Continuum Thermal-Hydraulic-Mechanical Modeling of Long-term Heat Production for the Utah FORGE EGS Concept

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ABSTRACT

A coupled thermal-hydraulic-mechanical (THM) model is applied to evaluate the long-term (30-year) performance of the Utah FORGE Enhanced Geothermal System (EGS) concept. The analysis has recently been expanded to a full-scale three-dimensional continuum model around injector and producer wells using the TOUGH-FLAC simulator. Propped-open fractures connecting injection and production wells spaced 100 meters apart is represented in the continuum model. To begin, the model was used to simulate the 2024 30-day circulation test at Utah FORGE, which involved water circulation at approximately 26 l/s. The simulation was then extended to cover 30 years of continuous heat extraction to assess the long-term influence of coupled THM processes. Results shows that THM effects play a much more significant role over the long term than during the short-term circulation test. Cooling of the rock surrounding the active flowing fractures leads to stress reduction and fracture opening. This suggest that the fractures may be held open over time, which could enhance heat production efficiency throughout the operational lifespan of the system.

1. INTRODUCTION

The Utah Forge Enhanced Geothermal Systems (EGS) concept is classified as a conductive-dominated system, developed in formations with relatively low intrinsic permeability and no hydrothermal activity (Horne et al., 2025). In these systems, localized vertical fractures can be induced using stimulation techniques in horizontal or highly deviated borehole trajectories. These engineered fractures connect the wells and act as local heat exchangers, heating injected fluids through conduction from the adjacent rock matrix (Horne et al., 2025).

The Utah FORGE pilot EGS project employs a plug-and-perf well completion strategy, inspired by the success of unconventional hydrocarbon production (Moore et al., 2019). This approach involves cementing casing into deviated wells and perforating them at regular intervals. Fractures are created and connected between injecting and producing wells, and proppants are used to keep the fractures open. A similar plug-and-perf completion strategy with proppants is being adapted in commercial EGS developments, such as Fervo's Project Red in Nevada and Project Cape in Utah (Norbeck et al., 2023; Norbeck et al., 2024; Fercho et al., 2025).

This article presents a coupled thermal-hydro-mechanical (THM) modeling study of short-term fluid circulation and long-term heat production for the Utah FORGE EGS concept. As part of a Utah FORGE research project focused on the evolution of proppants and proppant-filled fractures, this study investigates the long-term sustainability of the system over a 30-year period. Specifically, it examines how stress changes on proppant-filled, actively flowing fractures over time, due to thermal and poro-elastic stress changes, impact heat production. These processes are simulated using a continuum model that considers multiphase fluid flow, heat transport, and geomechanics (Rutqvist, 2011; 2017).

2. MODEL SETUP

Figure 1 illustrates the model geometry, taking into account symmetry in the vertical plane intersecting the injection and production wells. The horizontal wells are spaced 100 m apart, with a stimulated reservoir of enhanced permeability assumed to connect them. To replicate the geometry at Utah FORGE, the lateral length of the wells is set at 300 m. The permeability of the stimulation zone is calibrated to match the flow rate and heat response observed during the 2024 Utah FORGE circulation test, ensuring a reasonable reservoir cooling for evaluating long-term cooling-induced stress changes and fracture opening. Although the Utah FORGE wells are slanted to facilitate borehole logging, industry projects often involve long-reach horizontal wells, such as those used at Fervo's Red Project in Nevada's Blue Mountain and the Cape Project near Utah FORGE in Utah (Norbeck et al., 2023; Norbeck et al., 2024; Fercho et al., 2025). Consequently, the conceptual and numerical models developed in this study are designed to analyze circulation experiments at Utah FORGE, as well as longer-term heat production, considering the Utah FORGE Enhanced Geothermal System (EGS) concept. The reservoir stimulation zone is modeled using a ubiquitous joint model, which accounts for vertical fractures or weak planes oriented normal to the wells, representing proppant-filled hydraulic fractures created during stimulation. Currently, the model assumes a uniform fracture permeability along the wells, consistent with the relative flow uniformity observed by McClure (2025).

The main point is to be able to model the longer term (i.e. 30 years) THM responses and their impact on active fracture evolutions and heat production. The THM simulations are performed with TOUGH-FLAC (Rutqvist et al., 2002; Rutqvist 2011; 2017; Rinaldi et al., 2022). These THM models will be updated during the project considering results and findings and constitutive models for the short and long-term propped fracture behavior.

Initial conditions include initial stress, pressure and temperature gradients. The gradient of stresses for the Utah FORGE site are estimated in Moore et al. (2019) as

• SV = 1.13 psi/ft = 25,561.27 Pa/m

• SHmin = 0.61 psi/ft = 13,798.56 Pa/m

• SHmax = 0.75 psi/ft = 16,965.45 Pa/m

Considering a depth of about 2.3 km (7546 ft), the following stress magnitudes are obtained:

• SV = 8527 psi = 59 MPa

• SHmin = 4403 psi = 30 MPa

• SHmax = 5659 psi = 39 MPa

The initial thermal gradient was applied as defined in Moore et al. (2019), resulting in an initial temperature of approximately 200°C. An initial hydrostatic pressure gradient was assumed, with the modeling commencing with an initial reservoir at conditions following a stimulation. Specifically, we assumed the presence of a stimulation zone characterized by proppant-filled fractures with a specified fracture transmissibility.

In the context of the Utah FORGE field, the created fracture system is maintained at hydrostatic pressure by shutting in the wells after stimulation. This condition could serve as the starting initial pressure for the modeling. For vertical fractures created perpendicular to the least principal stress, the total stress normal to the fractures would be approximately 30 MPa (4403 psi). Under these conditions, a hydrostatic fluid pressure of about 23 MPa (3336 psi) would yield an effective stress of around 7 MPa (1015 psi). In contrast, for a dry system, the effective stress could be as high as 30 MPa (4403 psi). During active injection and production phases, the pressure might be maintained at a level higher than hydrostatic but lower than the least principal stress of 30 MPa.

The initial set of rock properties used in this study was derived from average values reported in Moore et al. (2019), as summarized in Table 1. These values were applied to the granitoid host rock outside the main active flowing fractures, where permeability is low and heat transfer occurs primarily through conduction. The Young's modulus of 58.5 GPa is consistent with that of intact granite, and a Biot coefficient of 0.6 was assumed. The linear thermal expansion coefficient of 2e-6 1/K significantly influences the cooling-induced strain and stress changes. For the stimulation zone, vertical fracturing was assumed, and it was considered incapable of withstanding tensile stress perpendicular to the fracture planes. This modeling effort assumes constant fracture permeability, unaffected by changes in fracture aperture; however, future modeling will incorporate permeability changes.

Table 1: Material properties for granitoid host rock from Utah_FORGE (2019)

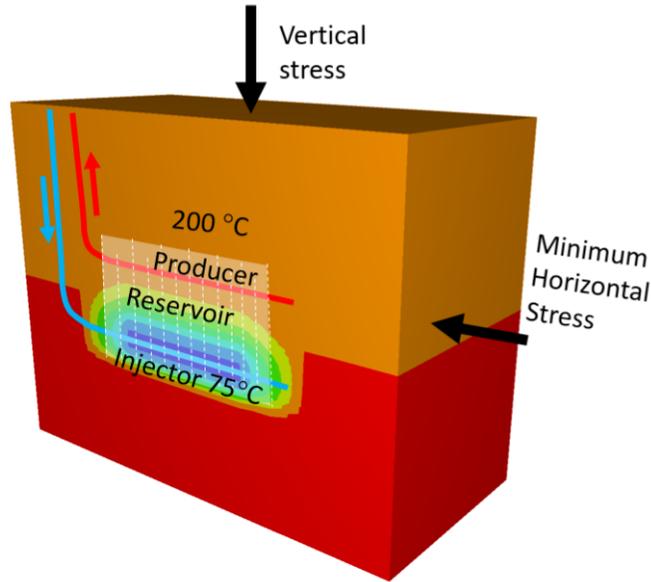| Parameter	Values
Rock Permeability	1e-18 m2
Porosity	0.01
Rock grain density	2750 kg/m3
Thermal Conductivity	3.0 W/m K
Specific heat	790 J/kg K
Young's modulus	58.5 GPa
Poisson's ratio	0.28
Biot Coefficient	0.6
Thermal expansion coefficient	2e-6 1/K

Figure 1: Three-dimensional continuum model for coupled thermal-hydro-mechanical analysis of cooling-induced stress evolution.

3. MODELING RESULTS

Figure 2 illustrates the time evolutions of a 30-day fluid circulation test and long-term heat production over 30 years. For this simulation, the permeability of the stimulation zone was set to 1e-14 m², which yielded a flow rate of 26 l/s, consistent with observations from the Utah FORGE 30-day circulation test (Figure 2a). The modeling parameters included a constant downhole injection pressure of 31 MPa and a temperature of 75°C, while the production well was maintained at a constant downhole pressure of 27 MPa.

During the 30-day circulation test, the temperature in the production well increased to approximately 200°C and remained relatively constant, with no significant decline observed (Figure 2b). This stable temperature profile suggests efficient heat transfer during the short-term circulation test.

The simulation was then extended to evaluate heat production over a 30-year period (Figure 2c and d). Over this extended timeframe, the production temperature declined to around 130°C, while the water circulation rate decreased to 14 l/s, despite maintaining constant well pressures. This decline in flow rate can be attributed to an increase in water viscosity resulting from the cooling effect.
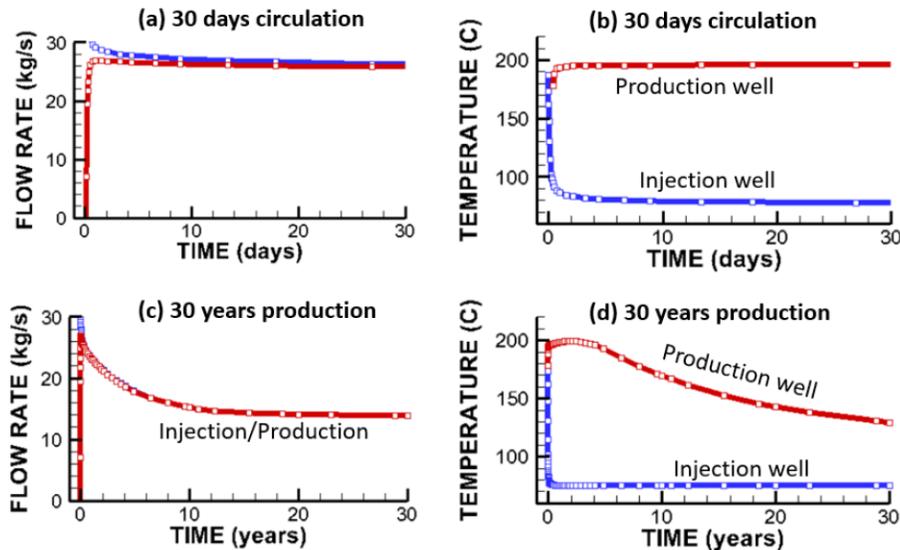

Figure 2: Model of the Utah FORGE geothermal concept showing results of flow rate and temperature for initial 30 days of fluid circulation followed by 30 years of heat production.

Figures 3-5 present simulation results for temperature, effective stress, and joint plastic tensile strain in a cross-section of the model at three distinct times: 30 days (end of circulation test), 10 years, and 30 years of heat production. The effective stress values in Figure 4 are specifically for the direction perpendicular to the perceived vertical fractures connecting the two wells, while the joint plastic tensile strain represents the opening of these fractures. Initially, after 30 days of circulation, some cooling is observed near the injection well, but changes in effective stress and joint tensile plastic strain are minimal. Figure 4 indicates a reduction in effective stress within the entire stimulation zone, primarily due to the increased pore pressure caused by injection pressures exceeding the initial hydrostatic pressure.

At 10 and 30 years, the results reveal significant cooling of the stimulation zone (Figure 3), leading to a substantial reduction in effective compressive stress (Figure 4) and notable tensile plastic strain (Figure 5). Figure 4 shows that the effective stress normal to the vertical fractures approaches zero, indicating that the fractures are nearly completely open with minimal mechanical contact. Figure 5 shows plastic tensile strain up to 3×10^{-4} (0.3 milli-strain) which signifies joint tensile opening in the ubiquitous joint model. This number can be translated into fracture aperture changes depending on the spacing between opened fractures. If there is a fracture every 10 meters, the fracture opening would be up to 3×10^{-3} m (3 mm), which is substantial considering the initial aperture for a 10-meter fracture spacing was estimated to be around 0.1 mm. This significant fracture opening is expected to enhance production by increasing the overall EGS permeability. Although stress-induced permeability changes are not currently considered in the simulation, this feature will be incorporated in future work.
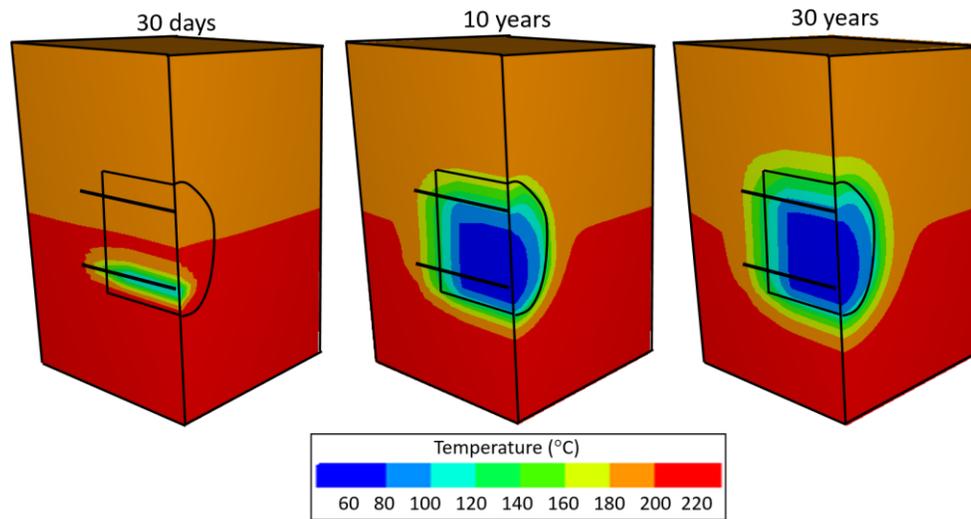

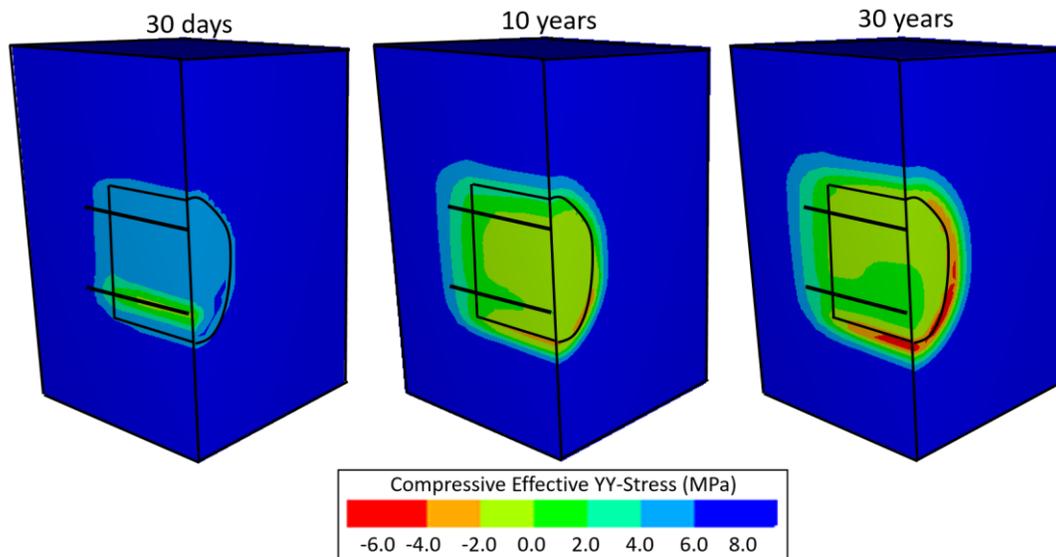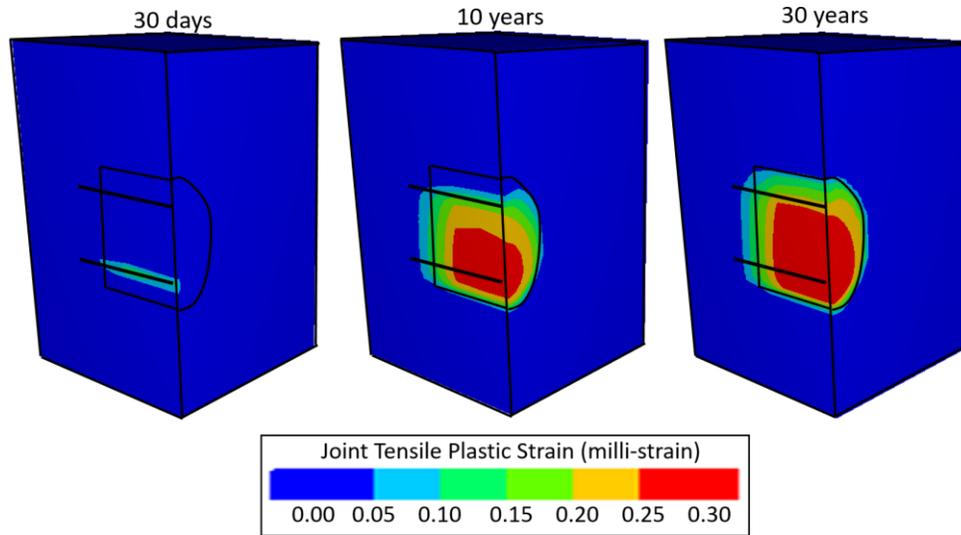**Figure 3: Results of temperature during the 30 years of simulated heat production.**

Figure 4: Results of effective stress in the direction along the wells that is normal to the perceived fracture planes in the stimulation zone.

Figure 5: Simulation results of joint tensile plastic strain that signifies joint opening in the ubiquitous joint model.

4. CONCLUDING REMARKS

A coupled thermo-hydro-mechanical model of the Utah FORGE EGS concept has been developed to investigate the impact on short-term (i.e. 30 days) fluid circulation and long-term (i.e. 30 years) heat production. The simulations show very strong impacts of thermal mechanical and poro-elastic responses over the 30-years heat production, effects that are not as pronounced in the 30-days circulation test. The results indicate that cooling of the rock matrix causes significant unloading and fracture opening. The overall impact is an increase in flow transmissibility with time that would contribute to enhance the heat production over the longer term.

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