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From Plugging Lost-Circulation Cross-Flow Zones to Wellbore Integrity

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Keywords
Lost circulation, cross flow, borehole stability, wellbore integrity, cementing, & drilling

ABSTRACT

Fixing each lost-circulation zone as it is encountered before drilling ahead has been standard practice because of the technologies historically available to drillers. In recent years, however, there have been significant developments in wellbore integrity technology including a) reactive and shear-setting plugs for lost-circulation / cross-flow control, b) the use of dual-tube reverse-circulation rigs to drill severe lost-circulation zones, and c) alternative emplacement techniques for primary cementing (reverse circulation and “tremmie” pipe). These and other new techniques are allowing lost circulation mitigation strategies to change dramatically. Instead of fixing each lost-circulation zone as it is encountered, drillers can consider the bigger question, “How do we get the next casing cemented in with minimal lost time and additional cost?”

The Wellbore Integrity Program at Sandia National Laboratories began with the development of polyurethane grouting as an advanced lost-circulation / cross-flow plug mitigative measure. While a technology specifically focused on plugging lost-circulation zones may be the only sure way of mitigating the effects of severe cross flows and to minimize overall drilling costs, there is a need to take a broad system perspective that considers how lost circulation impacts well design, drilling ahead, casing, primary cementing, etc. The ultimate goal is not controlling lost-circulation, but rather maintaining wellbore integrity.

In this paper, we describe the evolution of the Sandia National Laboratories program from developing polyurethane grouting to alleviating lost-circulation zones to ensuring wellbore integrity. We examine several possible new technologies, compare their distinct advantages to current methods, identify the factors inhibiting their use, and investigate ways in which they can be integrated into future drilling. The successful polyurethane grouting at the Rye Patch geothermal field in northern Nevada is interpreted as a guide for how to plug cross flows. Other potential approaches that have been utilized to successfully plug cross flows are discussed, and a roadmap to a comprehensive Wellbore Integrity Program is proposed.

Introduction

Several factors are key to successful wellbore integrity:

- Using standard drilling and cementing procedures properly (mud program, lost-circulation materials or bridging agents, cement plugs, etc.),
- Distinguishing between ordinary lost circulation and cross-flow, and if required, using a cross-flow plugging technique that does not wash away,
- Being able to drill ahead trouble free even in the worst lost-circulation zone,
- If required, being able to restore wellbore integrity up-hole after drilling ahead, and
- If required, applying alternative placement techniques for the primary cement job.

If the proper use of standard drilling procedures and primary cementing are inadequate (including the use of cement additives and nitrogen foamed cement), a number of emerging technologies can be applied, such as polyurethane grouting, dual-tube reverse-circulation, reverse circulation, and tremmie pipe twin-streaming sodium silicate and cement.

Polyurethane grouting at Rye patch proved applicability of this technology to plugging geothermal cross-flow zones. This grouting was done using materials and emplacement techniques borrowed from mine dewatering. The success of the Rye Patch grouting begs the question, “Can the same success be achieved with traditional drilling materials and emplacement techniques?” Yet polyurethane grout remains “the standard by which to judge other advanced cross-flow plugging material.” After the successful grouting at Rye Patch, InstantSeal™ Cement was identified as a new commercial material potentially capable of plugging severe cross flows. Twin streaming sodium silicate and cement.
is another possible technology for plugging geothermal lost-circulation zones.

Dual-tube reverse-circulation, developed for minerals and water well drilling, has significant potential to allow drilling ahead in incompetent wellsbores without caving or stuck pipe [Mackay, 2003]. This technique has been used at Rye Patch [Rickard, et al., 2001], Soda Lake, and Dixie Valley, geothermal fields in northern Nevada.

Reverse-circulation cementing and sodium silicate tremie pipe cementing offer alternatives for primary cement jobs i.e., cementing in the casing. Reverse-circulation cementing reduces Equivalent Circulating Densities (ECD) and allows better timing of the cement setting. If nitrogen is added, bubble expansion is better controlled through the cementing interval.

Tremie pipe twin-streaming sodium silicate and cement allows cement to be placed into a formation that will not hold the cement column pressure. This method allows the cementing of zones where cementing normally sloughs into the formation, requiring an unacceptable number of lifts or top jobs.

Finally, with the development of these available solutions comes the necessity for careful decision-making. The options discussed will not be useful unless they are utilized in the proper context.

**Background: Understanding the Problem of Lost Circulation**

Lost circulation occurs when pore pressure in the formation is less than the pressure of the fluid column in the wellbore, causing some or all of the drilling fluid to flow into the formation instead of recirculating back up the wellbore annulus. Lost circulation is a persistent problem in geothermal drilling and is frequently the root cause of other wellbore integrity problems including sloughing, caving, washouts, or bridging. Lost circulation related phenomena are very expensive — accounting for 10-20% of the total cost of drilling a typical geothermal well — and cause many additional drilling problems such as stuck drill pipe, damaged bits, slow drilling rates, and collapsed boreholes.

Cross flow occurs when the wellbore encounters permeable zones whose pore pressures are not hydrostatically balanced (Figure 1). This often occurs when alluvial deposits are separated from underlying volcanics by an impermeable layer. During seasonal runoff, lost circulation is usually not encountered while drilling the alluvium. However, the fluid level in the borehole may fall hundreds of feet below the surface (significant lost circulation/cross flow) when drilling penetrates the volcanics. Therefore, if the surface casing shoe is not set in the impermeable zone, the well may have cross flow from one zone to another sufficient to wash away all cement plugs and primary cement.

**Past Work: Polyurethane Grouting**

Polyurethane grouting was developed to stop cross flows because polyurethane grout:

1) will not be diluted by nor mixed with water,
2) forms a rigid plug of sufficient strength to withstand primary cement job pressures,
3) displaces rather than fingers through drilling mud, and
4) sets up fast enough that it is not easily washed away by cross flow (seconds to minutes).

These facts are best validated by the use of polyurethane grout to stop cross flow in dams where it has become the grout of choice [Bruce, et al., 1998]. The applicability of polyurethane grout to geothermal drilling has been demonstrated at Rye Patch geothermal field [Mansure, et al., 2001]. A rigid plug is preferred over a stiff gel because a rigid plug only has to penetrate a short distance (~1 foot) into a 1” to 2” crack to form a plug strong enough to withstand primary cement job pressures. Typical polymers have low yield strengths and require hundreds of feet of penetration into such cracks to form an adequate plug. (Note: this is in contrast to typical oil and gas reservoirs, where the pore throats in the formation are small enough that gels may be strong enough to form the required barrier).

Success at Rye Patch was dependent upon much more than using proper materials. Leading up to the field test was the development of best practices, which were incorporated into the planning of the job. These are summarized by Mansure and Westmoreland:

- **“squeeze job”**
  The grout must be placed in the formation, not the borehole. This normally requires a packer. Placing grout into the borehole and coating the borehole wall are not sufficient. Subsequent drilling will remove the grout, re-exposing the loss zone.
- **“use excess material”**
  The grout should be pumped until significant back pressure is achieved — pumping should continue until grout diverts into all the loss zones, not until a predetermined volume is displaced.
- **“pump for longer than the gel time”**
  When grout is pumped for longer than the gel time, the process becomes self-diverting and compacts the polyurethane to form a strong impermeable plug.

There are significant parallels between these polyurethane grouting practices and the best practices for successful cement squeeze jobs.
Wellbore Integrity Vision

New wellbore integrity technologies are needed to facilitate change in the ineffective standard practice of fixing each lost-circulation zone as it is encountered. Drillers should be focusing on the bigger question, “How do we get the next casing string cemented in with minimal lost time and low additional cost?” To facilitate growth in the new paradigm, we focus on the following needed technologies:

- Advanced methods for plugging lost circulation / cross-flow zones (e.g. polyurethane grout, twin-streaming sodium silicate and cement, and InstaSeal),
- Adequate options for drilling ahead to the next casing point (dual-tube reverse-circulation drilling),
- Methods for reestablishing wellbore integrity after drilling ahead (e.g. fill and re-drill, wellbore lining, etc.), and
- Alternative methods for primary cement placement (reverse-circulation and tremmie pipe cementing).

It is important to note that the areas discussed here illustrate how wellbore integrity problems will be solved in the future rather than proven/validated best practices. Many ideas discussed have not been field proven, but are visions for future testing.

Advanced Plugging Methods

Polyurethane grouting proves the practicality and economic viability of advancing methods for plugging lost circulation zones. Work continues to transfer polyurethane grouting from the civil engineering methodologies applied at Rye Patch to standard drilling service company practice. Other advanced plugging technologies in line with current service company practice are also being evaluated.

The deployment of polyurethane grout at Rye Patch used a two-part formulation. Plans to adapt this work to more standard drilling service company practice and allow deeper deployment (Rye Patch was ~700ft) have focused upon using a one-part prepolymer (Rye Patch) that is activated by water. The one-part prepolymer requires only one “tubing” rather than the two hoses used at Rye Patch.

The development of high temperature polyurethane formulations has not progressed as rapidly as hoped. Prior to Rye Patch, laboratory testing was done by baking samples in an oven, measuring compressive strength at ambient and elevated temperature, and measuring permeability at ambient temperature. A plug test was performed at 200°F and 500 psi differential pressure – comparable to in situ conditions at Rye Patch. After a week, during which leakage through the polyurethane plug was negligible, the temperature was increased to 300°F and the plug leaked excessively. Based on the results obtained in oven tests, it was assumed that changing to higher temperature polyurethane formulations would allow application temperatures in excess of 300°F. Unfortunately, subsequent testing demonstrated that combining temperature, pressure, and water introduces a new failure mechanism: hydrolysis, or reversing of the polymerization reaction. So far, results of subsequent testing have not been intuitive. The one-part formulation has the best stability and appears usable up to about 200°F to 250°F. The exact temperature depends upon how long the plug needs to last.

Though sodium silicate and cement have been used to plug geothermal lost-circulation zones, they have not gained a reputation for success. While they form a rigid plug, set up fast, and after mixing are less susceptible to being diluted by water than standard Portland cement, their application still poses a problem in the control of the downhole delivery/mixing process.

Sodium silicate has failed in past geothermal tests for batch jobs – pumping sodium silicate first, then chasing it with a water spacer followed by cement. Clearly the successful application of this process depends upon in situ mixing of the sodium silicate and the cement. Mixing can be accomplished in two ways: 1) turbulent action as the fluids flow through the formation and 2) contact adhesion between sodium clining to formation surfaces and subsequent cement flow. Laboratory tests suggest that most geothermal lost-circulation zones have apertures that are too wide for sodium silicate clining to the rock walls to adequately gel the subsequent cement and then seal voids. In the lab, batch jobs injected through 1/16” tubes (huge pores even for porous media formations) plugged easily, whereas batch jobs injected through 1/4” tubes (representative of a small geothermal formation fracture) did not readily plug.

Eliminating the water spacer significantly increased the chance of plugging open channels by allowing mixing of the sodium silicate and cement at the interface. If there is cross flow, however, the sodium silicate can be diluted sufficiently before mixing or blending with the cement so that the material does not gel, allowing it to be washed away. Twin streaming solves this problem by mixing the sodium silicate and cement downhole within close proximity of the zone to be plugged.

Before work on polyurethane grouting began, review of the state-of-the-art of lost-circulation control failed to identify a product with the attributes needed for cross-flow control. After the demonstration of polyurethane grouting at Rye Patch, however, a product with potential to stop cross-flow was identified: InstaSeal Cement. Plans are being made to test this product to determine its applicability to geothermal lost-circulation zones. Thus far, this product has been used to 130°C (266°F).

InstaSeal Cement is a two-phase emulsion that, when pumped through the bit nozzles, uses shearing action to allow the two parts to chemically react [Johnson, et al., 2002]. The resulting material is stiff enough to stand on, but not rigid. When lost circulation is encountered, the material is pumped through the bit into the loss zone. It sets in minutes and is then drilled out. In many applications, the resulting plug allows drilling ahead as if no loss zone had been encountered.

Drilling Ahead Options

Historically, the methods employed for drilling ahead with total lost circulation have been to drill blind (i.e., all the drilling mud and cuttings are lost to the formation), or use aerated or foamed drilling mud. These options have often proven inadequate to prevent stuck drill pipe and twist offs. Dual-tube reverse-circulation has been recognized as a superior option, but additional research is required to fully validate this approach and apply it with conventional geothermal drill rigs. Further, water well and minerals rigs are not normally designed for a BOP stack and blowout control [Rickard, et al., 2001].
As a result of the proliferation of options, the explosion of information, and increasing complexity, many "construction industries" that used to be vertically integrated are breaking up. Industry standard practice continues to vertically integrate drilling using the same rig from top to bottom, except in setting the conductor pipe. This begs the question, "Why not use a special rig to drill and set the top-hole casings through the severe loss zones? Using a separate top-hole rig would allow existing minerals or water well rigs to be used that may not be suitable for drilling to TD. This concept was carried out at Soda Lake, allowing a "smaller" rig, one not capable of handling surface casing diameters, to drill the deep hole. The use of the "smaller" rig for the deep hole saved enough in mobilization to pay for the extra mobilization required to bring in the top-hole rig. Further, if the well had passed through difficult lost-circulation zones (though it did not) the savings would have been considerable.

Recent drilling in Puna Geothermal Venture (Pahoa, HI) could have benefited from adapting the conventional rig to dual-tube reverse-circulation drilling. This issue is being investigated, in addition to how to incorporate blowout control.

Reestablishing Wellbore Integrity

Methods for reestablishing wellbore integrity after drilling ahead to the next casing point have not been demonstrated. Work in this area should begin with simple approaches such as using a tremmie pipe to fill the well and surrounding formation with fast setting, easily drillable, slumpless cement. Once the wellbore is filled, the cement is drilled out, leaving a competent cement-healed wellbore. If such approaches cannot be validated, work will progress to wellbore lining technologies [Finger and Livesay, 2002].

Alternate Primary Cement Placement Methods

Two alternatives to conventional placement of primary cement show promise: reverse circulation and twin streaming of sodium silicate and cement using a tremmie pipe.

The concept of reverse circulation cementing is not new [Maquaire, et al., 1996 and Griffith, et al., 1993] (Figure 2), but has not been widely practiced; however, in the last few years, new supporting technologies, such as downhole monitoring of when the cement reaches the shoe and improved process control, have made the process reliable. Over twenty of these jobs have been completed in the last few years in wells that have defied other approaches to cementing. Unfortunately, they have not been well documented. The first such jobs have been tried in geothermal wells this last year [McCulloch, et al., 2003a,b,c].

Twin streaming sodium silicate and cement was successfully applied recently to a top-hole primary cement job at Puna Geothermal Venture, Figure 3 [Livesay, 2003]. To cement in the casing shoe, cement was circulated conventionally up to the point it was lost to the formation. The top-hole job was done by pumping sodium silicate down a tremmie pipe while pumping cement down the annulus. There was no room for a second tremmie pipe. The top job was completed in 12 hours - previously as much as 4 days were required. About one-third the amount of cement was used.

Decision Making

Making appropriate decisions is key to drilling, i.e. when to fish and when to kick off. Decisions are based on experience, expected economic outcomes, and risk management. New technologies will have no impact until they can be incorporated into the decision making process. While this cannot be done until they have been tried and proven in the field, it is useful to examine how the new technologies discussed above may be applied.

Suppose proper use of standard drilling, mud program, and lost-circulation materials or bridging agents procedures have been applied and yet there is total loss of returns. Then a cautious use of the new technologies described above can be depicted as in Figure 4. If there is cross flow and it is not plugged off, then subsequently applied cement will be washed away. Thus, the conservative action is to stop and plug the cross flow. If there is no cross flow, there are options for drilling ahead. If one drills...
The fact that tremmie pipes require extra space in the annulus does not necessarily preclude their use. Often the surface casing is one size larger to allow for a contingency string, or the production string ends up one size smaller because of a contingency string. It may be better to do a tremmie pipe primary cement job in the string that fits rather than use a contingency string.

A primary cement job that includes both twin streaming sodium silicate and cement using a tremmie pipe may allow a less cautious approach than that described by Figure 4. Assuming it can be demonstrated that cross flow does not wash away the sodium silicate and cement mixed downhole, the primary cement job can be done in the presence of cross flow. This is an advantage because it is difficult to predict if there is cross flow in the wellbore.

Conclusions

A new paradigm for wellbore integrity is possible, but it requires the use of emergent technologies that are today being demonstrated in geothermal drilling. With the exception of the contingency tool of restoring wellbore integrity after drilling ahead, significant progress is being made in introducing each of these tools to geothermal drilling. Important to the success of this plan is having more than one tool in one’s tool kit to mitigate a given problem. Once these tools have been demonstrated, the paradigm can change from fixing each lost-circulation zone as it is encountered to asking more important questions such as, “How do we get the next casing cemented in with minimal lost time and additional cost.”

Acknowledgements

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

References


