Foamed Cementing Geothermal 13 3/8-in. Intermediate Casing: NGP #61-22

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Abstract

Geothermal wells in the Blue Mountain area of Nevada have experienced problems caused by losses during primary cementing of well casings, often requiring top jobs to complete. Conventional cement designs were not effective in solving the problem. Also, as deeper casing setting depths were required because of reservoir characteristics, the risk of not achieving good cement jobs increased. Analysis of cement jobs in this geothermal field led to the need for developing nontraditional cement designs. This paper documents the analysis, planning, and execution of foamed-cementing operations used to successfully perform primary 13 3/8-in. casing cement work. Previous cementing practices are presented, as well as the advantages and design of foamed cementing for this application. A post-job analysis and cost comparison of foamed versus conventional cementing is also presented.

Introduction

Geothermal reservoirs of heated water occur in regions of high heat flow and fractured, permeable-rock formations. To access the hot-water resource, production wells are typically drilled into these fractures and the heated water is brought to surface where it is either flashed to steam directly or used to heat a working fluid; the steam or working fluid is used to drive turbines to generate electricity; residual water is cooled and reinjected underground to recharge the reservoir.

Nevada Geothermal Power Company is currently developing a resource at Blue Mountain, near Winnemucca, Nevada, to power the Blue Mountain ‘Faulkner 1’ 49.5 MW gross binary power plant. The project has included fourteen temperature-gradient wells to depths generally less than 1,000 ft, two deep slim holes to depths greater than 2,000 ft, and more than fourteen full-diameter wells with measured depths ranging from 2,370 ft to 5,426 ft. Full-diameter wells are used as either production or injection wells; typically, they are completed with 13 3/8-in. casing from surface to approximately 2,000 ft, with a 12 1/4-in. openhole completion extending below the 13 3/8-in. casing to total depth. Two primary casing cement jobs are performed on each of these wells: a 20-in. surface casing and 13 3/8-in. intermediate casing. The primary goal of these cement jobs is to provide zonal isolation and to protect the casing from mechanical shock and corrosion.

The success of any given well is largely determined by the presence of both high temperature and high permeability. These desired high-temperature and highly permeable wellbore conditions lead to several major challenges when cementing a geothermal well. The first and foremost problem is that temperature has a direct effect on the hydration of Portland cement and will shorten its thickening time. Maximum measured temperatures at Blue Mountain have been approximately 370°F. In general, these high bottomhole static temperatures (BHST) can easily be lowered to approximately 200 to 250°F by circulating the well and pumping large volumes of cold water spacers ahead of cement. To successfully pump Portland cement at these high bottomhole temperatures, specialty synthetic cement retarders and fluid-loss additives are used to extend thickening times and prevent premature dehydration of cement slurries.

A second major challenge is lost circulation caused by highly permeable reservoirs, sometimes in the mega Darcy range, and low fracture gradients. While drilling, lost-circulation materials (LCM) are often added to the drilling fluid in an attempt to plug these loss zones. Another common option is to set lost-circulation cement plugs across these zones. During casing cementing operations, a low-density cement design is the preferred method to lower equivalent circulating densities (ECD) to minimize losses and cement fallback. There are a number of methods that have been used to reduce cement density, including the addition of bentonite, diatomaceous earth, fly ash, and perlite. However, these additives can have a detrimental effect on compressive strength development and permeability, especially at high temperatures.

The most common method of creating lightweight cement designs in the geothermal industry is the use of high-strength microspheres (HSM), which have a low specific gravity and can withstand high pressures. This allows the use of cement designs that can maintain low density at high pressures and still develop relatively high compressive strength over a broad temperature range. However, HSM are expensive and, when used in high enough concentration, can require special bulk handling and mixing equipment requirements to maintain a consistent slurry density.

Another option to using HSM is the use of foamed cement. Foamed cement is a mixture of cement slurry, foaming agents, and a gas (nitrogen). When properly executed, the process creates a stable lightweight slurry, with low permeability and relatively high compressive strength compared to conventional cements. For large volume, lightweight jobs, foamed cement is actually a less expensive option than using HSM and can produce better results because of inherent foamed cement properties.

The primary method of cementing the wells at Blue Mountain has been the use of a lightweight lead cement using HSM followed by a standard geothermal tail cement design. On most of the wells, this has produced good results. However, in certain cases, large top jobs were required, resulting in excessive cost in non-productive time (NPT). A couple attempts have been made using a reverse circulation method to minimize ECD. However, because of the particular method used on these reverse jobs, there was still a high potential for formation breakdown and cement fallback. Several other risks included the possibility of trapping fluid behind casing, poor mud removal, and the inability to accurately predict the location of cement during the job.

Most recently, two foamed cement jobs were performed on Wells #15-14 and # 61-22. Both jobs were highly successful and allowed the placement of 13 3/8-in. intermediate casings at depths deeper than many of the previous wells in the field, while still successfully bringing cement to surface. The deeper casing depths on both of these wells placed the intermediate casings within solid bedrock, potentially allowing better zonal isolation, and also improving the ability to perform more accurate leakoff and injection tests. However, the increased job depths also made cementing these wells more challenging because of higher hydrostatic pressures and ECD exerted on formation.

By using foamed cement on these wells, a lower cement density was achieved and was varied throughout the wellbore using just one base cement design. This lowered both the ECD during cement placement and the final hydrostatic pressures at the end of the job. By reducing the pressure exerted on the formation, not only was it possible to bring cement back to surface, but volume loss was minimized and smaller job excesses were needed than with conventional systems. In addition, the amount of cement fallback was minimized on Well #15-14, and completely eliminated on #61-22. Despite the added benefits and success of these two jobs, the actual cost per barrel of foamed cement was less expensive than using a conventional HSM cement design. Additional savings were also realized by reducing the size of, or eliminating, the need for a top job.

Reservoir Characteristics

The geothermal reservoir at Blue Mountain is hosted within a fault and fracture network at the western tip of Blue Mountain. The predominant lithology consists of varying grades of meta-sediments that have been intensely folded, faulted, and intruded by diorite, and have since undergone sedimentary burial concurrent with basin and range extension.

Well #15-14 is situated approximately 1/2 a mile from the western tip of Blue Mountain, where unconsolidated alluvial sediments reach a depth of approximately 1,280 ft. These sediments are predominantly composed of loose to moderately indurated gravels, silts, sands, and a significant amount of clay. Interlayered within the sediments are discrete sections of silicic breccias composed of strongly cemented (silica) gravels, usually containing voids capable of causing total and sustained lost circulation. One such zone was encountered between 504 ft and ~520 ft and required one cement plug to cure. The bedrock behind the cased portion of the hole consists predominantly of phyllitic meta-sediments with quartz veining and felsic dike, and a large amount of clay, often up to 60% and occasionally greater. The casing point for the 13 3/8-in. casing was chosen carefully when both the rate of penetration and clay content was significantly reduced and mud-out temperatures began to increase, indicating competent formation.

Well #61-22 is situated approximately one mile west of the Blue Mountain range front and, thus, encountered a thicker section of alluvium and unconsolidated to moderately consolidated sediments, which persisted to a depth of ~1000 ft. From 1,000 ft to ~1,350 ft, the borehole encountered silicic breccia with a minor void zone at 1,143 ft and a major void zone from 1,407 ft to an uncertain depth, which required three cement plugs to cure. Bedrock formation consists predominantly of clay-altered meta-sediments (phyllite) comprising up to 100% to a depth of 1,980 ft, and between 10% and 30% to depths well beneath the casing point (3,524 ft). The clay is presumed to be caused by hydrothermal alteration and is likely a component of the extensive hydrothermal reservoir cap.

Foamed Cement

Foamed cement is made by properly combining three elements: cement slurry, foaming agents, and a gas (usually nitrogen). When foamed slurries are properly mixed and sheared, they contain tiny (often microscopic), discrete bubbles that will not coalesce or migrate. The bubbles formed are not interconnected, which results in a low-density cement matrix with low permeability and relatively high strength (**Figure 1**).

Foamed-Cement Application

Geothermal wells in the Blue Mountain area of Nevada have experienced problems caused by losses during primary cementing of well casings, often requiring top jobs to complete. Conventional cement designs were not effective in solving the problem. Also, as deeper casing setting depths were required because of reservoir characteristics, the risk of not achieving good cement jobs increased. Analysis of cement jobs in this geothermal field led to the need for developing nontraditional cement designs. Foamed-cement technology was chosen primarily to solve lost-circulation problems during primary cementing. The application of this technology can provide the following advantages compared to conventional cements[1]:

- **Lightweight Cement—**The use of foamed cement as a lightweight slurry is based on the generation of discrete, non-interconnected pore space in a cement slurry. Such integration of discrete pore spaces reduces the density of the cement slurry, without significant reduction of compressive strength when compared to same density of diluted or extended slurries. The lesser the amount of water in a cement slurry, the higher the final compressive strength of its set cement.

When foamed cement in the density range of 9.0 to 11.5 lbm/gal is compared to a lightweight cement slurry extended with HSM, the initial advantage of the nitrogen's lower specific gravity has to be mentioned. Furthermore, foamed cement in comparison with such slurries has the benefit of no limitation respective to wellbore depth and pressure. Although the discrete hollow spaces created by nitrogen will be compressed with pressure increases, they will not disappear like HSM, which have a depth/pressure limitation; some spheres will actually crack and lose their ability to lighten the slurry when they are exposed to pressures higher than their pressure rating. Lightweight foamed slurries do have a smaller cement bulk volume and can be prepared with all mixing systems.

- **Fluid-Migration Control—**Migration of formation fluids through cement behind pipe is a well-know problem. Fluids migrate along flow paths, which are created either during or after a cementing job. A flow path along debonded cement-pipe interface (micro annulus) is, in most cases, created (1) when stressing the cement too early after a cement job (i.e., pressure testing, integrity testing), (2) because of tensile cracks and/or debonding and micro annulus formation between the cement sheath and casing or formation from cement shrinkage stresses, (3) by an incomplete hole-cleaning process and poor mud displacement before a cement job, which causes dehydrated drilling fluids left in the annulus, or (4) by channels forming during the cement job caused by a hydrostatic pressure drop below the required minimum before the cement slurry has built up enough static gel strength. The hydrostatic column is only partially effective at that stage.

Foamed cement's superior displacement properties caused by its high apparent viscosity, water-wetting ability, inherent shrinkage-control properties, and ductility aid against formation of flow paths, hence facilitating fluid-migration control.

- **Enhanced Cement Sheath—**It is desirable that a cement sheath behind casing lasts for the life of the well. The main purpose is to protect pipe against formation-related influx like steam, pressure, temperature, and corrosion. The cement must maintain its structural integrity to provide a sealing barrier as a major well component against migration of fluids.

In direct comparison to conventional cement slurries, foamed cement shows significantly better resilience and is able to withstand higher wellbore pressures. Laboratory tests using a tri-axial load-cell revealed a much more favorable Young's modulus (**Figure 2**) for foamed cement[3].

Compressive strength is neither the leading nor the only indicator for cement-sheath integrity most operators have considered throughout the last decades[2]. More important are mechanical properties, Young's modulus, and tensile strength of set cement when determining the capability to withstand stresses during such treatments. While a density decrease in conventional cements only corresponds to a lower compressive strength, without an effect on tensile strength, in foamed cement systems, a decrease in density improves the Young's modulus considerably.

Casing strings in geothermal fields need a supporting cement sheath that is able to protect the pipe throughout the life of the well against buckling, elongation, and/or parting induced by changing thermal loads and corrosion.

It must be mentioned that foamed cement is the recommended solution because it has better bonding properties, is more ductile, and shows better insulating properties, especially for use in geothermal projects. The insulating capacity of foamed cement is two to ten times higher compared to conventional cement slurries (**Figure 3**). Depending on slurry design, a heat transfer coefficient as low as 0.05 btu/(hr*ft*F) can be achieved.

Previous Primary Cementing Practices

For both 20-in. surface casings and 13 3/8-in. intermediate casings at Blue Mountain, HSM lead cement designs and standard tail cement designs have been used. The lead cement design is comprised of a Class G or similar Portland cement, plus 40% equivalent of silica flour and microsilica, HSM, a fluid-loss additive, and accelerator or retarder, as necessary. For shallower surface casings, no retarder is used; gypsum and calcium chloride are added to accelerate the design. On hotter and deeper intermediate casings, a liquid synthetic retarder is used as necessary.

The standard tail cement design has been a Class G or similar cement plus 40% equivalent of silica flour and microsilica, a fluid-loss additive, and accelerator or retarder. Just as with the lead cement, on the shallow surface casings, calcium chloride is used as an accelerator and on the deeper intermediate casings, synthetic liquid retarder is used.

Casing cement jobs have been performed using a conventional inner-string method. After casing is on bottom with drillpipe stung in, the rig circulates drilling mud to lower the viscosities and yield points. This not only conditions the mud system to improve mud removal while cementing, but cools the hole. An engineer on location can check the mud return temperature to help ensure that the hole has been adequately cooled based on previously run temperature simulations. Once the job has begun, a large volume of freshwater spacer, usually 100 bbl, is pumped to provide additional cooling. This fresh water is followed by 30 bbl of a viscous spacer. This viscous spacer is followed by freshwater spacers and sodium silicate before pumping the lead and tail cement slurries. Drillpipe is displaced using freshwater or mud. After cement is in place, the rig must WOC before checking for the level of cement in the annulus. Usually one or more top jobs have been required to bring cement to surface.

Well Profile

Table 1—Well Profile

Surface casing	20-in. 94 # K 55 BTC set at 830 ft
Intermediate casing	13 3/8-in. casing 68# K 55 BTC set at 3,525 ft
Drillpipe	5-in. 19.5 lb/ft X-95
Openhole	17.5-in., 830–3,533 ft
Job cement volume	1,535 sacks geothermal-stable Portland cement
Job Excess	20% excess

While drilling the 17 1/2-in. hole, a loss zone was encountered from 1,400 to 1,524 ft. There were partial losses from 1,400 to 1,441 ft, and total losses from 1,441 to 1,524 ft. The losses were cured by setting four cement plugs.

Job Objectives

The job objectives are listed below.

- Cement 13 3/8-in. intermediate casing in 17 1/2-in. openhole from 830 to 3,525 ft MD.
- Circulate foamed cement to surface and successfully pump cap cement
- Minimize the potential of losses during the cement job in the long 2,685 ft 17 1/2-in. × 13 3/8-in. annulus
- Provide a cost-effective cementing option
- Eliminate the need for a top job caused by volume losses and cement fallback

Job Design

The base cement slurry design was standard 15 lbm/gal geothermal tail cement, comprised of Class G cement with 40% silica flour and microsilica added for strength protection, and a small amount of fluid-loss additive was included primarily to aid mixability. Laboratory tests were performed to confirm foam stability at required densities to determine retarder concentration needed based on thickening time and to acquire rheology information to more accurately predict placement pressures. Temperature simulations were run to accurately predict BHCT, both for lab testing purposes and job-design parameters because of the effects of temperature on fluid rheology and foam quality.

Job Summary

All job calculations and procedures were confirmed between cementing engineers and company representatives on location. A safety meeting was conducted with all personnel to discuss the potential hazards associated with the cement job. After the safety meeting, all pumps and surface lines were isolated from the well and pressure tested. The high-pressure cement lines were pressure tested to approximately 3,000 psi and the nitrogen lines to approximately 7,000 psi. Pressure was bled off and the valve at the wellhead was opened to begin pumping. The cement pump truck came online and pumped 90 bbl of freshwater at 5 bbl/min to cool the well down. This pump rate of 5 bbl/min was held throughout the job. Mud returns were initially taken at the mud pits until they were full, and then returns were diverted to the sump. The backside pressure was continuously monitored throughout the job.

Approximately 35 bbl of scavenger cement was pumped and foamed at a constant nitrogen rate. The scavenger cement was followed by 390 bbl of lead cement foamed to 11 lbm/gal, 20 bbl of tail cement foamed to 13 lbm/gal, and 15 bbl of unfoamed 15-lbm/gal tail cement. The drillpipe was then immediately displaced with 60 bbl of water without washing pumps and lines (**Figure 4**).

Post Job Analysis

Foamed cement was seen at surface approximately 560 bbl into the job. According to job simulations run before the job and the nitrogen schedule, foamed cement was expected at surface after pumping 515 bbl if the 17 1/2-in. hole was gauge, and after 566 bbl if 20%-excess were used. Therefore, based on the job volumes, the actual annular hole volume was very close to the designed 20% excess. Cap cement was successfully pumped down the annulus to compress the low-quality foamed cement near surface. After WOC for 8 hours, the fluid levels did not drop and cement remained at surface. There was no need to perform a top job.

On Well #15-14, the surface casing was set at a shallower depth. During the foamed cement job, the backside was shut in while pumping unfoamed tail cement and during displacement. Although there was no indication of formation breakdown during the job, cement fallback occurred and a top job was performed. Nitrogen was later observed leaking out at surface between the 20-in. surface casing and conductor casing, indicating possible formation breakdown near the casing shoe. This might have occurred because of higher backside pressures during the job.

In comparison, the backside was left open until after displacement on Well #61-22 to minimize backside pressure. In addition, the surface casing was set at a deeper depth (830 ft instead of 300 ft). Because of the compressibility of foamed cement, any backside pressure at surface would have less of an effect as depth increases. Therefore, the lower backside pressures and deeper surface casing might have prevented breaking down the formation near the surface casing shoe.

Cost Savings

A cost analysis shows that for large-volume jobs, the cost per barrel of the foamed cement design used at Blue Mountain is less expensive than a HSM lead cement design. The analysis is based on the cost of goods sold and delivery to the worksite in Winnemucca, Nevada. For the foamed cement jobs, the price also includes the cost of nitrogen, foamer, associated equipment mileages out of Bakersfield, California, as well as additional charges for equipment and processes not used on a conventional cement job. Non-material charges, such as pumping charges, personnel costs, standby time, or other standard charges that would apply on both job types were not included in the analysis.

As seen in the two cost comparison charts (**Figures 5 and 6**), the nitrogen and equipment costs result in an initial flat rate charge of approximately $28,000. The nitrogen unit on location had a capacity of 135,000 scf. Assuming that this nitrogen was added to cement following the same rate increase used on Well #61-22 for the 11-lbm/gal lead cement, then this unit would be capable of foaming a downhole cement volume of approximately 790 bbl. Therefore, until the job size exceeds the capacity of the nitrogen unit, there are no added job costs for nitrogen. The price point at which it becomes advantageous to use foamed cement over a conventional HSM slurry design for this project is approximately 220 bbl of lead cement.

Conclusions

Overall, foamed cement job costs are comparable in cost to other specialized slurry designs.

- Because of the success of this foamed-cementing program, the foamed-cement process has become the first choice for primary cementing where conventional techniques have failed and where zonal isolation is critical.
- Because foamed cement is more ductile and shows better insulating properties than non-foamed cement, it is a recommended option in geothermal applications.
- Foamed cement lost-circulation properties can help enable successful cementing of geothermal wells in low fracture-gradient zones.

References

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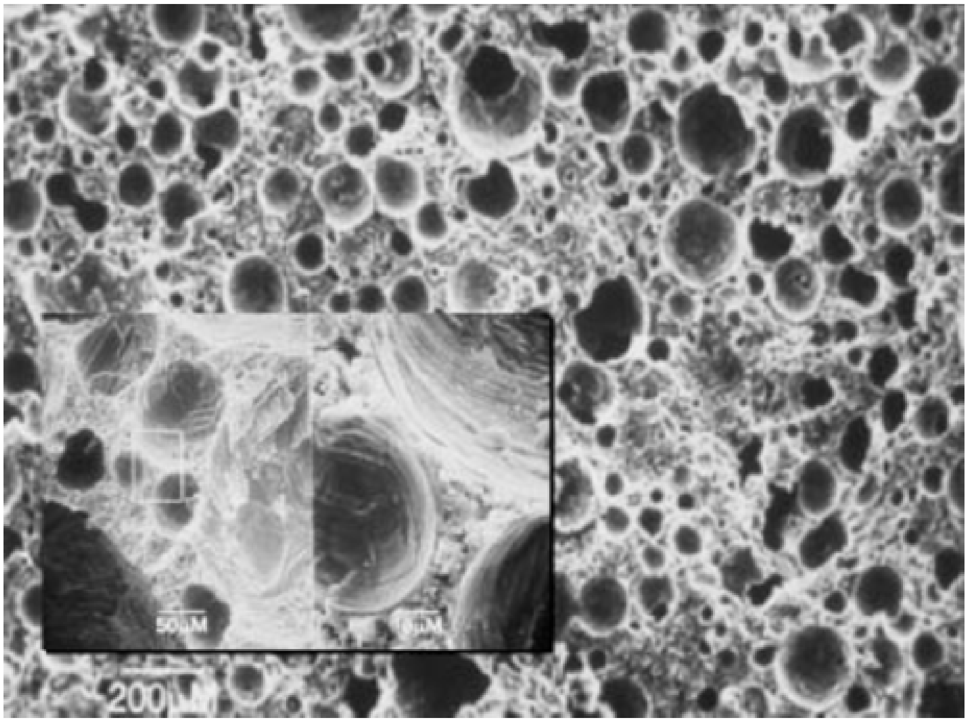


Figure 1—Microphotographs of a foamed cement sample.

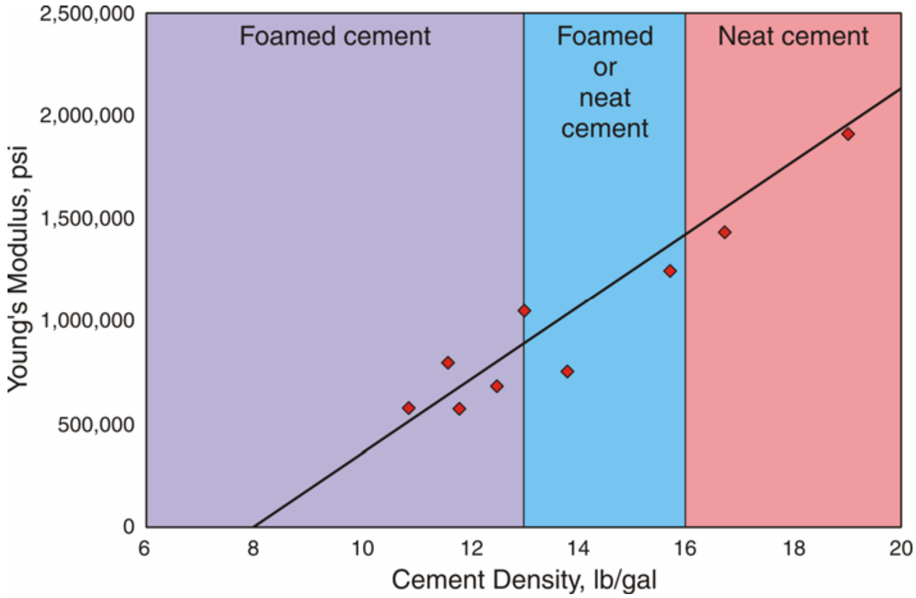


Figure 2—Young’s Modulus at different densities and types of cement.

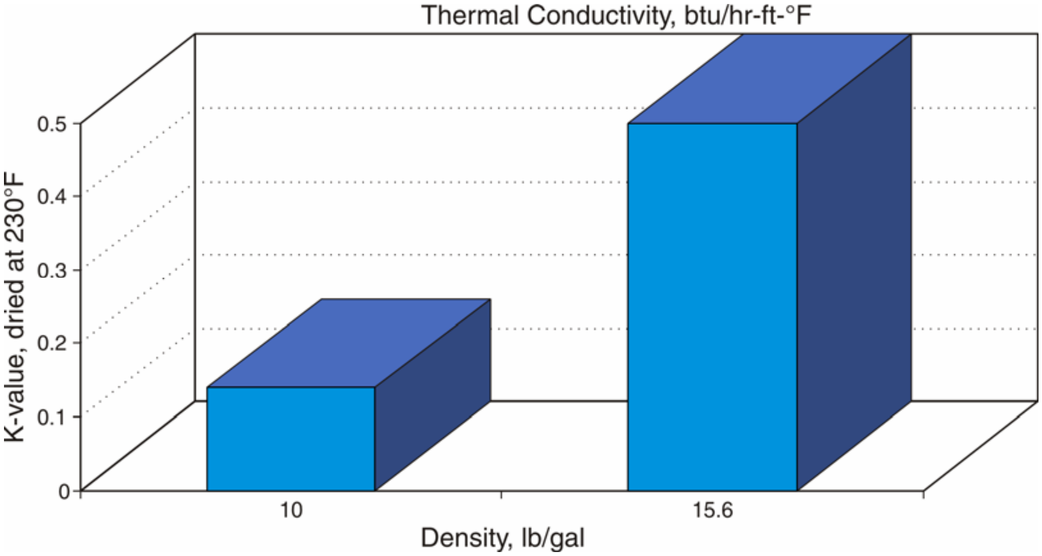
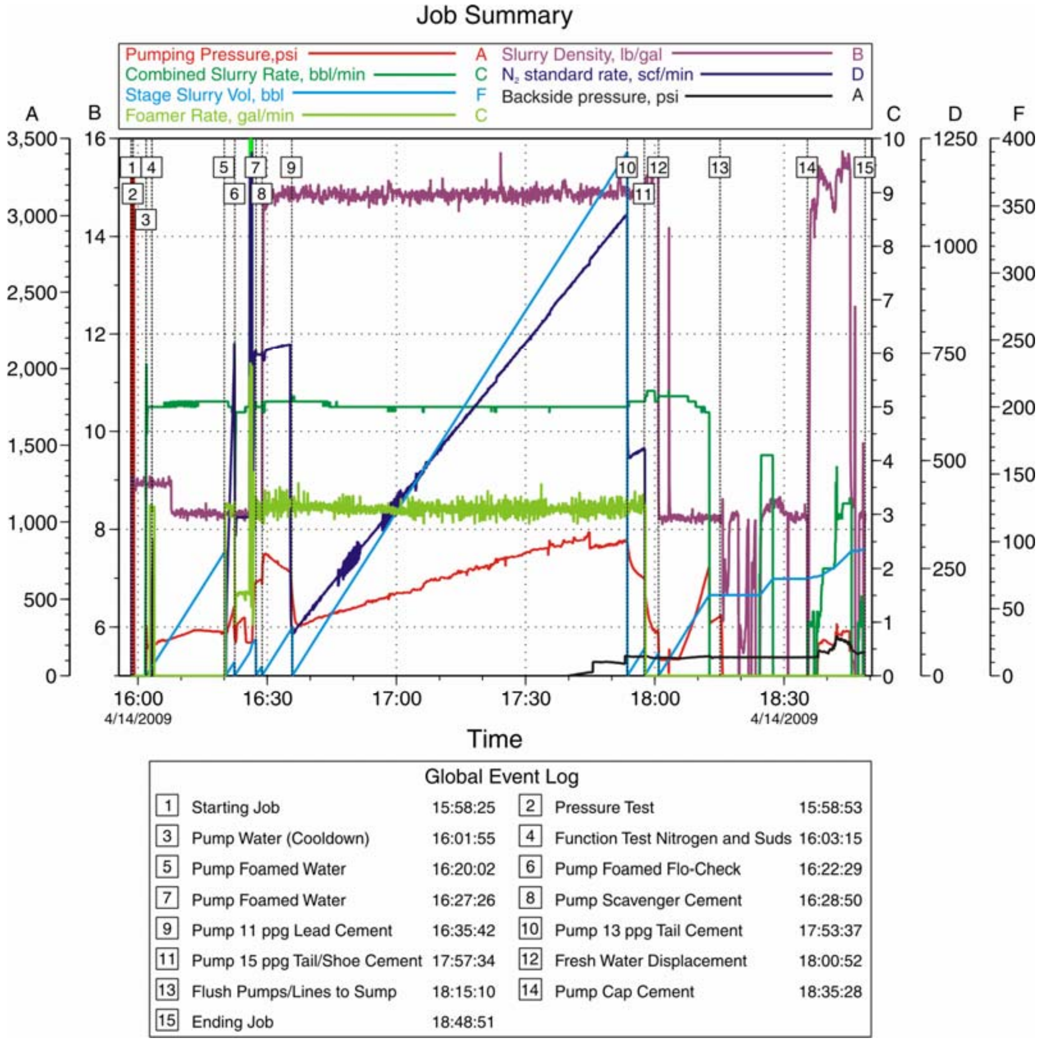


Figure 3—Thermal conductivity of foam cement versus conventional cement.



1	Starting Job	15:58:25	2	Pressure Test	15:58:53
3	Pump Water (Cooldown)	16:01:55	4	Function Test Nitrogen and Suds	16:03:15
5	Pump Foamed Water	16:20:02	6	Pump Foamed Flo-Check	16:22:29
7	Pump Foamed Water	16:27:26	8	Pump Scavenger Cement	16:28:50
9	Pump 11 ppg Lead Cement	16:35:42	10	Pump 13 ppg Tail Cement	17:53:37
11	Pump 15 ppg Tail/Shoe Cement	17:57:34	12	Fresh Water Displacement	18:00:52
13	Flush Pumps/Lines to Sump	18:15:10	14	Pump Cap Cement	18:35:28
15	Ending Job	18:48:51			

Figure 4 —Job data.

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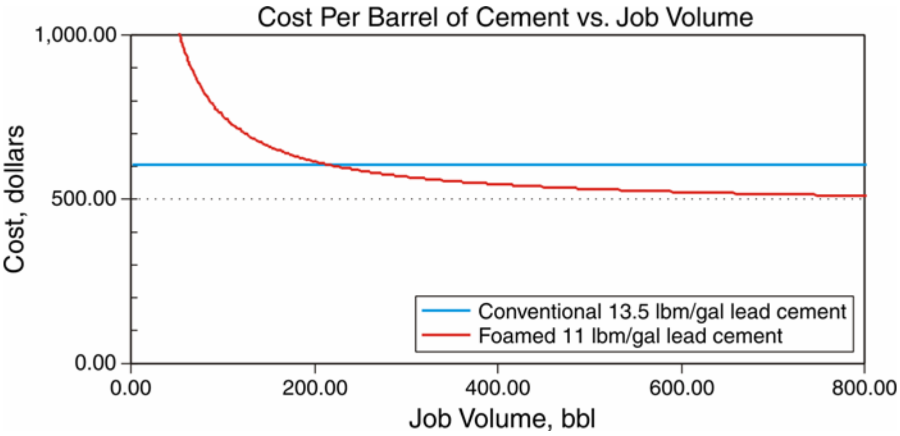

Figure 5—Cost per barrel of cement versus job volume.

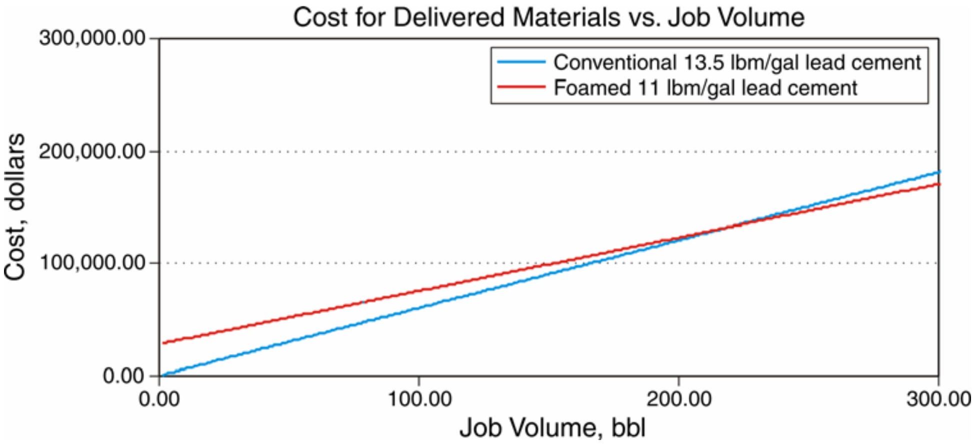

Figure 6—Cost for delivered materials versus job volume.