PROCEEDINGS, Thirty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 9-11, 2009
SGP-TR-187

ENHANCED GEOTHERMAL SYSTEMS (EGS) WELL CONSTRUCTION TECHNOLOGY EVALUATION SYNOPSIS

Yarom Polsky[1], A.J. (Chip) Mansure[1], Douglas Blankenship[1], Robert J. Swanson[2] and Louis E. Capuano, Jr[2]

[1]Geothermal Research Department
Sandia National Laboratories
PO Box 5800, MS 1033
Albuquerque, NM 87185
e-mail: dablank@sandia.gov

[2]ThermaSource, Inc.
3883 Airway Dr. Suite 340
Santa Rosa CA 95403

ABSTRACT

A synopsis of a report evaluating well construction technology for Enhanced Geothermal Systems (EGS) is presented. The assessment of well construction technology had two primary objectives:
1. Determining the ability of existing technologies to develop EGS wells.
2. Identifying critical well construction research lines and development technologies that are likely to enhance prospects for EGS viability and improve overall economics.

Towards these ends, a methodology was followed in which a case study was developed to systematically and quantitatively evaluate EGS well construction technology needs. This paper provides an overview of the analysis and highlights key findings.

INTRODUCTION

The concept of Enhanced Geothermal Systems (EGS) has long been recognized by geothermal energy experts as being the necessary technology for substantially increasing the contribution of geothermal energy to the nation's production of domestic electricity. This belief has been further bolstered recently by the 2006 DOE sponsored study led by MIT entitled "The Future of Geothermal Energy", hereafter referred to as the MIT Report (Tester et al). Commercial demonstration of EGS has not been achieved to date, although there are at least three ongoing pilot projects with this aim. The MIT Report therefore largely represents a feasibility study based on historical data and the current technical understanding of the geological conditions, physical processes, operational steps and technologies believed to be required to realize EGS. An examination of the assumptions and conclusions of the MIT Report, as well as a broad survey of existing industry technology in the context of EGS, has also been recently published in the 2008 DOE Geothermal Technologies report "An Evaluation of Enhanced Geothermal Systems Technology" (Jelacic et al). Both reports represent significant synopses of the current status and direction of EGS research and development.

This paper briefly summarizes a report recently published by Sandia National Laboratories on behalf of DOE entitled Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report (Polsky et al). The Sandia analysis endeavored to provide a more focused and in-depth investigation of the technologies currently available and needed for EGS well construction.

REPORT OVERVIEW

The foundation for the study is a hypothetical exercise performed by a leading geothermal drilling contractor, ThermaSource Inc., in which the steps, tasks and tools involved in the construction of a prospective baseline EGS well are explicitly defined in terms of sequence, time and cost. The report begins with a discussion of the factors that can influence nominal EGS well specifications in an effort to establish a reasonable case study basis. It is argued that there are many uncertainties associated with prospective EGS implementation that preclude a reliable definition of a baseline EGS well configuration at this stage of EGS development. The ensuing hypothetical well construction exercise and analysis in the report therefore primarily represents a methodology for better understanding well construction R&D needs.

The well specification used for the exercise is founded on recommendations in the MIT Report and current thinking within the EGS research community. The well specification targets an output of 5 MWe from 80 kg/s, 200°C well head fluid produced from a depth of 6 km. It is meant to represent a modest incremental advance beyond current geothermal hydrothermal practices, where wells rarely exceed 3 km in depth, and serves as a starting point for appreciating how simple EGS wells may differ from those currently developed in the geothermal industry.

The "drilling on paper" exercise performed by ThermaSource, Inc. provides a detailed account of how the well of interest might be constructed using today's technologies. The governing assumption of the exercise is that all construction steps must employ existing tools and practices. Much of the envisioned well construction description draws on proven deep gas well practice because of the absence of geothermal experience at the depths of interest. It provides both a script of the daily, sequential tasks used to build the well and accounting of the tools used to perform those tasks. Rental, service and consumable cost estimates are also provided in order to assess total well cost.

The well construction script is then subjected to an analysis in which all steps are described using a set of repetitive work elements. Distinct work elements, times and costs are summed in order to evaluate the relative importance of each element with respect to the well construction process as a whole. By logically decomposing the process in this manner a more manageable method for identifying where time and money are spent is achieved. The execution of each work element is dependent on the specific technology and operating process employed. Potential improvements for the well construction process can then be proposed in terms of the technologies or operational processes needed to improve the relevant work elements.

The remainder of the report focuses on defining proposed thrusts for well construction technology R&D and providing more detailed descriptions of some of the technologies of interest.

Finally, it is noted that the analysis within the report was presented at a DOE sponsored EGS well construction technology evaluation workshop attended by well construction experts from the geothermal industry, oil & gas industry and national laboratory complex. The R&D recommendations within this report reflect a combination of prior investigation and feedback received at the workshop.

WELL CONSTRUCTION CASE STUDY

The case study well specification is shown below in figure 1.

The ThermaSource Inc. "drilling on paper" exercise provided a script with approximately 400 steps describing in detail the well construction processes and tools needed to construct the specified baseline well. Due to the limited space in this paper, the reader is referred to the published report for details of the exercise. Operations in most instances are parsed to an hourly level. This resolution of description in the drilling script is intended to depict the effort associated with utilizing distinct technologies and processes so as to more easily identify improvement opportunities.

Figure 1 Case study well specification

This "bottom up" definition of the well construction sequence was complemented by lumped time and cost estimates for completing each interval. Lumped estimates are based on ThermaSource field experiences and discussions with other industry experts with deep gas well experience. Bottom up and top down time estimates were iteratively compared and modified to settle upon what ThermaSource considered to be a reasonable drilling scenario.

Many of the assumptions used in the analysis are presented in Appendix B of the report. It is important to note that the particular case planned does not incorporate mobilization and demobilization costs, site preparation costs, trouble time and does not assume a specific lithology profile. Drilling related parameters and performance are instead assumed based on experience in the general area in which the well is to be drilled. It is recognized in this report that future well construction analysis should focus on specific locations and lithologies based on near and longer term implementation strategies for EGS.

The presented well construction case is in some respects conservative and others moderate. Assumed drilling rates for example are reflective of favorable conventional geothermal situations. It is highly plausible that future EGS locations can be selected for which a large extent of less hard and abrasive rock overlies the low permeability zone of interest in order to improve drilling rates. On the other hand, as stated above, no non-productive time (NPT) is assumed in this analysis. NPT in many instances is caused by wellbore integrity issues, lost circulation, formation pressure problems and poor drilling control (stuck pipe, trajectory control, etc.). These causes of NPT tend to be formation related and therefore require a more precise definition of the geology to be drilled. Evaluation of NPT related influence on well construction technology and practice will be left to future investigation.

Drilling operations were divided into the following six phases:

PHASE (I): SURFACE: (36" Hole to 500' with 30" Casing)
PHASE (II): INTERMEDIATE 1: (26" Hole to 5000' with 20" Casing)
PHASE (III): PRODUCTION LINER 1: (17-1/2" Hole to 10,000' with 13-5/8" Casing)
PHASE (IV): PRODUCTION LINER 2: (12-1/4" Hole to 17,000' with 9-5/8" Casing)
PHASE (V): PRODUCTION LINER 3: (8-1/2" Hole to 20,000' with 7" Casing)
PHASE (VI): PRODUCTION TIEBACK: (13-3/8" Casing)

ANALYSIS OF WELL CONSTRUCTION EXERCISE

The drilling on paper exercise represents a substantial effort to describe in detail the sequence of steps and tools required to build the case study well. In order to better understand how time and money were spent in this well construction effort it was necessary to organize the nearly 400 listed steps in a categorical manner that reduces what effectively is a job log to operational elements. Representing the well construction process in terms of these elements provided a more manageable way to comprehend the critical building blocks of the process and facilitates the development of strategies to improve the economic bottom line through technological or operational process improvement.

In principle it is possible to break the well construction process down into numerous categorical levels of detail. The analysis in the report is intended primarily to illustrate the basic approach and therefore uses only two hierarchical levels in order to simplify analysis output. The first hierarchical level describing a step represents the general well construction objective or activity. For this analysis the three fundamental activities are:

- Drilling – Any action associated with extending or expanding the borehole
- Casing – Any action associated with installing permanent hardware within the borehole for the purpose of maintaining borehole integrity
- Logging – Any action associated with measuring borehole or formation characteristics.

Within each activity there are a number of repetitive operations, called tasks, which are performed to complete the activity. Some of these tasks may be performed in more than one activity and some are exclusive to a particular activity. The ten tasks defined in this analysis are:

- Drill: Extending or expanding the borehole
- Trip: Conveying tools or consumables in or out of the hole
- Circ: Circulating fluid for the purpose of cleaning the borehole
- BHA: Assembling or disassembling bottom hole assembly (BHA) components
- Rig U/D: Assembling or disassembling non-BHA surface equipment
- BOP: Conducting blow out preventer (BOP) related activities
- WH Ops: Conducting well head related activities
- RunCsng: Convey casing
- Cement: Cementing related activities
- Log: Logging activities

Brief summaries of the time and cost analyses will be presented in the following sections.

Time Analysis

The well construction script was placed in an Excel spreadsheet with column identifiers for activity, task, time and cost attributed to each step. Pivot tables and charts were then created for different parameter sets to indicate the relative influences of activities and tasks on the overall process. Table 1 and figure 2 below display, respectively, the cumulative time in days associated with each activity and task by interval and time percentage of each task associated with the overall well construction process.

In an ideal process, virtually all time would be spent expeditiously creating a borehole with little time required for ancillary drilling tasks and installation of borehole support hardware. Drilling is by far the largest operational time consumer in the presented case, but it only represents roughly 41% of overall operational time. This means that considerable time is spent performing functions not directly related to extending the borehole. In particular it is evident that

Activity	Task Code	1 Surface	2 INT-1	3 PROD-1	4 PROD-2	5 PROD-3	6 PL1-TB	Grand Total
Casing	BHA		0.3	2.4	0.4	1.6	3.4	8.1
	BOP	1.3	1	0	0	0	1.3	3.6
	Casing							
	Cement	0.6	0.8	0.7	0.4	0.5	0.8	3.8
	Circ	0.1	0.1	0.2	0.4	0.8	0.2	1.8
	Drill					0.1	0.1	0.2
	RigU/D	0.2	0.2	0.2	0.1	0.1	0.1	0.9
	RunCsng	0.5	1.5	1.5	2	2	0.7	8.2
	Trip	0.2	0.5	0.7	1.2	3.8	1.6	8
	WH Ops	0.7	1.2				1.1	3
Casing Total		3.6	5.6	5.7	4.5	8.9	9.3	37.6
Drilling	BHA	1.9	1.5	1.5	2.6	1.8		9.3
	Circ	0	0.1	0.2	1.3	1.2		2.8
	Drill	1.4	12.6	11.6	22.8	10.8		59.2
	Trip	0.3	1.9	2.8	7.8	6.4		19.2
Drilling Total		3.6	16.1	16.1	34.5	20.2		90.5
Logging	BHA		0.3	0.4	0.4	0.4		1.5
	Circ		0	0.1	0.1	0.2		0.4
	Log	0.1	0.7	1.3	2	2.5		6.6
	RigU/D	0.2	0	0	0	0		0.2
	Trip		0.4	0.8	1.4	1.6		4.2
Logging Total		0.3	1.4	2.6	3.9	4.7		12.9
Grand Total		7.5	23.1	24.4	42.9	33.8	9.3	141

Table 1. Task time in days for activity and phase

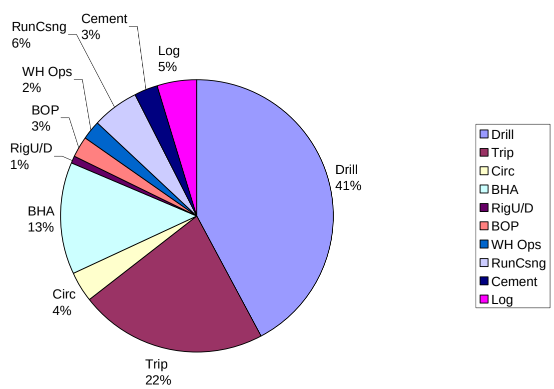

Figure 2. Well construction task time percentages

substantial time is spent tripping (31.4 days) and handling the BHA (18.9 days).

Figure 3 below provides an alternative representation of the time associated with individual tasks by interval. These graphical representations help provide insight into the relative influences of tasks as a function of drilling depth and interval length. It is evident, for example, that the relative time associated with tripping in the deeper intervals becomes a larger fraction of the overall time associated with that interval. This is in general intuitive, but the quantitative impact is particularly informative. It can be seen, for example, that more time is spent tripping than drilling in the 3,000 ft production interval. If drilling penetration rates and causes for tripping remain consistent, it can be assumed that this increasing trend continues for deeper wells. This will be shown to be very important later in the cost analysis section as the cliché “time is money” holds true when it comes to well construction.

Other obvious depth related trends include a greater amount of time spent running casing, circulating and logging as the well gets deeper. It is noted that liners are used for the final four intervals (including the production liner used to tie the production liner 1 back to the surface). If casing had been installed all the way to surface then time and cost associated with casing would be even greater. Tasks apparently not dependent on depth include BHA handling.

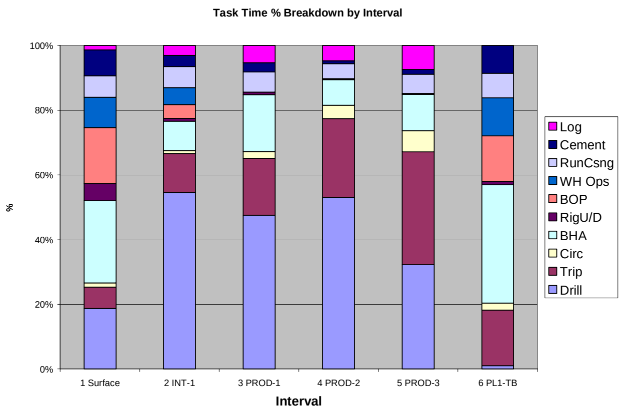

Figure 3. Task time percent chart by interval

Correlation of time consuming tasks with the drilling script provides an indication of the specific actions performed during the task. Tripping tasks, for example, are primarily comprised of bit changes, logging tool conveyance, wiper runs and deployment of casing tools. Further decomposition of tasks in this manner can be used to identify the specific time consuming technologies and/or processes and rank them with respect to quantitative impact. Table 2 shows a subtask breakdown of tripping times. Changing worn drill bits and conveying casing tools are by far the largest tripping constituents although significant time is spent on other tripping subtasks.

Subtask	Activity	Time
Changing bits	Drilling	9.8 days
Conveying casing tools	Casing	8 days
Changing tools/bit sizes	Drilling	5.7 days
Conveying logging tools	Logging	4.2 days
Wiper trips	Drilling	3.7 days

Table 2 Tripping subtask times

Understanding the temporal impact and nature of subtasks facilitates determination of improvement opportunities. Technology improvement strategies may have potential for diminishing the time associated with some subtasks. Increasing bit life, for example, has the potential to eliminate bit change trips and associated time. Technology substitution strategies may mitigate other subtasks. Casing drilling may represent one such instance by eliminating casing related trips, including running casing, and may potentially provide a more expedient method for changing bits. On the other hand, some subtasks may be deemed to have little improvement potential and therefore may merit little or no focus from the R&D perspective.

A summary of key findings in the time analysis is presented below.

- Rock reduction is the largest single time component (59/141 days)
- Tripping is a significant time component (31/141 days)
    - Bit replacement can add significant time to operation (9.8/141 days)
- BHA handling is a significant time component (19/141 days)
    - Improvement opportunity?
- Increasing depth amplifies main time contributors
    - Impact of drilling and tripping may be more pronounced for EGS!
- Increasing depth changes relative weights of different tasks
    - Deeper means less relative time spent drilling
- Interval length also changes relative weights of tasks
- Shorter intervals are less efficient

COST ANALYSIS OF CASE STUDY

The ThermaSource cost estimate represents a pairing of their traditional job cost estimation technique with the expected consumables and aggregate operational times of the presented well construction case. Understanding cost impacts of operational task elements and their related technologies is one of the goals of the well construction case study analysis. It was therefore required that estimated costs be associated with individual script steps in order to calculate aggregate element costs.

The association of costs with specific activities and tasks is in some instances straight forward and in others subjective. Consumable costs, for example, can readily be linked to the activities during which they are used and the particular tasks that employ them. Service rates, on the other hand, can be allocated on more than one basis. The daily rig rate is the simplest example of this ambiguity. The rig is assumed to be present for the duration of operations in the cost estimate. In one approach, costs associated with the rig can be allocated only to rig related activities and tasks. On the other hand, because the rig is being paid for while other tasks, such as logging, are ongoing, rig costs can also be factored into their operational costs.

Because time is such a crucial aspect of operational tasks, the latter approach was selected. The allocation assumptions in this analysis include:

- Costs spread over the duration of the well construction process were factored into the calculation of a universal daily rate. Such costs include rig and support equipment rentals, drilling engineering services, mud engineering, geological services and site services.

- Costs related to specific activities and tasks, such as directional drilling services, casing crew rates and liner hanger services were only apportioned to tasks utilizing those specific services.
- Cementing services and consumables are lumped and associated with individual intervals.
- Casing services and consumables are lumped and associated with individual intervals.
- Drilling consumables not clearly associated with particular drilling intervals or tasks are lumped into a single cost that is not apportioned to individual intervals.
- Drilling consumables related to specific intervals such as bit and mud costs are apportioned to specific intervals.

An extracted sample of the well construction script with cost allocations is displayed in table 3 below.

Figures 4 and 5 summarize well construction cost percentage by activity and task respectively. Figure 4 clearly indicates that drilling dominates the cost structure with respect to activity. Breaking down costs by task, however, paints a slightly different picture with no single task element comprising more than 23% of total cost. The latter view of costs from a task perspective implies that multiple focal points will be required to improve well construction economics. The larger components meriting focus are obvious, however it is explained in more detail in the report how many of the smaller cost components also warrant focus because they may be more amenable to improvement through technological innovation or operational optimization.

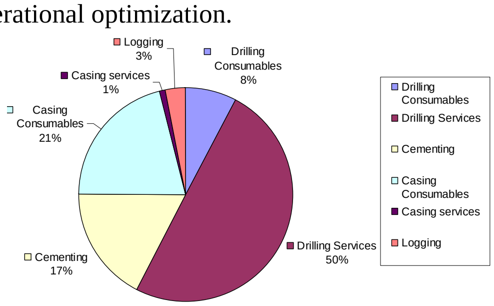

Figure 4. Well construction cost percentage by activity

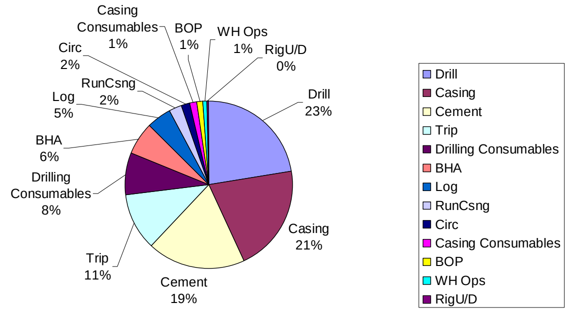

Figure 5. Well construction cost percentage by task

A strictly cost based ranking of tasks warranting R&D attention can be derived directly from the well cost breakdown by task category. In this manner the order of major tasks by cost fraction is:

1. Drilling (rock reduction)
2. Casing
3. Cementing
4. Tripping
5. Drilling consumables
6. BHA handling
7. Logging

The report also contains various charts and tables showing task cost magnitudes and percentages by interval. These representations provide insight into relative task cost influences as functions of interval length, depth and borehole diameter. Finer levels of task resolution are also provided in the report by segregating task costs by activity. As described in the previous section, analysis of the cost basis at this level, in the context of the drilling script, facilitates the identification of cost reduction strategies founded on technology development and/or operational process optimization. A large fraction of the cost of tripping, for example, results from bit changes. Bit change costs are also a significant portion of BHA handling costs. Improving bit life therefore represents a method for reducing the cost impact of both tasks.

Focus areas for well construction R&D based on cost drivers are summarized below. This list is rather general and primarily reflects the more obvious conclusions extracted from this study. The following section will provide a more detailed description of R&D focus areas that address both functional and cost driven well construction considerations.

- Improve ROP
  - Bits, tools and processes
- Develop more durable tools
  - Eliminate trips and handling
- Improve casing design
  - Minimize production borehole diameters

Phase	Activity	Task Code	GENERAL OPERATION TASKS	Hours	Days	Daily universal rate	Service specific rate	Consumable cost	Total rate
1 Surface	Drilling	BHA	1. Make up 26" bit and 36" hole opener on mud motor.	6	0.3	14532.58	5061.68		$19,594.26
1 Surface	Drilling	BHA	2. Pick up 36" stabilizer and cross over to 6-5/8" HWDP.	4	0.2	9688.387	3374.45		$13,062.84
1 Surface	Drilling	Drill	3. Drill and open 36" hole with motor and HWDP from 80' to 240'.	13	0.5	31487.26	10967		$42,454.22
1 Surface	Drilling	Circ	4. Circulate	1	0.0	2422.097	843.613		$3,265.71
1 Surface	Casing	WH Ops	14. Weld on 30" SOW x API 30", 2000 casing head.	6	0.3	14532.58	1163.56		$15,696.14
1 Surface	Casing	WH Ops	15. Pressure test weld to 500 psi.	1	0.0	2422.097	193.927		$2,616.02
1 Surface	Casing	BOP	16. Nipple up 30" BOP with blind ram and annular and connect to flow line.	28	1.2	67818.71	5429.96		$73,248.67
1 Surface	Casing	BOP	17. Function test and pressure test BOP and 30" casing to 250 psi low and 1000 psi high pressure.	3	0.1	7266.29	581.782		$7,848.07
1 Surface	Casing	Cement			0.0	0		$220,500.00	$220,500.00
1 Surface	Casing	Casing			0.0	0		$170,000.00	$170,000.00
1 Surface	Drilling	Drilling Consumables	Includes bits + mud		0.0	0		$193,155.00	$193,155.00
1 Surface	Logging	Log	Logging services		0.0	0		$125,000.00	$125,000.00

Table 3. Cost spreadsheet extract

  - Minimize or eliminate telescoping effects
  - Improve cementing practices
- Improve operational efficiency
  - Reduce trips
  - Improve BHA handling
  - Develop best practices

WELL CONSTRUCTION R&D RECOMMENDATIONS

This section of the report defines critical well construction research & development elements that enhance EGS viability prospects and improve well construction economics. Some of the research recommendations are directly related to the case study analysis. Prospective projects in this category can be more traditionally assessed using "return on investment" type valuation methods because they are readily compared to current practices. In general they supplant or augment existing methods and technologies.

Other recommendations related to the well construction considerations outlined in Section 2 of the report (EGS to be determined factors) do not address current practice, but are critical to increasing the probability of EGS success because they directly affect EGS proof of concept. Assessing the value of these potential projects is difficult due to the current conceptual nature of EGS and the inherent uncertainty associated with basic research. Projects of this type represent a best guess of the key technical hurdles that will have to be overcome in order to execute EGS. They are also critical components of any systematic approach to develop EGS in an efficient manner.

Three categories of well construction R&D are hereafter defined in order to logically organize efforts based on their direct relatedness to future EGS application. They are:

1. "Systems Engineering" type research areas to better define ill-framed EGS well construction issues and needs
   - Typically impact other critical EGS areas, e.g. reservoir creation, production, intervention
   - Will ultimately be used to add to category 3 research elements
2. Recognized enabling technologies
   - Applies to technology types with current limitations that are generally recognized as necessary to future EGS implementation, e.g. HT tools
3. Target technologies
   - Applies to well defined issues and problems

These research categories can more simplistically be summarized as: 1) Efforts to determine critical issues and needs not yet recognized. 2) Efforts to meet needs that are very likely to be important. 3) Efforts to meet needs that we know today to be important.
It is pointed out that the majority of research lines that are recommended reflect the historical focus of

the DOE Geothermal Technologies program. This congruence is hopefully perceived as a good indication of appropriate direction of the program. The primary difference between the recommendations in this report and previous technology evaluations is the method of categorizing research areas based on their role in the EGS research program and the attempt to rank, where possible, recommendations based on their quantitative impact on well construction activities. It is hoped that this approach can be further developed in the future as a method for both identifying critical R&D needs and determining how maximum value can be obtained from R&D efforts and funding.

The following sections will discuss recommended lines of investigation within each of the aforementioned R&D categories. Additional discussion of select technologies of interest is presented in Appendix C.

Category 1 R&D (Systems Analysis)

Category 1 research thrusts are most concisely described as EGS systems engineering. The main development components of EGS (site identification, resource characterization, well construction, reservoir creation and reservoir operation) exhibit high degrees of interdependency. Changes in the methods or technologies used in a particular stage of the EGS process may adversely affect or require changes to another stage as described in section 2 of the report. Understanding these interdependencies and understanding their potential impacts is therefore of the utmost importance to EGS development.

EGS systems engineering with respect to well construction broadly encompasses four topics: EGS economics, well field design, well field construction and well completion. Each of these topics will be briefly covered to illustrate how they are likely to affect well construction practice and R&D goals.

EGS economics – EGS economics is an overarching theme in all areas of EGS research & development. Functional realization, although unquestionably crucial, is only a step in the path towards EGS contribution to U.S. energy needs. Well field construction costs have historically proven to be large fractions of geothermal capital investment costs and this is generally assumed to be equally true for EGS. On the one hand, evaluating or predicting well field construction costs as EGS development progresses helps understand prospects for commercial success. On the other, a better and more detailed *a priori* appreciation of acceptable well field construction costs can help focus R&D efforts by imposing cost based design constraints. Such economic analysis requires a comprehensive view and study of all EGS components.

Well field design – The creation and exploitation of the EGS reservoir is vitally contingent on the ability to generate the volumes, surface areas and flow rates needed to effectively and economically extract the thermal resource. These three parameters in turn are heavily influenced by the specific manner in which the subsurface is accessed. Well field design is currently a very open aspect of EGS. There are numerous yet undetermined facets of its preferred form including: the number of wells to be used (e.g. doublets, 5-spots, etc.); preferred borehole orientations (e.g. vertical, inclined, horizontal); and monobore vs. multilateral designs. Resolving these fundamental issues can result in significantly different well construction strategies that are likely to impact well construction R&D objectives. Future investigation of well field design in the EGS systems context is warranted to develop a better appreciation of well construction needs and how they may change if well field design changes.

Well field construction - Systems level analysis of well field construction is required to efficiently synchronize this step in EGS development with preceding and following steps. This primarily involves the linking of real-time data to exploration data and well construction operations to subsequent formation behavior. The former is useful for ensuring that information acquired during well construction corresponds well to prior planning. Examples of the latter include managing pressure while drilling or dealing with lost circulation while drilling. In both cases actions taken during well construction can reduce formation permeability with consequent production problems. System understanding at this level is very mature in the oil and gas and current geothermal industries, often leading to different operational practices due to application differences, but perhaps should be evaluated in the context of future EGS development.

Well completion – In some respects, this is one of the biggest gaps in current EGS planning and understanding. Recognized subjects of significance in this area have primarily focused on casing design. Relevant objectives include:

- Appropriately sizing production intervals to meet necessary production rates
- Reducing cost through leaner casing design or elimination of casing strings
- Optimizing cementing practices to reduce cementing costs
- Devising strategies to improve life cycle costs by protecting casings (e.g. more resistant and long lasting cement) or using longer lived casing materials

- Incorporating well workover considerations into casing design to reduce life cycle costs

Production interval completion by contrast has received little or no attention in the geothermal literature. Current geothermal completions are generally open hole or at least present continuous communication throughout the production interval. This is in contrast to many oil and gas applications where complex completions are used in production intervals to more optimally engage the reservoir. These approaches should be evaluated for EGS with the following potential objectives in mind:

- Facilitation of selective stimulation along the production interval
- Controlling zonal injection to more effectively extract thermal resource from the formation
- Cost and functionally effective intervention to reduce injection loss
- Cost and functionally effective intervention to mitigate the effects of short-circuiting
- Cost and functionally effective intervention to address production loss due to chemical or erosion effects

In summary, EGS systems engineering is required to optimize R&D resources by anticipating potential issues and identifying the problems that must be solved to increase prospects of success. The currently fluid underpinning of the EGS concept makes this especially true. As more EGS field experience is gathered, this uncertainty will be reduced but it is likely that an umbrella of system level investigation will always be required for steady advancement to occur.

Category 2 R&D (Enabling Technologies)

There are numerous enabling technologies that have been historically deemed necessary to successful EGS development. These technologies are considered to be enabling because they relate more to general capabilities than specific needs in the EGS well construction process. They are mostly based on current practices in analogous industries, such as oil and gas, which have significantly improved operational efficiency or capabilities. These technologies and their general application will be subsequently described.

High temperature electronic components for drilling and logging tools (> 200 °C) – Drilling and logging tools for use in well construction and formation evaluation are mainstays of the upstream oil and gas operational inventory. These tools are used to optimize exploitation of and recovery from the reservoir. By comparison, very little use of these tools is made in current geothermal practice. The higher temperatures of geothermal applications typically prevent their use because of temperature limitations of the tools. Regardless of the specific function (sensor modality), a host of supporting components is required for the operation of all downhole tools. Supporting components with high-temperature capability must be developed in order to build specific high-temperature tools.

High-temperature, hard rock directional drilling tools – Although required borehole curvature specifications and directional drilling capabilities have not yet been defined for EGS, it is likely that directional drilling capabilities will be required. Directional drilling tools will have to withstand the high temperatures and hard rock lithologies expected in EGS applications. There is evidence that current industry capabilities can meet the former conditions in some applications. Baker-Hughes Inteq, for example, has recently directionally drilled a well in a Basalt formation for Ormat’s Puna geothermal project in Hawaii with a reported static temperature of 650°F using their 8” Ultra series motor with Navitrak MWD tool. Based on conversations with Inteq, the use of current directional drilling technologies is predicated on the ability to keep electronic components cool via drilling mud circulation. Future application and development of these types of directional drilling technologies should be monitored and discussed with both operators and service companies to assess and promote EGS applicability.

High-temperature production and service isolation tools – Zonal isolation capability is currently considered to be important to EGS production and intervention practices. The use of packers to selectively isolate or treat production zones is recognized to be essential to operations such as lost circulation remediation and stimulation. Application of existing tools in geothermal applications is primarily affected by temperature limitations of elastomeric components, differential pressure capabilities and maximum inflation diameters. The use of cement inflated packers is considered to be currently feasible among service companies, however, those surveyed indicate that the current capabilities of retrievable and swellable packers, particularly in open hole applications, are currently not suitable for geothermal applications. Advancement of these technologies will have to occur to increase temperature and differential pressure capabilities.

Improved telemetry capabilities – High baud rate telemetry in general and low baud rate telemetry in some applications will have to be improved for use in EGS applications. These capabilities are required for drilling and logging tools used in applications where operational decisions are made based on data acquired in real-time. High-temperature, high speed telemetry capabilities have been demonstrated in the past in Sandia's Diagnostics While Drilling program where real-time drilling dynamics data has been used to improve drilling performance and reliability. However, more cost effective telemetry methods will have to be developed for more wide-spread commercial use of these capabilities.

Low baud rate telemetry applications currently employ mud pulse technologies. There are many applications currently in the geothermal industry in which low density media, such as air or aerated fluids, are used to mitigate lost circulation problems. Telemetry methods in these fluids are either limited or non-existent meriting future development.

High-temperature pumps – It is likely that high temperature submersible pumps will be required to facilitate EGS fluid production. Although a significant improvement in capabilities has developed for these technologies, they are largely unproven in the deep, large wellbore, high temperature environment expected for EGS. Work with service companies to advance these technologies to meet EGS needs is warranted.

High-temperature smart completions – The value of developing high-temperature smart completions for measurement of production parameters and flow control applications should be evaluated. Successful development of this class of technology has the potential to improve reservoir operation and management practices. These technologies should be considered in the context of alternative methods for operating and managing the reservoir. Development of this technology will require advances in HT electronics, valves and telemetry.

<u>Category 3 (Target Technologies)</u>

Technology needs in this category are grouped in five areas in rank order of importance with respect to reducing well construction costs. They are: increasing rate of penetration (ROP), leaner casing design, reducing trip time, operational optimization and high-temperature tools.

Increasing ROP – This is a historically recognized focus area in geothermal technology research due to the low rates of penetration characteristic of many geothermal applications. The cause of this drilling difficulty (hard, abrasive and hot formations) has been a point of distinction in the past between geothermal and oil and gas applications. This distinction is quickly becoming blurred as the oil and gas industry more frequently encounters more geothermal-like drilling conditions as easy-to-drill discoveries become scarcer. This convergence of interests may set the stage for adapting some of the more effective oil and gas drilling technologies for use in geothermal-like conditions. Specific efforts should focus on:

- Transitioning aggressive O&G and waterwell/mining drilling technologies to geothermal (PDC bits and hammers)
  - Identify technical barriers and application issues
  - Conduct controlled field trials of candidate technologies to separate anecdotal failure reports from true technology limitations
- Developing economical drilling optimization tools using downhole data
  - MWD with drilling dynamics data
  - Methodologies for minimizing mechanical specific energy

Leaner casing design – Although this is partially covered in category 1 research recommendations, there are some existing niche technologies that are worthy of mention for future R&D focus. These technologies primarily mitigate telescoping effects by reducing the magnitude of diameter change between intervals.

- Expandable tubulars

Reducing trip associated time – This is a direct output of the operational analysis with significant cost saving potential. Sample objectives to address this area include:

- Development of longer lasting drill bits to eliminate trips
- Development of more efficient bit trip methods such as bit removal through tubing using wireline (as done for casing drilling)
- Use of techniques such as casing drilling that eliminate casing runs and expedite bit tripping

Operational optimization – Operational optimization may involve both surface operations (such as BHA handling) and downhole operations. It can be applied towards more expeditious execution of individual tasks or modifications to operating procedures involving multiple tasks. The latter can take the form of eliminating steps, combining steps or performing steps in parallel.

- Develop "best practices" for repetitive tasks
  - BHA assembly/disassembly
  - Lay down of drill pipe
  - Operational analysis of rig equipment
- Evaluate potential benefits of special purpose rig support equipment such as automated pipe handlers

- Supplement MWD with LWD to reduce time associated with switching over from drilling to logging operations

High temperature tools – The list of tools below represent deficiencies in the current geothermal tool inventory due to temperature limitations. These tools are critical to various components of EGS involving creation, operation or maintenance of the reservoir.

- 3D fracture monitoring: Reservoir creation
- Minimum principal stress magnitude and direction measurement: Reservoir creation
- Pressure/Temperature measurement: Stimulation
- Flow meters: Production and intervention
- Fluid samplers: Production and intervention
- Calipers: Well construction

More detailed descriptions of logging while drilling and measurement while drilling technologies are provided in Appendix C of the report. It is also noted that a large number of tools currently exist in the oil and gas industry for which a geothermal use is currently unclear. A thorough assessment of this inventory and its potential use in geothermal applications would require a team of experts from disciplines including tool and sensor design, the geosciences, well construction and reservoir engineering.

CONCLUSION

This paper summarizes a recent report published by Sandia National Laboratories in which well construction technology for EGS was evaluated. The report employed a case study analysis approach to define and quantitatively decompose the elements needed to construct a 20,000 ft prospective baseline EGS well. Selected details and conclusions of the analysis were presented in this paper. Recommended lines of investigation for R&D intended to support achievement of future EGS proof of concept and commercial success were also presented.

In order to apply this methodology, it was first necessary to establish prospective EGS well field specifications. It is explained in the report that the process of formulating a realistic description of a proposed well design led to the conclusion that the present understanding of EGS is too limited to generate a reliable specification. In particular it was argued that indeterminacy in other areas of EGS implementation including reservoir creation, operation and management introduce uncertainty in preferred well field characteristics. Thus, thoroughly evaluating the current status of well construction technology with respect to EGS itself requires a more specific definition of other fundamental EGS development areas. *The presented case study and analysis therefore primarily represents a demonstration of the utility of the methodology employed for analyzing well construction needs and ranking of R&D objectives.*

The current conceptual nature of EGS and associated uncertainties stated above highlight the importance of a systematic approach to understanding R&D needs beyond the current hydrothermal paradigm. Clarification or at least mitigation of these ambiguities will promote more effective use of program resources in the effort to realize EGS.

Two extensions of this work towards this end might include:

1. EGS Systems Engineering or Systems Analysis – This effort must include all subject matter experts across the program and focus on detailed planning, design and implementation of likely EGS scenarios. The determination of EGS component interdependencies in particular will be critical to anticipating potential problems and identifying R&D needs. In regard to well construction this will promote more robust well field designs and technology evaluations.

2. Conduct additional case study analyses – Application of the case study analysis method utilized in this report can be extended to a variety of well construction scenarios to improve understanding of potential variability in technological and cost drivers. This should ideally occur in conjunction with EGS Systems Analysis recommendations. As an immediate extension of the present work a representative set of specific target lithologies and well profiles can be established and analyzed.

REFERENCES

Tester et al, “The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century”, Massachusetts Institute of Technology, 2006.

Jelacic et al, “An Evaluation of Enhanced Geothermal Systems Technology”, DOE Geothermal technologies Program, 2008.

Polsky, Y., Capuano, L., Finger, J., Huh, M., Knudsen, S., Mansure, A.J., Raymond, D. and Swanson, R., “Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report”, Sandia Report SAND2008-7866, December, 2008.