Drilling Fluids for the Geothermal Industry—Recent Innovations

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ABSTRACT

Geothermal drilling activities place significant pressure upon drilling fluids design and product selection. The rigors of high bottom hole and circulating temperatures, deviated or directional wellbores, lost circulation, drilled solids buildup, excessive corrosion problems, prevalence of contaminates such as H_2S and CO_2, brackish formation waters, and other considerations, lead to specific product requirements that are difficult to satisfy. It becomes imperative to formulate a drilling fluid that can provide rheology and filtration stability at various temperature ranges, while at the same time providing formation stability and cost-effectiveness.

The scope of this paper is to identify recent technical innovations in the area of geothermal drilling fluids, and to discuss the field requirements of drilling fluids and their various properties and characteristics. Recent product development and geothermal field experience has led to potential cost savings from 15% to over 50%, when compared to conventional geothermal drilling fluid systems from several years ago. 'Project-specific' geothermal drilling fluids designs have created other recent benefits, including increased penetration rates, improved hole stability, and reduced trouble time while drilling.

Geothermal Drilling Fluids—Historical Perspective

The onset of aggressive drilling programs for geothermal resources took place shortly after the Arab oil embargo of the mid-1970's. As would be expected in a period of high energy prices, this was also a time of aggressive international exploration activities for oil and gas reserves. Operators were concentrating on finding new resources, and major service companies were concentrating on the explosive and profitable oil and gas drilling industry responsible for this boom.

Most early development of geothermal drilling technology (including drilling fluids technology) was inconsequential. Those few energy companies that were committed to define drilling fluids specifications for geothermal operations, often developed fluid selection criteria that demanded excessive flexibility of these geothermal mud systems; this typically increased the cost of 'approved' geothermal drilling fluids substantially, and limited the application of some drilling fluids that could cost-effectively satisfy most geothermal drilling operations. Therefore, much of geothermal drilling fluids technology developed were primarily a system of trials and errors, utilizing additives from the oil and gas industry and modifying them, where possible, to satisfy the demands of geothermal drilling. These drilling fluids systems were holdovers from oil and gas drilling; high pH, high solids lignite systems, KCl systems[1], lime-morrex, modified lignosulfonate systems, exotic (high cost) multi-additive systems, and others. Major service companies expended little concentrated effort to develop drilling fluids systems that were truly suited for the rigors and unique requirements of geothermal drilling, while virtually no effort was made to achieve cost-effectiveness with these new systems. Rather than identifying specialty additives that could effectively control rheologies and filtrate at elevated temperatures, inferior bentonite substitutes (Sepiolite, Attapulgite, etc.) and fluid loss additives were often utilized to address these problems. Independent drilling fluids companies and independent research and development groups, on the other hand, often led the way in the creation of new geothermal products and applications; this trend continues to this day.

Some of the more strict geothermal drilling fluids requirements from circa 1970-1980 were as follows:

API fluid loss<5cc

HTHP fluid loss <20cc

Rheology and fluid loss stability (over time) with 10% brine contamination

Rheology and fluid loss stability (over time) with 10% raw cement contamination

With the introduction of improved drilled solids removal (equipment) technology in the mid to late 1980's, and the concurrent development of 2nd generation polymeric additives with superior temperature stability, geothermal systems became potentially more cost-effective and simpler in makeup. However, also at this time the international energy crunch was 'over', energy prices had again dropped significantly, and the financial viability of geothermal resource development began to wane. As a direct consequence, geothermal drilling activity all but disappeared, leading to a reduction in technological advances and major service company R&D commitments to the geothermal drilling arena.

The past 10 years of geothermal resource development and drilling has continued to be marked by inconsistency and a general slump; however, solids removal equipment improvement, hydraulics and bit design, and drilling fluids technology have continued to develop. Now, any properly-designed geothermal project can be drilled in a timely, cost-effective manner, utilizing drilling fluids additives that will provide temperature stability, wellbore stability and inhibition, and control of contaminates. The various types of geothermal drilling fluids additives, and their project-specific selection criteria, are discussed in the remainder of this paper.

Viscosity and Rheology Control—API Bentonite and Polymer Viscosifiers

Viscosity control in geothermal drilling fluids includes the concepts of increasing and decreasing viscosity and yield point, apparent viscosity, and control of high temperature gelation. Viscosity control is a crucial characteristic of geothermal drilling fluids to promote good hole cleaning and reduce potential problems such as surge and swab pressures, excessive buildup of wallcake, differential sticking, lost circulation, and other potential problems. The current primary recommended viscosifier for geothermal drilling is API grade Bentonite (Sodium Montmorillonite). Desired particle size distribution and rheological properties can be maintained with reasonable concentrations (5-15 ppb) of API Bentonite, with an assurance that superior wallcake and viscosity properties can be obtained. Inferior clays (Sepiolite, Attapulgite, local low-grade Bentonites) are not recommended, as they can increase solids content, provide inferior wallcake properties, and promote wellbore instability and rheological control problems.

Various temperature-stable, polymer-based viscosifiers have been developed in recent years. Available as dry powders or liquid emulsions, synthetic polymers are currently utilized to provide instantaneous viscosity increases when the addition of bentonite is not desirable. These additives are especially useful for high viscosity sweeps, to enhance existing fluid carrying capacity and Yield Point, and for use in low solids geothermal drilling and workover fluids. A secondary benefit of the use of the polymer viscosifiers is the encapsulation of drill cuttings, thus leading to improved separation efficiency of rigsite solids removal equipment. Although many polymer viscosifiers are effective in obtaining instantaneous viscosity, they are generally only effective for a short period of time at the elevated temperatures common in geothermal drilling operations; therefore their primary application is for sweeps as opposed to long-term viscosity control.

Viscosity and Rheology Control—Thinners and Degelants

Temperature stability is a critical guideline for product selection to control (reduce) viscosities in geothermal drilling fluids. In wells encountering bottom hole temperatures no higher than 350°F (177°C), conventional thinners and deflocculants can be utilized (Lignin derivatives, short chain polyacrylate thinners). When used in conjunction with appropriate solids removal equipment and water dilution, the use of these conventional additives will provide cost-effective rheological control for moderate temperature projects.

Thermal degradation of conventional thinners becomes more apparent at approximately 350°F; therefore, viscosity and gelation control become more difficult and critical on geothermal wells encountering BHTs in excess of 350°F (177°C). Recent drilling fluids research and development efforts to address this problem have resulted in the development of a new generation of polymeric thinners and deflocculants; various configurations of products have been developed to provide thinning at elevated temperatures. Proprietary blends of low molecular weight co-polymers and modified starch derivatives can be used in low concentrations to not only control the circulating viscosity and yield point of a geothermal drilling fluid, but they are also highly effective in counteracting the gelation tendencies observed with most Bentonite drilling fluids at elevated temperatures. Funnel viscosities following bit trips are often only slightly higher than circulating viscosities when utilizing these innovative products to control viscosity.

Drilled Solids Removal

For efficient control of rheological properties in a geothermal drilling fluid, a well-planned drilled solids removal program is recommended. Good solids removal equipment can provide operational and cost benefits during all drilling stages; however, an effective solids removal program is critical on wells that will encounter temperatures in excess of 350°F (177°C). Drilled solids compete significantly for free water in the system, leading to fluid dehydration and dramatic increases in viscosity and hi-temperature gelation tendencies. Field experiences and laboratory analyses have shown that high viscosities from dehydration can seldom be cost-effectively treated with mud additives alone; massive water dilution is often the only solution to reduce excessive viscosities resulting from drilled solids buildup in a geothermal drilling fluid. In the presence of high drilled solids, or if an effective solids removal program is not implemented, high concentrations of secondary dispersants may also be required for adequate rheology control.

The applied method of drilled solids removal may vary significantly from operation to operation, and from area to area. Regional environmental considerations can play a big role in control of drilling wastes and the appropriate equipment required, ranging from the use of open reserve pits for drilling wastes, to the use of steel mud pits and containment bins for liquid and solid wastes.

In areas where a large reserve pit can be utilized, mud returns from the wellbore might be circulated directly to the reserve pit, where gravity provides the effective separation of drilled solids from the drilling fluid. In this scenario, often a selective or total flocculant can be utilized to enhance the settling process in the reserve pit. In this simplest scenario, a minimal of solids removal equipment may be required at the rigsite; however, environmental and operational considerations must be evaluated prior to implementation.

In geothermal drilling operations where environmental or operational requirements may be more stringent, a 'closed-loop' mud system may be required. Recent developments in state-of-the-art solids removal equipment, especially in the effectiveness and enhanced flow rates of the primary equipment (shakers), have significantly improved the efficiency with which drilled solids can be removed from drilling muds as soon as they leave the wellbore. If solids can be removed by the primary shakers, as opposed to being recycled and ground to a finer state by surface circulating equipment and secondary solids removal equipment, then the mud system remains cleaner, easier to maintain, and with lower dilution and chemical treatment demands.

Typical 'closed-loop' solids removal programs for geothermal drilling include the following state-of-the-art equipment: 1) multiple high G-force linear shakers, fitted with the finest screens possible to handle full flow; 2) one or more 10-20 cone mud cleaners (hydrocyclones fitted over a fine screen linear shaker), again fitted with the finest screens possible; 3) high speed centrifuge, for removal of colloidal size particles. In a 'closed-loop' mud system, it is imperative that a regular maintenance and repair schedule be implemented for all solids removal equipment, and that daily inspections are made to ensure optimum drilled solids removal efficiency. In addition, in drilling areas where water availability and disposal considerations are critical, a centrifuge dewatering operation may be implemented, to minimize the volumes of liquid drilling wastes that must be discharged offsite.

Filtrate (Water Loss) Control

Control of filtrate is a mud characteristic that requires significant attention in geothermal operations, with control of both API and HTHP filtrate being considered. Oftentimes in the past, geothermal Operators required strict control of API filtrates below 6cc and HTHP filtrate levels below 20cc, with little review of whether the filtrate levels were justified by actual field requirements. With the cost of filtrate/fluid loss mud additives occasionally in excess of 40% of the total mud cost, it is becoming critical to review actual needs, and to match these needs with an appropriate 'project-specific' mud program design.

Although filtrate levels are indeed important in drilling operations, recent geothermal drilling practices are becoming more analytical in determining the appropriate filtrate levels for any specific project, with a trend towards more 'relaxed' filtrate levels. These 'relaxed' filtrate levels can relate to significant mud cost savings, provided that wellbore stability can be maintained.

Lignite has been the most prevalent geothermal filtrate reducer, and is still utilized in many geothermal applications due to relative low cost and regional availability of the product. A high concentration (10-20 ppb) of lignite is often required for adequate filtrate control at elevated temperatures, thereby adding significant solids and a corresponding increased competition for water in the geothermal mud system.

The selection of additives for the effective control of filtrate levels in a geothermal fluid is a function of temperature and solids content, and polymer filtrate reducers are becoming more common. Up to about 350°F (177°C), filtrate levels can be maintained with conventional additives such as modified starch derivatives and polymers such as DMAs and PACs. These additives are typically utilized in a low-solids application, and specific selection of additives can be determined by matching the additive with any anticipated drilling contaminates and desired filtrate levels. The encapsulating nature of many of these additives provides the additional benefits of controlling drilled solids content and rheology.

At temperatures above 350°F (177°), temperature degradation attacks most conventional filtrate additives, with a corresponding deterioration of fluid properties (fluid loss, rheology, wallcake integrity, solids content, etc.) and significant increase in product requirements. Some anionic polymers are used to control filtrate levels in geothermal drilling operations in the presence of bottom hole temperatures in excess of 350°F (177°), and their efficiencies are improved by the use of other temperature-stable polymers and temperature 'enhancers'.

Recent product research and development efforts have resulted in the formulation of specialty additives to address filtrate control at elevated temperatures. Various proprietary, modified polymeric blends are available that have shown significant stability in the presence of temperatures exceeding 550°F (288°C). These additives, although costly on a unit basis, are often extremely cost-effective when used in geothermal drilling fluids at recommended concentrations. Additionally, a synergistic relationship is observed if polymeric filtrate reducers are used in conjunction with the newer high temperature thinners/deflocculants. The apparent temperature stability of each product is enhanced (increased) by the presence of the other.

In developing a 'project-specific' geothermal mud program, it is important to determine a targeted filtrate level for each interval of the drilling project based on temperature, anticipated hole stability issues, expected formations and their characteristics, directional program, etc, and then to select the appropriate, cost-effective filtrate control additive (and treatment range) based on the targeted mud properties.

Alkalinity Control

The control of alkalinity in a geothermal drilling fluid serves three primary purposes; 1) control of the effect of possible contaminates such as CO^2 and H_2S, on mud properties and safety considerations, 2) control of corrosion rates due to oxygen and other corrosion vehicles, and 3) solubilization of lignite and other mud additives. Alkalinity has typically been adjusted (increased) with additions of caustic soda and lime, with pH ranges of 10.5-11.5 not uncommon in geothermal drilling projects.

Recently, caustic potash (KOH) has been recommended for many geothermal drilling projects as a substitute for caustic soda (NaOH), especially on those projects encountering higher temperatures (>350°F, 177°C) where reactive formation clays may be present. Caustic potash serves the same alkalinity purpose as caustic soda, with the added benefit that formation and wellbore stability is enhanced by the significant amount of potassium (K+) ion that is introduced into the drilling fluids system by the caustic potash (see Formation Stability and Inhibition section). Laboratory analyses indicate that a treatment of 1 ppb of caustic potash will contribute 1,000 ppm K+ ion to a mud system, and caustic potash treatments of 1.5-2.5 ppb are reasonable to obtain a fluid pH of 11.0-11.5.

Formation Stability and Inhibition

Recent R&D efforts have generated significant improvements in the inhibitive qualities of geothermal drilling fluids. Geothermal drilling projects often encounter geologic formations that are characterized by hole deterioration, swelling, and other instability problems. In these cases, it is often the responsibility of the drilling fluid to provide additional inhibition and hole stability. Wellbore stability is especially important if drilling projects anticipate hole deviation, localized faults, or if directional programs include the potential creation of doglegs. Additionally, the mechanical aspects of drilling soft or hydratable formations will often create stability problems and/or keyseat conditions that must be anticipated.

Generally in the past, control of mud filtrate levels (API and HTHP), promotion of good hydraulics and flow properties, frequent wiper trips, and reaming of new hole provided reasonable (yet sometimes insufficient) formation stability for most geothermal drilling projects. The recent concern for formation stability and minimizing mud damage has focused on mechanical and chemical methods, specifically on additives that can provide enhanced wellbore protection through the use of active electrolytes.

Potassium and Aluminum cations have long been known to provide shale and clay stability based on the nature of their ionic structure, and potassium and aluminum based mud additives are used regularly in O&G drilling and workover operations to provide formation stability and to enhance well productivity. The molecular size of potassium (K+) and aluminum (Al+++) is such that they fit very well within the crystal lattice structure of hydratable clays (replacing Calcium and Sodium molecules) and, once in place, are relatively stable in the clay structure. This chemical property of potassium and aluminum provides wellbore stability by 'locking up' the clay structure, thus not allowing water to interact with the clays and promote swelling and sloughing; this inhibition quality results in improved hole conditions, reduced clay swelling, shale control, fewer wiper trips to maintain hole conditions, and other direct benefits.

Potassium and Aluminum based additives that have application in geothermal drilling operations include the use of caustic potash (KOH, pH adjuster), K-Lignite (filtrate and rheology controller, 1ppb K-Lignite imparts ~260ppm K+ ion), proprietary Aluminum Silicate blends (shale stabilizer and inhibitor), and others. The successful enhancement of geothermal drilling operations through the use of cationic protection is well documented, and the trend of using these specialty additives is expected to continue.

Various other specialty additives, many of which have been used in geothermal drilling fluids for many years, are available to provide mechanical stability of the wellbore. Each of these additives should be considered when designing a project-specific drilling fluids program for a geothermal operation, to enhance wellbore stability and to be part of a contingency program if problems are encountered.

Lubricity Concerns

Lubricity is a significant issue affecting directional wells, especially during the implementation of directional drilling (or redrilling) programs, or during workover operations in existing holes. During past years, diesel, mineral oils, graphite, and various 'snake oils' were utilized to free stuck pipe and reduce excessive torque and drag levels, with limited long-term effectiveness due to the products' general instability at high temperatures and/or incompatibility with other geothermal drilling fluids additives. Careful consideration should be made before adding any specialty additive to a geothermal drilling fluid. Due to potential chemical incompatibilities, only time-proven lubricants with sufficient laboratory and field success such as graphite and TORKease (an environmentally friendly lubricant that exhibits excellent temperature stability) should be utilized in geothermal drilling operations.

Lost Circulation

Geothermal drilling operations often encounter significant whole mud losses. Indeed, many desirable producing zones on geothermal projects are vugular loss zones that will allow the unrestricted flow of water or steam, as well as drilling mud. For this reason, effectively drilling and protecting these loss zones from damage becomes a critical aspect of successfully drilling and completing geothermal wells.

Historically, lost circulation has been combated with conventional LCM (lost circulation materials) additives and cement. Excessive whole mud losses have often promoted the desire for many Operators to drill blind, or with air/foam, to minimize formation damage, reduce mud costs, and to improve drilling rates. In this instance, a protective string of casing is generally run through any unproductive zones and above the potential production zone, to protect upper zones from instability due to loss of hydrostatic pressures. Then the producing/loss zone is drilled with air/foam.

In the mid 1980's, a rigid polyurethane foam was investigated for potential application as a lost circulation cure for geothermal drilling. This foam reaction resulted in an expansion ratio of 7 to 1 when the components were mixed together, and generates a foam compound that remains rigid in the presence of temperatures of 450°F (232°C). The sensitive placement equipment, need for a special trip of the drill string to pick up the placement tools, and the complicated chemical requirements for mixing and placing these 'pills' at elevated temperatures resulted in the eventual abandonment of trial projects and the return to using conventional LCM and modified cement plugs for massive lost circulation.

Recent resin technology has resulted in the development of time-released, one bag products that have shown good results in sealing massive losses in temperatures over 400°F (204°C). Further field testing of this innovative new product is forthcoming; if successful, this type of product may prove to be a viable geothermal lost circulation additive which will provide significant benefit and cost savings to the geothermal drilling industry.

In determining the selection of an appropriate lost circulation additive(s), it is important to first determine the eventual use of the zone. If it is an unproductive loss zone, then it can be sealed forever, if it is a desired producing zone, then temporary sealing may be preferred. For non-producing loss zones, readily accessible and cost-effective conventional LCM and cement may be appropriate treatment methods. Often, due to the massive losses involved, either air/foam drilling or repetitive cementing may be required to effectively seal these loss zones.

For sealing potential producing zones, a non-damaging lost circulation material is preferred. Cottonseed (hulls or pellets) and Sawdust have been shown in a laboratory environment to be almost totally degradable by temperature over time; however, recent field information has indicated that both Cottonseed Hulls and Sawdust are being recovered from geothermal wells in their native or partially degraded state, thus the fear that they have been creating blockage of the producing interval over an extended period of time?. With this new field information, it may be desirable to drill producing zones using as little LCM as possible. Indeed, the potential damage from LCM may lead the Operator to preferentially drill producing intervals with air/foam, when possible, using as little solids (Bentonite, etc.) and LCM additives as possible.

Clay Free Drilling Fluids Option

Recent interest has been generated in drilling producing geothermal zones with a 'Bentonite-free' drilling fluid, much in the same manner that other drilling industries penetrate sensitive production zones with 'drill-in' fluids. The primary advantage of drilling with a 'Bentonite-free' system is the minimization of damage resulting from invasion of fines and bentonite into the producing zone, as well as the maintenance of minimum mud densities and reduced chances of lost circulation problems.

In general, if geologic information suggests that adequate formation stability can be maintained without the formation of a firm wallcake, then a 'Bentonite-free' system can be designed that will provide other desired fluid properties (rheology control, lubricity, alkalinity, filtrate control, etc.). Indeed, 'Bentonite-free' air/foam geothermal systems have been utilized to drill and redrill/workover geothermal prospects for many years. Additives required for this application include a synthetic polymer viscosifier or high temperature foamer, a pH adjuster (generally caustic potash is recommended), a corrosion inhibitor/oxygen scavenger, and an appropriate lubricant (TORKease).

Conclusions

A significant amount of R&D effort has been expended, in an attempt to develop new geothermal drilling fluids additives that can provide temperature stability, formation inhibition, and cost-effectiveness. New product developments, and the implementation of state of the art solids removal equipment, have been instrumental in making this search a reality. An Operator can now design a 'project-specific' geothermal drilling fluid, and utilize geothermal specialty additives to satisfy the unique requirements of each project.

Worldwide geothermal development will increase with the recent emphasis on renewable energy sources, and in light of recent instability in the world energy market. Technical research will continue to develop new drilling fluids additives with superior temperature stability and characteristics. At the present time, the additives comprising geothermal drilling fluids are currently available to satisfy the needs of geothermal drilling projects on a global basis. Drilling fluids cost savings of 15% to 50%, as well as a significant reduction in drilling times and trouble costs, may be realized by utilizing this methodical approach to the selection and proper application of geothermal drilling fluids additives.

Table 1. Geothermal (High Temperature) Mud Systems Product Selection Criteria.

Property/Characteristic	<350°F (<177°C)	>350°F (>177°C)
Rheology Control (Viscosity Increase)	API Bentonite, Synthetic Polymers	API Bentonite, Synthetic Co-Polymers
Rheology Control (Thinning)	Polyacrylates, Desco CF	New Co-Polymer Blends, Lignite, Desco CF
Filtrate/Water Loss Control	PACs, Starch Derivatives, Acrylamides	HT PAC Blends, Modified Acrylamides,Lignite
Alkalinity/pH Control	Caustic Soda , KOH, Lime	Caustic Soda, KOH, Lime
Inhibition/Lubricity	K^+, Al^{+++}-Based Additives, Gilsonite, TORKease	K^+, Al^{+++}-Based Additives, Gilsonite, TORKease
Lost Circulation	Cottonseed Hulls, Sawdust, Crosslink Plugs	Cottonseed Hulls, Sawdust, Crosslink Plugs

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