PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Alternative Design Concept For Enhanced Geothermal Systems Through Reconfiguration of Stimulation Techniques From The Past

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Keywords: EGS, HDR, Stimulation, Explosives, Circulation, Conceptual, Semi-Close-Loop

ABSTRACT

The combination of hydraulic fracturing and directional drilling has transformed the oil and gas industry over the last century. These techniques provide needed permeability in large volumes to facilitate fluid drainage. Substantial efforts are being made to adopt hydraulic fracturing to create permeable fluid pathways in hot dry rocks for geothermal heat exchange. The common design for an enhanced geothermal system consists of parallel wells connected by vertical hydraulic fractures. While many successes and advancements have been made, the task of creating well distributed interconnected fractures in hard rock formations remains a challenge. Geophysical monitoring through microseismic event detection and circulation flow testing reveals that fracture propagation in geothermal reservoirs often encounters interference from natural features, which divert energy and limit the extent of induced fractures in zones where they are critical. This is less of an issue in oil and gas reservoirs where drainage is the main objective.

We propose revisiting a stimulation method that has largely been abandoned in modern oil and gas production: the use of conventional explosives as the primary stimulation agent. While this approach involves considerable safety and logistical challenges, it may allow for the creation of more predictable and usable fracture networks in hard rock environments with less loss of the working fluid. For a first order evaluation of the feasibility of this concept, we have conducted fluid and heat transport simulations using the Matlab Reservoir Simulation Tool's finite volume framework. These simulations are carried out on simple models of moderate-temperature, low-permeability rock matrix with idealized discrete fracture networks approximating conventional explosive stimulation results. Initial simulations suggest that if the stimulated volume is large enough, this design can sustain heat production for small geothermal plants or direct use for a 5 year period with the possibility of adding additional wells to the system. However, if the stimulated region is too small, rapid cooling severely limits long-term viability. Maximizing the stimulated radius will be critical to ensuring effective heat extraction and system performance with the proposed design.

1. INTRODUCTION

Hydraulic fracturing has been highly successful in stimulating sedimentary reservoirs for hydrocarbon production, yet its application in crystalline rock for Enhanced Geothermal Systems (EGS) presents unique challenges. Unlike hydrocarbon-bearing formations, where fracture propagation is primarily aimed at enhancing drainage efficiency, EGS requires a more controlled and distributed network of fractures to maximize inter-well connectivity, ensure long-term permeability, and sustain efficient heat extraction. The fundamental challenge lies in the complex nature of hard rock, where natural discontinuities, stress variations, and uncertain fracture geometries influence stimulation effectiveness.

While hydraulic fracturing has been the dominant method for geothermal reservoir stimulation, its suitability for EGS in crystalline rock remains an open question. Alternative approaches may be required to optimize permeability enhancement and fluid containment while mitigating risks such as short-circuiting and excessive water loss. This study investigates the potential for using conventional explosives as a controlled stimulation mechanism, leveraging dynamic loading to create a highly fractured zone along and between wellbores. By evaluating principles from both hydraulic fracturing and historical well-shooting techniques, we aim to assess whether an explosively stimulated EGS can provide a viable, scalable alternative for geothermal energy extraction. For a first pass at gauging the potential of using a semi-closed-loop EGS design with dynamic load stimulation, we conduct fluid and heat flow simulations using the MRST framework for a hypothetical discrete fracture network aimed at representing a reasonable model of the designed system.

2. A BRIEF HISTORY

In the late 1800s and early 1900s, After the Civil War, "shooting" wells with explosives became a widely used method of well stimulation in the United States. Edward A. L. Roberts notably patented a torpedo design filled with high explosives, detonated by dropping a weight downhole, an invention that marks the beginning of oil and gas well stimulation. (Adomites, 2011). Although popular, the method was imprecise and posed significant risks to operators and transporters.

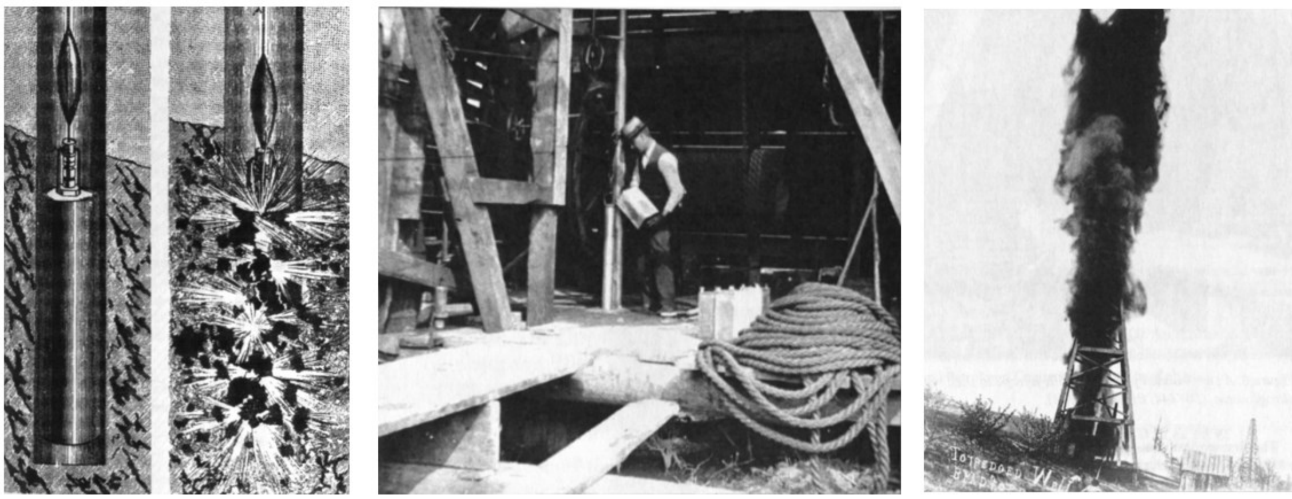

Figure 1: Depiction of a Roberts Torpedo before and after being detonated by a weight "go-devil" (left), image of a man preparing torpedo shell by filling it with nitroglycerin (center), image of an oil well gushing during a "shooting" stimulation in 1883. Images from Drake Wells Museum.

The first documented hydraulic fracturing treatment occurred in the Hugoton gas field in Kansas in 1947 (Clark, 1949). Two years later the technique was first used commercially, and its use grew rapidly (Montgomery et al, 2010). Hydraulic fracturing ultimately displaced the need for dangerous unpredictable explosive treatments in oil and gas wells. Around the same time, the development of horizontal drilling began to take shape. By the 1980s, innovations in downhole drilling motors and telemetry equipment made deep horizontal drilling commercially viable (Beckwith, 2012). The combination of hydraulic fracturing and directional drilling fostered what many consider the shale revolution, transforming global energy production and significantly expanding known reserves.

Recognizing the potential of hydraulic fracturing beyond oil and gas, researchers at Los Alamos National Laboratory conducted the first documented use of hydraulic fracturing for geothermal power generation in hot dry rock (HDR) at Fenton Hill, New Mexico, in the 1970s. Experiments continued until 1995 (Brown et al, 2012), successfully demonstrating the feasibility of creating confined geothermal reservoirs in crystalline rock. This pioneering work laid the foundation for modern EGS. Since then, hydraulic stimulation techniques have been increasingly tested for geothermal applications, including both creating entirely new reservoirs in HDR systems and enhancing permeability in naturally fractured formations to improve well performance in hydrothermal fields.

3. DESIGN OBJECTIVES

Hydraulic fracturing for EGS and hydrocarbons share a common goal: maximizing the hydraulic connection between a well and the surrounding rock. However, unlike hydrocarbon reservoirs, where the primary objective is to create fractures that enable drainage from the formation to the well, EGS stimulation must accomplish much more. This includes establishing inter-well connectivity with even fracture distributions, maintaining long term fracture conductivity, and minimizing fluid loss all while managing the challenges of operating in a hot crystalline rock environment.

3.1 High Temperature Endurance

Geothermal reservoirs are inherently hot. Thus, all downhole equipment and well components must be able to withstand the extreme condition. Thermal degradation of materials can limit system longevity. High temperatures also limit the instrumentation that can be used for downhole monitoring and control.

3.2 Distributed Connections

In oil and gas well-to-well connectivity is often undesirable and when experienced during fracking it is commonly referred to as "frac hits". In contrast, the leading EGS design concept requires inter-well connectivity via fractures for large volumes of working fluid to circulate. A useful parameter for evaluating geothermal reservoir connectivity is impedance (Z), which accounts for factors such as permeability, fracture conductivity, wellbore friction, as an overall well to well flow resistance for a circulating system. It is defined as:

$$Z = \frac{P_{inj} - P_{pro}}{Q_{pro}} \tag{1}$$

where P_{inj} and P_{pro} is the injection and production pressure respectively, while Q_{pro} is the circulation (production) rate. Lower impedance is preferred, as higher impedance requires greater injection pressures, leading to increased pumping cost. Impedance also puts a limit on the production rate if operators intend to keep pressures below fracture growth levels, as determined by the stress states.

In addition to inter-well connectivity, it is critical that the network of fractures is evenly distributed, all with reasonably similar conductivities. If a small number of dominating fractures occurs, impedance may be low, but these preferential flow paths will result in thermal short circuits reducing the system's long term heat extraction potential.

3.2 Operational Resiliency

Once a geothermal reservoir is created, minimal changes to the fracture network over its operational life are ideal. Pressure fluctuations, such as those caused by shut-ins or variable injection rates, can lead to fracture closure, reopening, or proppant movement, altering flow pathways which could result in short circuits and/or increased impedance. The most effective design should seek to avoid reliance on corrective measures after the system is completed by ensuring the initial fracture development is stable for a wide variety of pressure and flow states.

3.3 Fluid Containment

Tester et al. (2006) resource maps indicate that much of the hot dry rock potential in the continental U.S. lies beneath arid regions, where water is a scarce and valuable resource. Water is the most plausible subsurface working fluid for EGS. It is then crucial for the success of a project to be water conservative in their long term operational state. An easy way to gauge this is the fraction or percent of the injected fluid that remains in storage. Yes "storage", but not incredibly accessible storage from the perspective of other water users such as agriculturalists or municipalities.

$$water\ loss\ \% = \frac{Q_{inj} - Q_{pro}}{Q_{inj}} \cdot 100\% \tag{2}$$

For example, assume we have access to a high-quality geothermal resource producing at 200^{o}C, our injection water is 25^{o}C, and we can accomplish any flow rate. We want to produce 1MW of thermal energy output. Assuming the standard heat capacity and density of pure water, we will need to produce at a rate of 1.37 L/s. If we know the reservoir's water loss is 5% this will amount to 0.07 L/s, or 1.14 gpm, or 1.84 acre-ft/yr. This may not seem significant, but if water loss was instead 20%, the rate of water loss becomes 8.74 acre-ft/yr. According to USDA (2023), the average irrigated cropland in the U.S. requires 1.5 acre-ft per year, meaning the water cost per MW of thermal energy output could be equivalent to irrigating 13.1 acres of crops. There will also be energy losses in converting thermal power to electricity and potential additional water losses if flashing is used. Regardless, minimizing water loss in the reservoir is crucial for long-term sustainability, particularly in arid regions.

4. STATE OF THE ART

The fundamental design of modern EGS remains rooted in the concepts established at Fenton Hill—using hydraulic fracturing to create a subsurface heat exchanger in crystalline rock. However, the field has advanced significantly with the improvements in directional drilling, multistage stimulation, diagnostic techniques learned by the oil and gas industry throughout the shale revolution. Government-led initiatives such as FORGE and commercial ventures like Fervo Energy are refining these techniques to better meet the design objectives described earlier. This is however an international effort with approximately 80 active EGS projects around the world (Xie et al, 2024). The state-of-the-art HDR reservoir design consists of two or more horizontal wells with multistage hydraulic fractures connecting them. While progress has been promising, fundamental challenges remain. Due to the nature of crystalline rock, it is uncertain whether this current design approach can be universally applied across all EGS-suitable regions.

4.1 Design

The State-of-the-art approach involves drilling a horizontal or deviated well, then fracturing along the lateral section, with microseismic monitoring to assess fracture propagation. A second well is then drilled to intersect the established fractures before undergoing its own hydraulic stimulation to enhance connectivity. Fervo Energy has advanced this concept further at their Project Cape site adjacent to FORGE, where multiple parallel laterals are drilled from the same well pad (Norbeck et al, 2024).

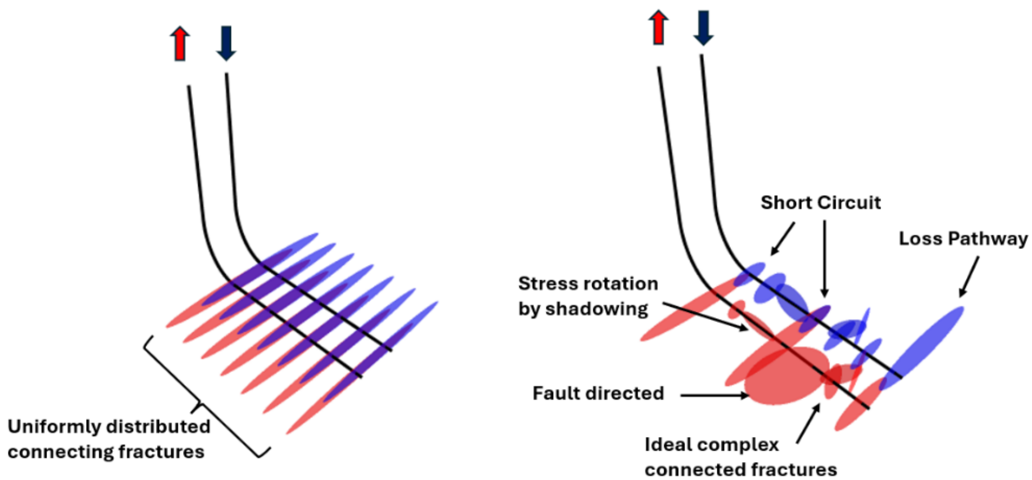

Figure 2 Conceptual diagram of state-of-the-art EGS approach: ideal fracture distribution in homogeneous host rock (left), potential flaws due to natural discontinuities, stress variation and shadowing. Not shown in both concepts are many likely secondary and tertiary fractures.

4.2 Challenges

HDR targets are primarily crystalline hard rocks, often near volcanic or tectonic activity, whereas hydrocarbon reservoirs typically form in less structurally complex sedimentary formations. Given this contrast, we assume greater variability in both the paleo-stress state and the spatial distribution of current stress states should be expected in geothermal projects more so than in hydrocarbons plays. Natural discontinuities such as joints, faults, and veins can be present in both settings, however increased complexity in the past and present stress state will translate to greater complexity in these features.

In normal faulting regimes with stresses $\sigma_v > \sigma_H > \sigma_h$ mode 1 tensile failure is the dominant deformation type in hydraulic fracturing. According to the Terzaghi effective stress law, failure initiates perpendicular to the minimum principal stress when pore pressure exceeds the minimum principal stress plus tensile strength. Planar fracture growth is then governed by the stress intensity factor K_I:

$$K_I = P_{net}\beta\sqrt{\pi a} > K_{Ic} \tag{3}$$

Where P_{net} is the difference between fluid pressure in the fracture and the effective stress normal to the plane, β depends on near tip geometries, and a is an effective radius related to fracture half length, and K_{Ic} is the fracture toughness. It should be noted that in practice higher than prescribed P_{net} to propagate fractures is often attributed to "tip effects" which increase the effective K_{Ic} (Miskimins, 2019, ch 3). The presence of natural discontinuities can have a significant role in controlling fracture growth though their influence on K_{Ic}. Figure 4 illustrates a few ways in which discontinuities caused in past normal faulting stress states may alter hydraulic fracture planes under the assumption that the discontinuity has a weaker bond than intact rock.

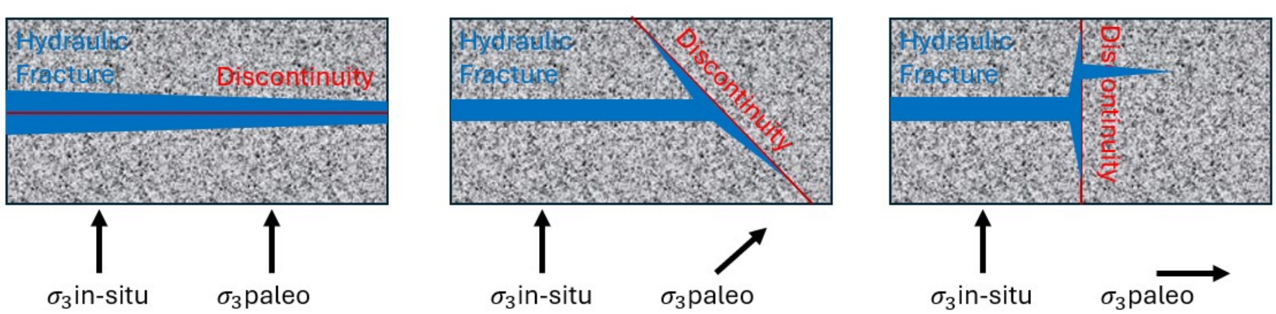

Figure 3: Likely propagation behavior of a hydraulic fracture influenced by natural discontinuities such as joints, veins, and faults in a normal faulting regime: paleo stress state aligns with current stress state (left), paleo stress has principal σ_2 and σ_3 oblique to those of current stress state (center) paleo stress has principal σ_2 and σ_3 perpendicular to those of current stress state (right).

Discontinuities aligned with the minimum principal stress may reduce fracture toughness promoting direct fracture, increasing connectivity while posing the risk of creating thermal short circuits. It also poses the risk of growing long in the opposite direction of pair wells leading to fluid loss pathways. Conversely, misaligned discontinuities may redirect fractures, possibly leading to further shear failure and increased complexity resulting in greater surface areas for heat exchange. It may also result in high impedances reducing well-to-well connectivity. Moreover, discontinuities can act as stress and strain boundaries, further complicating the local stress tensor. While major faults can be identified by geophysical imaging, smaller-scale discontinuities and local stress variations remain difficult to characterize pre-drilling. Even after drilling, imaging and stress measurement technologies beyond the wellbore remain limited.

Decreased productivity in hydraulically fractured and propped wells due to cyclic loading such as periods of shut-in for maintenance has been well observed in oil and gas. Studies including: Ouabdesselam and Hudson (1991), Holditch and Blakeley (1992), and Kim and Willingham (1987), conclude that this phenomenon is due to combined effects of proppant embedment, failure, and repacking. Certainly, the rock and proppant compressive strength will be important design factors. However, the potentially complex fracture paths imposed by natural discontinuities could further complicate the proppant distribution and likely the cyclic loading effect as well. EGS reservoirs will commonly be operated at an overpressure to drive production, but periods of injection or production shut-in will expose the proppant packs to many pressure and flow velocitiy changes throughout the lifespan of a reservoir.

4.3 Status

The cumulative efforts to develop hot dry rock reservoirs have resulted in considerable advancements. Notably, El-Sadi et al. (2024) presents substantial drilling efficiency improvements at Fervo's two main EGS projects, attributing this success in part to the learning curve gained from repeat drilling in similar conditions. Now, with multiple plug-and-perf stimulations performed at EGS sites, starting with Fenton Hill, the necessary downhole equipment and techniques are available and capable of operating in these environments. The operational performance of recent treatments is also quite remarkable; for example, Norbeck et al. (2024) report that at the Fervo Cape Project, a set of three wells was stimulated across 80 total stages, with 95% of the designed proppant successfully injected and no stages experiencing complete screen-out. Published results from circulation flow testing and microseismic monitoring demonstrate progress. However, in them there are indications that the challenges associated with unknown natural features could still hinder long term viability of hydraulically stimulated HDR reservoirs,

4.3.1 Circulation Testing in Literature

Extensive circulation testing was conducted at the Fenton Hill project in its final years (Brown et al., 2012), with the system in active circulation for 11 out of 39 months. These tests included surging, load-following, and steady-state experiments, revealing no decline in heat flow capabilities. Notably, cyclical shut-ins of the production well were often followed by short-term production increases. Given that EGS operates in an artificially overpressure state, proppant degradation may not be a major concern. However, the long-term impact remains uncertain, and any benefits may only last for a few years. While Fenton Hill exhibited significantly lower water loss compared to subsequent EGS projects, its impedance was notably high.

Utah FORGE has also conducted circulation tests, first with only one of its deviated wells stimulated (Xing et al., 2024) and later after both wells had been stimulated (McClennan et al., 2024). In both cases, injection pressures exceeded the known minimum stress, likely inducing further fracture growth. The substantial increase in production between the two tests suggests that connectivity was successfully achieved. However, while the impedance was lower than at Fenton Hill, the project experienced significant water loss.

A few circulation test results have been published from Fervo Energy's two major projects (Norbeck and Latimer, 2023; Norbeck et al., 2024). Both reported record-breaking production rates for EGS. One test, involving a single injector and single producer, demonstrated steady-state capacity with a water loss of approximately 100 gpm. In the other test, they used two injectors and one producer, and did not report an injection rate. However, given that both injection wells were positioned on the reservoir's exterior, the potential for substantial water loss is likely. Notably, Fervo is achieving considerably lower impedance from their long lateral wells.

Table 1: Comparison of long-term circulation test results from major HDR projects full scale demonstration. Note data in tables are interpreted from the respective publication's plots, text, or tables most indicative of steady state operating conditions.

Project	Duration	Driving Pressure (MPa)	Injection Rate (L/s)	Production Rate (L/s)	Water Loss (%)	Impedance ($MPa \cdot s/L$)
Fenton Hill (Brown et al, 2012)	55 days	17.7	6.5	5.7	6.6	3.1
FORGE (McClennan et al, 2024)	9 hr	24.1	25.8	16.3	36.8	1.1
Fervo Blue Mountain (Norbeck and Latimer 2023)	37 days	6.9 - 13.8	41.0 - 53.6	34.7 - 47.3	10.1 – 15.3	0.2 - 0.3
Fervo Cape Project (Norbeck et al, 2024)	30 days	11.7-13.4 (*2 wells)	(-)	95	(-)	0.2
Cooper Basin (Hogarth and Holl 2017)	6 months	9.7	(-)	17.5	(-)	0.6

While 30-day circulation tests provide valuable insights, they may not be sufficient to detect short-circuiting. Production logging can reveal major short circuits, but only time will determine whether hydrofracked parallel well EGS systems can sustain heat extraction long enough to be economically viable and do so with minimal water loss.

4.3.1 Microsesmic Monitoring in Literature

Event detection in microseismic monitoring is inherently uncertain, as numerous factors can limit the resolution of events, including survey design, ambient noise, and the specific fracture mechanisms involved. Deploying adequate sensors in high temperature offset wells is one limiting factor to obtaining accurate diagnostics of the quality the oil and gas industry is accustomed to. It still, however, can provide useful insight for interpreting reservoir performance characteristics.

Norbeck et al. (2018) revisited stimulation and microseismic data from the Fenton Hill project, using hydro-mechanical modeling to demonstrate that large networks of natural fractures, misaligned with the in-situ stress, underwent significant shear splay failure. This led to a mixed-mechanism permeability enhancement, where both shear and tensile processes contributed to fracture connectivity. Notably, microseismic activity at Fenton Hill remained well-confined, and flow testing indicated good fracture containment relative to many later EGS projects. The presence of oblique natural fractures to the minimum principal stress appears to have been beneficial in limiting water loss, though it may also explain the relatively high impedance observed at the site.

Niemz et al. (2025) analyzed near surface microseismic data collected during the latest round of stimulation at the FORGE site. They reveal two distinct, spatially separated fracture patterns, one which extended far beyond the intended circulation zone. It's not uncommon for microseismic events to locate outside the extent of hydraulic fractures, but these far-reaching trends of events outward suggest the development of substantial fractures extending away. McClure et al. (2024) argue that mode I failure is the dominant mechanism at Utah FORGE. These two insights combined are consistent with the high-water loss during circulation testing.

At the Gonghe EGS project, operated by the China Geological Survey, geothermal stimulations at a reservoir depth of 3,705 m exhibited strong correlations between microseismic activity and the presence of complex natural fractures (Xie et al., 2024). These pre-existing structures played a significant role in diverting fracture propagation, impacting overall permeability and fluid flow behavior. Yin (2024) further reports evidence of fault reactivation at Gonghe, with multiple failure mechanisms suggesting that stress conditions within the reservoir vary spatially.

Each of these case studies underscores the profound influence of natural fracture networks and stress heterogeneity on EGS performance with the state of the art design. The variability in reservoir responses highlights the uncertainty and inherent risk in predicting long-term system behavior before developing it.

5. ALTERNATIVE METHODS

While we are optimistic for the future of hydraulic stimulation in HDR development, it is not a one-size-fits-all solution. The success of hydrofracking between parallel wells depends heavily on geological conditions, and in some settings, it may not provide sufficient permeability enhancement or long-term reservoir sustainability. Given this variability, it is worth exploring alternative methods that may be better suited for complex geological environments. Both well design strategies and alternative stimulation techniques offer potential paths for improving heat extraction efficiency and reservoir performance.

An alternative to hydrofracturing is the use of deep closed-loop geothermal systems to access hot rock. A completely closed loop system only accesses heat near the wellbore due to the slow conduction of heat through rock. Wang (2009) conducted a modeling study assessing the heat transport effectiveness of various closed loop and single well configurations. Their study shows that single well systems that circulate fluid outside of the wellbore into fractures are still limited by the small volume accessed.

In addition to this fundamental limitation, drilling technology is not capable of creating large, closed-loop well paths at the depths required for HDR development. Even if such drilling capabilities existed, the restricted heat exchange surface area of a closed-loop system would necessitate an impractically high number of wells to achieve commercial-scale heat production. While closed-loop geothermal remains a topic of research, it is unlikely to compete with stimulated fracture-based systems for geothermal electrical production.

Alternative stimulation techniques also exist beyond hydraulic fracturing. The oil and gas industry has experimented with dynamic loading mechanisms since the early use of high explosives to "shoot" wells, and some limited research has explored their applicability in geothermal settings eg. (Maes 1976). The most extreme approach involved detonating nuclear devices for oil and gas reservoir stimulation. These tests ultimately failed, producing only a small release of gas, followed by poor production (Lorenz, 2000). Instead of generating an extensive network of fractures, the extreme heat from the detonation melted the surrounding rock, forming a glassy cavity that acted as an impermeable barrier, preventing fluid flow.

A more controlled approach is propellant stimulation, which involves the deflagration (subsonic combustion) of a combustible fuel to generate pressure pulses that create fractures. Unlike hydraulic fracturing, this method does not use proppant and instead relies on shear slippage to keep fractures partially open (Page and Miskimins, 2009). While propellant-based methods have been effective in mitigating near-wellbore damage, their impact is localized, making them unable to stimulate large reservoir volumes. Recent studies have explored combining propellant stimulation with acidizing to improve permeability near the wellbore. Aydin et al. (2024) conducted such an experiment in a conventional geothermal well in Turkey, demonstrating that the combined technique can be effective for reducing wellbore skin damage. Another novel approach is liquid CO_2 phase blasting, in which liquid CO_2 is rapidly depressurized, transitioning into a gas phase and inducing fracture propagation through dynamic loading. Nui (2024) conducted laboratory and numerical modeling studies on the effectiveness of this method, suggesting it has potential for enhancing near-wellbore permeability as well.

Ultimately, dynamic loading methods, except for nuclear detonation, have demonstrated the ability to enhance permeability near the wellbore, but none have been proven effective at generating a large, connected network between parallel wells suitable for commercial HDR use.

6. DESIGN OVERVIEW

We propose this design as a potential solution to address water containment, minimize uncertainty in short-circuiting, and reduce the resources required for stimulation while accomplishing sufficient heat exchange for direct use or power production. Rather than relying on traditional hydraulic stimulation, which is effective but prone to uncertainties, this approach seeks to adapt and enhance the concept of a semi-closed-loop system while overcoming its inherent limitations.

A completely closed-loop geothermal system is a well-known design that eliminates fluid losses but is severely limited in its access to heat. To address this issue, our design builds upon the simple two well head closed-loop layout but introduces controlled stimulation along portions of the well path. Instead of hydraulic fracturing, we propose reconfiguring the use of conventional explosives as the primary stimulation mechanism.

It is not feasible to drill deep, curve, and return to the surface due to the frictional and mechanical constraints of directional drilling. Instead, the primary drilling requirement for our design to succeed is to land the toes of at least two wells within a radius where large blasts of conventional explosives can connect them through a highly fragmented zone.

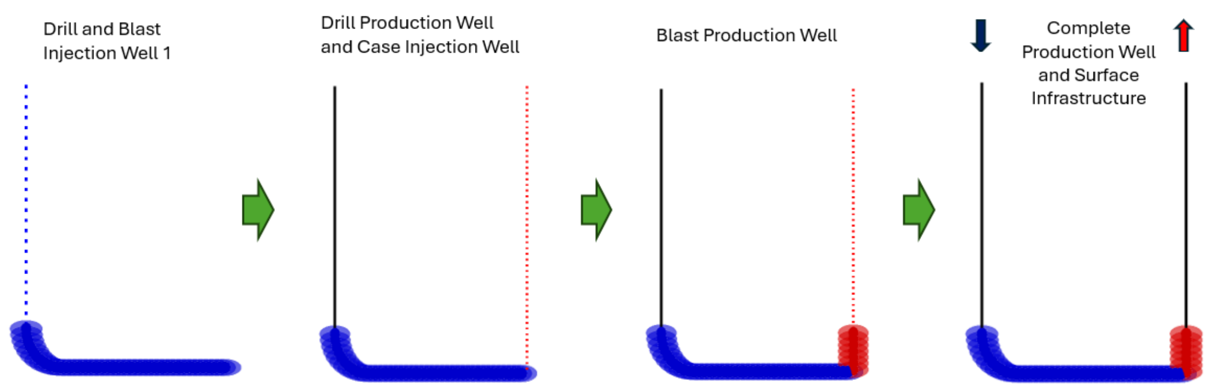

Figure 4: Initial suggestion of the general order of operations to develop the proposed EGS for a 2 well configuration. Fully shaded spheres indicate a volume of fragmentation. Opaque ellipses indicate open mode fracturing caused by forced fluids. It's not essential that either well is horizontal.

7 DESIGN CONSIDERATIONS

Unlike hydraulic fracturing, which relies on the slow pressurization of rock to propagate fractures, dynamic loading stimulation generates an intense but short-lived pressure wave. The shockwave produced by an explosion or the combustion of a propellant creates fractures rapidly in multiple directions, rather than favoring the direction of minimum stress (σ_3) as seen in hydraulic fracturing. This makes dynamic loading a fundamentally different mechanism, capable of producing a more complex and irregular fracture network.

The effects of a blast can be divided into three distinct zones based on the intensity of rock breakage. Closest to the charge, within a small radius, is the crushed zone, where the shockwave exceeds the compressive strength of the rock, pulverizing it into unconsolidated rubble. Surrounding this is the fragmented zone, where the rock remains in large but disconnected blocks, broken along pre-existing weaknesses and newly formed shear fractures. Beyond this, extending outward, is the open-mode fracture zone, where tensile fractures propagate into intact rock, enhancing permeability while preserving general positions (Liu et al, 2017).

The extent of these zones depends on the explosive energy, in-situ stress conditions, and rock properties. Mining excavation guidelines suggest that the burden, or distance from the blasthole to the edge of the fragmented zone, is typically 25 to 40 times the borehole diameter, (Dyno, 2010) though this does not account for pressure-induced fractures that extend beyond the primary damage region. This rule of thumb however was developed for surface and underground mining, where stress is not as intense as a HDR formation. Historical experiments in early oil-well "shooting" demonstrated fragmentation radii of up to 48 feet (14.6 meters) and tensile fracture extents reaching 90 feet (27.4 meters) in shallower oil and gas formations (Miller & Johansen, 1976). Given the higher in-situ stress and deeper rock confinement of HDR reservoirs, it is expected that fracture propagation will be reduced.

To enhance fracture extent, we hypothesize that the wellbore could be pre-pressurized just below the critical pressure for tensile failure prior to detonation. This would reduce the stress barrier required for fracture initiation, allowing the blast energy to create a more extensive network. The orientation of the well relative to the in-situ stress field will also play a critical role in optimizing fracture growth. If the well is drilled in the direction of minimum horizontal stress σ_3, fractures are more likely to propagate parallel to the wellbore, improving connectivity between laterals. If drilled in the direction of maximum horizontal stress σ_2, fractures may spread more laterally, increasing overall reservoir volume.

Unlike hydraulic fracturing, which requires proppant to prevent fractures from closing under stress, explosively generated fractures will rely on shear slippage and fragment repositioning, to remain open. If insufficient permeability is achieved post-blasting, limited proppant injection may still be required. Though controlling where it goes may be a challenge without wellbore plugs. Additionally, diverting agents may be necessary to prevent preferential flow through larger voids near the pre-existing anulus, ensuring distributed flow throughout the entire network.

Propellant stimulation has received some attention as an alternative to hydraulic fracturing, but dynamic loading stimulations are in general under-explored. As a result, many of the modern diagnostic and monitoring techniques used for hydraulic fracturing have yet to be applied to fully understanding and optimizing their effectiveness in subsurface permeability enhancement. Additionally, most applications of explosives in rock engineering, such as mining and construction, are designed to create localized damage while preserving the structural integrity of the surrounding formation. In contrast, our approach seeks a middle ground: one that avoids the risk of long, uncontrolled, and potentially leaking hydraulic fractures while also ensuring a larger, well-connected, and permeable fractured volume beyond simply a highly damaged near-wellbore zone.

Drill targeting precision could be a challenge, as wellbores need to be placed within a radius to ensure effective connection through the fragmented zone. However, if modern directional drilling techniques prove sufficient for achieving this level of accuracy, the design naturally lends itself to scalability. Additional horizontal laterals could be drilled to intersect with the central injector.

8. PRELIMINARLY SIMULATIONS

For an initial evaluation of this system, we use the single-component thermal code within the MATLAB Reservoir Simulation Toolbox's geothermal module (Collignon et al., 2021). This simulates coupled fluid flow and heat transport in porous media using finite-volume discretization. The mesh is constructed using the tetrahedral meshing software: Gmsh (Geuzaine et al., 2009), with fine cell refinement along a horizontal well segment. This approach naturally results in numerous available faces for a discrete fracture network, providing multiple fracture-fracture connections at various angles near the well center.

Due to the lack of precise knowledge about expected fracture geometries, we assign fracture apertures based on face proximity to the well, applying a square root decay function up to a defined maximum radius. The model assumes a homogeneous rock with hydrostatic pressure initialization. The well extends to a depth of 3000 m, with a lateral section of 1000 m. The injection well operates under pressure control at 250 psi, with an injection temperature of 20°C. The simulation adopts standard parameters for fresh water, enforces constant pressure and temperature boundary conditions, and runs for 30 years under continuous circulation.

Table 2 Rock Model Properties used in MRST simulations.

Geothermal Gradient	Surface Temperature	Fracture Permeability	Matrix Permeability	Rock Conductivity	Rock Capacity	Aperture Range	Density
40 (°C/km)	15 (°C)	$a^2/12$(mD)	1 mD	2 (W/m·K)	1000 (J/kg·K)	0.1 – 1 (mm)	2700 (kg/m³)

While all the parameters used here are hypothetical, we notice that the radius or boundary of the stimulation zone has a substantial effect on the system's performance in both water retention and heat production. The 30m radius example exhibits extremely high impedance, partly due to poor connections, an artifact of the DFM model. This may resemble the reality of poor connection at the common toe but does not account for leftover void space in the borehole path. The 120m radius case exhibits adequate temperatures for binary power plants or direct use for over 5 years.

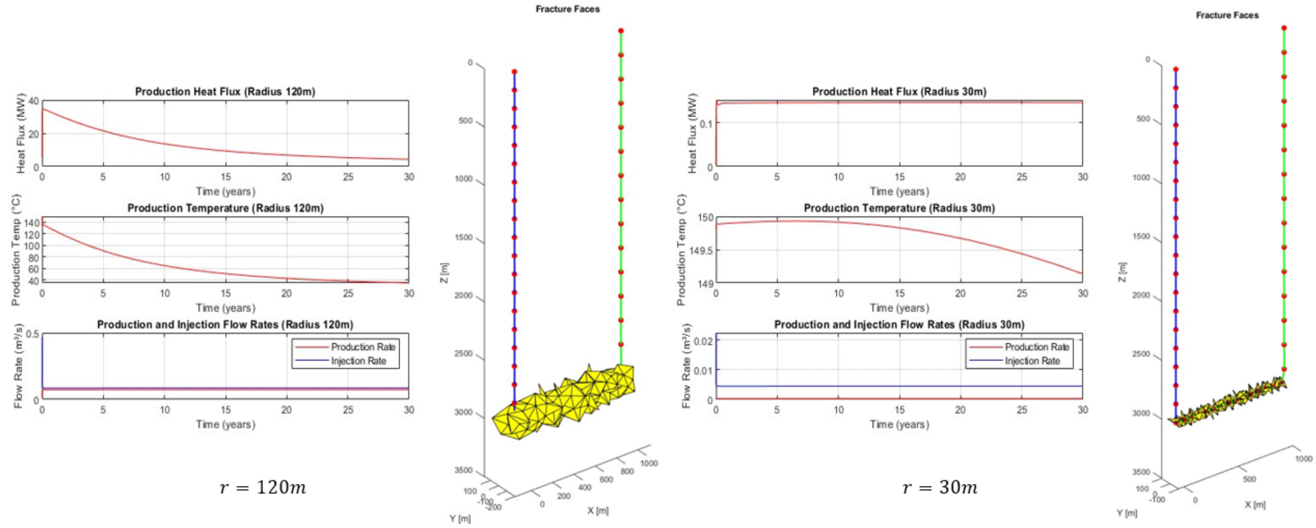

Figure 5 Discrete fracture network intended to represent stimulated volume with maximum fracture extent of 120m (left) and 30m (right).

These simulations only account for a single component fluid thus we chose to investigate only moderate temperature systems. A higher temperature reservoir could however produce temperatures high enough for electric generation. Additional injection wells connecting back to the main producer also should increase the thermal production or slow down the cooling mechanism depending on how they are operationally partitioned. However, we believe this is a sufficient first glance into the potential thermal behaviors. Further refinement of the radial fracture distribution function will be needed to represent this system better.

8. FURTHER INVESTIGATION

Future work should focus on simulating blast-induced fracture propagation under varying stress conditions, incorporating natural fractures and faults. High-resolution geomechanical modeling can help predict the extent and geometry of the fracture network, guiding explosive selection and deployment strategies for various HDR reservoir conditions. Further study is needed to evaluate explosive formulations capable of withstanding high downhole temperatures, including ANFO, emulsions, and high-density gels.

These studies will help refine model parameters for more advanced fluid flow simulations, improving predictions of permeability enhancement and reservoir performance. Additionally, assessing geophysical responses to such stimulations, both during the detonation phase and under operational conditions will be a valuable next step for monitoring and optimizing the techniques we could potentially use to deploy such a system.

9. CONCLUSION

Early modeling results indicate that explosive stimulation for the proposed semi-closed loop system may be a viable technique for hot dry rock geothermal development. However, achieving optimal performance will require careful refinement of charge placement, energy release, and geomechanical conditions to maximize the stimulated radius while maintaining long-term reservoir stability. The effectiveness of this approach will largely depend on surpassing the fracture extents achieved in 1976, as creating only a small radius of damage in a semi-closed-loop system would lead to short-lived heat production. Further optimization is essential to ensure sustained energy extraction, while safety considerations should also remain a high priority in deployment and operational planning.

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