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

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ABSTRACT

The combination of hydraulic fracturing and directional drilling has revolutionized the oil and gas industry by creating extensive permeable networks for fluid drainage. Efforts to adapt these methods for Enhanced Geothermal Systems (EGS) aim to develop fluid pathways in hot dry rock formations to enable heat extraction. The prevailing EGS design employs parallel wells connected by vertical hydraulic fractures. While advancements have been made, forming uniformly distributed and interconnected fractures in crystalline rock remains challenging. Geophysical monitoring and circulation flow testing reveals that fracture propagation in geothermal reservoirs is easily influenced by natural discontinuities, which can divert energy potentially causing suboptimal reservoir characteristics.

We propose revisiting a stimulation method largely abandoned in modern oil and gas production: the use of conventional explosives as the primary stimulation agent. Although this approach presents considerable safety and logistical challenges, it has the potential to create more complex and confined fracture networks compared to hydraulic fracturing. When combined with a proposed semi-closed-loop well configuration, this method may overcome the inherent challenges of fluid containment and thermal short-circuiting.

To conduct a first-order evaluation of this concept's feasibility, we performed fluid and heat transport simulations using the MATLAB Reservoir Simulation Toolbox (MRST) with a finite volume framework. These simulations were applied to simplified models representing moderate-temperature, low-permeability rock matrices with idealized discrete fracture networks that approximate volumes stimulated by conventional explosives. Initial results indicate that, provided the stimulated volume is sufficiently large and short-circuit pathways are mitigated, a simple two-well system can sustain heat production for small-scale geothermal power generation or direct use applications for approximately a decade. Conversely, if the stimulated region is too small, heat production is severely limited. Consequently, maximizing the stimulated radius emerges as a critical design objective to ensure effective heat extraction and sustained system performance. We suggest that further studies incorporating transient mechanical modeling are needed to continue this feasibility study and optimize the deployment strategy.

1. INTRODUCTION

Enhanced Geothermal Systems (EGS) offer a promising solution to expand geothermal energy production beyond conventional hydrothermal resources. However, stimulating crystalline rock formations to achieve the necessary permeability and inter-well connectivity remains a significant challenge. Unlike hydrocarbon reservoirs, where hydraulic fracturing primarily enhances drainage efficiency, EGS demands a more controlled and distributed fracture network to sustain long-term heat extraction and minimize issues such as thermal short-circuiting and excessive water loss.

Hydraulic fracturing between parallel wells has been the standard method for geothermal reservoir stimulation. It has been demonstrated effective at creating large fractures in crystalline rock. However, challenges arise from the complex geomechanical environments characterized by heterogeneous stress states, natural discontinuities, resulting in unpredictable fracture propagation. This presents the risk of creating preferential flow paths that limit the effective heat exchange volume and allow for water loss.

To this end we investigate the potential for using conventional explosives as a controlled stimulation mechanism, leveraging dynamic loading to create a highly fractured zone along deviated wells to create a semi-closed loop EGS system. 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 HDR heat extraction. For a first pass at gauging the potential of this design, 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.

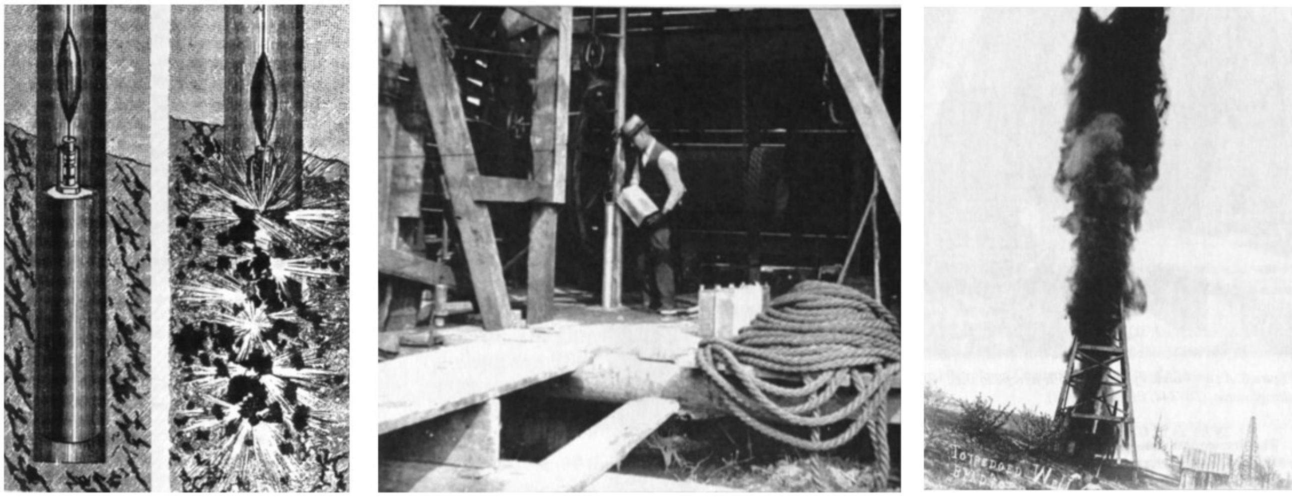

Figure 1: Depiction of a Roberts Torpedo before and after being detonated by a weight "go-devil" (left), image of a man preparing torpedo shell by filling it with nitroglycerin (center), image of an oil well gushing during a "shooting" stimulation in 1883. Images from Drake Wells Museum.

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. Moreover, preferential flow paths can create a positive feedback loop, where accelerated cooling in preferential paths cause thermal contraction of the rock potentially increasing fracture apertures accelerating thermal depletion (McLean and Espinoza, 2023).

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°C, our injection water is 25°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).

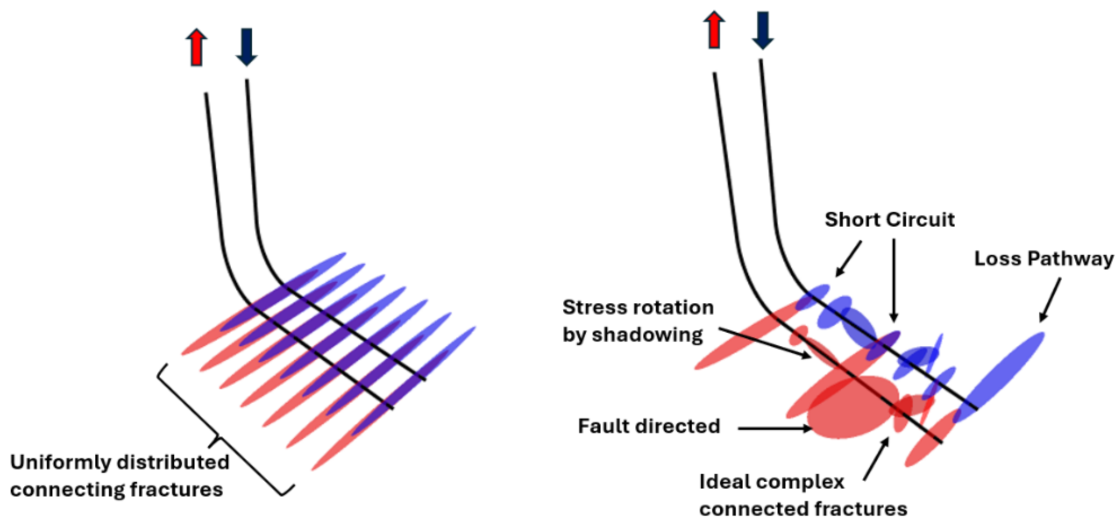

Figure 2: Conceptual diagram of state-of-the-art EGS approach: ideal fracture distribution in homogeneous host rock (left), potential flaws due to natural discontinuities, stress variation and shadowing. Not shown in both diasgrams are many likely secondary and tertiary fractures.

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, chapter 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.

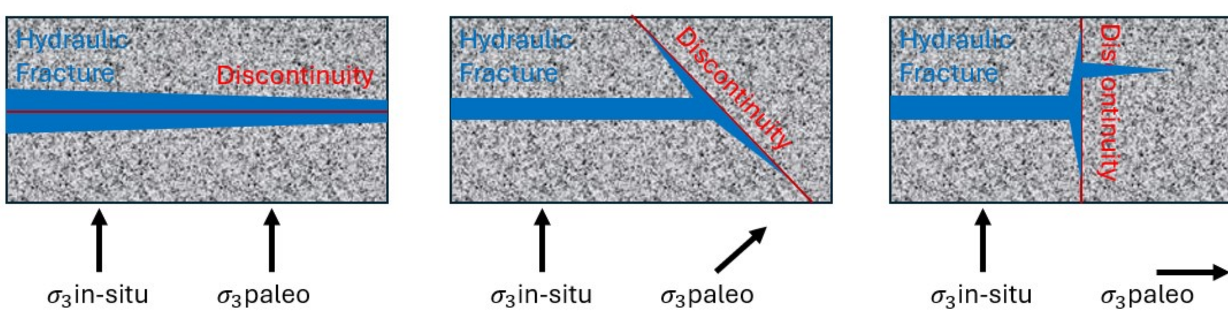

Figure 3: Likely propagation behavior of a hydraulic fracture influenced by natural discontinuities such as joints, veins, and faults in a normal faulting regime: paleo stress state aligns with current stress state (left), paleo stress has principal σ_2 and σ_3 oblique to those of current stress state (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 velocity 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, there are indications that the challenges associated with unknown natural features could still hinder long term viability of hydraulically stimulated HDR reservoirs,

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 condition with a water loss rate of approximately 100gpm. 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.

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, events 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 contribute to 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 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 seismic 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 in HDR formations 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 HDR 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.

5.1 Stimulation Techniques

Propellant and Acidization

Traditionally used in oil and gas for near-wellbore enhancement and skin reduction, propellant and acid treatments have found some application in geothermal settings. Aydin et al. (2024) demonstrated their combined use in a conventional geothermal well in Turkey, achieving effective skin damage reduction. Similarly, Sigurdsson (2015) reported successful near-wellbore permeability enhancement in an Icelandic hydrothermal well. Ultimately these methods are cost effective and readily available but are limited to near-wellbore effects, not sufficient for creating commercial scale HDR reservoirs.

Explosives

Explosive-based well stimulation was prevalent in early oil and gas operations, but this development tapered off as hydrofracking took over. Their use in geothermal applications has been very minimal. Ther only explosive stimulation of a geothermal well that we are aware of is described in Mumma, D.M., (1982). This was a field test on a low performance steam well in the Geysers geothermal field. Charges were positioned in an open hole at steam entry depths. While build-up tests indicated significant skin reduction at the blasted intervals, debris from the charge canisters caused well plugging off some lower steam entry points, ultimately reducing overall productivity. A notable positive outcome was the technical success in safely placing explosives in a high-temperature geothermal environment and achieving controlled detonation.

The most extreme well stimulation experiments involved detonating nuclear devices for gas production. 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. Reviving such techniques for geothermal use would likely yield similar ineffective results and remain socially unacceptable.

Other Proposed Mechanisms:

Liquid CO_2 phase blasting involves rapidly depressurizing liquid CO_2 to induce fractures through dynamic loading. Nui (2024) conducted laboratory and numerical modeling studies, suggesting the technique can enhance near-wellbore permeability. Electro-fracking, explored by companies like Eden GeoPower, uses high electrical currents to induce fractures. However, studies and field data are minimal, with little evidence supporting its effectiveness. A few other waterless fracturing techniques have been proposed and explored to various degrees primarily in oil and gas but are beyond the scope of this discussion.

5.2 Well Configurations

An alternative to hydrofracturing is the use of deep closed-loop geothermal systems to access hot rock. In HDR a completely closed loop system only accesses heat near the wellbore due to the slow conduction of heat through rock, necessitating an impractical number of wells for commercial scale heat production even with substantially long horizontal wells. 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. “U” shaped closed loop systems have been discussed but are not feasible to drill and still will not provide access to enough heat for commercial 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 solely on traditional hydraulic stimulation, which is prone to uncertainties, this approach seeks to adapt and enhance the concept of a semi-closed-loop systemin “U” configuration while overcoming its drilling feasibility constraint and heat access limitations with conventional explosives as the primary stimulation mechanism.

6.1 Drilling and Completion Routine

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. If modern directional drilling techniques prove sufficiently accurate, the design naturally lends itself to scalability. Additional horizontal laterals could be drilled in a star pattern to intersect with the central injector.

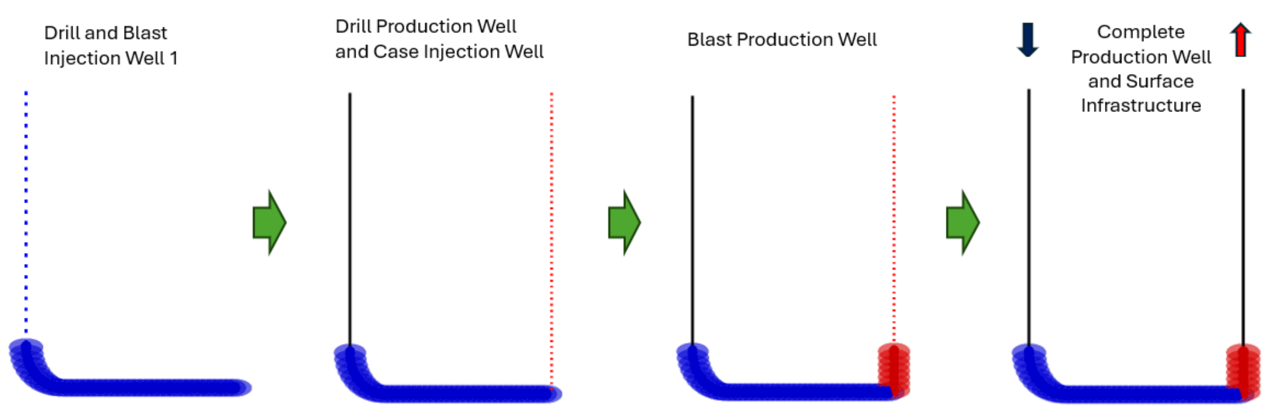

Figure 4: Initial suggestion of the general order of operations to develop the proposed EGS for a two well configuration. Fully shaded spheres indicate a volume of fragmentation. Opaque ellipses indicate open mode fracturing caused by forced fluids. It’s not essential that either well is horizontal.

6.2 Stimulation Mechanism

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 by overcoming more than just the minimum principal stress. This makes dynamic loading a fundamentally different mechanism, capable of producing a more complex and irregular fracture network.

The effect of a blast is often described by three distinct zones based on the intensity of rock breakage depicted in figure 5. 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 fines. 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 (Liu et al, 2017). Unlike hydraulic fracturing, which often employs proppant to prevent fractures from closing under stress, explosively generated fractures will rely on shear slippage and fragment repositioning, to remain open.

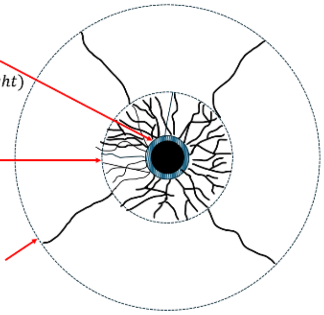

Figure 5: Illustration of damage pattern from blasting in a borehole.

The extent of these zones depends on the explosive energy, in-situ stress conditions, and rock properties. Most modern applications of explosives in rock engineering are often designed to create localized damage while preserving the structural integrity of the surrounding formation. This quality will be beneficial for avoiding excessive water loss. However, to maximize heat access in HDR the goal will be to maximize the fragmented and tensile fractured radii.

Experiments with high explosives being pumped into hydraulic fractures in shallow oil wells in the 1970s demonstrated fragmentation radii of up to 48 feet (14.6 meters) and extensive fractures reaching 90 feet (27.4 meters) (Miller & Johansen, 1976). Given the higher in-situ stress and deeper rock confinement of HDR reservoirs, it is expected that similar fracture propagation will require more explosive energy than was used then. To further 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 larger network.

6.3 Mitigating Short Circuits

Unlike prior explosive well stimulations, where the objective was to improve permeability or reduce wellbore skin for radial flow around a well, our design places the wellbore at the center of a long tubular volume intended for linear flow. We hypothesize that, after stimulation the path of the wellbore will be primarily filled with fines and fragments. However, it is possible that this pre-existing anulus will still exhibit higher permeability than the rest of the stimulated volume. It could then develop as a thermal short circuit. To mitigate this, diverting agents, possibly including cement, could be used to preferentially plug the center.

7. PRELIMINARLY SIMULATIONS

The primary objective of this simulation was to assess the potential heat recovery of the proposed design if it can be successfully created. To do this we use the single-component thermal code within the MATLAB Reservoir Simulation Toolbox's geothermal module (Collignon et al., 2021). This software package solves 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 around a stimulation well path. This approach naturally results in numerous available faces for a discrete fracture network, providing multiple fracture-fracture connections at various angles.

Due to our lack of precise knowledge about expected fracture geometries from deep blasting, we chose to assign fracture apertures based on face proximity to the well, applying a square root decay function out to a defined maximum radius. This simplified approach acts very similar to assigning dual porosity cells to a specific region. It will not capture all the characteristics of such stimulation and should be replaced by better approximations in future studies. Nonetheless it allows us to investigate some of the broad thermal behaviors of the proposed EGS design.

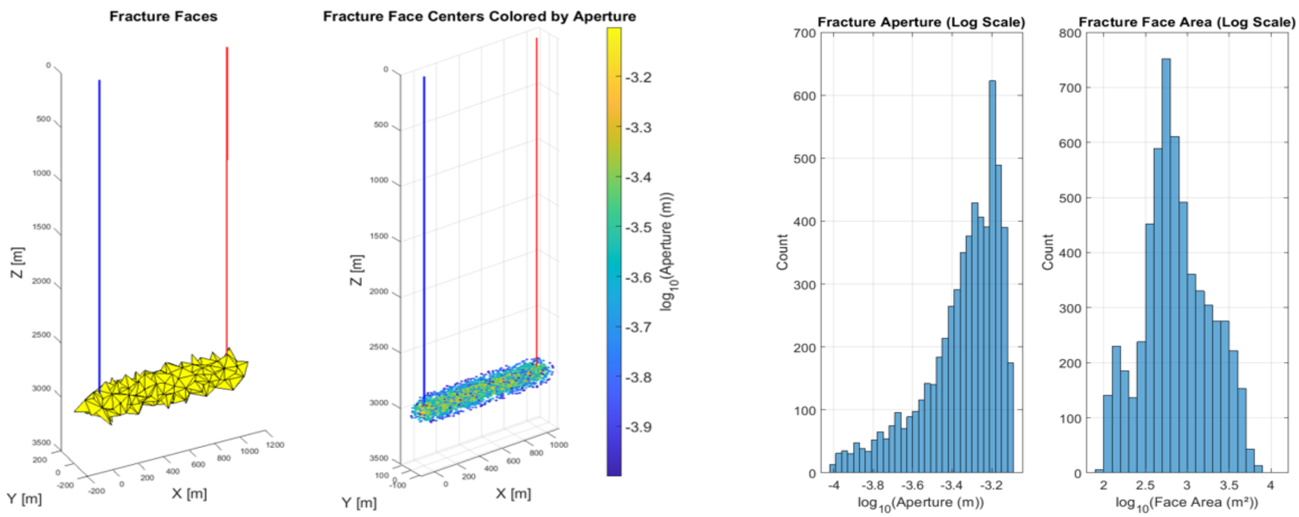

Figure 6: DFN characteristics for a stimulated max radius of 120m: fracture faces and fracture centroids (left) showing relative locations of wells, and histograms of generated DFN apertures and areas (right).

Our model is parameterized as a homogeneous tight rock with hydrostatic pressure and a constant geothermal gradient of $45℃/km$ as initial conditions. We simulate a 30-year continuous circulation with a constant driving pressure of 250 psi and injection temperature of 20℃. The simulation adopts standard parameters for fresh water and enforces Dirichlet boundary conditions for both pressure and temperature. More information about the modeling framework and parameterization can be found in the appendix.

The first round of tests assumes a stimulated radius of 120m shown in figure 6 and compares the effect of the background matrix permeability. Higher permeability results in increased water loss, which also leads to faster cooling and overall lower heat production rates. The system performs better with a lower background permeability, however the performance difference between $10\mu D$ and $100\mu D$ is minor. Heat production curves are in figure 7.

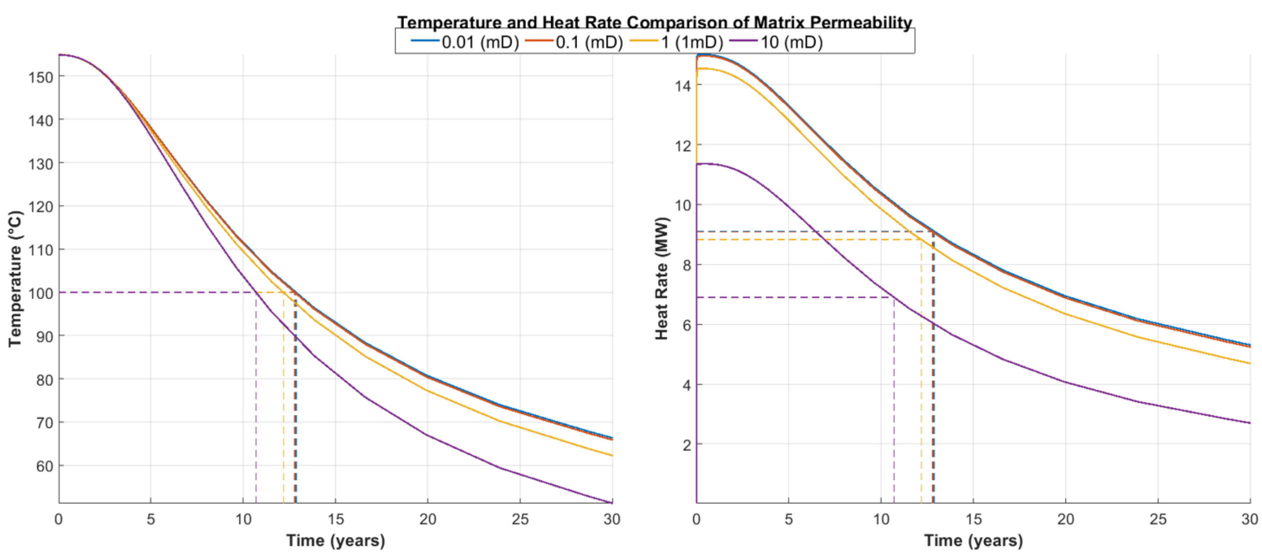

Figure 7: Simulated production temperature (left), and heat production rate (right) for the 120m stimulated radius scenario for a range of background matrix permeability. Dashed lines indicate a theoretical shut-in or conversion to direct use due set at 100℃.

The second test explores the effect of the stimulated radius on performance, and heat production performance can be seen in figure 8. For this we assume a background permeability of $100\mu D$. As expected a larger stimulated volume allows access to more heat but also cool faster due to having more flow pathways and low impedance. With a radius of 90m, 120m, and 150m the model produces heat above 5MWh until it cools to 100℃. If a binary electric generator could operate at 20% efficiency at temperatures as low as 100℃ this equates to achieving at least 1MWe until shut-in or converting to direct use only after just over 10 years.

With our model setup the smaller radius tests: 30m and 60m, do not achieve heat rates sufficient to produce 1MWe for any period. This is, however, a likely misleading result because we have not accounted for potential higher permeability in the pre-existing anulus, that would affect the small stimulation scenarios more than the larger ones. These smaller stimulation scenarios may then produce at high temperatures but for a much shorter lifespan. A table summarizing the simulated performance results can be found in the appendix.

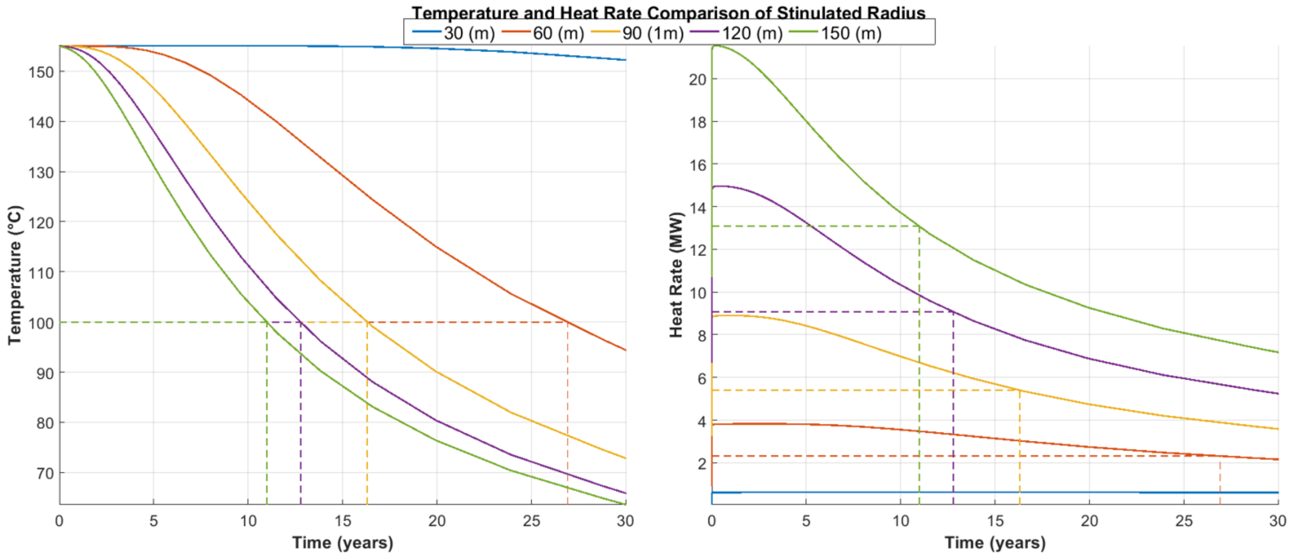

Figure 8: Simulated production temperature (left), and heat production rate (right) for the a range of stimulated radius scenarios with background matrix permeability of $100\mu D$. Dashed lines indicate a theoretical shut-in or conversion to direct use due set at 100℃.

Our current models only assume a single production well; however, we believe adding additional wells in a star pattern connecting back to the central injector would allow for increased total heat rate and extend the system's lifespan to be more comparable to a commercial scale system. This is a minor detail that could be explored with a better understanding of the expected fracture geometry and resulting permeability field. For a first pass evaluation, we confirm that achieving the maximum possible stimulated radius in low permeability rock will be a primary objective to make this design work.

8. FURTHER INVESTIGATION

Mechanical simulation with dynamic loading will be a valuable next step in evaluating the feasibility of this EGS design. These studies should revolve around predicting the spatial density and geometry of fractures and volumes of fragmentation. Doing so will allow for optimization of both explosive selection and deployment strategies. This should involve scenarios where the explosive is only placed in the wellbore and scenarios where it is injected into natural and hydraulic fractures. It should also explore the effects of pressurizing the well while blasting. To better understand a range of possible outcomes these models will need to also consider a variety of plausible stress states and the presence of natural discontinuities. Throughout these studies our fluid and heat transport model can be adjusted to more accurately predict performance. Furthermore, it will also be advantageous to formulate and re-configure modern diagnostic techniques to monitor blast stimulations, for both reservoir characterization, and safety monitoring which includes induced seismicity.

9. CONCLUSION

The proposed semi-closed loop Enhanced Geothermal System (EGS) design utilizing explosive stimulation presents a promising alternative to conventional parallel well hydraulic fracturing, particularly in formations with complex natural discontinuities and heterogeneous stress states. Our preliminary thermal and hydraulic modeling results suggest that achieving a stimulated radius of at least 120 meters in low-permeability rock formations could sustain temperatures suitable for electricity production for over a decade with a two-well system. This concept could be scaled to small commercial operations, potentially extending operational lifespan beyond initial estimates.

However, these results are highly dependent on the assumptions and parameter choices made during model development. To better constrain performance predictions, future work should include mechanical simulations capable of estimating more realistic fracture geometries from dynamic loading in deep HDR conditions. Such models will improve our heat transport simulations and provide insight into how varying geological conditions affect system viability.

Ultimately, the success of this design for EGS applications will hinge on achieving sufficiently large fractured and fragmented radii. Attaining the necessary extent of damage will be challenging and will require surpassing the levels achieved in the limited explosive stimulation case studies from the 1970s and 1980s.

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APPENDIX

Fracture Assignment

Fracture apertures are assigned based on a simple square root radial decay function:

$$a(r) = a_{max} - \sqrt{\frac{r}{r_{max}}}\,(a_{max} - a_{min}) \tag{3}$$

where r is the distance minimum distance from the mesh face centroid to the wellbore path. For this we used min and max aperture of 0.1mm and 1mm. Each face that has a non-zero aperture was used to create hybrid fracture cells. The permeability of these cells are assigned according to the parallel plate assumption:

$$k_f = a^2/12 \;\; [m\text{^}2] \tag{4}$$

General Simulation Setup and Parameterization

Table 2: parameters used for Gmsh tetrahedral mesh generator

X limits (m)	Y limits (m)	Z limits (m)	Number of Cells	Min Characteristic Size (m)
-500, 1500	-500, 500	2500, 3500	5463	5

The mesh is generated specifically to have fine cells along the path between the theoretical heel of the production well and the toe of the injection well. We approximate it has perfectly horizontal with not build length.

Table 3: parameters used for Gmsh tetrahedral mesh generator

	Injector	Producer
Whell Head [x,y,z] (m)	0, 0, 0	1000, 0, 0
Reservoir Connection [x,y,z] (m)	0, 0, 3000	1000, 0, 3000
Control Pressure	250 (psi)	0
Control Temperature	20 (^{o}C)	NA

For simplicity the only well controls used are temperature for the injector and pressure controls at both. Rate limiting was not necessary in our simulations, as none of the attempted scenarios resulted in unreasonable rates.

Table 4: simulation schedule parameters

Start time	End time	Initial time step	Increase factor	Number of steps
0	30 (year)	5 (minutes)	1.2	74

For computational efficiency we chose to use a geometrically increasing time schedule. This allows for short time steps at the beginning of the simulation where pressure gradients are most extreme and longer time steps once pressure gradients relax.

Table 5: Rock and fluid physical property parameters.

	Rock	Fluid
Thermal Conductivity	2 (W/m^{o}C)	0.6 (W/m^{o}C)
Heat Capacity	1.0 (J/g^{o}C)	4.18 (J/g^{o}C)
Density	2.7 (g/cc)	0.99 (g/cc)
Compressibility	0	4.4e-10 (1/ Pa)
Thermal Expansivity	0	207e-6 (1/^{o}C);
Viscosity	NA	1.002e-3 (Pa ·s)
Reference Pressure and Temperature	NA	1 atm & 20 ^{o}C
Porosity	0.05	NA

The MRST geothermal module uses a convenient set of equations of state for the fluid properties so all properties listed above correspond to the surface conditions, and are updated for reservoir conditions.

<u>Initial and Boundary Conditions:</u>

The model is initialized with pore pressure at hydrostatic equilibrium with depth assuming a surface pressure of 1(atm). The thermal initial condition is assigned based on a constant geothermal gradient of $45℃/km$ and a surface temperature of 20℃. The boundaries all use Dirichlet conditions of constant pressure and constant temperature equal to those of the initial condition.

Results

Table 6: Summary of simulated performance results for tests varying matrix permeability and stimulated radius.

Varying Matrix Permeability								
Matrix Permeability (mD)	Stimulated Radius (m)	Injection Rate (L/s)	Production Rate (L/s)	Water Loss (%)	Impedance $(MPa \cdot s/L)$	Shut-in Time $(year)$	Heat Rate at shut-in (MW)	Total Heat Extracted (PJ)
0.01	120	27.9	27.8	0.3	0.062	12.9	9.1	5.0
0.1	120	28.1	27.7	1.5	0.062	12.8	9.1	5.0
1	120	30.7	26.9	12.3	0.064	12.2	8.8	4.6
10	120	51.1	21.1	58.8	0.08	10.7	6.9	3.2
Varying Stimulated Radius								
0.1	30	1.3	1.1	12.1	1.5	-	0.6	0.6
0.1	60	7.3	7.0	3.3	0.2	26.9	2.3	2.7
0.1	90	16.8	16.4	2.0	0.1	16.3	5.4	3.8
0.1	120	28.1	27.7	1.5	0.06	12.8	9.1	5.0
0.1	150	40.5	39.9	1.3	0.04	11.0	13.1	6.1