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Planning and executing foamed cement system in Oklahoma enables full wellbore cement coverage under total lost circulation situation and provides for enhanced mechanical properties of the sealant

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Abstract

Successful drilling and completion of oil and gas wells depends largely on how effectively zonal isolation is performed. A common occurrence when drilling wells is loss of circulation of fluid due to presence of less competent formations, natural fractures or caverns in the drilled sections. A successful zonal isolation process is divided into two stages with multiple variables. First is the preplanning design and engineering, which enables specific maneuvers real time when necessary. Second is the execution of the plan, which requires experience and understanding of the wellbore, as well as proficiency using the applied tool. Knowledge and sharing between the operator and the service company are critical ingredients to success. This paper discusses how an engineered foam cement system will enable a successful cement job of an injection well that is experiencing total lost circulation.

Introduction

While drilling in mature fields has its advantages, it also can present certain challenges that may be due to natural causes such as faults, natural fractures, incompetent rocks, etc. Depletion of reservoirs or other factors can encourage and induce lost circulation as well. These natural causes, as well as human activities, could also induce influx of fluids, gases or a mixture that also includes formation water. The oil and gas industry has developed and deployed a variety of techniques to combat loss of drilling fluid and cement slurries into weak/damaged or fractured formations. While each of these techniques may enable a successful outcome, certain techniques can both enable continuous circulation of fluids, including cement slurries in primary cementing operations, and also offer additional benefits that provide for wellbore integrity over the life of the well.

A unique solution is to use nitrogen gas in reduced-density cementing operations. These cement slurries can effectively battle lost circulation, as well as provide a very competent and durable seal once they cure under wellbore conditions. Due to their three-phase nature, these foamed cement systems offer distinctive characteristics (to help ensure cement return to surface) that other cement systems may not. Another well-known and well-documented advantage of energized cement slurries is to control gas migration, as well as control of other formation fluids that may otherwise unwantedly enter the slurry column. Through an auto-pressure maintenance structure in the wellbore (as the cement slurry goes through the hydration process during setup), a properly designed foamed cement system can very effectively prevent intrusion of fluids and gases into the wellbore. From an operational standpoint, the flexibility of changing slurry weight in real time – by simply varying nitrogen concentration – has proven to be an asset. The set cement provides increased insulating properties, enhanced load-bearing tolerances and improved flexibility for well operations.

This paper discusses the reasons behind the selection of a foamed cement system over other available conventional products and describes the successful execution of the job using foamed cement on the Stack Water 6-14-5 SWD well in Canadian County, Oklahoma. The importance of full and proper zonal isolation becomes more critical in injection wells, thermal wells and other types of unconventional wells.

Pre-Job Collaboration and Decision Making

Like any activity in oilfield operations, pre-planning and communication between drilling, completion and cementing service companies is paramount to ensure the most suitable selection of cement slurry system(s). The objective for the well in discussion was to have full-length cement coverage around the production casing. It was critical to have cement returns to surface, since the well was going to be used for saltwater disposal (SWD). Similar to other injection wells, it is very important in SWD wells to maintain the cement-sheath support over the life of well to ensure casing integrity and zonal isolation. Operating life of the well is directly related to the integrity of the casing and the cement sheath. During the pre-operation discussions, focus was given to potential lost-circulation possibilities, as well as to the mechanical competency and flexibility of the selected cement system after setting. The potential for two multistage cement jobs was ruled out due to the potential for string and wellbore integrity compromise.

For the lead and tail cement-slurry systems, conventional-lightweight, beaded-lightweight and nitrified cement systems were considered. Computer hydraulic-pressure modeling was compared for each of these fluid systems. While it was possible to blend lightweight slurries with all three systems, the foamed cement system had distinct advantages:

- Dynamic flow capability (even under static/after landing plug), to ensure full-length radial cement coverage[1]
- Wellbore cleaning efficiency to facilitate improved bonding
- Enhanced mechanical properties to achieve and maintain zonal isolation under shocks and mechanical loads)[1]
- Ability to make real-time adjustments during execution of the cement job
- Rig-time savings by eliminating the need for a stage tool

After evaluating the benefits of a foamed slurry system, and once details of the operational requirements were carefully measured and addressed, it was clear that the best solution was a foamed slurry for the primary lead, followed by another foamed slurry with less nitrogen content for the secondary lead, and then finally a non-foamed tail slurry. To seal the casing-to-casing annulus at the surface, a cap cement was designed to be pumped on the back side once the foam returns were on surface. This would enable rapid continuation of drilling operations and reduce the time waiting on cement to set. It is noteworthy to mention that additional advantages of foam cement systems over traditional lightweight cement systems were considered. Some of these potential benefits are:

- Reduced hydrostatic pressure
- Enhanced elasticity/ductility
- Superior thermal-insulation properties
- Good strength-to-density ratio
- Prevention of gas migration
- Expansion
- Mud-removal efficiency
- Low fluid loss[9]
- Single slurry systems
- Improved economy

Pre-Job Engineering Design Factors

After the main goals of the job were identified, the design parameters had to be engineered to achieve the desired outcome. These primary design criteria were identified as:

- Maintain circulation throughout the job
- Based on the well's response, modify rates and slurry densities, as required, in real time
- Run a caliper log to get a better understanding of wellbore volumes and the accuracy of the wellbore geometry
- To achieve proper porosity and avoid permeability for the primary foam lead, maintain foam quality of 20 to 35%
- Use low foam quality of 14% for a portion of tail slurry – for inflow protection as well as limited mechanical enhancement
- Have a non-nitrified, higher-compressive-strength cement for the shoe and a short interval at the bottom of casing
- Achieve the above criteria while simultaneously staying below fracture pressure of the weakest formation, but above formation pore pressures to ensure well control

Laboratory Testing

All tests were performed prior to the job dates as per API and ASTM guidelines[8], as well as C&J's best practices. Some of the laboratory tests included:

- Thickening time
- Compressive strength
- Foam quality (in liquid form as well as solid specimen, to verify design)
- Crush tests
- Fluid-loss measurement
- Rheology measurement

Porosity

It is well documented that cements at optimum water ratios will have a certain amount of porosity. As an example, neat API class G cement with a water to cement ratio of 0.50 has enough liquid volume to allow for gas intrusion into the cement slurry during the hydration phase. Because the pore entries are very small (1.0 to 1.5 µm), only small gas bubbles can enter. However, if a channel is formed in the setting cement, the flow path will most likely be present even as the slurry goes through hydration and later crystallization, based on few other factors such as temperature and pressure. If this occurs, the zonal isolation will be compromised.

By introducing nitrogen, which is an inert gas, it becomes possible to produce energized slurry systems with a lower water ratio that can also impede formation-fluid and gas intrusion by maintaining pressure until the cement is set. For the Stack Water well on which we focused, FQ of 20 to 35% was selected for the main lead, and ~14% FQ was selected for the second part of the foam lead. Optimum FQ ensures that the nitrogen bubbles are not interconnected, and system porosity stays within the required range. Image 1 shows a 25% FQ cement system[2].

Enhanced Mechanical Properties

Working with 20 to 35% FQ, industry data has shown that the set cement will have lower Young's modulus (compared to conventional slurries of similar weight) while still providing better compressive strength, which in turn improves tensile strength.

These characteristics enable the sealant to possess higher elasticity limits and endure the mechanical loads of activities such as injection, perforation, etc. much more effectively. While it is important for a sealant to have sufficient compressive strength, it is secondary to the importance of Young's modulus, Poisson's ratio and tensile strength of the sealant system[3].

Young's Modulus and Tensile Strength

Years of experience and testing data have shown that, to achieve maximum benefits of the foamed cement systems, the FQ should be kept within a certain range. Proper FQ allows for porosity of a sealant system to stay within the desired range to retain internal isolation and to avoid permeability in the structure. This engineered foam sealant will also have higher tensile strength while it possesses lower Young's modulus. A more effective way of measuring sealants' capability in terms of load bearing capacity is to look at the ratio of Young's modulus to tensile strength. The most desired system will have the highest tensile strength and the lowest Young modulus[6]. Finite element analysis has demonstrated the chance of having radial cracks in a cement column is reduced most when the cement sheath has higher tensile strength with corresponding lower Young's modulus[7].

Young's Modulus and Poison Ratio

In line with effectively ensuring full cement length coverage, the focus of this blend was to enhance the elasticity and ductility of the set cement. Generally, foamed systems are more ductile and can handle stress-strain loads more effectively[4-5]. This capability of the sealant to return to its original shape after exposure to strain and stress in the system is its elasticity. The elasticity of solid bodies is commonly measured by:

- Young's modulus: The ratio between tensile or compressive stress and elongation of solids stressed in one direction. It can be modified with special additives or by simply introducing nitrogen bubbles, as is the case with foamed systems.
- Poisson's ratio: The absolute ratio of the transverse strain to the axial strain of a specimen under an axial tensile or compressive stress at its ends.

The required data is gathered by using stress/strain ratios and tensile-strength values. A common method to obtain the information is by using Brazilian tensile strength (BTS). This test will show the maximum tensile stress that the specimen can withstand before it fractures. In some literature, the tensile strength is referred to in stress units. BTS, also referred to as indirect tensile strength (σ_τ) is measured using core samples cut in an approximate one-half-length-to-diameter ratio (ASTM D3967 standard). BTS measurements are made using electronic-servo-controlled (material test system equipment) stiff testing machine having a capacity of 220,000 lb.

The equation below shows the relationship used to calculate σ_τ. It should be noted that materials (in this case, the cement specimen) will respond differently to the forces applied in confined conditions versus an unconfined environment (atmospheric).

Relationship:

$$\sigma_\tau = \frac{2.F}{\pi.L.D}$$

Where:

σ_τ = Brazilian tensile strength, psi

D = Diameter of the core sample, in.

F = Maximum failure load, lb

L = Length of the core sample, in.

Superior Displacement Efficiency

The mud-displacement efficiency of a foamed cement system, in combination with the engineered spacer design, provides clean surfaces on the casing and rock, to which cement can effectively adhere. Foamed cements, since they possess three phases (nitrogen gas, liquid, solid), have higher dynamic flow shear stress than non-energized cement slurries. This higher shear stress enables a significant improvement in mud displacement.

Mobilization, Rig-Up and Execution

For the actual job, the primary planned requirements and equipment were organized and inspected. Below is the itemized list of the equipment:

- Cement pumper and batch mixer for mixing spacer
- Nitrogen pumper and liquid nitrogen – with additional nitrogen available for contingency
- Specially designed surfactant pumping unit with an electronic metering system and backup pump
- Data van
- Iron trailer for additional iron to rig up to the back side for cap cement

The job began by pressure-testing surface lines. The expected maximum job pressure, per simulation calculations, was approximately 1,300 psi. Pumping began with 25 bbl of weighted spacer mixed at 10.5 ppg. It was followed with 205 bbl (805 sacks) of 13.6 ppg lead cement slurry, foamed down to 11.0 ppg by injecting the cement slurry with nitrogen and a foam stabilizer. The primary lead foamed slurry was followed by pumping 24 bbl (95 sacks) of 13.6 ppg primary cement slurry and foamed down to 12.0 ppg. The job continued with pumping 14 bbl (55 sacks) of conventional tail cement slurry mixed at 13.6 ppg.

Pumps were then shut down to allow for the lines and pumps to be washed. The top plug was released, and 327 bbl of calculated displacement was initiated. At about 250 bbl into displacement, the pump rate was slowed down from 5 bbl/min to 3 bbl/min to help maintain circulation to surface. Once indication of foam cement was noticed, valves were switched, and the annular blowout preventer was closed to divert the flow to the pit. The plug landed at the calculated displacement, and the pressure was taken from approximately 900 psi to 1,500 psi. The pressure was released to check the float equipment.

The floats held, and returns were then monitored for few more minutes. The backside valves were closed, and then cap cement was mixed and pumped on the back side. A total of 11 bbl of 15.2 ppg Class C cement slurry and accelerator were used to cap the foamed slurry, followed by 3 bbl of fresh water. At the end of the job, all goals had been successfully achieved. All fluids were mixed and pumped as designed, while maintaining returns throughout the entire job. Tables 1 through 5 show the well data as well as the materials used for lead and tail slurries. Graphs 1 through 5 show the final simulation runs and the actual job execution results.

Conclusions

The results from the implementation of foamed cement system for the well in discussion show that:

- The energized cement slurry system was the best choice
- Running a caliper log to have a good sense of hole volume was beneficial
- The elasticity of set foamed cement will have enhanced mechanical properties
- Stage (or DV) tools can potentially be eliminated by selection of dynamic foam cement systems

Acknowledgement

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References

1. Godfrey, W.K., and Methven, N.E.: "Casing Damage Caused by Jet Perforating," paper SPE 3043 presented at SPE-AIME 45th Annual Fall Meeting, Houston, Oct.4-7, 1970

2. Deep Offshore Technology Conference held in New Orleans, Louisiana, 13–15 November 2002. Use of Foamed Cement for East Canada Deepwater Fields—Case History Farzad Tahmourpour and James E. Griffith, Halliburton; Tom Wesling, Marathon Canada Limited

3. Deeg, W.F. et al.: "How Foamed Cement Advantages Extend to Hydraulic Fracturing Operations," World Oil (Nov. 1999) 51-53.

4. Benge, O.G. et al.: "Foamed Cement Job Successful in Deep HTHP Offshore Well," Oil & Gas J (March 1996) 58.

5. Goodwin, K.J. and Crook, R.J.: "Cement Sheath Stress Failure," paper SPE 20453 presented at the 1990 Annual Technical Conference and Exhibition, New Orleans, Louisiana, 23-26 September.

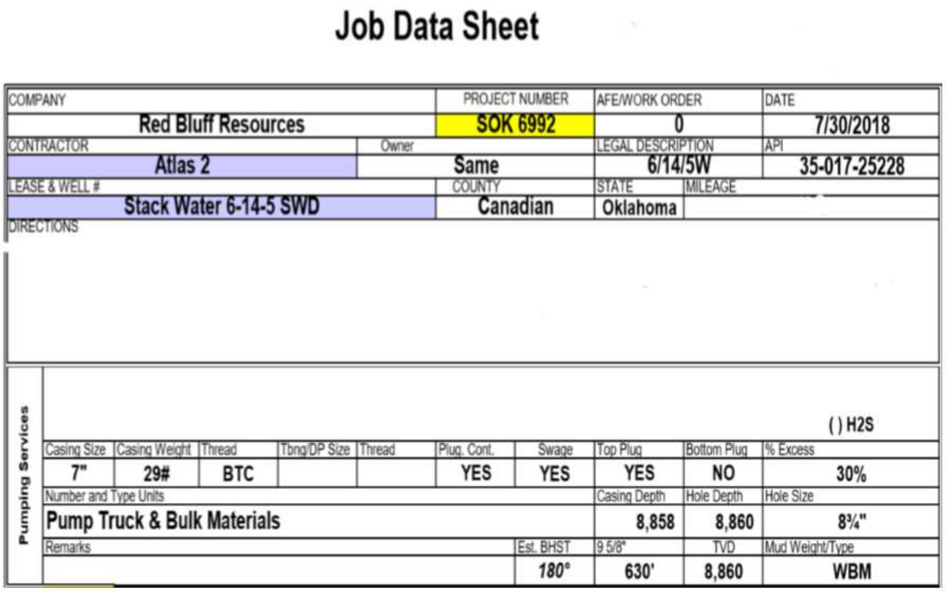
6 Ravi, K., Bosma, M., and Gastebled, O, ; "Improve the Economics of Oil and Gas Wells by Reducing the Risk of Cement Failure," paper SPE 77497 presented at the 2002 IADC/SPE Drilling Conference, Dallas, Texas, 26-28 February.

7. S. Iremonger, Mitchell Bolt and Sally C. Lawrence, Sanjel Corporation; " Enhanced Thermal Well Integrity Through The Use of A New Cement Tensile Strength-enhancing Fiber; SPE-174483-MS

8. API. API Recommended Practice 10B-4. Recommended Practice on Preparation and Testing of Foamed Cement Slurries at Atmospheric Pressure, First Edition; American Petroleum Institute: Washington, DC, 2004.

9. P.G. and Kulakofsky, D.S.: "Computer Simulation Program for Cement Squeeze Applications," paper presented at the 1987 Southwestern Petroleum Short Course, Texas Tech University, Lubbock, Texas, 22-23 April.

Table 1- General Well Data



Job Data Sheet

COMPANY		PROJECT NUMBER	AFE/WORK ORDER	DATE
Red Bluff Resources		SOK 6992	0	7/30/2018
CONTRACTOR	Owner		LEGAL DESCRIPTION	API
Atlas 2	Same		6/14/5W	35-017-25228

LEASE & WELL #	COUNTY	STATE	MILEAGE
Stack Water 6-14-5 SWD	Canadian	Oklahoma	

DIRECTIONS

Pumping Services

( ) H2S

Casing Size	Casing Weight	Thread	Tbng/DP Size	Thread	Plug. Cont.	Swage	Top Plug	Bottom Plug	% Excess
7"	29#	BTC			YES	YES	YES	NO	30%

Number and Type Units	Casing Depth	Hole Depth	Hole Size
Pump Truck & Bulk Materials	8,858	8,860	8¾"

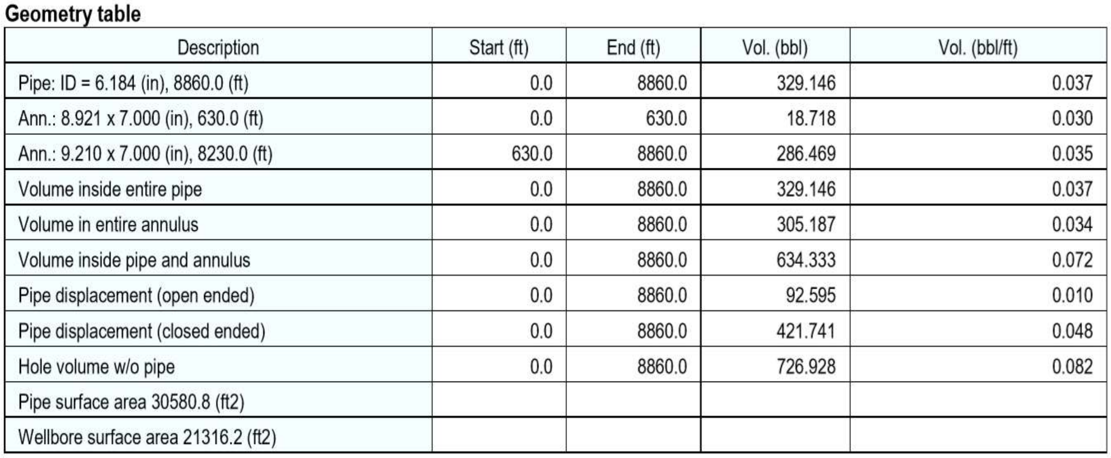
Remarks	Est. BHST	9 5/8"	TVD	Mud Weight/Type
	180°	630'	8,860	WBM

Table 2- Simulated anticipated job final pressure

Pressure at the end of the job

Depth ->	@ 8860.0 (ft)
Hydrostatic pressure (psi)	5160
Total pressure (psi)	5203
Pore/frac pressure (psi)	3686 / 5759
Hydrostatic Pout - Pin (psi)	1288

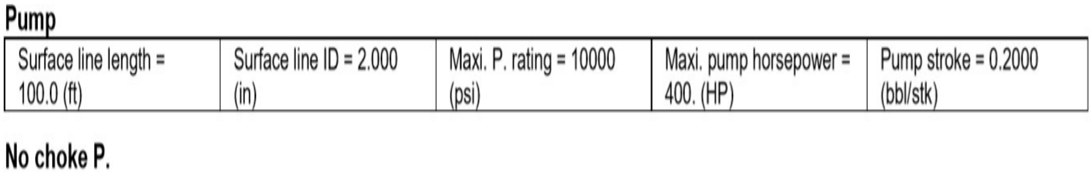
Table 3- Wellbore geometry/volume



Geometry table

Description	Start (ft)	End (ft)	Vol. (bbl)	Vol. (bbl/ft)
Pipe: ID = 6.184 (in), 8860.0 (ft)	0.0	8860.0	329.146	0.037
Ann.: 8.921 x 7.000 (in), 630.0 (ft)	0.0	630.0	18.718	0.030
Ann.: 9.210 x 7.000 (in), 8230.0 (ft)	630.0	8860.0	286.469	0.035
Volume inside entire pipe	0.0	8860.0	329.146	0.037
Volume in entire annulus	0.0	8860.0	305.187	0.034
Volume inside pipe and annulus	0.0	8860.0	634.333	0.072
Pipe displacement (open ended)	0.0	8860.0	92.595	0.010
Pipe displacement (closed ended)	0.0	8860.0	421.741	0.048
Hole volume w/o pipe	0.0	8860.0	726.928	0.082
Pipe surface area 30580.8 (ft2)				
Wellbore surface area 21316.2 (ft2)				

Table 4- Surface high pressure line to wellhead

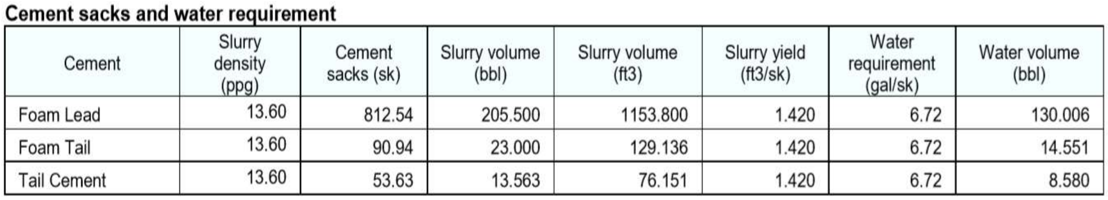


Pump

Surface line length = 100.0 (ft)	Surface line ID = 2.000 (in)	Maxi. P. rating = 10000 (psi)	Maxi. pump horsepower = 400. (HP)	Pump stroke = 0.2000 (bbl/stk)

No choke P.

Table 5- Material

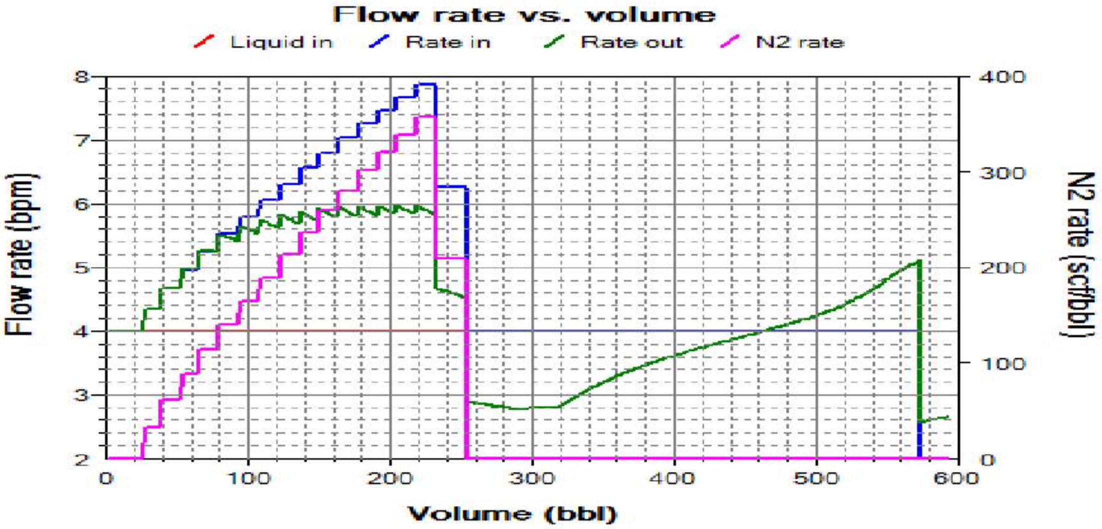


Cement sacks and water requirement

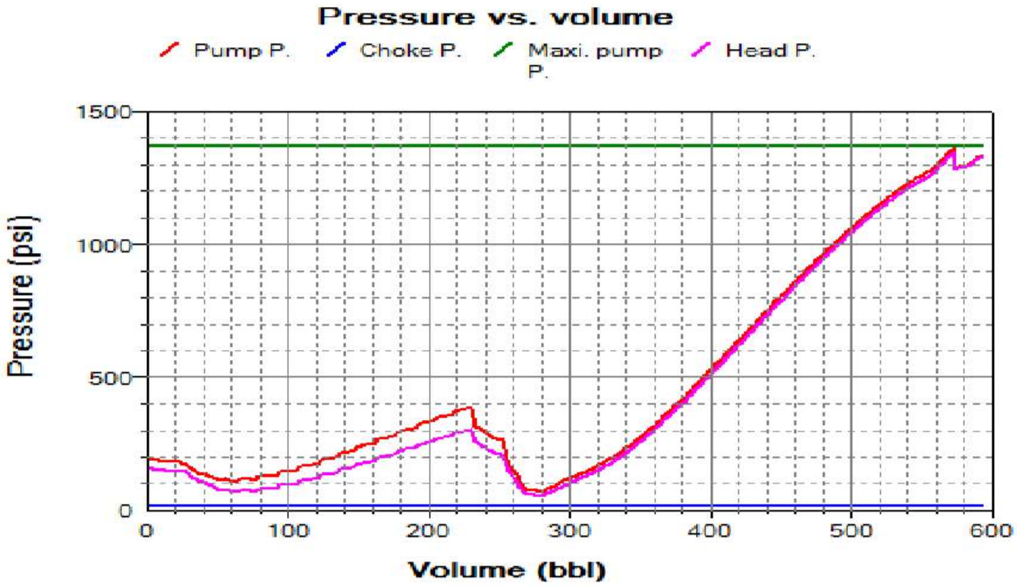
Cement	Slurry density (ppg)	Cement sacks (sk)	Slurry volume (bbl)	Slurry volume (ft3)	Slurry yield (ft3/sk)	Water requirement (gal/sk)	Water volume (bbl)
Foam Lead	13.60	812.54	205.500	1153.800	1.420	6.72	130.006
Foam Tail	13.60	90.94	23.000	129.136	1.420	6.72	14.551
Tail Cement	13.60	53.63	13.563	76.151	1.420	6.72	8.580

**50 sks cap is additional/optional*

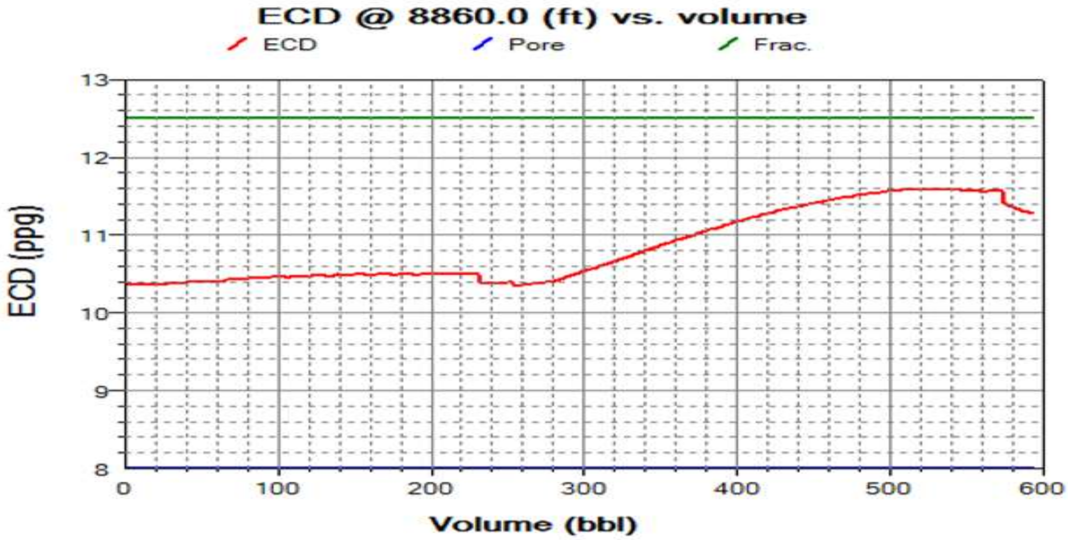
Graph 1- Simulated flow rates (cement and nitrogen)



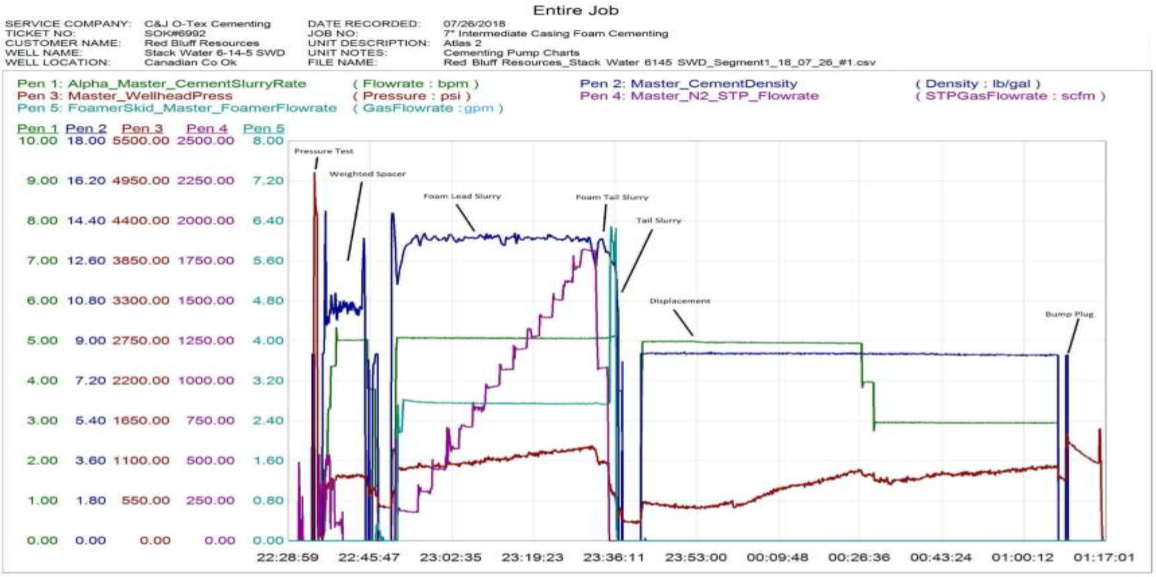
Graph 2- Simulated pump pressure vs. volume pumped



Graph 3- Simulated ECD vs. volume pumped at TD



Graph 4- Overall actual job summary



Graph 5- Actual lead and tail slurry pumping