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Application of Controlled-Porosity Ceramic Material in Geothermal Drilling

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ABSTRACT

Down-hole sealing systems are being developed using the Self-propagating High-temperature Synthesis (SHS) process. SHS uses the thermal energy of solid phase metal/oxide (thermite) reactions, supplemented by mixtures of minerals and oxides, to form monolithic ceramic components in place. These reactions are moderated and controlled, self-oxidized, and run to completion under down-hole water pressure. The method is being extended to applications benefitting from intentionally-generated porosity in the ceramic material, including ceramic screen formation. Lost circulation is a common problem in geothermal drilling and is often mitigated using Lost Circulation Materials and/or cement. However, these options are often not successful. A ceramic plug can be emplaced at the LCZ and the reaction initiated. The plug will then penetrate the zone and form an impermeable barrier. It can then be re-drilled within hours minimizing non-productive time. In a similar fashion, ceramic plugs can be used to mitigate sloughing of borehole walls caused by swelling clays, weak formations and differential stress. Lost circulation and borehole instability may require the premature use of a casing string that can reduce a well's completion diameter and therefore production capacity. We have performed an extensive program of laboratory testing, and we have begun field trials that are expected to continue this year. This technology has application in conventional large diameter boreholes as well as slim holes.

1. INTRODUCTION

Severe thermal, pressure, and corrosive conditions challenge conventional fluid control and sealing materials, particularly in geothermal exploration and production applications. Steel casing and screen materials suffer degradation from exposure to corrosive conditions, microbial activity and high dissolved solids in wellbore fluids. High temperature and pressure operating environments particularly challenge the development of advanced geothermal power systems. This paper describes a system under development that forms a high-service temperature, corrosion-resistant ceramic well components within the well bore.

2. CONTROLLED-POROSITY CERAMIC MATERIAL

Downhole sealing systems are being developed using the Self-propagating High-temperature Synthesis (SHS) process (Lowry *et al.*, 2017). SHS uses the thermal energy of solid phase metal/oxide reactions, supplemented by mixtures of minerals and oxides, to form monolithic ceramic components in place. These reactions are moderated and controlled, self-oxidized, and run to completion under downhole water pressure. The method is being extended to applications benefitting from intentionally-generated porosity in the ceramic material, including screen formation, lost circulation control, and borehole stabilization. The technology has application in conventional large diameter boreholes as well as slimhole drilling, and is particularly suited for high temperature, corrosive environments.

Ceramic materials are formed in the SHS process using thermite as the energy source and additives to control the reaction and product properties. Thermites are a class of energetic materials that combine a combustible metal with an oxide to release large amounts of thermal energy. A common formulation is aluminothermite: aluminum is the combustible metal and ferric oxide the oxidizer, yielding iron, aluminum oxide, and a large amount of energy upon reaction. The reactants are blended in powder form, compacted into the desired shape, packaged in a sealed aluminum canister, and ignited when placed at the desired location in a well. The reaction progresses at a relatively slow pace (fractions of a cm/sec) and is not considered explosive. Aluminothermite is insensitive as an energetic material due to its high activation energy, but once started will tend to react to completion (even under water, since it is self-oxidizing). The stoichiometric aluminothermite reaction reaches a peak temperature of approximately 2900° C (Fischer and Grubelich, 1999). A variety of additives can be combined with the thermite to alter peak temperature and tailor the final product form. High temperature oxides and mineral additives reduce the peak temperature, moderate the reaction rate, and combine with the thermite reaction products to yield other compounds, such as feldspars. Glass and alkali additives can produce a largely amorphous product with a lower melt temperature than the crystalline form.

Figure 1 Olympic Research ceramic plug tool emplacement field test.

Prior ceramic plug developments have focused on low porosity and permeability products that form a sealing plug in a well for decommissioning. Recent work has explored applications that will benefit from intentionally-induced porosity to produce a ceramic foam, to modify the flow and structural properties of the reactant product. Such ceramic foams are a common manufactured industrial product, offering unique mechanical, thermal, and flow properties. They are usually manufactured in a very controlled process of compaction and sintering followed by chemical or thermal dissolution of fillers to create porosity. The SHS process, however, offers the potential of forming high porosity ceramic materials in a single step, in-situ. The final porosity results from expansion of the initial air-filled porosity of the reactants, plus additional gas generation during the reaction if vapor-generating material is present. NASA has studied SHS formation of ceramic foam with porosity as high as 90%, as a method of manufacturing near net-shape structural components in low- or zero-gravity environments (Davidson *et al.,* 2008). This process benefits from the lack of buoyancy effects to produce uniform pore distributions and sizes. Porosity generation with the CuO/Al thermite system was evaluated, considering the effects of both the initial air-filled porosity in the compacted material prior to the reaction, and porosity developed by gas-generating constituents (Maloodia *et al.*, 2009). Their tests showed that porosity could be increased four-fold over the initial compact value, with final products of up to 86% porosity. Downhole applications require these processes to occur under more challenging conditions of elevated temperature, very high fluid pressures, and very dynamic thermal transport environments.

Olympic Research, Inc. is developing materials and emplacement processes to form low permeability ceramic sealing plugs in cased and uncased boreholes (an initial test of the ceramic plug for sealing applications is shown in Figure 1. Using this same emplacement process and downhole tooling, controlled porosity material can be formed in place for non-sealing applications. The general formation process is depicted in Figure 2. Compacted solid phase reactant is formed into a hermetic cylindrical package. The package is lowered into the well to the target depth, where it rests on a bridge plug or some other structural platform. The reaction is initiated from the bottom, and the package reacts and sinks down into the melt until it is completely consumed, where it then cools and solidifies. Depending on the length of the package, the reaction completes in minutes, cools and solidifies quickly, and reaches design strength in a matter of hours.

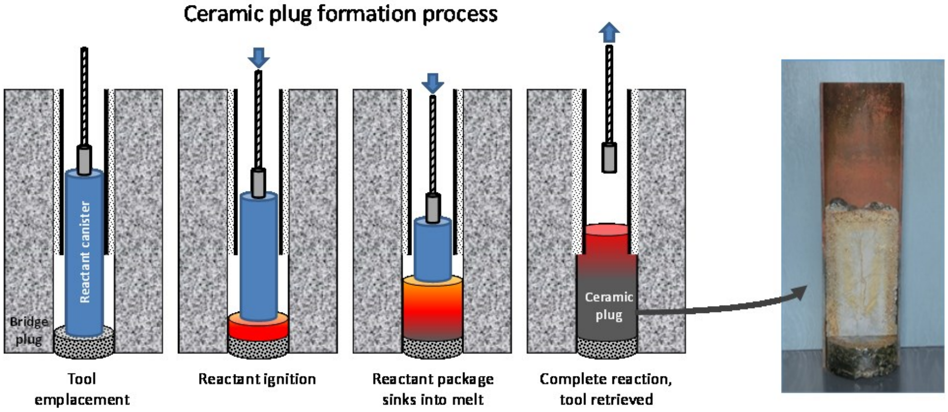

Figure 1 Ceramic plug formation process for downhole applications.

Intentionally induced porosity allows extension of this technology to applications benefitting from either higher permeability, such as screen or sand control, or an expansive product to fill enlargements or fracture zones in the borehole for stabilization or lost circulation control. In both applications the ceramic material would be formed in place, then drilled out to allow access to the hole below. This concept is depicted in Figure 3 for lost circulation control.

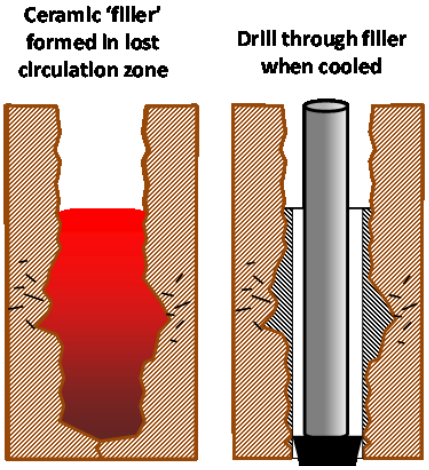

Figure 2 Application of the ceramic plug formation process to lost circulation remediation.

In the current project, porous ceramic products have been developed using a number of approaches. A range of porosity-generating methods include polymeric or ceramic inclusions, carbonates, and reactants that combine with other ingredients to generate non-condensable gas. These laboratory tests produced materials that were tested for density, permeability, compressive strength, and hardness. While high porosity was the initial objective of the material evaluation, it became clear that it was possible to induce acceptably high permeability without achieving porosity greater than 50%. The reaction products can be characterized in two basic forms. The first is a high solidification temperature matrix that appears more like a sintered product, in which the pores are highly connected. The other form is an amorphous product, with a lower solidification temperature, in which the porosity evolves within the more fluid material and the pores coalesce but do not collapse to yield connected pores. Several orders of magnitude difference in permeability exists with the two ranges of product types. This range of product forms is shown in Figure 4.

Figure 3 Range of reaction product porosities and permeabilities possible.

The mechanical properties of the ceramic foam products are important because they influence the ability to drill through the formed product and leave remaining annular material in the hole as a screen or borehole stabilization feature. High compressive strengths are possible in very low porosity products (as high as 30,000 psi measured for ~1% porosity product in the sealing plug application). However, the higher porosities observed in these samples (up to 45%) yielded compressive strengths in the range of 8,000-10,000 psi, which places these materials in the realm of drillable geologic media. Mohs hardness of 5.5 to 7.5 were measured.

The work to date on this project has shown that it is possible to generate ceramic foam with favorable flow and mechanical properties by the SHS process. The proposed follow-on work will adapt the formulations to perform in the high temperature and pressure conditions in the downhole application, and perform field demonstrations to evaluate the product forms in actual application environments.

3. APPLICATIONS IN GEOTHERMAL DRILLING

Finger and Blankenship (2010) provide a summary of potential problems associated with the drilling and completion of geothermal wells. Their summary provides a good framework for the discussion of the application and benefits of employing controlled-porosity ceramic material.

3.1 Lost Circulation

Lost circulation is a problem commonly encountered in the drilling of geothermal wells. It accounts for an average of 10% of the total cost of drilling in mature areas and more than 20% of the cost of drilling exploration and development wells (Finger and Blankenship, 2010). Lost circulation takes place when a permeable zone is encountered, most often a fracture in geothermal and mining applications, and the hydrostatic pressure of the circulating fluid forces it into the fracture. The impact is not only the cost of mud product loss, it also terminates circulation of cuttings to the surface. So, the hole is being drilled without geologic control (drilling blind). Particularly in rotary-drilled holes where the cuttings are relatively large diameter, the cuttings cannot exit the well bore and build up in the area of circulation loss forming mud rings and potentially falling back onto the drill pipe (contributing to borehole instability as discussed below). This is less of a problem with core holes where the cuttings are much finer grained. Often core holes are drilled without mud returns, but the cost of lost mud remains a problem. Traditionally, lost circulation zones (LCZ) are first addressed using a lost circulation material (LCM) that is basically any substance that will physically reduce the permeability of the medium. This material is injected through the drill string. If this is unsuccessful, the drill string is removed and cement pumped into the LCZ, a time consuming and expensive process. This method frequently fails for the same reason the LCZ existed in the first place: the cement flows out of the borehole through the high permeability media.

The ceramic LC system would be employed if traditional LCM materials failed and as an alternative to cementing. With the drill string removed, the reactant package tool is lowered to the bottom of the well and the reaction initiated. The reaction is completed in less than 5 minutes, and the reactant product has expanded to fill and stabilize the borehole rock. Within an hour or two it has cooled sufficiently to achieve its design strength and allow drilling to continue. If further LC zones are encountered, the process is repeated. The value of this method over cementing is significantly reduced non-productive-time (NPT) and a more likely success rate. The ceramic tool insertion process is fast due to wireline emplacement, and the formation and setting process completes in a few hours. Cementing, on the other hand, requires significant surface equipment preparation and cement blending, running tubing to depth through which the cement is pumped, injecting the cement, and waiting for it to set. During the setting process (several hours), if there is cross-flow of native fluids across the borehole, the cement may flow away. The ceramic plug, on the other hand, starts to solidify almost immediately, preventing loss into the formation.

3.2. Well Bore Instability

There are a number of causes of borehole instability in geothermal drilling including swelling clays, sloughing due to weak formations and differential stress that can produce borehole breakouts. Swelling clays are particularly prevalent in volcanic-hosted geothermal systems and result from alteration of volcanic glass that produces smectite. Smectite is a sodium clay that absorbs water and can swell several times times its dry volume. It is particularly common in the temperature range of 100o to 200o C, but has generally disappeared by prograde reactions by 200oC (Hulen and Nielson, 1986). At higher temperature, smectite reacts to form mixed layer illite-smectite (I/S) or chlorite-smectite (C/S) that are both also hygroscopic and can present drilling issues. The common method for mitigating clay swelling is to add salt, commonly KCl, to the drilling fluid (Widianto et al., 2016).

Weak formations can result in sloughing. The causes include the swelling clays discussed above, but also, in geothermal environments, commonly involve faults and fractures that are intersected by the borehole. Differential stress in the subsurface produces borehole breakouts that can result in spalling of wall rock into the well bore. Under high deviatoric stress conditions, it can become difficult to prevent the bit from following the least principal stress direction. The ceramic system emplacement process could be applied in the same fashion as for the lost circulation remedy. It would stabilize the borehole wall and provide a uniform strength media through which the drilling can proceed.

3.3 Screens and Sand Control

Production zones in high-temperature geothermal wells tend to occur in distinct high-permeability fracture zones, which can be less stable than the more competent adjacent rock. These zones may be structurally unstable and prone to collapse, posing a risk to the production capacity of the well. The production interval can be left uncased. However if caving is anticipated, slotted pipe is added in the entire zone, adding considerable expense, and increasing the potential of reduced flow due to scaling and/or corrosion of the tubular.

A ceramic screen can be formed by lowering the reactant package to the desired depth. The reaction is initiated and runs to completion, allowed to cool, then drilled drilled to establish flow of production fluids. The reactant formulation is designed to leave a porous, permeable annular skin at the borehole wall through which reservoir fluids can flow while preventing passage of rock or granular material.

3.4 Open-hole Packers and Bridge Plugs

Packers have a number of applications in drilling, testing and abandonment of geothermal wells. Basically, they are designed to isolate sections of the borehole by sealing against the wall. They are often made of elastomer and inflated with fluid or air. The present temperature limit of these packers is about 80^o C (Banta, 2014). In order to properly set at higher temperatures (170^o to 190^o C) at Soultz, packers were devised that used soft metal shells (Baumgartner *et al.*, 2000). In the current development effort, a process was demonstrated that would produce a rapidly expanding, hollow ceramic plug. In application the reactive package would be suspended in the open hole at the target depth. Upon initiation, the plug would expand to fill the hole, eventually supporting itself. The remaining structure could perform as a bridge plug for cementing operations above, or as a drillable packer for flow control and zonal isolation applications.

4. CONCLUSION

Geothermal resource development is challenged by high temperatures and corrosive environments that create unique well completion and operating problems. These extreme conditions challenge the existing tools and materials used for development, production, isolation, and decommissioning. The initial phase of our development program has shown that ceramic features could be formed in place with favorable strength, porosity, and permeability characteristics to perform a variety of functions in a geothermal well. Lost circulation, borehole stabilization, well screen, and plugging/packing applications are viable applications and are being explored in subsequent development efforts.

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