

## A 300°C Directional Drilling System for EGS Well Installation

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### ABSTRACT

Directional drilling is an essential service for well installation in an Enhanced Geothermal System (EGS) power facility. The array of injector and production wells must be accurately placed in the formation fracture system for efficient fluid circulation and heat production. Current commercial offerings for directional drilling tools are rated for 175°C (347°F) service while demands of the EGS drilling environment require operation for significant periods at temperatures up to 300°C (572°F). A US Department of Energy Geothermal Technologies Program (GTP) project was initiated to develop a 300°C- (572°F)-capable directional drilling system consisting of a drill bit, directional motor and fluid. Research and development performed thus far in the project has identified a system concept that meets program requirements. Design and manufacturing is ongoing to produce field prototypes to be run in geothermal wells in 2013.

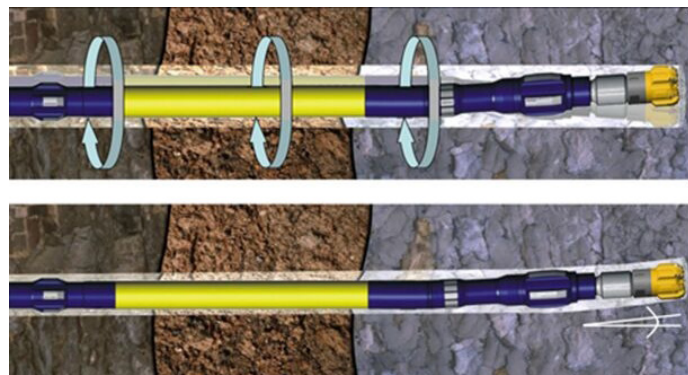
### Introduction

The US Department of Energy (DOE) Geothermal Technologies Program (GTP) has funded development of drilling technologies to reduce well installation costs and improve economics of conventional and enhanced geothermal wells. One area of focus is directional drilling systems that will enable accurate placement of the wellbore in an enhanced geothermal reservoir fracture system with bottomhole spacing up to 3,000 ft from closely spaced wellheads [1]. The GTP project, “High-Temperature 300°C Directional Drilling System, including Drill Bit, Steerable Motor, and Drilling Fluid, for Enhanced Geothermal Systems” has been undertaken to design, fabricate and test field prototype drill bits, directional motor and drilling fluid to operate at least 50 hours at 300°C (572°F) at depths up to 10,000 m. The system will be built for an 8.5-in. diameter hole.

Commonly used directional drilling systems available today can be described in two categories: directional motor drilling assemblies and rotary steerable assemblies. These two systems have advantages and disadvantages for a given application when considering the complexity of the well plan, cost, borehole quality

requirements, etc. While both systems contain electronic components for navigation, rotary steerable systems are more complex and involve downhole actuators and associated electronics that are prone to heat-related failures under geothermal well conditions. A directional motor drilling assembly is less complex and consists of a drill bit, mud motor and bent sub. When the drillstring is not rotated (slide mode), the bent sub deflects and creates a side load on the drill bit while the motor rotates the bit to drill a curved trajectory. Alternatively, when a drillstring is rotated (rotate mode), the bent sub deflects and applies a side load to the bit in all directions equally, resulting in a substantially straight borehole trajectory (Figure 1). By utilizing the drilling system rotate and slide modes, and information from a navigation device, a directional driller can construct a wellbore to intersect EGS fracture systems with precision.

This project has focused on gathering information on the anticipated drilling environment and developing technologies that enable the drill bit, directional motor and drilling fluid to function effectively. The program began in 2010 and has a three-year term to field-test nine drill bits, three directional motors and a drilling



**Figure 1.** Images show a conventional directional-drilling, bottomhole assembly consisting of two stabilizers, a directional motor with AKO and a drill bit. In rotate mode (top), the motor and drillstring provide rotation to the drill bit, and the assembly drills a straight hole. In slide mode (bottom), only the motor provides rotation to the drill bit and assembly drills a curved trajectory.

fluid batch. The field test will be performed in a geothermal well to verify function at 300°C (572°F).

## EGS Well Circulation Temperature Estimates

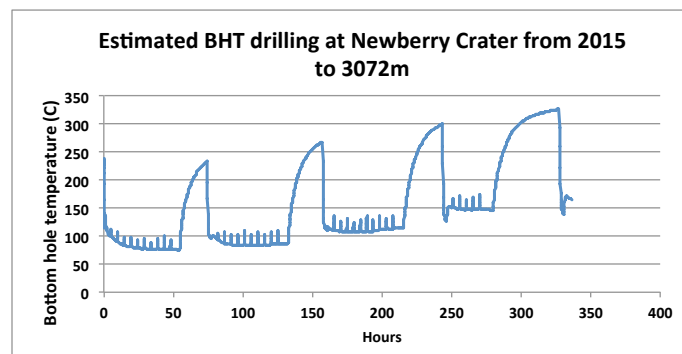
In areas where geothermal power plant development installation is considered, the undisturbed or static formation temperature may be as high as 500°C (932°F). When circulating, (where drilling fluid is pumped down the drillpipe and returned through the annulus) the drilling fluid cools the well and the exposure temperature experienced by the drilling tools may be significantly less [2].

Well-temperature simulation was undertaken to predict the temperature/time history experienced by drilling tools in EGS wells. A commercially available dynamic temperature and pressure modeling tool was used [3][4]. The model uses input thermophysical properties of all components including the formation, steel casing and drillstring, casing cement, and drilling fluid. The drilling fluid thermophysical properties are calculated based on drilling fluid composition. The simulation tool models heat generated in the drilling system from mechanical energy and hydraulic energy. Heat flow due to conduction and forced convection are calculated to arrive at temperature estimates of bottomhole temperature.

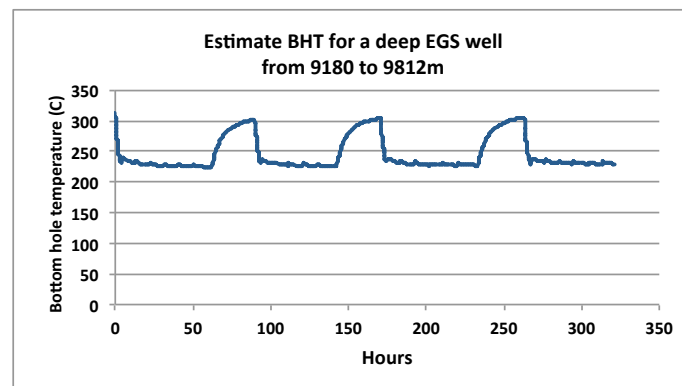
The MIT study *Impact of EGS in the 21st Century* [1] contains estimates of formation temperatures for the United States. The study identifies high-grade EGS targets as having above 200°C (392°F) static formation temperatures at a depth of 4 km, such as the Oregon Cascade range. The western United States has EGS targets over a large fraction of the land area where temperatures above 200°C (392°F) are found at a 6.5 km (21,000 ft) depth. Well-circulation temperatures were simulated for two scenarios representing 1) A 10 km (33,000 ft) deep EGS well with static formation temperatures of 350°C (662°F) at target depth and 2) a 3 km (10,000 ft) deep EGS well based on the Newberry Crater 55-29 well in the Oregon Cascade region. The models were built with temperature gradient and formation thermal conductivity estimates from the MIT study [1] and from drilling and logging information from 55-29 and other ultradeep wells [5]. Drillstring, bottomhole assembly, drilling parameters, casing programs and fluid properties were estimated based on the drilling reports and authors' past experience in geothermal operations.

Figures 2 and 3 show estimated bottomhole temperatures during drilling and rig operations that interrupt drilling fluid circulation. Every 27 meters (90 feet) of drilling, circulation is interrupted for approximately 15 minutes to add a stand of drillpipe. Every 50 hours, circulation is interrupted to trip the drillstring out of, and back into, the hole to change the drill bit that is worn from drilling hard rock. The temperature history for the Oregon Cascade region well predicts circulation temperatures that are between 80 and 150°C (176 and 302°F) during drilling. Predicted circulation temperatures for the deep EGS well are even higher at 220 to 230°C (428 to 446°F). However, when circulation is stopped, the temperatures recover and drilling tools can be exposed to near-static formation temperatures if enough time passes before circulation is reestablished. Although short in duration, the high-exposure temperatures are enough to potentially fail temperature-sensitive components such as rubber seals and

electronic components. There is also the risk of tools being left in the well during rig maintenance operations that may lead to lengthy high-temperature soak times. These simulations suggest a 300°C- (572°F)-capable directional drilling system offers a significant step forward in capability. The drill bit, directional motor and fluid can withstand long exposure periods without fluid circulation. The capability of the system to accommodate the practicalities of real drilling operations has potential to lower well installation costs.



**Figure 2.** Chart shows bottomhole temperature estimated with a commercially available modeling tool (Presmod) for an EGS well drilled at the Newberry Crater in the Oregon Cascade range. Model input data was taken or estimated from drilling reports and log information from well 55-29. Temperature history shows effect of drillpipe changes every 27 meters (90 feet), bit changes every 50 hours and a logging run at target depth.



**Figure 3.** Chart shows bottomhole temperature estimated with a commercially available modeling tool (Presmod) for a deep EGS well drilled in the western United States. Formation model input data was taken or estimated from MIT *Impact of EGS in the 21st Century* [1]. Temperature history shows effect of drillpipe changes every 27 meters (90 feet) and bit changes every 50 hours.

## 300° C-Capable Drill Bits

The geothermal well environment creates unique challenges for drill bits. EGS wells are typically drilled into the deep basement and are composed of igneous rocks whose high strength is amplified by the confining pressure. To gain an understanding of which drill bit cutting structures have been successful in drilling these hard rocks, past studies were reviewed from areas such as Iceland and west of Shetland basalt formations, and South Australia and Vietnam granite formations. Additionally, information from the Newberry Crater 55-29 well was reviewed to understand

anticipated lithologies encountered in EGS wells. A series of rock cores that were deemed to be suitable analogs for igneous formations and hard basement rock were procured and drilled in a bottom hole drilling simulator at 41.4 MPa (6,000 psi) confining pressure to produce rock drillability and performance information for four bit styles; polycrystalline diamond compact (PDC) drag bits, diamond impregnated bits, rolling cone and hybrid PDC-rolling cone bits (Figure 4). Recommendations based on results from the simulator tests and review of past drilling studies selected rolling cone or diamond-impregnated drill bits as best suited for drilling hard basement rocks. However, in some cases where basalts, granites, diorites and granodiorites can have lower strength or are interbedded with softer rocks such as volcanic tuff, a more aggressive bit style may achieve higher penetration rates and still provide sufficient durability to last 50 hours or longer. To meet these different operating requirements, four rolling cone bits and five hybrid rolling-cone/PDC bits will be fabricated for field testing. These studies also concluded the directional mud motor must be capable of producing 4,000 ft/lb of torque, 50 klb weight on bit (WOB) at a rotational speed of 100 RPM.

The recommended bit styles of rolling cone and hybrid PDC-rolling cone bits require a sealed grease-lubricated bearing system. Conventional bearing and seal packages consist of an elastomer rotary seal to prevent contaminants from the drilling environment entering the bearing grease, coupled with a grease pressure compensation system to minimize the pressure differential across the rotary seal. High-temperature elastomer compounds have been incorporated into rolling cone bit seals and grease pressure compensator bladder to extend their operating temperature, but commercial solutions are limited to less than 300° C (572° F) [6][7]. To achieve the project target of a 50-hour operation at 300°C (572°F), a new metal washer seal design was designed and tested to eliminate the elastomer components. A specialized, high-temperature-bearing grease formulation was developed and a metal bellow was used to replace the rubber grease pressure compensation bladder.

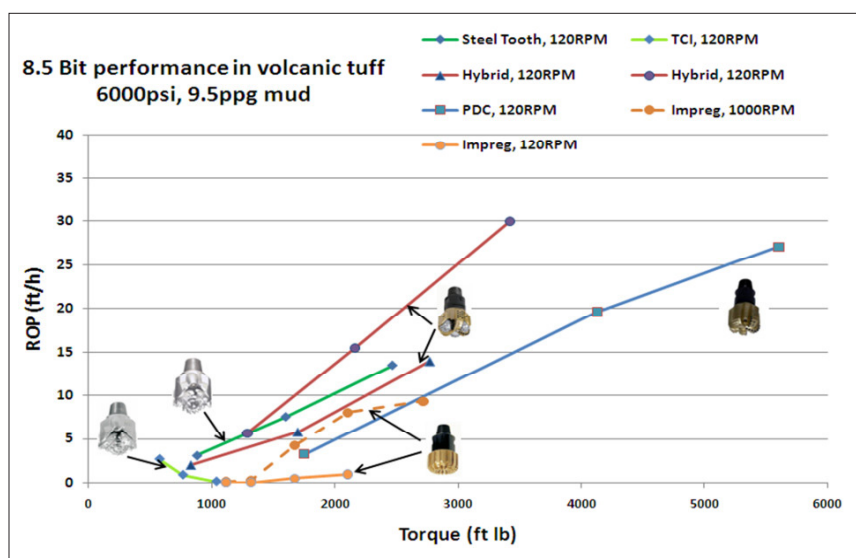
### 300°C-Capable Directional Motor

The directional drilling options today perform very well in more traditional drilling applications at temperatures at or below 200°C. EGS wells offer a new design and material challenge to make 300°C- (572°F)-capable tools. One type of tool that is currently being used for geothermal drilling is the turbine. The turbine is an acceptable tool and can work in high-temperature environments and is known for high-RPM capability but has low-torque capacity. Drill studies discussed in the previous section suggest use of rolling cone or hybrid PDC-rolling cone bits with high WOB/low RPM for drilling hard rock formations, thereby making the turbine a poor tool choice [8]. The primary bit used in combination with a turbine is a diamond-impregnated bit that has low aggressiveness which often leads to low ROP in hard rock formations. Except for the Positive Displacement Motor (PDM), other types of directional drilling products would be very difficult to develop for the rigors of the EGS environment.

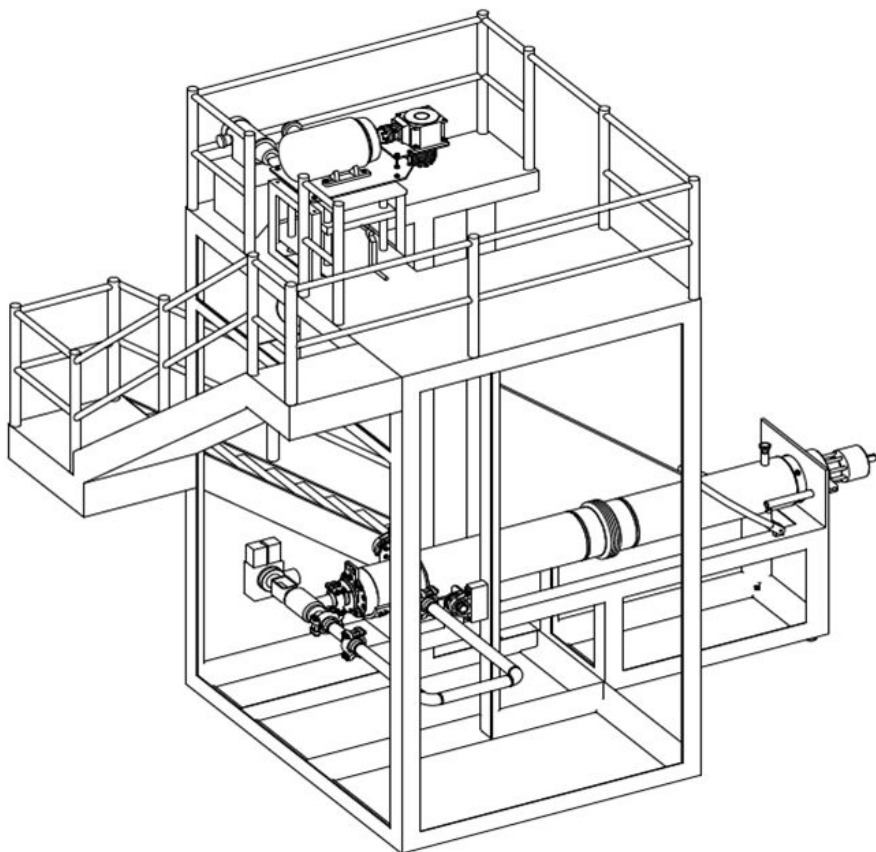
After considering all possible options, the authors have selected to pursue a directional motor based on the PDM. Additional reasons for choosing the PDM included existing experience with the technology in design and manufacturing methods. The PDM provides flexibility in operating parameters by means of RPM, WOB, and torque to the bit. This enables flexibility in bit choice with the option for using PDC, diamond impregnated, roller cone, and hybrid PDC-roller cone bits. A PDM is driven by mud flow through the power section of the tool, and its simple mechanical design can be built to offer excellent reliability.

The PDM has three main sections: the power section, adjustable kick-off section, and bearing section. Developing a tool to withstand 300°C (572°F) has challenges and close attention had to be given to the three main sections of the PDM. The first challenge was to understand the performance needed to drive the various drill bit options. This area includes torque and RPM generated by the power section. The RPM and torque capacity is controlled by lobe and stage design of the power section. Previously described drill testing and hard rock drilling studies have identified operating targets of 4,000 ft/lb of torque, 50 klb WOB at 100 RPM. The 5/6 low-speed (LS) lobe configuration was selected to accommodate the operating requirements of hybrid and rolling cone bits. Diamond thrust bearings were selected to accommodate the WOB requirement.

The most difficult obstacle to overcome in building a robust 300°C- (572°F)-capable PDM is the elimination of the ID stator elastomer. Rubber compounds that can withstand the high temperature have poor mechanical properties and are not able to withstand the general rigors the rubber stator lining is subjected to during downhole operation. The decision was made to design and manufacture a metal-on-metal (M2M) power section in the PDM. To successfully meet the 50-hr tool lifetime requirement, an extensive coating evaluation program was undertaken, in addition to developing precise manufacturing techniques. Forty-three coatings were evaluated using screening methods for coating adhesion, erosion resistance, corrosion resistance,



**Figure 4.** Bit performance from bottomhole simulator testing performed in volcanic tuff sourced near the Newberry Crater EGS site. All tests were performed at 41.4 MPa (6,000psi) confining pressure with 9.5 ppg water-based mud.



**Figure 5.** Schematic shows the high-temperature motor test stand being fabricated to evaluate the directional motor under simulated downhole conditions.

and slurry abrasion resistance. Three coatings selected for the rotor and stator showed the most promise for surviving the aggressive environment. After reviewing various manufacturing methods, a technique was selected to obtain high accuracy of the contoured rotor and stator profiles. This selected technique meets the requirements to optimize performance and reduce volumetric losses in the clearance gap between the rotor and stator.

The last challenge in the project included devising a way to conduct final simulated testing to verify directional motor operation prior to conducting field trials. A 300°C (572°F) test stand is being designed and manufactured that can accommodate a 4¾-in. two-stage rotor and stator that will have the select coating applied. The test stand will enable testing for 50 hours at 300°C (572°F) using drilling mud at pressures up to 13.8 MPa (2,000 psi) (Figure 5). The objective is to use the rotor and stator in pump mode for fluid circulation and monitor the torque, RPM, and flow rate. This method will enable mapping of a performance curve for comparison to a standard PDM to determine the magnitude of any performance losses. The test stand will enable testing of the PDM in combination with the 300°C- (572°F)-specialized drilling fluid formulations to verify system function. This test will also provide the final coating wear test on the select coatings to determine durability in a simulated EGS environment. After this testing is performed, any lessons learned will be incorporated into a final design of the 6¾-in. PDM for testing at the Baker Hughes Experimental Test Area (BETA) facility (a full-scale drill

rig) and then in a customer EGS or conventional geothermal well.

### 300° C-Capable Drilling Fluid

To determine fluid requirements, past experiences on geothermal, EGS and HPHT oil and gas wells were referenced. A survey was also conducted, and included meetings with operations, wellsite visits, and well record studies to understand drilling fluid requirements and solutions used in geothermal operations and exploratory wells at EGS sites at the Newberry Crater and in South Australia. Results found the requirements and practices varied greatly between locations. Based on experience and survey data, a laboratory test program was initiated to create fluid formulations suitable for the 300°C Directional Drilling System. The drilling fluid formulations researched were water with sweeps, unweighted water-based drilling fluid, and weighted water-based drilling fluid.

Most geothermal wells are drilled with unweighted water-based drilling fluid. If mud stability is not required, thermally degradable products are sometimes used. To stabilize drilling fluids to 300°C (572°F), at a minimum, requires the most thermally stable mud additives. Geothermal drilling fluids have progressed chronologically from lignosulfonate to sepiolite, to high-temperature (HT) copolymers, to synthetic Hectorite mud systems. The fluid that has been providing the most thermally stable rheological properties and high-pressure, high-temperature (HP/HT) filtration control contains bentonite stabilized with a low molecular-weight copolymer. HP/HT filtration control and supplemental viscosity is obtained with variations of vinyl sulfonated copolymers. In addition, the high-temperature copolymers systems are tolerant to contamination and provide corrosion protection to the drillstring. The ability to prepare high-density, thermally stable formulation that meets project requirements is most promising with the HT copolymer approach [9][10][11][12][13].

Project fluid tests have included variations of clays, polymers, copolymers and other filtration control materials. Lubricant testing has also been added to the testing regime because directional wells normally produce higher torque and drag than vertically drilled wells. There is a higher probability that these wells will require a lubricant because the wells will be directionally drilled into the hard rock. The majority of this testing has been conducted on lower-density formulations because this is the most interesting to the EGS and geothermal community. However, high-temperature density formulations have been prepared and have been helpful in support of an active EGS project.

To satisfy project targets for a 300°C (572°F) drilling fluid, a new set of aging cells that have metal-metal seals with bolted closures were obtained (Figure 6). An oven that could accommodate the weight of the cells and the desired temperatures was procured and installed (Figure 6).



Figure 6. Images show high-temperature aging cells (left) and the 350°C (662°F) oven (right) used in the drilling fluid development program.

To simulate drilled solids in laboratory drilling fluid evaluations, Revdust or OCMA clays are frequently used. It was determined that these materials do not represent the mineralogical composition of the anticipated formations where the 300°C Directional Drilling System would be used. A metamorphic or igneous material, as opposed to sedimentary rock, was desired. It was also necessary for the new material be commercially available. Silica, SiO<sub>2</sub>, is such a material. A laser particle size distribution (PSD) analysis was conducted on various silica samples to select the correct product to simulate drilled solids (Figure 7).

Fluid formulations were first evaluated after aging at 66°C (150°F) and 260°C (500°F). This testing occurred while waiting for the 300°C cells and oven, evaluating products, and had equipment issues with the 300°C cells. The 260°C (500°F) testing was executed during the waiting period while the 300°C (572°F) hardware was procured and installed. Mud rheological properties were tested on a viscometer at 49°C (120°F), and is reported as plastic viscosity in units of centipoise and yield point and gel strengths in units of pounds/100 ft<sup>2</sup>. API fluid loss and HPHT filtration rates were reported in units of ml/30 min. The HP/HT fluid loss was tested at 150°C (300°F) and 500 psi differential pressure. High-temperature rheological testing will be conducted based on anticipated circulation temperatures predicted by circulation temperature modeling.

Conducting directional operations within the high-temperature portions of EGS or geothermal wells have been limited because of the temperature limitations of the tools. In directional wells with inclined or horizontal sections, a lubricating agent can reduce friction of the drillpipe and bottomhole assembly with the formation and casing. It is anticipated that a high-temperature lubricant may be required. Lubricity testing has been conducted with encouraging results.

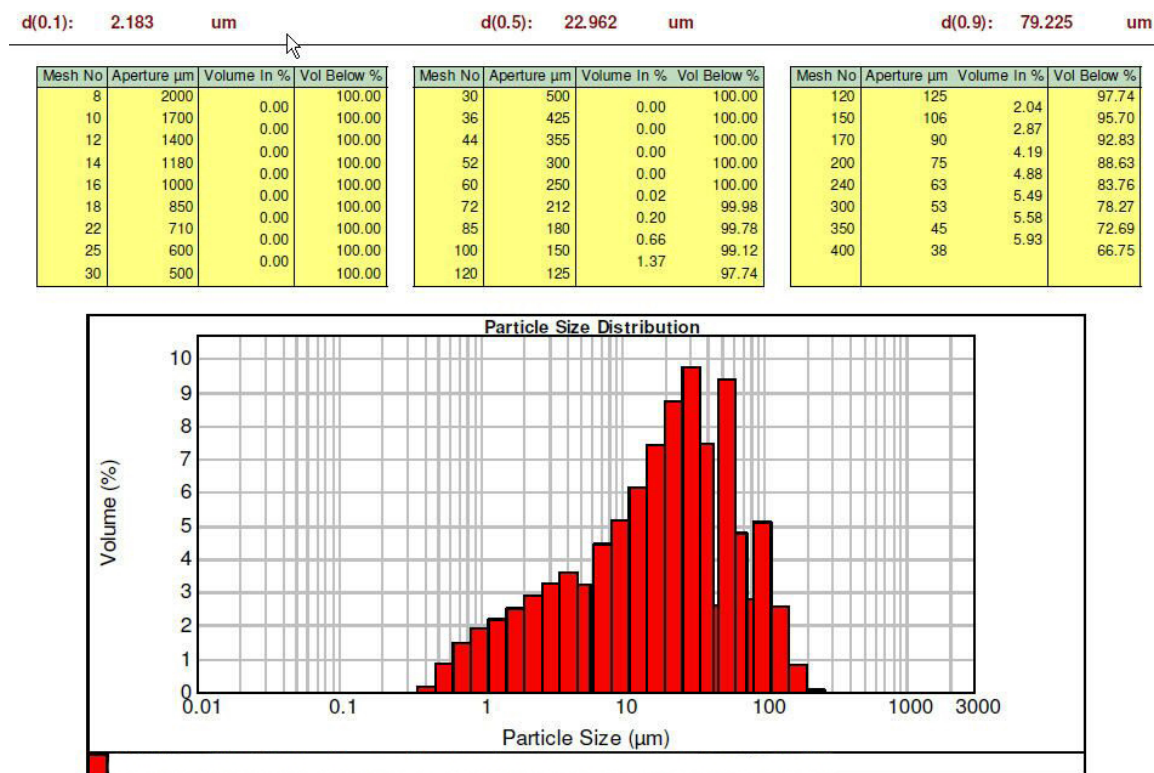
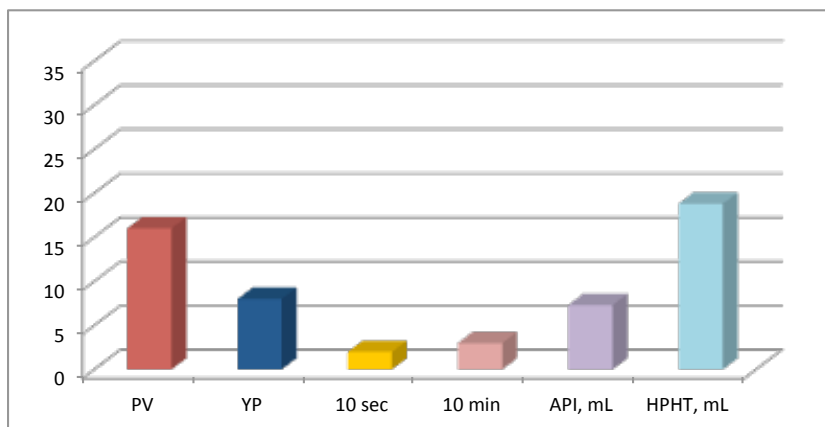


Figure 7. Particle size distribution is shown for a silica flour used to simulate drill solids in the drilling fluid.



**Figure 8.** Unweighted formulation test properties after aging at 300°C (572°F) for 24 hours.

Under conditions when drilling with a low-viscosity fluid system is used, sweeps (a small batch of higher-viscosity fluid circulated downhole) can be used to improve hole cleaning when drilling. These sweeps are very important when drilling with water or thin unweighted mud systems. Polymer sweep formulations will be evaluated with aging tests and with high-temperature viscometer testing based on predicted circulation temperatures.

## Summary

The US Department of Energy Geothermal Technologies Program project to develop a 300°C- (572°F)-capable directional drilling system for use in EGS and conventional geothermal wells has made considerable progress. The award recipient has identified operating requirements for a drill bit, directional motor and drilling fluid. Current efforts are focused on design and fabrication with the project teams on schedule to test field prototype tools in 2013. If successful, the 300°C (572°F) drilling system will offer a significant advance in drilling technology and enable accurate directional wellbore placement under extreme conditions encountered in deep EGS wells. This capability will contribute to GTP program goals to lower well installation costs and move EGS-renewable energy production closer to commercialization.

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