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Enhanced Sweep Efficiency in EGS Using a Bio-polymer Supplement from Over Fractured Oil/Gas Operations

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Sweep efficiency, fracture, bio-polymer, geothermal.

ABSTRACT

Geothermal electric power has the potential to contribute significantly to a sustainable energy future as the world transitions from fossil fuels to renewable energy sources. Conventional geothermal power operations access hot fluids in permeable rocks, but the concept for "energy everywhere enhanced geothermal system (EGS)" is to drill deep enough to reach high temperatures that exist in deep, impermeable, crystalline rocks. An EGS extracts heat from hot rocks at depth and moves it in a fluid to the surface where it can be converted to electrical power. There are no producible fluids in those rocks, and creating an effective fluid transport system requires the drilling of injection and production wells and connecting them using fracture stimulation. Heat extraction occurs by conduction from the fracture surfaces into the fluid as it moves through the fracture network, and the amount of heat that can be extracted is a function of the surface area in contact with the fluid and the fluid volume that can pass through the fracture network. The current challenge to EGS is to prevent the channeling of fluids into large aperture fractures and diminish the life of the system. In this study, we aim to improve the sweep efficacy by using a bio-polymer blocking agent to selectively reduce the unfavorable flow capacity of fractures that cause the most severe channeling. The concept is that the bio-polymer blocking agent can reduce or eliminate channeling through the most conductive fractures while diverting aqueous fluids through less conductive fracture pathways.

1. Introduction

Cement and mechanical devices often work well for problems that occur directly at the wellbore if the developed fracture orientations unexpectedly jeopardize the fluid's flow path; however, specialized methods are needed when the problem's source is beyond the well. A few sweep-improvement methods for geothermal energy recovery have been recently reported: steam injection using insulated tubing method for heavy oil wells and geothermal wells (Brown *et al.* 1980), mixed CO_2-water injection for simultaneous geothermal energy production and subsurface carbon dioxide storage (Wahanik *et al.* 2010), and well placement optimization using permeability anisotropy analysis (Talebian *et al.* 2020). Several methods have been studied and employed in field applications to improve the sweep efficiency of oil/gas fossil energy reservoirs. The primary methods include: (1) polymer floods (Seright *et al.* 2003; Sydansk and Romero-Zeron, 2011) and (2) gel treatments (Seright and Brattekas, 2021). However, for a geothermal reservoir with low (< 10 md) permeability oil/gas reservoirs where there is geothermal potential development, the aforementioned methods may not be feasible if the reservoir condition is different; for instance, if light oil is present.

This paper is suggesting a new method of improving geothermal sweep efficiency using four scenarios for low permeable geothermal formations (10-md rock), including:

(1) Geothermal reservoir fracture system characterization.

(2) Long-term stability of potential gels formulations identification that will be sufficiently stable for reservoir temperatures.

(3) Flow behavior study of promising gels in severe fractures and porous media under the described conditions.

(4) Geological and numerical model building to determine the optimal means for applying polymer treatments for heat flowing.

More detailed studies will be reported as each scenario progresses in the future by research participants from multiple disciplines.

2. Mythologies and Theoretical Expectations

2.1 Fracture System Characterization

Several techniques to detect fractures in subsurface formations have been summarized by Tiab and Donalson (2012) using core sample descriptions, well-logging, borehole electrical images, and mud invasion loss through rock porosity and permeability changes, especially based on pressure change vs. time. In this paper, a specific geothermal reservoir from Deadwood Formation will be our primary target for fracture distribution evaluation based on the outcrop rock observation and production well analysis.

The method to assess the significance of fractures using fluid production analysis is to compare the actual injectivity or productivity index for a well ($q/\Delta p$) to the value calculated using Darcy's equation for radial flow around a wellbore (Wang *et al*., 2008).

$$q/\Delta p = \sum kh/[\mu \ln(r_e/r_w)] \tag{1}$$

If the left side of Eq. 1 is substantially greater than the right side, a fracture or fracture-like feature probably intersects the well. On the other hand, if the left side of Eq. 1 is less than or equal to the right side, fractures may not contribute significantly to the well's flow capacity.

For those wells where fractures are present, injectivity or productivity indices can be used to estimate fracture widths (w_f).

$$k_f w_f = \{[q\mu/(\Delta p h_f)] - [k_m/\ln(r_e/r_w)]\} L_f/2 \tag{2}$$

$$w_f(mm) = 1.49(k_f w_f)^{1/3} \tag{3}$$

Where, k_f is the effective fracture permeability, md; w_f is fracture width, mm; q is the total fluid injection or production rate, bbl/day; μ is the fluid viscosity, cp, Δp is the well-formation pressure difference , ft; h_f is the fracture height, mm; L_f is the fracture half-length, mm; k_m is the effective permeability of the porous rock, md; r_e and r_w are the external drainage radius and the wellbore radius, m, respectively. We assume that fractures with widths greater than 1 mm may qualify as severe fractures

2.2 Bio-polymer Development and Stability

Polymer properties, especially their stability and ability to penetrate porous rock, are important for sweep improvement and conformance methods. Polymer flooding and conformance improvement using polymeric gels are some of the few effective methods to improve sweep efficiency in unfractured reservoirs with unfavorable displacing/displaced phases, assuming the polymer solution is the displacing phase and hot water is the displaced phase, mobility ratios, and some degree of heterogeneity (Willhite and Seright, 2011). However, polymer floods have challenges that must be overcome before they are applicable to hot, low-permeability reservoirs. The first challenge is that the polymer must be sufficiently stable.

Biomass-derived bio-polymers can be an excellent option for energy storage applications. Lignin, a naturally occurring aromatic heteropolymer, is one of the main building blocks of lignocellulosic biomass, providing structural integrity to plant cell walls (Ragauskas *et al.* 2014). In this paper, polymerization by grafting of the polymer is employed using ammonium persulfate as the initiator to produce polymeric radicals. The propagation reaction is carried out with acrylamide to produce a modified gel. This reaction can be terminated by reacting to the modified gel with a formulated crosslinker to enhance the chemical property of the modified gel for the application process. The following bio-polymers are under-developed and will be tested for the goal of this study, including cornstarch, hydroxyethyl cellulose, methyl cellulose, scleroglucan, and diuta, as shown in Figure 1.

Cornstarch Hydroxyethyl cellulose Methyl cellulose

Scleroglucan Diutan

Figure 1: Bio-polymer materials illustration for gel-forming

The fluid transit time through a geothermal reservoir is projected to be hours to years for water breakthrough (Kocabas and Horne, 1990). Therefore, there is hope that bio-polymer gels, which are being developed and tested at the University of North Dakota (UND), will be sufficiently stable for geothermal applications.

2.3 Fluid-Flow Behaviors in Low-Permeability Rocks

For the goal of bio-polymer treatment, the polymer gel must be able to readily penetrate low permeable formation rock to provide an effective polymer gel treatment. The large hydrodynamic volume of high-molecular-weight polymers makes them effective viscosifiers; however, it can also limit the pore-throat size through which a polymer can penetrate (Vela *et al.* 1976; Dann *et al.* 1982; Wang *et al.* 2008; Seright, 2010.). Information on the bio-polymer properties, including plugging characteristics, rheology in porous media, and retention for a low-permeability rock as well as elevated temperature, will be obtained using core floods at temperatures of up to 130°C or higher.

The bio-polymer treatment efficiency can be tested using the schematic of Figure 2. Bio-polymer solutions will be injected into a fractured rock sample, which represents the characters of a geothermal reservoir and observe the pressure change. We are expecting the gelation to occur during the bio-polymer formulation passes through the porous media a with severe fracture present. Bio-polymer efficiency can be calculated by Darcy's Law (Eq. 4). The increased pressure gradient indicates a positive potential of bio-polymer effectiveness.

$$k = {qu_p L}\Big/{\Delta P \bullet A} \tag{4}$$

Where, q is the flow rate, cm^3/s; k is the effective permeability, Darcy ($0.986923\ \mu m^2$); A is the cross-sectional area of the core sample, cm^2; ΔP is the pressure gradient, N/cm^2; μ_p is the bio-polymer viscosity, NS/cm^2; and L is the length of the core sample, cm.

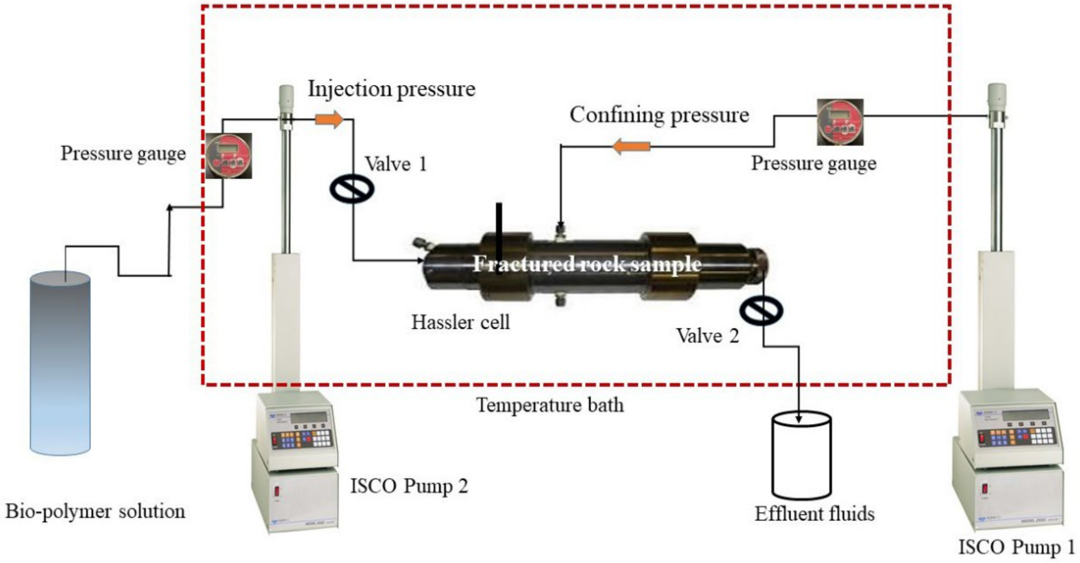


Figure 2: Schematic of fluid-flow behavior using bio-polymer

2.4 Geological and Numerical Modelling

Geological models based on the potential of severe fracture profiles of geothermal reservoirs and structural geology in the target formation, then upscale them to numerical reservoir simulation models for geothermal sweep efficiency predictions using the outcomes from the laboratory tests. The well geometries and fracture orientations and distributions will be characterized using models. Bottom-hole-pressure (BHP) information will be measured or provided from previous oil/gas well records. A high-performance tool, ***JewelSuite***, was developed by *Baker Hughes.* The models will focus on two goals based on the geothermal reservoir's geological features:

(1) How the displacement front is affected by the mixing zone during the migration of the polymer gels in various permeability reservoirs, especially for the low permeability zones.

(2) Well spacing and well configurations optimization on hot water flow path streamlines based on the fracture distributions, including length and width of the existing system of natural or hydraulic fractures associated with a lateral/vertical well sourced from micro-seismic or well-logs.

3. Preliminary and Anticipate Results

The Deadwood is one of the several formations currently being evaluated by the Geothermal Consortium of UND for geothermal potential reservoir development. It is the deepest sedimentary unit with the Williston Basin, which overlies the Precambrian sequence, and was deposited during the Late Cambrian to early Ordovician. The average depth is over 5000 m, and temperature is ranged 120°C to 150°C. The major rock classifications are sandstone, limestone, dolomite, and conglomerate with six members as described in Figure 3. The average permeability ranges from 10 md to 100 md.

3.1 Preliminary Naturally Fractured Profile Observation

Figure 3 illustrates the six members of Deadwood Formation, which has been produced in Deadwood Formation in North Dakota based on Well log analysis. Before core sample assessment from the Wilson M. Laird Core and Sample Library, rocks were collected from the outcrop of Deadwood Formation in South Dakota, as shown in Figures 4 to 9. Based on the observations during coring from these rocks, apparent natural fractures can be observed, especially from the Member *E* (Figures 5 and 6), were predominant by sandstone. As observed, the fracture width is about 1 *mm* and distributes across about the formation dip direction of 100^o degree to Northwest. The black material (Figure 5, left) indicates a pyrolucite mineral intrusion. As mentioned earlier in this paper, the existing fracture is our primary goal for sweep efficiency improvement.

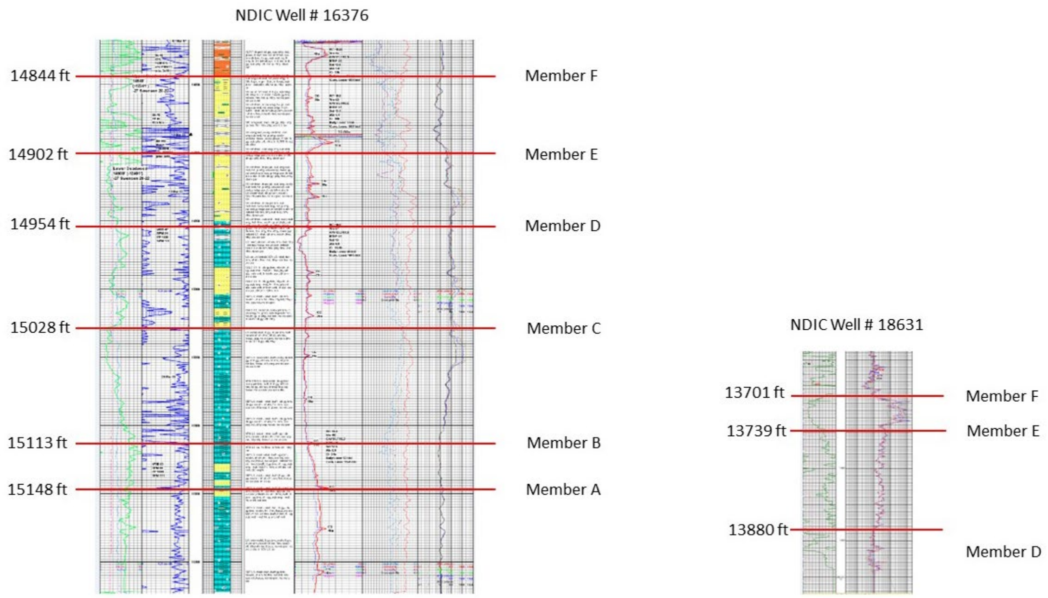
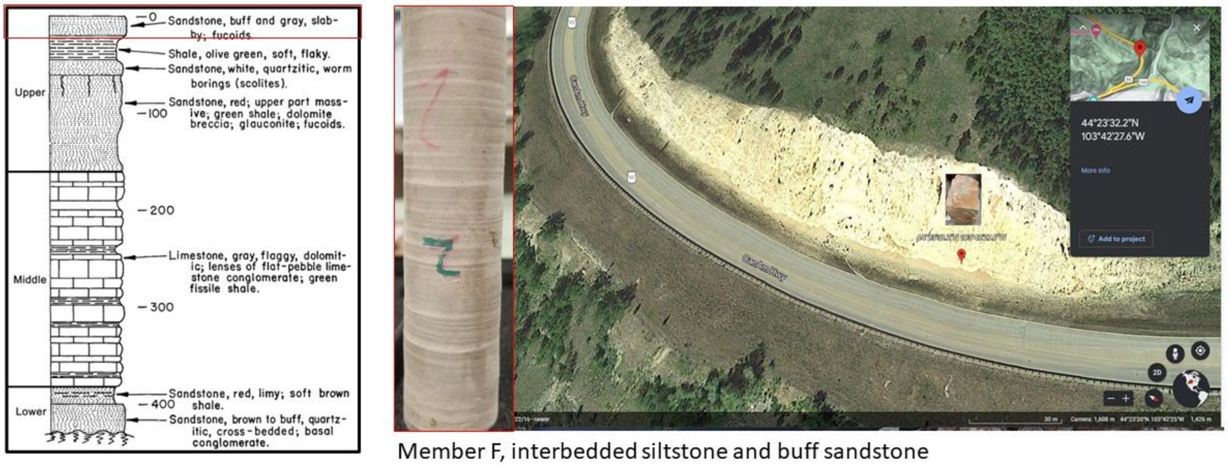
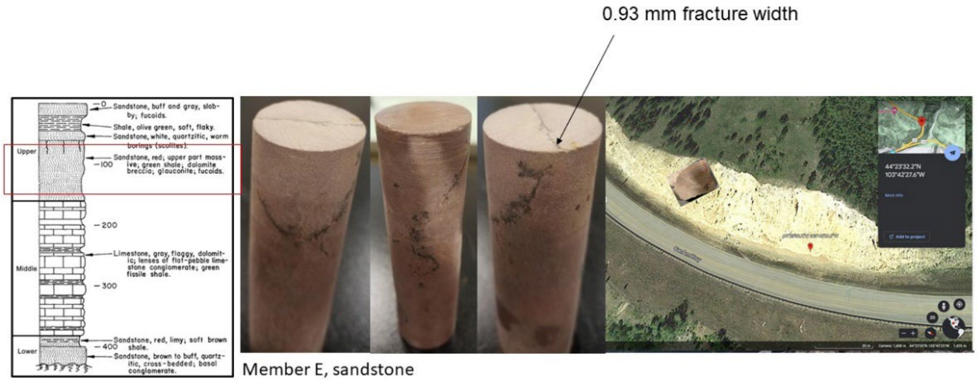


Figure 3: Well log (#16376) illustration of Deadwood Formation



Member F, interbedded siltstone and buff sandstone

Figure 4: Core sample illustration of Member F of Deadwood Formation



Member E, sandstone

Figure 5: Core Sample illustration of Member E of Deadwood Formation

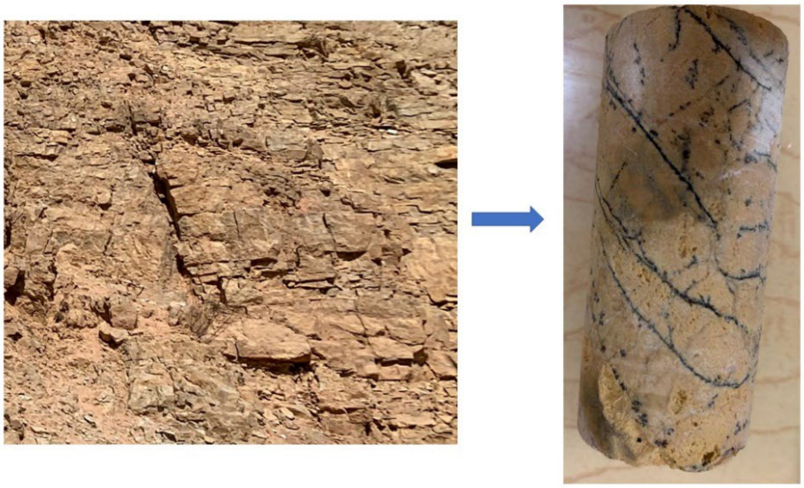


Figure 6: Fracture illustration of Member E of Deadwood Formation

Member C-D, limestone

Figure 7: Core sample illustration of Member C/D of Deadwood Formation

Member B, sandstone and limestone

Figure 8: Core sample illustration of Member B of Deadwood Formation

Member A, sandstone

Figure 9: Core sample illustration of Member A of Deadwood Formation

3.2 Bottom-Hole-Temperature (BHT) Correction

Thermostratigraphy method (TSTRAT) has been widely used to assess geothermal resources in sedimentary basins and create geothermal maps (Gosnold *et al,* 2010). This equation allows temperature calculation at a specific depth based on the known values of heat flow, formation thickness, thermal conductivity, and surface temperature. Thermostratigraphy relies on the assumption of conductivity and constant heat flow q, where the temperature gradient, $\frac{dT}{dz}$ varies inversely with the thermal conductivity λ of the rocks using Fourier's law, as described in Eq.5.

$$q = \frac{dT}{dz}\lambda \tag{5}$$

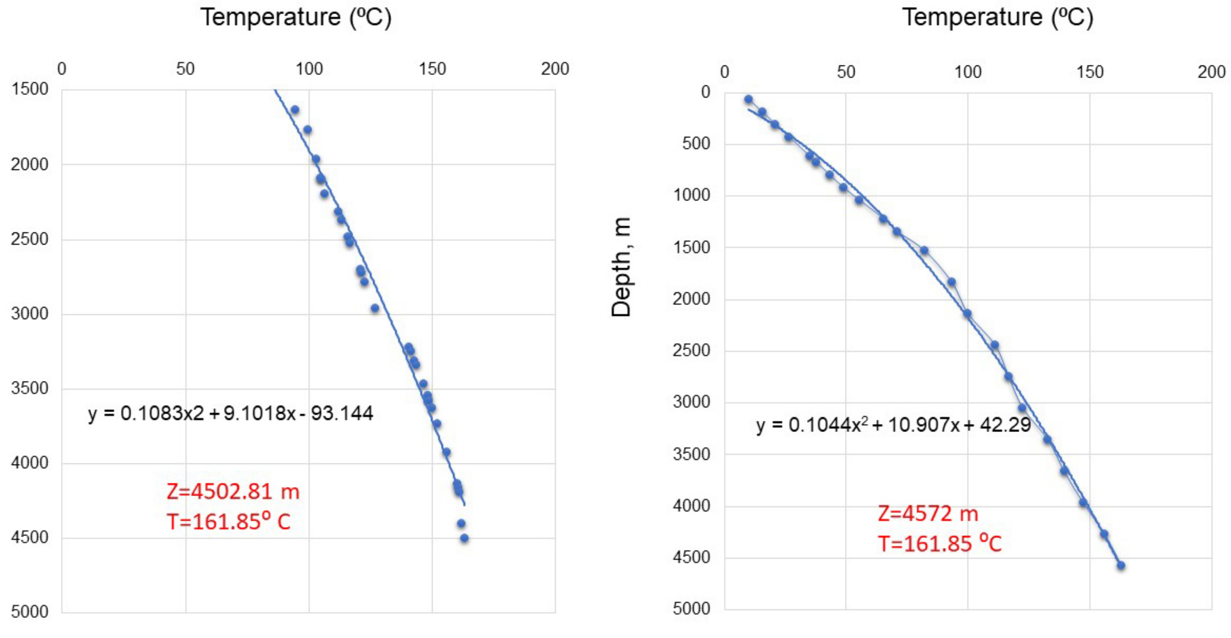
The temperature at a given depth can be calculated using the Eq.6:

$$T(z) = T_0 + \sum_{i=1}^{n} \frac{qz_i}{\lambda_i} \tag{6}$$

Where, T_0 represents the surface temperature in °C, q represents the heat flow in mW/m², z_i denotes the thickness of the formation in m, λ_i represents the thermal conductivity of the formation in W/(m·K). The summation (∑) encompasses the contributions of each formation layer. The temperature gradient (dT/dz) is implied in the equation.

To address this issue in the Deadwood Formation, thermostratigraphy (TSTRAT) is employed to calculate the temperature distribution. The results are then compared with bottom-hole temperature (BHT) correction introduced by McDonald (McDonald *et al,* 2015) for further analysis. A new temperature profile correction of Well # 8005, which has been produced in Deadwood Formation, is illustrated in Figure 10.

Based on Figure 10, we found that McDonald's downhole temperature measurements is more inclined to be fit for the shallow depths compared to Deadwood and the Precambrian BHT. The mud circulation in the shallow formation correlates with McDonald's equilibrium temperatures based on well log analysis. Furthermore, for an equation development for the geological conditions of Williston Basin, the upper and lower formations will require two different correction methods to accommodate the temperature profile difference. Therefore, TSTRAT will be employed for our continuing research on Deadwood and Precambrian BHT correction. This method will be validated against the work previously conducted by McDonald aiming to enhance the accuracy and reliability of temperature estimates in these geological formations.



Thermostratigaphy Method

McDonald Method

Figure 10: Bottom-Hold-Temperature (BHT) correction for Well #8005

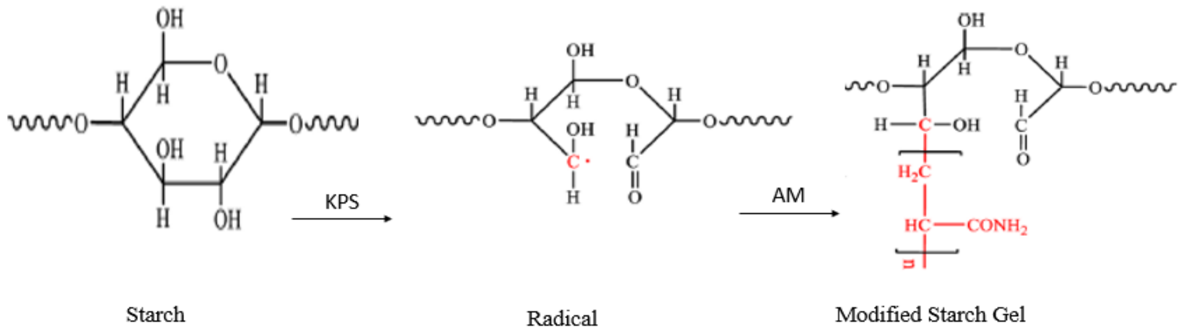
Further fracture width estimation will be conducted by the production index for the goal of treatment. The detailed temperature profile characterization and geochemistry analysis for the basis of bio-polymer stability application can be refer to the studies recently published by Alamooties and Namie (Alamooti *et al*, 2023; Namie *et al*, 2023).

3.3 Initiation and Polymerization by Grafting

The initiation process involves the production of radicals in preparation for graft polymerization with another monomer to achieve the stability of the polymer gels. The initiators of the reaction of potassium persulfate or ammonium persulfate. These initiators will produce the radical in which the Acrylamide /AM will be grafted. The polymers selected from Figure 1 are expected to be soluble in water. The procedures are considered for the synthesis and formulation of the polymer gel as illustrated in Figure 11.

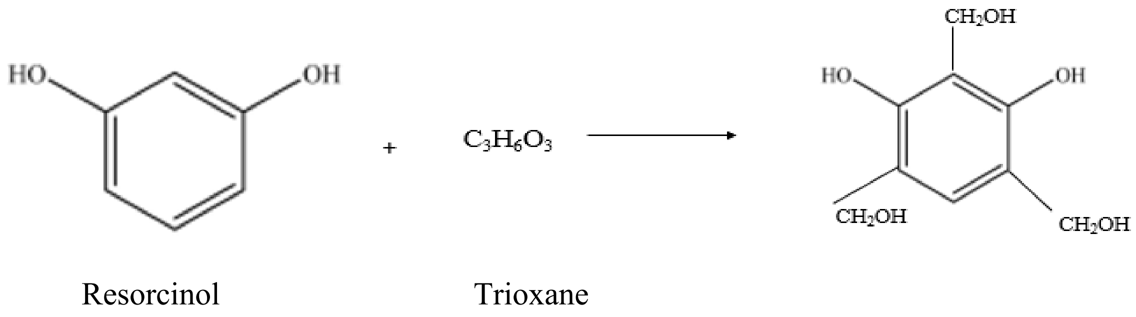
Bio-polymer gel gelation time and stability which contact with brine and at high temperatures (>120°C) will be presented in the future.

Step 1: Radical formation



Reaction One

Step 2: Preparation of crosslinker



Step 3: Polymer gel formulation

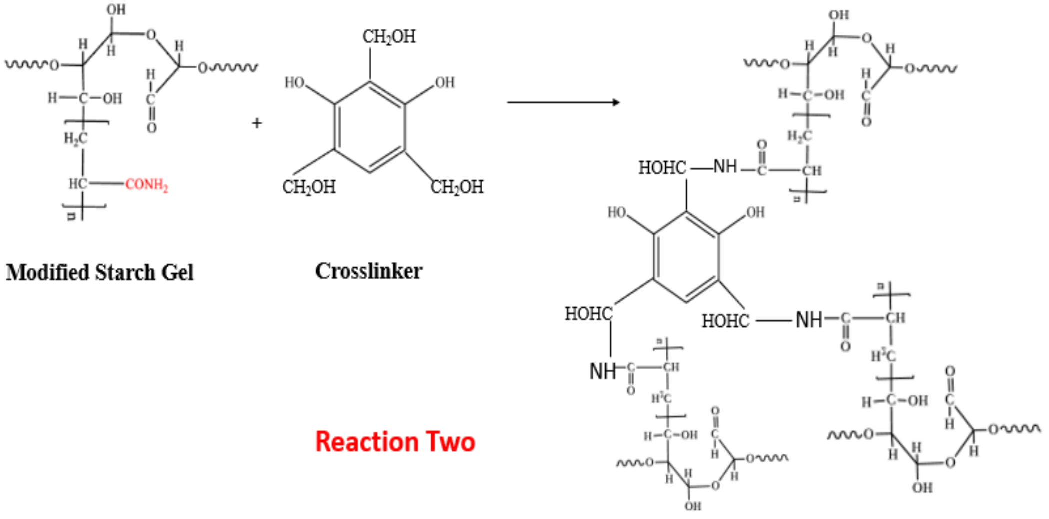


Figure 11: Initiation and Grafting (Reaction one) and cross-linking formulating (Reaction Two)

3.4 Anticipated result

As illustrated in Figure 12 by the numerical simulation conceptual model, aqueous polymer solutions can expand the heat flow streamlines to increase heat extraction without excessive pressure depletion in a sedimentary crystalline formation with heterogeneous strata and appropriate permeable zones. Blocking agents can reduce or eliminate channeling through the most conductive fractures while diverting aqueous fluids through less conductive fracture pathways. The subsurface pathway would be quickly cooled if cold water is injected into a formation, and it follows the most direct fracture pathway. Water can be diverted to contact hotter rock and sweep the hot-water reservoir better by selectively plugging part of the fracture pathway. We anticipate that the sweep efficiency of hot water production or heat recovery incremental factor will be enhanced by at least 5 to 10% for permeability zones greater than 100 md and 2 to 5% for the low permeable zones (<10 md) by using the proposed technology.

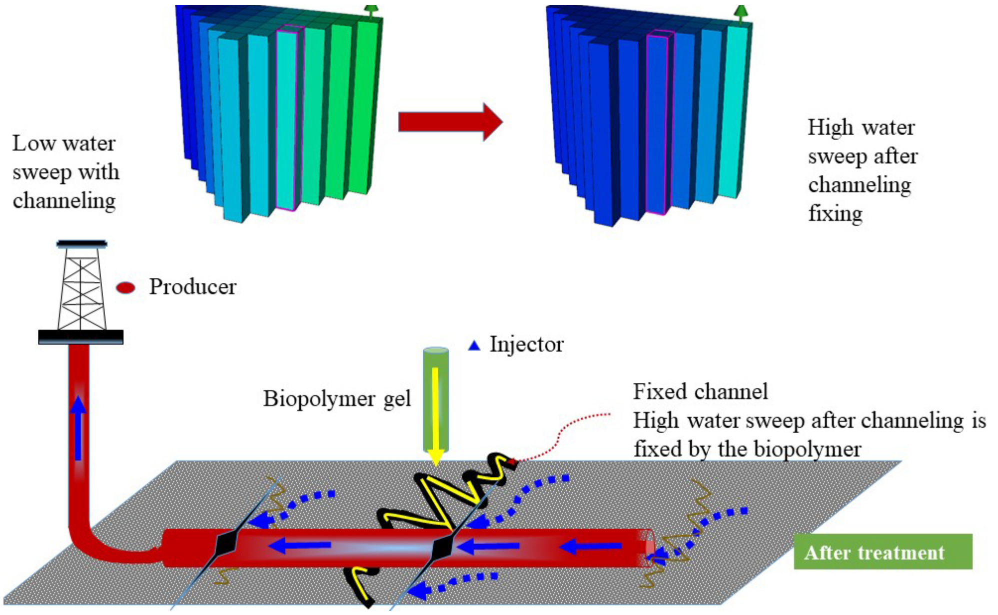


Figure 12: Bio-polymer treatment illustration and water saturation changes before and after treatment

4. Conclusion

- Our technology will apply to any low-temperature geothermal reservoir where polymers or gels may improve sweep efficiency.
- The results will lead to a substantially improved sweep in geothermal formations combined with the oil wells employed.
- Recovery factors are less than 10% using existing approaches for current geothermal reservoirs. Increases in recovery factor in the range of 5-10% of the original geothermal energy in place or more are expected with our proposed technology, and a potential 6% efficiency increase of approximately 3 to 4 *MW* in a low temperature (120 – 150°C) geothermal formation.
- Our technology should be beneficial to any hot reservoir where sweep efficiency is a problem.

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ABBREVIATIONS

BHP = Bottom-hole-pressure
BHT = Bottom-hole-temperature
EGS = Enhanced geothermal system
TSTRAT = Thermostratigraphy
UND = University of North Dakota