REAL TIME CEMENT SIMULATION DESIGN VS ACTUAL JOBS

David McKenzie, Mark Briney, Heath Pipes, Italo Bahamon
Halliburton Energy Services, Inc.

ABSTRACT

The cementing design process has been improved by using new technology to predict actual downhole conditions, allowing both the service company and the operator to manage fluid positions, critical circulating pressures, and surface parameters while cementing casings in wells presenting challenging conditions.

This paper will explain how design data and real-time simulation of cementing jobs can be used to make detailed predictions of many well parameters and provide information so that adjustments can be made during the cementing operation to alter the outcome of the job. These tools can allow the operator and service provider to (1) more accurately predict cement tops, change casing programs, control flow-back rates and pressures, and monitor equivalent circulating density (ECD) on specific zones, or (2) enable personnel to create better design for the next well in the field.

INTRODUCTION

The zonal isolation behind casings achieved in the cementing processes is critical for the well's oil and/or gas drilling and producing operations. Successfully performing a primary cement operation presents constant challenges and is best planned with up-to-date knowledge and engineering technology to achieve wellbore integrity and an extended life.

The development of computer simulations to model surface and downhole conditions has been a valuable tool used now for over 25 years to improve and facilitate cementing operations under different and variable scenarios. By using this engineering computer program, many cementing failures can be prevented not only before the actual cementing operation is performed, but during the operation itself. Maintaining control and predicting problems can be determined by taking into account all the monitored and calculated variables on a real-time mode and comparing the predictions with the pre-job design and the actual job.

Ideally, in the simulation process, many steps need to be taken to give precision to predictions and calculations. The computational process gathers information and with multiple logical sequences provides the most suitable solution for the scenario under study. Multiple design program runs may be taken without actually jeopardize the integrity of the well. While designing a plan, several parameters can be changed to predict the job performance or end results. Modifications or changes in various operational events for performance predictions are used as decision planning for recommendations. A recommendation may be altered by changing such components as cementing materials, placement methods and even casing configurations to ensure a better performance.[1-6]

The well conditions and the operational issues will provide an understanding that should help determine the type of job needed. Through use of the simulation program, case studies have shown that many variables can affect the output of a job. Predicting and optimizing a cement job with the simulation program gives both the operator and the service company a means to tailor the materials and placement methods to meet their expectations and to help ensure that the most cost-efficient solution has been provided.[7, 8]

This paper will detail several scenarios in case studies where the use of a simulation program has made a difference in successfully approaching solutions. The logical process that provides a solution, and the real-time decision options based on the program outputs during the job, demonstrate that the quality of the cementing operations can be improved even under extreme conditions.

A FULLY INTEGRATED PROCESS

The comparison between the design data and the actual output of a job is usually the last step in the process. The previous steps are also critical for the success of the operation and include:

1. Simulation. The logical process of designing the best solution should start on the simulation program and, in fact, finalized in the same point, where the comparison is made. The software will calculate how different variables affect the well conditions. Then a complete analysis of mud displacement and removal, spacer

rheology, friction pressure, equivalent circulating density (ECD), flow rates and pressures can visualize problems before the cementing operation begins and correct them.

2. Laboratory testing. Every well is a new challenge. The specific conditions on each well vary and the laboratory analysis of the materials included in the design program has to reflect as close as possible, the downhole conditions where the slurries are moving through and are going to be placed. The laboratory testing includes analysis on the muds, spacers, flushes, compatibility issues, pump times on the cement, and the verification of pumping and mixing characteristics.

3. Data Acquisition. After the best solution has been provided and the laboratory testing has been done, the actual data during the cementing job needs to be acquired. Densities, rates, pressures, and additive concentrations are recorded. The program then calculates critical downhole parameters and allows the designer/operator to compare them with the design. If the cement delivery is developed as designed, and the initial simulation was provided with the most accurate data, the output of the job should be as expected. But if the well conditions changes during the cement placement or simply the conditions are very complex, real-time decisions can improve the results. One way or the other, the simulation program allows the designer the ability to analyze the data and improve the next cementing operation.

THE BEST SOLUTION

Like any computer simulator program, the output obtained will be impacted significantly by the information included in the designing process. To find the most suitable solution for a given scenario, every issue ideally needs to be considered. The main problems should be addressed, but the overall big picture and even small details need to be taken into account. Understanding the different phenomena that a cement job involves are significant in selecting the proper materials and placement methods to simulate.[9-11]

The highest quality data that the designer can obtain from a specific scenario will help ensure the best reproduction of the actual conditions of the well to be cemented. The data required to load the program includes:

1. Wellbore geometry and tubular characterization
2. Directional data
3. Temperature survey or readings
4. Formation pressures
5. Fluid characterization for muds, spacers, flushes and cements
6. Back pressure to be applied on annulus
7. Equipment utilization
8. Mechanical aids
9. Cement job placement including rates and volumes

Once all the conditions are analyzed and the main issues and complexity of the job have been addressed, different options can be modeled and several solutions may be provided. A deeper analysis, then, will tailor the scenarios to meet the best possible solution.

Case 1. How to Determine Properties of Foamed Cement Once in Place

Indian Basin Unit
Eddy County, New Mexico

Surface casing	0 – 1,800 ft (MD)
Outer diameter	9.625 in.
Inner diameter	8.921 in.
Linear weight	36 lb/ft
Casing grade	J-55
Openhole section	± 1,800 ft (MD)
Inner diameter	12.250 in.

The operator was experiencing excessive cost and uncertainty about the quality of the annular casing seal needed for protecting the freshwater-producing formations on their surface casing strings set at ±1,800 ft. Conventional methods were not gaining thorough annular coverage during these applications. Developments in addressing the problems being encountered were constructed during training sessions with the regulatory body and the unit operator, where clarifications were made and logical policies formed for the situations. Foamed cement was determined to be the most suitable solution to isolate the vugs and fractures encountered while drilling these surface casings. The control in placement was maintained by adding a conductor casing string at the surface. A two-step process of placing foamed cement down the casing and circulating up to surface, if possible, would be the initial cementing step. Once placed to surface or if not, an annular injection of foamed cement would then be squeezed down to a point of least pressure resistance followed with a capping slurry.[12-16]

When pumping foamed cement, several parameters should be taken into consideration. Factors such as downhole pressures, temperatures, wellbore geometries are needed. Final placement depth and in-situ energy will determine the final properties of the nitrified cement.

The well data was input into the program for modeling and included the laboratory analysis of the fluid's rheology and the pressure cycles the cement slurry was going to encounter during the job. The chosen design was simulated and based on the resultant output, an operations plan was developed. The nitrogen concentrations required to achieve the desired densities situated across the final placement intervals for the foamed cement was determined. Several simulation runs were made to determine the best option to use from the well parameters, generating the final scenario. The range of densities between 9.5 lb/gal and 11 lb/gal was determined to be the most suitable. This information is shown on Figure 1.

The design incorporated a technique of circulating the foamed cement up to surface from the well's setting depth. The treatment was controlled at the return monitoring system by maintaining pressure and rate with a choke assembly mounted on the return line between the conductor and surface casing annulus. Once the foamed cement was circulated to surface, a follow-up squeeze using densified slurry as a "cap" to rapidly solidify and control the annular placed foamed cement was performed. Following the "cap" securing the foamed cement, the surface control system could be rigged down.[17-20]

The program's output tables and plots were used to clarify and explain the placement and final conditions of the job to the governmental agencies in order to obtain their approval. Since the procedures were not conventional, time involvement and technical meetings were necessary to provide an understanding and functionality of the foamed cementing properties and generation system. After several discussions, the regulatory entities agreed that foamed cement could be a good solution for the problem scenario and gave their permission to use it. Under these circumstances, the logistics of the operation were developed. An automatic process of mixing liquid cement with nitrogen and a foamer/stabilizer was incorporated into the design that would help ensure the proper delivery of the foamed slurry.

A proposal was made and the following procedure was developed:

1. Immediately before cementing, pump 10,000 scf of nitrogen.
2. Precede cement with 20 bbl freshwater spacer.
3. Mix and pump 450 sk Class "C" cement, mixed at 14.8 lb/gal and foamed to a weight of 9 to 11 lb/gal.
4. Mix and pump 150 sk Class "C" cement, mixed non-foamed at a weight of 14.8 lb/gal.
5. If cement circulates to surface, rig up and pumped 50 sk Class "C" cement, as "cap" at a weight of 14.8 lb/gal.
6. Contingency plan is to use sufficient foamed cement in an annular squeeze and follow with a "cap" placing down to the least resistant interval if slurry did not circulate on the primary stage.

The job used the different data monitoring and recording sources during the actual job so that a comparison could be made of the designed model. The actual ratio of nitrogen mixed with the cement and the foamer-stabilizer chemical rates were compared. The program's capability to generate plots in real-time showed the deviation of actual treating data versus the designed parameters. Comparisons are shown in Figures 2 and 3. If desired, these deviations could have been corrected while performing the cement job and improve the results of the operation. The more operational performance matches the real-time calculations to the design parameters, the better the results of the job. The goal was to provide the best coverage and integrity for the life of the well.[2, 3] All of the job information was processed and the simulator output showed the final conditions and placement properties of the cement, including its final density. This is displayed on Figure 4 and the final fluid positions shown on Table 1.

The processes developed on this project have been successfully applied on numerous other problem wells. The data acquisition and processing program has been used on every job of this type showing an extremely accurate prediction as compared to actual results. The operator has saved more than $25,000 per well using this technique as compared to the previous conventional methods.

Case 2: Gas Flow Issues on Slurry Designs

Morrow Unit
Eddy County, New Mexico

Intermediate casing	0 – 9,000 ft (MD)
Outer diameter	7.000 in.
Inner diameter	6.276 in.
Linear weight	26 lb/ft
Casing grade	P-110
Production casing	0 – 12,300 ft (MD)
Outer diameter	4.500 in.
Inner diameter	4.000 in.
Linear weight	11.6 lb/ft
Casing grade	P-110
Openhole section	9,000 – 12,300 ft (MD)
Inner diameter	6.125 in.

An operator was experiencing gas channeling issues after performing primary cementing jobs on production casing strings. A high-pressure zone was encountered during the drilling operations along with other low-pressure zones. The scenario was analyzed and a design program was used to accurately calculate the gas flow potential at any point of the wellbore geometry outside of the casing. A computer design model was built that could satisfy the operator requirements addressing the gas influx potential. Using this technique solved the gas flow problem and kept the integrity of the formations being drilled.

The gas flow potential (GFP) basically is the capability of gas (or any fluid) to percolate into the cement slurry from the time is placed in the well's annulus until the time it becomes a solid. The presence of static gel strength development and volume loss within the cement are the mechanisms that normally allow the GFP to become an issue on wells. The static gel strength is defined as the internally developed rigidity within the fluid's matrix that resists forces placed upon it. In other words, when the cement is strong enough to support its own weight, it begins to lose the hydrostatic pressure from above and through its length, allowing high-pressure zones to filtrate fluid inside the cement sheath, creating channels. The mathematical model that demonstrates this phenomenon will not be discussed in this paper, but it is defined in Eq. 1.

$$GFP= 1.67*(L/D)/OBP \text{................Eq. 1}$$

Where:
L = Length of the cement column
D = Diameter between the casing and the formation
OBD = Overburden pressure

The value obtained from the formula (typically between 1 and 10) will determine the severity of the gas flow potential and will affect the selection criteria of the materials and placement methods to be used to achieve the desired results in zonal isolation.[21-24]

The pressure profiles of the various formations in the operator's well were entered for (1) the high pressure and weak zones, (2) the gas flow potential was calculated, and (3) the high value obtained made it necessary to redesign the slurries and the placement method to be used on the job. Several program design runs were made, resulting in the possible solution suggestions that were modeled:

a. Increase mud weight
b. Improved displacement efficiency
c. Increase back pressure
d. Lower top of cement

After several simulations were performed, a design was developed that could be used without compromising the integrity of the well. It was determined that a foamed cement solution using an automated process as shown in Figure 5 could overcome the gas flow potential and protect the weak zones at the same time. A slurry consisting of 330 sk class "H" cement foamed from its base density of 15.2 lb/gal down to 13 to 11 lb/gal could be placed at an

ECD above the reservoir's pressure in the high pressure zone and be below the fracture gradient in the well's weakest zone. The real-time mode of the program was performed during the treatment to help ensure that the equivalent circulating pressures (ECP's) were kept according to the design. This would provide the necessary conditions to achieve the desired placement during the job. Figures 6 and Figure 7 display the pressure evaluations. The gas flow potential was also calculated using the real-time parameters and compared with the designed values. This information is shown in Table 2.[3, 13, 14, 15, 18, 19, 24, 25, 27 28]

Case 3. Reverse Cementing Operations While Controlling Rates In and Out

North Wasson Clearfork Unit
Yoakum County, Texas

Previous casing	0 – 8,450 ft (MD)
Outer diameter	5.500 in.
Inner diameter	4.950 in.
Linear weight	15.5 lb/ft
Casing grade	J-55
Window in 5 ½" casing	±7,800 ft
Open hole	7,800 ft - 8,400 ft
New liner casing	0 – 8,400 ft (MD)
Outer diameter	4.000 in.
Inner diameter	3.548 in.
Linear weight	9.5 lb/ft
Casing grade	N-80

Due to the lack of cement across some of the intervals behind the production casing string of an old well, the operator decided to perform a workover to repair this problem. A design to open a window in the previous casing by cutting through the casing at a chosen depth was performed. By deepening the well to its total depth (TD) and then, completing it, a problem with the well's production could be solved. A weak section with a low fracturing gradient in the openhole interval and a moderate water flow presented a challenge for the cement operation. Under these circumstances and due to the small annular area between casings, performing a cementing operation would generate excessive friction pressure while cementing and possibly exceed pressure restrictions. The planned job was modeled with the program, displayed in Figure 8. The design showed that a conventional placement method would not be the best solution to achieve the desired zonal isolation. Designs also indicated that the excessive pressure generated in cementing the replacement liner would possibly compromise the integrity of the formations.[4, 16, 20, 26, 28]

The solution that was developed used a modification in the normal direction cements are placed. The design method was to place the liner's slurry by pumping in a reverse cementing technique.

The job that was performed is described:

1. Inject 20 bbl of spacer fluid ahead with color dye mixed into it down the annulus between the liner and prior casing.
2. Pump the interior casing's capacity with fresh water.
3. Mix and pump 100 sk of modified Class "H" cement at a weight of 13.0 lb/gal.
4. Mix and pump 200 sk of lightweight cement at a weight of 11.8 lb/gal.
5. No displacement was performed down the annulus.
6. The returns of the casing were monitored and when the dye fluid returned, the casing returns were choked back and the injection of cement down the annulus was stopped.

The technique of pumping down the annulus helped prevent the high friction pressure during normal cement placement from exerting an excessive pressure on the weak zones. This ability to stay below the fracturing gradient helped maintain integrity of the wellbore, but the noted presence of a water-flow influx from a portion of the annulus during the placement of the cement required consideration also. If the water-flow's influx started to percolate into the cement slurry either during placement or thereafter, the characteristics of the slurry would change due to contamination. This could compromise the zonal isolation on the zones of interest. The design techniques incorporated in the simulation program were used again to overcome this issue.

Using the well parameters loaded in the program, the simulation generated the rate profile that would be expected during the cement job. This feature allowed the designer to visualize not only the rate of the fluid coming into the wellbore (rate in), but also the rate going out of it (rate out). The design was based on the differential hydrostatic pressures, freefall height, all steps during the treatment's volume, and the fluid velocities. If a water flow were present, the rate out during the actual operation would be observed as higher than the one on the design model. A turbine flow meter could be installed in the treating line and also in the return's line to monitor these rates both "in" and "out" and their variables. By pumping at a specific rate-in, the rate-out could be regulated to control any external influx of the water flow encountered in the well's annulus. This is shown in Figure 9. This procedure's technique was observed while the job was executed. The well's zonal isolation was achieved in most of the wellbore; with an exception that only one additional job was needed to complete the cementing operation. Under other past circumstances, by not using the logical sequences suggested by the program's simulation, the cementing processes would have more time consumed, additional stages in cementing, and the results in gaining zonal isolation would not be good. Historically, eroded channels within the placed cement have occurred and annular water flows have resulted if the influx problems were not addressed.[6, 9, 16, 19, 28]

Case 4. Water Shutoff Controlling Backside Pressure

Maverick Unit
Lea County, New Mexico

Surface casing	0 – 1,375 ft (MD)
Outer diameter	16.000 in.
Inner diameter	15.124 in.
Linear weight	75.0 lb/ft
Casing grade	K-55
Openhole	1,375 ft - 3,510 ft
Intermediate casing	0 – 3,510 ft (MD)
Outer diameter	11.750 in.
Inner diameter	10.880 in.
Linear weight	54.0 lb/ft (changed to 65.0 lb/ft based on model outputs)
Casing grade	J-55

While drilling the intermediate hole, the operator encountered a water-flow that compromised the operator's ability to achieve his desired TD. The water flow was identified at ±2,500 ft and flowing into the wellbore up to surface at a rate of approximately 160-bbl/hr. If the well were shut-in, the surface pressure from the water influx would build up to 1,200 psi with 10 lb/gal fluid in the hole. This critical parameter was input into the program simulation to provide a solution. The first design analysis made looked at using a special slurry, trying a heavy cement with a rapid and short transition set time. Laboratory testing was performed and the pumping schedule was proposed as listed:

1. Mix and pump 1,170 sk of Class "C" cement mixed at a weight of 16.5 lb/gal.
2. Mix and pump 1,200 sk of Class "C" cement mixed at a weight of 16.1 lb/gal.
3. Displace cement to the casing shoe.

The computer simulation model indicated a need for two additional control issues. The first one was that the hydrostatic pressure on the backside after finishing the job and closing in the annulus would generate enough upward force to lift the casing out of the hole. This analysis is shown in Figure 10. The results were shown to the operator so that considerations could be studied. To overcome the problem, the casing design was changed. Instead of running the original designed casing with a 54.0-lb/ft weight, the selected casing had a weight of 65.0-lb/ft. The second issue was that the hydrostatic pressure of the cement once circulated still would not be enough to overcome the pressure generated by the water flow under downhole conditions. Some additional pressure would be needed and applied on the annulus controls to keep the water flow from influxing into the cement slurry.

Using the simulation program, a "backside pressure schedule" was generated to keep the water flow from influxing into the slurry at anytime during the job placement and maintaining enough pressure after the cementing job. Using live data acquisition from pressure transducers placed in specific locations while running the real-time mode of the program, the model calculated the pressure being applied on the water flow depth during the job. This information is displayed in Figure 11. Once the cement slurry reached the water flow depth, the backside pressure schedule was monitored and compared to the design. This is displayed in Table 3.[10, 15, 28]

The cementing operation was successfully completed. After the cementing job, the annulus was closed in for 8 hours. The backside did not build any pressure during this period. The use of the simulator not only impacted downhole conditions but also changed surface configurations.

CONCLUSION

The logical processes including the use of computer simulators to provide solutions for cementing operations has proven to be beneficial for drilling operation under several environments and harsh conditions. The use of new engineering technology has improved the quality of the zonal isolation considerations in many scenarios that translate directly to more cost-effective drilling operations. The real-time mode of the jobs performed while running the program has lead to making relevant changes while performing actual jobs on location and have made possible the success of some operations where big challenges were present.

REFERENCES

1. Benge, O., G., Sauer Jr., C., W., Spangle, L., B.: "Foamed Cement - Solving Old problems with a New Technique," paper SPE 11204 presented at the 1982 Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, held in New Orleans, Louisiana, September 26-29.
2. Bour, D. L., Creel, P., and Kulakofsky, D. S.: "Computer Simulation Improves Cement Squeeze Jobs," paper CIM/SPE 90-113 presented at the 1990 Society of Petroleum Engineers Joint International Technical Meeting, Calgary, Ontario, Canada, June 10-13.
3. Creel, 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.
4. Degni, C.D., Fuller, G.A., and Chumpitaz, D.: "Successful Liner Application Using Foamed Cementing Technology for Low-Pressure, Naturally Fractured Formations," paper SPE 69489, presented at the 2001 Latin American and Caribbean Petroleum Engineering Conference held in Buenos Aires, 25 March.
5. Garvin, T.R., and Creel, P.G., "Foamed Cement Restores Wellbore Integrity in Old Wells," *Oil & Gas Journal,* August 20, 1984.
6. "Low Density Foamed Cements Solve Many Oilfield Problems," *World Oil* (1982) 171.
7. Ravi, K., Bosma, M., and Gastebled, O.: "Safe and Economic Gas Wells through Cement Design for Life of the Well," paper SPE 75700 presented at the 2002 Gas Technology Symposium, Calgary, Alberta, Canada, 30 April-2 May.
8. 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.
9. Pappas, J., Creel, P., Crook, R.: SPE 35249, "Problem Identification and Solution Method for Water Flow Problems," paper presented at the 1966 Permian Basin Oil & Gas Recovery Conference, Midland, Texas, 27-29 March.
10. Tullos, G., Minnery, G., Creel, P.G., Haest, J., and Snelson, J., "Foamed Cement Utilization on an Infill Drilling Project – Water Flood – Grayburg Formation – Southeast New Mexico – Need for Zonal Isolation—Case History," paper presented at the 50th Southwestern Petroleum Short Course, Lubbock, Texas, April 16-17, 2003.
11. Kazufusa, Kimura, *et. al*: "Custom-Blending Foamed Cement for Multiple Challenges," paper SPE 57585 presented at the 1999 SPE/IADC Middle East Drilling Technology Conference, Abu Dhabi, November 8-10.
12. Kopp, K., Reed, S., Foreman, J., Carty, B., and Griffith, J.: "Foamed Cement vs. Conventional Cement for Zonal Isolation—Case Histories," paper SPE 62895 presented 2000 SPE Annual Technical Conference and Exhibition, Dallas, Texas, October 1-4
13. Whitfill, D.L. *et al*: "Fluids for Drilling and Cementing Shallow Water Flows," paper SPE 62957, presented at the 2000 SPE Annual Technical Conference and Exhibition, Dallas, Texas, 1-4 October.

14. Bour, D.L., *et al*.: "Foam Cement Technology Solves Lost Circulation Problem," paper presented at the Twelfth Biennial Business and Technology Conference and Exhibition, Port-of-Spain, Trinidad and Tobago, March 11-13, 2000.

15. Vargo Jr., R.F., *et al.*: "Practical and Successful Prevention of Annular Pressure Buildup on the Marlin Project," paper SPE 77473 presented at the 2002 SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 29 September–2 October.

16. Marquaire, R. and Brisac, J.: "Primary Cementing by Reverse Circulation Solves Critical Problem in the North Hassi-Messaoud Field, Algeria," *JPT* (February) 146–150.

17. Bour, D.L., *et al*.: "Foam Cement Technology Solves Lost Circulation Problem," paper presented at the Twelfth Biennial Business and Technology Conference and Exhibition, Port-of-Spain, Trinidad and Tobago, March 11-13, 2000.

18. Crook, R. J., Wilson, J. M., Heathman, T., and Carpenter, B: "Effective Cement Placement," *Well Servicing* (March/April 1999).

19. Griffith, J.: "Method for Cementing in a Formation Subject to Water Influx," U.S. Patent No. 5,484,019 (1996).

20. Moore, R., Bour, D.L., Reed, S., Hernandez, R., "High-Temperature Wells with Lost-Circulation Demands and Reverse Circulation Placement Technique Using Foamed Cement Systems: Two Case Histories," paper SPE 84563 presented at the SPE Annual Technical Conference and Exhibition held in Denver, Colorado, U.S.A., 5 – 8 October 2003.

21. Frisch, G.J., Graham, W.L., and Griffith, J.: "Assessment of Foamed Cement—Cement Slurries Using Conventional Cement Evaluation Logs and Improved Interpretation Methods," paper SPE 55649 presented at the 1999 Rocky Mountain Regional Meeting, Gillette, Wyoming, May 15-18.

22. Pettit, I., Diggins, E., Williams, T., Abdulkadir, R., and Griffith, J.E.: "Study of Foam Cement for Prevention of Gas Migration," paper presented at the 2000 Annual Technical Seminar of the Petroleum Society of the Canadian Institute of Mining, Halifax, October 4.

23. Kopp, K., Reed, S., Foreman, J., Carty, B., and Griffith, J.: "Foamed Cement vs. Conventional Cement for Zonal Isolation—Case Histories," paper SPE 62895 presented 2000 SPE Annual Technical Conference and Exhibition, Dallas, Texas, October 1-4.

24. Deeg, W.F., Griffith, J.E., Crook, R.J., and Benge, G.: "How Foamed Cement Advantages Extend to Hydraulic Fracturing Operations," *World Oil* (Nov. 1999) 51-53.

25. Degni, C.D., Fuller, G.A., Chumpitaz, D., "Successful Liner Application Using Foamed Cementing Technology for Low-Pressure, Naturally Fractured Formations," paper SPE 69489 presented at the ATC Exhibition, Dallas, Texas, October 1-4.

26. Harlan, T.D. et al.: "Foamed Cement Selection for Horizontal Liners Proves Effective for Zonal Isolation—Case History," paper SPE 71055 presented at the 2001 Rocky Mountain Petroleum Technology Conference, Keystone, Colorado, 21-23 May.

27. Halliburton Permian Basin Conformance Database and Evaluations, 1965 – 2004 Engineering Reports, Midland, Texas.

28. Carrasco, A., Trela, J., Bahamon, I., Creel, P., "Surface Casing Cementing with Energized Slurries", paper presented at the 51th Southwestern Petroleum Short Course, Lubbock, Texas, April, 2004.

ACKNOWLEDGEMENTS

The authors extend sincere thanks to those whose cooperation facilitated compilation of the case histories presented in this paper. Thanks are also given to Halliburton for allowing the publication of this paper.

Table 1
Fluid Positions, Case 1

Measured Depth	Density	Quality	Optimum Stress Protection (Quality 18% - 38%)
ft	lb/gal	%	
0.0	14.80	0.0	☐
136.6	14.80	0.0	☐
292.9	14.80	0.0	☐
450.0	14.80	0.0	☐
463.4	14.80	0.0	☐
518.4	8.87	42.4	☐
540.0	8.87	42.4	☐
572.2	8.97	41.2	☐
625.0	9.13	40.1	☐
655.7	9.39	38.3	☐
680.9	9.46	37.8	☒
706.0	9.54	37.3	☒
730.9	9.62	36.8	☒
755.5	9.69	36.3	☒
780.0	9.76	35.9	☒
852.5	9.96	34.6	☒
876.3	10.02	34.2	☒
900.0	10.39	31.7	☒
922.8	10.45	31.3	☒
936.4	10.56	30.6	☒
958.9	10.62	30.2	☒
981.2	10.67	29.9	☒
990.0	10.67	29.9	☒
1003.4	10.72	29.5	☒
1025.6	10.77	29.2	☒
1047.6	10.82	28.9	☒
1069.5	10.87	28.5	☒
1091.3	10.92	28.2	☒
1113.0	10.97	27.9	☒
1134.7	11.01	27.6	☒
1156.2	11.06	27.3	☒
1177.6	11.10	27.0	☒
1199.0	11.15	26.8	☒
1220.3	11.19	26.5	☒
1241.5	11.23	26.2	☒
1260.0	11.23	26.2	☒
1262.6	11.27	25.9	☒
1283.7	11.31	25.7	☒
1304.6	11.35	25.4	☒
1325.5	11.38	25.2	☒
1346.4	11.42	24.9	☒
1350.0	11.42	24.9	☒
1367.2	11.46	24.7	☒
1440.0	14.80	0.0	☐
1530.0	14.80	0.0	☐
1620.0	14.80	0.0	☐
1710.0	14.80	0.0	☐
1800.0	14.80	0.0	☐

Gas Flow Potential	7.4	
at Reservoir Zone Measured Depth	10750.0	ft

Table 2
Gas Flow Potential, Case 2

Time of Events				
	ECD at Zone		Stage	
Time	Fracture	Reservoir	Starts Pumping	Enters Annulus
min	lb/gal			
0.40	10.55	10.56	Fresh water	
2.40	10.55	10.56	Flush	
7.20	10.55	10.56	Fresh water	
9.30	10.78	10.80	Class H cement	
25.10	10.58	10.59	Class H cement	
25.10	10.58	10.59	3.00 min shutdown	
28.30	10.43	10.43	Fresh water	
40.30	10.48	10.50		Fresh water
42.50	10.43	10.52		Flush
47.50	10.48	10.47		Fresh water
49.70	10.39	10.45		Class H cement
59.12	11.11	10.69	Fresh water	
73.62	11.55	11.18	Prior to plug landing	
73.72	10.61	10.32	Plug landed	

Table 3
Backside Pressure Schedule, Case 4

RETURN VOLUME (BBLS)	DESIGN BACKSIDE PRESSURE (PSI)	ACTUAL BACKSIDE PRESSURE (PSI)	CALCULATED ECD AT FLOW DEPTH (PSI)
400	14.6959	14.7	17.7
550	700	705	17.5
600	650	630	16.9
650	500	500	17.5
700	350	330	17.3
750	200	130	17.7
0	14.7	14.7	16.3

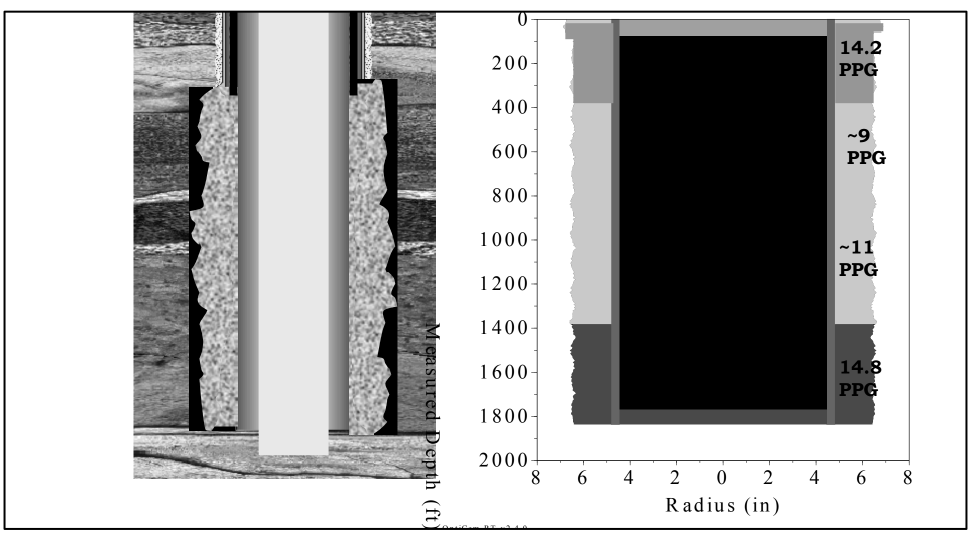

Figure 1 - Solution Provided, Case 1

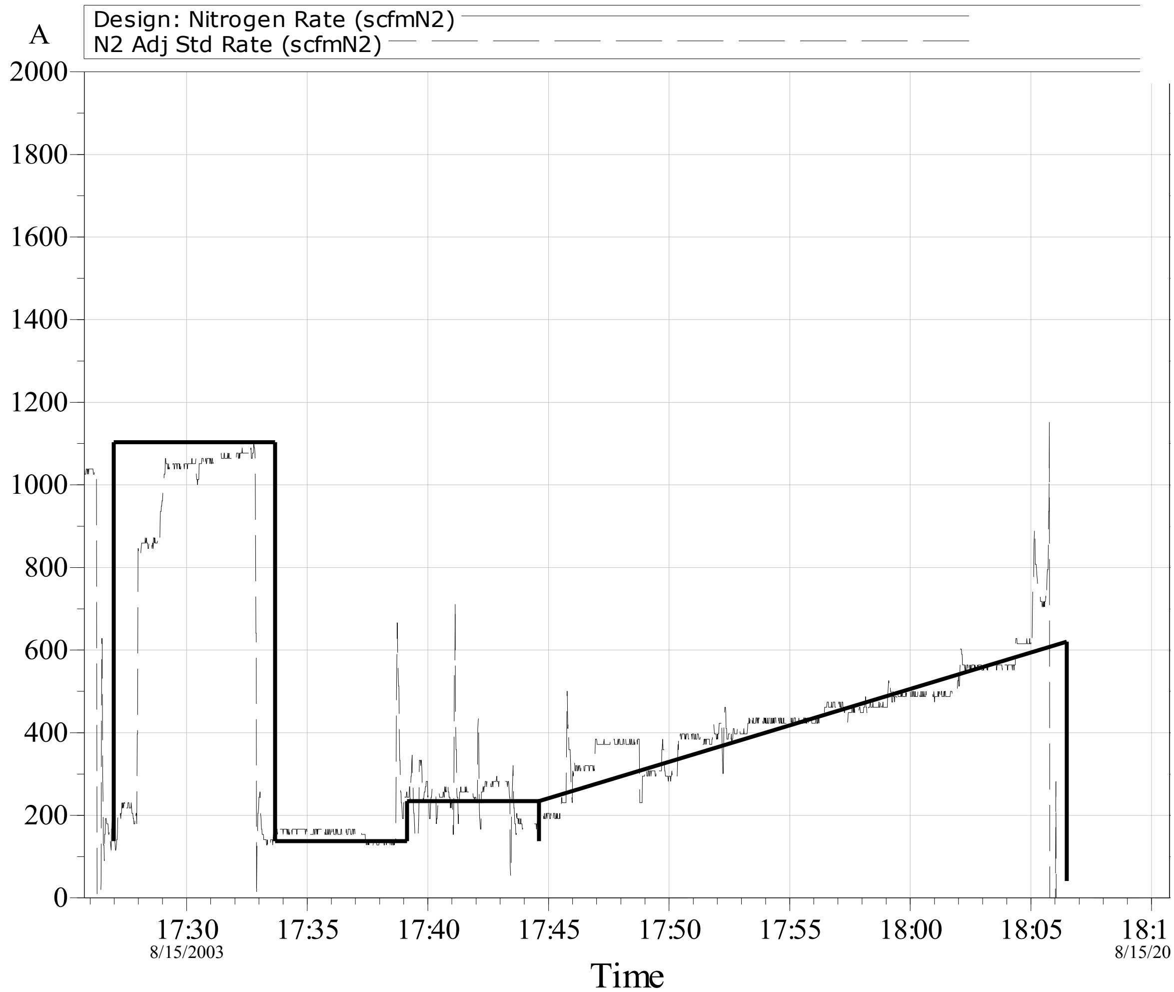

Figure 2 - Comparison Between Actual and Design Nitrogen Concentration, Case 1

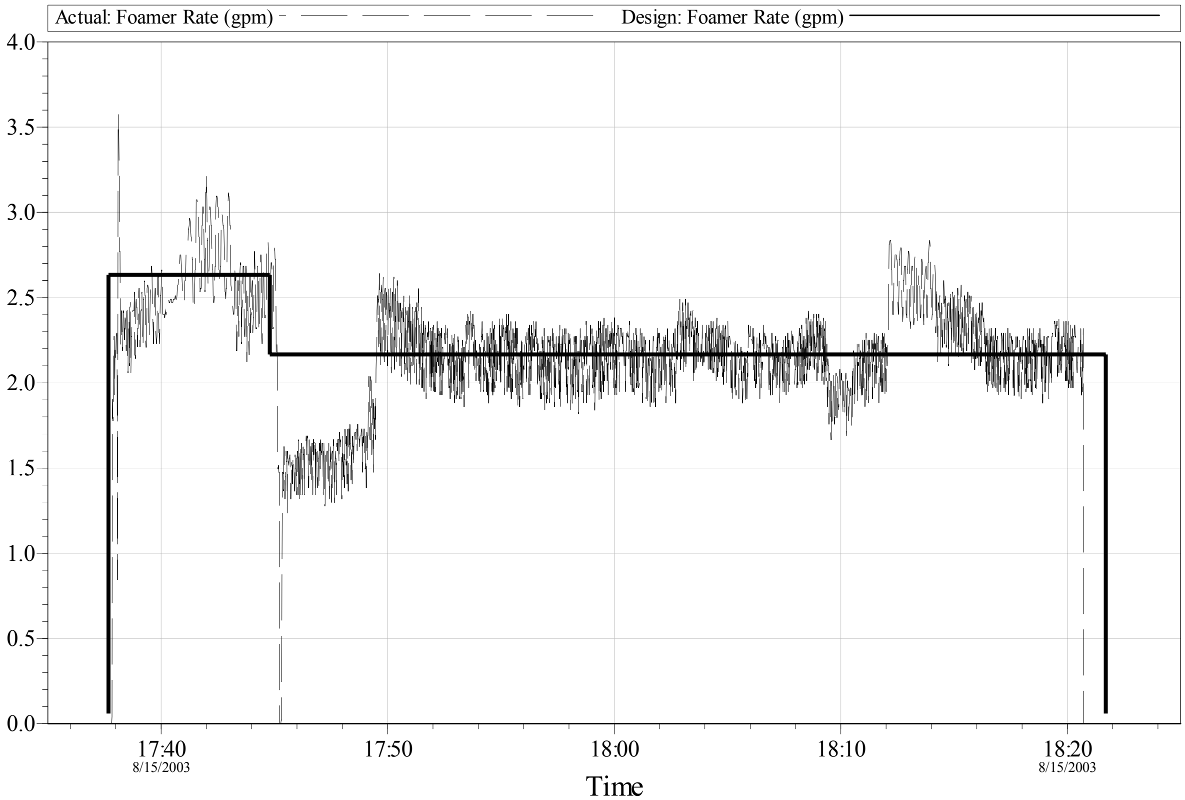

Figure 3 - Comparison Between Actual and Design Foamer Rate, Case 1

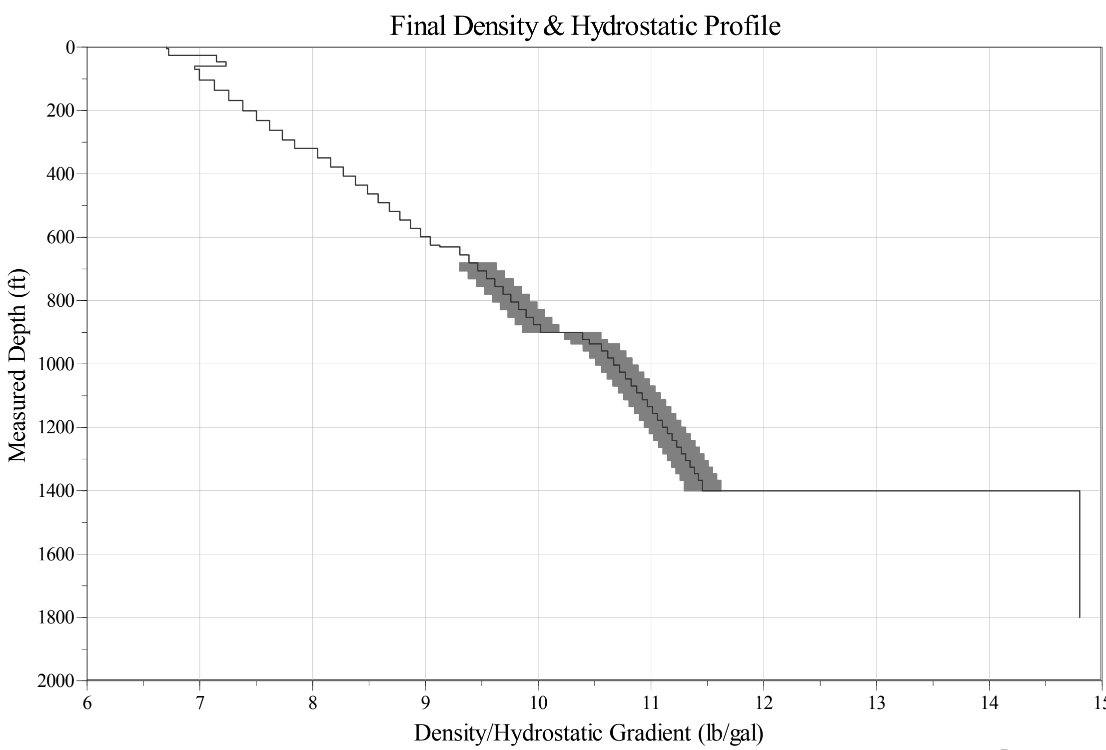

Figure 4 - Density Profile on Real Time Mode, Case 1

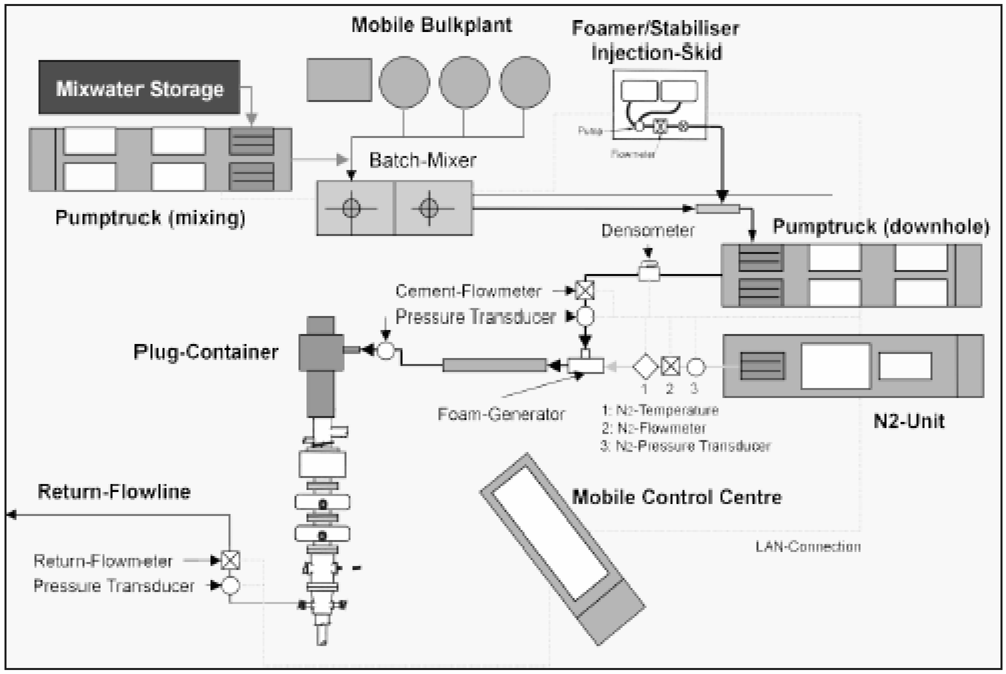

Figure 5 - Foamed Cement Set-up, Case 2

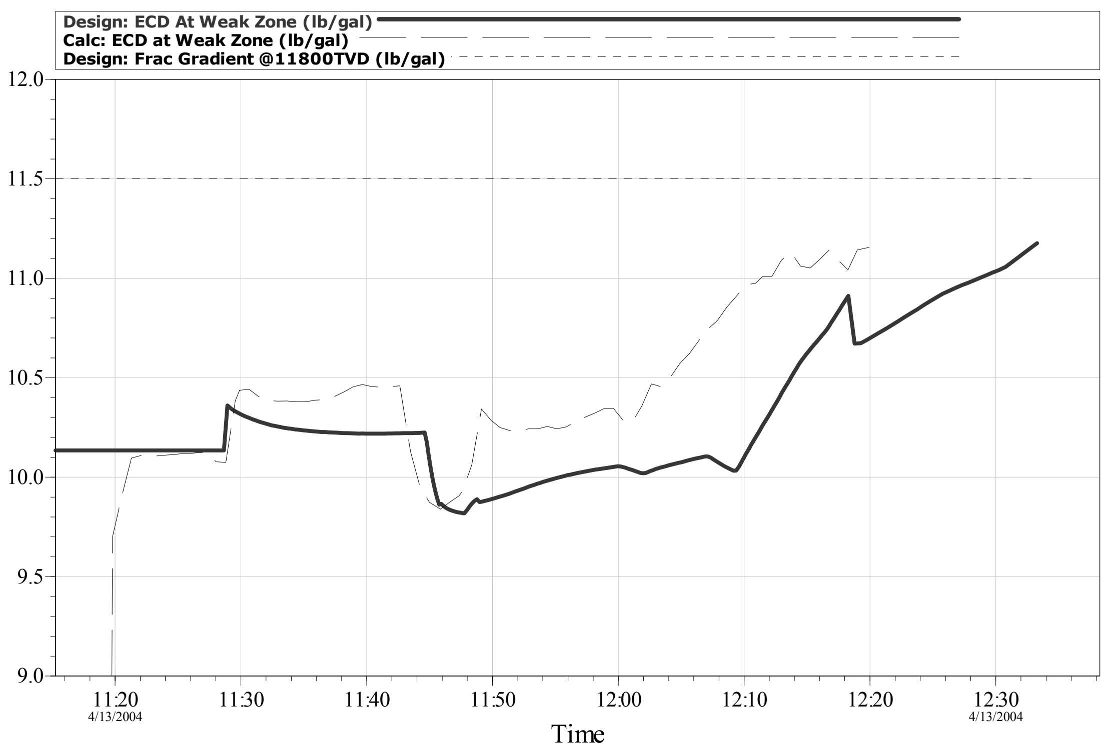

Figure 6 - Equivalent Circulating Density - Fracture Zone, Case 2

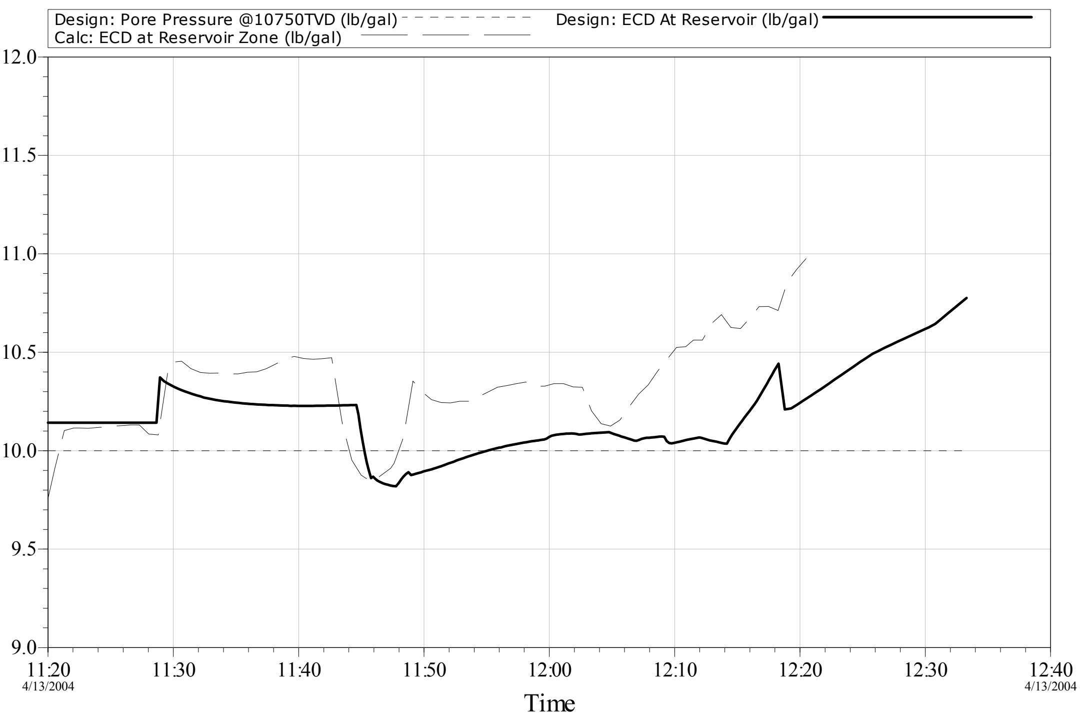

Figure 7 - Equivalent Circulating Density- Reservoir Zone, Case 2

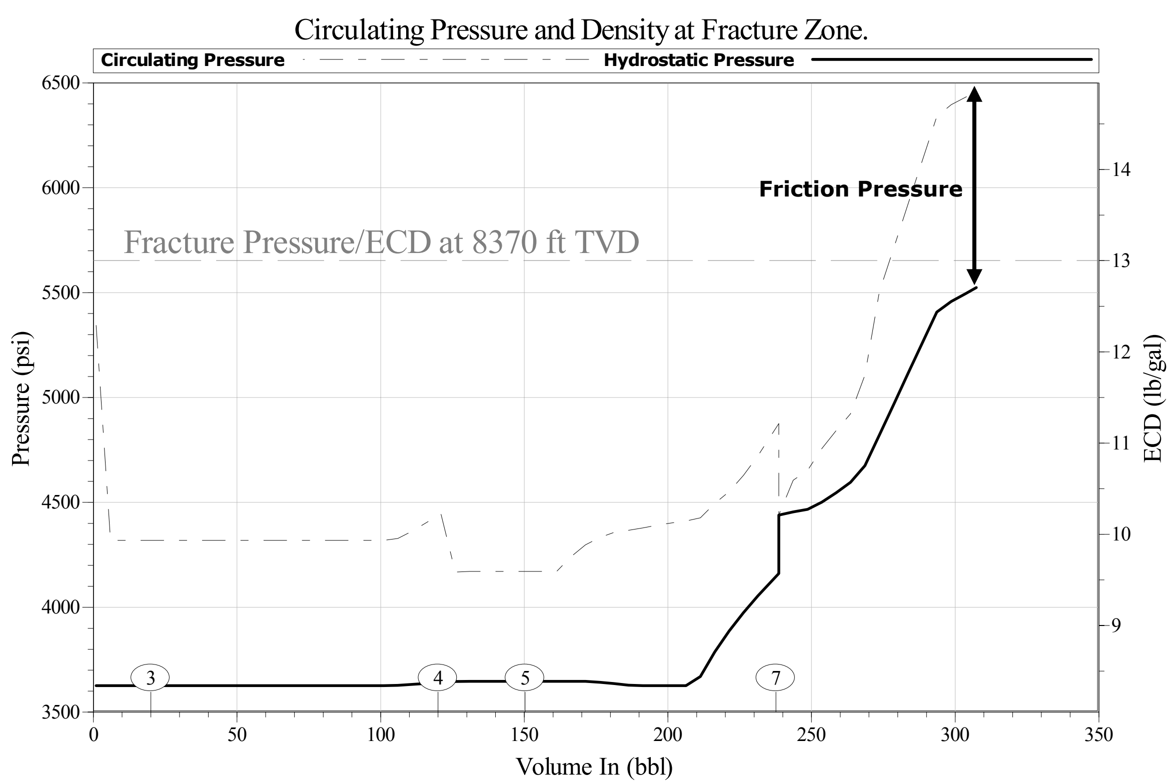

Figure 8 - Friction Pressure Model, Case 3

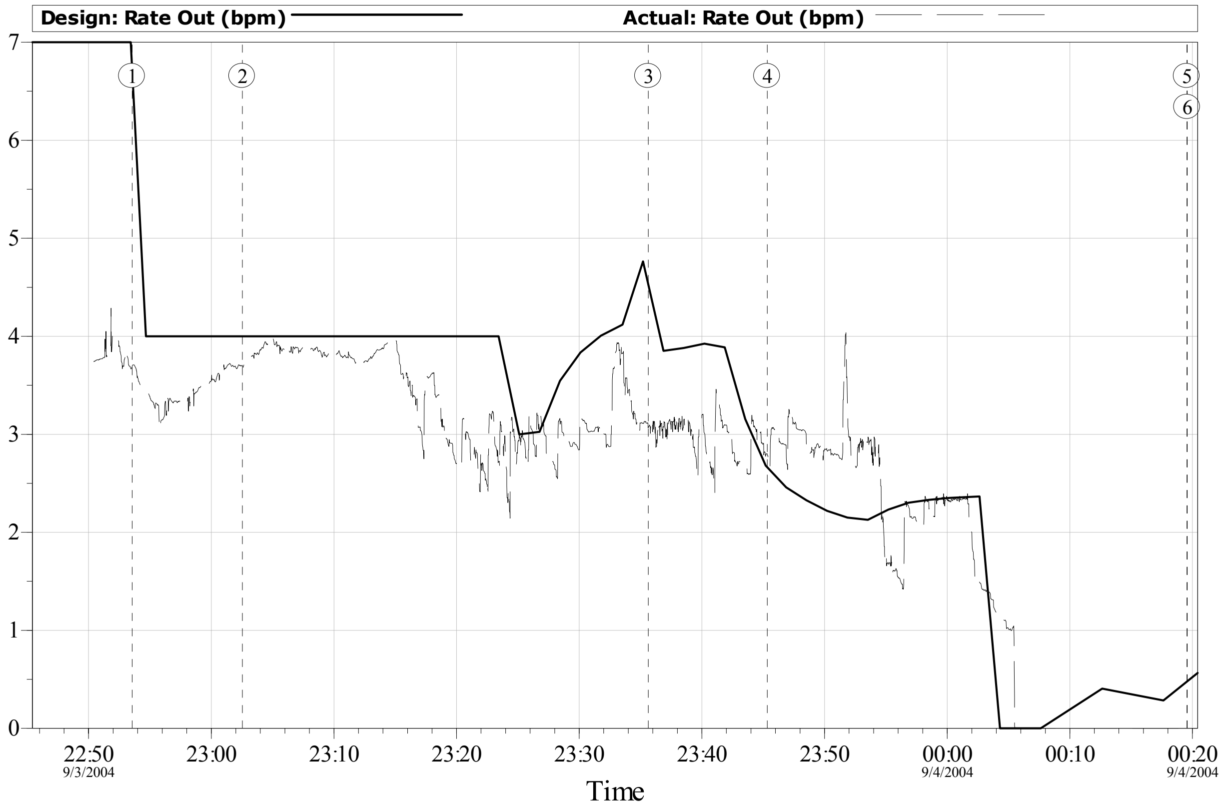

Figure 9 - Control of Rate "Out" During Real-time Mode, Case 3

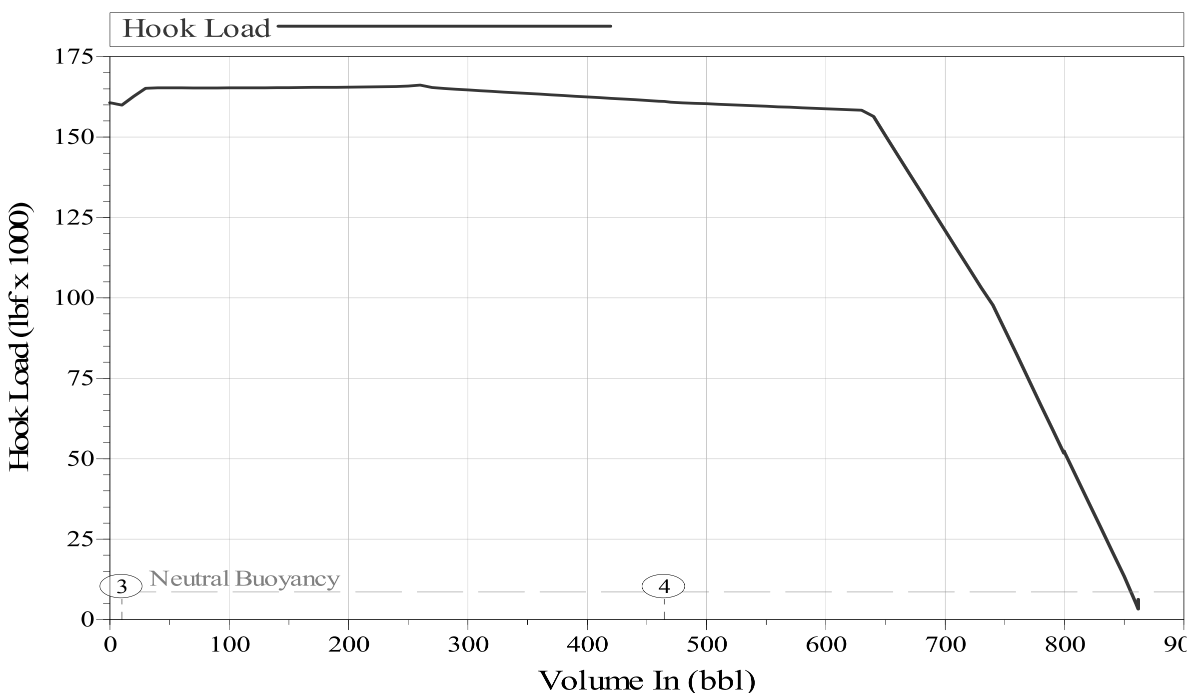

Figure 10 - Force Modeling, Case 4

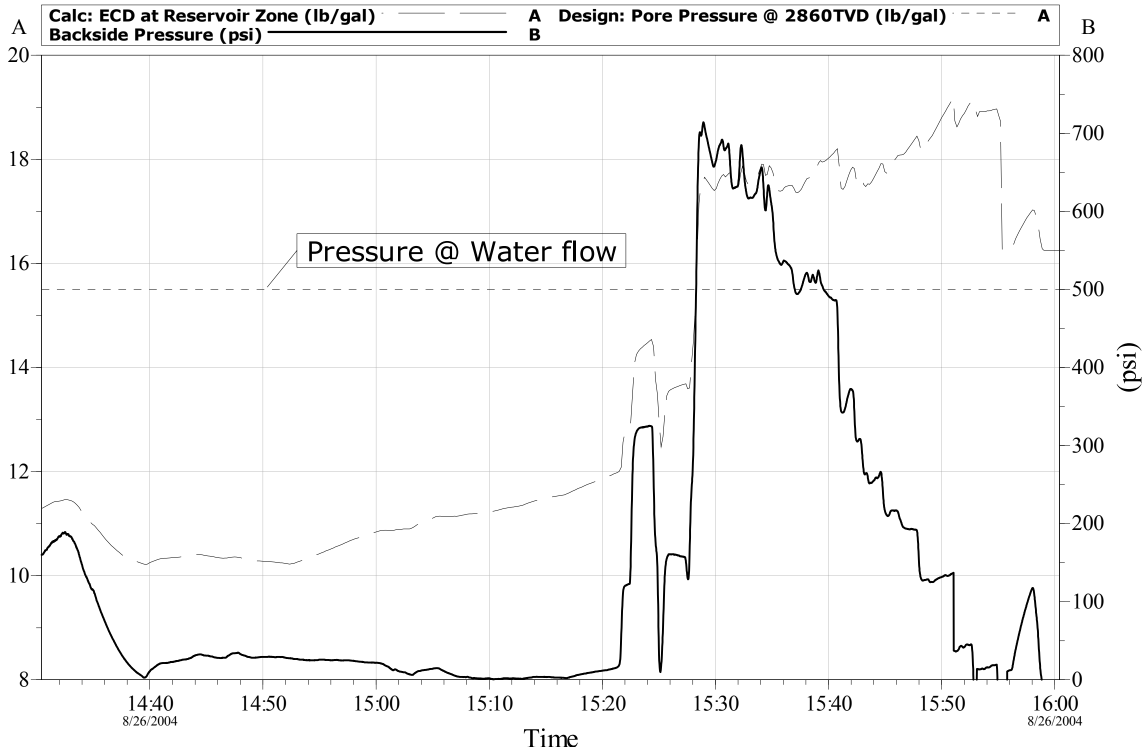

Figure 11 - Control of Backside Pressure, Case 4