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Integrated Research & Development for Advancing EGS Commercialization – Tipping the Scales

Chris Strickland[1], Jeff Burghardt[1], Hunter Knox[1], Pengcheng Fu[2], Paul Schwering[3], Tim Johnson[1], Tim Kneafsey[4], and the EGS Collab Team

[1]Pacific Northwest National Laboratory, [2]Lawrence Livermore National Laboratory, [3]Sandia National Laboratories, and [4]Lawrence Berkeley National Laboratory

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ABSTRACT

Fundamental to successful commercial scale enhanced geothermal systems (EGS) operations is the ability to maintain both fluid temperatures and flow rates at sufficiently high levels and durations to provide a return on investment. The persistence of such operational conditions will be required for many years to decades.

Confidence in long term EGS performance is not yet sufficient to justify the level of private capital investment required for widespread commercialization. While a number of technical and non-technical barriers exist, we believe that a fundamental obstacle to establishing confidence is the lack of data associated with long-term thermal-flow performance of EGS. Data collected from long-term circulation tests are needed to validate model predictions and reduce uncertainties in predicted economic outcomes. Without these well-validated predictive modeling tools, long-term reservoir management will be fraught with uncertainties and this will hinder capital investment in EGS. Therefore, we postulate that understanding long term EGS reservoir performance and evolution requires datasets, initially from experimental demonstrations but ultimately from commercial-scale EGS sites, and validated modeling suites. We note here that similar tools and techniques, proposed herein, have become invaluable in the petroleum industry where dynamic reservoir characterization is used in the long-term management and optimization of oil and gas recovery. Techno-economic analyses have also been performed for EGS but owing to the dearth of available long-term performance data, their validity has not yet been demonstrated.

In this paper, we discuss the potential for carefully scaled intermediate-scale field experiments that can serve as a time and cost-effective step toward building the necessary technical basis for validating predictive modeling tools. It is widely accepted that integration of laboratory, intermediate-scale, and field-scale efforts can be an important framework for lowering overall R&D costs, accelerating technology development timelines, reducing risks, and ultimately achieving the goal of commercializing EGS. We show here that an important step in developing those linkages lies in fundamental physical and dimensional analysis, and that with careful implementation seemingly intractable challenges of decoupling phenomena can be overcome.

1. Introduction

EGS holds enormous potential for baseload, always-on, renewable energy, not only within the United States but worldwide. Unlocking this potential has been the focus of various organizations and diverse research teams since the 1970s. One example is the major thrust inside the US Department of Energy's Geothermal Technologies Office (GTO), which aims to facilitate commercialization and widespread adoption of EGS through research and development (R&D) investments like EGS Collab and Utah FORGE. In their recent Geovision evaluation, the team shows that demonstrating long-term heat extraction from subsurface reservoirs across a wide range of geologic settings is critical to advancing EGS (Geovision, 2019). Such demonstrations build investor confidence and produce a comprehensive library of best practices, lessons learned, and technical innovations that will serve the industry in the many years to come. Unfortunately getting to that point requires that we overcome or mitigate many of the technical and non-technical barriers present today, one of which is the lack of validated predictive reservoir modeling tools. Even though EGS demonstration projects have been conducted for nearly 50 years (e.g., Fenton Hill, Rosemanowes, Le Mayet, Hijiori, Soultz. etc.), examples of long-term, commercial scale, EGS power generation are almost non-existent (Ziagos et al. 2013; Zhang & Zhao 2019). Uncertainties regarding economic viability will persist and serve as impediments to commercialization until this need is satisfied.

As alluded to above, numerous technical challenges exist for EGS. Many of these are a direct result of the high temperatures, target depth, lack of native matrix permeability, and complexities of fracture dominated fluid flow involved in the decadal scale operation of a geothermal reservoir. Throughout the entire life of an EGS reservoir, a plant must maintain operational conditions (e.g. flow rates and temperatures) sufficient for commercial scale energy production or storage to provide the minimum return on investment (ROI).

An important component for understanding, quantifying, and predicting subsurface phenomena is field scale demonstrations in actual EGS reservoirs (i.e. FORGE). These highly characterized and densely instrumented experiments provide insight into data requirements for model validation. This is largely how the base of knowledge and experience was developed for unconventional petroleum reservoirs and how many other R&D efforts are tackling large scale subsurface problems (i.e. nonproliferation, carbon sequestration).

In the case of unconventional petroleum reservoir development, a single company with an enormous risk tolerance and favorable market and tax conditions conducted hundreds of field trials in the Barnette shale (Martineau 2007; Economist, 2013; BEG, 2005). Eventually, after hundreds of millions of dollars of unrecovered investment, the trial-and-error approach paid off and a technique was found that more than doubled the production per well, finally resulting in an economically viable technology. This subsequently drew additional capital investment that created an energy revolution.

While such full-scale field testing alone could, in principle, be used to develop EGS technologies, we suggest that such a trail-and-error field-test driven approach is not the most cost- or time-effective. The latter detriment maybe the most important given that the world is desperately aiming to reduce carbon emissions and develop sustainable renewable energy as soon as possible. To do this we must build investor confidence in the economic viability for EGS. We note here, since it might not be intuitive, that geothermal and unconventional oil and gas investments generally have significantly different ROI timeframes. For instance, shale gas reservoirs typically reach their minimum ROI within the first couple of years, while EGS reservoirs likely to require a decade or more to reach minimum ROI. Therefore, the overall risk involved with long term performance EGS are substantial. Given the urgent need and the budding opportunities, we use this opportunity to highlight intermediate-scale testing complementary to full-scale that can be performed at reduced costs and in shorter time frames.

Laboratory scale experiments can provide valuable information on fluid flow and heat transfer within fractured rocks (e.g. Luo et al., 2017; Shu et al., 2020). Precise control of flow rate, temperature, and pressure/stress conditions can be imposed, and detailed measurements of the system responses obtained. Laboratory scales, however, limit the occurrence of heterogeneities (e.g., natural fractures) often present in full-scale EGS settings that can have a dominant influence on overall system behavior (Wallroth et al. 1999; MIT 2006; Breede et al. 2013).

Intermediate-scale experiments can provide a means for investigating EGS across scales and often contain natural fracture networks with characteristics more closely aligned with full scale EGS settings (Amann et al. 2018; Kneafsey et al. 2018; Roggenthen & Doe, 2018).

Fundamental laboratory testing combined with intermediate-scale testbeds have seen widespread use for accelerating scientific understanding and advancing technology development across a broad range of applications including atmospheric research, carbon sequestration, nuclear waste disposal, as well as geothermal energy. An example that illustrates the importance of intermediate-scale testing with relevance to EGS are early efforts towards studying and understanding hydraulic fracturing (Warpinski 1983; Warpinski et al. 1987; Jeffrey et al. 2009). These early intermediate-scale tests provided ground truth of how hydraulic fractures behaved. Prior to these tests, the orientation (vertical vs horizontal) and shape (shattered glass vs. planar) of hydraulic fractures as well as the role of the stress field, elastic and strength properties, and rock fabric were poorly understood. These tests provided essential validation and refinement of model predictions for hydraulic fracture behavior that then informed unconventional shale gas efforts.

Integration of laboratory, intermediate-scale, and field-scale efforts are an important framework for reducing overall R&D costs, accelerating technology development timelines, and ultimately achieving the goal of commercializing EGS.

2. Geothermal Techno-Economics

Techno-economic analysis can be used to evaluate EGS profitability given a set of assumptions regarding system parameters. When coupled with a sensitivity analysis, the uncertainties in individual parameters can be used to estimate likely economic outcomes and which parameters the modeled results are most sensitive. Several techno-economic approaches have been used to evaluate the performance of geothermal systems including EGS (Heidinger 2010; Van Wees et al. 2012; DOE 2016; Becker & McCabe 2018). Fundamental inputs are time histories of production well flow rate and temperature that are estimated using a representative model of the subsurface reservoir. Engineering design parameters (e.g. injection production well spacing, well length, or well spacing) can be adjusted to optimize the simulated EGS performance. Reservoir properties such as permeability can also be varied but subsurface heterogeneities are not typically considered.

Large uncertainties are often associated with inadequate knowledge/constraints on the presence and spatial distribution of the parameters that control fluid and heat flow within EGS reservoirs (e.g., fracture network permeability and geometry, stress variations). The use of approximate analytical solutions and/or numerical simulators remain standard approaches in reservoir characterization and risk reduction. However, uncertainties in reservoir properties substantially effect both the conceptual and numerical models of system behavior. Recent work incorporating uncertain subsurface heterogeneities into the techno-economic analysis have shown that predicted median economic outcomes are three times lower than models that ignore subsurface heterogeneity uncertainties (Pollack & McCabe, 2019). Variable, heterogeneous subsurface properties are ubiquitous in nature and can therefore serve as an important controlling feature for the commercial success of EGS.

To accurately reproduce real systems and ultimately reduce risk, modeled inputs must be derived not only initially through comprehensive subsurface characterization efforts but subsequently refined over time using monitoring data that sufficiently samples the controlling features and processes. Similar techniques are used in petroleum reservoir management and can be adapted to long-term geothermal operations as a methods for reducing the impacts associated with subsurface uncertainties (Aminzadeh & Dasgupta 2013).

3. EGS Fluid Flow and Heat Transfer Scaling Relationships

The governing equations for many processes can be nondimensionalized so that the that the underlying physics are independent of specific spatial and/or temporal scales. Fluid flow and heat extraction from fractured rock reservoirs can be formulated using characteristic temporal and spatial scales to generate dimensionless parameters that are functions of rock and fluid properties, flow rates, fracture spacing, fracture aperture, and number of fractures (Bear, 1972; Gringarten et al. 1975). In this way, the same nondimensionalized results can be obtained for different scale problems under specific constraints on the relationships between material properties, spatial scaling, and temporal scaling. Examining these equations helps to understand the advantages and disadvantages of different experimental test beds.

4. Planar Fractured Rock Example

A simplified example will be used to illustrate how intermediate scale experiments can be representative of full scale EGS. In this example heat transfer results from a fluid uniformly flowing in the z-direction through a collection of evenly spaced planar fractures with aperture b, imbedded within an impermeable rock mass.

Assuming that the rock is impermeable the general fluid flow and heat transfer equations can be integrated across the fracture to provide the following coupled equations (Gringarten et al. 1975; Doe et al. 2014):

$$b\rho_f c_f \left[\frac{\partial T_f(z,t)}{\partial t} + v\frac{\partial T_f(z,t)}{\partial z}\right] = \lambda_R \frac{\partial T_R(x,z,t)}{\partial x}\bigg|_{x=b^+} - \lambda_R \frac{\partial T_R(x,z,t)}{\partial x}\bigg|_{x=b^-}$$

The governing equations can be nondimensionalized by using a characteristic time scale of τ and spatial length scale of L, W, and H in the x, y, and z, directions. Temperature can also be nondimensionalized using initial rock and fluid temperatures as follows.

$$\tilde{x} = \frac{x}{L}; \quad \tilde{y} = \frac{y}{S}; \quad \tilde{z} = \frac{z}{S}; \quad \tilde{t} = \frac{t'}{\tau}; \quad t' = t - \boldsymbol{r}\cdot\boldsymbol{s}; \quad \tilde{T}_M = \frac{T_{R0} - T_M}{T_{R0} - T_{f0}}, M = R\ or\ f$$

Where T denotes temperature, ρ density, c_f, c_R specific heat, λ_R thermal conductivity, and q_i the fluid Darcy flux component in the ith direction. Subscripts are associated with each material: fluid or rock.

Transforming the time derivative using the definition of t' gives:

$$b\rho_f c_f v\frac{\partial T_f(z,t)}{\partial z} = \lambda_R \frac{\partial T_R(x,z,t)}{\partial x}\bigg|_{x=b}$$

$$\frac{\partial^2 T_R(x,z,t)}{\partial x^2} = \frac{\rho_R c_R}{\lambda_R}\frac{\partial T_R(x,z,t)}{\partial t}$$

Leads to

$$\left(\frac{W}{L}\frac{(2bv)(\rho_f c_f)}{K_R}\right)\frac{\partial \tilde{T}_f(\tilde{z},\tilde{t})}{\partial \tilde{z}} = \left.\frac{\partial \tilde{T}_R(\tilde{x},\tilde{z},\tilde{t})}{\partial \tilde{x}}\right|_{\tilde{x}=b}$$

$$\frac{\partial^2 \tilde{T}_R(\tilde{x},\tilde{z},\tilde{t})}{\partial \tilde{x}^2} = \left(\frac{W^2(\rho_R c_R)}{\tau\lambda_R}\right)\frac{\partial \tilde{T}_R(\tilde{x},\tilde{z},\tilde{t})}{\partial \tilde{t}}$$

Setting

$$W = \frac{L\lambda_R}{(2bv)(\rho_f c_f)}$$

$$\tau = \frac{W^2(\rho_R c_R)}{\lambda_R}$$

The above equations define the constraints between scaling factors and system parameters which finally result in the nondimensionalized governing equations

$$\frac{\partial \tilde{T}_f(\tilde{z},\tilde{t})}{\partial \tilde{z}} = \left.\frac{\partial \tilde{T}_R(\tilde{x},\tilde{z},\tilde{t})}{\partial \tilde{x}}\right|_{\tilde{x}=\tilde{b}}$$

$$\frac{\partial^2 \tilde{T}_R(x,z,t)}{\partial \tilde{x}^2} = \frac{\partial \tilde{T}_R(x,z,t)}{\partial \tilde{t}}$$

For fixed fracture aperture, fluid velocity, and fluid rock physical properties, the above formulation illustrates that the same nondimensionalized results can be obtained if the temporal scale follows the square of a change in spatial length. Applying this result to an intermediate scale experiment where the spatial size, W, is a factor of ten less than the full scale equivalent, reduces the time, τ, required to reach the same non-dimensionalized thermal breakthrough by a factor of one hundred. Other combinations of material properties, fluid velocity, and scaling factors can also be chosen that result in the same non-dimensionalized solution and provide the experimentalist a tool for designing experiments to best reproduce full scale EGS.

Although this example has several simplifying assumptions, the general approach can be applied to more complex systems, providing a framework to ensure that smaller scale tests can be used to study the essential behavior of a full-scale EGS reservoir. In the following sections, we will discuss several aspects of the scaled governing equations and their influence on scaled EGS experiments.

4. Proppants

The governing equations assumed that the fracture aperture and therefore the hydraulic conductivity is independent of fluid pressure, however, for fluid flow in fractured media, this is generally not the case. Hydraulically propping fractures to control aperture leads to additional complexity and will greatly impact the selection of scaling parameters for intermediate scale experiments.

Experimentally, fracture aperture can be treated as a parameter that is independent of spatial or temporal scales. This can be implemented using injected proppants of the selected size. Injection of proppants should thus be performed to control the fracture aperture for long-term flow tests. Achieving fracture aperture that is similar in size to full scale EGS will also likely require comparable fracture lengths and should be a consideration in the design of an intermediate scale experimental testbed. While the overall fracture length needed to deliver a given proppant may be relatively large, the thermal circulation distance between injection and production wells can be independently selected to scale the spatial size of the system.

5. Natural Fractures

The EGS system described above assumes that the spatial distribution of material properties can be scaled proportionally with the size of the experimental system. One complication is that full scale EGS will have natural fractures that can greatly influence fluid and heat transfer within the reservoir and may not scale well to small experimental systems.

The prevalence and attributes (i.e. length, aperture) of fractures in geologic media have been shown to generally follow power scaling relationships (de Dreuzy et al. 2001; Bonnet et al. 2001). As a result, intermediate scale testbeds are substantially more likely than laboratory samples to possess natural fracture networks similar in character to full scale system.

6. Intermediate Scale Experiments

Intermediate-scale experiments can be representative of and used to study full scale EGS heat transfer but at accelerated timelines and reduced cost. While thermal breakthrough in a successful EGS system will take a decade or more, a properly scaled intermediate testing could achieve the same dimensionless timeline in a year or less.

While laboratory and intermediate-scale experiments can, in principle, be scaled to represent a full-scale EGS reservoir, they are not well suited to address every technical challenge. Development and testing of drilling, zonal isolation, and downhole sensing at high temperatures/pressures are examples of efforts better suited to actual full scale conditions. Testing at each scale is complimentary in nature. Identifying which research aspects each experimental scale can address and to what extent, can serve as an initial step towards integration. Here we define four experimental categories: 1) laboratory, 2) low temperature deep mine intermediate-scale (e.g., relevant stress), 3) low temperature shallow intermediate-scale, and 4) full-scale EGS. The spatial dimensions, temperature, depth, and stress state, rock accessibility, possible measurement locations, and finally relative costs are all features critical to each experimental category (Table 1).

In many cases, geophysical monitoring methods also scale with the imaging target dimensions by adjusting energy source magnitudes and frequencies (Lee & Kim 2003; Maraschini et al 2011). Point and distributed sensing along wellbores (e.g., temperature) also clearly scales well with a reduction in the physical size of the system.

Ideally, both intermediate and laboratory scale experiments should be representative of full scale conditions to the maximum extent possible. The color codes in Table 1 reflect how close each experimental category can achieve ideal conditions which, except for cost and ease of rock access, correspond to those of the full EGS reservoir (green = most applicable, yellow = neutral, red = least applicable). The intermediate-scale categories together clearly achieve many of the key features that comprise the full EGS reservoir system with temperature being the outlier.

Table 1. Key attributes of four experimental categories: laboratory, two intermediate-scales, and an EGS reservoir scale.

EGS Critical Features	Laboratory	Low Temperature Deep Mine Intermediate-scale	Low Temperature Shallow Intermediate-scale	EGS Reservoir
Reservoir Lateral Dimensions	1mm - ~1m	10 - 50m	10m - 0.5km	~1km
Temperature	0 - 300°C	15 - 40°C*	15 - 40°C*	175 - 300°C
Stress/Depth	0 - 10km	1 – 3 km	0.1 – 0.5km	1.5 - 10km
Rock Access	Surface from all sides and borings	Boreholes emanating from mine tunnels	Boreholes from surface	Deep boreholes from surface
Measurement Locations	Surface from all sides and borings	Boreholes and mine tunnels	Boreholes and land surface	Boreholes and land surface
Experimental Cost**	$	$-$$	$-$$	$$$-$$$$

*Typical of most mines and near surface settings but shallow geothermal areas are possible
**Cost symbols reflect relative order of magnitude estimates (e.g., $$ is 10 times more than $)

The strengths and limitations for each experimental category must be recognized. For instance, elucidating fundamental chemical or microbiological mechanisms that lead to fracture permeability reduction can be studied under conditions similar to an actual EGS reservoir in the laboratory. However, characterization and monitoring techniques that provide useful data at the reservoir scale may not be effectively downscaled to the laboratory. Additionally, some experimental techniques cannot yet be used at full reservoir scale due to current technological limitations. A good example is zonal isolation which will be required to enable pressure monitoring or variable injection rates at multiple depths within a borehole. To date zonal isolation devices have not yet been demonstrated to work, particularly over long-time frames, in the very high temperature environment of an EGS reservoir.

Experimental categories represent a continuum for developing EGS, with laboratory and EGS reservoir as end members that can be mapped to technology readiness levels (TRL) 1-4/5 (basic development) and 9 (system operations) respectively. Intermediate-scale testing then provides the critical experimental framework for advancing technologies from TRL 5 to 9. The transition between laboratory- and intermediate-scale, and between intermediate- and field-scale is not sharp, and each can be adjusted to optimize integration and facilitate improvements in EGS understanding and technology development.

The advantages and disadvantages of each intermediate scale test bed should be carefully considered. Low temperature intermediate scale experiments will not address every technical challenge. Intermediate scale experiments can provide a great deal of value towards building confidence in EGS. The performance of subsurface systems often exhibits larger uncertainties relative to other engineered applications. Observations are needed to understand the likely EGS performance outcomes. Investigating the role of integrated novel characterization and monitoring technologies should then be a major component of intermediate scale experiments focused on long-term reservoir thermal evolution. Proppants can be used to simplify the problem by allowing independent control of fracture fluid flow/pressure and should be considered as part of the design of scaled long-term thermal evolution experiments. Sites with favorable geology (e.g., relatively homogeneous, competent, low permeability rocks) can be readily found that are representative of target full scale EGS settings.

5. Conclusion

Confidence in long-term EGS performance is not yet sufficient for widespread commercialization. We argue that intermediate scale field experiments can be designed to be representative of full scale EGS and serve as a time and cost-effective step toward building the necessary technical basis, lowering overall R&D costs, and reducing risks. Field demonstrations targeting long-term circulation and reservoir heat extraction data sets in both intermediate and full scale EGS reservoirs can provide experience and knowledge regarding the set of data necessary and sufficient to validate predictive models. Without this base of experience, uncertainties will remain high and impact investment in EGS.

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