

## Challenge Problem Statements for a Code Comparison on the Fenton Hill Reservoir - An Invitation to the Geothermal Modeling Community

M.D. White<sup>1</sup>, D. Elsworth<sup>2</sup>, E. L. Sonnenthal<sup>3</sup>, P. Fu<sup>4</sup>, and G. Danko<sup>5</sup>

<sup>1</sup>*Energy and Environment Directorate, Pacific Northwest National Laboratory, Richland, WA 99352, USA*

*mark.white@pnnl.gov*

<sup>2</sup>*Energy and Mineral Engineering and Geosciences, Penn State University, University Park, PA 16802-5000, USA*

*elsworth@psu.edu*

<sup>3</sup>*Earth and Environmental Sciences, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

*elsonnenthal@lbl.gov*

<sup>4</sup>*Atmospheric, Earth and Energy Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

*fu4@llnl.gov*

<sup>5</sup>*Mining and Metallurgical Engineering, University of Nevada, Reno, Reno, NV 89557, USA*

*danko@unr.edu*

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### ABSTRACT

The U.S. Department of Energy, Geothermal Technologies Office is supporting a code comparison study of numerical simulators for enhanced geothermal systems to test, diagnose differences, and demonstrate modeling capabilities of these modeling tools. By design, this study comprises two stages: benchmark problems and challenge problems. During the now completed benchmark problem stage, numerical simulators were exercised on a series of seven problems that considered various double and triple couplings of thermal, hydraulic, geomechanical, and geochemical (THMC) processes. Problems were selected and designed to isolate selected coupled processes, to be executed on workstation class computers, and have simple but illustrative metrics for result comparison. Simulation results and comparisons between the participating simulation groups for the benchmark problems have been published. Whereas the concepts for the seven benchmark problems selected for this study were the outcome of a single workshop, defining the objectives and nature of challenge problems required a longer-term effort. This paper describes the steps taken by the study to create two challenge problems and provides full problem statements to encourage international participation in providing solutions. Both challenge problems are based on the enhanced geothermal systems research conducted in hot dry rock at Fenton Hill, near Los Alamos, New Mexico, between 1974 and 1995, covering two research stimulation, development and circulation phases in two separate reservoirs. Both challenge problems address specific questions via numerical simulation in three topical areas: 1) reservoir creation/stimulation, 2) reactive and passive transport, and 3) thermal recovery. Challenge Problem #1 considers the Phase II Reservoir at Fenton Hill, located at true-vertical depths between 3,283 and 3,940 m, between wells EE-3A and EE-2A. Challenge Problem #2 considers the shallower Phase I Reservoir at Fenton Hill, located at true-vertical depths between 2,615 and 2,758 m, between wells EE-1 and GT-2B. The series of benchmark problems devised for this study were designed to test capabilities for modeling coupled processes under specified conditions. In contrast, the challenge problems seek to demonstrate what new understanding of enhanced geothermal systems can be generated via numerical simulation by the scientists and engineers that develop and apply these analytical tools.

### 1. INTRODUCTION

Enhanced geothermal systems (EGS) are a promising yet currently under-utilized energy resource (Wood, 2009). Extracting energy from geothermal sites can be accomplished in a seemingly straightforward fashion (i.e., drilling a pair of wells to depths where rock temperatures are sufficiently high, fracturing and hydraulically connecting the rock between the wells, and circulating a geofluid from one well to the other through the fractured rock). Potential geofluids are natural brines, compressed CO<sub>2</sub>, or exotic liquid mixtures, including those with nanoparticles. The geofluid flashes to steam at ambient surface pressures or exchanges heat with a working fluid, which vaporizes during the heat exchange process and subsequently drives an electricity-producing turbine. The cooled geofluid is re-injected into the thermal reservoir directly, or further cooled via secondary heat recovery systems (e.g., building heating). Although conceptually straightforward, like geologic sequestration of greenhouse gases, EGS presents challenges to hydrogeologists to fully realize this energy resource. Mathematical models and numerical simulation are the analytical tools that will be used to help meet these challenges, evaluate the feasibility of EGS at various geothermal sites, and will be essential in designing and evaluating operations of geothermal systems. To establish the credibility of numerical simulators as practical analytical tools, it is essential to demonstrate their capabilities for accurately and reliably modeling key physical processes involved in EGS, both individually and coupled. A common approach to evaluating numerical simulators, which contributes to their acceptance as practical analytical tools, is to exercise a suite of numerical simulators on problems that embody key processes of interest – to conduct a code comparison study.

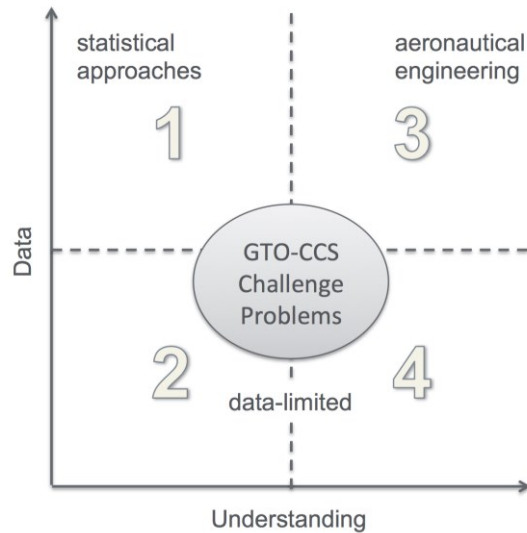
Pacific Northwest National Laboratory (PNNL) is supporting the Department of Energy (DOE) Geothermal Technologies Office (GTO) in organizing and executing a geothermal code comparison study (CCS). This project is directed at testing, diagnosing differences, and demonstrating modeling capabilities of a worldwide collection of numerical simulators for evaluating geothermal technologies. This study comprises two stages: 1) benchmark problems and 2) challenge problems with teams of participants developing solutions to the problems using a collection of numerical simulators. Participating teams on the study are principally from the United States and include those from universities, industry and DOE National Laboratories. One strength of the study is that the participating teams generally have unique numerical simulators and analytical approaches, providing a diverse set of mechanistic approaches, modeled processes and solution schemes. During the first stage of the study seven benchmark-scale problems were chosen by the participants, with each problem having a champion. Benchmark-scale problems were designed to investigate specific coupled processes typical of enhanced geothermal systems. The plan for the second stage of the study is to undertake problems having laboratory-scale or field-scale observational data. Problem descriptions in the benchmark suite were sufficiently specific to define the required coupled processes to be modeled and the expectation was for numerical simulation results to be comparable between the participating teams. For the challenge problem suite, laboratory or site data will be made available to the participating teams, but the processes to be modeled and the approach for modeling those processes will be the responsibility of each individual team. The benchmark-problem stage of the study was specifically designed to compare numerical simulators under controlled problem conditions; whereas, the challenge-problem stage of the study is designed to investigate the ability of participating teams and numerical simulators to follow key reservoir processes and process interactions and to recreate experimental observations.

Over the course of the year, since the close of the Fortieth Workshop on Geothermal Reservoir Engineering, held at Stanford University, Stanford, California, January 26-28, 2015, the teams participating in the GTO CCS have been collaboratively developing two challenge problems, against which solutions will be sought and submitted over the course of the U.S. Governmental fiscal year 2016, ending October 31, 2016. This paper serves to document and provide historical context for the challenge problems, and solicit international participation in the code comparison study, particularly in the challenge problems. During the opening workshop for the GTO code comparison study, which was held on February 14, 2014 at Stanford University, participants were tasked with developing concepts for the benchmark and challenge problems, which were to be more fully developed into problem statements for the code comparison study. Whereas a suite of nine benchmark problems were proposed, which did form the foundations of the seven benchmark problems for the study, the challenge problems remained relatively undefined. The outcome of the workshop in terms of the challenge problem descriptions was that they would be based on field demonstration sites and utilize actual data from those sites to the extent possible, but would provide complete specification where field data are not available through synthetic assignment. In this manner we would maintain as much geological realism as possible while still creating a problem that is well constrained and for which numerical solutions are directly comparable. After completing the synthetic problem, if time and funds allow we will proceed to a purely field-based problem where we attempt to match field observations. The two challenge problems described in this paper are based on a field demonstration site, the Fenton Hill Phase I and II Reservoirs, but the objective of the challenge problems have changed from the original perspective of being a more traditional code comparison exercise.

The year spent by the GTO CCS on the suite of seven benchmark problems was documented in four papers at the Fortieth Workshop on Geothermal Reservoir Engineering, held at Stanford University, Stanford, California, January 26-28, 2015 (White and Phillips, 2015; Podgorny et al., 2015; Kelkar et al., 2015; and White et al., 2015). The principal conclusions from this work were that while the U.S. EGS simulation community has a diverse set of computational tools with respect to conceptual approaches, they are able to simulate coupled subsurface processes with comparable results. The evolution of numerical simulators over the last thirty five years, since the 1980 geothermal code comparison study (Molloy et al., 1980) has been impressive, but work remains to be done. Uncertainties in simulation results as measured by the ISO-13528 standard tend to increase with the number of coupled processes in the problem and the modeling of strongly coupled THMC processes remains challenging. The collaborative nature of this study has formed the foundation for the EGS simulation community to collectively address field-scale systems, where coupled process modeling will be essential for understanding the system and experimental observations. Confidence in numerical simulation grows from agreement among field experts, especially when diverse perspectives are represented. This study yielded convergence in understanding over the course of each problem via open dialogue and discussions among the participants.

The suite of benchmark problems developed and solved by the participants on the GTO CCS were ideal for comparing computer codes as they were both rich with respect to data and understanding of the physical processes. Following the approach of Starfield and Cundall (1988) these types of modeling problems would fall within the Hollings (1978) scheme as being in Region 3, as shown in Figure 1. Region 1 represents modeling problems where the data are rich, but the process understanding is poor; and statistical modeling approaches are favored. Region 3 represents modeling problems where both data are known and available and the processes are well understood, such as in the design of airplane components. At first glance, one might consider all EGS problems as being more data limited because of the inherent heterogeneities in geologic material (e.g., fracture densities and orientations), but the suite of GTO CCS benchmark problems were sufficiently prescribed to not be data limited. Moreover the specific processes to be considered in the problems were well understood and prescribed in the problems. The test of the benchmark problems then became the solution of problems involving coupled EGS processes such as thermal, hydrological, geomechanical, and geochemical by the various computer codes involved in the study. Analytical solutions to these problems were generally not available so the solutions from the various computer codes were compared using the ISO (International Organization for Standardization) standard ISO-13538 for proficiency testing of numerical simulators. This approach was adopted for a recent code comparison study within the radiation transfer-modeling field of atmospheric sciences, which was focused on canopy reflectance models. This standard specifies statistical methods for analyzing laboratory data from proficiency testing schemes to demonstrate that the measurement results do not exhibit evidence of an unacceptable level of bias.

The challenge problems selected and described in this paper for the GTO CCS are based on the research activities conducted at the Fenton Hill Hot Dry Rock (HDR) Test Site, referred to by the Los Alamos Scientific Laboratory (LASL) (now the Los Alamos National Laboratory (LANL)) as Technical Area 57 (TA-57), or more simply as Fenton Hill (Brown et al., 2012). Fenton Hill is located about 1.9 miles west of the main ring-fracture of the Valles Caldera in the Jemez Mountains of north-central New Mexico, USA. Principal research activities at Fenton Hill took place in two HDR reservoirs. Development and testing in the Phase I Reservoir occurred between 1973 and 1980, over the approximate depth interval from 3,000 to 10,000 ft (871 to 3064 m) at temperatures between 105°C and 205°C. In contrast, the Phase II Reservoir activities spanned from 1979 through 1995 at greater depths and higher temperatures, over the approximate depth interval from 12,000 to 14,000 ft at temperatures between 260°C and 317°C. In terms of Holling's classification of modeling problems the GTO-CCS Challenge Problems are data rich with respect to the details about the experiments conducted at the Fenton Hill Test Site thanks to the recent publication by Brown et al. (2012), but at the same time data limited with respect to the rock mass. Even critical information about the stress state in both reservoirs remain uncertain, which puts the GTO-CCS Challenge Problems in the realm of data-limited modeling problems, as shown in Figure 1. Starfield and Cundall (1988) state that "the purpose of modeling data-limited problems is to gain understanding and explore potential trade-offs and alternatives, rather than to make absolute predictions." The desired outcome for the GTO-CCS Challenge Problems is that the modeling efforts yield new understanding or interpretations of the complex coupled processes that occurred during the Fenton Hill experiments, and hopefully that a collective agreement is found among the field experts often with diverse modeling approaches and capabilities. Available data sets for these problems are described in detail in White et al. (2016).



**Figure 1: Holling's (1978) classification of modeling problems and the location of the GTO-CCS Challenge Problems.**

## 2. PROBLEM #1 (FENTON HILL PHASE II RESEVOIR)

The GTO CCS Challenge Problem #1 is based on Phase II field activities at the Fenton Hill test site. A detailed account of these activities can be found in Part II, Engineering the HDR System: Development and Testing of the Phase II Reservoir at Fenton Hill of Brown et al. (2012). Problem champions are Derek Elsworth, Departments of Energy and Mineral Engineering and Geosciences, Penn State University, and Eric Sonnenthal, Earth Sciences Division, Lawrence Berkeley National Laboratory.

### 2.1 Problem Statement

The Phase II Reservoir at the Fenton Hill test site, located near Los Alamos, New Mexico, USA, was designed to test the enhanced geothermal system concept in hot dry rock at temperatures and geothermal heat production rates near those required for a commercial electrical power plant. Phase II field activities at Fenton Hill started with the drilling of well EE-2 on April 3, 1979 and ended with reservoir circulation being discontinued on July 14, 1995, following an annular breakthrough in the injection well EE-3A. The culminating experiment at Fenton Hill was the Long-Term Flow Test (LTFT), which lasted 39 months, with 11 months of active circulation through the reservoir. The Phase II Reservoir at Fenton Hill comprised a single injection well, EE-3A and a single production well, EE-2A, which were hydraulically connected via a complex joint network in otherwise impermeable hot rock. Tracer tests conducted during the LTFT indicate, via the nature of the tracer recovery profiles during steady-flow operation periods, that reservoir fluid pathways were becoming longer over time; an indication of shorter pathways being closed off. Temperatures across the four fluid-entry points in the open-hole portion of the production well EE-2A during the LTF show a decline in temperature over time of 7.2°C at the deepest point and 1.8°C at the shallowest point. Because continuous long-term circulation periods were not fully achieved within the Phase II Reservoir at Fenton Hill, there remains uncertainty about the thermal recovery performance of the reservoir over an extended period of time.

This problem seeks solutions via numerical simulation that answers specific questions concerning the Phase II Reservoir at Fenton Hill, in three topical areas: 1) reservoir creation/stimulation, 2) reactive and passive transport, and 3) thermal recovery. The response of the Phase II Reservoir to fluid injection and production is considered to be governed by strongly coupled hydrologic, thermal, geomechanical, and geochemical processes. Solutions shall address the coupled nature of these processes and demonstrate consistency with the experimental observations made during the reservoir creation and circulation tests as part of the Phase II Project at Fenton Hill. Models of the hydraulic connection between wells EE-3A and EE-2A can be conceptual or fracture networks generated via numerical simulation of the Phase II reservoir development via the hydraulic stimulation. Within the descriptions of each of the three topical areas, problem statements will include a question, metrics, and output section. The metrics section includes key experimental observations made during the Phase II Project at Fenton Hill, but we encourage solution submissions that utilize additional metrics to demonstrate coupled processes or defend submitted solutions.

### 2.2 Reservoir Creation/Stimulation

A hydraulic connection between wells EE-2 and EE-3 was never realized at Fenton Hill in spite of repeated attempts using thermal and hydraulic stimulation. A hydraulic connection however was realized between wells EE-3A and EE-2A, after directionally drilling of EE-3A through the cloud of seismic events that occurred during the stimulation activities. Whereas the achievement of hydraulic

connectivity allowed the Phase II Project at Fenton Hill to transition to flow test, there remains uncertainty about the structure of the stimulated volume and whether it comprises natural fractures, hydraulic fractures, or a combination of fracture types.

2.2.1 Question

What is the spatial extent and nature of the stimulated zone/volume that comprises the Phase II Reservoir?

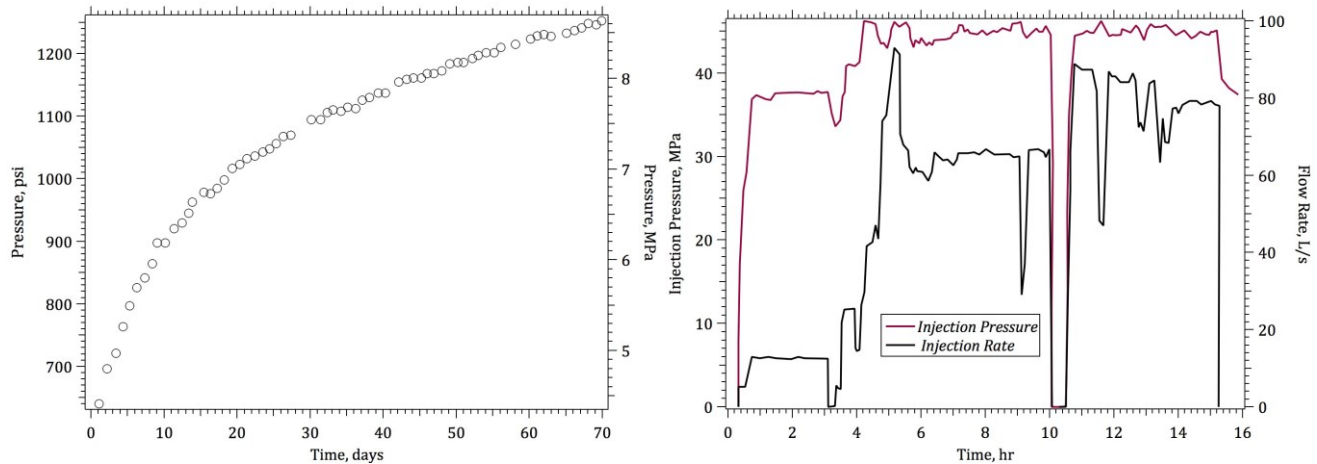
2.2.2 Metrics

Six key observations from the experiments conducted during the Phase II Project at Fenton Hill should be considered in developing a fracture network to model the Phase II Reservoir: 1) during circulation with a constant production pressure the injection pressure rapidly increases, but then plateaus and shows little sensitivity to injection rate; 2) the plateau pressure does not show a linear trend with depth (Brown, 1989; Kelkar et al., 1986); 3) fluid flow at the wellbore is principally localized to specific fractures; 4) the micro-seismic cloud from the Massive Hydraulic Fracturing (MHF) test is not aligned perpendicular to the minimum principal stress; 5) local impedance at the production well is strongly reduced with an increase in back pressure; and 6) reservoir pressure recovers to levels above the ambient pressure, after extended periods of venting after a closed injection test. References to specific metrics are listed below:

- 1) an apparent discontinuity in the fracture opening pressure between the phase 1 and phase 2 reservoirs (Brown, 1989; Kelkar et al., 1986)
- 2) pressure buildup to above ambient conditions in EE-2 after being shut-in, following a 10-month period of venting, small injections, and shut-ins, as shown in Figure 2
- 3) pressure and micro-seismic response to the injection experiment Exp. 2020 in EE-2, as shown in Figure 3 and in Figure 6-11 in Brown et al. (2012)
- 4) pressure response to injection experiment Exp. 2025 in EE-3, as shown in Figure 4.
- 5) pressure and micro-seismic response to the MHF test and pre-pump test, as shown in Figure 5, 6, and 7a-c.
- 6) the variety of seismic interpretations available, such as the fault plane solutions from the MHF, as shown in Figures 6-25 (Brown et al., 2012), and the results from the 3-point method as shown in Table 6-2 (Fehler, 1989) and Roff et al., (1996).

2.2.3 Output

A reservoir stimulation analysis of the Phase II Reservoir at Fenton Hill.



**Figure 2 (left): Pressure buildup in EE-2, beginning about 10 months after Exp. 2020, starting on July 13, 1983. Source Fig. 6-15, Brown et al. (2012). Figure 3 (right): Injection pressure at surface and injection rate in EE-2 during Exp. 2020, starting on 16:00 October 6, 1982. Source Fig. 6-9, Brown et al. (2012).**

**2.3 Reactive and Passive Transport**

The Phase II Reservoir comprises an injection well (EE-3A), a production well (EE-2A), a network of hydraulically conducting fractures, relatively impermeable blocks between the fractures, and an impermeable zone outside the spatial extent of the fracture network. Experiments during the Phase II Project included the injection and recovery of passive (i.e., unretarded) tracers to help understand the nature of the fracture network and chemical analysis of produced water during the circulation flow tests. In the interim period between the first and second steady-state production segments of the Long-Term Flow Test (LTFT), recirculated water was replaced with fresh water and the concentration of dissolved species were measured in the produced water.

2.3.1 Question

Given the state of the Phase II Reservoir at the conclusion of the LTFT, how long would it take for the produced fluid to reach steady chemical concentration conditions, assuming fresh water was injected for 48 hours, followed by closed recirculation of produced water, for constant injection conditions in the EE-3A injection zone (5.7 kg/s @ 100°C) with a constant production well backpressure of 1600 psi above hydrostatic in EE-2A?

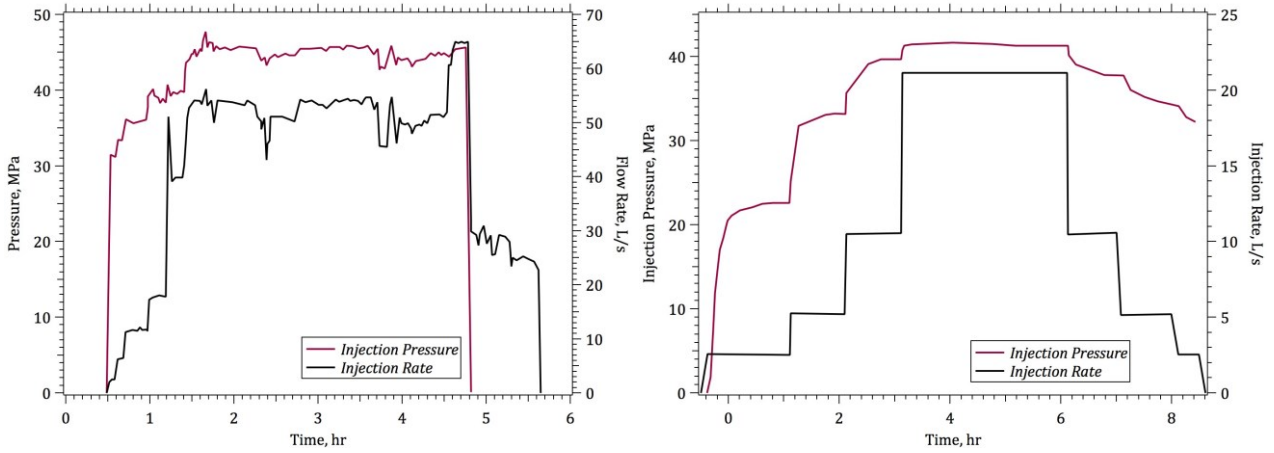


Figure 4 (left): Injection pressure at surface and injection rate in EE-3 during Exp. 2025, starting on 11:00 December 14, 1982. Source Fig. 6-13, Brown et al. (2012). Figure 5 (right): Injection pressure at surface and injection rate in EE-2 during the Pre-Pump Test, with zero time being 12:00 November 30, 1983. Source Fig. 6-18, Brown et al. (2012).

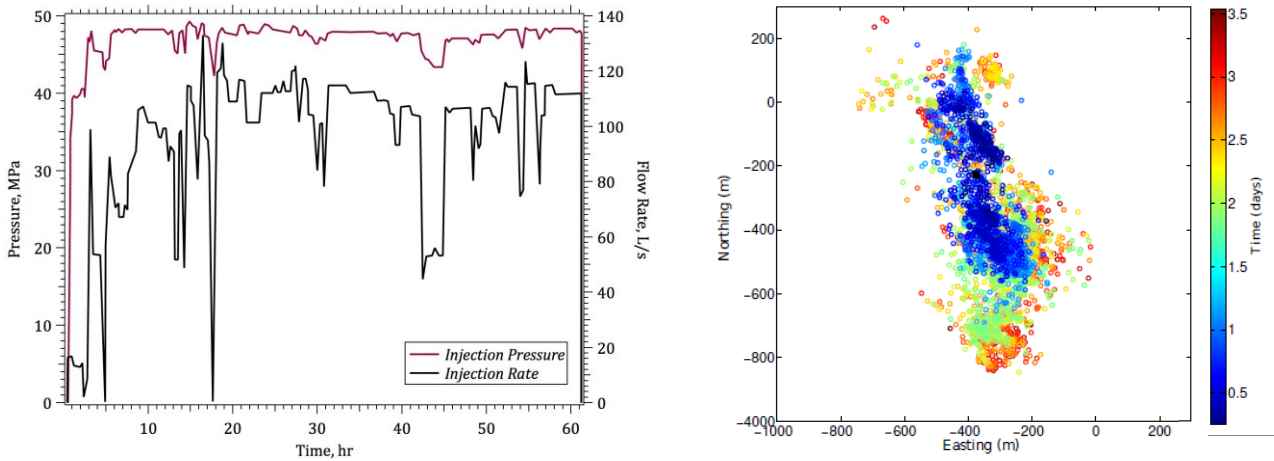


Figure 6 (left): Injection pressure at surface and injection rate in EE-2 during MHF Test, starting on 16:00 December 6, 1983. Source Fig. 6-21, Brown et al. (2012) from Dreesen and Nicholson (1985). Figure 7a (right): Micro-seismic events detected by downhole seismic instruments during the injection phase of the MHF Test (plan view), color-scaling by event time from 16:00 December 6, 1983.

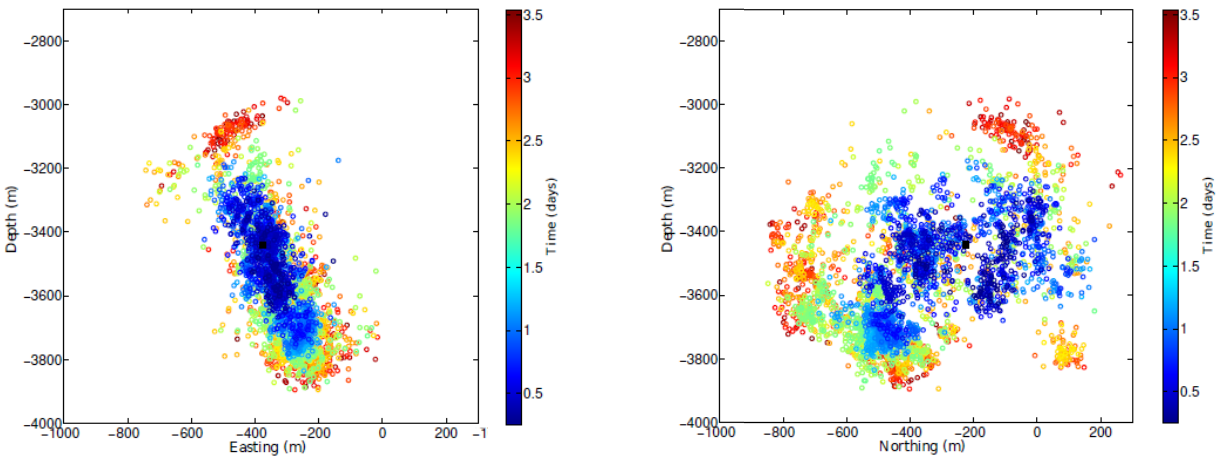


Figure 7b (left): Micro-seismic events detected by downhole seismic instruments during the injection phase of the MHF Test (west-east vertical cross section viewed toward north), color-scaling by event time from 16:00 December 6, 1983. Figure 7c (right): Micro-seismic events detected by downhole seismic instruments during the injection phase of the MHF Test (south-north vertical cross section viewed toward west), color-scaling by event time from 16:00 December 6, 1983.

### 2.3.2 Metrics

An experiment conducted as part of the Interim Flow Test (IFT) between the first and second steady-state production segment of the LTFT involved the replacement of recirculated water, which was assumed to be in equilibrium with the Phase II Reservoir minerals, was replaced with fresh water. Tables of dissolved species concentrations prior to the IFT were reported in Table 9-11 in Brown et al. (2012), reproduced in Table 1, and concentrations of the same species in the fresh water and produced water at two points in time were reported in Table 9-12 in Brown et al. (2012), reproduced in Table 2.

**Table 1. Concentrations of dissolved species in produced water during the LTFT (ppm)**

Species	First steady-state production segment		Second steady-state production segment	RVFT Stage 1	RVFT Stage 4
	April 1992	July 1992	March 1993	May 1995	July 1995
Chloride	1220	953	1002	890	1160
Sodium	1100	900	899	839	1020
Bicarbonate	552	588	556	469	505
Silicate (as SiO <sub>2</sub> )	458	424	402	419	445
Sulfate	285	378	342	328	385
Potassium	95	89	91	90	94
Boron	47	35	34	30	39
Calcium	19	18	17	13	15
Lithium	19	16	15	15	17
Fluoride	14	17	13	15	15
Bromide	6.5	5	5.1	4.6	6.8
Arsenic	3.8	7.2	3.5	3.0	4.0
Iron	1.0	0.8	0.3	0.3	0.2
Aluminum	0.9	1.2	0.8	0.8	0.9
Ammonium	0.8	1.1	1.3	1.0	0.4
Strontium	0.8	0.8	0.8	0.6	0.8
Barium	0.2	0.2	0.2	0.1	0.1
Magnesium	0.2	0.1	---	---	0.1
Total Dissolved Solids	3845	3434	3387	3118	3713

**Table 2. Concentrations of dissolved species during and following the FWF (ppm)**

Species	Injected Fresh Water	Produced Fluid	
	2 September 1992	8 September 1992	28 September 1992
Chloride	101	615	1109
Sodium	54	569	935
Bicarbonate	259	430	419
Silicate (as SiO <sub>2</sub> )	81	396	451
Sulfate	21	235	361
Potassium	10	53	94
Boron	1.9	18	40
Calcium	89	9.3	18
Lithium	0.7	8.7	16
Fluoride	0.5	15	14
Bromide	0.6	3.2	5.6
Arsenic	<0.1	2.7	3.4
Iron	0.5	0.3	0.5
Aluminum	0.2	1.3	0.6
Ammonium	0.1	1.1	1.3
Strontium	0.3	0.4	0.7
Barium	0.1	0.1	0.2
Magnesium	8.6	<0.1	0.1
Total Dissolved Solids	633	2358	3471

### 2.3.3 Output

Concentrations (ppm) of the dissolved species shown in Table 3 are to be reported over time at the inlet of the production well EE-2A. Equilibrium concentrations of the same dissolved species are to be reported at the temperature and pressure conditions of the inlet of the production well EE-2A.

**Table 3. Species concentrations to be reported (ppm)**

Cl-	Na+	HCO <sub>3</sub> <sup>-</sup>	SiO <sub>2</sub> (aq)	SO <sub>4</sub> <sup>--</sup>	K+	Ca <sup>++</sup>	Mg <sup>++</sup>	H+
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## 2.4 Thermal Recovery

Thermal recovery performance of the Phase II Reservoir was demonstrated via a series of circulation experiments referred to as the Long-Term Flow Test (LTFT), which covered a time period from April 1992 to July 1995. Sustained circulation between wells EE-3A and EE-2A marked the start of the LTFT and the end of the test came soon after a disastrous annular breakthrough was detected in the injection well EE-3A on July 6, 1995. (Brown et al., 2012). The LTFT comprised three periods of steady-state circulation and thermal recovery, a series of surging flow tests, and interim periods of minimal circulation through the reservoir. The individual experiments conducted during the LTFT period are the source of metrics about the reservoir characteristics, performance, and behavior.

### 2.4.1 Question

What would be the thermal recovery from the Phase II Reservoir if circulation had been continued under the conditions of the LTFT for an additional 20-year period, under constant injection conditions in the EE-3A injection zone (5.7 kg/s @ 100°C) with a constant production well backpressure of 1600 psi above hydrostatic in EE-2A?

### 2.4.2 Metrics

Four metrics have been selected to represent the behavior of the Phase II Reservoir under circulation conditions. Problem participants are encouraged to include additional experimental results to serve as metrics for this problem.

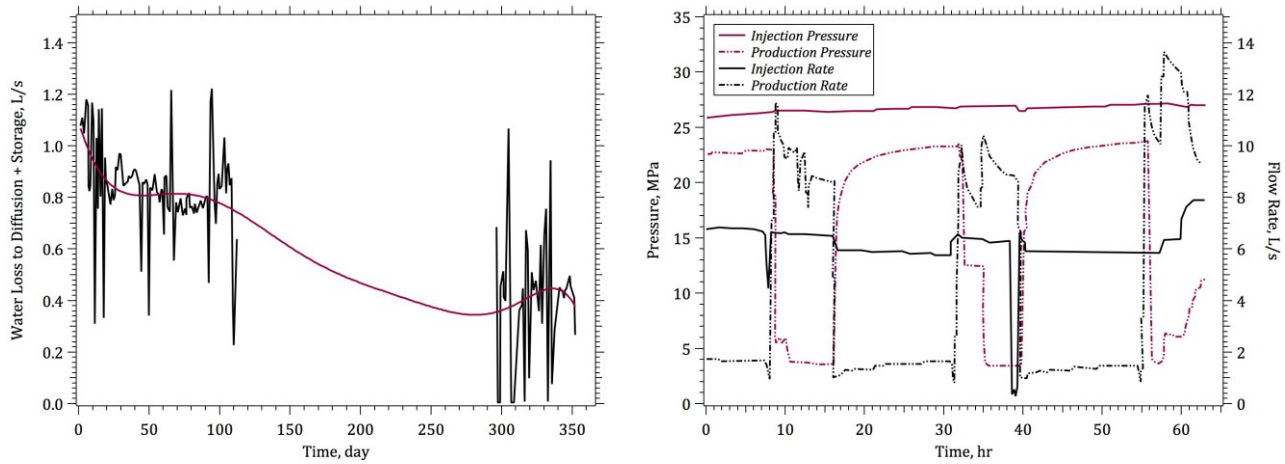
- 1) Water loss during the Fenton Hill experiments was defined with respect to the surface activities, and was the makeup water that needed to be added to the injection stream to offset the deficit in the produced water. The water-loss trends during the first two steady-flow circulation tests confirm the conclusions from earlier static reservoir pressurization tests that under constant pressure conditions, the water-loss would decline with time. A graphic showing the water-loss trend during this period is shown in Figure 8.
- 2) The first investigation of a cyclic “load-following” operation of the reservoir involved a period of continuous injection at 6.30 L/s with a very high pressure (20.68-22.75 MPa above hydrostatic) in the production well EE-3A, which kept the production flow at about 1.58 L/s. At the end of this 16-hr period the pressure in the production well EE-2A was dropped sharply for 8 hrs, yielding production flow rates of 8.83 to 9.46 l/s. The pressure and flow rates for two cycles are shown in Figure 9.
- 3) Flow impedance across the Phase II reservoir was thought to be concentrated around the production wellbore. Evidence of this was provided in the measurement of pressure recoveries in both the injection well EE-3A and production well EE-2A after shutdown of the circulation system. Changes in surface pressures of these two wells over the course of 95 minutes are shown in Figure 10.
- 4) The fracture network within the Phase II Reservoir was developed via a series of hydraulic and thermal stimulation activities, yielding a hydraulic connection between wells EE-3A and EE-2A. Uncertainty remains about the dynamic nature of the fracture network. Both geochemical analyses and passive tracer experiments were conducted on the Phase II Reservoir. Interpretations of the passive tracer experiments have suggested that the reservoir was becoming more diffusive over the periods of steady-flow operations. Fluorescein tracer recovery profiles during steady-state operations: 1) 18 May 1992, 2) 12 March 1993, 3) 15 May 1993 are shown in Figure 11.

### 2.4.3 Output

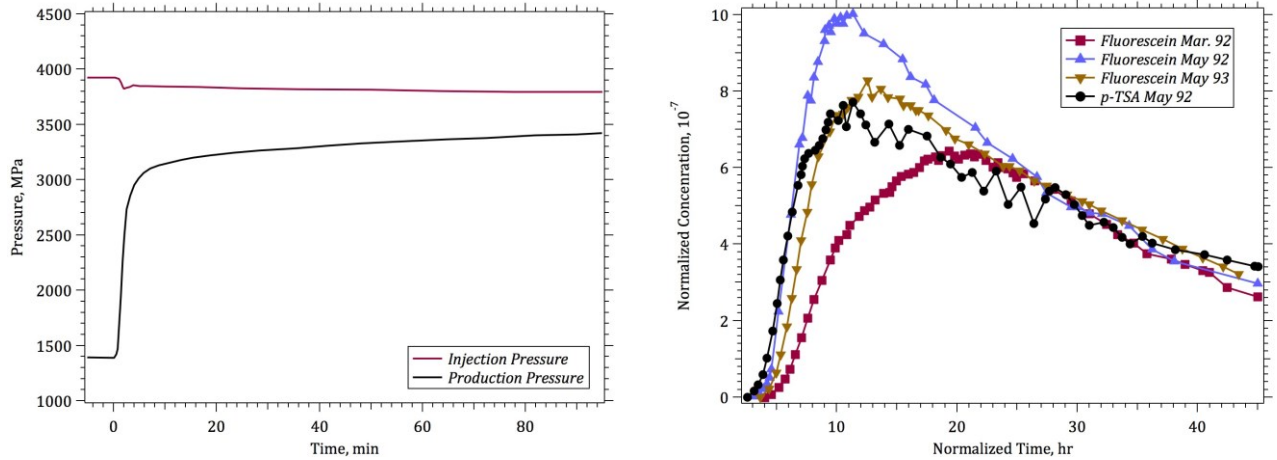
For the purposes of comparing numerical simulation results between participants the following outputs are requested for this problem:

- 1) Production well fluid temperature (°C) at the surface versus time.
- 2) Overall flow impedance (MPa/L/s) versus time.
- 3) Reservoir volume (m<sup>3</sup>) at 5, 10, 15, and 20 years after the LFTF period.
- 4) Wetted surface area (m<sup>2</sup>) at 5, 10, 15, and 20 years after the LFTF period.
- 5) Reservoir temperatures (°C) at 5, 10, 15, and 20 years after the LFTF period.
- 6) Passive tracer recover curves (normalized concentration) at 5, 10, 15, and 20 years.

If a dynamic fracture network is being used to model the reservoir volume then both a scalar value and spatial distribution is requested for the reservoir volume output.



**Figure 8 (left):** Water loss during the first two steady-state production segments of the LTFT starting April 1, 1992, Source: Fig. 9-13, Brown et al. (2012) from Brown (1999). **Figure 9 (right):** Injection and production pressure and rates during the first load-following experiment starting 00:00 May 4, 1983, Source: Figure 9-6, Brown et al. (2012) from Brown and DuTeau (1995).



**Figure 10 (left):** Injection and production surface pressures following shut-in of the HDR system during the LTFT, Source: Fig. 9-14, Brown et al. (2012) from Brown (1994). **Figure 11 (right):** Tracer recovery profiles during steady-state operations during 1992 and 1993 for three Fluorescein and on p-TSA experiments, Source: Figure 9-10, Brown et al. (2012).

### 3. PROBLEM #2 (FENTON HILL PHASE I RESEVOIR)

The GTO CCS Challenge Problem #2 is based on Phase I field activities at the Fenton Hill test site. A detailed account of these activities can be found in Part I, Hot Dry Rock Geothermal Energy: History and Potential of the Newest and Largest Renewable Energy Resource of Brown et al. (2012). Problem champions are Pengcheng Fu, Atmospheric, Earth and Energy Division, Lawrence Livermore National Laboratory and George Danko, Mining Engineering Department, University of Nevada, Reno.

#### 3.1 Problem Statement

The Phase I Reservoir at the Fenton Hill test site, located near Los Alamos, New Mexico, USA, was designed to demonstrate the technical feasibility of the enhanced geothermal system concept in hot dry rock. Phase I field activities at Fenton Hill started with the drilling of the GT-2 borehole on February 17, 1974, and ended with the shut-down of final circulation on December 16, 1980. Various tests, including injection and flow-back experiments, well logging and coring, chemical tracer and chemical leaching were performed concurrently with the drilling program. After the establishments of hydraulic connections between the two wells, a series of five circulation tests, referred to as Run Segments 1-5, were conducted in the Phase I Reservoir. Heat was produced from two different stimulated fractures/fracture networks in Run Segments 1-3 and in 4-5. A full set of evidences suggest that the sub-reservoir producing heat in Run Segments 1-3 consists of a major fracture intersecting Well EE-1 at 9050-ft (2758-m) depth and Well GT-1B at 8769-ft (2673-m) depth. The majority of the circulated fluid entered into the major fracture via the intersection with Well EE-1 and exited from the fracture through the intersection with Well GT-2B. Temperature logs along the wellbore indicated that the flow entry points at 8620 ft (2627 m) and 8900 ft (2713 m) in Well GT-2B also contributed to the flow. The hydraulic impedance of the producing reservoir was very low, especially when a high back-pressure was applied to dilate the fracture. The fracture that produced heat during Run Segments 1-3 was of modest size and substantial thermal drawdown had taken place. The sub-reservoir responsible for Run Segments 4 and 5 was

of a much larger volume and only limited thermal drawdown evolved during the 9-month Run Segment 5 circulation. However, the high hydraulic impedance and its insensitivity to back-pressure suggested that the reservoir was likely composed of multiple intersecting fractures under high confining stresses. However the available evidence was insufficient to constrain a definite fracture network model. Challenge Problem #2 seeks solutions via numerical simulation that answer specific questions concerning the Phase I Reservoir at Fenton Hill, in three topical areas: 1) reservoir creation/stimulation, 2) reactive and passive transport, and 3) thermal recovery.

### 3.2 Reservoir Creation/Stimulation

Multiple pressurization and venting experiments were performed in Zone 7 of well GT-2 after stage 2 drilling. Those provided intriguing field observations that make it possible to infer the hydraulic stimulation mechanism at the Fenton Hill Phase I experiment. Zone 7 is the open-hole interval at the bottom of well GT-2 after stage 2 drilling. Field observations indicated that two natural joints (between 6529-6540 ft [1990-1993 m] and 6559-6568 ft [1999-2002 m] deep, respectively; probably dipping 70 degrees below horizontal) might have been opened by the stimulation. A few rounds of injection-shut-in and subsequent venting operations were performed.

#### 3.2.1 Question

Assuming natural joints were being opened by the hydraulic stimulation, what are the hydro-mechanical responses of the joints to fluid injection, shut-in, and venting (flow-back)? If this natural joint opening model (preferred hypothesis in Brown et al. (2012)) can reproduce the set of observations described in the “Metrics” section below, is it likely to be the true stimulation mechanism at Fenton Hill Phase I.

#### 3.2.2 Metrics

Three key observations from the experiments conducted during the Phase I Project at Fenton Hill should be considered:

- 1) The pressure history during and following the first pressure-stimulation test, as shown in Figure 12.
- 2) The observation that much less than half of the injected fluid was recovered in each of the three subsequent tests. In these three injection-venting experiments between September 25 and 27, 1974, 11,000, 20,000, and 36,000 gal of water (corresponding to 41.64, 75.71, and 136.27 m<sup>3</sup>) was injected, respectively, at a maximum injection pressure (wellhead) of 2,500 psi (17.237 MPa) and a maximum flow rate of 4 BPM (10.6 L/s).
- 3) The observation that a much greater portion of the injected fluid was recovered after an injection experiment using cross-linked polymer mixed with sand (proppants) performed on September 28, 1974. In that experiment, 4,500 gal (17.03 m<sup>3</sup>) of treated fluid (mixed with 9,500 lb [4,309 kg] of sand) was pumped at a rate of 9 BPM (23.9 L/s). The pumping pressure was as high as 2,950 psi [20.34 MPa] during the treatment. Over 90% of the injected fluid was recovered in less than an hour, and continued venting recovered another 8%.

#### 3.2.3 Output

- 1) Assuming (i) 2,500 psi (17.237 MPa, wellhead pressure) to be the joint/fracture opening pressure (the pressure at which the fracture intersecting the wellbore was jacked open to receive the injected fluid), (ii) a constant flow rate of 4 BPM (7.9 L/s), (iii) a shut-in period of 60 min. after each of the injections (41.64, 75.71, and 136.27 m<sup>3</sup>) of water, and (iv) subsequent free flow-back, simulate the wellhead pressure/flow rate responses during the injection, shut-in, and flow back. From this, calculate the flow-back volume within one hour following each injection.
- 2) Assuming (i) the main effect of the proppant is to maintain a minimum hydraulic aperture of 1.0 mm near the wellbore (as opposed to a minimum hydraulic aperture of 0.1 mm [or any other small value that can be justified] when no proppant is present), (ii) the viscosity of the cross-linked gel to be 10 times of that of water, and (iii) injection of 4,500 gal (17.03 m<sup>3</sup>) of gel at 9 BPM (23.9 L/s), simulate the wellhead pressure/flow rate responses during the injection, shut-in, and flow back for the gel treatment. From this, calculate the flow-back volume within one hour following each injection.

### 3.3 Reactive and Passive Transport

This problem is based on the quartz-leaching experiments (Experiments 137 and 138) performed in November 1976. The experiments were performed on the deep joints stimulated from and connected via Wells EE-1 and GT-2. A variety of experiments had been performed to characterize the joints/reservoir before the quartz-leaching experiments, as summarized in Table 3-12 of Brown et al. (2012). Before experiment 137, the hydraulic impedance of the system was approximately 30 psi/gpm (3.278 MPa/(L/s)) and the recovery rate was relatively low. The objective of the quartz-leaching experiments was to reduce the flow impedance by geochemical means.

#### 3.3.1 Question

How did the circulation of sodium-carbonate solution affect the hydraulic impedance of the joints/reservoir?

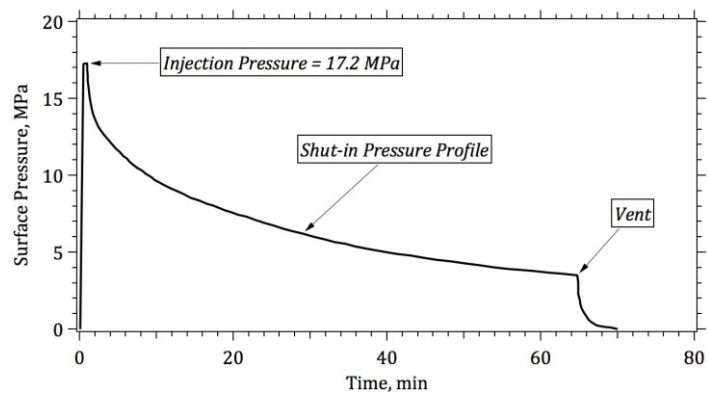


Figure 12: Surface pressure during the first hydraulic fracturing (Zone 7) in GT-2. Figure developed from Blair et al. (1976).

### 3.3.2 Metrics

- 1) The baseline hydraulic impedance is established by Experiment 137 (Brown et al., 2012). Approximately 250,000 gal (946 m<sup>3</sup>) of water was injected into EE-1 over 7 days at a controlled pressure of 1,200 psi (8.27 MPa). The flow rate evolved from the initial value of 43 gpm (2.713 L/s) to 20 gpm (1.262 L/s) at the end of pumping, indicating an increase in hydraulic impedance. Near the end of this phase of injection, GT-2 production leveled off at 15 gpm (0.946 L/s) and a steady-state flow impedance of 75 psi/gpm (8.19 MPa per L/s) was recorded.
- 2) The complex geochemical and hydraulic responses of the reservoir during Experiment 138 (Brown et al., 2012). Experiment 138 was conducted immediately following Experiment 137 on the afternoon of November 11, 1976 with a smooth continuation of injection rate and injection pressure. The fluid was switched to 1-normal solution of sodium carbonate and a total of 48,000 gal (181.7 m<sup>3</sup>) of this solution was injected before the injection fluid was switched back to water. The main hydraulic response was that the injection rate first increased from 20 gpm (1.262 L/s) to 88 gpm (5.552 L/s) due to a decrease of impedance. It then gradually declined to 9 gpm (0.568 L/s) before another small increase occurred. The outflow in GT-2 decreased from 18 gpm (1.136 L/s) to 12 gpm (0.757 L/s). Complex responses in geochemistry are described in pages 138 to 139 in Brown et al. (2012), and are not repeated here.

### 3.2.3 Output

Assuming a constant injection pressure that results in a plain water injection rate of 20 gpm (1.262 L/s), simulate the evolution of injection rate for the injection of 48,000 gal (181.7 m<sup>3</sup>) of 1-normal solution of sodium carbonate.

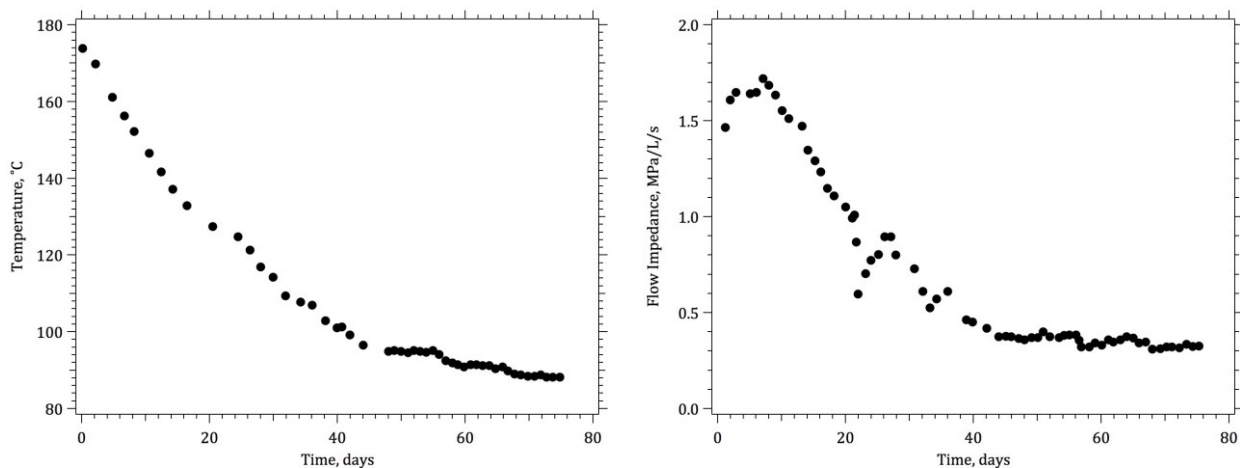
### 3.4 Thermal Recovery

Three circulation tests were performed at the Fenton Hill Phase I reservoir between 1977 and 1978, referred to as Run Segments 1-3. Strong evidence exists to support a reservoir model consisting of a major near-vertical fracture/joint connecting GT-2B (at 8769 ft [2672.8 m]) and EE-1 (at 9050 ft [2758.4 m]) and a few minor entry/exit points in the two wells. The three Run Segments served distinct yet complementary purposes:

- Run Segment 1 (September 1977, 4 days) was a preliminary test of the closed-loop heat-extraction system and an initial assessment of the reservoir's flow characteristics.
- Run Segment 2 (January to April, 1978, 75 days) was a relatively long-term circulation operation to access the thermal production capability of the reservoir. This was considered a major milestone: the first-ever successful operation of an engineered HDR system.
- Run Segment 3 (October 1978, 28 days) was to investigate the effects of high backpressure on reservoir impedance.

#### 3.4.1 Question

- 1) What are the thermo-hydro-mechanical processes that operate during the circulation experiments that have produced the suite of observations detailed in the "Metrics" section below?
- 2) If the major fracture connecting the two wells had been five times larger (five times greater distance between the entry and exit points and five times wider) but with comparable aperture distribution, what would be the effective heat production life?

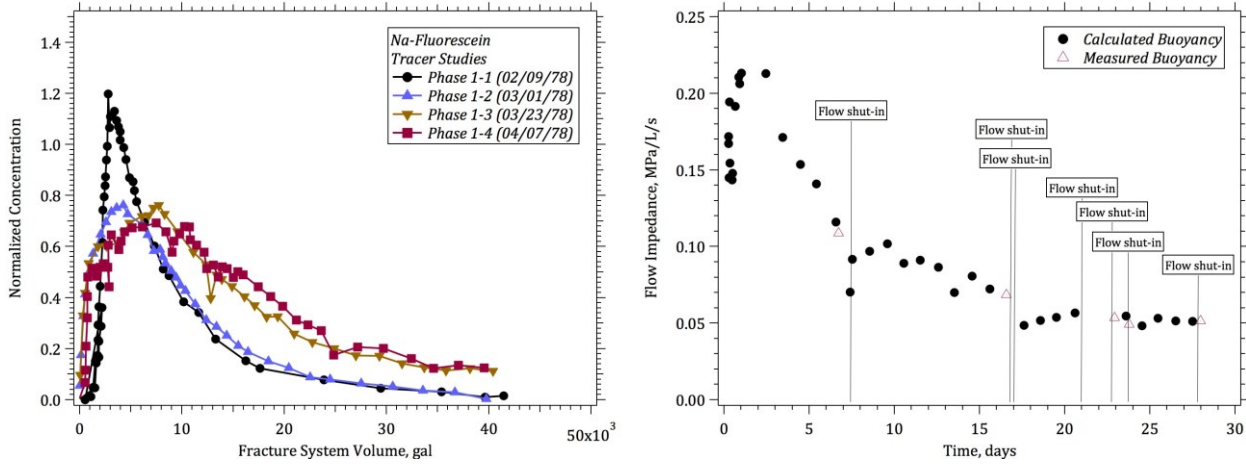


**Figure 13 (left):** The evolution of production temperature during Run Segment 2 circulation test in the Fenton Hill Phase I experiment. Figure developed based on data published in Tester and Albright (1979). **Figure 14 (right):** The evolution of hydraulic impedance during Run Segment 2 circulation test in the Fenton Hill Phase I experiment. Figure developed based on data published in Tester and Albright (1979).

### 3.4.2 Metrics

- 1) The initial condition assessed by Run Segment 1. Over the four days of this test, injection pressure varied between 1000 psi (6.89 MPa) and 1350 psi (9.31 MPa) with a water loss decreasing from 86 to 30 gpm (5.43 to 1.89 L/s). By the end of the test, the production flow rate was at 100 gpm (6.31 L/s) with an outlet temperature of 130 °C.

- 2) The thermal drawdown observed during Run Segment 2 as shown in Figure 13 (shown above).
- 3) The flow impedance evolution as shown in Figure 14 (shown above) is likely due to thermal contraction of the reservoir rock.
- 4) The inter-well tracer transport test results presented in Tester et al. (1979). Figure 15 from Tester et al. (1979) shows that the tracer concentration evolution from the first test (day 12) had characteristics significantly different from those of the three subsequent tests (day 32, day 54, and day 69). This difference possibly reflects the observed sudden change of flow impedance on day 22.
- 5) The flow impedance evolution in Run Segment 3 under high backpressure as shown in Figure 16.
- 6) The evolutions of the production temperature and flow impedance, if the major fracture connecting the two wells been five times larger.



**Figure 15 (left) :** The evolutions of production well tracer concentration (normalized) for the four tracer tests during Run Segment 2 circulation test in the Fenton Hill Phase I experiment. The method of normalization is described in Tester et al. (1979). **Figure 16 (right):** The evolutions of flow impedance during Run Segment 3 circulation test, in which a high backpressure was applied.

### 3.4.3 Output

- 1) The injection and production flow rates for an injection pressure history that simulates Run Segment 1.
- 2) The production temperature history under a given (to be provided later) injection history that simulates Run Segment 2.
- 3) The temperature profiles along the production wellbore between 8500 ft and 8900 depth (2591 m to 2713 m) on day 7, day 12, and day 16 into the circulation.
- 4) The evolution of the hydraulic impedance during the 75 days of circulation.
- 5) Tracer concentration evolutions for the four tracer tests carried out on day 12, day 32, day 54 and day 69 into the circulation.
- 6) The flow impedance evolution under injection conditions (i.e. high backpressure) that simulate Run Segment 3.
- 7) The evolutions of the production temperature and flow impedance in the long term (years) for an assumed larger fracture. Detailed parameters for the assumed system are to be provided.

## 4. CONCLUSION

Numerical simulation provides scientists and engineers with analytical tools for understanding complex physical processes and the capabilities of current multiprocessor workstation computers allow the consideration of coupled processes. For EGS, hydrologic, thermal, geomechanical and geochemical processes all contribute to realizing the energy potentials from geothermal resources. The inherent heterogeneity of the earth's crust contributes greatly to the uncertainty in modeling EGS via numerical simulation, but the modeling of more idealized systems provides opportunities for an in-depth understanding of the impacts of design and field operational choices. In 1980 the geothermal community dedicated the annual Geothermal Reservoir Engineering workshop to defining an appropriate role for numerical simulation in terms of investment decisions related to geothermal performance predictions and to assessing the state of development of geothermal reservoir numerical simulators. The technical foundation for achieving the workshop objectives was a code comparison study, which involved six geothermal problems. In 2014 the U.S. Department of Energy, Geothermal Technologies Office (GTO) sponsored a second geothermal code comparison study, which comprised a suite of seven benchmark geothermal problems. This study was directed at testing, diagnosing differences, and demonstrating modeling capabilities of a worldwide collection of numerical simulators for evaluating geothermal technologies. The outcomes from the study were publications of solutions to the seven benchmark problems and a demonstration that while the U.S. EGS simulation community had a diverse set of computational tools with respect to conceptual approaches, they were able to simulate coupled subsurface processes with comparable results.

This paper is specifically designed to announce to the U.S. national and international geothermal community two new problems that mark the Challenge Problem stage of the GTO's code comparison study, and to invite interested research teams to participate in the study. Both of these challenge problems are based on the research activities conducted at the Fenton Hill Site near Los Alamos, New Mexico, by the Los Alamos Scientific Laboratory, between 1974 and 1995. The problems are based on the stimulation, development and circulation phases of two separate reservoirs. Both challenge problems have specific questions to be answered via numerical

simulation in three topical areas: 1) reservoir creation/stimulation, 2) reactive and passive chemical transport, and 3) thermal recovery. Challenge Problem #1 considers the Phase II Reservoir at Fenton Hill, located at true-vertical depths between 3,283 and 3,940 m, between wells EE-3A and EE-2A. Challenge Problem #2 considers the shallower Phase I Reservoir at Fenton Hill, located at true-vertical depths between 2,615 and 2,758 m, between wells EE-1 and GT-2B. Whereas this study is referred to formally as the GTO Code Comparison Study, the principal objective for this stage of the study is to have the research teams work in a collaborative fashion, each bringing their own numerical simulation tools and expertise to bear. The desired outcome for the GTO-CCS Challenge Problems is that the modeling efforts yield new understanding or interpretations of the complex coupled processes that occurred during the Fenton Hill experiments, and hopefully that a collective agreement is found among the field experts often with diverse modeling approaches and capabilities.

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