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Novel Frac Sleeve Design for Water Conformance in Enhanced Geothermal Systems (EGS) Leads to Improved Thermal Efficiency

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INTRODUCTION

Enhanced Geothermal System (EGS) technology continues to demonstrate commercial viability and potentially deliver more gigawatts of clean energy. The relationship between the injector and producer wells is also becoming clearer with more downhole data, introducing a new opportunity to study the downhole water distribution, or conformance.

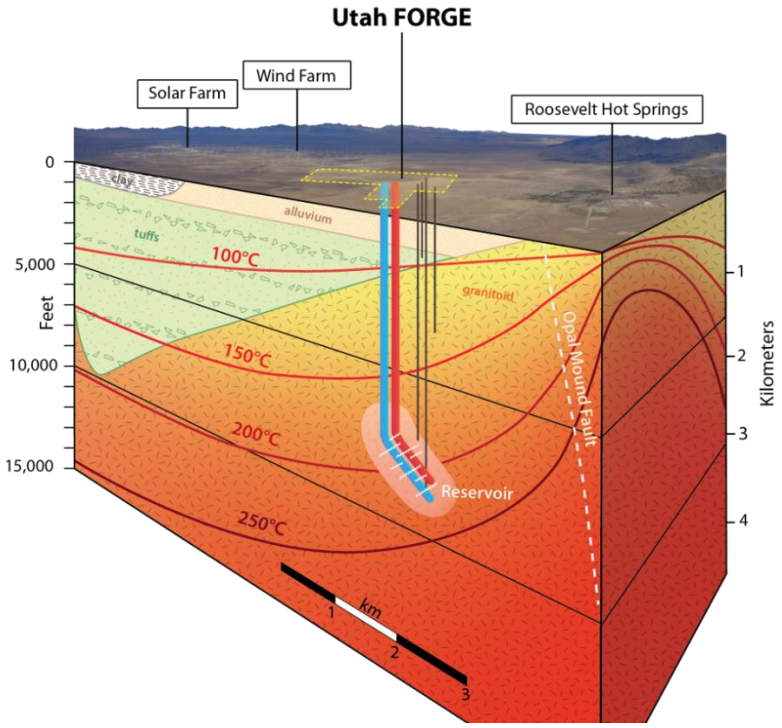


Figure 1. EGS Generalized Diagram. Source: https://egi.utah.edu/research/geothermal

Data collected at Utah FORGE in 2024 included injectivity tests with production logging tools (PLT) to monitor water flow rates into the network of fracture stimulation stages, and it illustrated very unbalanced downhole water distribution. Poor conformance means the injected water cannot absorb the optimal heat energy, and the heat reservoir is not optimally depleted. The thermodynamic efficiency in the reservoir of EGS depends on the injector/producer relationship. To achieve sufficient heat transfer requires even distribution of water.

Several operators have tested deviated and horizontal well pairs to study the effects of hydraulic stimulation on geothermal reservoirs. The 2024 Forge data includes PLT that highlighted the uneven water distribution between frac stages.

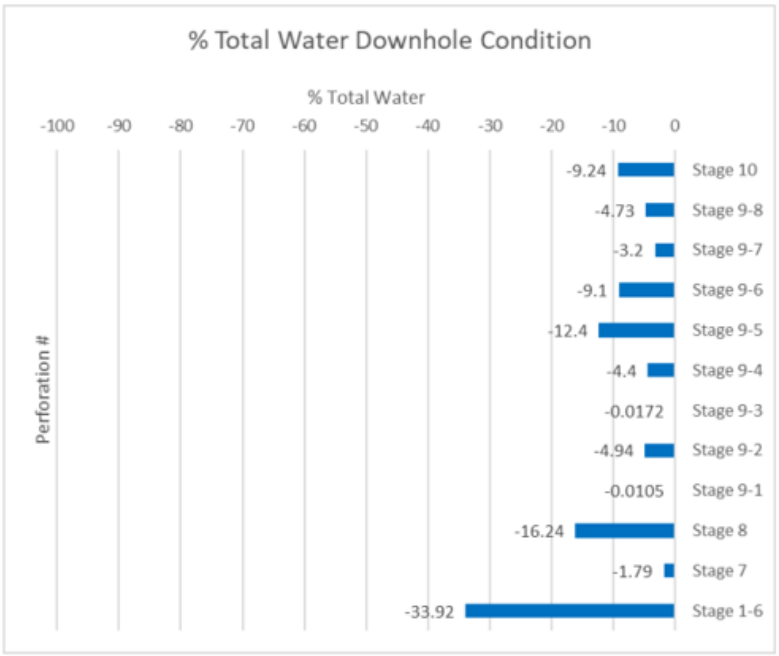


Figure 2. 2024 Forge Data - 22 stops recorded throughout the logging interval with average injection rate of 15 bbl/min of 8.36 lb/gal slick water

While not directly quantifiable, it can be inferred that unequal water distribution will lead to sub-optimal thermodynamic efficiency from an EGS well pair. High water volumes will lead to localized cooling of the rock, while other sections of the well are not contributing as much thermal energy.

Several operators have expressed concerns about water conformance in EGS wells and are pursuing technical solutions that are compatible with multi-stage frac operations and provide some form of in-reservoir flow control. Standard equipment such as inflow control devices (ICD) are designed to evenly distribute flow in both injector and producer wells, but it is not possible to pump an effective frac stimulation through the ICD choke restrictions. Similarly, installing the ICD string, post-frac, would require a smaller tubing diameter which would severely reduce the water volumes required for a commercial EGS project.

1 METHODS & RESULTS

An innovative approach to water conformance in fractured reservoirs was recently deployed in Algeria, using ported frac sleeves to control water breakthrough. This strategy involved using three sleeves per stimulation stage, each being configured differently to 25%, 50% and 75% of open flow area. Pending the results of a PLT log, any combination of the three sleeves can be shifted closed to balance the flow rates between the frac stages, achieving a more even injection/production profile in the well. This solution could be applied to EGS wells to achieve the objectives of both effective fracture stimulation and balanced water injectivity across the lower completion. The study will include nodal analysis of water distribution based on stimulation heterogeneity, and an analysis of the choking effects of different sleeve closure scenarios.

1.1 Ported Frac Sleeves

A ported frac sleeve refers to a tool that is included in the production casing string of a well in order to achieve communication with the reservoir prior to stimulation. The tool is run in hole in the closed position, later opened by ball dropped from surface or by shifting tool run on coiled tubing. Typically multiple frac sleeves are installed within a casing string to treat stages individually and are either cemented or combined with packers for zonal isolation.

The flow area through the open sleeve is adjustable by restricting or plugging ports of the tool. By installing multiple tools per zone with different plugging configurations, various downhole choke positions are created by manipulating the sliding sleeves open or closed. For example, the Algeria deployment provided an operator with eight positions utilizing three tools with different number of ports open vs. plugged.

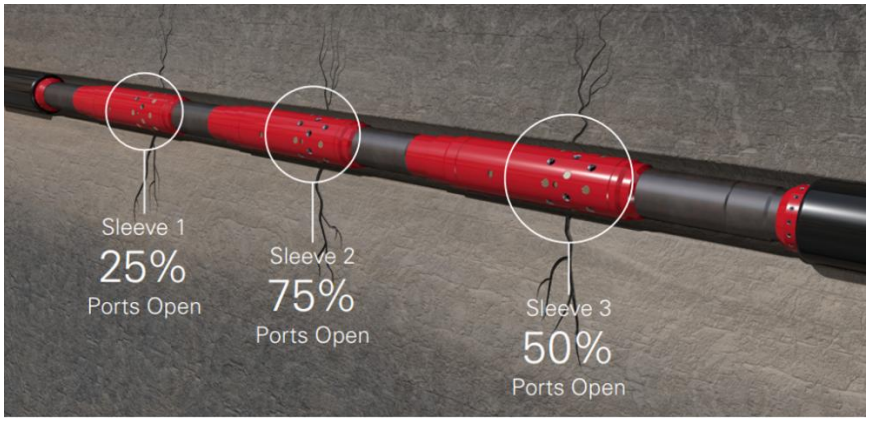


Figure 3. Algeria Deployment - three ported frac sleeves in one zone, eight choking positions

Applying this solution to EGS allows operators to have enhanced control over water distribution, subsequently impacting the heat transfer and thermodynamic efficiency between the injector and producer wells. Because the frac sleeves are intended for high flow rate and pressure stimulation, no hydraulic fracturing limitations have been set on the system, as would be the case with an ICD.

1.2 Nodal Analysis

In order to test the theory of improved water conformance with selective downhole choking via closeable frac sleeves, a NETool nodal analysis well model was created to represent a theoretical EGS injector well. The initial model was created using a Uniformity Index of 100%, meaning each fracture stimulation stage had an equal distribution of proppant. For the purposes of this study, proppant distribution will be used as a correlation of permeability, which determines water injectivity (Wei et al, 2021). For example, Qw of 10 stb/d/ft is the baseline for the model (Figure 4) for an injector well with a 5,000 ft horizontal section divided into 40 equal fracture stimulation stages. Total water injection rate is set at 60,000 bbls per day. With a nearly perfect UI of 100%, the only variation is downhole water injection profile is the predictable heel-to-toe effect due to flowing friction along the length of the 7-inch liner.

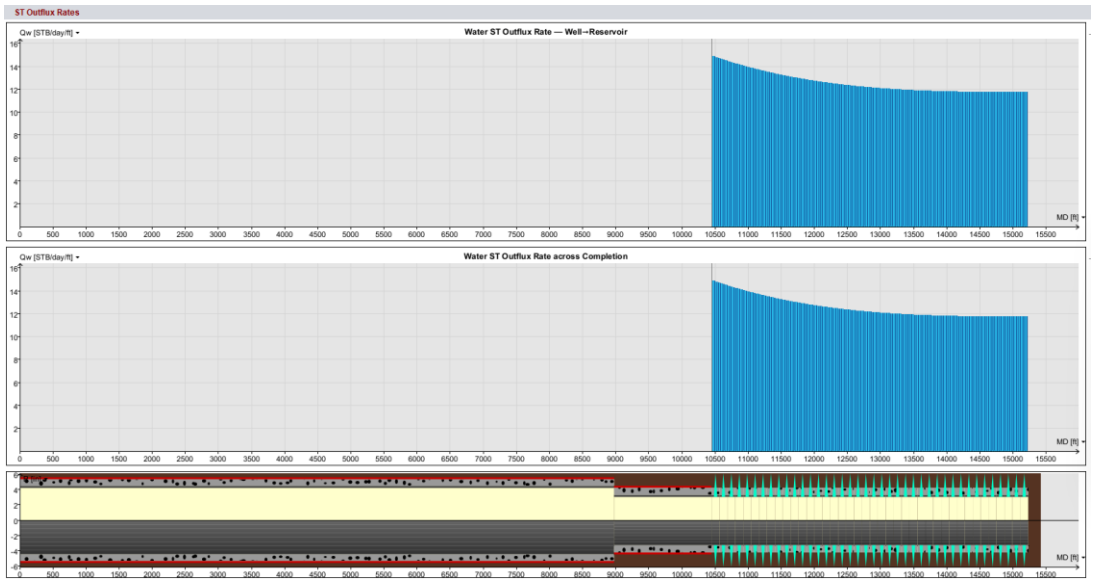


Figure 4. Nodal analysis results of EGS injector well's downhole outflux rate based on UI of 100%

To illustrate the effect of a UI <100%, a synthetic permeability profile was created to represent a random distribution of proppant between the frac stages. The model gave an outflux range between 5 and 40 bbl/d/ft, representing an injector well with a UI of approximately 60%. The expected effect of the outflux heterogeneity illustrated below (Figure 5) would be a reduction in thermal energy recovery due to increased water volumes flowing through the frac stages with the highest proppant distribution, which would cool those zones while starving the rest of the well of sufficient water volumes.

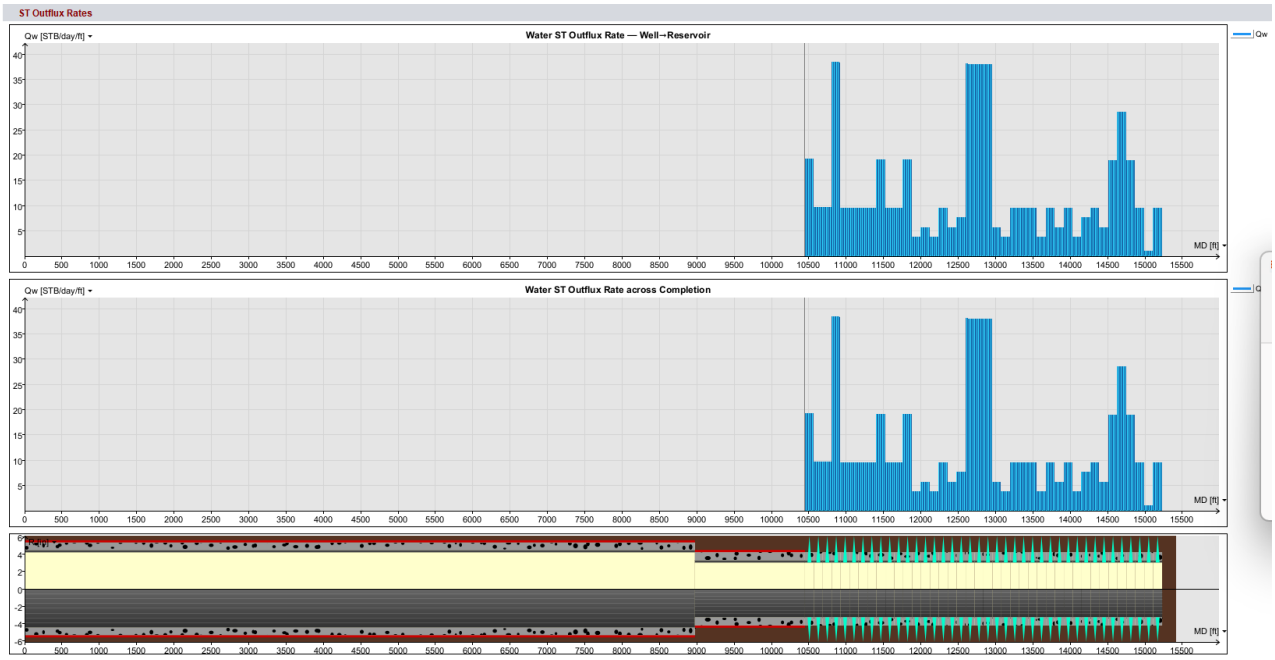


Figure 5. Nodal analysis results of EGS injector well's downhole outflux rate based on UI of ~60%

Further study of field results is required to understand the correlation between UI and thermal power generation, but it stands to reason that lower frac uniformity will be detrimental to the efficiency of the EGS well pair.

Nodal analysis is commonly used in the oil and gas industry to model, design and optimize production wells. It is common for horizontal oil wells in conventional hydrocarbon reservoirs (sandstone and carbonate geology) to suffer from permeability and porosity heterogeneity that leads to premature water or gas ingress. For example, if the desirable oil column is underlain by a water aquifer, the undesirable water can flow preferentially (due to lower in-situ viscosity and higher mobility) into the wellbore. This can lead to high water-cut (WC%) production which hampers oil production and negatively affects the well's economics.

2 DISCUSSION & CONCLUSION

Over the past 30 years, the oil and gas industry has developed technologies to compensate for non-uniform geology and/or preferential water/gas mobility and improve oil production from challenging reservoirs. At the forefront of these efforts are inflow control devices (ICD) that are designed to place a series of carefully designed mechanical choke mechanisms between the wellbore and the reservoir to help compensate for unfavorable geology or fluid properties along the length of a horizontal well (Qudaihy, D. S., et al, 2005).

The theory behind the ported frac sleeve concept is to apply the ICD benefits to EGS injector wells. The principal challenge in doing so is to allow for high-rate proppant fracturing during well construction, while retaining the ability to selectively choke to injection profile to optimize water conformance. In oil production wells, the ICD choke diameters are typically small (2-6mm each) which would be too restrictive to pump an effective hydraulic stimulation treatment (Okpalla et al, 2019). Ported frac sleeves, however, have a larger total flow area to allow the high-rate stimulation, with the advantage of being selectively closeable (via intervention) to gain the "ICD effect" and improve water injection conformance along the length of the horizontal section.

To analyze and demonstrate this ICD effect, our previous EGS injector well model with a low UI of ~60% was equipped with ICD technology in the modal analysis model. The objective is to mechanically overcome the heterogeneity in the reservoir to target a more balanced injection profile with outflux rate between 10-20 stb/d/ft. It is also desirable to balance the outflux without creating a large pressure drop through the ICD devices, which could necessitate an increase in injection pumping horsepower at surface.

The following nodal analysis model (Figure 6) shows the results with an ICD completion consisting of 4 x 0.5-inch ports per frac stage. The improvement in water conformance is minimal because of the large flow area with all ported frac sleeves in the open position.

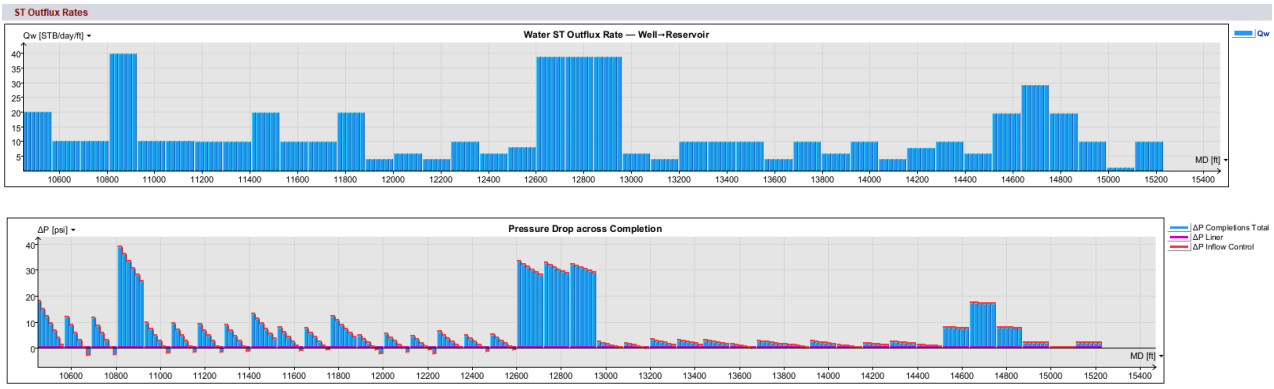


Figure 6. Water outflux profile with ICD completion; additional pressure drop is less than 40 psi

In accordance with the ported frac sleeve approach, the EGS injector well would be spinner-logged under flowing conditions to identify the stages/zones that are taking a disproportionate share of the total water volume, such as the sections at 10,800 - 10,900 ft MD, 12,600 - 12,950 ft MD, and 14,500 -15,000 ft MD. The ported frac sleeves in these problem zones would then be selectively shifted to the closed position, restricting the flow area into each of them. Having multiple frac sleeves per stage allows for some flexibility in the injection choking strategy.

By actively analyzing and controlling the downhole injection profile, the EGS injector's water conformance can be improved by about 40% with the same injection rates and pressures. This required the closure of one or two of the available ported frac sleeves in the problematic stages.

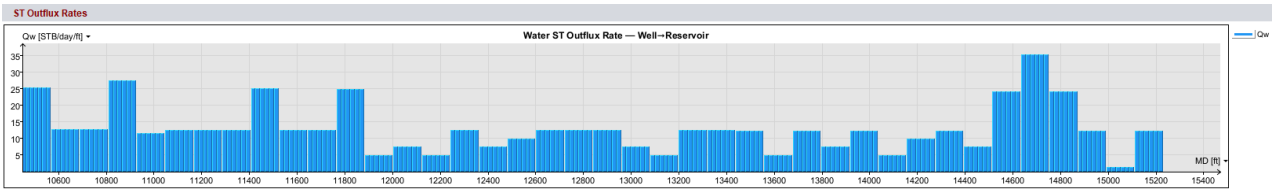


Figure 7. Water outflux profile with ICD completion with high flux zones restricted by closing frac sleeves

By activating the ported frac sleeves, water losses were reduced by up to 60% into the most active injection stages (Figure 7). This improves the balanced average water rate per zone, helping to recover more thermal energy from the geothermal reservoir. The UI of this well would now be closer to 85%, a significant improvement from the previous 60%.

In summary, managing water conformance in oilfield waterflood projects has been an area of study for decades. Inflow control devices (ICD) have emerged as an effective mechanical solution to improve the efficiency of waterflood and water injector wells. While EGS well pairs require further study to understand how water conformance effects thermal energy generation, observations from the Utah Forge project in 2024 point to significant challenges in balancing the water injection profile. Inflow control devices could help but they are not compatible with the required hydraulic fracturing and proppant pumping operations. Therefore, a potential solution would be the use of ported frac sleeves that allow normal stimulation operations, with the ability to selectively close the sleeves in the future. A well intervention would identify problematic frac stages, and a shifting tool would close a combination of sleeves to limit the flux of those stages. This concept has been shown to improve the UI (uniformity index) of the EGS injector from 60% to 85% in nodal analysis simulation models.

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