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Foamed CaP Cement Enables Drilling and Cementing of Geothermal Wells: Case History

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ABSTRACT

In Southern California, the operating company successfully cemented a geothermal well using foamed calcium aluminate phosphate (CaP) cement to achieve long-term zonal isolation. The well was drilled in a highly corrosive carbon dioxide (CO_2) environment. Weak formations along the wellbore required careful planning and selection of the drilling fluid and cement properties to minimize lost-circulation potential during the drilling and cementing of the well. This cementing case history describes primarily the benefits of CaP cement and discusses the performance of Portland cements to that of CaP cement.

Naturally occurring CO_2 can be found in formation waters or as the result of CO_2 injection processes. When CO_2 comes into contact with Portland cement, it reacts with its components, deteriorating the cement matrix. This reaction, known as carbonation, over time, can cause serious damage to well tubulars and destroy zonal isolation integrity, resulting in costly remedial services or even abandonment of a well. The results presented in this work should help in the design of solutions to contain both reservoir and injected fluids in the presence of CO_2.

1. INTRODUCTION

Drilling and completion of geothermal wells poses a number of unique challenges, including very high temperatures at relatively shallow depths. These high temperatures pose challenges while the well is being drilled and completed, and after construction has been completed. Because of the typically fractured nature of formations in a geothermal field, lost circulation can be a serious problem both while the hole is drilled and when casing strings are cemented in place. In addition, CO_2 that may be encountered in some of the formations can be a serious corrosive threat to both the cement and the casing in the well. Bour and Hernández (2003).

A major concern of geothermal well construction is long-term wellbore integrity, especially in highly corrosive carbon dioxide environments. CO_2 causes cement pore water acidification and leads to different dissolution/precipitation mechanisms.

Portland cement strongly reacts with wet supercritical CO+ or CO_2-satured water, especially in the presence of high temperatures and pressure. The quality of the cementing phase during well construction often establishes the life expectancy of the well. As drilling environments become more hostile, the need for CO_2-resistant cements becomes more critical. It is well known that alkali metal catalyzed reactions between CO_2-saturated water and calcium silicate hydrate compounds and calcium hydroxide (free lime) in conventional well cements result in rapid deterioration of the cement sheath caused by carbonation.

2. CO2 DETERIORATION PROCESS

When cement is exposed to CO_2 gas it will react with it, especially in a wet environment. An increase in gas pressure or CO_2 content in the gas phase will lead to an increase in CO_2 in the aqueous phase and consequently a drop in pH. CO_2 is therefore in reality a carbonic acid. Randhol et al (2007). High concentrations of CO_2 will lead to a very low pH of the water phase. It is therefore very corrosive to materials such as cement and steel **(Fig. 1)**.

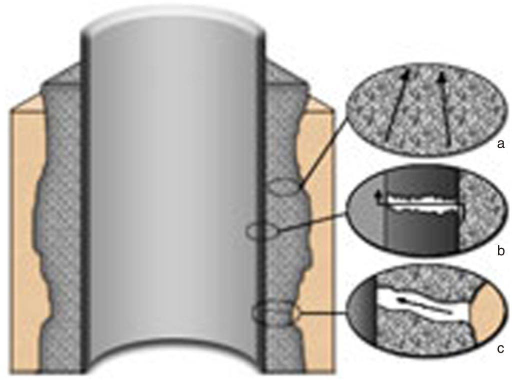

Figure 1: CO2 attack deterioration process in a cemented well (a) carbonation through permeable cement sheath (b) carbon steel corrosion (c) carbonation through cement sheath cracks.

2.1 Portland Cement Carbonation

Carbonation of Portland cement systems in CO_2 environments is well known geothermal in the industry. The carbonation is of significant concern if the CO_2 can enter the cemented annulus.

It is reasonable to assume that additives to Portland cement such as silica, latex, and polymers, can change the properties of the cement, but it will not hinder the carbonation from occurring because Portland cement is thermodynamically unstable in contact with CO_2. Randhol et al (2007).

Carbonation is typically observed in the outer regions of the cement sheath at low temperatures and pressures while complete carbonation is observed at high temperatures and pressures.

The attack of Portland cement by CO_2, is described in the following equations:

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (1)$$

$$H_2CO_3 + C\text{-}S\text{-}H \rightarrow silica\ gel + CaCO_3 \quad (2)$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O \quad (3)$$

$$H_2CO_3 + CaCO_3 \rightarrow Ca(HCO_3)_2 \quad (4)$$

Dissolved CO_2 (Equation 1) reacts with water to form carbonic acid. The free carbonic acid reacts with calcium silicate hydrate in the cement matrix (Equation 2) to form a low strength amorphous silica gel and calcium carbonate. Free calcium hydroxide (Equation 3) also reacts with carbonic acid to form calcium carbonate and water. The last reaction (Equation 4) shows calcium carbonate to react with carbonic acid to form calcium bicarbonate, also called calcium hydrogen carbonate, does not refer to a known solid compound; it exists only in aqueous solution, thus the cement dissolves in the acidic water. As long as a continuous supply of CO_2–laden water exists, the above-described process will continue. Cementitious material is leached from the cement matrix, increasing the permeability and porosity and decreasing the cement sheath volume and strength. The eventual result is lost casing protection and lost zonal isolation.

2.2 Casing Corrosion:

Acidic environments can induce corrosion in different types of steel. H_2S, CO_2 and oxygen and chloride can all lead to corrosion of the well. The main reaction in carbon steel is:

$$Fe + 2H^+ \rightarrow Fe^{2+} + H_2$$

The iron dissolves into iron ions in the solution and leaves a corroded surface. The important factor is the pH of the solution in contact with the steel. Usually carbon steel is not sufficient for normal well conditions. If steel with high chromium concentrations content or titanium casing is used, better corrosion protection can be obtained. Randhol et al (2007).

3. SOLUTION:

In order to reduce CO_2 attack in Portland based cements, the surface area of the cement sheath that is exposed to CO_2 should be minimized to help prevent carbonation. This can be attained by (1) reducing the permeability of the cement sheath, (2) preventing the formation of cracks and micro-annulus, and (3) reducing the components in the cement sheath prone to CO_2 attack. To ensure long-term sealing properties of the cement sheath during the life of the well a proposed solution is foamed calcium aluminate phosphate cement. The combination of foam cement properties in conjunction with a CaP cement designed to resist carbonation is a viable solution. The CaP cement is foamed for two primary reasons. First, foaming the cement enables a low density that reduces the pressure against the formation during placement and still provide good compressive strength. Second, foamed cements have physical properties that help prevent cement sheath failure during cyclic stress loadings expected in a geothermal well.

3.1 Calcium Aluminate Phosphate (CaP) Cement

CaP is a specially formulated non-Portland cement that is both CO_2 and acid resistant. This cement system is essentially a ceramic that is much less susceptible to attack by CO_2 and acid. CaP cement is resistant to CO_2 even at lower pH, thus an increase in permeability due to foaming would not compromise the mechanical/chemical integrity of the cement sheath. Calcium aluminate phosphate cement is a blend of high-alumina cement, sodium phosphate, and class F fly ash—which is pozzolanic in nature, and contains less than 10% lime (CaO). CaP cement provides advanced resistance to carbonation and acid corrosion. When CaP cement is exposed to CO_2-laden water or supercritical CO_2, some carbonation of the cement can occur, forming calcite that is susceptible to the reaction with acid. This reaction can result in the deposition of gypsum gel scales as the acid-corrosion product on the cement surfaces. The scale layer clinging to the cement can protect it from further corrosion. It is proposed that passivation of the surface of the cement by deposition of gypsum is the acid corrosion-inhibiting mechanisms of CaP cements (Sugama). The carbonation rate of calcium-aluminate cement is significantly slower than the Portland cement carbonation rate.

Fig 2: Weight loss comparison of CaP and Portland cement systems in a solution of carbonic acid and sulphuric acid.

3.2 Foam Cement

Foamed cement is a "system" containing cement, additives, foam-stabilizer, and a gas (usually nitrogen) and water that provides a means of preparing lightweight cement slurries. Foam cements prepared at low densities allow the placement of cement across weak a formation, which prevents loss of circulation and fallback problems. The use of foamed cement offers a low-density material that develops relatively high compressive strength and low permeabilities and enhanced protection against annular gas invasion. This technology was implemented because the stresses caused by temperature changes that occur in a cement sheath in a geothermal well can crack a conventional cement sheath because of heat-induced changes in casing diameter. Foam cement sheaths are more ductile and can tolerate expansion and shrinking without losing their sealing capabilities. Spielman et al (2003).

4. JOB SUMMARY

The operation consisted of performing an inner-string cementing foam cement job in a 20-in. casing string inside a 26-in., 1407 ft deep hole. The main objective was to bring cement back to surface and providing log-term zonal isolation throughout the entire wellbore. The inner-string cementing method provided the following advantages: (1) A large-diameter cementing plugs is not required. (2) By pumping through the smaller inner string, cement contamination resulting from channeling inside the casing can be reduced. (3) Cement is discharged outside the casing much faster after mixing, reducing the risk of the cement slurry within the casing having a highly-accelerated setting time. (3) Reduces the amount of cement that has to be drilled out of large-diameter casing. (4) Less circulating time is required with inner-string cementing.

Preflushes/Spacers were designed for 500 linear ft coverage in the annulus and pumped in the following order: 50 bbls of fresh water, 50 bbls of unfoamed retarded water and 50 bbls of foamed retarded water. Subsequently 50 bbls of 10.0 ppg foamed excess CaP cement was pumped ahead to: (1) Promote hole cleaning for good bonding with pipe and formation. (2) Lower hydrostatic pressure and equivalent circulating density ECD. (3) Ensure that foamed CaP Cement returns to surface.

287 bbls of 11.0 ppg foamed lead CaP Cement and 125 bbls of 14.5 ppg unfoamed tail CaP Cement were pumped as designed. 31 bbls of 14.5 ppg unfoamed CaP cement was pumped into the annulus from surface to compress the foamed CaP cement to its final density. Approximately 137 bbls of CaP cement returned to surface and 25 bbls of CaP Cement were compressed by shut in the returns during the displacement stage. Adequate circulation was observed throughout the entire job.

Proprietary software was used to simulate flow and heat transfer of the cement slurry during the cementing operation, providing full transient analysis. Estimated BHCT was 152°F.

The well information used on the cement job is provided in **Fig 3.** The following parameters in **Table 1** applied to this well:

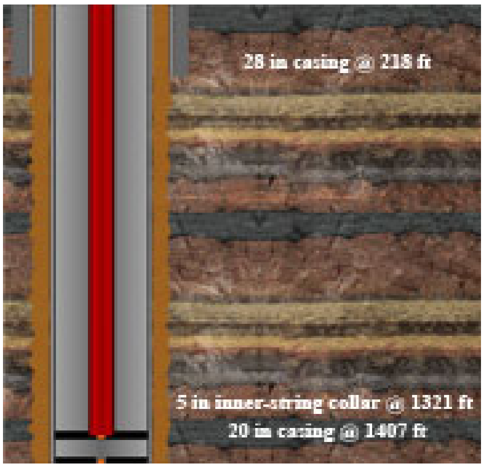

Figure 3: Schematic of the Del Ranch Well 14 wellbore before cementing.

Table 1. Well Parameters

Casing Size:	20-in., 106.5 lb/ft
Inner-string:	5-in.
Casing Depth:	1,407 ft
Top of Float Collar:	1,321 ft
Previous Casing Size:	28-in., 218.27 lb/ft, X-56
Previous Casing Shoe:	500 ft
Open Hole Size:	26-in.
Job Excess:	35%
Wellbore fluid density	9.3 lb/gal

Figure 4: Schematic of the Del Ranch Well 14 wellbore after cementing.

CONCLUSIONS

The following conclusions were determined from this work:

- Calcium aluminate phosphate cement (CaP) resists the corrosive effects of carbonic acid, making CaP slurries a viable choice for cementing geothermal wells containing carbon dioxide.
- Portland cement is subject to corrosion by carbonic acid, which develops when cement comes in contact with CO_2, especially at high temperatures. The corrosion process reduces the Portland cement-sheath volume, increasing the incidence of annular and casing communication of well fluids, hydrocarbons, and CO_2 to the surface and from one zone to another.
- The potential benefits of using foam-cement technology include reducing loss of circulation, gas migration, and improved zonal isolation.
- Elimination of the Portland cement component in a geothermal cement slurry design allows for maximum protection in CO_2 environments.
- Calcium aluminate phosphate cement is a viable solution for CO_2 environments.
- Foaming cement is an effective method of reducing slurry density where lighter-weight slurries are appropriate. As a result, foamed cements can greatly reduce the hydrostatic pressures applied to the exposed formations in the annulus, reducing the potential for circulation losses.
- Foam cement may minimize the potential for cement sheath failure caused by its inherent mechanical properties, providing long-term zonal isolation.

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