Research and Development in Geothermal Exploration and Drilling

Source: GEA

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Preface

In November of 2009 the Electric Power Research Institute (EPRI) and Tri-State Generation and Transmission Association, Inc. invited the Geothermal Energy Association (GEA) to participate in a Geothermal Power Summit it was holding in Westminster, Colorado. The proposed theme for the summit was research and development (R&D) needs in the geothermal energy industry. GEA was asked to specifically address R&D needs in geothermal exploration and drilling.

Recent developments in the geothermal industry call for additional articulation of the subject of R&D and GEA has decided to write a paper, to parallel its presentation at the summit, addressing challenges and opportunities in geothermal exploration and drilling technologies. The awarding of approximately $338M from DOE's Geothermal Technologies Program to various organizations in the industry for the further development of geothermal technologies has been a significant development in the industry's R&D efforts. In addition to providing an overview of current exploration and drilling technology this paper identifies the need to stay abreast of recent technology research and development, especially that occurring under the American Recovery and Reinvestment Act (ARRA) awards. Thus, ARRA awardees developing or testing corresponding exploration and drilling technologies are identified throughout this paper.

This paper is not an exhaustive listing of every geothermal exploration and drilling technology and their attendant R&D needs. Its purpose is to provide an introduction of present technologies and current R&D efforts and opportunities in order to provide a starting point for additional monitoring of exploration and drilling technology progress.

Acknowledgements

This paper would not have been possible without the guidance and input of a number of people within the geothermal industry. First of all, I would like to thank Karl Gawell for the opportunity he provided for me to work on this report. I would like to thank my coworkers at GEA (Kathy Kent, Leslie Blodgett, Daniela Stratulat, and John McCaul) for helping to provide a supportive environment in which to work.

I would like to thank the following people for their guidance via research discussions, phone interviews, and review of the paper at various stages: Ann Robertson-Tait, GeothermEx; Clay Nichols; Joel Renner; John Pritchett, SAIC; Lou Capuano Jr., ThermaSource, Inc.; Doug Blankenship, Sandia National Labs; Mack Kennedy, Lawrence Berkely National Laboratory; Lisa Shevenell, John Louie, and Greg Arehart, The Mackay School of Earth Sciences and Engineering, The University of Nevada, Reno; Roy Mink, U.S. Geothermal; Malcolm Ward, Geothermal Advisory Pty Ltd; Dan Fleischmann, Ormat Technologies, Inc.; Stuart Johnson, Ram Power, Corp.; Joe Moore, Energy and Geoscience Institute, University of Utah, Hildigunnur Thorsteinsson, DOE Geothermal Technologies Program.

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1. Introduction

A significant amount of the financial risk associated with geothermal power development results from uncertainties encountered in the early stages of resource development; namely geothermal exploration and the drilling of production wells. Costs associated with the exploration and drilling stages of a geothermal project can account for at least 42% of overall project costs.[1] While current exploration and drilling technologies and practices are somewhat effective, opportunities to significantly improve upon conventional technology as well as develop more advanced "revolutionary" exploration and drilling tools exist. Increased research and development (R&D) that is focused on improving current conventional exploration and drilling technologies in the near term as well as bringing "breakthrough" technologies will help to establish a strong geothermal industry base and improve project economics.

Success in initial geothermal exploration directly influences success in geothermal drilling operations. Geothermal developers depend upon exploration of surface features to determine first; whether or not a resource is worth the large amount of investment required to drill a geothermal well, and second; where to place a drill rig so as to reach an optimal target depth, permeability and resource temperature. Once surface features have been investigated, several techniques are used to help identify drill targets without having to put a drill bit into the ground. These exploration technologies not only need to better locate geothermal resources but they must be able to provide more accurate imaging of the structure of the subsurface reservoir and provide accurate reservoir temperatures at specified depths. In order to better locate geothermal resources improved remote sensing technologies are necessary. The development of more reliable geothermometers with the ability to detect soil/water gases or dissolved minerals and isotopes would improve geochemistry information gleaned in the exploration phase. The increased resolution and reliability of geophysical surveys would provide a much needed improvements in imaging subsurface geothermal reservoirs.

Significant improvements in conventional geothermal drilling and well development techniques are achievable in the near term. Building upon incremental improvements in polycrystalline diamond compact (PDC) technology could result in the implementation of PDC drill bits in geothermal drilling practices. Additional improvements in drilling technology that produce drill bits that will drill for longer periods of time without breaking down are needed. Developing casing techniques and technologies that reduce the number of casing strings needed to line a well merit more R&D. The increased development of geothermal resources will require subsurface development to take place at depths of significant temperature and pressure. The development of drilling materials and tools capable of withstanding higher down-hole temperatures and pressures for long periods of time is an important technological advancement needed to improve drilling success rates.

Geothermal exploration and drilling technologies, while currently adequate, present a unique opportunity. R&D resources, properly allocated to the advancement of conventional exploration and drilling technologies, will result in important and

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[1] Department of Energy Geothermal Technologies Program. *National Geothermal Action Plan.* (Draft). 2009. (http://www1.eere.energy.gov/geothermal/pdfs/ngap.pdf)

substantial gains. The same technological issues facing increased enhanced geothermal systems (EGS)[2] development are typically the same obstacles facing conventional hydrothermal technologies. Therefore, geothermal R&D should be focused on developing technologies that will help create a robust industry base centered on near-term conventional resource development as well as developing "breakthrough" technologies that will continue to expand the geothermal resource base beyond conventional hydrothermal.

[2] Enhanced geothermal systems are geothermal reservoirs that have been engineered to produce electricity from low permeability and/or porosity geothermal resources. This is done by pumping water down an injection well and into hot rock which has been artificially fractured. The water is then brought back to surface, once it has been heated, for utilization in a geothermal power plant. Taylor, Mark. *The State of Geothermal Technology, Part I: Subsurface Technology.* GEA. November, 2007.

2. Exploration Technologies

Prior to constructing a geothermal power plant and delivering power to the electrical grid a series of steps must be taken by a geothermal developer to ensure the successful completion of a geothermal development project. The first of these steps is conducting a thorough exploration program of any given geothermal resource site.

The only means by which a developer can know for certain whether or not their geothermal site contains an economic resource is to drill at least one full size production well.[3] However, drilling a production well is costly. Most developers will drill their first production well only after a complete exploration regimen has provided enough information to ensure some degree of confidence of reaching a specific reservoir temperature, at a specific depth, with adequate flow rates. The exploration regimen consists of a combination of geological, geochemical, and geophysical surveys, all of which are designed to provide increased rates of success in drilling the initial production well.

The exploration and drilling phases of developing a geothermal resource are often compared to those of the oil and gas industry. However, while some of these techniques may be useful in geothermal exploration, the subsurface characteristics of geothermal resources can significantly limit their effectiveness.[4] At the same time, as the oil and gas industry has had to locate resources in geological regimes more similar to geothermal (i.e. oil or gas shale), and opportunities for technology transfer between the industries may soon be possible.[5]

There is no panacea for increased success in geothermal exploration. Exploration needs vary on a global and regional scale. Areas for drilling are more broadly defined in the United States than in a country like Australia where geothermal exploration activities are very much in their infancy.[6] Even within the United States regions such as the Cascades in the Pacific Northwest have undergone less exploration than the Great Basin region and merit a different approach due to geographic differences and other extrinsic factors. As such, varying exploration needs require an open minded approach to future research and development.

Future research and development in exploration stage technologies should focus on those factors that affect project success rates regardless of extrinsic factors. It is certain that the success of initial production well construction is directly related to the quality of previously conducted exploration. While there is no substitute for the information gleaned and the confidence gained from drilling an initial production well exploration technologies and practices will certainly need to be improved in order to ameliorate the up front risk associated with the high costs of geothermal drilling.

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[3] Additionally, in developing an EGS resource the resource must be properly "fracked" to see if it will flow successfully. Ward, Malcolm. Personal communication.

[4] Geothermal systems are often more complex than oil and gas resources. A geothermal reservoir is network of fractured rock through which fluid percolates. Fluid fractures can be small – inches wide and over a mile deep, making it difficult to locate and drill to. Taylor, Mark. *Ibid.*

[5] Nichols, Clay. Personal communication.

[6] Ward, Malcolm. Personal communication.

Technology Overview

In order to better identify research and development needs in geothermal exploration commonly used technologies must be identified. While breakthrough technologies will certainly make an impact on exploration success in the future improvements to current technologies and techniques used within the geothermal industry as well as others will make a significant contribution to the increased development of conventional hydrothermal and EGS resources.

Remote Sensing Technologies

Many geothermal resources exhibiting clear surface manifestations (i.e. hot springs) have already been located. The majority of future geothermal megawatts will come from resources that exhibit more subtle surface features such as altered rock, salt crusts/evaporites, tufas, travertines, sinter, and opal. These features are usually detectable over large areas using remote sensing techniques.[7]

Remote sensing is usually conducted by satellite or airborne observation which uses sensors to detect different wavelengths of light to differentiate between different rock types. The main advantage of conducting a remote sensing survey is that it can be done prior to initiating the expensive and lengthy procedure of obtaining the land rights to a resource. Thus remote sensing is an important "first step" in the exploration process.[8]

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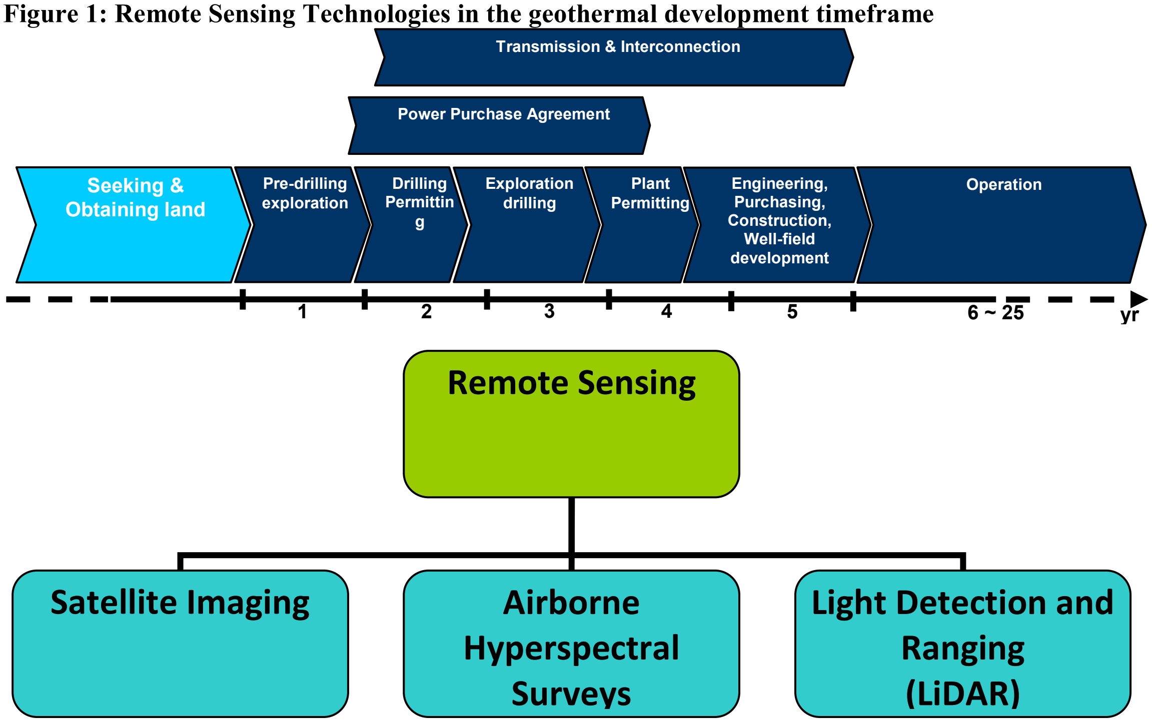
[7] Taylor, Mark. *The State of Geothermal Technology, Part I: Subsurface Technology.* GEA. November 2007.
[8] Taylor, Mark. *Ibid.*

Figure 1: Remote Sensing Technologies in the geothermal development timeframe



Source: GEA

Remote sensing technologies are not without their challenges. Satellite imaging usually covers a larger area at a lower cost than airborne hyperspectral surveys and is a good remote sensing option when surveying larger regions. However, airborne hyperspectral surveys typically produce greater spatial and spectral imaging of surface indicators and are usually optimal in more site specific remote sensing operations.[9]

Despite small setbacks in cost and imaging resolution remote sensing technology is advancing rapidly. One possible advancement in the remote sensing is the possibility of combining thermal infrared technology with a hyperspectral survey to image surface heatflow in addition to detecting different light wavelengths.[10] Another possible development in remote sensing technologies used in geothermal development is the implementation of Light Detection and Ranging (LiDAR) technology. LiDAR scans are a potentially cost effective way[11] to obtain highly detailed topographical maps of a resource area in order to detect recent changes in areas topography resulting from fault offsets. The Department of Energy recently decided to fund a number of geothermal exploration projects utilizing thermal infrared and LiDAR remote sensing technologies and there is a renewed interest in the technology in Australia.[12]

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[9] Taylor, Mark. *Ibid.*
[10] Taylor, Mark. *Ibid.*
[11] Burtch, Robert. *LIDAR Principles and Applications.* Ferris State University. 2002. (http://www.ferris.edu/faculty/burtchr/papers/lidar_principles.pdf)
[12] Department of Energy, Geothermal Technologies Program. *GTP Research and Development Projecs by Awardee.* (http://apps1.eere.energy.gov/geothermal/projects/by_awardee.cfm). Ward, Malcolm. Personal communication.

Table 1: Comparison of Remote Sensing Technologies

Technology	Advantages	Obstacles
Satellite Imaging	Covers large area Less expensive	Reduced spatial and spectral resolution
Airborne Hyperspectral	Higher spatial and spectral resolution	More expensive Covers smaller area
LiDAR	Can penetrate dense vegetation Data layers are easy to integrate in a GIS	Processing data requires specific skill sets and software

Source: GEA

The following table lists ARRA awardees receiving funding for projects employing advanced remote sensing technologies in geothermal exploration.

Table 2: List of ARRA awardees utilizing remote sensing technologies

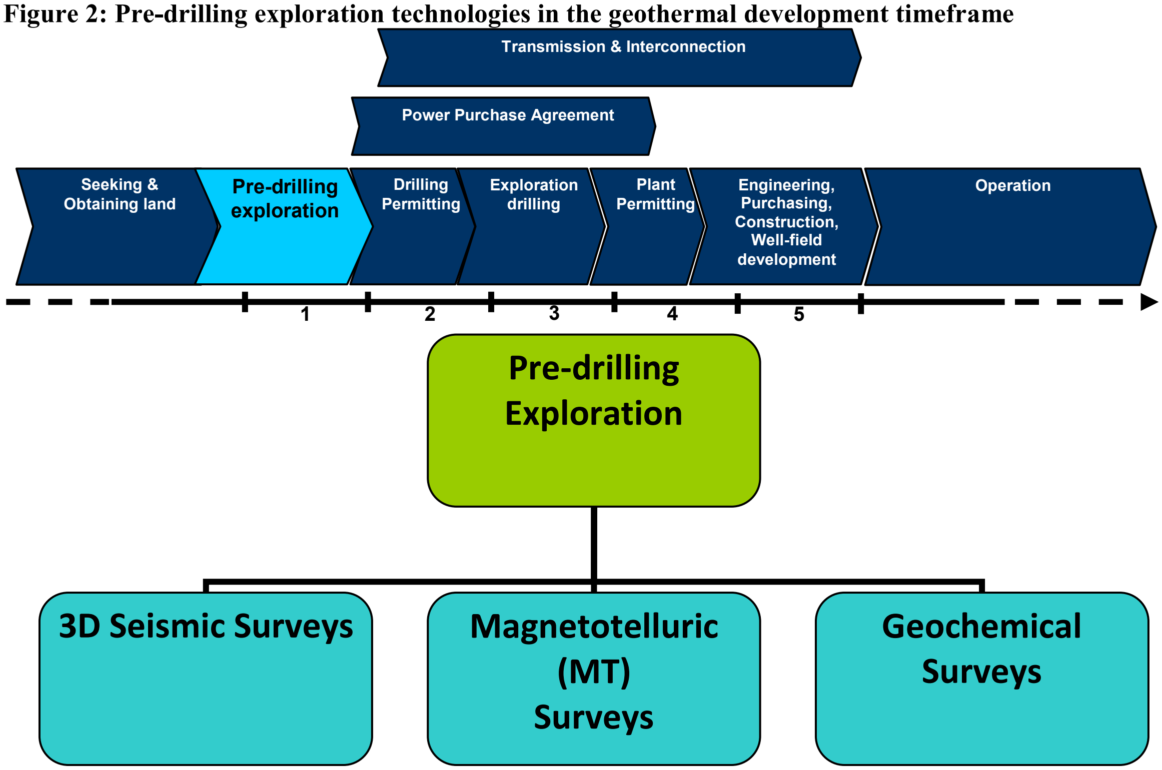
Awardee	Amount ($)	Location
Flint Geothermal	4,778,234	CO
Ormat	4,377,000	Glass Buttes, OR
University of Alaska	4,616,879	Pilgrim Hot Springs, AK
Sierra Geothermal Power	5,000,000	Alum, NV
Vulcan Power Company	3,825,973	Colado, NV
GeoGlobal	4,040,375	Gabbs Valley, NV
Sierra Geothermal Power	5,000,000	Silver Peak, NV
Surprise Valley Electrification	2,000,000	Paisley, OR
Total	**33,638,461**	

Source: GEA, DOE

Geochemical Technologies

Geochemical, along with geophysical and other pre-drilling exploration methods, are initiated upon the obtaining of land rights. If conducted previously they are typically continued after a developer gains access to the geothermal resource.

Figure 2: Pre-drilling exploration technologies in the geothermal development timeframe



Source: GEA

An important issue in developing geothermal resources is how to determine how hot the resource might be at depth without drilling? Fortunately, minerals and springs on the surface can indicate the temperatures below necessary to create those mineral properties. The underlying assumption of geochemical analysis in geothermal exploration is that surface manifestations of geothermal fluids can provide information on temperature and physiological conditions in the subsurface geothermal reservoir. Obtaining this information is accomplished by using geothermometers that are based on the relative amounts and ratios of various elements or isotopes in the water. The levels of these elements within the geothermal fluid and with respect to each other provide insights into the geothermal reservoir temperature. Geochemists will gather and interpret data points from multiple geothermometers in order to make the most reliable subsurface temperature estimates.

Some technologies and techniques which could be further developed to improve geochemical exploration are soil and gas geochemistry and rare earth element (REE) geochemistry. Soil and gas geochemistry entails the placement of detectors in or on the ground to detect gases (such as mercury or carbon dioxide) associated with geothermal reservoirs at depth. Background calibrations for local conditions must be taken into account and sometimes detectors must remain in the ground for months to obtain useful data. The advantage of soil and gas geochemistry is that it can be used to locate information on hidden geothermal systems. More advanced technology is enabling the use of REE geochemistry in geothermal exploration. Modern ultra-low-level measurement techniques enable geochemical explorers to measure elements associated with geothermal activity that were previously below the levels of analytical detection.

The development and implementation of new types of geothermometers such as the use of nitrogen isotopes, would add another data point with which to estimate resource temperatures.

Surface manifestations of geothermal fluid are not necessarily required to perform geochemical analysis. Occasionally, upwellings of geothermal fluid that have since dried out will leave traces of evaporites such as boron-bearing salts. These evaporites can sometimes be located with exploration technologies such as remote sensing.[13] Table 3 provides a list of ARRA awardees conducting projects with identified geochemical components.

Table 3: List of ARRA awardees utilizing geochemical exploration technologies

Awardee	Amount ($)	Location
NGP Company	1,597,847	Black Warrio, NV
El Paso County	5,000,000	El Paso, TX
Newberry Geothermal	5,000,000	Newberry, OR
Ormat	4,911,330	Maui, HI
AltaRock Energy	1,450,120	Dixie Valley, NV
Total	**17,959,297**	

Source: GEA, DOE

Geophysical Technologies

Geophysical technologies can also provide clues as to what is happening in the subsurface. Rather than identify potential temperatures, geophysical techniques provide indications of the structure of subsurface geology and how those structures can be drilled to bring hot water from the geothermal aquifer to the surface. Combined with geochemical studies, geophysical analysis seeks to identify temperatures, permeability, and the orientation of fractures at depth. While the oil industry has found 3D Seismic Tomography to be extremely effective in locating subsurface oil and gas plays, no such geophysical "silver bullet" currently exists for the geothermal industry. Rather, geothermal developers will employ various studies from a suite of geophysical exploration methods to better understand a geothermal reservoir prior to drilling.

The combination of geophysical survey methods employed in an exploration program are dependent on intrinsic (i.e. local geology, hydrogeochemistry) and extrinsic (local weather, economic, and land issues) factors. As such, some methods will be more effective in certain resource areas than others, guaranteeing their widespread use. Still, certain geophysical technologies are more widely used than others and incremental improvements in their technology or use could yield improved exploration success rates. Please see Table 1A in the appendix for a more exhaustive list and description of available geophysical exploration methods.

[13] Arehart, Greg. Personal Communication

Seismic Imaging

Seismic-imaging surveys use explosive charges or man-made vibrations to direct waves into the subsurface at the location of a suspected geothermal resource. Waves that reflect off subsurface structural features are used to render a 3D image of the geothermal reservoir.

The oil and gas industry began to experience great success in using 3D seismic imaging in the 1990's. Currently few oil or natural gas wells are drilled unless a thorough seismic-imaging survey of the resource has been conducted. Seismic imaging had until the 1990s met with less success in the geothermal industry. Some experts in the geothermal industry have long asserted that rocks in geothermal reservoirs are too broken up for seismic waves to render a proper subsurface picture.

Overcoming past difficulties with obtaining subsurface imaging from seismic surveys in most geothermal prospects, the technology is being used successfully in areas such as Imperial Valley and Coso, Calif., and throughout central and western Nevada. Additionally, some experts believe that the industry is on the cusp of developing seismic-imaging technology that could significantly improve the economics of developing geothermal resources by providing a more accurate 3D model of subsurface geothermal reservoirs. Problems associated with imaging the broken-up subsurface reservoirs through seismic surveys have mostly been addressed. Current seismic-imaging research is focused on identifying the seismic attributes shown by geothermal systems. Current case studies and ARRA-funded projects will clarify the additional research needed to identify the seismic signature of geothermal reservoirs. Table 3 provides a list of ARRA awardees that involved a seismic-imaging component in their development projects.[14]

Table 3: List of ARRA awardees utilizing seismic imaging technologies

Awardee	Amount ($)	Location
Magma Energy	5,000,000	Soda Lake, NV
Ormat	4,475,015	Wister, CA
Oski Energy	4,214,086	Hot Pot, NV
Presco Energy	2,277,081	Rye Patch, NV
Pueblo of Jemez	4,995,844	Jemez Pueblo, NM
Pyramid Lake Paiute Tribe	4,845,534	Pyramid Lake, NV
Sierra Geothermal Power	5,000,000	Alum, NV
US Geothermal	3,772,560	San Emidio, NV
Utah State University	4,640,110	Snake River Plain, ID
Total	**39,220,230**	

Source: GEA, DOE

Other Geophysical Exploration Technologies and methods

While improved 3D seismic survey technology could significantly improve the success rate drilling initial production wells advances in other exploration technologies

[14] Louie, John. Personal communication.

are also available to geothermal developers. Gravity surveys consist of gravitational field measurements being taken at several prospect locations to identify the different density profiles of subsurface rock types and are especially important in delineating buried granites, an important component of EGS.[15] Airborne gravity gradiometry technology has been developed that allows for the measurement of gravity changes over large distances. This new development of gravity survey technology would aid in imaging of the subsurface landscape and the location of faults in a geothermal reservoir.[16] Lastly, magnetotelluric (MT) surveys can be used to locate higher conductivity associated with geothermal reservoirs at depths of 2 – 5 km. MT surveys have been used successfully in geothermal exploration and are important in EGS as well as conventional hydrothermal exploration.[17]

[15] Ward, Malcolm. Personal communication.
[16] Kohrn, Bruce. Personal communication
[17] Ward, Malcolm. Personal, communication.

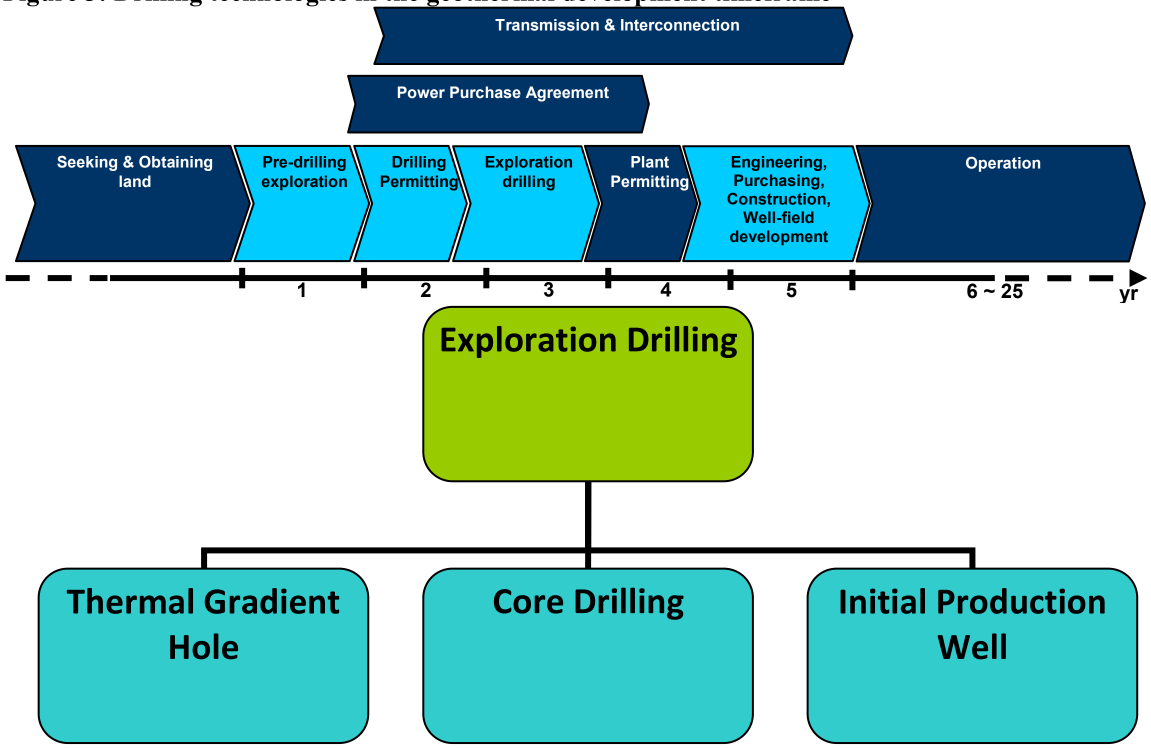
3. Drilling Technologies

Drillling at a geothermal prospect typically begins long before construction of the power plant is initiated. Thermal gradient holes (TGH) are usually drilled before drilling a deeper exploration hole (“slim hole”), which are then followed by drilling a full-scale production well in order to glean more information about the temperature of a geothermal reservoir at depth. In certain regions (such as Australia) developers will conduct shallow and intermediate cored drilling to obtain a temperature profile and measure thermal conductivity in order to estimate heat flow in areas where insufficient prior data exists.[18]

The drilling of the first production well at a geothermal resource is widely considered to still be an exploration phase activity. A prospect is usually not considered as being in the drilling phase until after at least one production well has been drilled successfully. The drilling of the first “wildcat” well has a success rate probability of approximately 25%. After the first production well is drilled success rates approach 60% to 80% during the resource confirmation and construction stages.[19] With production well success rates around 25% improvements in exploration technology that would give more information on resource temperatures at specific depths would directly influence drilling success. In other words, drilling success is directly correlated to exploration success. At the same time, the drilling of production wells accounts for a significant portion of project costs in geothermal projects.[20] Drilling and well construction technology improvements would go a long way to improving geothermal project economics. While breakthrough drilling technologies stand to impact industry operations in the long term there are still opportunities for significant evolutionary improvements to be made to conventional drilling technologies.

[18] Ward, Malcolm. Personal communication.
[19] Hance, Cedric Nathanael. *Factors Affecting Costs of Geothermal Power Development.* GEA. August, 2005.
[20] Exploration and production drilling can account for up to 42% of the total cost of geothermal development. Department of Energy Geothermal Technologies Program. *National Geothermal Action Plan.* (Draft). 2009. (http://www1.eere.energy.gov/geothermal/pdfs/ngap.pdf)

Figure 3: Drilling technologies in the geothermal development timeframe



Source: GEA

Thermal Gradient Holes

The drilling of thermal gradient holes (TGH) is an important step prior to drilling a production well. The drilling of a TGH may even precede some geophysical surveys. TGHs are shallow and narrow, and can be drilled quickly using a truck-mounted rig. TGH measure the gradient – i.e. the change in temperature vs. depth. A higher gradient indicates a greater temperature anomaly. The basic purpose of drilling a TGH is two fold. First, a TGH is designed to assess whether deeper temperatures in the geothermal reservoir will be hot enough to support commercial production. Second, a series of TGHs should also help to delineate a thermal anomaly and define the extent of the resource.[21]

In drilling a TGH, developers will first drill shallow holes to depths of 500 to 1000 feet. Once shallow holes have been completed the developer will attempt to drill to depths of 1000 to 4000 feet in order to penetrate the geothermal reservoir.[22] If this last step is successfully completed it will provide a wealth of information regarding the geothermal resource. As such, TGH are widely used, but the technology is not without its limitations. The depth to which a TGH can be drilled is often dependent on geologic and hydrologic conditions. For example, in some volcanic settings TGHs may have to be drilled to depths of thousands of feet because of thick "rain curtains". Drilling to such

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[21] Taylor, Mark. *Ibid.*

[22] The drilling of TGHs to depths of 1000 to 4000 ft. in order to penetrate the reservoir is common in EGS exploration. Ward, Malcolm. Personal communication.

depths in volcanic geology safely can become expensive to the point where a TGH may not be cost effective.[23]

Core Drilling

Core drilling or "slim-hole drilling" is a method of drilling in which a drill bit with a hollow center is used to extract cylinders, or 'cores', of rock. Core drilling is sometimes used in the drilling of production wells as the well bore is drilled to greater depths. The cores that are recovered are analyzed in order to better understand subsurface geology and locate fractures within a particular resource. Coring bits are also sometimes used when drilling in loss of circulation zones.[24]

Geothermal developers in certain regions rely more heavily on core drilling to help delineate a geothermal resource. Many geothermal developers in Australia, for example, use broad spaced, shallow core drilling methods (<500m) to measure temperature profiles and thermal conductivity to calculate heat flow where prior data from oil and gas drilling is not adequate. Intermediate depth (up to 2 km) core drilling can also be used to obtain information on insulating sediments and thermal properties of a suspected geothermal resource in order to better constrain the estimation of temperature at reservoir depth. Using core drilling as an exploration technique is very expensive especially at intermediate depths. Some experts in the global geothermal industry cite improving the ability to drill core holes to depths of 2km and greater as a significant opportunity to improve exploration and drilling technologies.[25]

Table 4: Advantages and Obstacles in Slimhole Core Drilling

Technology	Advantages	Obstacles
Slimhole Core Drilling (3-4" diameter)	• Greater understanding of subsurface geology and fractures • Less expensive than drilling production wells	• Depth limits (~2.5km), 3-5 km needed • Difficult to control as depth increases • Too small to allow for current down-hole logging and pump systems

Source: GEA

Production Well Drilling

The drilling of production wells represents the transitional step from the exploration to the drilling and construction phase of developing a geothermal resource. However, this step is only complete once a production well is deemed successful. For this reason a significant emphasis is placed upon improving exploration technologies in order

23 Taylor, Mark. *Ibid.*

24 Taylor, Mark. *Ibid.*
25 Ward, Malcolm. Personal communication.

to improve drilling success rates. At the same time, opportunities for the technological improvement of drilling technology abound and could significantly improve costs associated with drilling regardless of exploration success.

A number of factors affecting the cost of drilling in geothermal operations exist and they vary from resource to resource. The following technologies would address issues associated with rates of penetration, reduced trip-time, and high down-hole temperatures.

Injection Well Drilling

In order to complete the confirmation of a geothermal field, injection wells must be drilled in order to return hot water from the production zone back into the ground and into the geothermal aquifer. A geothermal resource cannot be fully confirmed until this process is completed to demonstrate that an underground plumbing system can be created to fuel a power plant sustainably over time.[26]

Drilling bits

Costs associated with geothermal drilling are largely a function of depth which directly influences the time spent drilling.[27] Increasing the rate of penetration (ROP) in production well construction would significantly improve project economics.

Due to the hard rock formations encountered in geothermal drilling, drilling contractors typically use rotary cone bits that grind and crush rock. While rotary cone bits have been sufficient to drill production wells to date, other conventional drilling technologies as well as potential "breakthrough" technologies could potentially be implemented into geothermal drilling to increase ROP. The diamond PDC drill bit is commonly employed oil and gas operations with success and is viewed as inherently more efficient than rotary cone bits. Some experts have estimated that PDC bits have an ROP twice that of rotary cone bits and that their implementation could eliminate as much as 15% of geothermal well development costs.[28] However, PDC bits are sensitive to bit vibration, a problem in geothermal well drilling associated with increased depths and the hard-crystalline environments of geothermal reservoirs. Also, in geothermal drilling operations conditioned "mud" is circulated through the bore-hole in order to cool and lubricate the drill bit as well as to deliver rock cuttings to the surface. Currently, diamond PDC bits do not have a proper circulating media for cooling during drilling.[29] While these have proven to be obstacles to the implementation of PDC bits into the geothermal industry some experts feel that PDC bits are on the verge of being ready for

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[26] Taylor, Mark. *Ibid.*
[27] Hance, Cedric Nathanael. *Ibid.*
[28] Green, Joe. *New PDC bit cutters improve wear life and ROP.* Schlumberger. (http://www.iadc.org/dcpi/dc-jan-feb02/j2-pdc.pdf)
Hoch, G. Jeffrey. *Is There Room for Geothermal Energy?* Innovation: America's Journal of Technology Commercialization. January, 2007. (http://www.innovation-america.org/archive.php?articleID=215)
[29] Mansure, Chip., Capuano, Louis Jr. *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report.* 2008.

implementation in geothermal drilling operations. Additionally, PDC bits are a conventional drilling technology requiring minor "evolutionary" improvements to get them "geothermal ready" in a relatively short amount of time.

Other drilling technology breakthroughs also hold potential to significantly improve ROP in geothermal drilling and associated project costs. Hydrothermal spallation utilizes water at high heat and pressure instead of a conventional drill bit to drill through hard igneous rock. The induced temperature caused by the introduction of super heated water into the well causes the subsurface rock at the bottom of the well to expand, crack, and flake off. Because there is little or no mechanical contact with the actual rock in the well, drill bit wear is significantly reduced which in turn reduces the amount of time needed to change worn out bits. Hydrothermal spallation technologies have been shown to have an ROP of 50 ft/hour in the lab[30] and are could cut drilling costs by as much as 50%.[31]

Table 5: Advantages and Obstacles of diamond PDC and hydrothermal Spallation Technologies

Technology	Advantages	Obstacles
Diamond PDC bits	• Up to twice the ROP of rotary cone bits • Reduce drilling costs • Consistently improved in analogous industries	• Sensitive to bit vibration as well bore depth increases • Lack a proper circulating media
Hydrothermal Spallation	• Significantly increased ROP than conventional technologies • Reduced bit wear	• Not yet proven outside of the lab • Water consumption?

Source: GEA

High Temperature Technologies

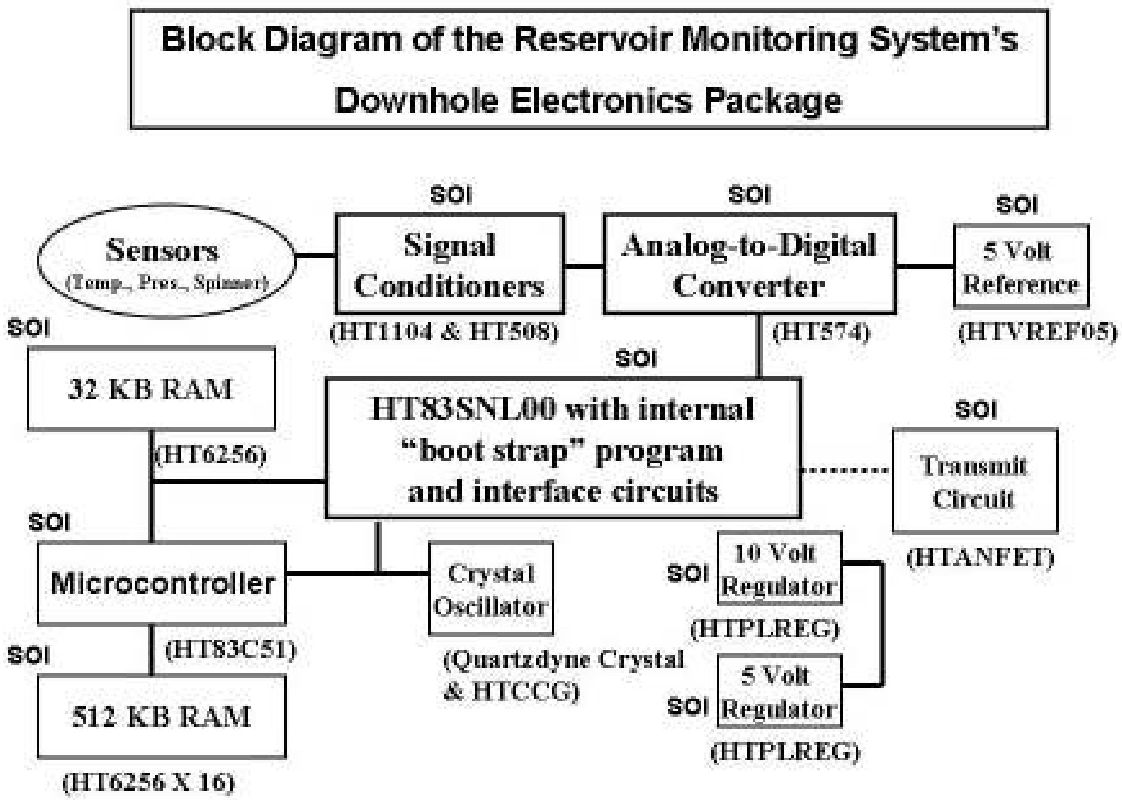
There are number of applications for high temperature drilling technologies in drilling geothermal production wells. For example directional drilling is used widely in the oil and gas industry. Undoubtedly, increased directional drilling capabilities would benefit conventional hydrothermal drilling in the geothermal industry. Additionally, if EGS resources are to be developed increased directional drilling capabilities in geothermal operations is a must. However, in order for directional drilling tools to be of use they must be able to operate in high temperature and hard rock formations of geothermal reservoirs. Directional drilling has been employed with some success in geothermal operations and according to some contractors current success rates of directional drilling in geothermal are directly related to the ability to cool electronic

[30] Department of Energy, Geothermal Technologies Program. *GTP Research and Development Projecs by Awardee.* (http://apps1.eere.energy.gov/geothermal/projects/projects.cfm/ProjectID=143)
[31] Pruitt, Alison. *Reducing the Costs of Geothermal Energy with Hydrothermal Spallation Drilling.* September 21, 2009. (http://www.energyboom.com/geothermal/reducing-cost-geothermal-energy-hydrothermal-spallation-drilling)

directional components via mud circulation.[32] While this has worked in some applications the development of downhole electrical components with higher heat tolerances are integral to increasing directional drilling.

Directional drilling is just one of many examples of downhole technologies that could see increased use in geothermal well construction given the development of higher heat tolerances in downhole technologies. A report by Sandia National Labs and drilling contractor ThermaSource identified high downhole pumps, zonal isolation tools, and telemetry capabilities as technologies whose increased use in geothermal operations is predicated on the development of high temperature technology. The report also identified list of baseline tools and components that must be developed to support opertions in downhole environments.[33]

Figure 4: Typical Downhole Tool Architecture



Source: Sandia National Labs, ThermaSource, Inc.

Recent industry developments indicate that developers and government organizations understand the overarching need for drilling technology to be able to operate in high temperatures. Table 6 lists recent ARRA awardees developing high temperature technologies in their projects.

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[32] Mansure, Capuano. *Ibid.*
[33] Mansure, Capuano. *Ibid.*

Table 6: List of ARRA awardees utilizing high temperature technologies

Awardee	Application	Amount ($)	Location
GE Global Research	Directional Drilling	3,439,991	Niskayuna, NY
Honeywell International	Directional Drilling	3,960,000	WA, MN, CA
Baker Hughes	Directional Drilling	5,000,000	The Woodlands, TX
Schlumberger	Downhole Tools	4,731,449	Rosharon, TX
Draka Cableteq	Downhole Cables	3,222,398	North Dighton, MA
Composite Technology Development	Circuit Boards	557,150	Lafayette, CO
Trabits Group	Cements	2,154,238	AK, CA, NV
Total		**23,065,226**	

Source: GEA, DOE

Well Casing Technologies

During the drilling of a production well the geothermal drilling contractor will extend metal casing down the length of the well bore and secure it by cementing the area between the casing and the wellbore wall.[34] Installing casing in a geothermal well serves a number of purposes including the prevention of wellbore collapse, the containment of well fluids, prevent the contamination of surface aquifers, and to counter loss of circulation during drilling. However, as a well is drilled deeper its diameter must decrease in order to protect it from potential collapse. The installment of metal casing and cement aids in preventing collapse from occurring but also lends to decreased well diameters as depths increase. However, this telescoping effect also necessitates the frequent replacement of larger drill bits with smaller ones that fit the smaller diameters of the well.

Expandable liners are a technology capable of addressing the telescoping issue. By inserting an expandable liner into a deep wellbore and then expanding and cementing it to fit the diameter of wellbore contractors can feasibly conserve the size of the wellbore, thus reducing the number of bit changes.[35] Another well casing method with potential to reduce project costs is to use casing drilling to install well casing as a wellbore is drilled. Such a technique would significantly reduce bit tripping time and thereby improve project economics. Lastly, the development of steel casings that are more versatile regarding how they interact with geothermal fluids of varying geochemical composition is also important to the further development of geothermal resources.[36]

[34] Taylor, Mark. *Ibid.*
[35] Mansure, Capuano. *Ibid.*

[36] Ward, Malcolm. Personal communication.

4. Conclusion

The geothermal exploration and drilling technologies outlined in this paper are by no means exhaustive. The potential technological improvements possible in the geothermal industry are many and documenting them would require an effort beyond the scope of this paper. Understanding the basic exploration and drilling technologies and the challenges they face is a necessary first step to developing technological improvements that will improve the industry's ability to bring more geothermal electricity to the grid.

Exploration technologies are typically less expensive than technologies associated with well construction. However, with the initial production drilling success rates currently at ~25% it is imperative that exploration technology be able to direct drilling contractors to the optimal locations to ensure drilling success. Drilling success cannot occur in a vacuum independent of exploration success. Thus, improvements in exploration technology will result in improvements in drilling success rates.

The research and development opportunities in geothermal exploration and drilling technologies are many as evidenced by the recent DOE ARRA awards. Future R&D should continue to focus on evolutionary improvements to conventional technologies as well as "breakthrough" technologies. Improvements in conventional hydrothermal technology will translate into improvements in EGS technology with the reverse also being true.

5. Appendix

Table 1A: Geophysical Exploration Technologies

Method	Characteristics:
Magnetotellurics (MT)	• Measure subsurface electricity created by naturally occurring magnetic fields • Indirectly detects temperature and permeability patterns by imaging the resistivity pattern associated with temperature-sensitive clay alteration • Can measure tens of kilometers deep • Can be used to develop 3D images of subsurface • Very commonly used • Cost-effective
Controlled Source Audio-Frequency Magnetotellurics (CSAMT)	• Similar to MT, but uses a man-made signal source • Lower cost than MT and works near power lines • Used for measurements of relatively shallow depths: 20-2000m
Time Domain Electromagnetics (TDEM)	• Electrical signal from artificial circuit placed on surface creates magnetic field over time • TDEM has no static distortion, unlike MT, CSAMT, E-Scan and all other techniques that use electrodes
DC Resistivity, Electrical Resistivity, Schlumberger, Vertical Sounding (VES)	• Electrical currents are sent into the subsurface creating voltages by which resistivity and its inverse, conductivity, can be measured • Resistivity depth is directly proportional to distance between surface electrodes • Resistivity methods are widely used
E-Scan	• E-Scan is somewhat commonly used and relatively new proprietary method of DC resistivity • Not always cost-effective, especially for large prospect areas
3D Seismic Tomography	• Seismic waves are directed into the subsurface. Waves that are reflected off of subsurface structural features are recorded, rendering a 3D image of the subsurface. • Used commonly in geothermal • Few well targeting success case histories are published

	• Among the more costly geophysical surveys
Self-Potential (SP)	• Electrodes placed in contact with surface at a number of survey stations—from these stations measurements of natural subsurface electrical potentials are taken. • Most useful when shallowest groundwater flow is of interest • Relatively inexpensive
Induced Polarization (IP)	• Direct current is run between electrodes placed in contact with the surface. When shut-off, measurements are taken of residual conductivity • IP data difficult to interpret over most geothermal fields
Aeromagnetics	• Detection instrumentation is flown over a given area in equally spaced flight lines—subsurface magnetic fields are recorded. • Detects demagnetization related to low temperature geothermal alteration • Currently some problems with noise from lava flows (when done in volcanic regions) • Data already exist and are available for much of the US • Can do without land ownership
Paleomagnetics[i]	• Small cores of rock are drilled and subjected to intensive analysis using instrumentation that measures variation (rotation) of the magnetic field as chronicled in rocks • Used to locate dilations in crust which are used to predict possible geothermal resources
Synthetic Aperture Radar (InSAR)[ii]	• Detection instrumentation is flown over a given area in equally spaced flight lines on two different dates—detects subsidence and inflation due to changes in reservoir (usually from pumping)—measures contraction caused by cooling of rock or volume change. • Contraction data then used to map prospect • Works well in arid regions and pine forests • Can do without land ownership
Gravity	• Gravitational field measurements are taken at several locations on prospect—varying subsurface rock types are identified based on different density profiles • Used to render structural image of subsurface landscape

	• Relatively inexpensive

Source: GEA

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[i] Faulds, J., personal communication. Cited by Taylor, M. in *The State of Geothermal Technology, Part I: Subsurface Technology.* November, 2007.
[ii] Oppliger, G., personal communication. Cited by Taylor, M. in *The State of Geothermal Technology, Part I: Subsurface Technology.* November, 2007.