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Application of Foamed Cement on Hawaiian Geothermal Well

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ABSTRACT

Drilling and completing geothermal wells involves a number of unique challenges. Included in these challenges is the cementing of various casing strings across what are typically weak formations prone to lost circulation. Not only must the cement systems used on these wells be light enough to be circulated in place, they must also withstand the stresses occurring in the cement sheath from cyclic loading. This paper presents a case history in which foamed cement was used in multiple casing strings of a Hawaiian geothermal well.

Introduction

The geothermal well discussed in this paper was drilled to replace declining steam production from other wells. The well was drilled by Puna Geothermal Venture in the Kapoho State lease in the Puna District on the island of Hawaii. The well is located in the Kilauea East Rift Zone. Kilauea is an active volcano in the southeastern part of the island. All materials necessary for cementing the casing strings were shipped from California on a sea-going vessel. The cement was supplied by a local manufacturer. Necessary cement additives had to be predetermined and then shipped to the job site.

The drilling and completion program was designed for production of over 600 kw/h steam at 650°F and 2,230 psi. Table 1 compares design data with actual production data.

Table 1. Design Data vs. Actual Job Data.

Well/Production Data	Estimated	Actual
Temperature Encountered	650°F	618°F (maximum)
Steam Production	600,000 lb/hr	600,600
Steam Flow	90%	78%
Liquid Flow	10%	22%
Total Mass Flow	670,000 lb/hr	770,000 lb/hr

Previous Cement Jobs on Neighboring Geothermal Wells

Cement Designs with Hollow Microspheres

Previous wells drilled in this area were cemented with lightweight cement containing hollow microspheres. These slurry designs provide a lightweight cement that can still achieve a compressive strength higher than that of conventional lightweight cements. One of the wells completed with a hollow-microsphere cement (HMC) experienced steam breakthrough at the surface, indicating that the cement sheath had failed as the result of stresses from thermal cycling. Another well cemented with an HMC included an expandable casing packer (ECP) in the annulus between the 13 3/8 and 20-in. casing strings near the shoe of the 20-in.casing. This well did not experience steam breakthrough at the surface, and this success was attributed to the presence of the ECP.

Lost-Circulation Problems

During drilling, lost-circulation cement plugs had to be placed in some wells to help provide sufficient resistance to formation breakdown. These plugs allowed the HMC slurries to be circulated in place without causing lost circulation. However, despite the use of the HMC slurries and the lost-circulation plugs, multiple stage tools were required for two-stage cement jobs, which allowed a cement column to be placed back to surface without breaking the formation down during placement.

Because of (1) the problems that occurred with HMC slurries and (2) the potential benefits of foamed cement, the operator decided to use foamed cement on the KS No. 11 well.

Well Plan

A schematic of the well is provided in Figure 1. The 22-in. casing was Grade B, butt-welded line pipe with a wall thickness of 0.5 in. The setting depth was designed for 1,000 ft. The 26-in. hole was drilled without returns with water and thick mud sweeps. The casing was cemented conventionally to secure the shoe and raise the cement to a level of 600 ft, which is approximately sea level in the field. No surface-casing

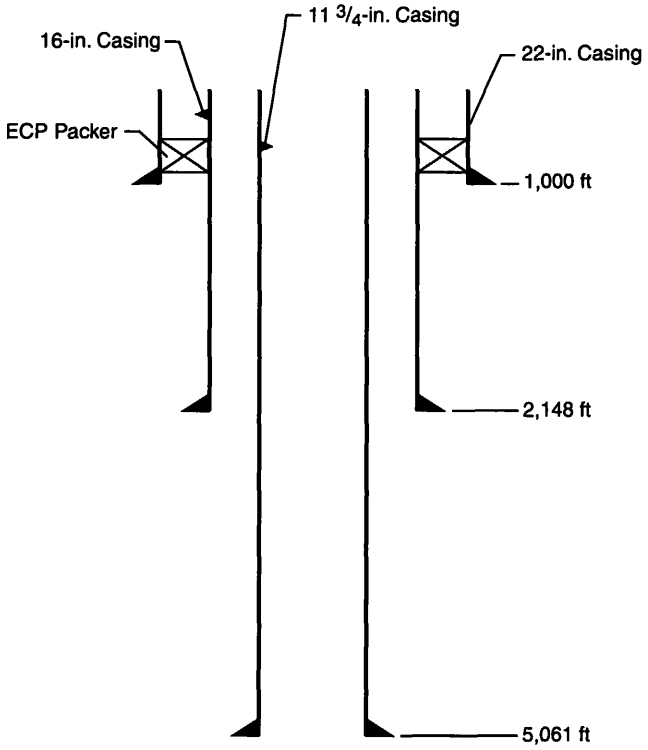


Figure 1. Well schematic (stick diagram of different casing strings) (om002833)

cement had previously been circulated above this depth in the field. The casing was cemented to the surface with pea gravel, and ready-mix concrete was dumped from the surface.

The 16-in. casing was 97-lb/ft, L-80 BOSS. The planned setting depth was 2,200 ft. The production wellhead and expansion spool were attached to this intermediate casing string. Premium connections provided the tensile joint strength required for the well's elevated temperatures. The 22- × 16-in. annulus was open to the atmosphere. In previous wells, hydrogen sulfide gas (H_2S) migrated to the surface through microannuli in the cement sheath below the surface casing shoe. On the last production well drilled, an expandable casing packer (ECP) successfully prevented gas migration to the surface. Preventing gas migration is important in Hawaii because only low levels of H_2S are allowed at the lease boundary. Therefore, a packer was also set near the shoe of the surface casing for this well's intermediate casing string. Most of the wells previously drilled in this formation exhibited lost circulation and/problems related to circulating cement to the surface in this hole section. Some losses were encountered while the well was drilled, but all loss areas were treated with a lost-circulation material (LCM) rather than being cemented.

The 11 3/4-in. casing was 65-lb/ft C-90 SLHC with a planned setting depth of 5,000 ft. The premium connections were run to increase joint strength and eliminate H_2S leakage. Foamed cement was used to circulate cement back to the surface. Stage tools were not used because they can provide a point of stress concentration in the casing string when thermal stresses are severe. The production casing string was previously run as a liner-tieback combination because of problems with cement circulation during the primary cementing job. Most of the previous liner laps had to be squeezed. Log data showed that the tieback casing separated from the liner top as the result of thermal cycling in at least two previous wells. The latch-in tieback stem incorporated in one of these wells could not prevent separation. A polished joint was run as the surface-casing joint to minimize the tolerances in the expansion-spool pack-off assembly because commercial assemblies are not rated for the temperatures exhibited in geothermal wells. No significant lost circulation was encountered while this hole section was drilled. The foamed-cement slurry was designed to maintain the hydrostatic pressure of the cement column at a level lower than the leak-off pressure at the previous casing shoe.

The well was completed with a 10 5/8-in. hole drilled to a depth of 6,500 ft. The first sign of a producing zone was encountered as a 2-in. drilling break at 6,403 ft. A 40-bbl mud loss was treated with LCM. Total lost circulation and voids were encountered at depths between 6,450 and 6,500 ft. Therefore, drilling was discontinued at 6,500 ft. The well was killed with water and a blank, and a perforated 8 5/8-in. liner was run and set on bottom. Weighted mud was not required during drilling.

Benefits of Foamed Cement for Use in Geothermal Wells

Conventional cements cannot always withstand the cyclic loading that occurs in the cement sheath during the life of a geothermal well. This loading is the result of temperature fluctuations (400° to 750°F).[1] Foamed cements, however, exhibit several properties that make them suitable for use in geothermal wells.

Lost Circulation

Lost circulation is a common problem in geothermal wells. Conventional cements used in such wells need to be lightweight and low-strength, and stage tools are sometimes necessary for cementing the casing string all the way back to the surface. Foamed cements, however, can be designed for high strength and low density, eliminating the need for stage tools. Because foamed cements are lightweight, they are less likely to exceed formation fracture gradients and cause lost circulation.

Ductility

Unlike conventional cements, foamed cement is ductile/elastic in nature, making it resistant to both temperature- and pressure-induced sheath stresses. Conventional cements can fail when exposed to the cyclic stress loading of a geothermal environment[2] Foamed cement, however, is at least one order of magnitude more ductile than other cements and can produce a cement sheath capable of withstanding higher internal casing pressures, allowing the cement sheath to yield while the casing expands. Consequently, the cement sheath has less potential for cracking on a long-term basis and is more resistant to stress cracking caused by the cyclic activity associated with geothermal wells.[3-4]

Mud Displacement

A primary concern in the execution of any cement job is drilling-fluid displacement. If the drilling fluid is not completely displaced, mud channels can form, leading to interzonal communication, casing corrosion resulting from exposure to corrosive formation fluids, and even casing collapse resulting from high-pressure steam buildup in undisplaced pockets of drilling fluid. A particular challenge in the displacement process is the removal of the partially dehydrated gelled mud (PDG mud) located next to the mud filter cake (Figure 2). The removal of the PDG mud is a function of the shear stress imparted by a fluid flowing past it. The higher the viscosity of a fluid at a given flow rate, the higher the shear stress imparted on the PDG mud.[5] The base slurry for a foamed-cement job typically has relatively high rheological properties. When surfactants and nitrogen are used to foam the base slurry, the viscosity of the slurry increases proportionally to the amount of gas phase (quality) of the foamed slurry. This high viscosity makes foamed-cement slurries ideal for removing PDG mud and achieving excellent mud displacement during a cement job.

Economic Benefits

The lightweight foamed-cement system provided a number of economic advantages. It provided a lighter density slurry capable of achieving compressive strengths equivalent to those of the HMC slurry, eliminating the need for using a two-stage cement job to bring cement returns all the way to the surface. Consequently, overall job costs were reduced because the tool itself and the additional rig time to use it were both eliminated. In addition, the low slurry density eliminated the need for increasing formation strength with lost-circulation plugs, which also reduced costs associated with materials and rig time.

Depending on the logistics of the particular well, foamed cement can provide significant economic savings during geothermal completion operations. Although the foamed cement itself may cost as much or more per unit volume of HMC, it eliminates costs associated with materials and rig time. While it is too early to determine the durability of the foamed cement placed in the well, initial results show no steam breakthrough. Placing an ECP in this well could prevent potential steam breakthrough; however, laboratory test data and field experience indicate that foamed cement is far more resistant to cyclic loading than conventional nonfoamed cement systems.

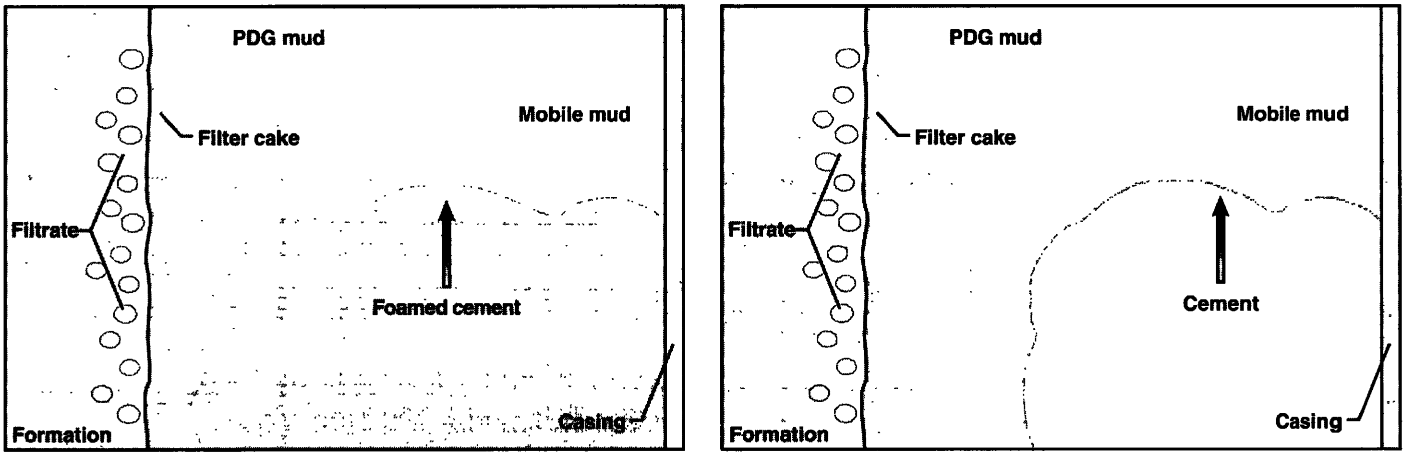
Other Benefits

In addition to helping prevent lost circulation and providing better ductility and mud displacement, foamed cement has the following benefits that make it suitable for use in geothermal wells:[6]

- Flexibility—Because foamed-cement density is a function of the amount of nitrogen injected into the base slurry, the density of a foamed cement placed in a well can be adjusted at any time before the job is pumped. Conventional cement systems are typically reformulated and tested in the laboratory, and then either re-blended or replaced by a completely different blend if slurry density must be adjusted.
- Lower Environmental Impact—Because nitrogen gas constitutes a large portion of the slurry pumped into the well, using foamed cement typically decreases the amount of materials that must be brought to the job location. In addition, foamed-cement base slurries are composed of a bare minimum of raw materials and chemical additives. Consequently, the manufacture, transportation, and utilization of foamed cement can have less impact on the environment than that of conventional cements.

Challenges of Foamed Cementing

Although using foamed cement for geothermal well cementing has numerous benefits, it also presents two main challenges. Foamed-cement systems are more complex than other systems



Foamed-cement

Conventional-cement

Figure 2. Mud displacement: foamed cement vs. conventional cement. (om002836)

because they incorporate nitrogen in the slurry and require nitrogen equipment. In addition, evaluating foamed cement after job requires special interpretation techniques to properly evaluate bond logs.

Nitrogen and Nitrogen Equipment

Using a nitrogen pumping unit on location increases the complexity of executing a foamed-cement job because the nitrogen and cement pumping units must be coordinated to ensure that the base cement slurry contains the nitrogen volume necessary for achieving proper downhole density. Small deviations from designed nitrogen-injection rates will not impede job success. However, large deviations can produce foamed cement that is either too light or too heavy. If the density of the foamed cement is too low, the cement may not provide the strength and ductility necessary for resisting cyclic loading and the associated stresses it produces on the cement sheath. If the density of the foamed cement is too high, the cement may place excessive pressure on weak formations, leading to lost circulation when the actual job is pumped.

A number of methods and equipment are available to aid help ensure proper nitrogen volumes in the cement slurry. Condensing the overall job design into two or three nitrogen-rate stages can minimize job complexity and help ensure that proper nitrogen-mixing ratios are maintained when the cement job is pumped. Although it was not used for the job described here, automated nitrogen-control equipment is available. During the cement job, this equipment can adjust the nitrogen-injection rate based on preplanned nitrogen ratios and continuous pump-rate data from the cement pump truck.

Because the foamed cement is compressible, the simulation of a foamed cement job in the design stage becomes much more complex. A compressible foamed fluid will vary in density, rheology, and flow rate continuously throughout the job as the fluid is moving down the casing and up the annulus. To properly design and model a dynamic placement of foamed cement, specialized, complex computer simulation programs are required.

Evaluating Placement and Bonding of Foamed Cements

Evaluating the quality of a foamed-cement job poses particular challenges. While conventional bond-logging tools can be used for effectively evaluating foamed cement, conventional interpretation techniques cannot. The acoustic impedance of conventional high-strength cement is significantly higher than that of drilling mud, making it easy for operators to distinguish between the two with conventional acoustic-impedance tools. However, the acoustic impedance of foamed cement can be essentially equal to that of drilling fluid, making it nearly impossible to distinguish between the two. Consequently, conventional interpretive techniques may not indicate the presence of foamed cement.

Although the absolute acoustic impedance of foamed cement is nearly equal to that of drilling fluid, the statistical variation of this impedance is significantly higher. Consequently, Harnes *et. al.*[7] have developed a technique for distinguishing between foamed cement and wellbore fluids. Similar techniques are also available. These specialized techniques are necessary for accurately evaluating foamed-cement jobs.

Good foamed-cement returns were observed for both of the jobs described in this paper. The cap cement was placed successfully; therefore, no logs were necessary for evaluating cement density

Case Histories

16-in. Job

A 15-lb/gal cement slurry was used for cementing the 16-in. casing string. Table 2 provides well information for the job, and Table 3 provides information about the cement slurry. During the cementing job, a single-rate nitrogen job was performed. After the job, a cap cement (unfoamed cement slurry with a composition similar to that of the foamed slurry) was squeezed down the backside of the annulus. Although foam returns were obtained during the job, some nitrogen breakout occurred, resulting in channeling through the cap cement. At some point after job completion, steam built up in the annulus. Apparently, water had seeped into the channel created by the nitrogen breakout and was transformed into steam by the well's high temperature. After vapor was vented for some time during well heat-up, the channel was plugged off, and approximately 60 ft of cement was blown out of the annulus from the steam pressure buildup. For future applications a larger volume of cap cement will be used, and a metering system may be implemented to measure cement pump rate, and, consequently, improve job quality by eliminating channeling and pressure buildup. Figure 3 provides a job summary of the 16-in. casing job. Figure 4 is a plot of the foam density vs. depth immediately after the job but before a cap cement slurry was placed on top of the foamed cement column.

11¾-in. Job

During the 11 ¾-in. job, multiple nitrogen rates were used. No nitrogen breakout or other problems occurred. The improved quality of this job may have resulted from better execution of surfactant injection. Table 4 provides the well information for

Table 2. Well Information for 16-in. Job.

Casing Size	16 in.
Casing Weight	97 lb/ft
Casing Depth	2,148 ft
Previous Casing Size	22 in.
Previous Casing Weight	0.5-in. wall
Previous Casing Depth	1,000 ft
Hole Size	20 in.
ECP Packer	950 ft
Cement Excess	50%

Table 3. Cement Slurry for 16-in. Job[a].

Cement Retarder	0.8%
Temperature Stabilizer	30%
Extender	10%
Cement Friction-Reducer	0.2%
Fluid Weight	15 lb/gal
Fluid Yield	1.76 ft³/sk
Fluid-Water Ratio	7.85 gal/sk
Total Displacement Volume	444.44 bbl

[a]Mixed with fresh water.

this job. The cement slurry used for this job was identical to that used for the 16-in. job, but the total displacement volume was 562 bbl. Figure 5 provides a job summary of the 11 3/4-inch casing job. Figure 6 is a plot of the foam density vs. depth immediately after the job but before a cap cement slurry was placed on top of the foamed cement column.

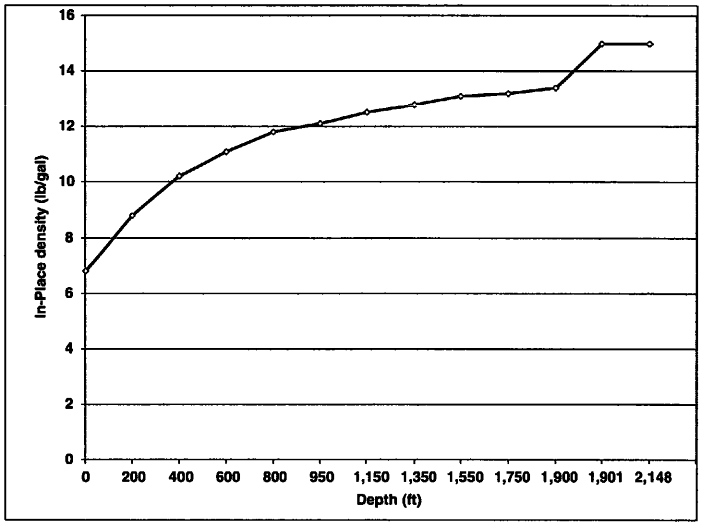


Figure 4. Foam density vs. depth for 16-in. foam job. (om002834).

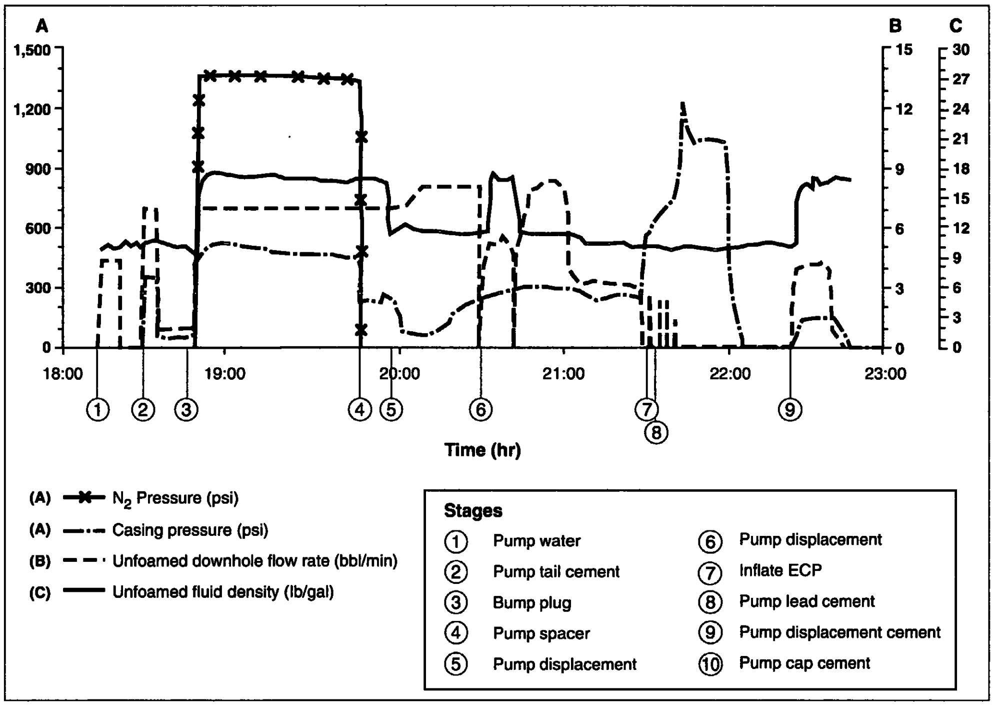


Figure 3. Data for 16-in foamed casing job. (om002831).

Conclusions

Overall, both jobs were very successful. Thermal casing expansion occurred primarily during the initial heatup. The annuli in the foamed cement are not leaking measurable volumes of vapor, and no H_2S is migrating through the casing to the surface. This well is achieving significantly better results than those achieved in previous wells cemented with HMC slurries. Using a foamed rather than an HMC slurry allowed us to eliminate the need for (1) lost-circulation cement plugs before cementing, (2) a multiple-stage tool, and (3) performing a two-stage cement job. In addition, we were able to place a more durable cement system in the well, which provided economic benefits to the overall drilling process and provided a more durable well that should not be as prone to annular gas leakage.

Although the well is relatively new, no problems are currently apparent. Operators have found no indication of casing collapse or excessive casing movement. The well is online, providing steam to the Puna Geothermal Venture power plant and electricity to the people of Hawaii.

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Table 4. Well Information for 11 3/4-in. Job

Casing Size	**11 3/4 in.**
Casing Weight	**65 lb/ft**
Casing Depth	**5,061 ft**
Previous Casing Size	**16 in.**
Previous Casing Weight	**97 lb/ft**
Previous Casing Depth	**2,200 ft**
Hole Size	**14 3/4 in.**
Cement Excess	**50%**

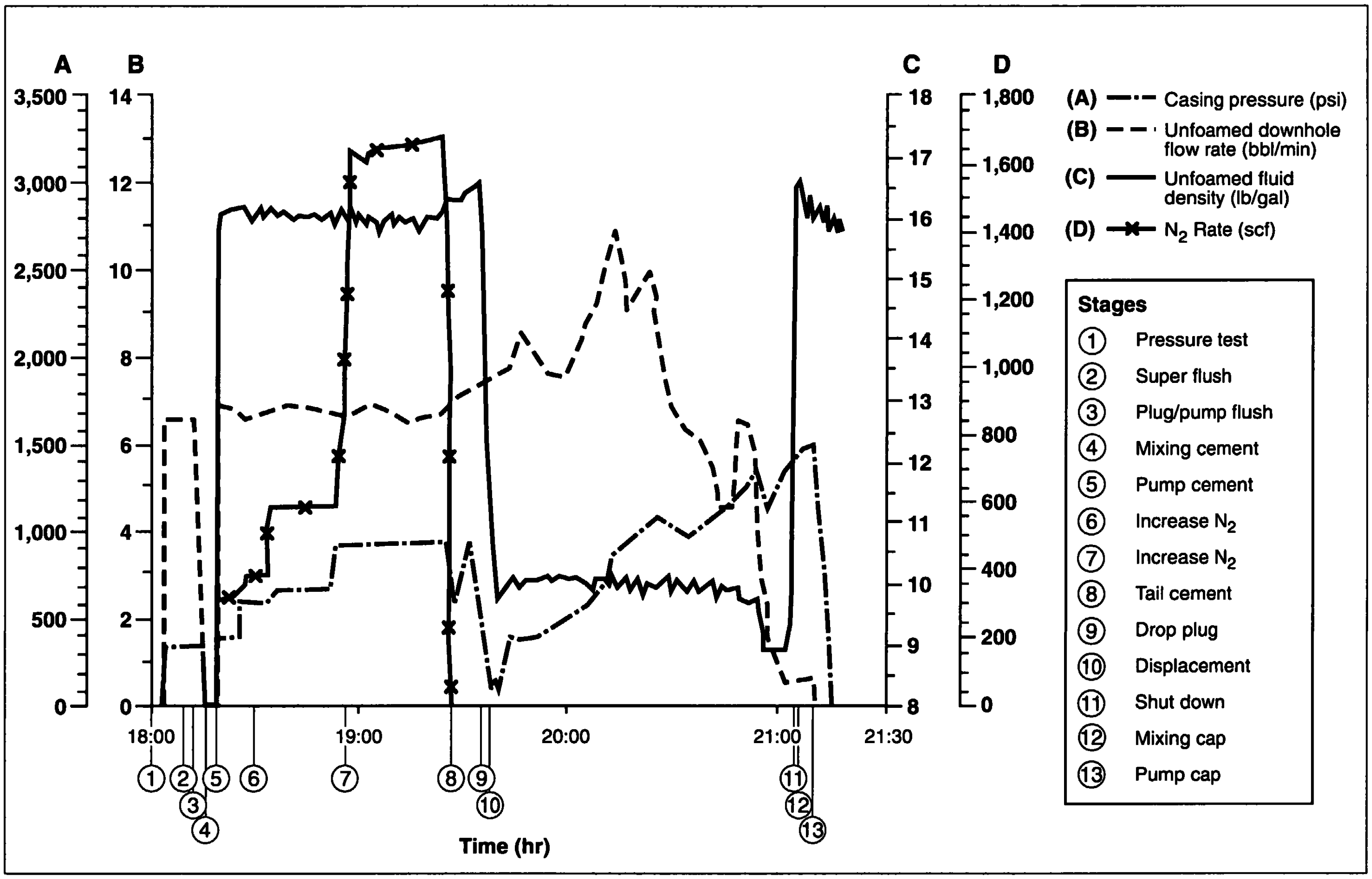

Figure 5. 11 3/4-in. foamed casing job data. (om002832)

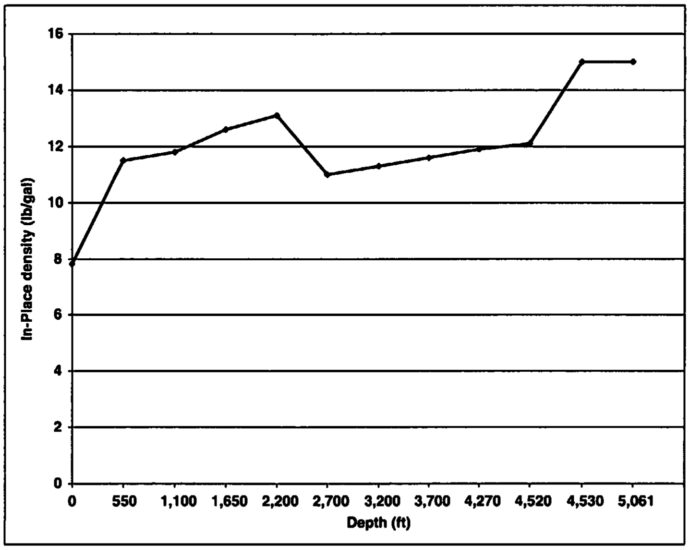

Figure 6. Foam density vs. depth for 11 3/4-in. job. (om002835)

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