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Performance Evaluation of Engineered Geothermal Systems Using Discrete Fracture Network Simulations

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ABSTRACT

This paper summarizes the major conclusions of a panel commissioned by the US Department of Energy (DOE) to study the behavior of engineered geothermal systems (EGS) using discrete fracture network (DFN) approaches. Sandia National Laboratories (Sandia) and Lawrence Berkeley National Laboratory (LBNL) directed the study, and they in turn selected the Itasca Consulting Group (Itasca), Golder Associates Inc. (Golder), Lawrence Livermore National Laboratory (LLNL), and LBNL to develop numerical experiments using DFN models to determine the conditions under which EGS may be viable and to understand its critical parameters and sensitivities. The results of this study have recently been published in electronic form (Kennedy et al, 2021).

The major conclusions included the following: (1) A successful EGS system will likely involve multiple fractures and multiple zones. These may be achieved either by multi-staged stimulations, as in unconventional oil and gas developments, or by stimulation methods that develop critical shearing stresses on natural fractures. (2) Optimizing well layouts to develop EGS by stimulating natural fractures needs to consider the geometry of the natural fractures and the in-situ stress field. (3) A multiple fracture or stimulation system will require either separate management of each stimulation to avoid premature breakthrough on the most transmissive pathways or will require an active management approach that shuts down the more permeable pathways as they experience thermal breakthrough at the production well. (4) Chemical effects are important particularly to reservoir longevity and demonstrations of a hybrid DFN-continuum approach provide a potential way forward. (5) Although most of the simulations in this report were two dimensional, , three- dimensional effects may be important for depth gradients of temperature and stress, which vary significantly with regional tectonic settings and influence the extent of EGS applicability within the USA.

INTRODUCTION

Purpose

This paper presents the synthesis and conclusions of a recently published report assessing engineered geothermal systems (EGS) from the standpoint of discrete fracture network models. The work is the result of panel convened by the US Department of Energy. Sandia National Laboratories (Sandia) and Lawrence Berkeley National Laboratory (LBNL) directed the study with M. Kennedy and D. Blankenship as panel co-chairs. A full list of panel members appears in the acknowledgements. The panel in turn selected the Itasca Consulting Group (Itasca), Golder Associates Inc. (Golder), Lawrence Livermore National Laboratory (LLNL), and LBNL to develop numerical experiments using DFN models to determine under what conditions EGS may or may not be viable and to understand critical parameters and sensitivities. The results of this study have recently been published in electronic form (Kennedy et al, 2021). The full report text is downloadable from ***https://escholarship.org/uc/item/4168d73x***. As this paper is a summary of the report's conclusions, this paper refers frequently to sections of the report for background. These references use the symbol for section " §".

EGS has considerable potential for electrical energy production (INL, 2006), but realizing this potential has been elusive for a variety of reasons (JASON, 2013). Reservoir conceptualization may be one area of concern. Most methodologies for designing and assessing EGS performance use numerical simulators that treat the rock as a porous, continuous material (e.g., Sanyal and Butler, 2005). Porous, continuous approaches have had considerable success in geothermal development, but generally overlook the impact of networks of discrete conductors. These fracture pathways may be discontinuous as well as heterogeneous and anisotropic. Furthermore, their flow behaviors may be very sensitive to coupled thermal, mechanical, and chemical effects. Discrete fracture network (DFN) models are distinct from the porous continuum models conventionally used for EGS stimulation. They represent fractures explicitly as individual, fluid-conducting features rather than averaging and homogenizing fractures into a continuous porous medium (Figure 1). DFN approaches were developed initially for radioactive waste disposal research and have subsequently had broader applications in petroleum engineering and groundwater resources (Dershowitz and others, 2010) with limited application to geothermal systems (for example, McClure and Horne, 2013).

Despite the considerable progress in developing DFN models over the past 40 years, at the start of this project there did not exist a widely applied or accepted DFN simulator that could handle coupled hydro-thermal-mechanical-chemical behaviors in fracture networks. Furthermore, simulation capabilities were often two-dimensional and not three-dimensional. Thus, a significant portion of the work performed for this study involved expanding the coupling capabilities of DFN models (Raihi and others, 2014 a, b, c, 2015, Fu and Carrigan, 2014, Fu and others, 2016). This report presents the results of discrete fracture network (DFN) models to assess EGS performance.

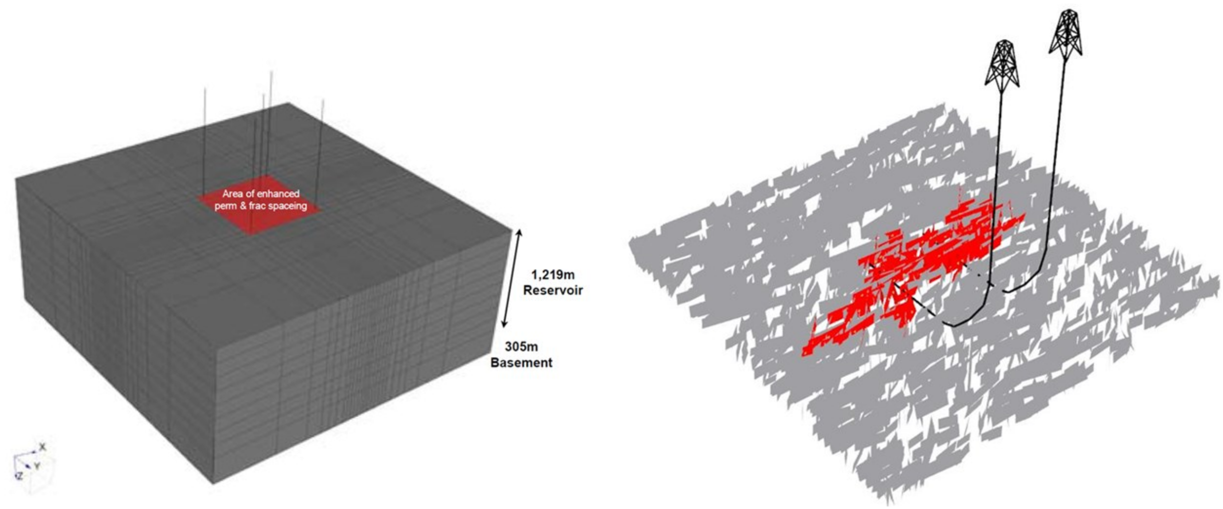


Figure 1. Continuum versus Discrete Fracture Network (DFN) representation of EGS system. Left from Butler and others (2004)

Goals

The primary goals of the DFN simulations were the following:

- Determine under what conditions EGS may or may not be viable,
- Guide analyses, including coupled hydro-thermo-mechanical-chemical modeling to understand critical parameters and sensitivities, and
- Provide input to future field operations and EGS demonstrations.

CRITERIA BASIS FOR EGS VIABILITY

Two basic EGS performance criteria guided the modelling efforts –

- a circulating flow rate that would achieve 5 MW_e power production, and
- the sustainability of the production water temperature over time, or *thermal longevity*.

The circulating flow rate criterion for 5 MWe power production was a volumetric flow rate of 0.08 m3/s (80 liters/s) or mass flow rate of 80 kg/s based on

$$W_e = \eta \rho_f q \Delta T c_w$$

- the temperature difference, ΔT, between the injection fluid and initial reservoir rock
- the circulating fluid density, ρ_f (kg/m^3), and specific heat capacity, c_w (J/kg/°C),
- the thermal efficiency of the generating system, η, which is number between 0 and 1, and

- a fluid density of 1000 kg/m3, fluid heat capacity of 4180 J/kg/°C, a temperature difference of 150°C, and efficiency of 10%.

The second requirement was thermal longevity. The EGS system should produce for twenty years with a temperature decline no greater than 10% of the temperature difference between the injection fluid and the initial reservoir temperature. Ideally thermal longevity depends on the rate of depletion of the stored thermal energy in the rock; however, early thermal breakthrough may occur due to "short circuits" in the fracture circulation system. Short circuits are fracture connections where the circulation rate outpaces the heat exchange from the rock, resulting in production temperature drops without significant depletion of the heat stored in the rock.

In addition to power production, we used the time to 10% thermal decline, t_{D10}, as a performance criterion for comparing EGS simulations. This measure is very useful for assessing EGS performance under varying parameters such as distance between injection or producer or locations of injectors or producers relative to the orientations of the major fracture sets.

An additional concern is the stability of the heat exchanger over time with respect to chemical or biological fouling. Circulating fluids may create dissolution or precipitation conditions (or both). Chemical and biological effect may reduce, enhance, or redistribute permeability within the heat exchanger. Chemical effects not only affect the impedance of the system but also change the characteristics of the heat exchanger. LBL's coupled chemical simulations addressed this concern (Xu and others, 2006; Finsterle and others, 2014; Sonnenthal and others, 2015).

SUMMARY OF SIMULATION ACTIVITIES

The work by Itasca involved expansion of the capabilities of UDEC, their well-established rock engineering simulator (Itasca, 2011). The expansions included fracture-matrix heat exchange, conduction, and transport in fracture networks with explicit thermal-mechanical coupling (Riahi and others, 2014 a). The UDEC code was verified for this use using analytical solutions and applied to investigate the variable effects of well positions and spacing, thermal conductivity, and thermo-mechanical coupling. The simulator included a capability for simulating shear dilation in natural fractures and creating new hydraulic fractures if necessary (Riahi and Damjanac, 2013). The investigation considered effects including fracture size distributions, stress-field orientation relative to fracture orientations, and fracture dilation angle, rock thermal conductivity and thermo-mechanical coupling, The models employed mostly 2-dimensional simulations with some 3-dimensional simulations (Riahi and others, 2015) that considered multi-stage versus single state simulations as well as the effects of cased versus open borehole completions.

LLNL used a hybrid discrete-fracture and continuum approach called GEOS that involved the interaction of three separate codes, a fracture network model, a continuum heat and fluid flow model, and a finite-element mechanical code. Each time step started with the DFN model; passed it through a hydro-thermal calculation to determine the stress changes due to temperature; and finally updated the DFN model with apertures for thermomechanical effects (Fu et al., 2016). LLNL considered three major applications, (1) flow and heat transport in a single heterogeneous fracture with and without thermomechanical coupling, (2) studies of well positioning relative to major and minor fracture set orientation, and (3) EGS production in a multi-stage, multifracture system with thermomechanical coupling.

The Golder work had two components. The first focused on implications of the Gringarten (and others, 1976) analytical solutions to determine EGS feasibility space and numerical stimulations to investigate the effects of heterogeneity in multistage EGS production (Doe and McLaren, 2014; Doe and others, 2016). The second investigated the question of whether EGS could be equally feasible in any part of the United States. The simulation designs posed archetypical settings representative of the regional variability of in-situ stress and geothermal gradients (Finnila and others, 2015, 2016; 2017). The simulations used Golder Associates' FracMan DFN codes with Hydrogeosphere (Brunner and Simmons, 2012) for the coupled heat flow calculations (Doe and McLaren, 2014).

LBNL investigated the effects of chemical coupling on EGS performance through thermal-hydrological-mechanical coupled simulations employing a hybrid DFN-continuum approach using Itasca's UDEC codes and LBNL's well-established TOUGH and TOUGHREACT codes (Xu and others, 2006; Finsterle and others, 2014). Simulations based on the DOE Newberry Volcano (Oregon) EGS demonstration site (Sonnenthal., 2012) showed the importance of chemical coupling to EGS performance.

SOME MAJOR CONCLUSIONS AND FOCUS OF THIS PAPER

A complete summary of all the DFN modeling activities is beyond the scope of this paper, which focuses on a few of the major conclusions and encourages the reader to access the full panel report for details.

- For the baseline viability criteria, an EGS requires several square kilometers of effective fracture area for heat exchange. Creating a reservoir with this surface area will likely require multiple fractures or stimulations.

- Heterogeneity of transmissivity between fractures in a multi-stage stimulation EGS and within single fractures reduces the effective heat exchange area. Heterogeneous EGS systems may lead to further localization of deformation and flow resulting in short-circuited systems that have early thermal breakthrough at the production well, without significantly depleting the rock's stored heat.

- EGS developments may utilize shear-stimulated natural fracture networks that have multiple fracture-sets favorably oriented relative to an anisotropic in-situ stress state. Among other factors, placement of wells to create circulation pathways through multiple fracture sets may enhance access to fracture surface area for heat exchange.

- Chemical effects can be effectively simulated in continuum models (TOUGH) to show permeability changes with dissolution and precipitation during EGS production.

- EGS development strategies may regionally depend on the geothermal temperature gradients, the natural fracture network geometries, the natural fracture hydro-mechanical properties, and especially the orientations of natural fractures relative to the principal stress directions and magnitudes. Three-dimensional simulations are required to capture the effects of DFN and stress and fluid pressure gradients that may drive preferential vertical growth into cooler or hotter portions of the reservoir.

FRACTURE SURFACE AREA REQUIRED FOR AN EGS HEAT EXCHANGER AND NEED FOR MULTIFRACTURE EGS

Lessons from analytical solutions

Analytical solutions provide simple approximations of the surface area required to meet the power production and thermal longevity. A rearrangement of the equation defining dimensionless time in the analytical solution of Gringarten (and others, 1975, and described in §2.2.1 and §2.2.4) provides this approximation of the required surface area, A:

$$A = q\sqrt{\frac{t_l}{t_{D10}} C_1}$$

where

- t_l is the target thermal longevity (assume 20 years or 6.3 x 10^8 seconds),
- t_{D10} is the dimensionless time corresponding to a 10% decline in the production well temperature. t_{D10} is approximately 0.74 for a single fracture(dimensionless spacing, x_{eD}=∞) and reduces to 0.5 for a closely- spaced fractures, (x_{eD}=0.5). For the dimensionless spacing definition see Gringarten and others, 1976 or §2.2.4.
- q is the volumetric flow rate (0.080 m^3/s),
- C_1 is a lumped parameter containing the rock and water properties (~2.6 x 10^6 s/m^2, see §2.2.4)

The area of a single fracture that satisfies the performance criteria described above is 3.4 x 10^6 m^2 (3.4 km^2) for material properties like those for the Newberry, Oregon, experimental EGS site (Cladouhos et al. 2011). This area is equivalent to a fracture that is 0.5 km high and 6.8 km long assuming a 100% effectiveness in the surface area for heat transfer (Figure 2). The spacing of the injector and producer wells for such a single fracture is an unrealistically large 6.4 km.

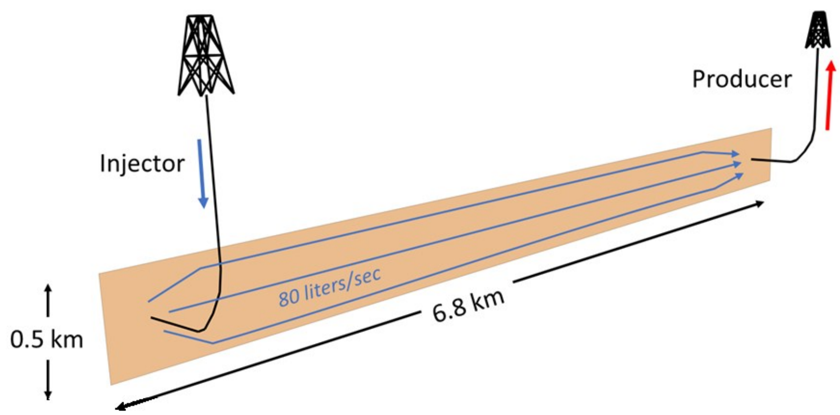


Figure 2. Single fracture EGS required to meet study basis criteria.

Second power dependency of thermal breakthrough on rate and area and need for a multifracture EGS

An important implication of analytical solutions is the second power relationship of thermal longevity to surface area and flow rate. Rearranging the equation in previous section gives

$$t_l = \frac{t_{D10}}{C_1}\left(\frac{A_e}{q}\right)^2$$

Decreasing the flow rate or increasing the effective surface area has second power effect on increasing the thermal longevity. Conversely, increasing the flow rate or decreasing the effective surface area shortens the time to thermal breakthrough by a second power. For example, doubling the flow rate in an EGS system will decrease thermal longevity by a factor of four.

If the spacing between injector and producer wells is limited to a range of 500 m to 1 km, a single fracture may be unlikely to support EGS production that meets both the rate and thermal longevity criteria. The design approach may require determining the flow rate within a single fracture or stimulation that will produce the desired thermal longevity. If this flow rate is less than the desired power production, then the EGS design will require multiple stimulations (Doe and McLaren, 2014) whose cumulative production meets the power production criterion.

As an example, an EGS system producing at 80 l/s from a single 524-m square fracture (

Figure 3) meets the power target of 5 MWe but fails the thermal longevity target having breakthrough of 51 days. Reducing the flow rate to 7.6 l/s meets the thermal longevity of 20 years but falls short on energy production. Meeting both the power and thermal longevity targets requires 12 fractures producing 6.7 l/s (Figure 3 and Figure 4).

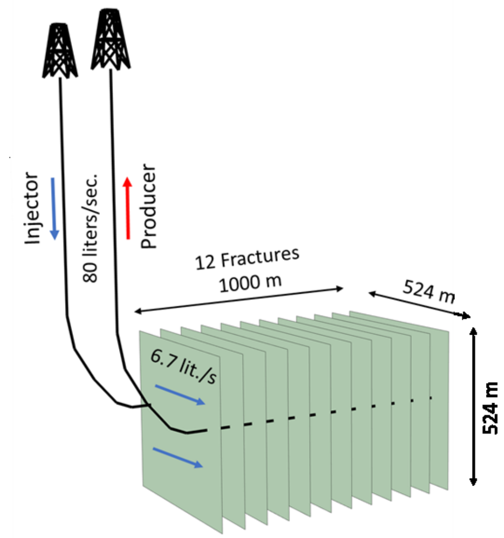


Figure 3. Multi-fracture EGS meeting study basis criteria.

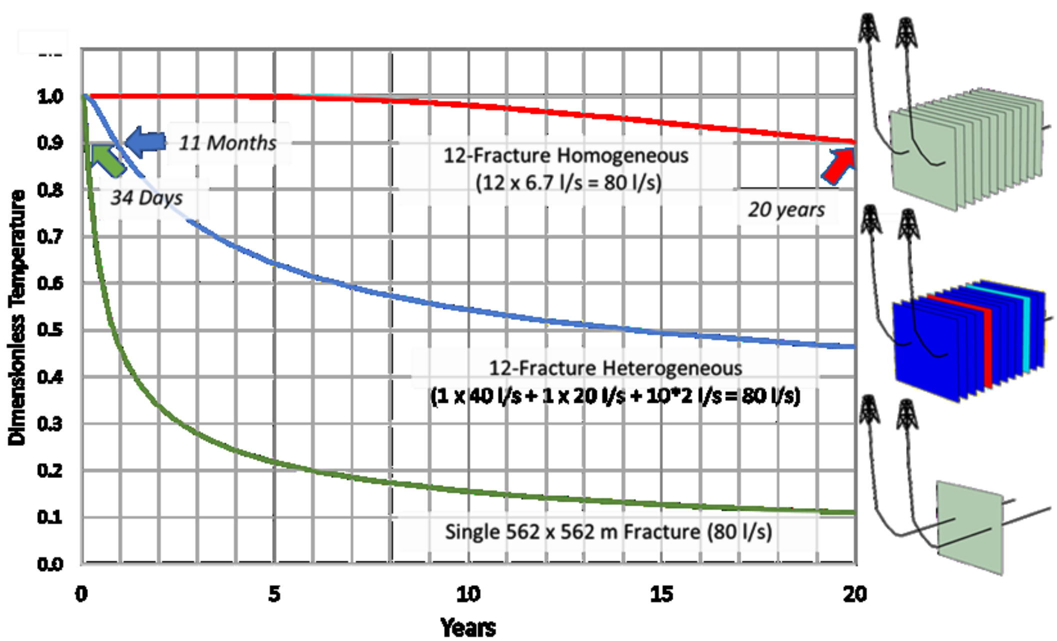


Figure 4. Single fracture EGS thermal performance (green); multi-fracture EGS that meets performance criteria with homogeneously transmissive fractures from Figure 3 (red). Effect of transmissivity heterogeneity on thermal breakthrough in a multi-fracture EGS (blue).

The number of fractures and their spacing is a critical consideration. Another illustration of the importance of surface area came from Itasca's simulations (§4.2.7) varying fracture spacing (Figure 5). With smaller fracture spacings and higher fracture intensities, the EGS may have more surface area available for heat exchange between the rock and the EGS circulating fracture network.

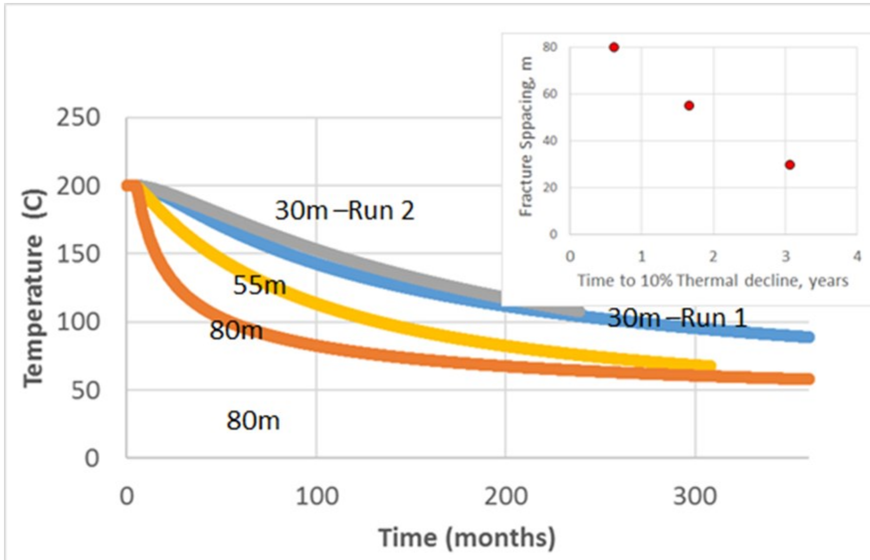


Figure 5. Production temperature versus time for fracture spacing study. The smaller spacing creates stimulated regions with more pathways and surface area for heat exchange, thus improving thermal performance. Inset shows the time to 10% production temperature decline.

Importance of surface area to future field operations and EGS demonstrations

The prediction of surface area is a critical need for EGS design. Overestimating the surface area may lead to unexpectedly early thermal breakthrough. The simple models also demonstrate the need for realistic surface-area estimates to determine flow rates that will assure thermal longevity.

In situ experimentation at all scales should validate the second power relationships of flow and thermal longevity Early breakthrough is not an indicator that the rock is thermally depleted. Methods for mitigating the effects of early breakthrough could include reducing flow rate or allowing time for thermal recovery before restarting, albeit at the lower flow rate. Early thermal breakthrough in one stimulation might indicate a need to change the circulation to another existing or new stimulation zone.

EFFECTS OF HETEROGENEITY BETWEEN FRACTURES AND WITHIN A SINGLE FRACTURE

The problem of heterogeneity

The hydraulic properties of fractures are not uniform. The transmissivity may vary both among fractures and within a single fracture. The variability of transmissivity distributes flow non-uniformly over the fracture surfaces, concentrating flow in the most transmissive fractures in a multi-fracture EGS system and in transmissive channels of heterogenous single fractures.

Heterogeneity within a single fracture

The heterogeneity of flow within a single fracture reduces the time to the thermal breakthrough and causes a significant degradation of thermal performance (§5.5). Thermal-mechanical coupling further enhances heterogeneity (localization) of flow and the reduction of effective surface area for heat transfer.

Consider a homogeneous fracture where the injection and production wells are 500 m apart (Fu et al., 2016; Guo and others, 2016). With a 12 l/s flow rate, the thermal breakthrough occurs in 5.8 years. Adding heterogeneity to the fracture reduces the breakthrough time ~70% to 1.7 years (Figure 6).

Thermal-mechanical coupling increases the aperture of the fracture in the areas of greatest cooling, creating channelization effects. A fracture that is initially homogeneous therefore becomes heterogenous along the main flow lines reducing the breakthrough time to 4.2 years. The thermal-mechanical coupling effects are even more dramatic in the heterogenous case, where the breakthrough time reduces to 0.92 years.

Heterogeneity between fractures in a multiple stimulation EGS

Heterogeneity of transmissivity among the fractures in a multifracture stimulation has a significant effect on thermal breakthrough time. Consider a 12-fracture case identical to the homogenous system in Figure 3 except one fracture is taking 50% of the flow, a second fracture is taking 25%, and remaining 25% of the flow is distributed uniformly among the other ten fractures (Figure 4). Assuming these fractures have a large enough spacing that they are not thermally interacting, the Gringarten solution provides a basis for calculating the production well temperature. For this example, the thermal breakthrough occurs in eleven months compared with 20 years for a set of homogenous fractures.

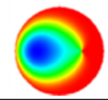
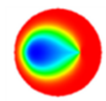
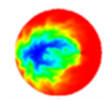
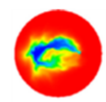
		10 % Production Temperature Decline	30-year Temperature Field
Homogeneous	No Coupling	5.8 years	
	Thermal Coupling	4.2 years	
Heterogeneous	No Coupling	1.7 years *(~70% reduction from homogeneous)*	
	Thermal Coupling	0.92 years *(~80% reduction from homogeneous)*	

Figure 6. Thermal performance, t_{D10}, in a homogeneously and a heterogeneously transmissive fracture with and without thermal-mechanical coupling. Heterogeneity channelizes the flow resulting in earlier thermal breakthrough. This channelization increases with thermal-mechanical coupling. Results from Fu and others (2016) and Guo and others (2016).

Heterogeneity's importance for future field operations and EGS demonstrations

Understanding effective surface area

Heterogeneity reduces the effective surface area for heat exchange in an EGS. A critical need for predicting EGS performance will be having a means of identifying this heterogeneity and estimating an effective surface area for heat exchange. Among the possible characterization methods could be geophysical monitoring and tracer testing.

Microseismic monitoring of fracture behavior during stimulation and production is well established for determining the spatial extent of fracture stimulation; however, it may not be able to determine the total fracture surface area or the heterogeneities within the fractures to a resolution necessary to make performance predictions. Other forms of tomographic characterization may be capable of resolving heterogeneities within fractures, but these would need to be checked against actual thermal circulation tests.

Tracer tests provide a direct means of assessing heterogeneity mainly using tracers with behaviors that depend on interacting with the rock over the fracture surface area. Estimates of both sorption onto surfaces and diffusion of tracers into the rock will constrain the effective surface area.

Whatever methods may be used, the effect of heterogeneity on thermal circulation requires testing at multiple scales, including laboratory, 10-100-meter field scale, and in EGS test sites. These experiments need to include thermal circulation to compare estimates of total fracture surface area with those coming from geophysics and tracer tests. One approach for designing EGS systems could be the development of "rules of thumb" from thermal circulation experiments. Such experiments would compare the calculated surface areas from the production versus time behaviors with the fracture surface areas known from geomechanical calculations and geophysical characterization.

Controlling flow to multiple stimulations in an injection well

Heterogeneity among fractures in a multifracture stimulation causes the most transmissive fractures to take most of the flow in an open-hole injection. The dominance of the more transmissive fractures (flow-paths) results in early thermal breakthrough.

A critical need may be the development of zonal isolation strategies that allow separate control of each stimulation stage in the well to ensure the stages are taking uniform rates, albeit at different injection pressures. This will also require characterization methods including flow logging that clearly show the rates being taken by each stimulated fracture.

Testing strategies for multiple completions and separate control of stimulation stages will be a key technology development for EGS if multiple stimulations will be employed.

STIMULATION OF NATURAL FRACTURE NETWORKS AND OPTIMIZING EGS PERFORMANCE

Natural fractures and EGS

Fracture surface area is the key to a successful EGS development. The previous sections showed that ~3 square kilometers of effective surface area are required to sustain 5MWe power production over 20 years. Furthermore, that heterogeneity of permeability within and between fractures reduces the effective heat exchange area.

The stimulation of natural fractures may be one approach to creating the large surface areas necessary for a successful EGS development. Under the right conditions of in situ stress and fracture orientation, fluid injection may cause these fractures to dilate and shear to create the pathways necessary for EGS circulation. The effective surface of the natural fractures may be further enhanced if

• the stimulated networks contain fractures with multiple orientations and

• the wells are positioned to create tortuous pathways through these networks.

Well positioning and fracture networks

The positioning of wells in a reservoir with multiple stimulated fracture sets has a very strong influence on thermal performance especially if the fracture sets vary in their transmissivity. Such transmissivity variations may be related to the in-situ stress (Barton and other, 1995). For a reservoir with two sets – a major and a minor set – this alignment is crucial in determining the sweep of the circulation through the fracture network (Figure 7).

Alignment of the wells with the major fracture set (that is, the set with greater permeability) creates a limited number of direct pathways between the injection and production wells. The short circuiting along the major fractures results in early thermal breakthrough and inefficient heat production from a relatively small portion of the reservoir.

Well alignment in the minor fracture set direction or in a direction intermediate to the two sets create tortuous pathways that enhance the effective surface area for heat exchange. These pathways improve the sweep of the circulating fluids through the fracture network. The main drawback of positioning wells in the direction of the minor fracture set are the possibility of higher impedance and poorer connectivity. The poor connectivity may create challenges for establishing circulation between the wells, especially if the inter-well distances are large.

These drawbacks can be mitigated by positioning the wells in an alignment intermediate to the two fracture sets. Numerical simulation using fracture networks models may assist in optimizing heat exchange area, impedance, and connectivity for specific sites.

Itasca (§4.2.3 and Riahi and others, 2014c) investigated the effects of well placement and spacing (Figure 8). The Itasca 2-D network contained two fracture sets, a major set which was more conductive and continuous and a minor set which was less so. The production and injection wells were laid out in three configurations, one parallel to the major set, one parallel to the minor set, and a third positioned in a direction intermediate to the two sets.

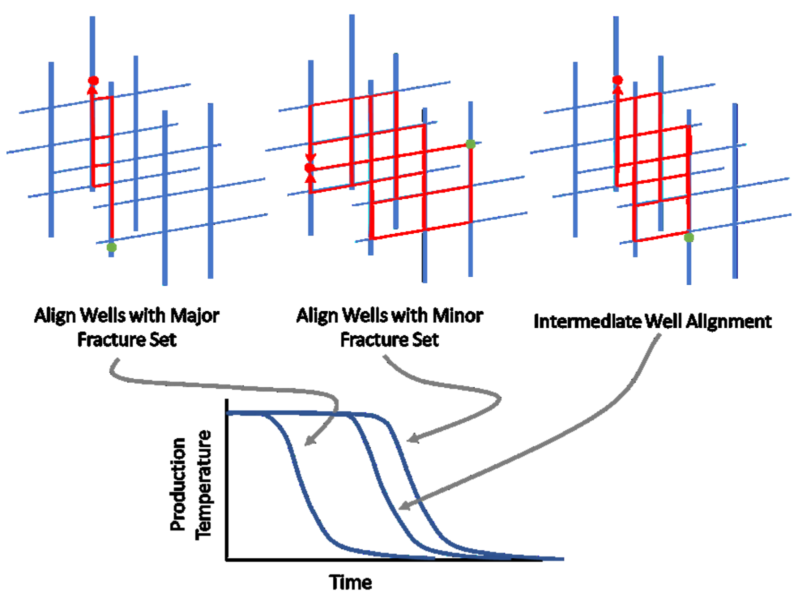


Figure 7. Conceptual model of the effects of well positioning with respect to major and minor fracture sets. Thermal performance improves when the well layout exploits tortuous pathways through multiple fracture sets

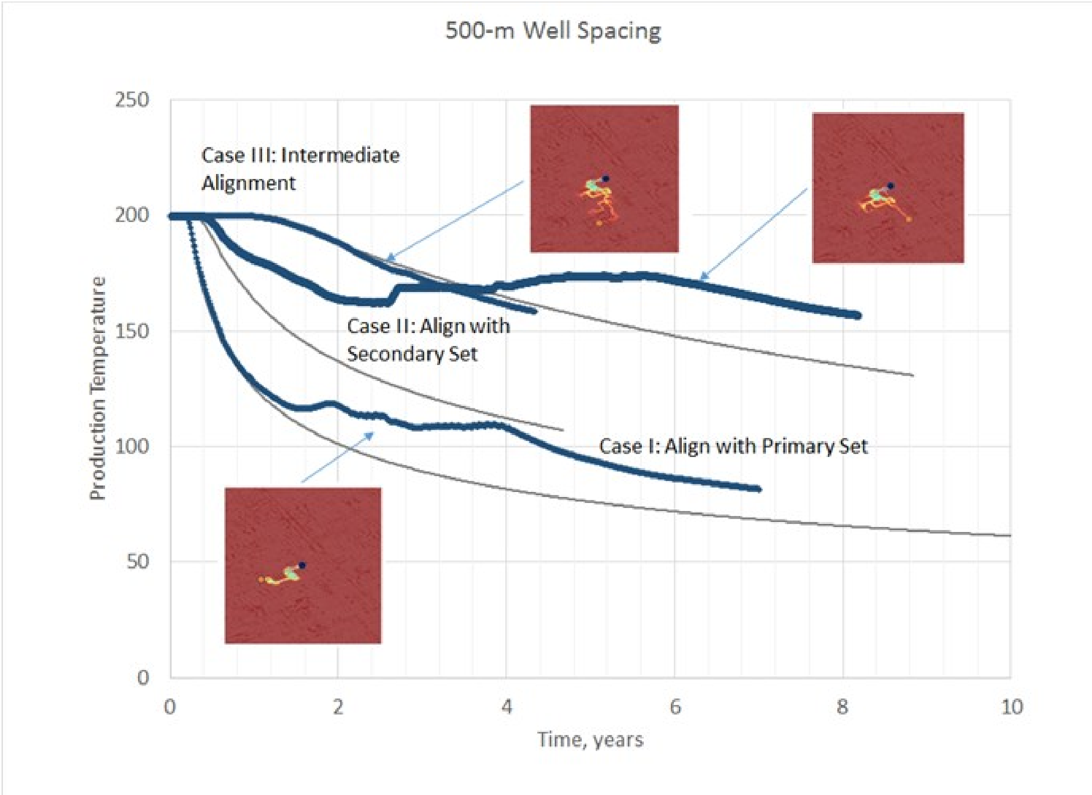


Figure 8. Production temperature, well positioning study using UDEC; 500 m well spacing (gray lines are without thermomechanical coupling).

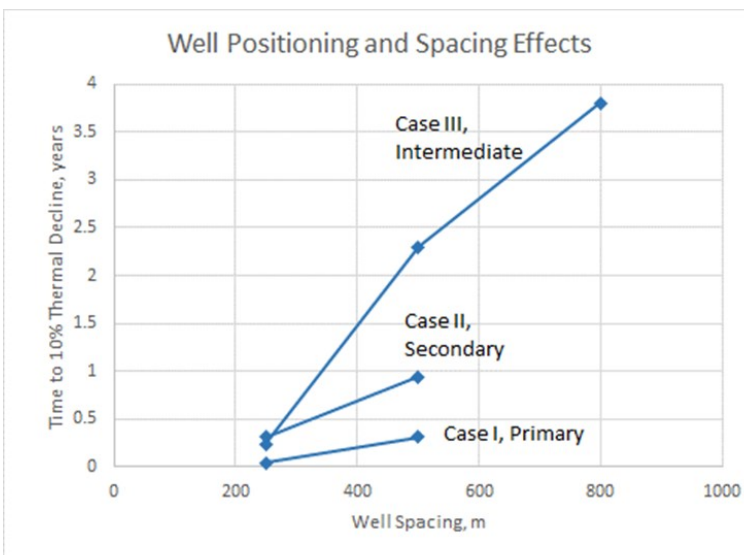


Figure 9. Time to 10% thermal decline by well position and spacing in Itasca simulations.

The intermediate well positioning produced the best production performance based on thermal longevity (time to 10% thermal decline). For a spacing of 500 m, the well pair aligned with the major declined by 10% in temperature in roughly 4 months, while the intermediate well alignment took 28 months to decline that amount. The well pair aligned in the secondary set direction behaved between the intermediate and major set alignments breaking through in about 12 months. Figure 9 summarizes the well positioning study results in terms of the well spacing and alignment relative to the primary and secondary fracture sets. Alignment of wells with the primary set encourages early thermal breakthrough.

The LLNL well positioning studies (§5.3) also used two fractures sets. Like the Itasca simulations, the alignment in the minor set direction performed considerably better than the alignment in the major set direction. Single well pairs spaced 800 m apart with 20 kg/s flows had thermal break through times of 17 years for circulation in the major fracture-set direction and greater than 30 years for the minor set direction. LLNL did not specifically simulate flow in a direction intermediate to the two sets, however, they did look at a so-called 5-spot configuration with four production wells at the corners of an 800-m square and an injector at the center. The overall pattern of the wells aligned two of the production wells more closely with the major fracture set, and the other two more closely with the minor set. The wells aligned more closely with the major set had breakthrough in 18 years compared with nearly 25 years for the wells aligned more closely with the minor set.

Optimizing shear stimulation for fracture surface area

The DFN simulations of Itasca and LLNL explored the creation of fracture surface by shear stimulation and its effects on heat transfer. Among the factors these simulations considered were fracture network geometry, fracture properties, and in situ stress conditions.

Itasca's two-dimensional simulations used a fracture network with two stochastic sets to investigate the effects of fracture network geometry and properties on shear-stimulated area and thermal performance during fluid circulation. The simulations took two forms — coupled hydromechanical models without thermal coupling and coupled hydro-thermo-mechanical models. The hydromechanical models (§3) mainly investigated factors that affected stimulated fracture surface area during stimulation of EGS, while the hydro-thermal-mechanical models (§4) were used to simulate the production phase to predict produced temperature and energy versus time.

Among the variables considered by hydromechanical models were fracture size and intensity, fracture dilation angle, and in-situ stress conditions. The fracture size and intensity variation studies found that these parameters strongly influenced the connectivity of the fracture network over the model space. Simulations with longer fractures tended to localize deformation and flow along single pre-existing fracture resulting in relatively short breakthrough time during production. Networks of shorter fractures with multiple sets favorably oriented to slip during stimulation resulted in a connected network of fractures that were relatively uniformly stimulated in shear.

The models applied a major and a minor principal in situ stress at the boundaries. The ratio of these stresses influences the shear stimulation potential, where a large difference allowed shear stimulation at lower injection pressures for a wider range of fracture orientations, while more equal stresses required higher stimulation pressures for a limited range of fracture orientations.

In summary, Itasca's coupled hydro-thermo-mechanical simulations identified factors that increased the surface area for heat exchange and improve thermal performance. Increasing the distance between the injection and production wells is one of these effects provided the distances are not too large for fracture networks to retain their connectivity. Higher fracture intensity (more fracture per unit area) also increases the surface area for heat exchange (Figure 5).

Three-dimensional DFN simulation of multi-stage stimulation

Itasca compared multi-stage and single-stage stimulation strategies (§3.5.3) using 3D DFN simulations. Single stage stimulation injects over the entire open hole section of the well. In such a case, the most naturally conductive zones take most of the stimulation fluid to the detriment of less conductive zones. Multi-stage stimulations use multiple isolated sections, which distribute the injection fluid more evenly along the length of the well resulting in a larger number of fractures being stimulated. The area of shear stimulated fractures from multi-stage stimulation was more than double that of single-stage stimulation.

Effects of Thermal-Hydro-Mechanical Coupling

<u>Basic Effects</u>

During EGS production the rock thermally contracts as it cools. A portion of that contraction increases the apertures of the fractures. The opening of fractures, in turn, increases the transmissivity of the fracture and decreases the flow impedance. The thermal contraction is more pronounced in the portions of fractures that are flowing, and any heterogeneity of transmissivity that exists prior to cooler water circulation will be enhanced by thermomechanical effects. Both Itasca and LLNL compared EGS simulation with and without thermal-mechanical coupling.

<u>LLNL DFN simulations</u>

The LLNL simulations found that thermal effects increase the heterogeneity of the flow properties significantly. These effects follow a positive feedback where cooled portions of fracture network become more transmissive as apertures increase. The localization of thermal contraction further concentrates flow enhancing channeling effects both among fractures (§5.4) and within single fractures (§5.5). As discussed above, thermal-mechanically induced channeling reduces the effective heat-exchange area and results in early thermal breakthroughs.

LLNL also looked at thermomechanical effects in a multistage EGS with heterogeneous fracture transmissivity and proposed a strategy of active reservoir management (ARM) that shuts down stages that have early thermal breakthrough (§5.5.2.2). This approach assumes a multistage EGS where the stages have heterogeneous transmissivity. The earliest breakthrough stage is the one with the highest initial transmissivity, which thermomechanical coupling enhances as the rock cools and the apertures open. After breakthrough, ARM stops the flow to the most transmissive stage, which diverts the major portion of circulation to the second most transmissive stage. Moving forward, the ARM strategy continues to shut down stages that break through and push the circulation to the remaining open stages. Figure 10 shows the thermal performance of an EGS using ARM.

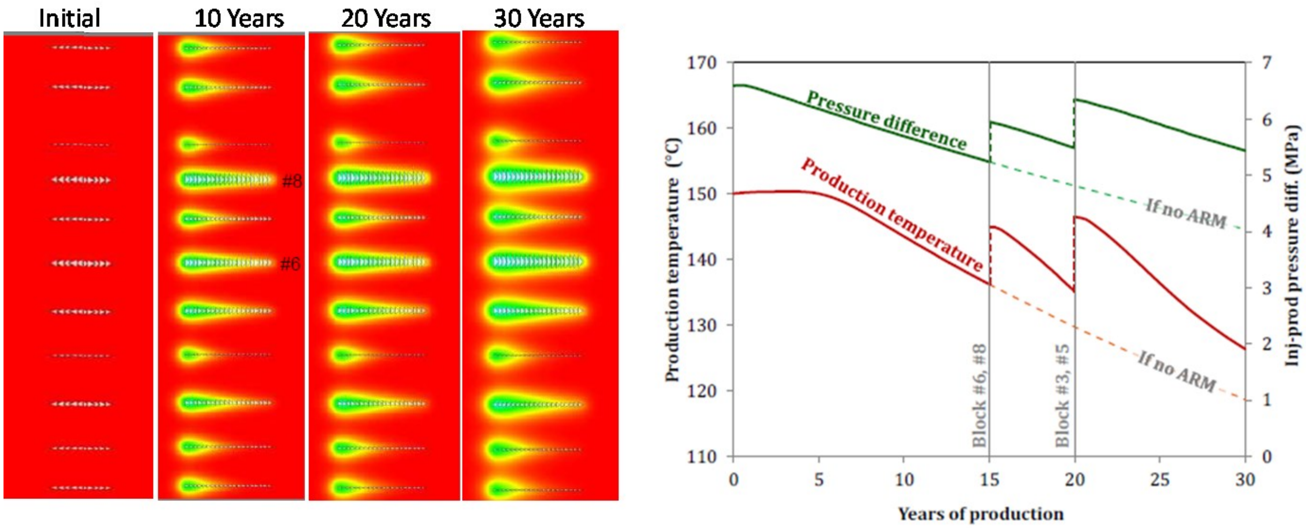


Figure 10. LLNL simulations of thermal drawdown and production temperature in a multistage EGS using active reservoir management (ARM). The most transmissive (Block 6) shuts down at 15 years and the second most transmissive stage shuts down at 20 years. Dashed lines show the effect on production temperature without ARM interventions.

Itasca DFN simulations

Itasca performed their simulations of well positioning and spacing effects using both coupled and non-coupled models (§4.2.4 and Figure 8). The uncoupled production-well temperature curves have a smooth decline with time. The coupled results, while following the general trends of the uncoupled curves, include occasional jumps and reversals in decline trends (i.e., non-monotonic histories). The similarity in the coupled and uncoupled trends seems to indicate that coupling (which is computationally more demanding) was not necessary to determine the overall trends in production performance. Sometimes non-monotonic temperature and produced energy histories predicted by these DEM models imply the complex coupled behaviors with fractures opening (secondary stimulation) or closing relatively quickly in different parts of the fracture network (potentially shutting off or opening entire flow paths between the wells) with sudden effects that can explain jumps in the production temperature.

Coupled thermo-mechanical importance for future field operations and EGS demonstrations

DFN simulations show the value of stimulating multiple fracture sets and positioning wells to optimize the circulation through the stimulated fracture networks for enhancing heat-exchange surface area. This is an important topic for both field operations and EGS demonstrations and it has several components including:

• Identifying natural fracture sets that are prone to shear stimulation

• Knowing the in-situ stresses well enough to accurately predict the conditions for shear-stimulating one or multiple sets

• Understanding the tradeoffs in fracture connectivity and impedance associated with positioning wells to avoid localization of deformation and flow along the major fracture sets and exploit tortuous pathways including minor fracture sets.

• Validating fracture exploitation strategies using production temperature behaviors in field experiments.

• Validating in field experiments the ability to create and characterize shear-stimulated natural fracture pathways for EGS circulation.

SIMULATION OF COUPLED CHEMICAL EFFECTS

Importance of chemical effects

Coupled chemical effects have importance both in the characterization and operation of an EGS reservoir. The successful production of the EGS reservoir requires recognizing, predicting, and mitigating changes in the flow circulation caused by the chemical processes that locally reduce or enhance the openings of fractures.

The coupled chemical simulations discussed in Section 6 use a hybrid modeling process that maps fracture properties from a DFN model into TOUGHREACT, a well-established continuum code for geothermal applications (Finsterle and others, 2014). The simulations were based on fracture data and conditions from the Newberry, Oregon, geothermal development site (Smith and others, 2015; Cladouhos and others, 2011). The Newberry simulation results clearly show that the circulation system evolves over time due to chemical processes (Sonnenthal and others, 2012, 2015).

Chemical effects input for future field operations and EGS demonstrations

The results presented in this report serve primarily as a demonstration of a simulation approach that upscales fracture properties from a DFN model to a well-established continuum code, TOUGH and its chemical supplement, TOUGH-REACT. As such, this report acknowledges progress that has been made to date and recognizes the need to develop further an ability to predict chemical effects in EGS production from fracture networks using information from field sites. A successful EGS development requires not only the existence of a fracture network with sufficient area for heat exchange, but also the ability to maintain that surface area through the production life of the reservoir. Chemical effects are extremely important to the sustainability of the reservoir and should be a focus of EGS field demonstrations and further model development.

THREE-DIMENSIONAL DFN MODELS IN DIFFERENT REGIONAL SETTINGS

Regional settings

A major attraction of EGS development is the possibility of producing geothermal energy anywhere that rock with sufficient temperature exists, and not just the few places where there is a naturally conductive geothermal reservoir (INL, 2006). Hot rock exists in the subsurface everywhere; however, the depth to an exploitable thermal reservoir will vary depending on the geothermal gradient.

This section of the report considered regional variations of EGS performance within the continental United States. The approach simulated EGS power production using 3D DFN models of fracture networks of three archetypical regional settings (§7; Finnila and others, 2015, 2016, 2017):

• A thrust faulting setting in granitic rock in the northeastern US with low geothermal gradient

• A normal faulting setting in metavolcanics rock in western basin and range province with a high geothermal gradient (based on Desert Peak, Nevada), and

• A strike-slip faulting setting in basalt proximal to California's San Andreas Fault in the Salton Sea Basin with a very high geothermal gradient.

The ability to shear stimulate varied greatly among the three cases. The normal and strike-slip settings were very close to critical stress conditions even before stimulation, while the thrust faulting case proved very difficult due to the high stress conditions and depths required to reach the target reservoir temperature of 200°C.

Estimating the effect of shear stimulation on transmissivity

A significant area of uncertainty in the modeling was the transmissivity increase due to shear stimulation. The modeling used multipliers of 10, 100, and 1000 over the natural fracture transmissivity. Flow simulations targeted an impedance of 0.15 MPa/l/s, which could be achieved with multiplier of 10 in the strike-slip setting but required multipliers of 100 or more for the normal and thrust fault setting. Achieving low impedance was particularly challenging for the thrust faulting case where initial fracture transmissivity values were very low due to the depths and stresses. In general, at least one fracture set needs to be optimally aligned for shear stimulation to achieve acceptable impedance values.

Three-dimensional behaviors

The three-dimensional modeling revealed two key behaviors that would not be evident in two-dimensional modeling. For the thrust-faulting case, shear stimulation favored shallow-dipping fractures at shallower depths. This negatively affected thermal performance as shallower fractures are also cooler fractures.

The second key behavior in three-dimensional modeling appeared in the normal faulting stimulations where fracture growth also was favored by shallower stress conditions. Simulations of hydraulic stimulation for a basin and range, normal faulting environment (§ 7.2.3.3, Figure 11) can result in upward growth of hydraulic fractures and hydraulically stimulated natural fractures. The vertical growth depends on the relative gradients of the minimum horizontal stress and the fluid pressure (Secor and Pollard, 1975). Assuming the reservoir temperature is decreasing with shallower depth, the upwards growth means that the circulation system will produce from cooler rock than at the depth where the stimulation initiates. Preferential vertical growth was also observed at the Rosemanowes test site in the United Kingdom (Pine and Batchelor, 1984) albeit in a downwards direction. The vertical migration was attributed to the stress and fluid pressure gradients.

Importance of regional stress and thermal gradient for future field operations and EGS demonstrations

The results of the three-dimensional modelling in different regional setting reinforce several key points including the following:

• Understanding the in-situ stress conditions

• Characterization of the major fracture set orientations with respect to critical stress and shear stimulation.

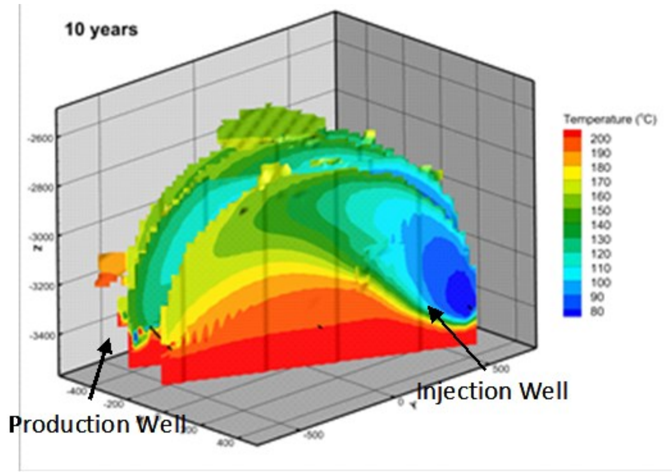


Figure 11. Water temperature in vertical hydraulic fractures of normal faulting regional model after 10 years. Injection well located on right side with Production well located on left side of figure (scale is in meters). Note preferential cooling due to larger opening (apertures) of fractures at shallow depths.(Finnila et al., 2015).

Additionally, these simulations point out the needs for the following:

• Better estimation of the transmissivity changes that result from shear stimulation from field data and

• Better understanding of the influence of stress and pore pressure gradients with depth and their effect on vertical growth of stimulated fracture networks.

CONCLUSIONS

- For the baseline viability criteria, an EGS requires several square kilometers of effective fracture area for heat exchange. Creating a reservoir with this surface area will likely require multiple fractures or stimulations.
- Analytical solutions make clear that higher surface area for heat exchange and lower flow rates have a second power effect on delaying breakthrough at the production well. Conversely, underestimating the effective heat-exchange area for a given flow rate results in early thermal breakthrough with a second-power effect. The early breakthrough reflects cooling along the circulating fractures and does not represent thermal depletion of the reservoir.
- Heterogeneity of transmissivity between fractures in a multi-stage stimulation EGS and within single fractures reduces the effective heat exchange area; heterogeneous EGS systems may lead to further localization of deformation and flow resulting in short-circuited systems that have early thermal breakthrough at the production well.
- EGS developments may utilize shear-stimulated natural fracture networks that have multiple fracture-set favorably oriented relative to anisotropic in-situ stress state. Among other factors, well placement to create circulation pathways through multiple fracture sets or increase the tortuosity of fracture pathways enhances the effective fracture surface area for heat exchange and improves thermal performance.
- Chemical effects can be effectively simulated in continuum models (TOUGH) to show permeability changes with dissolution and precipitation during EGS production.
- Three-dimensional simulations are required to capture the effects of DFN and stress and fluid pressure gradients that may drive preferential vertical growth into cooler or hotter portions of the reservoir.
- EGS development strategies may regionally depend on the geothermal temperature gradients, the natural fracture network geometries, and the natural fracture hydro-mechanical properties, and especially the orientations of natural fractures relative to the principal stress directions and magnitudes.

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