Enhanced Geothermal Systems
Wellfield Construction Workshop
San Francisco, CA
October 16, 2007

Summary Report

Executive Summary

A workshop on Well Construction for Enhanced Geothermal Systems (EGS) was held in Houston, Texas on October 16, 2007. Hydrothermal and EGS well construction activities are similar to the oil & gas industry, but geothermal wells are larger in diameter; temperatures are higher; they are typically drilled in harder rock; formation fluids can be corrosive; and systems are often underpressurized, leading to lost circulation problems. Fewer tools are available for geothermal applications because of these differences.

The design and construction of wells and well fields must efficiently exploit the EGS resource. EGS well construction options should include highly deviated directional wells, multilaterals completions, multiple completions zones, etc. Cost reducing well design alternatives should be considered, such as not cementing casing all the way to the surface. High-temperature directional drilling tools (including motors, turbines, steering and logging-while-drilling devices) are required to increase flexibility in well design. Alternatives to traditional casing systems can improve economics. Casing-while-drilling, expandable tubulars, and low-clearance casing designs are needed. Robust hard-rock underreamers are required to take advantage of lean casing designs.

High-temperature packers and other zonal isolation tools are needed to address well construction problems and allow stimulation and interventions in selected zones in the wellbore. High-temperature electrical submersible pumps capable of variable speed operation will be required to regulate flow. Additional high-temperature borehole logging and long-term monitoring tools will be required for EGS applications. Proppants and fracturing fluids that work at high temperatures and pressures may be required. Geothermal drilling can benefit from advances in drill bit performance.

EGS Well Construction Workshop
October 16, 2007

A workshop on Well Construction for Enhanced Geothermal Systems (EGS) was held in Houston, Texas on October 16, 2007. This was the last of a series of four workshops, of which the first evaluated the assumptions set forth in the recent report by the Massachusetts Institute of Technology (MIT) entitled *The Future of Geothermal Energy,* and three (on Reservoir Creation, Reservoir Operations, and Wellfield Construction) focused on identifying technology gaps associated with aspects most critical to EGS development. The intent of the workshops was to motivate facilitated discussion on technology gaps related to well construction.

Well construction for EGS development encompasses all reservoir access activities, including well (and wellfield) design, drilling, well integrity, interventions, stimulation, logging and monitoring, and production. The two general topic areas covered were:

- System-level issues associated with drilling EGS wells: Differences and similarities between geothermal drilling and oil & gas; where oil & gas is today; differences between traditional hydrothermal and EGS wells; economic drivers for EGS well construction; possible EGS well locations; and possible well field design options.
- Tool requirements for construction of EGS wells: Current oil & gas capabilities; crossover between oil & gas and geothermal; high-temperature operations and issues; conventional and advanced drilling tools and systems; downhole equipment and assemblies for drilling; stimulation, monitoring, logging and intervention; and well design issues.

Workshop participants were encouraged to speak freely and discussions were allowed some latitude to encourage dialog. While notes were taken, the proceedings of the workshop were not transcribed, again to encourage discussion. Participants were also encouraged to provide written comments to the workshop organizers following the day's discussion. The key discussions from the workshop are covered here.

General Issues of EGS Well Construction

This workshop was designed to identify technology gaps for constructing wells in EGS environments, but specific needs will be determined by the environment in which the wells are constructed; the technology to be used is likely to be site-specific, and it is not possible to define the economics of drilling without knowing the location. The question "What is the site?" was asked in all of the technology needs workshops. It may be preferable to select sedimentary formations for early sites in order to be able to model the site better and avoid creation of "stranded" wells that cannot be connected to the reservoir. Also, it may be possible to avoid drilling issues at first by selecting sites where existing wells have high heat flow, enabling inexpensive reservoir development experiments that would otherwise cost hundreds of millions of dollars for drilling. In addition, since the MIT report assumed that the developer would have to pay for well costs, it might be possible to get an economic system with a lower flow rate than the 80 kg/second identified by the report if the well is free.

Technologies involved in hydrothermal and EGS well construction activities are similar in principle to those used in the oil & gas industry, but there are substantive differences. Geothermal wells are larger in diameter because of the required high mass flow rate (thus requiring more steel and cement); they are typically drilled in harder rock formations; formation fluids can be quite corrosive; and geothermal systems are often underpressurized (leading to often severe lost circulation.) While oil & gas wells are being drilled into hotter resources, temperatures associated with geothermal wells are typically higher, with the result that fewer tools are available than in the oil & gas industry.

The geothermal industry is currently able to drill to given target depths, fix lost circulation during the drilling process, steer and survey the well using motors (albeit with older technologies), and complete wells open-hole or with slotted liners. Drilling technology limitations have not prevented geothermal development, however the costs of drilling geothermal wells remains high and drilling costs continue to be an issue. The geothermal industry drills wells at temperatures in excess of 250°C.

Technology crossover between oil & gas and geothermal well construction is generally slow. While major improvements in drill bits (e.g., bearing assemblies in roller bits) have aided the geothermal driller, hard rock drilling in geothermal environments uses older generation bits. State-of-the art logging tools, underreamers (hole openers), measurement-while-drilling systems, and other technologies employed by the oil and gas industry are not generally available to the geothermal market because of unique tooling requirements (e.g., ability to function with high temperatures and hard rock), and because the geothermal industry is a niche market that is too small to induce service companies to develop these tools. However, advanced well construction technologies will likely be developed in the future due to the increasing pressures and temperatures encountered by the oil & gas industry.

Geothermal and oil & gas industry costs are linked to some degree because the geothermal industry competes with the oil & gas industry for drilling rigs. As the price of oil increases, so does the price of drilling rigs and supporting services, and therefore the cost of constructing geothermal wells goes up as well. However, historic cost data show that the cost of geothermal well construction has decreased relative to the cost of oil and gas drilling over the last 30 years due to improved technologies and methods. As described in the MIT report, cost models based on hydrothermal experience indicate that the cost of constructing EGS wells may be lower than that for oil & gas wells at depths below about 5000 m for a number of reasons (e.g., well control issues are anticipated to be simpler for EGS and longer casing intervals are possible for geothermal wells.) The cost impact of low rates of penetration (ROP) in deep drilling is often underappreciated, and the concept that deep EGS wells would be less expensive than oil & gas wells was viewed with skepticism by workshop participants.

EGS economics are affected by both technology and market factors. Modeled cost factors included site-specific geology, distance from services, and the rate of penetration. Wide variations in geothermal well cost are largely due to site selection and trouble costs. Siting plants in geographical areas where energy can get to market is an important cost factor. The plant has to be tied into the grid system, and must be near a demand center. Workover costs are not included in the MIT report's cost estimates; redrilling is included instead.

EGS Well and Wellfield Design Considerations

The MIT report indicates that making EGS economic will require a three- to four-fold increase in productivity over previous EGS efforts; accommodating this productivity need by reducing the cost of well construction by a similar factor is unlikely (it certainly cannot be done with current technology.) The alternative is to construct wells and wellfields that exploit the resource more efficiently. Well design alternatives should be considered that balance cost (including options that reduce cost, such as not cementing casing to surface) against productivity to provide more favorable overall economics (i.e., higher-cost well options may result in lower overall electricity costs.) The goal is to maximize the efficiency of the well.

As with oil & gas, the cost of casing and cementing and other tangible items accounts for about 30% - 35 % of the costs of geothermal wells. In traditional well construction activities, the casing is extended into open-hole sections by nesting decreasing diameters of casing strings (cemented to the surface in geothermal wells.) Reducing the amount of casing installed can markedly reduce costs. Alternatives for doing this are being pursued by the oil & gas industry, including the use of low-clearance casing designs (where the annular space between nested casing strings is reduced, making cementing more difficult) and expandable tubulars or casing-while-drilling systems (which can eliminate full strings of casing). At the extreme, casing drilling and expandable tubular methods could be used to produce a well drilled at a single diameter. While not the norm in oil & gas well construction practices, many see these alternative casing systems as the future for well construction. These options are not currently employed in geothermal well construction for a number of reasons: lean casing systems are expensive; the available material diameters are too small; expanding tubulars generally employ elastomers for annulus sealing (which are problematic at high temperatures); and quality underreamers needed for these advanced casing programs are not available for hard rock environments. (Underreamers are bits that can drill hole diameters larger than the diameter of a hole they can fit through, either by expanding or rotating eccentrically.)

The geothermal well construction practice of cementing all casing strings to the surface deserves evaluation. This practice constrains the thermal expansion of the casing when flowing high-temperature fluids (it is also employed in steam injection wells used for enhanced oil recovery). Casing and wellhead design alternatives that would allow the casing to float could reduce the cost of cementing the casing and also mitigate the difficulties associated with circulating cement in deep wells.

ROP in oil & gas wells is reduced when drilling in deep environments. Whether this will be as important an issue in deep EGS wells is a matter of debate, since there is very little geothermal well data below 5,000 m. Oil & gas experts believe this will be an issue. Methods to increase ROP being employed by oil & gas include drilling with advanced PDC (polycrystalline diamond compact) and impregnated bits; downhole motors and turbines (motors and turbines either are or have been used in geothermal drilling efforts); and measurement-while-drilling and steering systems, as well as advances in best practices and tools to minimize drilling dysfunctions (vibrations, whirl, etc.) at depth and maximize energy in cutting the rock (e.g., ExxonMobil's well publicized "Fast Drill Process"). These issues may need to be addressed in future EGS well design and development work. Deep drilling rate of penetration could be the topic of a study to determine the effects of bit type, rotary speed, etc.

The modeled cost of the wells in the MIT report reportedly included the cost of fracturing, but stimulation was not a major cost element in the analyses. The fracturing cost may not be modeled correctly; the modeled costs are based on industry input, rather than objective data.

Flexibility in well design options will have to be exercised to maximize the effectiveness of drilled holes. Directional drilling is employed in geothermal well construction, but capabilities are limited relative to the state of the art in oil & gas. Steering systems used in geothermal drilling have advanced beyond basic "point and shoot" systems where downhole positive displacement motors and bent subs are used to develop directional wells, and surveying is accomplished with wet-connect wireline or single-shot surveys. Efforts to use more advanced MWD devices have been problematic. For example, high downhole accelerations when using light aerated muds have resulted in failures, and mud coolers are required to keep tool temperatures within operational requirements. Real-time MWD measurements of the build angle and formation character information are needed. Advanced drilling systems and MWD-type devices should be part of the drilling engineer's options.

Development of wells to access greater volumes of stimulated rock should be a focus of efforts to advance EGS. Active steering of the well trajectory to optimally orient the hole relative to the producing fractures can increase the effectiveness of the well. Development of a series of multilaterals off a single wellbore to produce from a larger portion of the reservoir may increase productivity. Use of lower-cost drilling systems to effectively increase the diameter of the primary wellbore can be considered; for example, small microholes using coiled tubing may provide a low cost method of creating "capillaries" for monitoring or production/injection wells. While small-diameter coil tubing drilling is currently limited to soft formations and shallow depths, advanced technology may provide a less expensive solution to reservoir access. Depending on site conditions, drilling many inexpensive wells might improve EGS economics. While more complicated well completion scenarios will certainly increase development cost, it is possible the economics of the system can be improved using more expensive completion methods.

Corrosion is also a major risk in geothermal wells. The chemical constituents of geothermal fluids include hydrogen sulfide, hydrogen chloride vapor, and salt at concentrations as high as 250 ppt. Titanium casing is required in some situations. Production through tubing is reportedly not the norm in geothermal wells, while production tubing is common in oil & gas. The feasibility of using tubing should be considered to mitigate casing corrosion and perhaps add flexibility in extending the life of the wellbore.

The technology that exists today enables reservoir creation, but recompletion is difficult. Systems and tools should be designed for recompletion.

Zonal Isolation

Selective isolation of sections of the wellbore is a key issue for EGS. Zonal isolation will be required to shut off potential cold water horizons, selectively stimulate sections of the wellbore during reservoir creation activities, inject and recover tracers, and to control wellbore flow during reservoir operations. The lack of tools capable of operating in high-temperature environments limits zonal isolation in geothermal development. Options for zonal isolation include open-hole and cased-hole packers, selective liner and screen placement, employing expandable tubulars, or liners with "swellable" sections followed by use of cased-hole packers, among others.

The limiting factor on seals for packers is elastomers that work at high temperature. Development of high-temperature packers may require dropping elastomer seals in favor of metal-to-metal technology, which will have to improve to provide the needed capabilities. A liner may be required to provide a seat for a packer, seal a short circuit zone, or reconfigure multilateral completions. It may be possible to set a slotted liner with zonal isolation and then fracture through the slotted liner. Expandable tubulars can be used with packers to isolate fractures of interest. It is possible to open a window in the casing, but the technology is not very advanced. Carbide tooling is used to open windows in casing but this is not a precise technique and suffers from increased risks of getting stuck. Ideally, it would be possible to start with a solid pipe, punch through it in one spot and fracture the zone, then pack it off and fracture another section. This would be easier because the packer would be sealing against the pipe, and it would be easier to redo the job later if needed.

Tools and Materials

While geothermal well construction technologies parallel those used in oil & gas wells, the tools and materials required for geothermal drilling differ. Technologies required to fulfill EGS requirements that are not offered by service industry providers include high-temperature packers and other zonal isolation tools, high-temperature electrical submersible pumps capable of variable speed and pressure (current versions operate at 175°C, and 225°C operation is required), robust hard-rock underreamers, expandable tubulars for blocking short circuits, high-temperature directional drilling tools, including motors, MDW and LWD devices, high-temperature borehole logging tools and long-term downhole monitoring systems, proppants and fracturing fluids that work at high temperature, improved cables and cable heads, active downhole well control devices (e.g. sliding slotted downhole valves that can choke wellbore flow), and improved connections for large diameter casing.

High-temperature tools are needed for reservoir characterization, monitoring, and to improve drilling. The effect of temperature on oil and gas tools is significant, leading to elevated costs. Current downhole tools for oil & gas generally operate at 150°C with a limited lifespan. At 200°C, most sensors have very limited capabilities (according to some experts, 200°C is optimistic). There are few high-temperature wells in the oil and gas industry; this is a niche market, and funding for high-temperature tools research is small. Tools will be produced if geothermal becomes a major market, but the market size has to be hundreds of millions of dollars to draw the attention of service companies, rather than a few million dollars. The high-temperature electronics industry is driven by aerospace, large oil and gas firms, and the automotive industry, rather than the geothermal industry. An overdesign factor is required for high-temperature tools, both to provide a margin of error and to increase reliability and lifetime. A 10°C change in temperature significantly affects the lifetime of many components. The desirable margin of safety is roughly 30°C above the nominal operating temperature. Increasing the operating temperature by 10°C -20°C is a major challenge.

During drilling operations, high-temperature issues can be mitigated through the use of commercially available equipment. Commercially available insulated drill pipe reduces conductive heat transfer during drilling, which extends the service life of tools. Mud coolers can also be used to increase the flexibility of operations at high temperature and mitigate shortcomings with tools that fail at higher temperatures. Logging tools can be used in the well if they are not high-temperature qualified by cooling the wellbore or using heat shields, but long-term monitoring tools must be capable of operating reliably at high temperature. For MWD, the system has to be able to tolerate an indefinite period at the bottom of the well. Monitoring systems that will operate reliably for a long period are not available. Heat shields won’t work for monitoring; high-temperature-qualified electronics are required. Developing high temperature systems is expensive and with limited funding available for research, the Geothermal Program will have to concentrate on a few of the most the most important components/tools.

Instrumentation, downhole tools, and pumps

EGS wells are expected to require a higher level of supervision than current geothermal wells. Relatively little logging is done in the current geothermal industry because of economics, and because only basic properties must be known in hydrothermal regimes. EGS developers will need to know fracture aperture and direction and stress state in addition to temperature, pressure, and flow rate. The logs to be run for EGS reservoir characterization have not been standardized.

Downhole instrumentation will improve management capabilities. Robust and affordable MWD and logging-while-drilling (LWD) systems that operate at long-term at high temperatures (at least 200°C) would be valuable to enable drilling into previously stimulated sections of the EGS reservoir. Logging tools for borehole imaging, geometry, velocity, and electrical properties are selectively available for high temperature applications but the temperatures are typically below geothermal applications or the tools are dewared. Other desirable devices include tools that would detect formation temperature, fluid flow, and rock properties during drilling.

Downhole information is desirable for predictive reservoir health models. Downhole monitoring tools are required to track reservoir response (mechanical, hydraulic, thermal, and chemical) during operation, enabling detection of short circuits, lost circulation, changing fluid characteristics, reservoir growth, and changes in participation of different production zones.

Permanently installed optical-fiber based devices are used in downhole applications for measuring temperature profiles along the wellbore. Fiber optic temperature probes are used in oil & gas applications and have been tested in geothermal environments. Results to date in geothermal environments have been disappointing due to hydrogen induced fiber degradation. Further investigation into fiber based techniques may be warranted.

EGS will require submersible pumps in the production wells both to increase the rate of fluid production and for controlling pressures. Artificial lift like that for oil and gas wells is not required, because the well may be expected to self-flow at some rate, but pumps are needed to assist flow and provide downhole reservoir control functions Current submersibles are either of the line-shaft variety (powered from the surface) or electrical submersible pumps (ESPs). Line shaft pumps can be used at less than about 2,000 feet, but these do not provide control over the flow and pressure drop through the reservoir and the inflation of the fractures. The MIT report considered the use of ESPs in production wells. For ESPs, the connection between the pump and the cable may fail at high temperature. The cable must be protected to maintain the electrical connection. Deeper EGS reservoirs would benefit from high-temperature-capable ESPs. High-temperature electrical submersible pumps capable of variable speed and pressure currently operate at 175°C, and 200°C - 222°C operation is required.

Fracturing and Proppant

It is generally assumed that stimulation associated with EGS will be performed by hydraulically stimulating the rock mass by opening pre-existing fractures. In the correct geologic environment, these fractures will tend to be critically stressed, and the stimulation process will open the fractures and induce shear along the fracture plane. This shear will cause fracture dilation and increased hydraulic permeability. This scenario obviates the need for proppant (solids injected to keep the fractures open).

Only a few attempts at EGS reservoir stimulation have employed proppants, and these attempts were not successful. In addition to previous operational problem, materials normally used as proppants may not be stable in geothermal environments. A major issue is identification of a proppant material that won't be destroyed by geothermal fluids. Also, a method is needed to allow injection of the proppant hundreds of meters into the fracture network. For these reasons, the use of proppants has been dismissed in EGS development, but given how limited experience with proppants is, their dismissal may be premature.

Underreamers and Rock Reduction

Underreamers will be required if expandable tubulars and/or low clearance casing designs are to be employed in EGS well construction. Underreaming in high-strength rock is a major technical challenge. Underreamers available today focus on low strength formations, generally employing polycrystalline diamond compact (PDC) cutters although some rollercone underreamers do exist. This enabling technology is not generally available for geothermal applications. Expandable percussion drills may be an option for underreaming that would work in geothermal wells.

The bits available to the geothermal industry are mostly old designs, since the industry constitutes a niche market for drilling bits. Geothermal industry demand has not had an effect on bit development, and the O&G industry has never needed large high-temperature bits, so the bits are very expensive (for example, a 26-inch high performance fixed cutter bit can cost $65,000.) Since the performance advantage of fixed cutter bits has not been demonstrated in geothermal environments, they are currently considered to be too economically risky. No market for bits tailored to geothermal drilling exists, but industry interest could be (and has been) motivated through partnerships with governmental programs.

While mud motors are being used in geothermal environments, turbines may hold more promise, since they have fewer elastomeric components and have been demonstrated in high-temperature drilling. The issue with turbines is that they rotate at high RPMs and are generally not suitable for use with roller bits now used in geothermal drilling; they are generally used with diamond impregnated or hybrid PDC/impregnated type bits. Industry efforts in speed-reducing transmissions (to allow roller cone bit use) or alternative bit designs should be assisted.

DOE has funded development of no-contact systems such as flame-jet spallation, high pressure abrasive water jets, and other hybrid methods such as cavitating mud jets to augment the rock reduction process. Other methods such as particle impact drilling may hold promise. These alternative rock reduction technologies may provide a research pathway for reducing drilling cost.

AGENDA
U.S. Department of Energy
EGS Reservoir Well Construction Workshop
Sheraton, Houston Airport October 16, 2007

The objectives of the workshop are to provide participants with a brief overview of geothermal well construction operations and to define technology needs and pathways to advance geothermal well construction to allow economic development of enhanced geothermal systems.

Invited speakers will provide a framework for open discussion by the audience, with the session chair acting as facilitator. Audience members will be permitted to expand, rebut or make their own point with an impromptu mini-presentation of less than 5 minutes. A lap top computer with PowerPoint will be available.

Time	Session	Chair	Speaker	Topics
7:15-8:00 am	Continental Breakfast			
8:00-8:20 am	**Introductions and Opening Remarks**		Allan Jelacic	Overview of EGS
8:20-8:40 am	**Previous Workshops**	Mack Kennedy	Gerry Nix	A brief overview of previous workshops
8:40-9:30 am	Open Discussion			
9:30-9:50 am	Break			
9:50-10:30 am	**Geothermal well drilling. Issues and economic drivers? Does a Generic EGS Well Exist?**	Doug Blankenship	Chip Mansure and Bill Livesay	Why geothermal drilling is different – Issues associated with traditional Geothermal Drilling Possible range of EGS well development (shallow/deep, basement/sedimentary, single well/multilateral)
10:30-11:30 am	Open Discussion			
11:30am -12:30 pm	Lunch			
12:30-12:50 pm	**Tool and Equipment Requirements**	Carol Bruton	Randy Normann	High-temperature tools, down hole pumps and equipment – well diagnostics and intervention hardware and tools - drilling systems
12:50-2:00 pm	Open Discussion			
2:00-2:20 pm	Break			
2:20-2:40 pm	**State of the Art and Predictions of the Future**	Joel Renner	Mike Payne	Where is O&G today and what will they be doing in the future. Drilling/completions/ operation/interventions
2:40 – 3:40pm	Open Discussion			
3:40-4:50pm	**General Discussion**	Facilitated by Clay Nichols		Technology gaps/barriers, technology development paths, synergy with other industries
4:50-5:00pm	**Closing**	Allan Jelacic		

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Firms Represented:

Schlumberger
Humboldt Drilling and Pump Company
Thermasource
ConocoPhillips
BJ Services
Novatek
Baker-Hughes
GeothermEx, Inc.
Ormat
ExxonMobil Upstream Research Company
British Petroleum (BP)
Hughes Christensen
Maurer Enterprises
Baker Oil Tools
Chevron Energy Technology Company
Potter Drilling LLC
Technology International

Academic:

Stanford University
Texas A&M
Houston Advanced Research Center