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Geothermal Drilling Fluids: R&D and Field Trials for Conventional and Unconventional Geothermal Resources

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ABSTRACT

Derisking geothermal drilling has obtained significant emphasis in recent years, in an attempt to create a more viable, cost-effective business model. The current drilling transition, sharing O&G and geothermal technologies and experiences, is improving drilling efficiency, and the implementation of an appropriately designed drilling fluids system can significantly enhance the drilling results. The design and selection of drilling fluids additives and applications for these increasingly hostile environments relies upon unique laboratory testing and subsequent field trials. The new, more intense challenges of the various types of geothermal drilling applications (conventional, EGS, HDR, SHR) require varying and project-specific drilling fluids characteristics; hence, various laboratory techniques and fluids selection processes are required. Laboratory testing is implemented to monitor and predict fluids behavior, test compatibility and temperature stability, as well as to design systems with optimum performance under critical conditions. Following laboratory testing, field trials ensue to prove and modify the technology.

As geothermal drilling operations pursue deeper and more critical well paths and higher sustained temperatures, drilling fluids research continues to create drilling additives and practices which will provide enhanced fluid lubricity, corrosion protection, wellbore stability, fluid loss control, mechanical specific energy (MSE), and reduced non-productive time (NPT), providing the additional benefits of efficient hole cleaning, control of lost circulation, temperature stability, and other desired properties, all at greatly elevated circulating and bottom hole temperatures.

1. INTRODUCTION

As the renewable energy industry gained emphasis and interest during the Arab Oil Embargo of the late ‘70s and early ‘80s, many oil and gas (O&G) companies diversified into the geothermal industry; major companies such as Chevron, Unocal, Shell, Phillips, Arco, Mobil and others all leased and drilled on geothermal prospects in the Imperial Valley, Nevada, the Geysers and in various International arenas. They utilized conventional O&G drilling and drilling fluids technologies, and implemented limited research on high temp drilling fluids systems for this new industry application; Unocal Research is the only company that dedicated an extensive amount of effort to drilling fluids design during this era. The standard O&G deep hole drilling fluids systems were costly, prone to high temperature degradation and gelation, yet few studies were undertaken to optimize fluid properties and production enhancement specific to the geothermal arena. The major oil companies left the domestic geothermal industry by the early 1990s, replaced by a number of independent renewable operators who focused more intensely on field development and cost containment. Therefore, since ~1990, and until recently, there has been an emphasis by geothermal operators to improve operations based on the unique aspects of geothermal resources and drilling challenges.

During the past 5 years, there has been a renewed interest and investment in geothermal’s position in the renewables marketplace. Collaborative efforts have been made to incorporate O&G technology into geothermal drilling practices, resulting in significant reductions in drilling times and costs, trouble and non-productive time (NPT). Innovative drilling practices, bit technology, high temperature tooling design, and focus on drilling efficiency have all had a direct impact on results.

Current geothermal drilling requirements have expanded to include a variety of challenges, along with expectations to enhance drilling efficiencies and reduce overall costs. Drilling for conventional geothermal projects (producing from existing fractures and/or permeability) continues to encounter the generally known challenges of potentially severe or total lost circulation in both non-productive and productive intervals, elevated downhole and circulating temperatures, hole cleaning concerns, corrosion of tubulars, obtaining good cement jobs, and other considerations. Drilling for newly supported unconventional geothermal resources, including enhanced geothermal systems and super-hot rock resources, often are designed with deep, highly deviated wellbore paths and strict directional control requirements, with plans to target bottom hole temperatures more than 750°F/400°C. These new drilling activities will encounter the additional challenges of hole cleaning in a highly deviated wellbore, greatly elevated torque and drag levels, cooling of the drilling fluid while tripping with tools through extended intervals at elevated temperatures, while also enhancing drilling efficiency to obtain increased rates of penetration (ROP).

Few companies and individuals, typically independent service companies and operators, have remained active in both the O&G and geothermal drilling industries over the past decades, as the geothermal drilling industry is very small in scale compared to O&G, and low domestic geothermal rig counts relate to inconsistent markets with limited sustainability. However, recent emphasis on geothermal as a viable baseload energy source has resulted in the incorporation of O&G technology into the geothermal drilling arena. Individuals with significant critical O&G drilling experience, as well as research laboratories, universities, O&G companies and drilling vendors, are sharing in and promoting a technical transition to bring additional value and savings to the geothermal industry, combining new drilling R&D developments while merging successful technologies to provide benefits to the geothermal drilling industry.

The geothermal drilling arena is changing rapidly and will require industry collaboration on many levels to provide the necessary R&D and field trials to support continued improvement. This will be especially important in continuing to develop innovative, stable drilling fluids systems and practices for the challenges that lie ahead with more critical temperatures and well configurations.

2. RESEARCH AND DEVELOPMENT (R&D) EFFORTS AND INDUSTRY COLLABORATION

Research efforts have been undertaken to identify new technology for drilling innovations, with much of the drilling technology derived from operators' extensive experience in drilling deep horizontal unconventional shale plays for oil and gas over the past decade. Collaboration and technology transfer involving O&G and geothermal operators, research laboratories, universities, industry organizations, and vendors have become critical in identifying opportunities for improvement, leading to potential field trials for validation. Internal and external funding has supported many of the laboratory and university studies and field tests, with special focus on the Utah FORGE project as a federally funded field laboratory.

2.1. Drilling Fluids Laboratory Test Tools

Various laboratory instruments are utilized to identify drilling fluids additives that may have potential for support of existing and higher temperature geothermal operations.

2.1.1 Hot roller ovens (Figure 1) are used regularly in the geothermal laboratory to subject test fluids and products to simulated downhole temperatures with constant gentle mixing to simulate circulating of the fluids. Sealed containers containing sample fluids are hot-rolled for a predetermined amount of time and elevated temperature with this unit, with the capability to reach and maintain a steady testing state of over 650°F/340°C for extended periods. Both qualitative (visual) and quantitative observations are obtained from this testing process, generating information regarding individual products and fluid systems' temperature stability limits, changes in rheology and filtrate properties, compatibility with contaminants, severe gelation or thinning tendencies, and other observations. Testing at varying temperatures and time intervals also identify potential degradation temperatures and degradation by-products.

Figure 1: Hot roller oven with high temperature test cells

2.1.2 Capillary Suction Time (CST) test equipment (Figure 2) is utilized to screen various drilling fluids configurations for optimum formation inhibition. Performed at ambient temperature and utilizing actual field-collected prepared cuttings samples and simulated drilling fluids filtrates, with or without specialty additives and modified pH, this laboratory test helps with the identification and pre-selection of an appropriate fluid or brine based on the fluid's ability to inhibit swelling or destabilization of a known formation. Varying ranges of fluids and inhibitor concentrations can be tested in order to provide a comparative review and cost-benefit analysis (Figure 3). More applicable for use in supporting drilling fluids selection in well intervals with bottom hole temperatures (BHT) below ~450°F, the

CST test is potentially an important consideration in dealing with unstable wellbores, swelling tendencies, potential formation damage, and fluid compatibility with drilled formations.

Figure 2: Capillary Suction Time (CST) Test Equipment

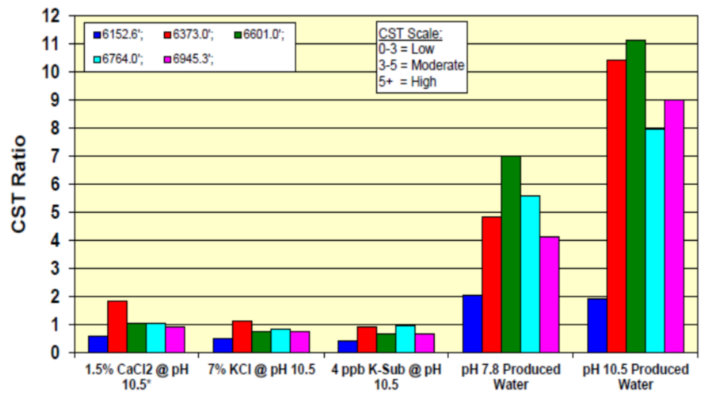

Figure 3: Capillary Suction Time Sensitivity Test Results

2.1.3 Extreme Pressure (EP) Lubricity Tester (Figure 4) is a metal-to-metal lubricity tester, utilized to identify a baseline for drilling fluids and/or additives lubricity characteristics in a controlled environment, and to evaluate the effect of adding lubricity additives to a base fluid, in varying concentrations. The tested fluids can be heated to ~200°F with a supplemental heater cup, and recorded test results will help in the selection of potential successful lubricants, as well as identify potential lubricity enhancement at varying product concentrations, thus suggesting cost-effective treatment levels for operational success. This unit is also utilized to pre-screen additives for more aggressive testing prior to consideration for a field trial.

Figure 4: Extreme Pressure Mud Lubricity Tester

2.1.4 High Pressure High Temperature (HPHT) Dynamic Drilling Lubricant Simulator (Figure 5); this highly specialized, computer-controlled laboratory equipment measures the lubricity performance of fluids at high temperature and high pressure, utilizing pre-cut cores and sampled for formulated drilling fluids systems. Equipment testing ranges are up to 600# force applied to a core sample at up to 2,000 psi circulating pressure at maximum 500°F. Utilizing actual formation core samples for testing, the dynamic drilling simulator can allow adjustment or hold constant drilling properties such as revolutions per minute (RPM), circulating rate, temperature, circulating pressure, and applied force, while generating real time data such as torque, Coefficient of Friction (COF), and % increase or decrease in lubricity properties. Repetitive tests with varying drilling fluids properties and/or additives concentrations, holding the primary variables constant (RPM, circulating rate, temperature, force applied, etc), provides a good data base for review of products and cost-effective treatment ranges. Once a full battery of tests are completed and data analyzed, results can be considered for field application of successful bench tested products.

In addition to lubricity testing, this drilling simulator unit can also be utilized to perform differential sticking test to determine filter cake deposition and torque levels required to move a rubbing shoe against the deposited filter cake, and particle plugging tests to compare the effectiveness of varying types, concentrations and blends of lost circulation materials. Both tests can be performed at elevated temperature and pressure.

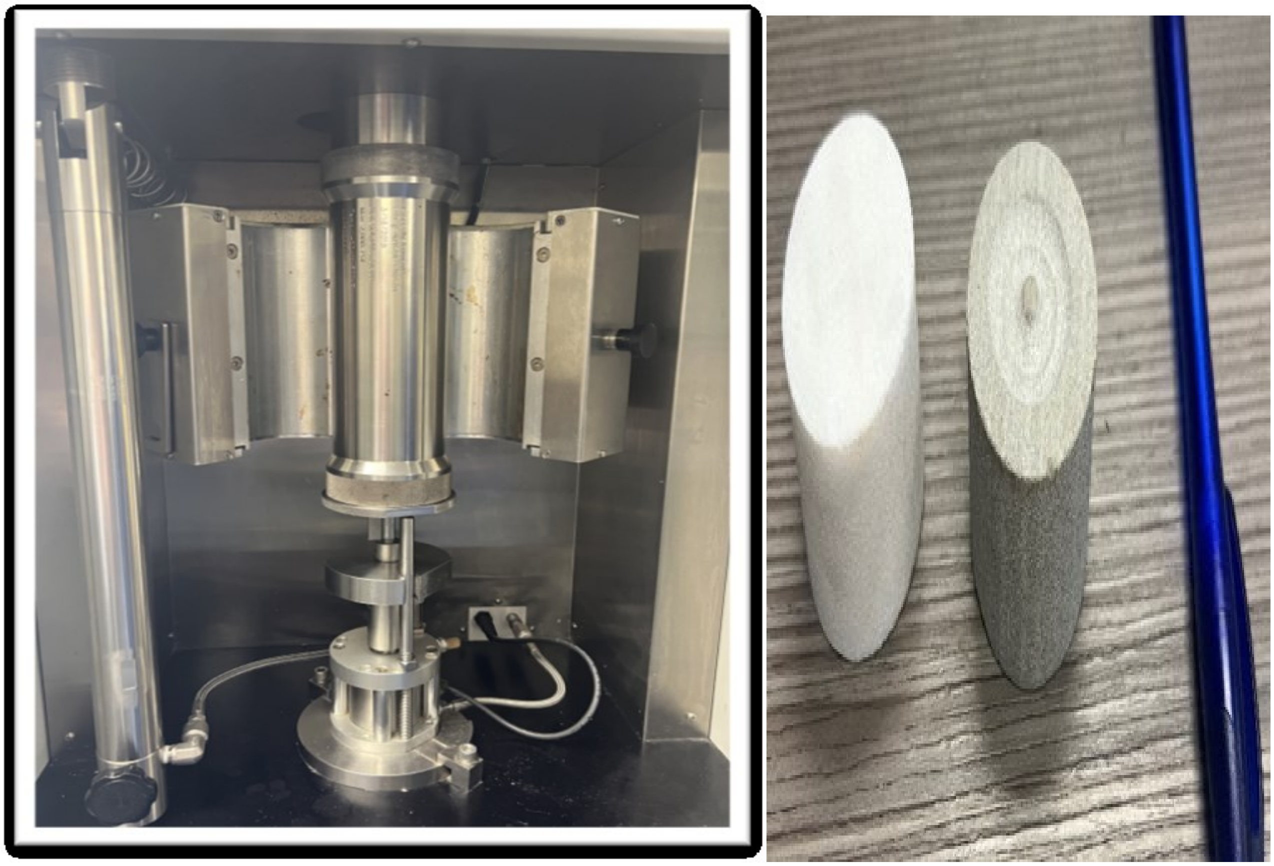

Figure 5: HPHT Dynamic Lubricity and Drilling Simulator, with representative core samples

2.1.5 Other geothermal drilling fluids R&D support and testing are being performed at numerous laboratories, universities and vendor facilities, much of which is focused on specialty drilling fluids lubricants and applications for fluids rheology control, controlling lost circulation, and enhancing drilling efficiencies at elevated temperatures and conditions. With the recent pursuit of super-hot rock (SHR), stability at bottom hole temperatures more than 750°F/400°C is of major interest. Each of these entities has utilized unique protocols, testing processes, and equipment applications for defining their specific testing goals.

3.0 DRILLING FLUID RHEOLOGY, VISCOSITY, FILTRATE CONTROL, AND HOLE CLEANING

For decades, the primary viscosifier for drilling hot holes has been API grade bentonite (sodium montmorillonite), with filtrate control provided by cellulosic or polyacrylamide/polyacrylate copolymer blends. As wells reached deeper and hotter environments, the low-temperature benefits of bentonite became compromised by high-temperature gelation, the potential for formation damage, and possible destruction of wellbore permeability by the transformation (by formation heat and pressure) of the bentonite to an impermeable barrier of metamorphosed clay. Bentonite is still used extensively to provide desired particle size distribution and rheological properties through low temperature and non-production intervals. Cellulosic products are still used for geothermal drilling; however, their relatively low temperature stability (generally <300°F) limits the effectiveness for hotter EGS and SHR wells. Significant laboratory and pilot testing and field trials have identified alternative additives and systems for higher temperature geothermal resources, and low- or no-bentonite concentration systems have been utilized for conventional geothermal drilling for over a decade, utilizing non-reactive clays and viscosifying polymers for supplemental rheology.

Unconventional geothermal projects are (and will be) encountering higher circulating and downhole temperatures, often with highly deviated or lateral wellbores and strict directional considerations. Efficient hole cleaning will continue to be an important variable, and filtrate control will typically be less critical due to the generally unreactive nature of higher temperature rock (gneiss, granite, basalt), although the use of filtrate control additives in moderation does enhance fluid performance. Wellbore stability will be dictated by the presence (or lack) of fractures, and recent deep EGS projects have encountered good rock stability and wellbore conditions.

Modifications in drilling practices have supported the drilling fluids hole cleaning requirements for geothermal wells. In addition to modifying drilling fluids properties and utilizing viscous hole sweeps to remove cuttings, drilling rigs with larger pumps provide higher fluid circulation rates (18-20+ barrels per minute), maintaining the drilling fluid in a state of turbulent flow in the hole annulus. The use of a top drive on large rigs provides back-reaming while circulating in the event of tight hole or directional doglegs, and state-of-the-art solids control equipment (SCE) provides exceptional removal of drilled solids at the higher circulating rates. Mud coolers or chillers, along with increased surface area and volume in drilling fluids pits, storage tanks, or reserve pits, provide sufficient cooling of the drilling fluids upon return to the surface; return temperatures near 200°F, and sometimes flashing at surface, are often reduced to ≤145°F prior to recirculation downhole.

Supported by fluids testing and contingencies, drilling fluids properties requirements for deeper, hotter projects have trended toward maintaining a lower solids content, lower fluid rheology and viscosity system, and utilizing viscous sweeps to supplement hole cleaning needs. Drilling with water and viscous sweeps has become a common practice where rock is stable, through conventional production intervals, and/or where severe lost circulation is encountered. Independent laboratory research and field tests have identified temperature degradable additives, effective for use in formulating viscous sweeps. In addition, a few organic and inorganic additives that were once only considered for filtrate and/or rheology control are now considered to be fluids 'conditioners'; in addition to their primary applications, roller oven and field observations have indicated that these additives work synergistically with other additives to extend temperature stability to the entire drilling fluids system (Figure 6). Secondary observed benefits include improved fluid rheology stability during trips, mitigation of foaming tendencies, and better control of filtrate levels at elevated temperatures.

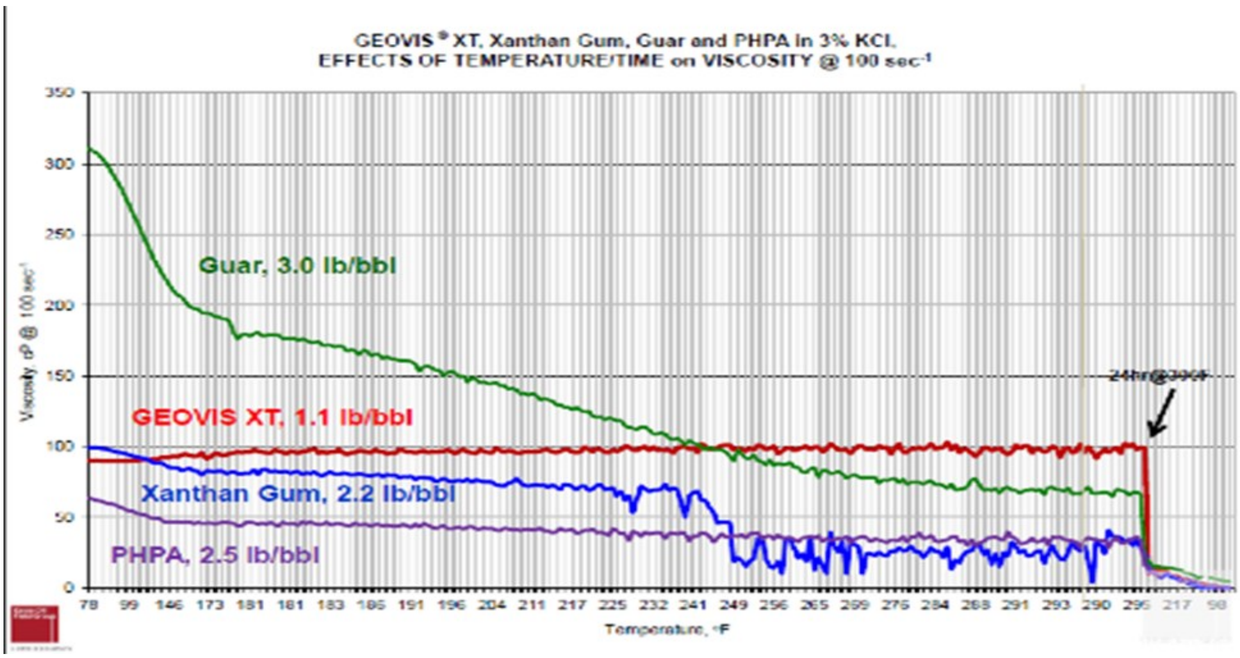

Figure 6: Thermal stability of various rheology additives, to 300° (ref: Kelco Rotary)

Site-specific drilling fluids design is utilized globally, based on numerous parameters including the formations drilled, availability of local resources, drilling challenges, production technique, anticipated downhole temperatures, drilling and casing design program, directional considerations, contaminants and many other considerations. Lab and field testing is often implemented on core or cuttings samples to determine the most effective drilling fluid to obtain the desired objective in a cost-effective manner. Testing for high temperature stability of drilling fluids systems and supplemental additives has providing a good selection of options for current conventional geothermal projects. Considering projects with bottom hole temperatures (BHT) in excess of 750°F/400°C and/or highly deviated wellbores, however, research continues for effective drilling fluid additives for rheology and filtrate. Investigations include the use of nano-aluminum oxide (NAM), nano-silicon dioxide (NSM), synthetic copolymers, synergy between polymers for enhanced performance and temperature stability, and other unique approaches. Two of the lab and field-tested geothermal drilling fluids systems utilized in support of higher temperature environments, are discussed briefly below.

3.1 Low Bentonite Systems

Low bentonite concentration (<10ppb bentonite) geothermal drilling fluids systems have been tested and proven to provide sufficient rheology and filtrate control for projects with bottom hole temperatures in excess of 680°F/380°C. Readily modified with specialty additives, this system utilizes attapulgite or sepiolite if/as needed for supplemental increases in rheological properties, with additional polysaccharides, cellulosic, polyacrylamide/polyacrylate, and organic dispersant additives for filtrate and rheology stability, and other additives as needed. With a concentration of <10ppb Bentonite, this system can be densified as needed for pressure control, and viscous drilling fluids pills utilized to sweep the hole clean if/as needed. Supplemental additives might include lubricants, corrosion inhibitors, wellbore strengthening additives, and pH modifiers.

Fluids research efforts, coupled with field trials, continue to pursue optimum drilling fluids rheology performance to support the higher resource temperature and wellbore deviation challenges of ongoing conventional and unconventional geothermal projects. Significant laboratory pilot testing and field trials, utilizing attapulgite or sepiolite as a secondary viscosifier and rheology modifier, have validated this potential for higher temperatures, as attapulgite and sepiolite do not exhibit the high temperature gelation tendencies of regular bentonite. Additionally, there is much research and field trial incentive to reduce drilling fluids densities and solids content while drilling hotter geothermal regimes; increased ROP and reduced chemical treatment costs are among numerous benefits of drilling with low solids drilling fluids systems in general.

3.2 Water Drilling System

Drilling with fresh water as the drilling fluid has been undertaken at multiple geothermal operations, with specific interest and monitoring at the Utah FORGE drill site. Although water thins with temperature, increasing the challenge of hole cleaning efficiency (and especially on deviated wellbores where cuttings will tend to fall out to the bottom side of the hole), hole cleaning has been sufficient even in highly deviated and horizontal wellbores, as long as drilling parameters and drill cuttings returns are monitored while drilling. Additional hole cleaning is provided by viscous drilling fluids pills containing a high-temperature polysaccharide biopolymer and mechanical hole sweep material such as conventional LCM or fibrous synthetic fibers, in a combined polymer/mechanical sweep formulation that provides suspension properties as well as carrying capacity. Upon return to the surface, any drill cuttings and residual conventional LCM from the sweep material are removed from the drilling fluids system by the solids control equipment. Other tested and field-proven additives to the water system include lubricants, corrosion inhibitors, wellbore strengthening additives, and pH modifiers.

Figure 6: Suspension properties of synthetic fibers mixed in fresh water (ref: Forta Corporation)

4.0 LOST CIRCULATION

Both O&G and geothermal drilling operations often encounter significant drilling fluids losses, and much research and field testing of lost circulation material (LCM) additives and procedures has been allocated to this serious issue. Various methods are utilized for dealing with lost circulation occurrences, and opportunities for field trials are regularly available. Good casing cement jobs are imperative in constructing geothermal wells, in order to avoid potential casing collapse when the wells are heated up and cycle; potential water or voids trapped behind exposed casing can create this condition. Therefore a stable wellbore, minimal lost circulation at the time of cementing, and/or other measures are undertaken to ensure a competent cement sheath is obtained. Reverse circulated cement jobs, foam cement, and cement top jobs are often appropriate methods to mitigate weak formations and are considered on a site-specific basis.

4.1 Historical lost circulation control methods

Generally, the location and severity of drilling fluids losses during a geothermal drilling program will determine how to proceed with a solution, with treatment options for whole mud losses separated into non-productive intervals and productive intervals. Through ***non-productive*** intervals, lost circulation has typically been combated with conventional LCM additives and techniques and/or cement plugs. Excessive losses have often prompted operators to drill ahead underbalanced or 'blind' with little or no fluid returns to surface, to attempt to cure losses with LCM pills and/or cement plugs, or to run protective casing strings to seal off the lost circulation interval completely and permanently. Constant review of potential treatment techniques and field observations continues to add value to geothermal drilling's lost circulation challenges.

For healing whole mud losses while drilling through potential ***productive intervals***, a non-damaging lost circulation approach has typically been preferred for conventional geothermal projects. Recent drilling developments for unconventional geothermal resources often result in the running of a final casing/liner string to total depth and perforating into the zone of interest (or working inside casing), therefore formation damage is less of an operational concern and a full range of LCM additives, including cement, may be utilized. Utilizing hot roller oven and other laboratory apparatus to validate product degradation, laboratory work has identified various temperature-degradable LCM materials for use when avoiding long-term formation plugging or damage; field application of these preferred additives appear to support the minimally-damaging nature of these additives at elevated temperatures. If not totally successful in curing lost circulation with LCM, then operators may choose to preferentially drill producing intervals with water or drill underbalanced, using aerated mud or 'drill-In' fluid, air/foam, and when possible as little solids (bentonite, etc.) and LCM additives as possible.

Lab testing and field trials have identified a series of operational considerations when lost circulation is anticipated and/or encountered. Further investigation of lost circulation options has promulgated the creation of a Lost Circulation Decision Tree (figure 7). Created and compiled on a project-specific basis for approval by the operator's drilling team, this decision tree is utilized as a guide for avoiding and/or curing various types and severities of drilling fluids losses.

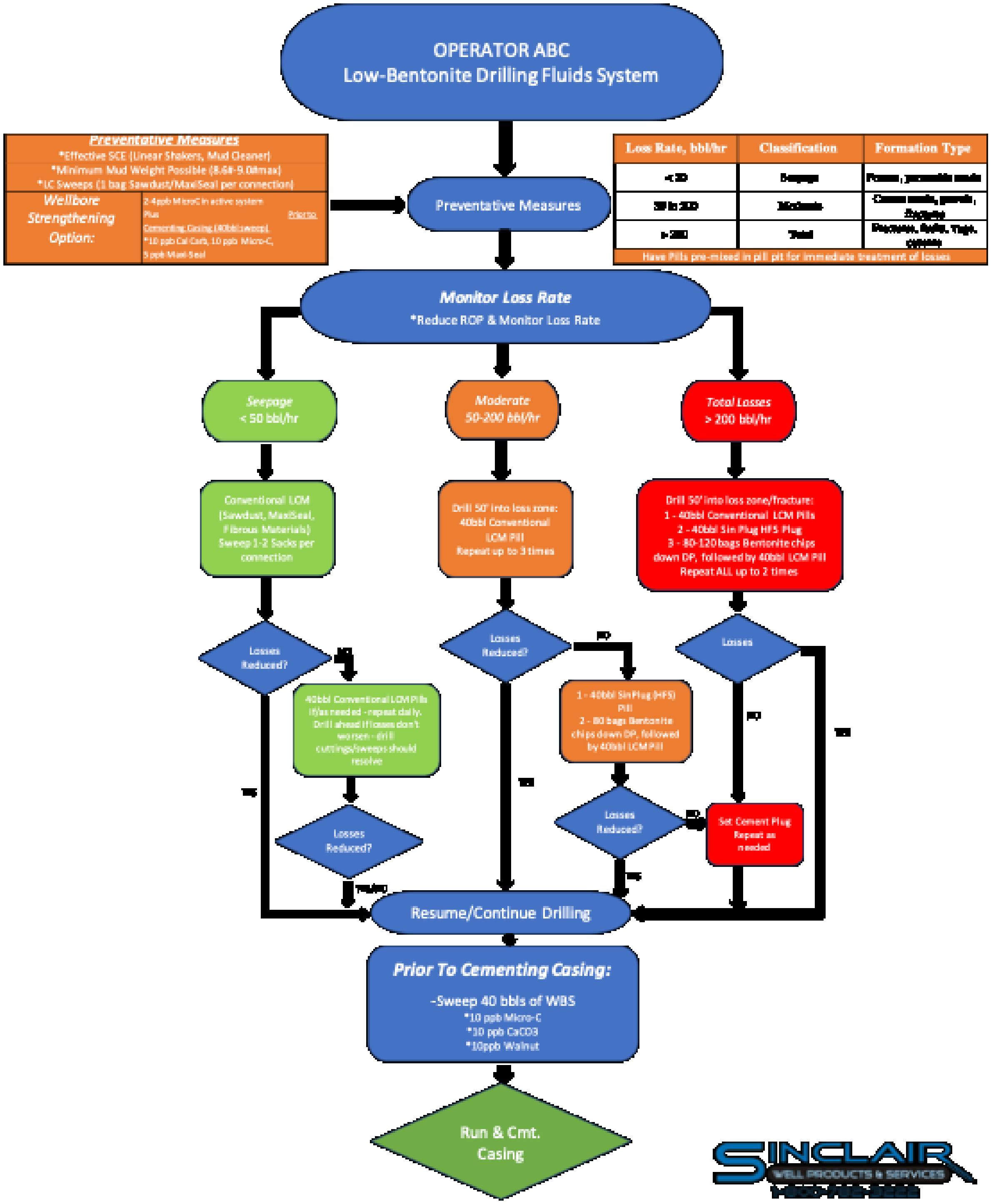

Figure 7: Sample Lost Circulation Decision Tree, for guidance in preventing and treating drilling fluids losses

4.2 Wellbore strengthening and microsized cellulose

Wellbore strengthening (WBS) is a preventative method of utilizing a blend of lost circulation materials to continually drill with or without losses. This process has been utilized in O&G operations for decades, and to a lesser extent in conventional geothermal operations. The introduction of fine WBS materials into the active drilling fluids system is becoming more commonplace on critical conventional geothermal drilling projects, based on observed field improvements in lost circulation and casing cement operations. The specific goal and benefits of implementing WBS while drilling includes the potential to increase the frac gradient of drilled formations, possibly reducing the need for additional casing, reducing seepage and whole mud losses, enhancing casing cement jobs by minimizing cement fallback, and to enhance wellbore stability. Specifically for geothermal operations, WBS utilizes fine materials such as <100μm sized cellulosic material, Micro C (Rickard et al, 2012, Rincon, Teodoriu et al, 2022) and Calcium Carbonate, applied in pills often in conjunction with a small amount of fibrous LCM, or applied/added to the entire drilling fluids system in a predetermined concentration; this formulation allows for the finer materials to remain in the drilling fluids system for recirculating and reused to avoid elimination by the solids removal equipment. Wellbore strengthening in a geothermal application generally consists of a 3% concentration of MicroC/Calcium Carbonate by volume incorporated into the active drilling fluids system, and/or implemented as pretreatment sweeps, generally containing 10-15 ppb (~7.5-12% by volume) MicroC in the sweeps prior to running and cementing casing. The implementation of WBS techniques has helped minimize seepage losses, enhance wellbore stability, and reduce cement fall back and top jobs in field observations, when compared to results from past wells in the general area.

4.3 Conventional lost circulation additives

Conventional lost circulation materials (LCM) are used regularly to prevent and cure drilling fluids losses. Supported by laboratory testing and relative availability of products, occasional preemptive LCM sweeps or pills while drilling often reduce lost circulation tendencies, and a combination of particle sizes is normally more successful in eventually healing losses in the field. Bench testing at ambient temperature, with varying concentrations and blends of additives have led to site-specific applications for geothermal drilling activities. Specific lost circulation concentrations and blends are recommended based on the severity of losses, downhole temperatures encountered, directional tooling that might have flow restrictions, and other considerations. Generally, concentrations of 40-60ppb blended lost circulation in a viscous bentonite pill has successfully plugged ¼” screen (figure 8) in laboratory testing. Field operations generally support ~40ppb lost circulation pills due to considerations of rig mixing capabilities, directional tools being used, and jet nozzle sizes in the bit, with pill volumes and repetitive treatment adjusted as required by the operation. Conventional lost circulation materials may include items such as sawdust, walnut, drilling paper, MaxiSeal/KwikSeal, cedar fiber, mica, cottonseed hulls, calcium carbonate, and other available fibrous and granular materials.

4.4 High Filtration Squeezes (HFS) and Lost Circulation Pills (LC Plugs)

Geothermal research, again sharing historical knowledge from extensive O&G experiences, has led to the occasional use of ‘site-specific’ high-filtration squeezes (HFS, Figure 7) and lost circulation (LC) plugs to cure more aggressive, massive or vugular losses. If applied timely and successfully to control whole mud losses, a well implemented lost circulation program will reduce NPT (non-productive time) and help reduce overall drilling costs. Laboratory testing simulating large aperture loss zones (Figures 8, 9) and field trials have shown that these methods for fighting lost circulation are cost-effective, can be mixed readily on location, placed through the existing drillstring and downhole tools with rig pumps, and often effectively seal off medium to high loss intervals that normally would require costly cement plug operations and expensive rig time. Multiple treatments may be required, and once the loss zone is successfully plugged, the lost circulation plugs can be drilled out readily and drilling resumed with a normal bit configuration.

Figure 7: High Filtration Squeeze Test Result

Figure 8: LC Plug Test Result – ½” hole plugging test

Figure 9: Vugular lost circulation testing apparatus, with variable screen opening sizes to simulate large vugs or fractures

4.5 Lost circulation through open ended Drillpipe

Occasionally, in the presence of massive shallow losses, it may be desirable to place lost circulation materials to the loss zone through open-ended drill pipe. In this case, there is no reasonable limit on the size concentration of materials used, since the lost circulation materials will pass through open drillpipe without a bit restriction. When encountered, materials of choice may include granular bentonite, cottonseed pellets, fireplace pellets, pea gravel or other large materials that might tend to plug or swell once placed across and into the zone of loss. With technology shared from the environmental grouting industry, swelling bentonite (chips or pellets) provide significant swelling and effective plugging and zonal isolation once they expand by absorbing water, and are often used in conjunction with cement plugs.

5.0 DRILLING FLUIDS LUBRICITY

Drilling torque and drag are significant issues affecting both O&G and geothermal wells, especially during the implementation of directional drilling of highly deviated well paths or redrilling programs, or during workover operations in existing holes. In the past, mineral oil, B-99, drilling detergents, and various other chemical and mechanical additives (including polystyrene and glass beads, walnut) have been used to address excessive torque and drag levels and to attempt to free stuck pipe in geothermal wells. Very few liquid additives have been successful in providing reliable lubricity in geothermal drilling operations, due to product volatility, temperature instability, and environmental concerns.

TORKease is a lubricant that has been utilized for decades in the industry with favorable results in reducing torque and drag in both O&G and geothermal applications (DSC Incorporated, Technical Literature, TORKease). Developed in collaboration with Sandia Laboratories in the 1970s primarily for geothermal core drilling, this product remains applicable to geothermal drilling and workover activities. Additionally, medium and coarse grind walnut has been effective with O&G and geothermal open hole torque and drag reduction. Also, polystyrene beads have worked well to reduce torque between metal and metal or between metal and hard formations on geothermal workovers, with temperature stability to 500°F.

In a recent development to support EGS and more critical geothermal operations, the specific goal is to identify a temperature stable, system-compatible, non-petroleum hydrocarbon based lubricant(s) that can provide system compatibility along with sufficient torque and drag reduction in a cost-effective treatment level. An in depth R&D investigation was undertaken that included prescreening of potential lubricant candidates from various manufacturers, utilizing a combination of testing protocol followed by a successful field trial. The lubricant selection process included a discussion with various manufacturers regarding product temperature stability, degradation issues, Safety Data Sheet review, compatibility with the drilling fluids to be used, foaming tendencies, pH and saponification concerns, environmental impact, cost and other potential concerns. Limiting the process to only non-petroleum hydrocarbon based lubricants, laboratory investigations followed that included hot roller oven product stability tests at 450°F for 24 hours, mud system compatibility tests with 2% lubricant concentration at 450°F for 24 hours, and initial testing with an EP Lubricity Tester at 200°F, to prescreen and select the primary candidates for further, more intensive testing. Following the pre-screening, the selected candidates were subjected to a HTHP Dynamic Drilling Simulator using granite cores from the FORGE project in Utah. Testing conditions were held constant for each lubricant, while varying weights/force applied to the core, recording all data; metal-on-granite dynamic drilling conditions were simulated, circulating each test fluid at 280°F and 400psi. This laboratory process provided relative Coefficient of Friction (COF) results, and % of lubricity improvement for each test (Figures 10, 11). Thereafter, the most favorable lubricant candidate was engaged for further sensitivity testing, varying lubricant concentration from 1-3% by volume and simulating bit trips with non-circulating in the test apparatus for varying time periods.

The laboratory testing concluded with the identification of a cost-effective, highly lubricious, non-petroleum-based drilling mud additive. This additive demonstrated stability across various pH levels, showed no signs of saponification at high temperatures, and proved to be highly effective in reducing the coefficient of friction (COF). A 2% concentration by volume was determined to be the optimal target based on COF reduction and cost considerations. Additionally, it was observed that friction progressively decreases as the lubricant has more time to coat the metal and granite at elevated temperatures (Gierke et al., 2024)

Following the extensive laboratory protocol, field testing was conducted with the EGS drilling team. Varying concentrations and methods of lubricant addition were implemented, while monitoring drilling performance and drilling fluids properties. Field observations included 14 out of 14 successful liner runs to target Total Depth (TD) in a highly abrasive horizontal EGS well with friction factors over 0.4, and 3,000-6,000 foot pounds reduction in drilling torque, allowing for higher drilling weight on bit and higher ROP through a critical lateral hole interval (Gierke et al., 2024).

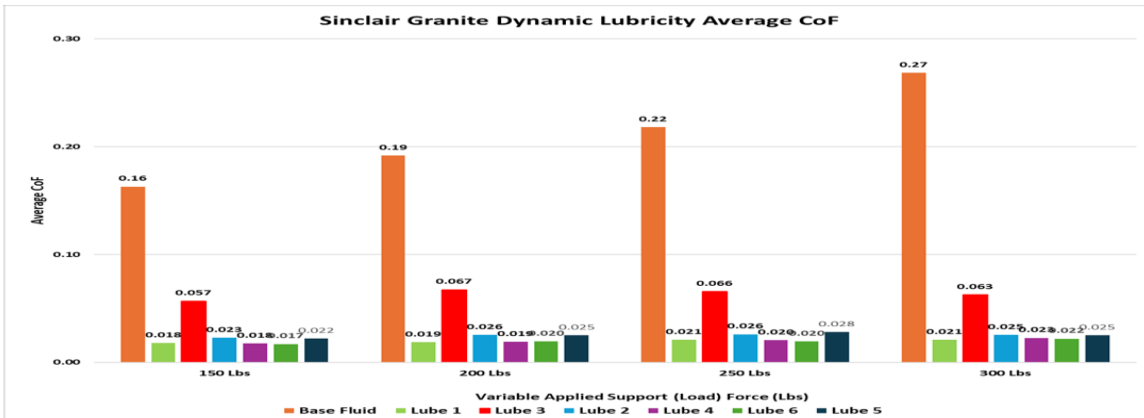

Figure 10: Drilling lubricity/COF results from the Dynamic Drilling Lubricity Simulator (Gierke et al, 2024)

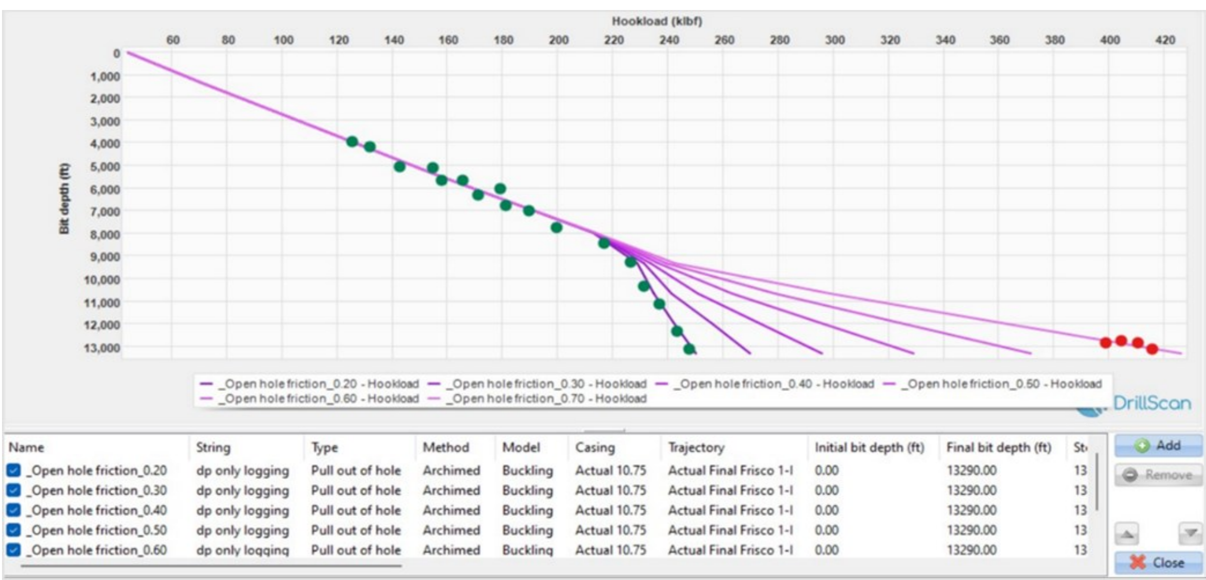

Figure 11: Open hole friction field test (Gierke et al, 2024)

Lubricity challenges will continue to be a high priority as longer extended reach wells are designed for EGS, and as higher bottom hole temperatures are targeted for SHR and other geothermal technologies. Current R&D and laboratory testing have identified two modified lubricants that satisfy all the pre-screening criteria, with temperature stability >550°F. Compatibility and secondary lubricity testing is ongoing to determine if these or other products are viable for field application, while other modified lubricant blends are being considered for the more rigorous Super Hot Rock (SHR) projects forthcoming.

6.0 DRILLING EFFICIENCY CONSIDERATIONS, MECHANICAL SPECIFIC ENERGY (MSE), FLUID SPURT LOSS

Mechanical Specific Energy (MSE) relates to the amount of energy required to destroy a unit volume of rock with the destruction efficiency of the bit; as in the formula below, monitored and adjustable variables include weight on bit (WOB), rotary speed, torque, and rate of penetration (ROP). MSE is an equation that was developed in 1965 to determine the energy being used by the bit, per volume of rock drilled (Teal 1965). The equation and its application in modern drilling is described in detail in SPE 208777 (Dupriest et. al. 2022). In support of the most recently drilled DOE FORGE wells, focus was placed on the monitoring of MSE while drilling, and especially with adjusting key drilling parameters utilizing well-planned step tests to optimize the drilling progress and identify or predict bit failure.

Constant monitoring of numerous parameters is required to quantify and optimize the direct benefits of MSE, and it requires a personal commitment of operator management, the entire drilling staff and all support vendors; extensive classroom and rigsite training was provided by drilling efficiency experts. The specific goal is to reduce MSE through adjustment of various drilling properties, then to monitor changes in MSE when any properties are adjusted. For instance, if MSE is 55ksi and rises to 65ksi when the WOB and/or RPM is increased, then the bit is probably becoming less efficient and will encounter more wear and a shorter life; if the MSE stays at 55ksi during the increase in WOB and/or RPM, then the bit is still cutting efficiently and a further increase in WOB and/or RPM may be appropriate. This is referred to as a ‘step-test’, and is an effective method to determine the appropriate drilling parameters to optimize ROP and bit life. Step tests were an integral part of the DOE FORGE operations.

By using real time management of MSE monitoring as a drilling efficiency method, results indicate that ROP, time-on-bottom and PDC bit life were all enhanced; drilling efficiency was improved significantly. Penetration rates of over 120 feet per hour were realized and maintained, and bit life was increased by over 250% in many cases. The future implementation of MSE optimization should provide similar results and cost savings in similar geothermal drilling programs.

Drilling fluids field testing and observations at the DOE FORGE project included recording and identifying the effect of drilling fluids solids content on drilling efficiency, and specifically identifying the impact of increased drilling fluids spurt loss on drilling results (Figure 12). Results indicated that when clear water (solids free) pills were circulated, MSE dropped significantly (from 85 to 45 ksi) and ROP doubled from 30 to 60 feet per hour instantaneously; once the water pill passed completely through the bit and drilling resumed with the drilling fluids system with <2% solids, MSE returned to the 85ksi baseline and ROP reduced to the prior baseline of 24fph. Both solids content and spurt loss have been investigated and implemented in O&G drilling projects in many areas, and the FORGE research project gave an excellent opportunity to field-test and validate the effect of these concepts in a controlled geothermal drilling environment.

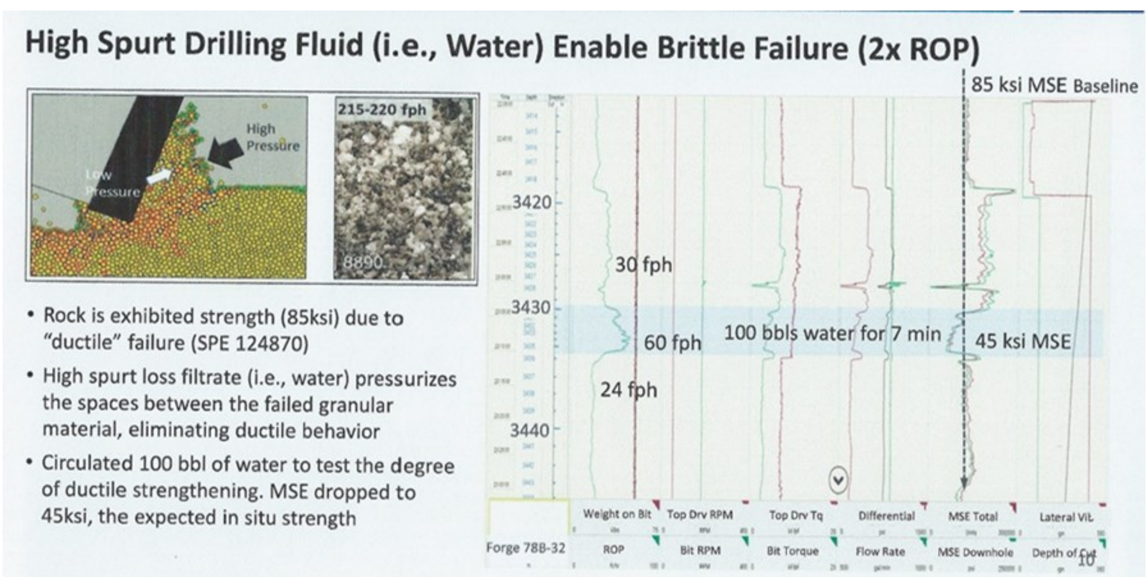

Figure 12—FORGE ROP doubled and MSE dropped by half as a 100 bbl fresh water pill passed through the bit. The 45 ksi MSE observed is closer to the expected confined rock (Dupriest/Noynaert, 2022)

Spurt loss of a drilling fluid is best defined as the volume of fluid that passes through a filtration medium before a filter cake is formed. Testing for spurt loss is accomplished by measuring the first fifteen (:15) seconds of fluid filtrate in a standard API filter press test, at approximately five-second intervals (Figure 13). Drilling with a higher spurt loss fluid should tend to promote a higher ROP, as the water from the drilling fluid can enter the rock structure and equalize pressures below the bit faster than a fluid with a lower spurt loss; this proposition was verified at DOE FORGE and other geothermal projects where spurt loss has been monitored. Therefore, in a geothermal drilling environment with stable formations, it may be advisable to drill with water and sweeps alone, and to ensure that even fine drilled solids are removed from the drilling fluids/water as effectively as possible. In the DOE FORGE field application, running a water sweep increased ROP by 100%, while reducing MSE by almost 50% (Figure 12). No other specialty additives or drilling adjustments were made to obtain this observed result at DOE FORGE.

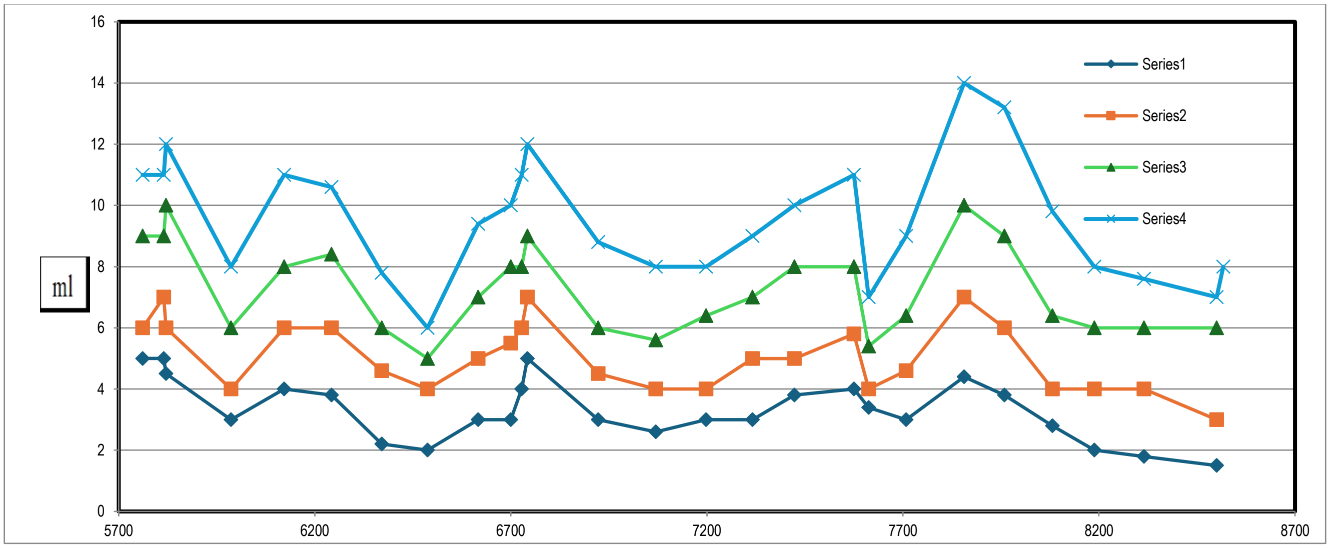

Figure 13: Charted results of spurt loss monitoring at DOE FORGE Well 78B-32

Laboratory pre-testing is planned to identify other additives and methods to increase spurt loss in a drilling fluid system, with the specific goal of enhancing the impact of drilling fluids on drilling efficiency. This investigation may include the addition of surfactants, deflocculants, or other specialty additives. Secondary prequalification of potential candidates will involve similar laboratory and field trials to determine compatibility and efficacy at elevated temperatures, as well as the direct impact on ROP in field trials.

7.0 SOLIDS CONTROL EQUIPMENT (SCE), DRILLED SOLIDS REMOVAL

Removing contaminating drilled solids is an important consideration in maintaining good drilling fluid properties in geothermal mud systems. Recent SCE (solids control equipment) configurations for deep, hot holes will generally consist of dual or triple high G-force linear shakers, followed by a desilter/mud cleaner, and complemented with one or more high volume centrifuge(s) to remove ultrafines from the drilling fluid. For O&G and geothermal wells with circulating mud temperatures over ~145°F, one or more mud coolers are included in the configuration, which can significantly reduce the circulating temperature of the recirculated drilling fluid.

Recent drilling fluids developments have trended towards drilling with low-bentonite or low-solids, clay-free mud systems. Highly effective solids removal systems have created a condition where the solids contents of drilling fluids may be below 2% by volume, even when drilling in excess of 50 feet per hour and circulating in excess of 18 barrels per minute. An efficient closed loop SCE system will generally include 3+ primary linear shakers, multiple drying shakers, mud cleaners and a primary and dewatering centrifuges. High circulating flow rates and ROP require this level of commitment for removal equipment, especially in large hole diameters. Cleaner drilling fluids result in reduced wallcake and differential sticking tendencies, increased spurt loss, increased ROP, and reduced mud additives requirements, and a continued focus on low solids, high spurt loss, and solids removal are incorporated into aggressive geothermal drilling programs.

8.0 CORROSION

Considerations of corrosion rates and treatment are important factors in all deep, hot hole drilling, regardless of the eventual goal of the well. This is especially important when drilling with non-damaging geothermal 'Drill-In' fluids, which may promote greater corrosion tendencies, especially at elevated temperatures and/or with aerated mud systems.

Corrosion coupons have been an effective method to monitor corrosion tendencies in O&G since the late 1970s, and have found specific application in the geothermal drilling arena due to the hostile drilling environment and severe wear experienced on drilling tubulars and downhole tools (stabilizers, MWD/directional tools, bit subs, and other downhole equipment). Corrosion coupons should be run continuously and analyzed both quantitatively and qualitatively, along with a prescribed Corrosion Control Program implemented to maintain corrosion rates less than ~4#/sqft/yr. A water/mud pH of ≥10.0 is generally recommended to assist with corrosion protection, and various corrosion additives incorporated into the new-generation mud system; corrosion considerations can be mitigated effectively when monitored continually at the jobsite

Corrosion Control Program: Critical in elevated BHT environments in both O&G and geothermal. Deep hot wells encounter increased drill pipe corrosion challenges, especially in hostile geothermal environments that may contain corrosive well fluids and CO_2/H_2S. A well-designed corrosion control program, including the regular use of corrosion rings inserted in the drillpipe and analyzed onsite, provides timely information on corrosion tendencies and the need for any corrosion treatment.

Recent trends in corrosion protection in drilling fluids has led to the use of non-hazardous temperature-stable additives. Polyphosphonate and film forming amines, combined with adequate pH and a low bentonite content, have been effective in controlling corrosion rates to acceptable levels. However, brackish water environments, formation fluid and gases, fluid aeration or foaming, will put continued stress on corrosion control at elevated temperatures. Continued bench studies with new corrosion formulations and combinations are being undertaken to address this concern.

9.0 CONCLUSIONS

Many drilling fluids innovations have been applied over the past three decades to enhance geothermal drilling operations. Recent accelerated and focused research has led to the development of drilling fluids additives and practices that add significant value to the current geothermal and future drilling operations. The collaboration of O&G and geothermal lab and field R&D efforts at projects such as DOE FORGE continues to develop new drilling fluids products and applications that can support the challenges associated with high temperatures, wellbore stability, lost circulation, hole cleaning, lubricity, corrosion control, fluid flexibility, enhanced drilling efficiency, and cost-effectiveness. Merging the capabilities and experiences of the O&G and geothermal drilling industries, laboratories, universities and vendor partners, and implementing new geothermal drilling fluids technologies and drilling practices for continuous improvement, has already resulted in direct operational and cost savings of well over 50%, which should be repeatable on future endeavors (Figure 13). These savings through applied research and field trials provide the tools for geothermal drillers to drill faster and at lower cost, thus derisking the process and expanding the viability and value of existing and newly considered geothermal projects

The global focus on development of geothermal resources will continue to target more challenging geothermal targets including deeper hot holes for direct use and development of naturally-fractured geothermal resources (conventional geothermal), enhanced geothermal systems (EGS), super hot rock (SHR) and other unique geothermal opportunities encountering highly deviated wellbores and bottom hole temperatures in excess of 750°F/400°C. Accelerated R&D efforts will be required to address the drilling fluids requirements for these more challenging geothermal opportunities, identifying the products and techniques that can be cost-effective in the field operations. The application of Artificial Intelligence (AI) techniques may also provide new approaches with planned R&D efforts.

Future research efforts should include proactive, direct interaction among research groups, vendors, and geothermal operators to identify specific challenges and opportunities for improvement. As research is undertaken and solutions identified, strategically applied field trials will validate the value of the research ideas and potential value to the drilling operations. The eventual goal is to provide cost-effective drilling fluids options to continue derisking of the geothermal drilling process.

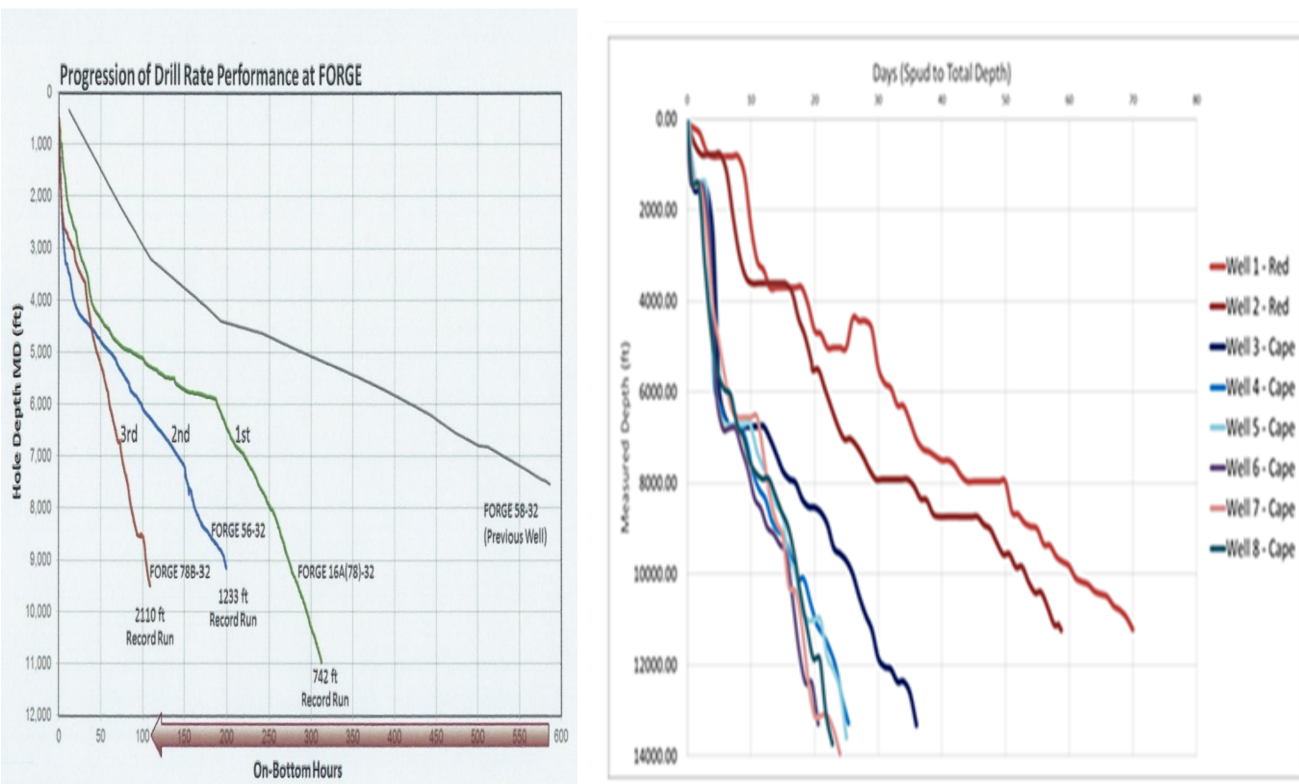

Figure 14: DOE FORGE and FERVO Drill Rate Performance – note continuous improvement, leading to reduced drilling time and record bit runs

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