concern.

The cement slurry used for the Phase 1 test was Class "G" mixed to 1.89sg and pumped as 97 bbls of foamed lead at varying rates, followed by 20 bbls of non-foamed tail.

Phase 1 test demonstrated the AFCS's ability to deliver the required additives accurately in response to varying slurry rates.

Phase 2 specified a constant rate of 5 bpm with 90 bbls of foamed lead and 20 bbls of non-foamed tail. The slurry density was again 1.89sg, and the additive concentrations were the same as Phase 1. AFCS accurately tracked and responded to changes in the cement slurry rate as was indicated by the rate reduction that occurred in response to a bulk cement delivery failure – which was actually welcomed during the testing phase. The cement unit slowed the mixing rate to 1 bpm to allow bulk delivery to catch up. Once it did, the test commenced as planned. Based on field trial results, the AFCS was accepted for use.

FOAM CEMENT JOBS

B-013: Prior to cementing the 20-in. string, the hole was drilled with a 22-in. bit and underreamed to 26 in. to a final depth of 605m TVDBRT. A multi-arm caliper provided an accurate depiction of the hole size and concluded the 26-in. hole was within specified requirements.

Slurry testing: Several densities were tested and evaluated for foam stability in accordance with ISO 10426-411. The foamed slurry showed remarkable stability at densities as low as 1.2sg. An Ultrasonic Cement Analyzer was used to test the compressive strength of the base slurry. It exhibited an extremely short time to 50 psi, of 3 hrs 10 min., and a time to 500 psi of 7 hrs 3 min. A 1.39sg foamed slurry was then tested using the destructive method of compressive strength and yielded 1,650 psi in 24 hours. Initial slurry temperature was 25ºC, until 50 psi was reached; temperature was then ramped to 49ºC to accommodate for heat of hydration in the large cemented annulus. Although no Static Gel Strength tester was available at the time, identical slurry was tested and exhibited a transition time of less than 45 minutes.

A challenge and lesson learned had to do with the mix water temperature and the role it played in controlling slurry set time. In accordance with ISO-10426-3 mix water should be within 2ºC of the temperature of the mix water anticipated during actual cementing operations. Even though the ISO document is aimed at slurries used in deepwater applications, higher standard were held here based on the similarities to the deepwater scenario. Original slurry testing was conducted earlier, during summer, and since the slurry was mixed with water straight from the Caspian, the recorded laboratory mix water temperatures were congruent, at that time, with the recommendations in the ISO document. The original tests were done with a mix water temperature of 25ºC. The recorded mix water temperature at the time of the job in late November was 16ºC. The wellbore computer temperature simulators indicated that in the absence of the cooling effects experienced with riserless drilling and with the current well configuration, and a bottomhole static temperature around 32ºC, the bottomhole circulating temperature would be governed almost entirely by the slurry mixing temperature. The tests run with the cooler mix water temperature produced a longer than desired time to 50 psi and required the use of an accelerator. This accelerator produced a high initial slurry viscosity upon mixing. The increased viscosity became a concern, so as an alternative, mix water was heated in a mud pit prior to the job.

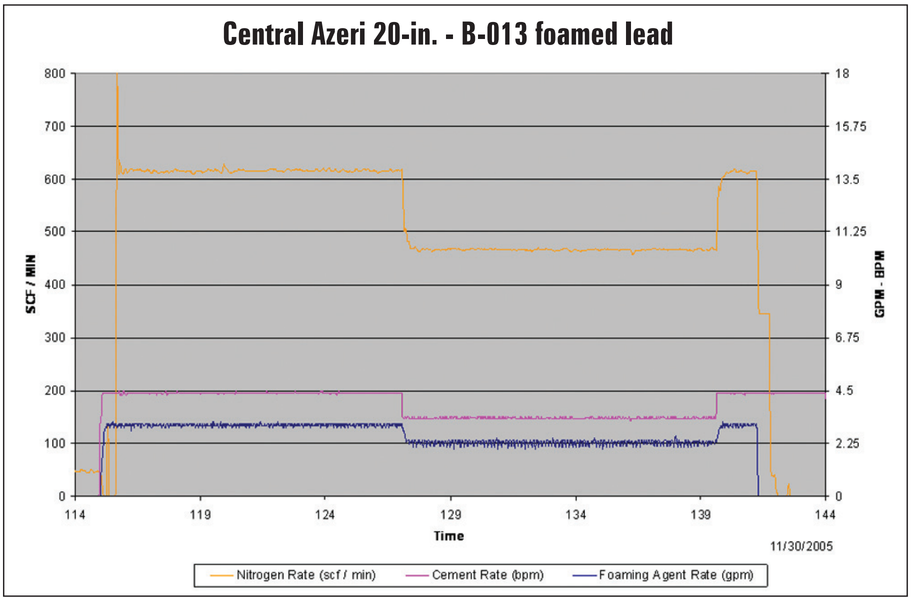

Figure 1 shows that the actual job differed very little from Phase 2 testing, demonstrating the accuracy of the system and its ability to react to changing rates.

CEMENTING

The 20-in. casing was cemented with the planned Class "G" base 1.89sg lead and tail system. The base system differed from the system used during the field trial only in that it contained the aforementioned additives to combat shallow water flow and a foam stabilizer. Additionally only 1 slurry density (1.89sg) would be mixed at the unit with the lead slurry differing by the addition of the foaming agent and nitrogen via the constant nitrogen method. This method is usually limited to shallow jobs with a very short column of cement in that it produces a cement column with a variable density downhole. The average density of the cement column, combined with the fluids above, must not exceed the anticipated fracture gradient. Additionally, the leading edge of the column should have a density greater than, or nearly equal, to the mud weight. This particular slurry was injected with 140 scf/bbl of nitrogen producing an average downhole density calculated at 1.33sg. The column produced ranged from 1.28sg at the top, to 1.40sg at the bottom.

The calculated volume of cement was pumped to bring the lead slurry 50m inside the 24-in. casing, thus isolating the shallow soil units. The non-foamed tail slurry was calculated to be placed just below the suspected flow zone in the Apsheron at 530m TVDBRT, allowing the foamed slurry to be placed solely across the potential flow zone. This was done to take advantage of the slurry's expansive properties as well as its inherent pore pressure and short transition time.

Figure 1 shows the actual job as recorded. The actual job chart differs very little from the Phase 2 testing, demonstrating the accuracy of the system and its ability to react to changing rates. The job was pumped as planned, and no spacer or foamed cement returns were seen at the surface. Additionally no flow after cementing was ever encountered.

B-014: The 22-in. hole was drilled to 591 m and was underreamed to 26 in. to a depth of 587m TVDBRT. The interval was drilled with a lower mud weight (1.15sg) in an attempt to verify SWF potential. A 73 bph SWF was encountered between 560-575m TVDBRT, and the mud weight was increased incrementally in order to identify the pore pressure at the flow zone. Flow did not diminish until the mud weight reached 1.31sg, and ultimately a 1.33sg mud weight was utilized to provide a trip margin. The caliper log showed a large washout in this section due to the lengthy circulation attributed to raising the mud weight. The caliper showed washed out sections as large as 39 in.

SLURRY TESTING

A static gel strength testing device was obtained for the testing the slurries on the CA platform. To produce the shortest transition time, the mix water was heated, to 35ºC – slightly higher than the predicted formation temperature at the shoe. This temperature increase was instrumental in shortening the time to set, and thus, the time that the slurry would be exposed to water influx. The CGS for slurry in this well configuration was 250 lbf/100 sq ft. Laboratory testing concluded that the time between 250-500 lbf/100 sq ft was less than 30 minutes. Figure 2 shows the improvement of CGS with an increase in temperature.

Static gel strength

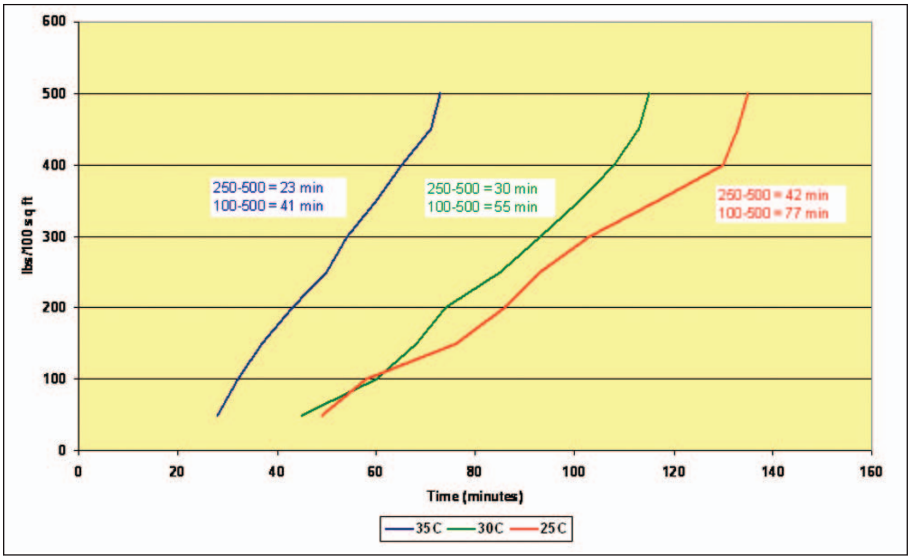

Figure 2 shows the improvement of the critical static gel strength with an increase in temperature of the mix water to 35°C, which shortened the time to set.

CEMENTING

With the new pore pressure data, as well as the increased mud weight, the foam cement density had to be adjusted to maintain the balance between pore and frac pressure. Cement density was reduced, and the foamed lead was pumped in 2 stages. The original TOC was planned to match the TOC of B-013, which was 50m inside the 24-in. liner. Lead No. 1 consisted of 107m of 1.31sg average density, foamed with 150 scf/bbl of nitrogen. Lead No. 2, which was placed across the suspected flow zone, consisted of 50m of 1.49sg average density foamed with 90 scf/bbl of nitrogen. The tail slurry was 11m of 1.89sg non-foamed base slurry. The top of the non-foamed tail slurry was also reduced to fall just at the bottom of the flow zone.

The job was pumped as planned with the unit mixing the 1.89sg base slurry at 5 bpm. At no time was cement delivery to the mixing unit disrupted as it was in the test mix and the B-013 cement job. No excess cement slurry is used in these jobs, and slurry volume is based solely on the caliper volume. This was considered important for precise slurry placement.

Full returns were maintained during the job, and no spacer or cement was seen at the surface. About 24 hours after the job, the well exhibited an intermittent bubbling on the 30-by-20-in. annulus, which eventually subsided. This was attributed to nitrogen breakout originating from the contaminated interface between the spacer and cement produced in the washed out annulus. This contamination of the lead cement by spacer changes the slurry properties leading to unstable foam and the resultant gas breakout.

DISCUSSION

Although flow potential isn't encountered in every wellbore, it can cause severe damage if allowed to flow around the outside of the casing and therefore impact the platform integrity. Research and experience led the CA drilling team to implement foam cement to control the SWF. The combination of a modified well design to complement the new cementing program proved successful when a 73 bph flow in the B-014 well was encountered and successfully cemented.

Even though foam cementing requires additional personnel and equipment, in this case the benefits far outweigh costs and the negative aspects.

CONCLUSIONS

- The AFCS system was introduced into a new region in a timely fashion with few logistical problems.
- Field tests proved that the AFCS system could provide accurate additive delivery even when faced with unexpected slurry rate changes.
- The actual job on B-013 was performed as expected with no flow after cementing or free nitrogen at the surface.
- SWF was encountered on the B-014 while drilling. The job was performed as planned with no flow after cementing. Nitrogen breakout was reported at the surface and was not unexpected due to the dynamics associated with the washed out 26-in. hole section.
- The critical gel strength for a particular cement design is a function of water depth, depth of SWF zone below mudline, cement density and SWF zone pore pressure.
- Due to unexpected mud weight changes, foam cement provided the necessary flexibility to vary slurry density.
- The period of susceptibility for a cement slurry to SWF can be estimated by calculating the critical gel strength for a set of well conditions, then measuring the elapsed time from the critical gel strength to 500 lbf/100 sq ft as determined on the static gel strength apparatus.
- Foam slurry design was extremely stable to 1.2sg.

References

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