

## Modeling the Onset of Thermal Short-Circuiting in EGSs with a Coupled THM-Wellbore Approach

Qitao Zhang, Arash Dahi Taleghani, Kun Ji and Weiyun Hua

The Pennsylvania State University, University Park, PA 16801

Email: arash.dahi@psu.edu

**Keywords:** EGS; thermal short-circuiting; flow plane channeling; early thermal breakthrough.

### ABSTRACT

Thermal short-circuiting significantly undermines the long-term productivity and economic sustainability of Enhanced Geothermal Systems (EGS). This research examines the synergistic physical mechanisms—thermal edge effects, non-isothermal wellbore flow, and thermal distressing—that drive this phenomenon using a coupled Thermo-Hydro-Mechanical-Wellbore (THM-W) framework. The model reveals that an initially uniform reservoir eventually develops preferential flow channels through a self-reinforcing feedback loop. This evolution begins with wellbore friction and thermal edge effects, which induce rock contraction and cooling near central fractures. By the 28-year mark, thermo-mechanical opening becomes the primary flow regulator; central fracture apertures expand from 5 mm to over 7 mm, while permeability escalates from  $5 \times 10^{-11} \text{ m}^2$  to  $4.06 \times 10^{-8} \text{ m}^2$ . This high-conductance path captures a disproportionate 30% of injected fluid, triggering premature thermal breakthrough. Furthermore, while proppants enhance hydraulic conductivity, they also expedite thermal decline. These findings offer a quantitative evaluation of the mechanisms precipitating thermal short-circuiting, providing essential insights for the development of future engineering interventions and mitigation strategies.

### 1. INTRODUCTION

The global transition toward a decarbonized energy future has intensified the search for reliable, carbon-free baseload power. While intermittent renewables like solar and wind have seen massive deployment, their inherent variability presents significant challenges for grid stability and long-term resilience. Geothermal energy emerges as a unique solution to this problem, offering a renewable resource capable of providing consistent, high-capacity power 24/7. Historically, however, geothermal energy has been geographically restricted to rare "hydrothermal" sites where heat, water, and rock permeability naturally coexist. Enhanced Geothermal Systems (EGS) represent a paradigm shift in this field, aiming to unlock the vast thermal potential stored in deep, low-permeability basement rock—often referred to as Hot Dry Rock (HDR)—virtually anywhere on Earth (Wang et al., 2025). The core concept of EGS involves engineering an artificial subsurface reservoir where natural permeability is lacking. This is typically achieved by drilling a doublet of deep wells—one for injection and one for production—and using hydraulic stimulation to create an interconnected network of fractures. Cold water is circulated through these fractures, mining heat from the vast surface area of the hot rock before returning to the surface to drive turbines or provide direct heating (Ji et al., 2025). The U.S. Department of Energy (DOE) suggests that EGS could transform geothermal from a niche local resource into a major contributor to the national energy supply, projecting a potential 26% increase in total geothermal generation by the middle of the century (DOE, 2019).

Despite the technical feasibility demonstrated in various pilot projects, the widespread commercial adoption of EGS has been hindered by a persistent and destructive challenge - thermal short-circuiting (Chen et al., 2025). This phenomenon occurs when the circulating fluid fails to sweep the reservoir volume uniformly, instead concentrating its flow within a few dominant, high-permeability pathways. These "thermal shortcuts" rapidly deplete the heat from a very narrow zone of rock, leaving the vast majority of the thermal resource untapped. The immediate result is a premature thermal breakthrough, where the production temperature drops sharply long before the project's intended lifespan is reached. This rapid decline in enthalpy cripples the power plant's efficiency and can render an otherwise promising project economically unviable (Zhang and Dahi Taleghani, 2024). Thermal short-circuiting is not merely a theoretical risk but a well-documented reality observed in major EGS field sites globally. In the United Kingdom, the Rosemanowes project provided early diagnostic evidence of the issue when tracer tests revealed that more than half of the injected fluid was being carried by a single dominant fracture (Parker, 1999). Similarly, the Soultz-sous-Forêts project in France—one of the world's most advanced EGS facilities—observed faster-than-anticipated temperature declines, with nearly 70% of the total flow localized in a fraction of the stimulated area (Held et al., 2014). In Japan, sites like Hijiori and Ogachi encountered similar bottlenecks, where temperature logs and tracer data consistently pointed to the formation of uncontrolled "super-highways" that bypassed the bulk of the reservoir (Ito and Kaieda, 2002; Kaieda, 2012). These international lessons have identified the management of flow distribution as the primary barrier to making EGS a sustainable commercial success.

To understand why these shortcuts form, one must look at the complex physical interactions occurring at the reservoir scale. Thermal short-circuiting is driven by a self-reinforcing feedback loop. When cold water is injected, the fractures with slightly higher initial conductivity cool the surrounding rock more rapidly than their neighbors. This localized cooling causes the rock matrix to contract, a process known as thermal distressing (McLean and Espinoza, 2023). This contraction reduces the compressive normal stress holding the fracture faces together, allowing the fracture to physically widen. Because the hydraulic conductivity of a fracture is highly sensitive to its aperture, even a small increase in width dramatically reduces flow resistance. This makes the widened fracture even more attractive

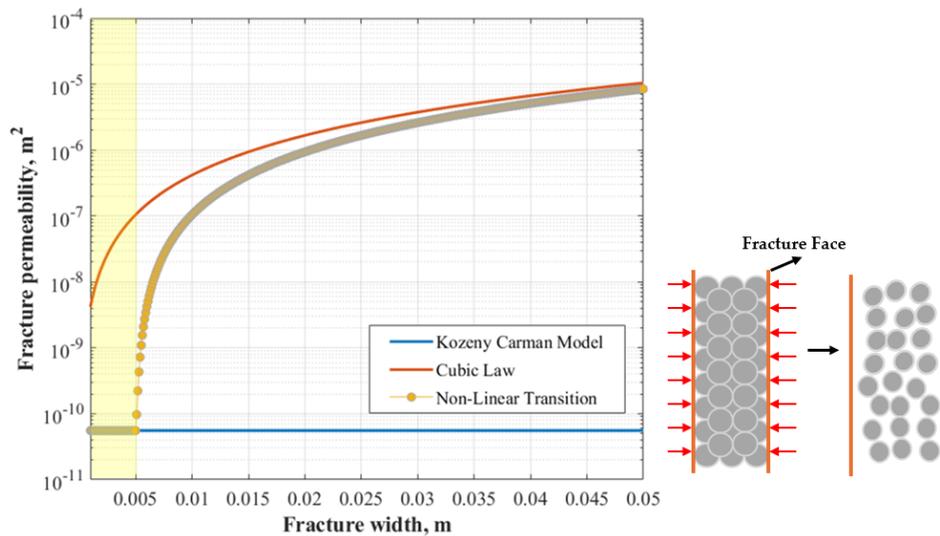
for incoming fluid, which in turn leads to further cooling, more contraction, and even greater widening. This runaway cycle eventually creates a few dominant channels. The difficulty in predicting this behavior stems from the limitations of conventional modeling. Many existing studies utilize simplified frameworks that treat the reservoir as a static entity, ignoring the dynamic mechanical evolution of the fractures. Furthermore, the interplay between the reservoir and the wellbore itself is often overlooked. In a real-world EGS operation, the non-isothermal flow within the wellbore—impacted by friction and transient density changes—dictates the pressure and temperature boundaries at the fracture mouth. Neglecting these coupled effects can lead to a fundamental misunderstanding of how and when short-circuiting will occur (Zhang et al., 2026).

This study aims to address these limitations by developing a comprehensive framework that integrates reservoir geomechanics with transient wellbore dynamics. By focusing on the underlying physics of inter-fracture plane channeling and the role of proppants in maintaining—or unintentionally accelerating—these pathways, this research seeks to provide a quantitative understanding of the drivers behind thermal decline. Such insights are essential for the development of future engineering interventions and mitigation strategies, ensuring that the next generation of EGS projects can achieve the long-term stability and economic viability required to support a clean energy grid. The manuscript is structured as follows: Section 2 establishes the foundational assumptions and governing equations, detailing non-linear fracture aperture evolution and the transition of permeability. Building upon these physics, Section 3 outlines the construction of the fully coupled model. The core findings are presented in Section 4, which illustrates how a self-perpetuating feedback loop triggers significant thermal short-circuiting, even within uniform, isotropic reservoirs. These findings offer a quantitative evaluation of the mechanisms precipitating thermal short-circuiting, providing essential insights for the development of future engineering interventions and mitigation strategies.

## 2. METHODOLOGY

The methodology utilizes a fully coupled Thermo-Hydro-Mechanical-Wellbore (THM-W) numerical framework to resolve the complex, multi-decadal interactions driving thermal short-circuiting. Fluid flow is calculated via Darcy’s law for the reservoir matrix and a discrete fracture model (DFM) for induced pathways, while heat transfer is governed by conduction and convection under local thermal equilibrium assumptions. The geomechanical component treats the rock as a porous, linear elastic medium, solving a constitutive equation that relates stress and strain to pore pressure and temperature changes. A specialized non-isothermal wellbore model is integrated to capture transient pressure losses and heat exchange through the wellbore walls, providing realistic boundary conditions for the reservoir. These governing equations are solved simultaneously using the Finite Element Method (FEM) with a fully coupled solver to ensure that all physical interdependencies are balanced within each time step.

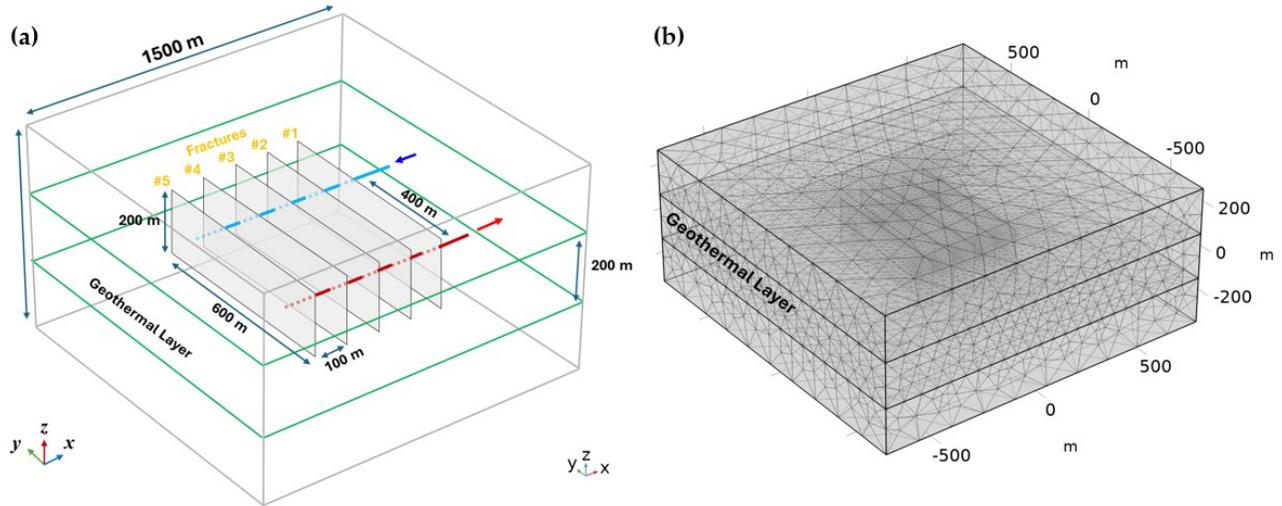
In this paper, fractures are fully propped. Crucially, the model incorporates a non-linear permeability transition that bridges proppant-pack Darcy flow (governed by the Kozeny-Carman equation) and open-channel flow (described by the cubic law) as fractures physically widen due to thermal distressing. Initially, propped fractures are assumed to be fully compacted, where fluid movement is restricted by the porous proppant pack and governed by the Kozeny-Carman relationship. As cold fluid injection induces rock contraction and thermal distressing, the fracture faces separate, causing the proppant particles to lose contact and allowing the fluid to flow through the newly created open space. During this widening phase, the hydraulic behavior transitions from Darcy flow through a packed bed to open-channel flow described by the cubic law. Assuming the thickness of the proppant pack is 5 mm, this transition is mathematically captured using a non-linear function that bridges the two regimes (see **Figure 1**), demonstrating that a small increase in fracture aperture—such as from 5 mm to 7 mm—can lead to a permeability surge of approximately 400 times. By accounting for this drastic increase in conductivity, the framework provides a realistic basis for modeling the formation of the preferential pathways that drive thermal short-circuiting.



**Figure 1: Non-linear fracture permeability transition model that bridges proppant-pack Darcy flow (governed by the Kozeny-Carman equation) and open-channel flow (described by the cubic law)**

### 3. MODEL DESCRIPTION

To explore the drivers of thermal short-circuiting, a fully coupled THM-W numerical framework was developed using the governing equations established in the previous section. The simulation represents a field-scale EGS featuring horizontal well doublets and a multi-stage hydraulic fracture network (see **Figure 2a**). The 3-D computational space, measuring  $1500\text{m} \times 1500\text{m} \times 600\text{m}$ , is partitioned into three distinct 200-meter zones: an overburden, a central reservoir, and an underburden. While the central layer facilitates geothermal production, the capping layers serve as thermal boundaries to simulate indigenous heat flux from the surrounding rock. The reservoir configuration consists of an injection and production well with 500-meter lateral segments separated by a 400-meter interval. These wells are linked by five vertical fractures, each with dimensions of  $600\text{m} \times 200\text{m}$ , placed at 100-meter intervals. To match standard geothermal industry completions, a wellbore internal diameter of 0.152 m (6 inches) was utilized. The domain is discretized using an unstructured finite element mesh, with high-density refinement applied specifically around the wellbores and fracture surfaces (see **Figure 2b**). This localized refinement is necessary to resolve the sharp pressure, thermal, and stress gradients while maintaining overall computational tractability.



**Figure 2:** The diagram of (a) the geometry model of an EGS consisting of horizontal wells in the 3-D plane view and (b) the mesh generation of the simulation model in the 3-D view.

The parameters needed for the EGS simulation can be found in **Table 1**.

**Table 1: Parameters for the simulation of EGS with horizontal wells.**

Parameters	Value	Unit
Permeability of geothermal formation	1	mD
Permeability of neighborhood layers	0.001	mD
Initial porosity of the geothermal formation	5	%
Initial porosity of the neighborhood layers	0.1	%
Young's modulus of the reservoir rock	$20 \times 10^9$	Pa
Poisson's ratio of the reservoir rock	0.25	-
Initial reservoir pore pressure	$3.0 \times 10^7$	Pa
Initial reservoir temperature	473.15	K
Horizontal stress in x-x direction	$5.0 \times 10^7$	Pa
Horizontal stress in y-y direction	$6.0 \times 10^7$	Pa
Vertical stress	$8.0 \times 10^7$	Pa
Thermal conductivity of reservoir rock	2.8	W/(m·K)

Specific heat capacity of reservoir rock	900	J/(kg·K)
Biot's coefficient	0.8	-
Thermal expansion coefficient	$6.0 \times 10^{-6}$	1/K

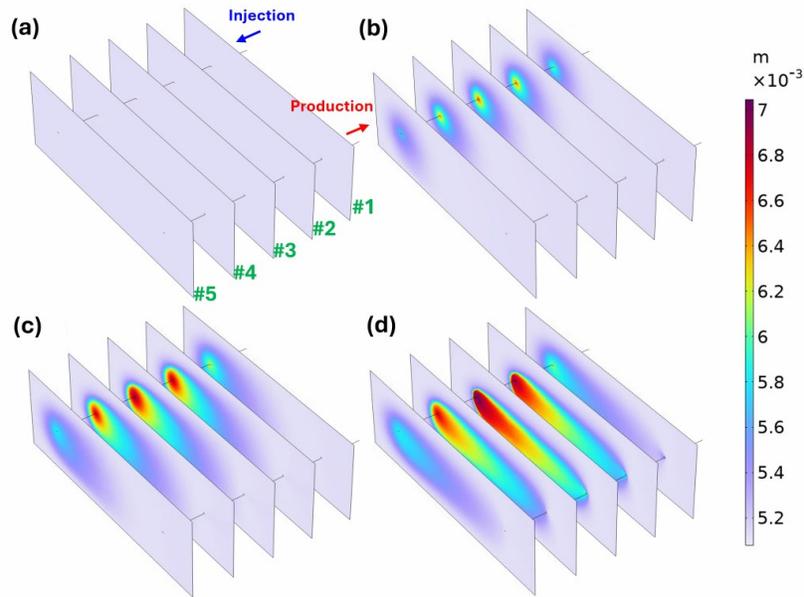
#### 4. RESULTS AND DISCUSSION

Although all fractures begin with uniform properties, complex THM-W interactions trigger significant heterogeneity over time. Three primary mechanisms drive this non-uniform behavior:

- **Thermal Edge Effect:** Inner fractures cool faster due to thermal competition from both sides, whereas outer fractures sustain higher temperatures by accessing unexploited hot rock on one side.
- **Wellbore Flow Dynamics:** Frictional losses favor proximal (heel) fractures, but the progressive heating of fluid toward the toe reduces viscosity, enhancing mobility in distal fractures.
- **Thermal Destressing:** Accelerated cooling in central fractures induces rock contraction and reduces normal stress, causing apertures to widen.

This creates a self-reinforcing feedback loop: widened fractures lower hydraulic impedance, channeling more flow into central pathways and exacerbating thermal short-circuiting.

**Figure 3** shows fracture width evolution over 50 years of EGS operation. While fractures begin with a uniform 0.005 m width, they diverge significantly over 50 years. Driven by the thermal edge effect, inner fractures (#2–#4) cool faster due to bilateral thermal interference, causing greater rock contraction and aperture widening. Central fracture #3 achieves the largest opening due to maximum stress reduction. Wellbore hydraulics further influence this; fractures nearer the injection point (heel) experience lower frictional losses and higher circulation, making #2 wider than #4. Ultimately, these inner fractures form high-conductivity channels, becoming primary pathways for thermal short-circuiting.

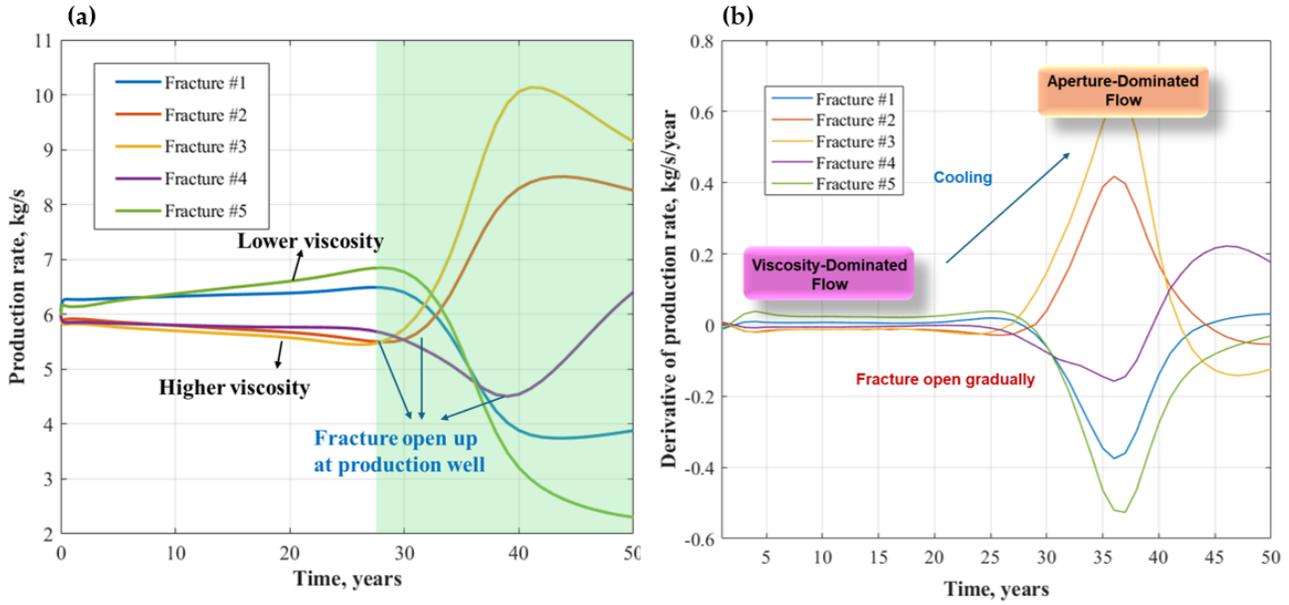


**Figure 3: Fracture width distribution after years of EGS operation: (a) 0 year; (b) 10 years; (c) 25 years; (d) 50 years.**

The evolution of fracture production rates (**Figure 4a**) and the derivative of fracture production rate (**Figure 4b**) reveal two distinct operational phases with a critical transition at approximately 28 years:

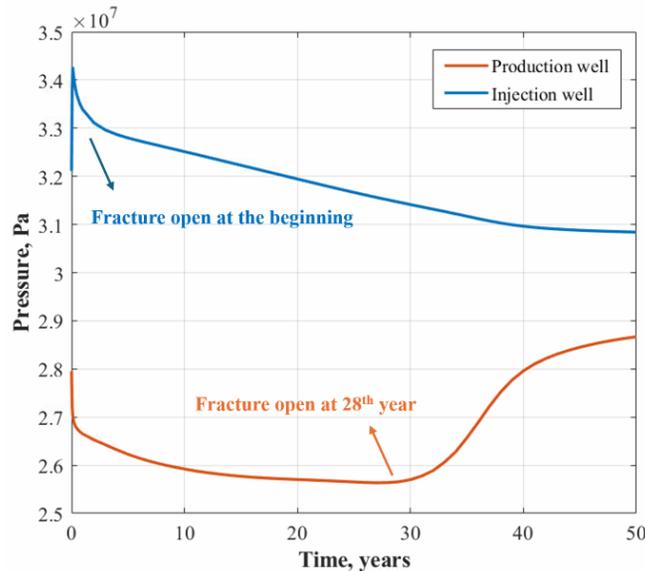
**Phase 1: Viscosity-Dominated Flow (Years 0–28):** Outer fractures (#1, #5) initially outperform inner ones because they maintain higher temperatures and lower fluid viscosities. Although inner fractures widen near the injection well, their restricted apertures near the production well maintain high flow resistance.

**Phase 2: Aperture-Dominated Flow (Years 28–50):** As sustained cooling causes inner fractures to widen along their entire path, mechanical conductivity gains outweigh viscosity effects. Inner fracture #3 eventually captures ~30% of total flow (9.15 kg/s). This shift confirms that thermal short-circuiting is ultimately driven by aperture-dependent permeability rather than fluid properties alone.



**Figure 4: Evolution of (a) production rate at each fracture and (b) their derivatives with respect to time over 50 years of EGS operation.**

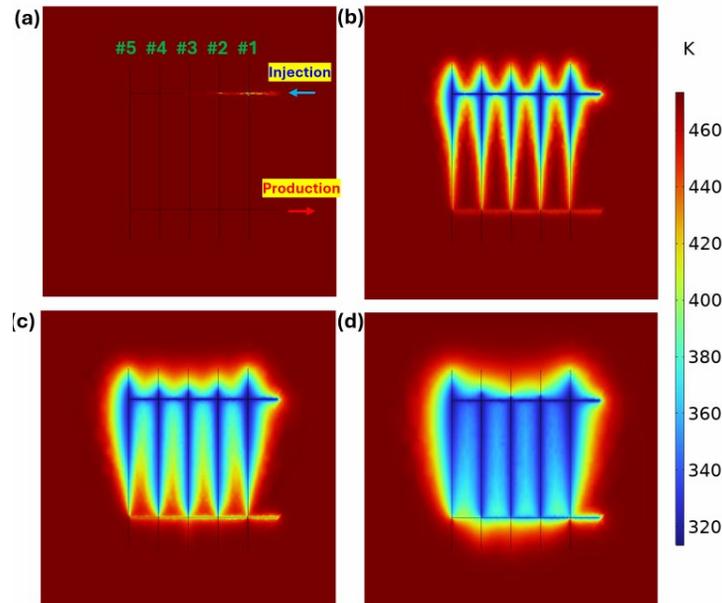
Operational pressure at the well heel follows highly non-linear trends dictated by coupled THM processes (see **Figure 5**). The injection pressure spikes initially to initiate fracture opening and then steadily declines as thermal distressing continues to widen fractures, reducing the resistance required to maintain a constant injection rate. In contrast, the production well pressure exhibits a non-monotonic evolution with a distinct turning point at year 28. During the first 28 years, production pressure declines as productivity gains from the injection side have not yet propagated across the reservoir. After this threshold, the pressure reverses and begins to rise, directly corresponding to the breakthrough of highly conductive flow channels at the production well. This dramatic increase in system conductivity allows target fluid rates to be produced with significantly less energy, resulting in increased bottom-hole flowing pressure. This complex pressure behavior, where injection pressure falls while production pressure initially drops and then recovers, is a definitive signature of dynamic fracture aperture changes that can only be accurately captured through a fully coupled THM-W model.



**Figure 5: Operational pressure during the 50 years of EGS operation.**

In a five-fracture EGS that is initially uniform, the evolution of highly varied performance and eventual thermal short-circuiting is driven by intricate THM-W feedback cycles. The sequence begins with the thermal edge effect: central fractures (#2, #3, and #4) undergo rapid cooling due to thermal competition from neighboring fractures, whereas the peripheral fractures (#1 and #5) maintain higher temperatures by tapping into larger, undisturbed heat reserves. This concentrated cooling in the reservoir core triggers substantial rock contraction, lowering the normal stress on central fracture planes and causing their widths to expand significantly. By approximately Year 28, this

mechanical aperture expansion becomes the primary driver of fluid distribution, surpassing the initial flow advantages provided by the lower fluid viscosity in the hotter outer regions. Consequently, the expanded central fractures—most notably fracture #3—intercept a dominant portion of the injected water, establishing a preferential flow shortcut (see **Figure 6**). This transition is marked by a spike in production rates alongside a sharp decline in fluid temperatures within the inner fractures, resulting in the formation of a localized cold zone at the reservoir's center. Reliably modeling these coupled interactions, including the vital reheating of fluid through wellbore heat exchange, is essential for evaluating the long-term productivity and viability of EGS projects.



**Figure 6:** Temperature profile (2-D top view) in the reservoir at (a) 0 year; (b) 10 years; (c) 25 years; (d) 50 years.

## 5. CONCLUSIONS

This study provides a comprehensive investigation into the complex feedback mechanisms driving thermal short-circuiting in Enhanced Geothermal Systems (EGS), demonstrating that even initially homogeneous reservoirs will inevitably develop preferential flow paths. This study utilizes a coupled Thermo-Hydro-Mechanical-Wellbore (THM-W) framework to investigate the combined physical drivers—thermal edge effects, non-isothermal wellbore dynamics, and thermal destressing—that precipitate this phenomenon. Findings demonstrate that an initially homogeneous reservoir develops preferential flow paths through a powerful, self-perpetuating feedback loop. The process is initiated by wellbore friction and the thermal edge effect, which cause localized cooling and rock contraction around central fractures. By approximately the 28-year mark, thermo-mechanical expansion becomes the dominant flow control mechanism; central fracture apertures widen from an initial 5 mm to over 7 mm, and permeability surges from  $5 \times 10^{-11} \text{ m}^2$  to  $4.06 \times 10^{-8} \text{ m}^2$ . This high-conductance channel intercepts a disproportionate 30% of the total injected fluid (9.15 kg/s), leading to premature thermal breakthrough. The analysis further indicates that while propped fractures improve hydraulic performance, they inadvertently accelerate thermal drawdown. These results provide a quantitative basis for understanding the mechanisms of thermal short-circuiting, offering vital insights for designing future mitigation strategies and engineering interventions.

## ACKNOWLEDGMENT

The authors are grateful for financial support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Geothermal Technologies Office, Award Number DE-EE0009787.

## REFERENCES

- Chen, S., Zhu, H., Zhao, P., Jiao, Z., McLennan, J. D., and Zhou, J.: Exploratory Study on Regulation of Thermal Short-Circuiting in Multi-well Enhanced Geothermal Systems, *Rock Mechanics and Rock Engineering*, (2025), 1-18.
- Held, S., Genter, A., Kohl, T., Kölbl, T., Sausse, J., and Schoenball, M.: Economic Evaluation of Geothermal Reservoir Performance Through Modeling the Complexity of the Operating EGS in Soultz-sous-Forêts, *Geothermics*, 51, (2014), 270-80.
- Ito, H., and Kaieda, H.: Review of 15 Years Experience of the Ogachi Hot Dry Rock Project with Emphasis on Geological Features, *Proceedings, 24th New Zealand Geothermal Workshop*, Auckland, NZ (2002).

Zhang et al.

- Ji, K., Taleghani, A. D., Liu, S., Zhang, Q., Dai, K., Li, H., and Tang, C. A.: Comprehensive Investigation on the Heat Extraction Performance of a Novel Enhanced Geothermal System Based on Mining Technology, *Renewable Energy*, 249, (2025), 123233.
- Kaieda, H.: Ogachi EGS Reservoir Analysis, *Geothermal Resources Council Transactions*, 36, (2012), 487-92.
- McLean, M. L., and Espinoza, D. N.: Thermal Destressing: Implications for Short-Circuiting in Enhanced Geothermal Systems, *Renewable Energy*, 202, (2023), 736-755.
- Parker, R.: The Rosemanowes HDR Project 1983–1991, *Geothermics*, 28, (1999), 603-15.
- U.S. Department of Energy: GeoVision Analysis for Enhanced Geothermal Systems, U.S. Department of Energy, Washington, D.C. (2019).
- Wang, D., Dong, Y., Wei, C., Zhang, Q., Sheng, M., and Yu, B.: Expansion-induced Fracture Propagation in Deep Geothermal Reservoirs Under Alternate-temperature Loading, *Advances in Geo-Energy Research*, 15(3), (2025), 261-272.
- Zhang, Q., and Taleghani, A. D.: Downhole Flow Control: A Key for Developing Enhanced Geothermal Systems in Horizontal Wells, *Renewable Energy*, 237, (2024), 121578.
- Zhang, Q., Ji, K., Taleghani, A. D., and Hua, W.: Coupled Thermo-Hydro-Mechanical-Wellbore Modeling of Thermal Short-Circuiting in Enhanced Geothermal Systems, *Energy*, 344, (2026), 140038.