MAXIMIZING HEAT EXTRACTION AND MINIMIZING WATER LOSSES IN HYDROTHERMAL SYSTEMS: A NUMERICAL INVESTIGATION

William Bourcier, Souheil Ezzedine, Jonathan Hunt, Sarah Roberts & Jeffery Roberts

Lawrence Livermore National Laboratory
7000 East Avenue, Mail Stop L-188
Livermore, CA, 94550, USA
e-mail: ezzedine1@llnl.gov

ABSTRACT
In the current numerical study we demonstrate the use of diverters, such as inorganic silica gel, in enhanced geothermal systems (EGS) to 1) enhance heat extraction, 2) minimize fluid exchanger losses to the surrounding formation and 3) remediate short circuits, i.e. fast pathways, in a fracture or fracture network. The approach is extended to conventional porous geothermal systems (CGS). Several simulations illustrating pre- and post-deployment of diverters in EGSs and CGSs to remediate in-situ short comings and to extend the longevity of the system will be presented.

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 physicochemical conditions colloidal silica forms an impermeable solid gel that, if emplaced strategically in the subsurface, may create new circulation cells and pathways that enhance heat extraction and minimize short-circuiting pathways while reducing water use.

WHY SILICA GELS
Organic vs inorganic Diverters
Diverting agents have been effectively used in the petroleum industry to enhance recovery; however, these are often organic polymers that raise environmental concerns. Moreover most have not been tested or applied under geothermal conditions. Silicas, however, are inorganic and environmentally friendly (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. 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).
LLNL’s geothermal Silica mining

In geothermal power plants, as a component of the heated underground fluids, silica clogs pipes, wells, and heat exchangers. LLNL has developed a technology for extracting silica from geothermal fluids, allowing plants to work more efficiently and have a marketable silica by-product. The Livermore extraction process involves running a geothermal fluid through a reverse-osmosis separation process to create freshwater and concentrated brine. The brine is pumped into a reactor where chemicals are added and silica is extracted. The silica-free brine can then be pumped through another process for extraction of other metals before the fluid is pumped to a surface pond and reinjected into the subsurface (Figure 1). Simple silica molecules bond together to form colloids—silica particles about 10 to 100 nanometers in size (Figure 2). These larger molecules cluster to form particles that can be removed by filters downstream from the reactor.

The Livermore extraction process allows controlling the size of colloids and agglomerates so that their surface areas and pore sizes match those of commercially useful silicas. (Figure 3).

LLNL’S EXPERIMENTAL STUDIES

Gel Timer measurements

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, 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 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. A gel time meter, Figure 4-left, was used to quantitatively determine the effects of SiO₂ 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 gel time meter was used to quantitatively determine the effects of SiO₂ concentration, pH, and
salt concentration on the gelation time of colloidal silica sols made with commercially available LUDOX SM-30 at 25 °C, to provide a foundation for experiments at higher temperature. The major finding of this investigation is that there is a simple and clear relationship between gelation time and SiO$_2$ concentration.

Figure 5: Log gel time versus log silica Concentration (Hunt et al, 2012)

Previous investigations varied SiO$_2$ concentration while keeping pH and NaCl concentration constant. However, 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 5). While the NaCl concentration and pH are changing as the mixtures become more diluted, the molar ratio of NaCl to SiO$_2$ and the molar ratio of added HCl to the Na$^+$ stabilizer present in the colloidal sol (hereafter referred to as universal neutralization ratio or UN ratio) remains constant. Figure 5 depicts the log-gel time as function of the log-concentration of silica at a specific UN value, temperature, pH and ratio of brine to silica. Red dot represent measurement, while black line depicts the proposed regression model and its 95% confidence internal.

PVS Rheometer measurements

Preliminary results from the rheometer (Figure 4 right) indicate that gelation times can be reliably obtained from plots of viscosity over time, and that shear rate does not affect gelation time. An example of a viscosity over time plot is shown on Figure 6. The data on Figure 6 are for a colloidal silica solution with 17 wt% SiO$_2$, a NaCl/SiO$_2$ ratio of 0.11, and a universal neutralization (HCl/Na$^+$) ratio of 0.5, subjected to a continuous shear rate of 5Hz. The viscosity remained near that for water for approximately 1600 seconds, which agrees well with the gelation time of 1634 seconds recorded by the gel time meter for the same colloidal silica solution. During the gelation process, the colloidal solution starts thickening, the viscosity significantly increases, and reaches a maximum of 9000 cP at around 2400 seconds. At this point, the gel starts to slip past the inner cylinder rather than exerting a constant torque on it, causing the measured viscosity to drop and become irregular.

Figure 6: Viscosity (cP x 10$^3$) as a function of time (seconds), measured at room temperature at a constant shear rate of 5 s$^{-1}$. (Hunt et al, 2012)

However, the gel itself continues to stiffen and become brittle. This experiment was repeated using several different shear rates. The measured gelation time for each shear rate was within 2-3 minutes of the measured gelation time in the gel time meter; however, the maximum viscosity was dependent on the shear rate. If the shear rate doubles, the maximum viscosity recorded will be halved. This is entirely due to the interfacial layer of gel/water at the inner cylinder, and not reflective of the actual viscosity. These data have been used to develop a model to predict gelation times and incorporated into our gel emplacement model described in the next section.

NUMERICAL IMPLEMENTATION OF GEL EMLACEMENT

Modeling approach

Our modeling philosophy calls for a multi-level approach by increasing the level of modeling difficulties. It encompasses three-steps. Firstly, we have implemented the physical-chemical process of gel transport in a single smooth and rough-surface fracture. Secondly, we have embedded the single fracture model into a simple fracture network (3 to 5 horizontal parallel fractures) for technology evaluation, and thirdly, we integrated the resulting model into a SDFN-THMC (Ezzedine, 2005) model for technology assessment and predictive response.
Through this step-wise process, 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 7) 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 8 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.

The numerical implementation of gelation time is given by the following equation (Hunt et al., 2012):

\[
\log(t_{gelation}(s)) = \log(SiO_2 \text{ wt%}) + \ldots - \frac{NaCl (15.2UN^2 + 26.1UN + 4.6)}{Si} + \frac{5.4UN^2 - 11.25}{Si} + \ldots + \frac{NaCl (0.00)}{Si} + \frac{1.0UN^2 + 0.18}{NaCl} + \frac{7.2UN + 17.1}{Si}
\]

\[ (1) \]

The simplified version of the coupled flow, mass and heat transport equations are:

\[
\nabla \left( K(C_{SG}) \nabla P \right) = S_S \frac{\partial}{\partial t} P + S_P
\]

\[
\nabla \left( D(C_{SG}) \nabla C_{SG} - V(C_{SG}) C_{SG} \right) = R_{SG} \frac{\partial}{\partial t} C_{SG} + S_{SG}
\]

\[
\nabla \left( \mathcal{A}(C_{SG}) V T - V(C_{SG}) T \right) = C_P (C_{SG}) \frac{\partial}{\partial t} T + S_T
\]

\[ (2) \]

where \( C_{SG} \) is the concentration of silica gel, \( P \) is the pressure, \( T \) is the temperature. \( S_P, S_{SG} \) and \( S_T \) are the source/sink terms for pressure, silica concentration and heat, respectively. \( S_S, R_{SG} \) and \( C_P \) are specific storativity, retardation coefficient and heat capacity, respectively. It should be noted that these equations are fully coupled through \( K, D, \mu \) and \( V \) which are the hydraulic conductivity, the dispersion, the thermal conductivity and the velocity, respectively. These equations were solved numerically using SDFN-THMC (Ezzedine, 2005).

ENHANCING HEAT EXTRACTION FROM EGS USING GEL EMPLACEMENT

2D simulations with no gel deployment

We have simulated 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, 200\( \mu \)m). A geothermal doublet (one injection and one production well) shown in Figure 9 (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 9 (middle) depicts the random fractal field of the aperture with a mean aperture equal to the smooth fracture initially simulated, i.e. 200 m. The flow and streamlines are then resolved for this case and depicted on Figure 9 (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.

**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 Figures 5 & 6). 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 its maximum of 120°C. At this time we start injecting the silica with a gelation time of 20hrs (see Figure 10 bottom).

Once the gel settles in the initial circulation cell it created a crescent-like shape (blue area on Figure 10 middle which should be compared to Figure 9 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 by the gel deployment are depicted on Figure 10-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 deep. Prediction under conditions of uncertainty is therefore a must and has been covered by Ezzedine et al. (2010-2012).

**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.
Figure 10: 2D doublet flow and transport simulations of gel in a single rough fracture. Top right: flow network showing the impact of gelled silica on streamlines and flow cells. Top left: aperture random field with crescent-like diverter i.e. gelled silica. Bottom: Thermal test protocol and temperature responses as function of time.

Example of such parameters are, but not limited to: Peclet number, Reynolds number, Damkohler number, and Fourier number. For example for high Peclet number (advection dominates) the gel deployment topology takes a different shape than in the previous simulations. For example, Figure 11 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 12 depicts several outcomes as functions of two key parameters. This strategy might be used to reduce water use in geothermal power production.

Figure 11: 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.

We have begun exploring the space parameters and correlating the outcomes. In the subsequent section
we illustrate the use of silica gel to minimize the injected water loses to the surrounding formation. Given our goal of gel deployment in targeted fractures one can design different outcomes such as enhanced heat recovery, zonal isolation, or modified fluid circulation. Charts such as the one presented in Figure 12 will assist technologists to target the right set of space parameters to produce the right design.

MINIMIZING WATER LOSES FROM EGS USING GEL EMIPLACEMENT

To illustrate the use of silica gel for minimizing water loses to the formations we revisited the problem of Figure 11. First, we have turned off the extraction well allowing the ring-like slug of silica to propagate through to fracture until it encloses the extraction well. The concentration of silica should be designed to allow gelation only after the silica-ring enfolds both wells.

Once the silica gel is hardened, the extraction well can then be turned on and the injected water is limited to the circulation cell bounded by the hardened silica. This technology will limit the water loses to the surrounding formation and will lower production costs. Figure 13 depicts the process of creating the silica-gel bounded circulation cell. The left column depicts the process in a smooth fracture while the right column depicts the emplacement of silica-gel in a rough fracture. The first four rows depict the process of deployment while the last row depicts the process of the extraction mode when the production well is turned on.

Each frame depicts the concentration of the silica gel and the flow net (pressure and stream lines). Figure
14, however, depicts the initial and the last frames of Figure 13 to better illustrate the impact of silica deployment and the roughness of the fracture.

![Image](image1.png)

**Figure 14**: Initial (left) and final (right) snapshots of two dimensional doublet flow and transport simulations of gel in a single smooth (top) rough fracture (bottom). Each frame depicts the gel location and the flownet. In the left frames the production well is off, while in the right frames the production well is on.

It is worth noting that within the inner circulation cells (Figure 14 right column) one could apply the same concept of enhancing heat extraction, previous subsection, within the inner cell: creating different sweeping surface areas within the inner circulation cell, thus enhancing heat extraction while minimizing water loses to the surrounding formation.

**MODELING OF GEL DEPLOYMENT FOR REMEDIATING SHORT-CIRCUITTS**

In the current subsection we will demonstrate the impact of deployment of silica for remediating short-circuits between the operational wells. We have numerically built a finite element model that mimics the following problematic conditions: the reservoir is a porous fractured one; two fast-pathways fractures are embedded within the reservoir, an upper one that intersect both wells and can easily be characterized through the wells while the bottom one, a more conductive path than the first, can only be characterized, for example, through tracer or thermal tests. The geological settings of the problem are depicted on Figure 15. An adaptive finite element scheme has been used to mimic with high fidelity the geological settings especially the fractures themselves. The use of homogenized properties or non-adaptive numerical schemes will fail to capture the essence and the challenges that this problem present. Figure 16 illustrates the vertical cross-section through a 3D mesh used to solve the problem. The number of nodes used in the current 3D exercise counts 500 Million nodes.

![Image](image2.png)

**Figure 15**: Schematic of a vertical cross-section through a 3D geothermal reservoir. Figure shows the operational wells which are embedded in a double porosity medium (DP), the background reservoir is considered as a (single) porous medium (SP). Several fractures are also embedded with the reservoir; two of them intersect both wells. The bottom fracture, non-characterized – invisible through both wells, plays the role of high conductive fracture and thus short-circuiting both “wells”.

![Image](image3.png)

**Figure 16**: Schematic of a vertical cross-section through a 3D geothermal reservoir. Figure shows the operational wells. Adaptive mesh refinement was used to represent the fractures with high fidelity and illustrated through several zoom-outs.

We have enhanced the model with a streamline solver. Streamlines are essential for tracking the silica gel though not only the porous medium but more importantly in the fractures themselves. Because we are targeting short-circuits, essentially
highly conductive fractures, resolving the physics of mixing and transport with fractures is essential to the successfully deployment of silica gel by assessing the impact of mixing within fractures on the gelation time. Figure 17 depicts the schematic of a vertical cross-section through a 3D geothermal reservoir near the injection well. It depicts streamlines with the domain. Adaptive mesh refinement was used to represent the fractures and the streamlines with high fidelity and illustrated through several zoom-outs.

**Figure 17:** Schematic of a vertical cross-section through a 3D geothermal reservoir near the injection well and streamlines throughout the domain.

In order to illustrate the impact of silica gel deployment on the circulation of the fluid within the geothermal system we proceed by: 1) simulate the injection of a tracer (or thermal test) in the subsurface prior to silica emplacement, 2) deploy silica gel to obstruct the fast path and 3) re-simulate the injection of a tracer (or thermal test) to illustrate the difference between 1 and 3. Figure 18a depicts a vertical cross-section through a 3D geothermal reservoir before gel deployment. A tracer (thermal) test was injected. Figure depicts time-snapshots of the tracer/heat transfer through the reservoir. Time flows from top to bottom. Blue color depicts cold regions while red color represents hot regions. One can see that the bottom fracture plays the role of a fast-path short-circuiting fracture; notice the arrival of cold water at the heel of the extraction well (left column) and once the fracture is healed using silica gel the cold region initially observed before gel deployment has vanished.

**CONCLUSIONS**

We have attempted to address the main issues in deploying silica gel to enhance heat production from an enhanced geothermal system. We have demonstrated through several hydro-thermal designs and exercises silica gel deployment in fractured and/or porous reservoir for a) heat production enhancement, b) flow circulation efficiency and minimizing fluid exchanger, c) zonal isolation and surface area sweeping and d) short-circuiting remediation. We believe that this technology can be applied successfully at all stages of management of hydrothermal reservoirs.

**REFERENCE**


13. STR, Science and Technology Review, Lawrence Livermore National Laboratory, Mining geothermal resources, Jan-Feb, 2005.


Acknowledgments: This work was partially performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work was partially supported by an LDRD/SI grant from LLNL and partial fund from GTP/DOE award #***** to LLNL. LLNL-PROC-xxxxxx-DRAFT