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Discrete Fracture Network Analysis of Controlling Factors for EGS Performance

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ABSTRACT

A series of simple discrete fracture network (DFN) models explore the factors that control the performance of Enhanced Geothermal Systems (EGS) by studying the behavior of the long-term circulation experiments conducted at Rosemanowes in the UK during the late 1970's through the 1980's. The Rosemanowes site was chosen for the richness of its database and the existence of a thermal decline curve. The Rosemanowes program advanced microseismic technology and understanding of natural fracture stimulation but ultimately did not reach its goal of commercial power production due to low flow rates and early thermal decline. The injection and production wells tapped mainly the shallow portion of a stimulated rock volume that migrated to depths greater than 4 km. The models in this study explore whether or not larger well spacings and different rates could have produced slower thermal decline. Matching the existing thermal decline curve required enhancing the fracture intensity and adding cross-fractures to a parallel fracture model to create a system that drew its heat preferentially from rock blocks within the stimulated zone over heat flow from outside the zone. Once calibrated the model explored changing the well spacing in 200 m increments from 200 to 800 meters. These changes delayed the thermal breakthrough from less than a year to six years, but were short of the 20-30 year target. Decreasing flow rates from the 14 l/s of the experiment to 9 and 5 l/s further delayed the thermal breakthrough with 10% decline occurring at 20 years for the lowest rate case. While this case maintains the temperature of the production, the single stimulated volume falls short of rates that may be needed for production. Meeting the joint requirement of low thermal decline and total production rate may require multiple independent stimulated volumes as suggested by MacDonald and others (1992) in their review of the Rosemanowes program. While this study is not adequate to develop design guidelines, it shows that useful information can be gathered from past EGS experiments for designing future development of this important resource.

1. INTRODUCTION

Enhanced, or engineered, geothermal systems (EGS) extract heat from a network of stimulated fractures in otherwise low-permeability rocks like those found in crystalline basement. Compared with hydrothermal systems, which are both porous and permeable, EGS produces heat by conductive transfer from the rock to a circulating fluid rather than producing directly the hot water in the hydrothermal system. MIT (2006) estimates that crystalline basement rocks may contain 13,000,000 Exa-Joules of thermal energy compared with 2,400 to 9,600 Exa-Joules in hydrothermal systems. The allure of this large and untapped resource has given rise to several major field experiments and pilot development projects worldwide (Breede, and others, 2013) starting with the experiments at Fenton Hill in New Mexico USA in the 1970's, to the Rosemanowes project in the UK in the 1980s, Soultz in the 1990's and 2000's, to Habanero in Australia in the 2010's among others.

The stimulation technologies developed within these projects helped to create the unconventional fossil-fuel revolution of the past few decades; however, they are yet to realize their full impact on geothermal energy development. Despite over 40 years of research and development, the widespread use of EGS for energy production has been slower in coming than many initially expected. As Breede and others (2013) point out, EGS is still on a learning curve possibly because the conditions vary greatly between potential sites. More fundamentally, the understanding of how underground stimulation and the resulting heat exchanger work may be as elusive today as it was in the 1990's (MacDonald and others, 1992).

In addition to the Jason panel report (Jeanloz and Stone, 2014), the US Department of Energy through Sandia Laboratories commissioned another panel to take a fresh look at reasons why the potential of EGS remains unrealized. Recognizing that many past analyses of EGS systems have relied on simplified models, the panel decided to investigate the use of discrete fracture network models, which could incorporate the heterogeneity, anisotropy, and complexity of realistic fluid pathways in a stimulated EGS volume.

As part of that effort we previously presented the results of a series of simulations (Doe and others, 2014) starting with the analytical solutions of Gringarten and Witherspoon (1975) for parallel fractures and gradually adding complexity with the following steps:

- Equally-spaced, uniformly transmissive parallel fractures
- Unequally-spaced, uniformly transmissive parallel fractures
- Unequally-spaced, non-uniformly transmissive parallel fractures
- Realistic fracture networks with variable orientation, size, and transmissivity.

All but the first step was accomplished using a numerical simulation approach that used the FracMan discrete fracture network code to generate fractures along with HydroGeoSphere, a numerical simulator with strong fracture-matrix interaction capabilities including heat transport (Brunner and Simmons, 2012). These are described in more detail in Doe (and others, 2014).

The major findings of that work were the following:

- Based on the dimensionless terms in Gringarten and Witherspoon's (1975) analytical solutions, thermal breakthrough and decline depend to a second power on fracture area and flow rate.
- High flow rates cause a thermal breakthrough in advance of significant thermal contribution from the rock
- Lowering the flow rate delays thermal breakthrough up to point where the thermal front in the rock is at or only slightly behind the thermal advance in the fractures
- Increasing complexity through variable fracture spacing and transmissivity degrades the EGS performance relative to a uniform spacing and transmissivity case
- Complex fracture networks show a composite of finite and infinite fracture spacing behaviors of three stages: (1) constant temperature production pre-breakthrough, (2) thermal depletion of finite-spaced blocks inside the network and (3) an infinite system where the entire stimulated volume behaves as a single thermal sink (Figure 1).

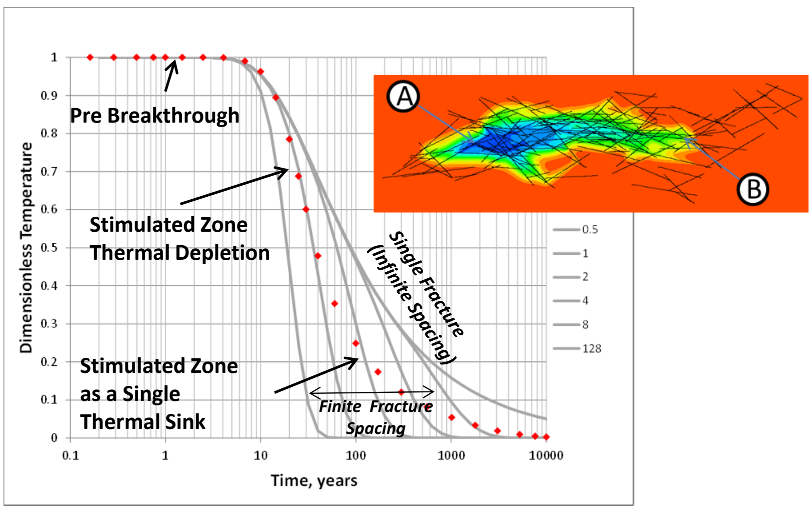

Figure 1. Example temperature behavior in an EGS reservoir producing the A and B well pair; comparison of DFN model results (red points) with Gringarten and Witherspoon (1975) analytical solutions (Doe and others, 2014)

As a next step in this effort, we decided to look at a well-documented EGS experiment that included information on natural rock fractures, micro-seismic mapping of the stimulated rock volume, and, above all, a thermal breakthrough curve. The UK's project at Rosemanowes (Richards and others, 1994; Parker, 1989) had the desired attributes.

The Rosemanowes project did not meet its goal of engineering a commercial-scale EGS heat exchanger. The target for a commercial system (Richards and others, 1994) was 50 kg/s circulation for 20 years without a major decline in the production water's temperature (< 10%). The main circulation experiment at Rosemanowes lasted three years from August 1985 to November 1988. Despite considerable reduction in the system's flow impedance through viscous gel injections, the production rate was 14 kg/s. At this production rate, the experiment produced early thermal declines with the temperatures falling below the 20-year target of a 10% drop in less than one year.

Even with this result, the circulation test only tapped a small portion of the stimulated volume as mapped by microseismic activity. The distance between the main injection and production points was only about 200 meters, while the zone of stimulation may have extended as much as a kilometer.

The impetus for our study was to see if the thermal performance of the Rosemanowes reservoir could be improved with different well placements, and possibly even meet commercial viability criteria of rate and thermal stability. Specifically we were interested by the possibility of increasing the distance between the wells and tapping the deeper stimulated rock volume. The first step in the work was to build a model that matched the existing Rosemanowes breakthrough curve. Having matched that behavior with the existing wells, we then added deeper wells to see how much they improved the thermal performance. We were aided in this effort by previous discrete fracture models that used simple parallel fractures (Nichol and Robinson, 1990), a deterministic fracture network (Kolditz and Clauser, 1998), and complex stochastic networks (Lanyon and others, 1993; Bruel, 1995)

There are many factors in the behavior of an EGS system, particularly coupled hydro-mechanical and hydro-chemical effects. This study did not consider these, rather focusing simply on the geometry and flow behaviors of the heat exchanger. While coupled effects are very important, we view them as secondary effects relative to the presence or absence of the basic heat exchanger.

2. THE ROSEMANOWES GEOTHERMAL PROJECT

2.1 Overview

The Rosemanowes geothermal test site was the focus of EGS research activity in the UK in the late 1970's through the 1980's (Richards and others, 1994). The work began at the Rosemanowes quarry near the Camborne School of Mines in Cornwall close to the southwestern tip of Great Britain. The quarry provided excellent exposures of the Carmenellis granite, which was the host rock for the experiments at all depths. The three phases of the work proceeded from a first phase that focused on the proof of the concept, followed by Phase 2, which was the drilling, stimulation, and circulation of the reservoir at about 2 kilometers, and Phase 3 involving further improvements to the circulations system.

Phase 2 had an eight-year duration from 1980 to 1988, and it was executed in three sub-phases. Phase 2A drilled two wells, RH-11 and RH-12, to about 2 kilometers depth. The microseismic activity (Parker and others, 1989) along with in situ stress measurements by hydraulic fracturing (Pine and Batchelor, 1984) showed a strong downward migration of the seismic activity caused by the gradients of the in situ stresses with depth. This activity extended to four kilometers. The information from the stress measurements and the microseismic activity made clear that the growth of the stimulated volume was by pore-pressure induced shearing on natural fractures, which had two dominant and nearly orthogonal vertical orientations. The results also showed that the two wells were poorly oriented to intersect the stimulated fractures. Nonetheless the project was able to establish circulation between the wells albeit with large impedances and water losses to the deeper system.

Phase 2B added well RH-15 which had a spiral track to a vertical depth of about 2650 meters (Figure 2). After encountering high impedances and water losses, a program of viscous gel injections was successful in establishing the connection between RH-12 and RH-15 with acceptable rates and water losses below 21%. Frequent flow logs during the development provided the locations and relative transmissivities of flowing fractures in both holes. These data are essential to discrete fracture network modelling. Figure 1 shows a plan view of the RH-12 and RH-15 wells along with discs that show the locations of flow points. The disc radius values are proportional to the flow rates. The flow in each hole is dominated by a single flow point. These points are co-planar in the plane of the major stimulated fracture set, and the point-to-point distance is 196 meters.

A series of circulation tests were carried out throughout Phase 2 culminating in a 3-year circulation that took up most of the duration of Phase 2C. The RH-12 injection rates varied from an initial 5 l/s to over 33 l/s. Most of this fluid went to RH-15 and a smaller portion went to RH-11. The RH-15 production rates averaged about 14.6 l/s; however, the rate for the first 177 days was about 6.4 l/s followed by an increased average rate of 17.6 for the following 800 days. In the production well RH-15 production temperatures at the casing show were initially slightly below 80°C and dropped to about 56°C over the three year circulation period (production figures appear in Section 3).

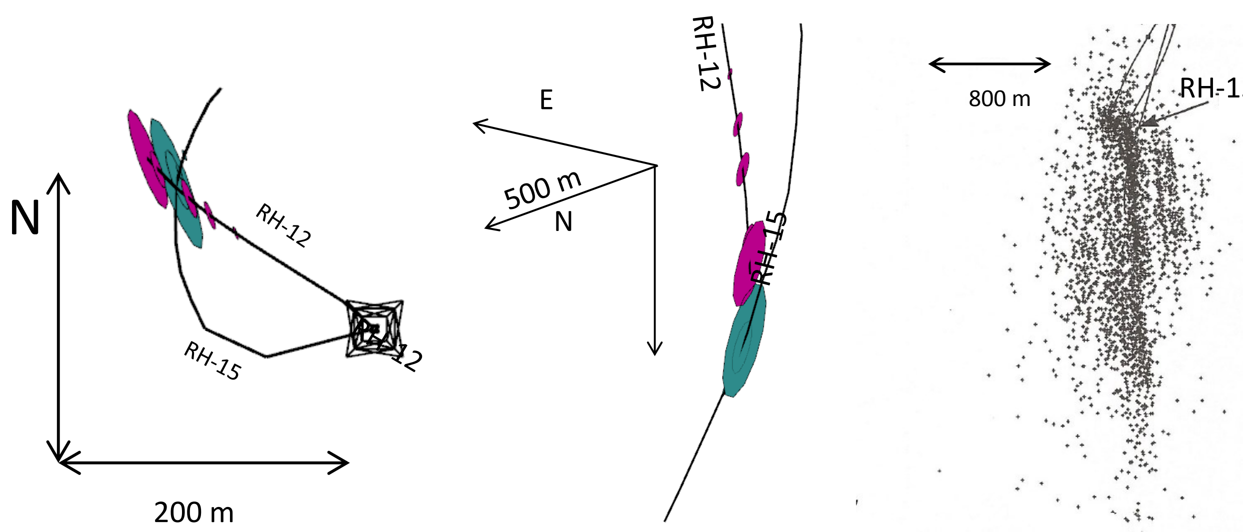

Figure 2. Rosemanowes wells for long-term circulation test. Left: plan view, center: side view, right: microseismic locations (Parker, 1989). Discs show flowing points with size proportional to rate and orientation corresponding to major fracture set. (RH-12 fractures in red, RH-15 fractures in green)

2.2 Previous Simulation Work on the Rosemanowes Circulation Experiment

Nicol and Robinson (1990) used both analytical solutions and a parallel fracture model similar to Gringarten and Witherspoon (1975) but with additional flexibility to allow for variable fracture sizes, spacings, and volumes around the fracture network. They were not clear in their paper if they used wells with converging flow lines at the injection and production points or if they applied their rates uniformly across the edges of the fractures as in the Gringarten and Witherspoon solution.

The Nichol and Robinson model started using a single flow path but could not match the data regardless of the fracture areas and fracture spacings within that flow path. They found that the match was improved by using two flow paths with different rates and areas, and that the match could not be improved by adding additional flow paths beyond those two. In the numerical model the first flow path had an area of 168,000 m² and the second was 4800 m² with the flow rates divided 84% to the larger flow path and 16% to the smaller. The two flow paths in this model are sufficiently spaced that they do not thermally interfere with one another. One challenge with applying this model to the actual site is that the smaller fracture's size is equivalent to a square 69 m on a side. In the actual site the minimum distance between the inflow points of the two wells 196 m, which is the largest flowing path, and paths with smaller flows have longer flow paths. Hence, the smaller flow path in the Nichol and Robinson model would require a very large elongation in order to connect the wells. As support to the two flow path model they noted that two concentration peaks had been observed in tracer tests through the network. The Nicol and Robinson matches appear in the figures of Section 3.

A somewhat more complex model was developed by Kolditz and Clauser (1998). This model employed deterministic fractures in two sets with strike directions of 165N, the major flowing set, and 250N, the minor flowing set. The model region was approximately 100 m² in plan view extending to a vertical depth of 500 m. They located their fractures at flowing points in the injection and production wells to produce a model with six fractures in the major set and seven fractures in the minor set. The outer fractures form a box that is approximately 75 m x 55 m. The model used uniform aperture and transmissivity values for each set and considered to cases where the aperture ratio between the major and minor set was either two or five.

Given the previous experiments in Phase 2A they also assumed a thermal drawdown from Phase 1 circulations in the upper part of the reservoir above -2150 m. They set the initial temperature at 50° in the upper reservoir and 80° in the lower reservoir. Note that all of the production points are below -2150 m as this is the highest flow point in the injection well. Rather than using wells in the model, where flowing points in the well would have the same hydraulic head, the variability in flow was introduced by defining a flow rate at each well-fracture intersection. Given that all fractures within a set had the same aperture, this condition would produce different injection pressures at each flow point along the production well.

The Kolditz and Clauser (1995) model produced an excellent match to thermal drawdown data using matrix hydraulic conductivity as one of their variable parameters (see Figures in Section 3). The hydraulic conductivity in their match was 10^{-4} m/s, which, as they note, corresponds to an extremely high permeability for crystalline rocks. As a rough calculation, a 100 m well interval injecting at a 10 MPa overpressure in rock with these hydraulic conductivity values would have a flow rate of 10 m^3/s to the matrix. The maximum injection rate in any part of the circulation test was 0.03 m^3/s at an overpressure of 11.1MPa, thus one may conclude that the model's matrix hydraulic conductivity is inconsistent with the flow observations in the wells.

Lanyon (and others, 1993) build a stochastic discrete fracture network model using realizations encompassing 200 m cubes. Although the code was designed for flow and solute transport, they implemented a one-dimensional finite difference heat flow solution for each fracture face in their model. The stochastic DFN model was able to reproduce Rosemanowes tracer tests but was not able to match the RH-15 thermal responses of the long-term circulation test.

Bruel (1995) used a stochastic DFN model to simulate the long-term circulation test. The paper provides a quite generalized description of the simulator, but the work involved 25 network realizations within a 500x500x1000 meter block. The paper presents some example thermal breakthrough curves, which bracket the experimental results. The model results are presented in terms of a thermal index which is the percent of temperature drop at the end of the experiment. This index varied between 0.4 and 0.8. The modeling provided estimates of the fracture area contributing to heat production, noting the simulations produced effective channeling that strongly affected the performance between realizations.

3 MODELING RESULTS

3.1 Simulation Approach

The simulation program for our work used the combination of FracMan as a fracture generator and HydroGeoSphere as the thermal flow solver. The tools and workflow are described in Doe (and others, 2014). As discussed above the focus of this study was to compare the Rosemanowes experiment results with a performance that would be required from a commercial EGS operation in terms of two major criteria (1) no greater than 10% thermal drawdown at a production well over 20 to 30 years of operation and (2) a 50 to 70 kg/s fluid production rate. By comparison, the Rosemanowes circulation experiment produced a 10% thermal decline in less than one year with production rates of about 14 kg/s. The basic objective of this simulation study was to see how one could redesign the Rosemanowes circulation to meet these two criteria. Such a study could use a variety of different models, but whatever model was chosen it would need to reproduce the thermal drawdown of the long-term circulation experiment.

Our initial approach involved expanding the Kolditz and Clauser (1995) model to a larger volume. We started by reproducing their model in HydroGeoSphere and obtaining a similarly good match to the thermal drawdown curve. Initial attempts at enlarging the model lost the quality of the match, and once we appreciated the high matrix hydraulic conductivities in the model, we decided to pursue an approach similar to Doe (and others, 2014) using parallel fractures like those of Nichol and Robinson (1990). Although this approach is simplified compared with models like Lanyon and others (1993) and Bruel (1995), it is easier to understand the major controls on the model behavior in simple models, and such models provide a firmer basis for designing more realistic, but complex numerical experiments.

For all simulations we used the rock and water properties given in Kolditz and Clauser (1995) except for matrix hydraulic conductivity (Appendix Table). Except for the results of the analytical solutions, all model results are given in actual temperatures, where the casing-shoe injection temperature was taken as 25°C and the initial reservoir temperature was taken as 80°C. These temperatures are lower than those of an expected operating EGS; however, we assume that one would create a Rosemanowes-like system in a site with higher temperatures, and our main interest is not absolute temperature but relative thermal decline.

3.2 Gringarten Analytical Solution and its Representation in a Numerical Model

A useful starting point for understanding thermal drawdown behaviors at Rosemanowes is doing a simple match to the Gringarten and Witherspoon (1975) analytical solution. Figure 3 presents the match, which visually is quite good. The main feature of the match is the low value of dimensionless fracture spacing. For the thermal properties of Rosemanowes these dimensionless time parameters translate to a fracture area of 132,000 m^2, which is equivalent to a square with a 363 m side. Given the fracture area, one can calculate from the dimensionless fracture spacing a half spacing, X_e, of 10.6 m or a spacing of 21.2 m.

Simulations of realistic networks in Doe (and others, 2014) show that there could be three major sections (Figure 1) to a thermal drawdown curve (1) a period of zero to low thermal drawdown prior to breakthrough along the fracture network, (2) a period of production where blocks within the fracture network thermally deplete, and (3) where the entire stimulated zone acts as a single conductor in an infinite medium. In terms of Gringarten's curve the second period would track one of the finite-spacing fracture curves while the third period would have a slower thermal decline consistent with the infinite spacing, or single fracture, curve. The Rosemanowes data may exhibit the first two of these thermal drawdown periods. A longer circulation test might have shown a later flattening of the thermal drawdown corresponding to the infinite fracture spacing behavior.

One limitation of the Gringarten solution is the difference between its boundary conditions and those of a real system. The analytical solutions apply uniform fluxes across the edges of the fractures and all flow paths have the same length. For the realistic cases the flow lines diverge away from the injection well and converge at the production well (Figure 4). This produces flow paths with varying lengths caring varying amounts of fluid as compared with the analytical solution. The second major difference in the boundary conditions is what one might call a buffer zone. The analytical solution assumes a no heat-flow boundary at a distance of one half of the fracture spacing outside the two outer fractures. In a realistic case the fracture network is embedded in a very large if not infinite rock mass. Thus, a simulation needs to have a sufficient buffer around the fracture network that the outer thermal boundary does not affect the simulation.

Figure 5 shows the results of a HydroGeoSphere model that includes the appropriate well boundary condition and compares the use of a half-spacing buffer with a 50-m buffer. The half-spacing buffer matches the data but is unrealistic, while putting in a 50-m buffer, which is sufficient to approximate infinite conditions, results in a mismatch with lower thermal decline than the experiment. The next step involved changing the fracture network to match the decline while maintaining the larger buffer.

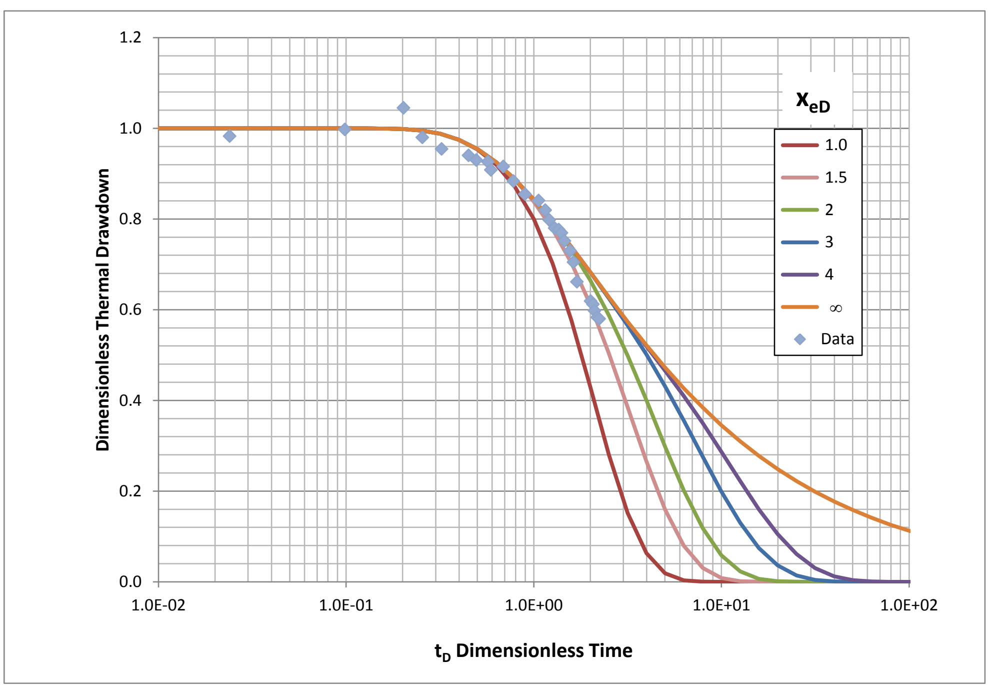

Figure 3. Match of Rosemanowes long-term circulation test to Gringarten and Witherspoon (1975) analytical solution

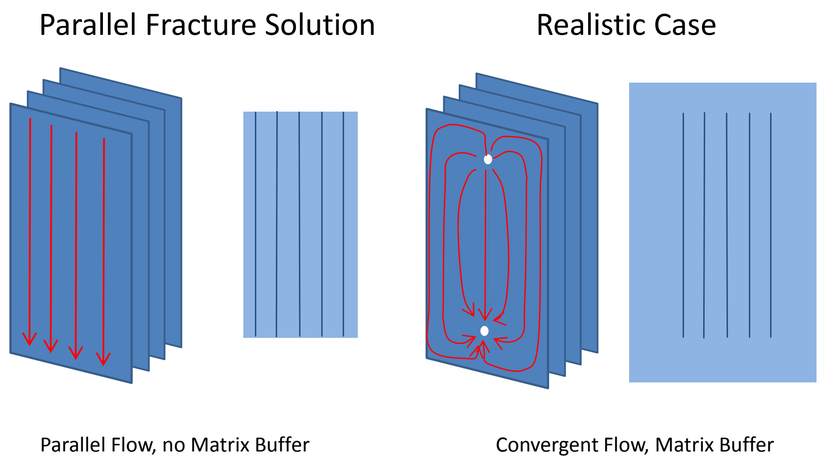

Figure 4. Distinction between Gringarten (1975) boundary conditions and an actual reservoir.

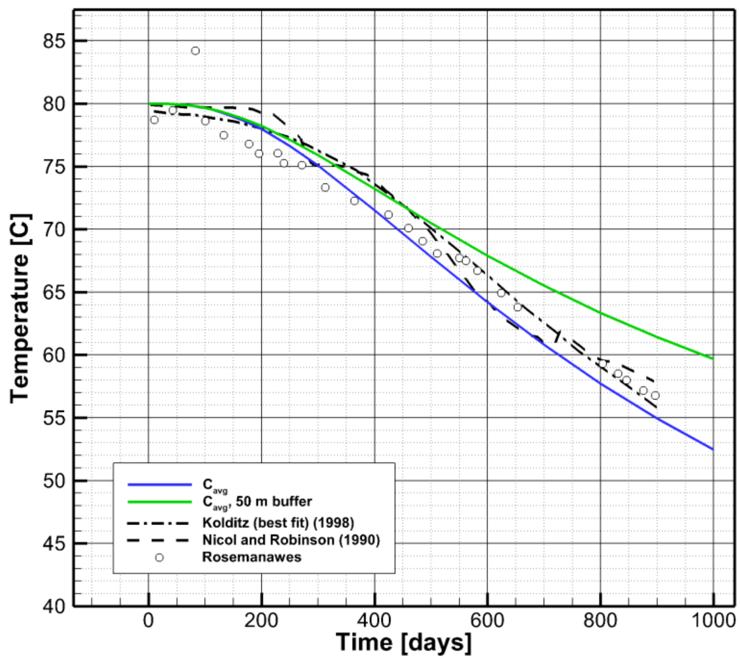

Figure 5. Comparison of HydroGeoSphere parallel fracture models with (green) and without (blue) a 50-m buffer.

3.2 Incorporation of Cross Fractures

The discrepancy between the Gringarten parallel fracture model and the numerical model including a buffer zone suggested that the model's heat flow was being dominated at mid- to late- time by the flux from the buffer zone, that is, from the region outside the fracture network. Improving the model match required enhancing the thermal depletion within the fracture network to dominate the heat flux coming from outside the fracture network. One could do this by adding more parallel fractures; however, this would add more surface area, which would delay thermal breakthrough. Our solution was to add a second set of cross fractures (Figure 6). The cross fractures change the block geometry from slabs to rectangular prisms. With adjustments to preserve flowing area, the final model for matching the Rosemanowes data uses four parallel fractures 179-m wide by 800-m high with 15-m spacing and constant aperture of 2.4×10^{-4} m. The aperture was set to reproduce the appropriate injection pressure for the 14 l/s flow rate. The parallel fractures are cut by ten cross fractures with spacing of 15-m and the same apertures as the parallel fracture set. The injection and production wells are simplified to horizontal wells with a vertical spacing of 200 meters (Figure 6), which is similar to the distance between the largest flow zones in RH-12 and RH-15 (Figure 2). The thermal properties are the same as Kolditz and Clauser (1998) and the rates and other model properties are taken from that reference (see Appendix table). The flow rate is considered a constant 14 l/s. This change in the block shape had the effect of increasing the heat transfer rate from the matrix blocks, and the resulting simulation greatly improved the match the Rosemanowes data (Figure 7). Having matched the experiment we next vary the well spacing and rates.

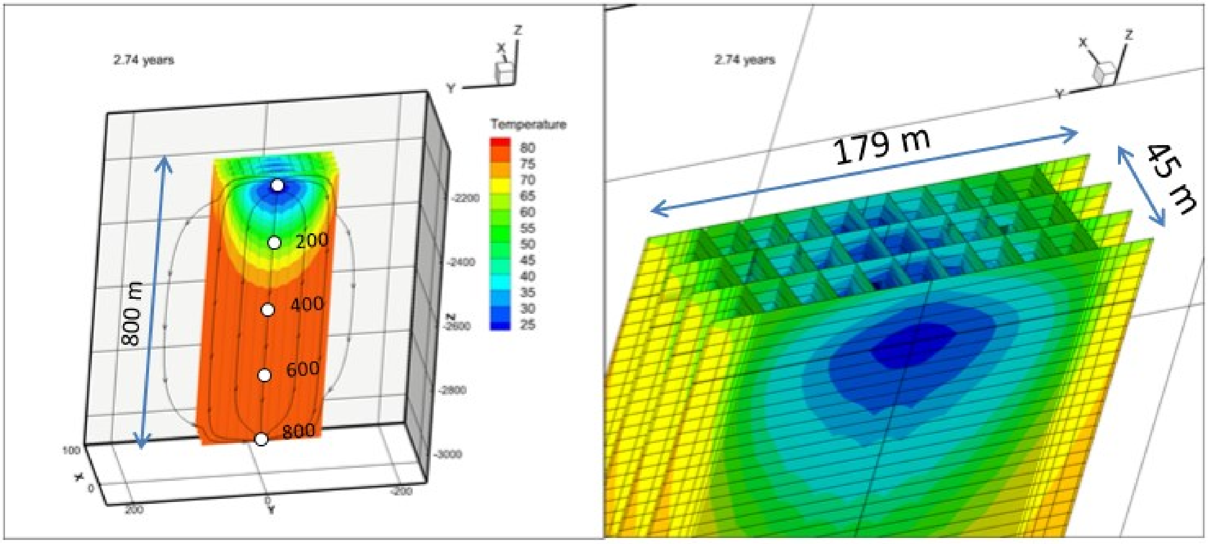

Figure 6. Cross fracture model with well locations, isotherms and example flow lines (note: temperatures shown for fractures only. Due to matrix hydraulic conductivity of 10^{-12} m/s there are minor flow lines outside the fracture network).

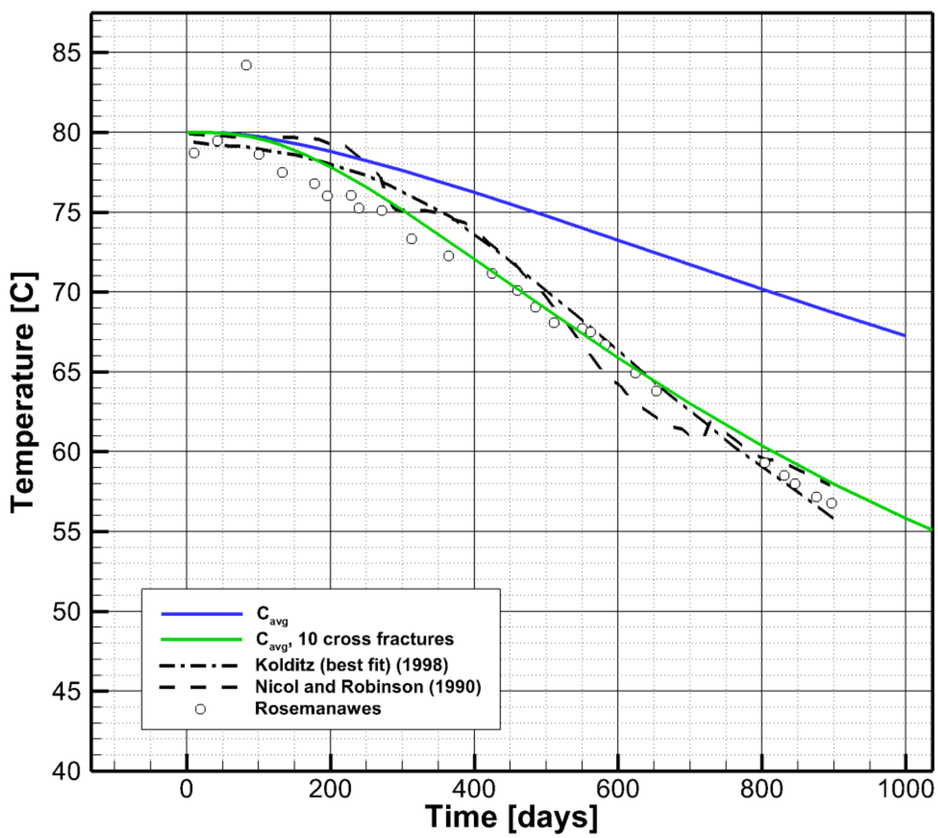

Figure 7. Results of HydroGeoSphere parallel fracture models without (blue) and with (green) cross fractures.

3.3 Simulations with Variable Well Location

The next simulation sees if larger well spacings can improve thermal performance and by how much. Inspection of Gringarten and Witherspoon's (1975) analytical solution shows that thermal drawdown has a second power relationship to fracture surface area and to flow rate within the limitations of the solution's boundary conditions. Although the area of the model is fixed, the well pair for the circulation test is located relatively high within the microseismic stimulation zone and has minimum path length of about 200 m. Our next set of simulations change that path length by 200-m increments to 400, 600, and 800 m. As the fracture area does not change, changing the well spacing increases the flow path lengths and should increase the accessible area for heat transfer (Figure 6).

The results shown in Figure 8 show a clear delay in thermal breakthrough and an overall delay in the thermal decline with spacings up to 800 m. The time to a temperature reduction of 5 degrees increases from 0.8 years for the 200-m case to 6 years for the 800-m case. The delay in time is linear with respect to the well spacing, which is less than the second power improvement one would expect from the analytical solution based on increasing the area for heat transfer. By extrapolation of the linear relationship, meeting a performance goal of a 5 degree temperature decline in 20 years (red point in Figure 8) would require a well spacing of about 2.4 km for this system.

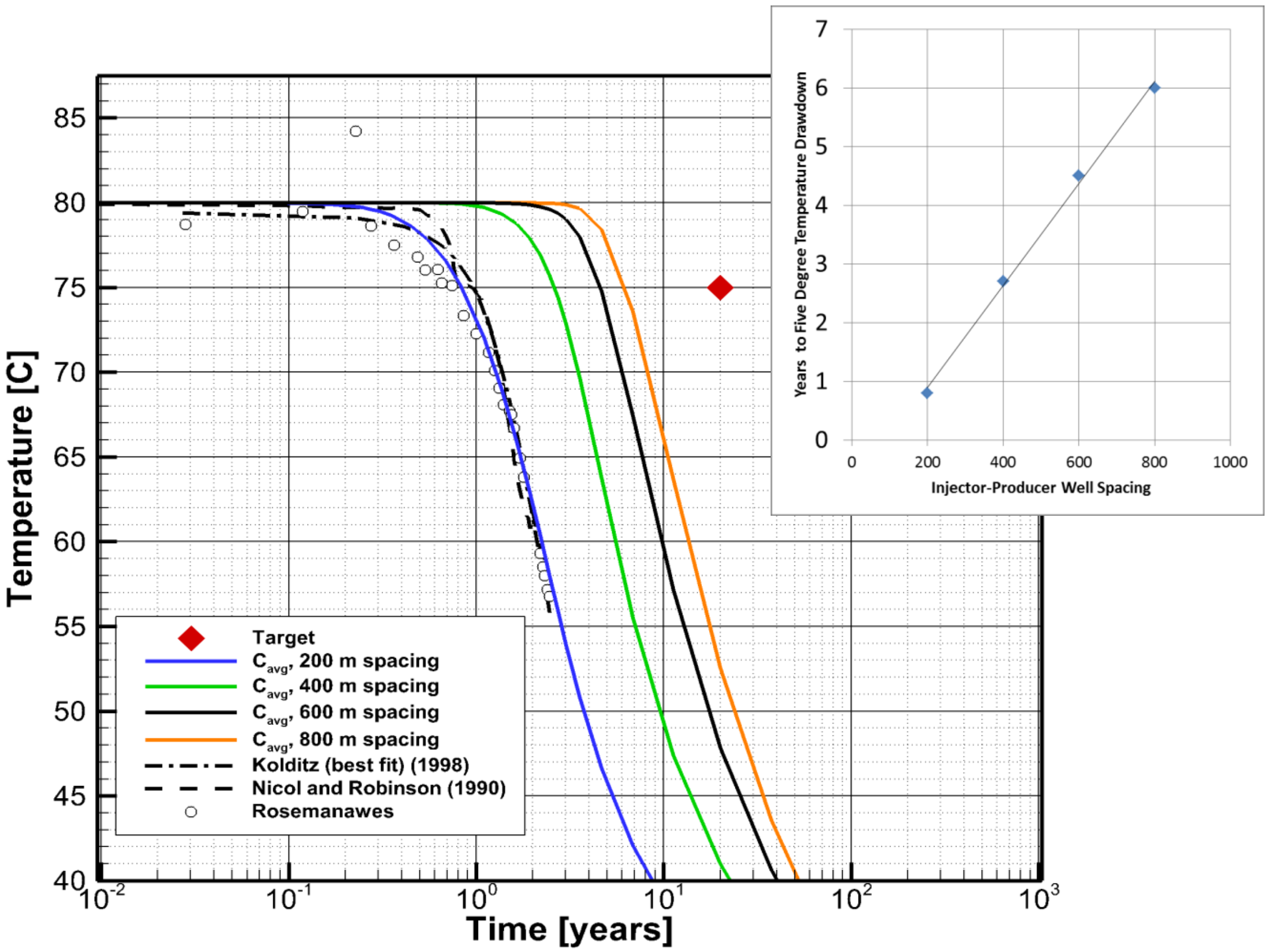

Figure 8. Effect of injector-producer spacing and thermal drawdown.

3.4 Simulations with variable flow rates

The previous section described the results of models that explore the effect of well position on thermal breakthrough. Without increasing the well spacing further, the other variable that can affect thermal breakthrough time is the flow rate. The 14 l/s flow rate of the Rosemanowes experiment is already well below a commercial target of 50 to 70 kg/s. Nonetheless, if a single stimulated volume may meet thermal drawdown but not flow rate targets, it may be possible to meet flow rate targets by creating and producing from multiple stimulation zones.

For this case we started with the 800 m well spacing and reduce the flow rates by two increments to 9.8 and 5.0 l/s. As expected, decreasing the flow rate improves the thermal performance. By decreasing the rate from 14 l/s to 5 l/s the simulations achieve a 20 year production before seeing a 5 degree C thermal decline (red point in Figure 9). The improvement with flow rate is nonlinear; however, rather than being a second power improvement as one would expect from the analytical solution, a decreasing rate the simulation gives a 1.25 power improvement with lower rate.

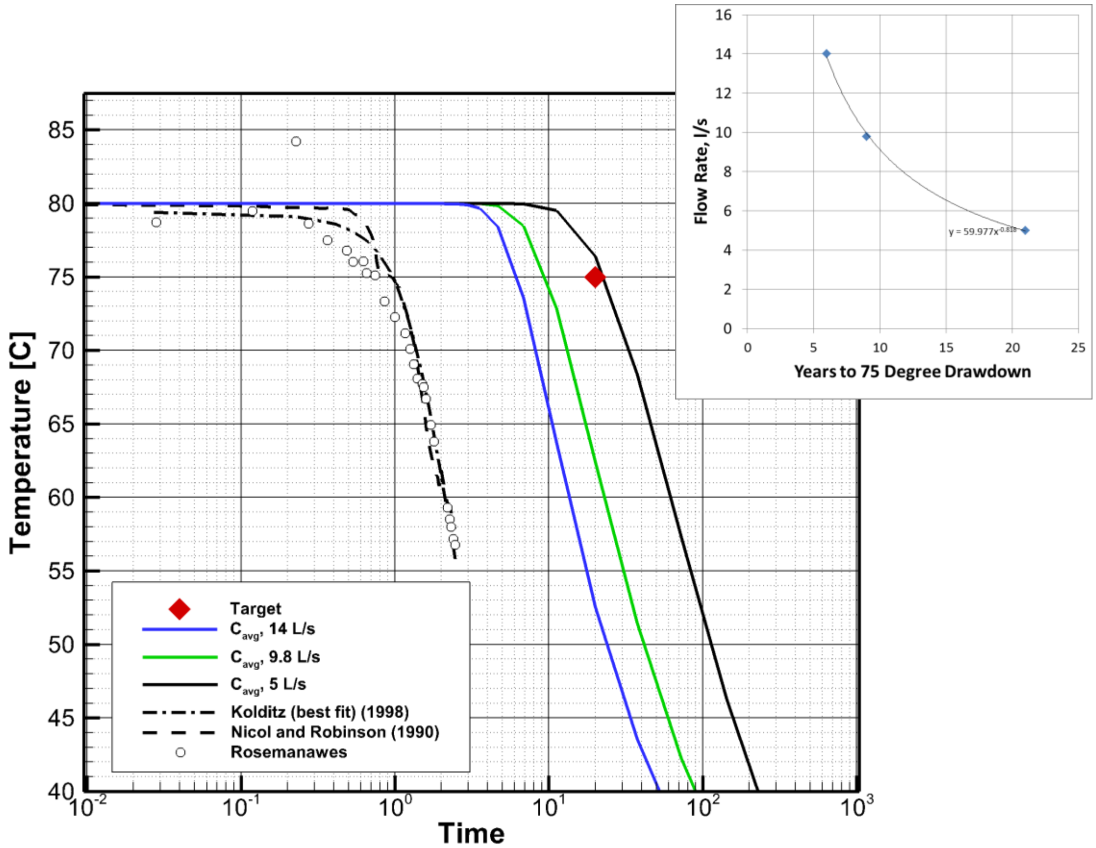

Figure 9. Effect of flow rate on thermal breakthrough

4. DISCUSSION AND CONCLUSIONS

The Rosemanowes experiment is one of the most comprehensive and well-documented attempts to understand EGS performance and to attempt to achieve commercial power production. Following on the Fenton Hill work in the United States, the Rosemanowes project achieved much including expanded the use of microseismic data and viscous gel injections to improve rates and impedances. Ultimately, however, the project did not meet its goal of achieving commercial production defined here as less than 10% thermal decline over a 20 to 30 year period and a 50 to 70 kg per second flow rate.

This study has used simple models to see if changing the well placements at Rosemanowes to take advantage of the extent of the microseismic stimulation zone could have achieved performance closer to commercial expectations. We started with a simple parallel fracture model, whose data match required additional cross fractures to increase the portion of thermal depletion coming from within the stimulation zone. Once we had a calibrated model for the experiment data we increased the well spacings from the original approximately 200 m to 800 m using the 14 l/s flow rates of the experiment. The model produced results that showed a linear delay of thermal depletion with well spacing from 0.8 years at 200 m to 6 years at 800 m -- still short of the target thermal drawdown. Achieving the thermal drawdown target required decreasing the flow rates from 14 l/s to 5 l/s.

As expected the models showed that increased well spacing and lower flow rates delay thermal decline. What was unexpected was that the spacing effect was linear rather than second power, and the flow rate effect had a power relationship but between linear and second power. These relationships likely reflect the complexity of variable flow path lengths in a well-pair dipole as compared with parallel flow lines in the analytical solutions.

Further improvement in the performance of this reservoir would require access to larger stimulated volumes. This could be achieved either by increasing the size of the current stimulated volume and increasing the well spacings within it, or by having multiple stimulated zones as suggested by MacDonald (and others, 1992).

The models presented here are simplified, idealized representations of a complex geothermal system. More complex models have been created and reported elsewhere (Lanyon and others, 1993; Bruel, 1995); however, these models were only applied to matching the current system and not to engineering or designing an improvement to that system's performance, as we've done in this paper. Other than noting some directions for improving EGS performance, the models presented here are too simplified to be applied to detailed design or engineering studies. The fractures in the study were uniformly spaced with constant apertures. Some further applications of this model may include variable spacings and variable fracture apertures within the stimulated volume, or should attempt to include the effects of flow channeling such as explored by Guo and others (2016). That said, prior experience (Doe and others, 2014) suggests that increasing complexity and heterogeneity in fracture networks concentrates flow in a smaller portion of the system and does not improve EGS performance.

As a final conclusion, we believe this study shows that there continues to be value in understanding the results of past experiments particularly as regards research and development at future EGS sites.

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APPENDIX: PROPERTIES FOR SIMULATIONS

Thermal heat capacity of rock	2.172×10^{-6}	$J\ m^{-3}\ K^{-1}$
Thermal heat capacity of water	4.127×10^{-6}	$J\ m^{-3}\ K^{-1}$
Thermal conductivity of rock	3.1	$W\ m^{-1}\ K^{-1}$
Thermal conductivity of water	0.68	$W\ m^{-1}\ K^{-1}$
Density of rock	2.642×10^{3}	$kg\ m^{-3}$
Density of water	0.978×10^{3}	$kg\ m^{-3}$
Matrix hydraulic conductivity	1×10^{-12}	$m\ s^{-1}$