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IMPACT OF SILICA GEL DEPLOYMENT ON SUBSURFACE FLOW AND HEAT EXTRACTION FROM ENHANCED GEOTHERMAL SYSTEMS

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ABSTRACT

We carried out modeling studies to demonstrate how the silica agent can be used and show how we anticipate the silica blocking and diverting agent will perform on a simple thermal test within a single fracture. The modeling code enables us to calculate the drawdown and flow rates for desired scenarios for comparison to those without the silica blocking agent. We illustrate gel deployment mainly in a single fracture; however, we have begun simulating silica gel in a three dimensional fracture network. Logistics for a parametric study for optimal use of silica gel are discussed. We conclude by a short discussion on gel deployment under conditions of uncertainty in the EGS subsurface characterization.

INTRODUCTION

Effective heat extraction requires sufficient permeability to allow substantial quantities of fluid to circulate through the subsurface, while simultaneously allowing for adequate residence time for conductive heat transfer between the host rock and the circulating fluids. Unfortunately, techniques commonly used to enhance permeability, such as hydraulic fracturing, can result in short-circuiting between injection and production wells. Thus, development of effective techniques for reducing permeability is also necessary for advancing EGS technology. Ideally such techniques will: (i) utilize materials that are readily available and environmentally sustainable, (ii) be reversible to preclude the possibility of permanent degradation of the reservoir, and (iii) be controllable, such that permeability can be reduced in targeted regions of the reservoir to enhance overall heat extraction. In the current study we are investigating the use of colloidal silica as a diverting agent. Under certain physico-chemical conditions colloidal silica forms a low-permeability gel that, if emplaced strategically in the subsurface, may create new circulation cells and pathways that enhance heat extraction and minimize short-circuiting pathways.

WHY SILICAS AS DIVERTERS

Silica gels are abundant in various surface and subsurface applications, yet they have not been evaluated for EGS applications. A significant benefit related to EGS is that colloidal silica can be co-produced from geothermal fluids using an inexpensive membrane-based separation technology that was developed previously at LLNL (Bourcier et al., 2006). Diverting agents have been effectively used in the petroleum industry to enhance recovery, however, these are often organic polymers that raise environmental concerns and they haven't been tested and applied under geothermal conditions. Silicas are inorganic and environmentally friendly as opposite to organic gels often used in oil/gas industry (Mungan, 1965, Udell & Lofy, 1989, Liang et al, 1992). Unlike conventional blocking agents, the gel material is not a brittle solid and if needed might be hydraulically removed after emplacement. Silica gelation can be triggered externally, for example by mixing with salt solutions, changing the pH, or increasing temperature. There should be fewer environmental restrictions and permitting requirements for their use given that the material originates in the same place it is to be injected. We are unaware of prior studies aimed at quantifying permeability reductions in fractures caused by the in situ inorganic silica-gel solution. Furthermore, at the geothermal field scale, the problem is to develop a methodology for emplacing silica gels into zones where reduced permeability is desired, and avoid gelation along flow paths that need to remain open.

LLNL'S EXPERIMENTAL STUDIES

Batch Gelation Time experiments

A quantitative understanding of the kinetics of silica gelation is required to predict when injected silica colloids turn into gel. Because of the lack of any quantitative method or model for predicting gel times from colloidal silica compositions, LLNL (Hunt et al., 2012), began a laboratory study of the gelation time of colloidal silica by setting up a facility for measuring gelation time. Such instrumentation (Figure 1) is needed to develop colloidal silica solutions for given geothermal applications. In addition, there is very little information on gel times at elevated temperatures. Because of these needs, LLNL also began to acquire additional data that target high temperature conditions for geothermal applications. This additional data could be combined with the existing data to develop a more comprehensive quantitative model for use in our geothermal application.

Figure 1: Sunshine Gel Time Meter (http://www.davis.com)

The gel time meter was used to quantitatively determine the effects of SiO_2 concentration, pH, and salt concentration on the gelation time of colloidal silica sols at ambient temperature, to provide a foundation for experiments at higher temperature. The major finding of this investigation was that there is a simple relationship between gelation time, SiO_2 concentration, and salt concentration. If the dilution is done by adding different amounts of water to identical mixtures of colloidal silica sol, NaCl, and HCl, a linear relationship arises between the logarithm of gelation time and the logarithm of the silica concentration (Figure 2).

Gelation experiments in 2d Hele-Shaw

Preliminary proof-of-concept experiments carried out at LLNL demonstrate the potential for using visualization experiments to explore the mechanisms controlling permeability alteration caused by in situ silica gel formation (Figure 3). Initial experiments illustrated the formation of a gel surrounding the injection port caused significant diversion of the injected dye during the second injection, supporting the concept of using silica gel as an effective diverting agent in fracture media. Several experiments are planned to explore the behavior of gel deployment on the topological shape of created gel diverters.

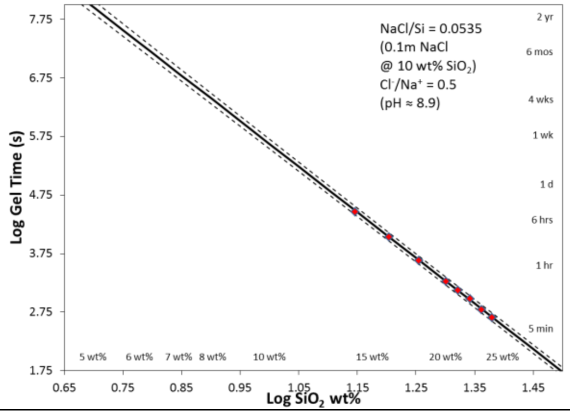


Figure 2: Log gel time versus log silica Concentration

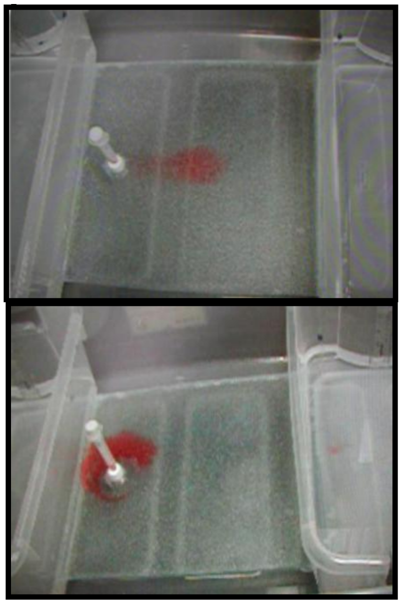


Figure 3: Proof-of-concept visualization experiment; dye flowing from injection port with right-to-left gradient (top image) and dye flowing under same conditions after injecting a mixture of colloidal silica and sodium chloride (bottom image).

LLNL’S MODELING STUDIES

Modeling philosophy

Our modeling philosophy calls for a multi-level approach by increasing the level of modeling difficulties. It encompasses three-steps:

1. Implement the physical-chemical process of gel transport in a single smooth and rough-surface fracture.
2. Migrate the single fracture model into a simple fracture network (3 to 5 horizontal parallel fractures) for technology evaluation.
3. Integrate the resulting model into a SDFN-THMC (Ezzedine, 2005) model for technology assessment and predictive response.

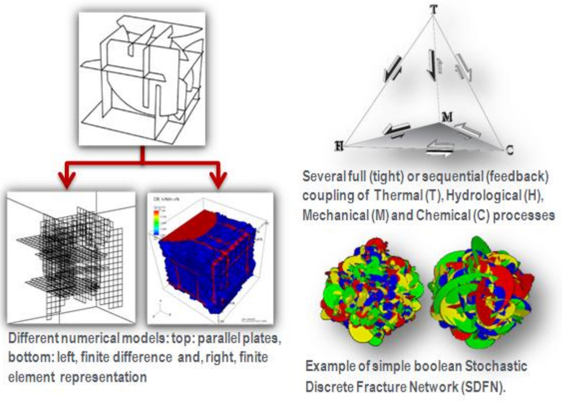
By using existing codes and/or leveraging other code developments we will be able to develop gel deployment protocol in predictive mode with an estimated probability of success. Our ultimate goal is a three dimensional numerical simulation of a realistic EGS site. The subsequent results are a step forward toward that goal.

The numerical simulation tool: SDFN-THMC

The model used to perform the subsequent simulations is described in Ezzedine (2005) and has been extensively used in recent years to address the impact of uncertainties in the geological characterization of fracture on the thermal response of an EGS (see Ezzedine, 2009-2011). It was originally coded to simulate the system at Soultz-sous-Forêts. Fractures are either deterministic or stochastic. Fractures are characterized by their density, orientation, size and aperture. The model allows for multiple sets of fractures, each having their own probability distribution (density) functions. The model is equipped with several numerical schemes for solving the different previously mentioned processes and different protocol for the numerical coupling of those processes (see Figure 4) Moreover, it offers different geological conceptualization of the fractures and how the physical processes are solved within each fracture of the fracture network.

Newtonian vs. non-Newtonian fluids

It is worth noting that gels behave as non-Newtonian fluids (gel viscosity is dependent on the shear rate). To better mimic the physical processes we have implemented the non-Newtonian fluid behavior in the model. Figure 5 depicts the velocity profile with the aperture for three different cases: a) sub-Newtonian (flat profile), b) Newtonian (parabolic profile), and c) hyper-Newtonian (peaked profile). We expect that silica gel velocity profile shape will be non-parabolic and thus non-Newtonian.



Several full (tight) or sequential (feedback) coupling of Thermal (T), Hydrological (H), Mechanical (M) and Chemical (C) processes

Different numerical models: top: parallel plates, bottom: left, finite difference and, right, finite element representation

Example of simple boolean Stochastic Discrete Fracture Network (SDFN).

Figure 4: SDFN-THMC (Ezzedine, 2005) offers an ideal numerical framework to address the problem of deploying silica gel in EGS. The model allows for flow, thermal, and mechanical & chemical simulation in a 3d stochastic discrete fracture network.

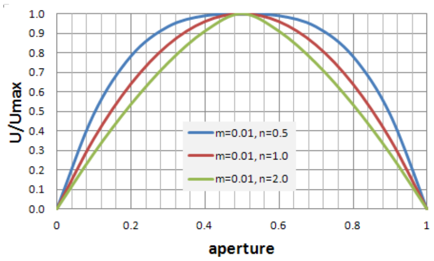


Figure 5: Normalized velocity profile of fluid within fracture aperture. Parameters m and n are characteristics of the fluid and the profile. Red profile, parabolic, is the Newtonian; the other two (blue and green) are non-Newtonian.

2D simulations with no gel deployment

We have simulated the flow without gel deployment in a two dimensional setting. As an initial step, the fracture is assumed to have smooth walls (i.e. constant aperture, 200μm). A geothermal doublet (one injection and one production well) shown in Figure 6 (top) depicts the pressure field distribution throughout the fracture, the location of the injection and production wells as well the streamlines. The flow network shows the circulation cell and stagnation point. As a second step toward a more complex fracture, we have simulated a fractal aperture field. Figure 6 (middle) depicts the random fractal field of the aperture with a mean aperture equal to the smooth fracture initially simulated, i.e. 200μm. The flow and streamlines are then resolved for this case and depicted on Figure 6 (bottom). It is worth noting the impact of heterogeneity in the aperture field on the flow streamlines. Flow circulation cells are no-longer smooth and their roughness reflects the tortuous paths that the fluid emanating from the injection well takes to reach the extraction well.

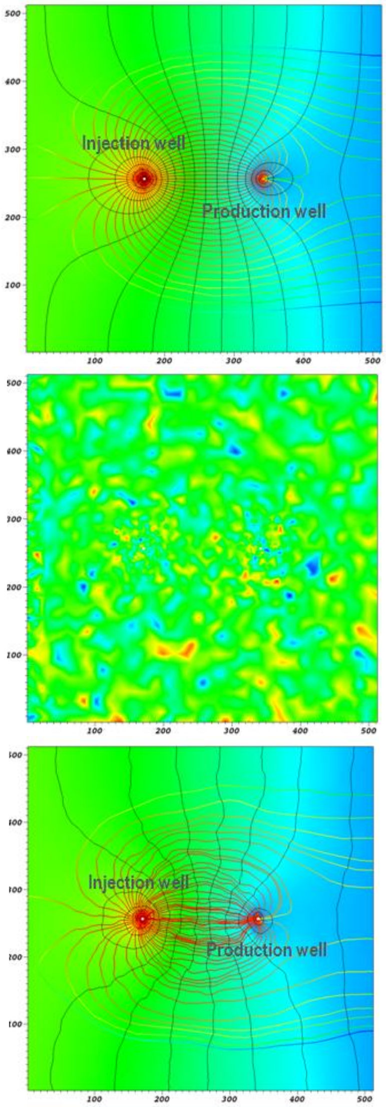


Figure 6: 2D doublet flow simulations in a single fracture. Top: flow network (pressure and streamlines) in a smooth fracture. Middle: aperture random field, red depicts large aperture while blue depicts small aperture. Bottom: flow network in a rough fracture.

Two dimensional simulations with gel deployment

Here we are considering the deployment of the silica gel using experimental gelation time curves obtained from experiments conducted at LLNL by Hunt et al. 2012 (see Figure 2). To further illustrate the impact of gel deployment on the thermal response of the doublet we have solved not only the flow and transport of gel within the fracture but also the heat transfer from the host rock. A thermal test of 250 hrs has been simulated. At ~80 hrs the temperature signature started to decrease from it maximum of 120°C. At this time we have started injecting the silica with a gelation time of 20hrs (see Figure 7 bottom).

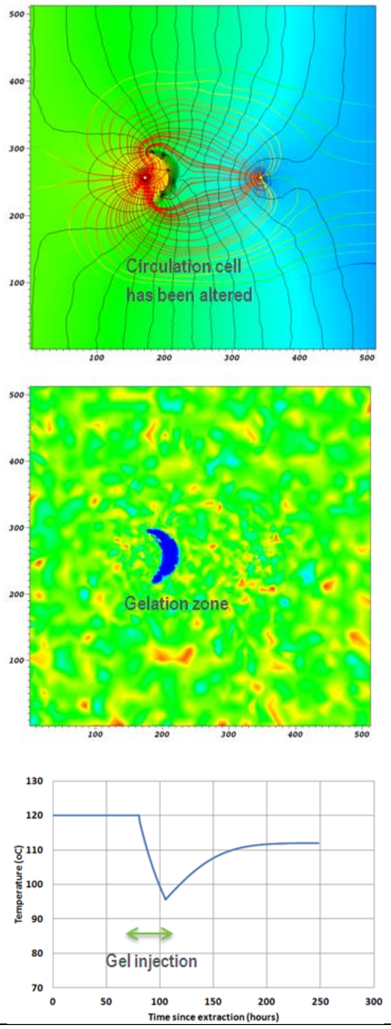


Figure 7: 2D doublet flow and transport simulations of gel in a single rough fracture. Top: flow network showing the impact of gelled silica on streamlines and flow cells. Middle: aperture random field with crescent-like diverter i.e. gelled silica. Bottom: Thermal test protocol and temperature responses as function of time.

Once the gel settles in the initial circulation cell it created a crescent-like shape (blue area on Figure 7 middle which should be compared to Figure 6 middle). Because the streamlines now have been diverted by the presence of gelled silica the injected flow follows different paths to reach the extraction well thus creating a new sweeping zone (circulation cells) from both sides of the crescent diverter. The new pressure field and streamlines impacted with the gel deployment are depicted on Figure 7-top. It is expected that the aperture field around the gelled area will dictate the roughness of the streamlines. It should be noted however that the newly injected geofluid now comes in contact with new surface areas leading to an increase in the fluid temperature to ~110°C from ~95°C. The temperature did not reach its initial 120°C which is attributed to mixing, loses to the surrounding area and most importantly the flow and thus the streamlines are sweeping area with different apertures and therefore different advective flux (velocities).

It should be noted that this simple exercise serves as proof of concept of positive impact of gel deployment on the thermal response of an EGS, when it is used appropriately and judicially. It is also worth noting that the response of the system and the gelled area prediction depends on how well the fracture is characterized. Often we are faced with limited data, especially when fractures are too deep. Prediction under conditions of uncertainty is therefore a must and will be touched upon later.

2D parametric study with gel deployment

Gel deployment in the fractures involves several sensible key parameters that govern the flow, transport and gelation time processes. Example of such parameters are, but not limited to: Peclét number, Reynolds number, Damkohler number, and Fourier number. For example for high Peclét number (advection dominates) the gel deployment topology takes a different shape than in the previous simulations. For example, Figure 8 depicts a series of snapshots for an advective flow with short gel injection time. Injection is conducted into the left well while extraction is performed from the right well. The snapshots show the distribution of the gel within the fracture. At early time, a ring-like signature of the gel diverges away from the injection well (point) and then travels downstream and gets captured by the extraction well. If designed correctly each one of these snapshots could correspond to a particular gelation time leading to a closed circulation cell. By changing the values of the key parameters one can expect different outcomes of the shape topology of the gel. For illustration purposes, Figure 9 depicts several outcomes as functions of two key parameters. This strategy might be used to reduce water use in geothermal power production.

Given an ultimate goal of the gel deployment in fractures one can design different outcomes such as enhanced heat recovery, zonal isolation, or modified fluid circulation. Charts such is the one presented in Figure 9 will assist technologists to target the right set of space parameters to produce the right design. We have began exploring the space parameters and correlating the outcomes.

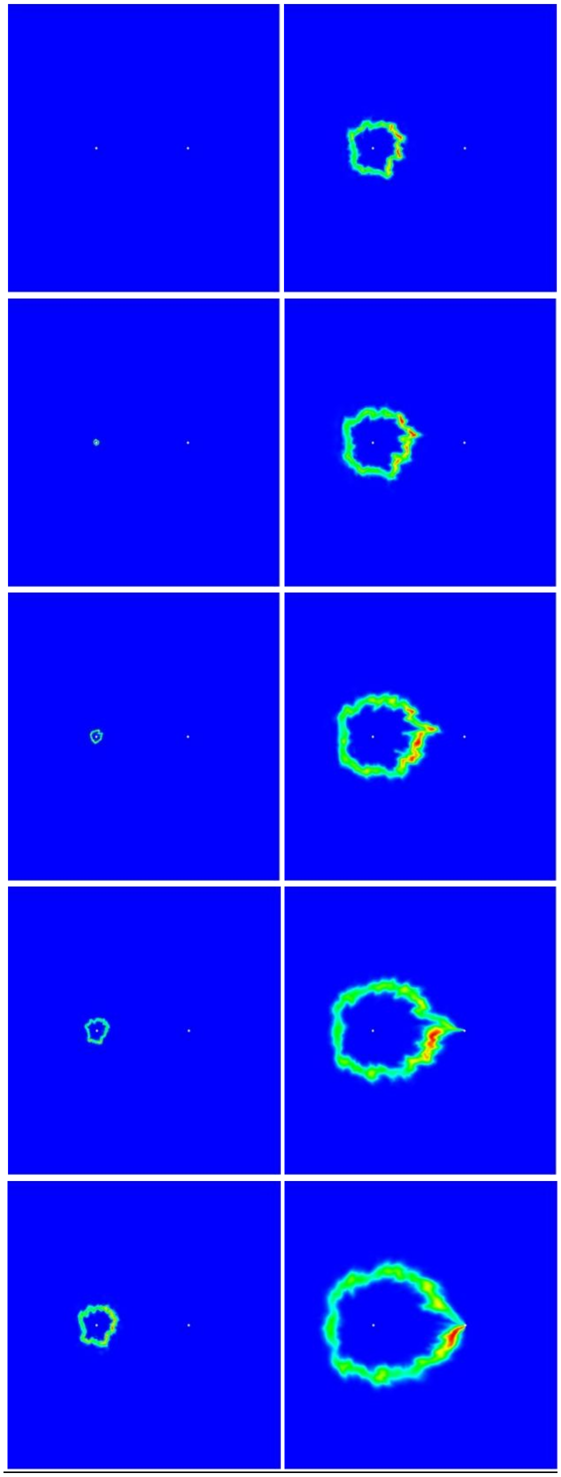


Figure 8: Snapshots of two dimensional doublet flow and transport simulations of gel in a single rough fracture. Time flows from top to bottom and left to right. Top left picture depicts the hydrological conditions. Painted colors are not at the same SCALE; these pictures are for illustration purposes.

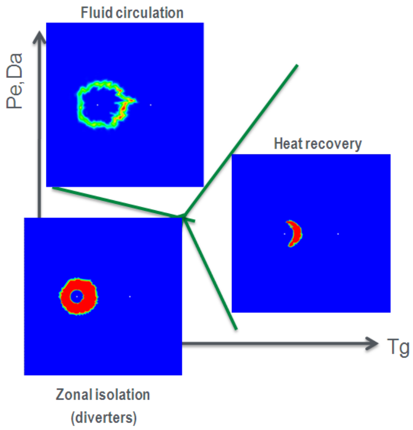


Figure 9: Illustration of different outcomes of gel deployment as a function of the key physico-chemical parameters that govern flow, heat, gel transport and gelation time.

Preliminary three dimensional gel deployment in multiple fractures

Real applications are three dimensional. To illustrate the application of gel deployment in a simple 3-D fracture network we have modeled flow in a system of five parallel fractures, each having a different aperture field. All factures are connected through the operational wells. Figure10 depicts the aperture random fields (left), the calculated pressure field (center) and the particle streamlines (right). The results illustrate the complexity of the flow field. It should be noted that the rock matrix between the fractures has been omitted for display purposes. We are planning to conduct additional simulations on more complex fracture network such as those illustrated in Ezzedine (2010-2011) in order to identify useful gel emplacement strategies.

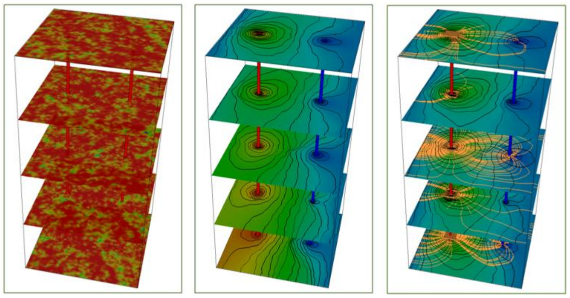


Figure 10: Illustration of 3D fracture network composed of 5 parallel fractures each having its own aperture field (left). The pressure distribution within each fracture is depicted on the middle plate, while particles emanating from the screen interval (intersection of the injection well with the fracture) and flow downstream to the extraction well are depicted on the right plate. Injection well is depicted as a red cylinder while the extraction well is in blue.

IMPACT OF UNCERTAINTIES ON GEL DEPLOYMENT IN AN EGS

When dealing with real three dimensional subsurface applications we have to cope with the uncertainties associated not only with the intrinsic thermo-hydrological properties of the host rock but also the chemical uncertainty associated with the gelation time of silica (see experimental results). Moreover, the deeper the geothermal system, the more expensive is the data collection. We often deal with incomplete characterization of the site at the target depth and moreover it is practically impossible to characterize each fracture of the fracture network in detail. Uncertainties and limited data usually call for uncertainty propagation, quantification and sensitivity analysis (UQ) of key design parameters. We have already touched on this matter in the previous sections using a single realization of each aperture field for each fracture. A probabilistic UQ could be accomplished through a classic Monte Carlo analysis. The prediction of the system response is the ensemble average of all realizations. As stated before, there are several keys design parameters and several fractures; each is characterized by several other parameters (e.g. correlation length, mean aperture, correlation function of the aperture and others). Furthermore, the characterization of the fracture network (density of fractures, fracture size etc.) is itself tainted with limited data and thus uncertainties in the geological characterization of the fracture network. LLNL has already invested for several years in this problem. For example Figure 11 shows a flowchart of UQ analysis that has been customized for UQ in EGS (see Ezzedine, and Ezzedine et al., 2009-2011 with several applications). In the coming year we plan to leverage existing technology available at LLNL to address the stochastic nature of gel deployment in realistic fracture networks.

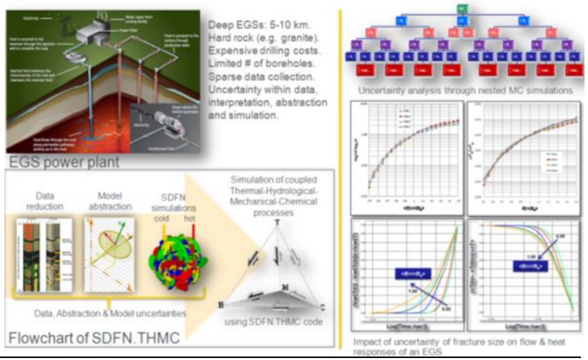


Figure 11: Flowchart of uncertainty propagation and quantification for EGS applications. Using a Monte Carlo scheme one can assess the impact of characterization uncertainties on the EGS response.

SUMMARY

We have attempted to address the main issues in deploying silica gel to enhance heat production from an enhanced geothermal system. Several hydro-thermal and chemical properties of the host rock as well the governing processes are all key parameters for gel deployment design for both a) heat production enhancement, b) flow circulation efficiency and c) zonal isolation and surface area sweeping. The characterization of the fracture network is essential for optimal gel deployment. However due to either budgetary constraints or technical accessibility, we often deal with limited data and high uncertainties associated with the characterization. To address this problem we have illustrated the impact of random aperture fields on pressure, streamlines and transport of gel in two and three-dimensions. LLNL has previously developed several tools that can address the uncertainty propagation, quantification and sensitivity analysis for large space parameters such as the one at hand. We have begun implementation of the gelation process into a more realistic three dimensional fracture network.

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