APPLICATION CHECKLIST tolerance

Use this checklist as a tool to ensure that you have all of the components of the application package. Please note, this checklist is for your use only and does not need to be included in the package.

[X]	Application
[X]	Transmittal Letter
[X]	$100 Application Fee
[X]	Tax Liability Statement
[X]	Letters of Support (If Applicable)
[ ]	Other Appendices (If Applicable)

When the package is completed, send an electronic version to Ms. Karlene Fine at kfine@nd.gov, and 2 hard copies by mail to:

Karlene Fine, Executive Director
North Dakota Industrial Commission
State Capitol – 14th Floor
600 East Boulevard Ave Dept 405
Bismarck, ND 58505-0840

For more information on the application process please visit:
http://www.nd.gov/ndic/renew/info/submit-grant-app.pdf

Questions can be addressed to Jonathan Russo at (701) 328-5347.

Renewable Energy Program

North Dakota Industrial Commission

Application

Project Title: Enhanced Sweep Efficiency for Geothermal Renewable Energy Using Bio-Polymer Supplement

Applicant: University of North Dakota

Principal Investigator: Dongmei Wang

Date of Application: 7/19/2022

Amount of Request: $468,877

Total Amount of Proposed Project:

$942,877

Duration of Project: 2 years

Point of Contact (POC): Dongmei Wang

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POC Email: Dongmei.Wang@und.edu

POC Address: 81 Cornell St. Stop 8358

Grand Forks, ND 58202-8358

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Enhanced Sweep Efficiency for Geothermal Renewable Energy Using Bio-Polymer Supplement

ABSTRACT

Objective:

Geothermal energy production can significantly contribute to sustaining the energy supply during the current fossil energy transition. The University of North Dakota (UND) developed a geothermal consortium in 2021, led by UND's Dr. Gosnold, to add a sustainable, renewable, and ecologically sound sector to North Dakota's economy to respond to the new green energy requirements. This consortium was formed by industries, faculty, graduate students, and researchers from various disciplines, combining scientists and engineers in geothermal, petroleum, and electric production. To further the goal of the development in geothermal engineering in North Dakota, this proposed project will investigate if heat flow sweep efficiency and geothermal energy recovery from heterogeneous or fractured reservoirs can be significantly improved by using green-viscous polymer gels to selectively reduce the unfavorable flow capacity of fractures that cause the most severe channeling, which will further the goal of geothermal engineering development in North Dakota.

Expected Results:

This project's anticipated results will positively impact the sustainability of North Dakota's energy supply. Aqueous polymer gels can expand the streamlines of heat flow to increase heat extraction without excessive pressure depletion in a sedimentary crystalline formation with heterogeneous strata and appropriate permeable zones. This biopolymer blocking agent can reduce and eliminate channeling through the most conductive fractures while diverting aqueous fluids through less conductive fracture pathways. The subsurface pathway can be cooled quickly if the injected cold aqueous solutions in a water phase follow the most direct fracture pathway. Selectively plugging part of that fracture pathway can allow the water to be diverted, contacting hotter rock and sweeping the hot-water reservoir better.

Duration:

Phase I (1/1/2023 – 12/31/2023): A green-polymer/biopolymer will be developed based on current materials owned by the UND. A stability study will be conducted at elevated reservoir temperatures, which are stable at low temperature (90~130ºC) geothermal applications. Flow behavior studies on geothermal hot water recovery using laboratory-based core flooding experimental tests will be performed using developed and commercially available biopolymers.

Phase II(1/1/2024-12/31/2024): This phase will consist of developing geological and numerical simulation models for geothermal sweep efficiency predictions for potential field applications based on geological and structural formation properties and laboratory study results using selected well geometries from the current UND geothermal consortium project (Contract No. R-046-057).

Total Project Cost: $942,877. UND is requesting $468,877 from the NDIC with a 50.3% in-kind cost share supported by Baker Hughes.

Participants:

University of North Dakota

PI: Dr. Dongmei Wang, Harold Hamm School of Geology and Geological Engineering, UND
Co-PI: Dr. Will Gosnold, Harold Hamm School of Geology and Geological Engineering, UND
Co-PI: Dr. Yun Ji, Department of Chemical Engineering, UND

Industry Collaborator: **Baker Hughes**

Enhanced Sweep Efficiency for Geothermal Renewable Energy Using Bio-Polymer Supplement

PROJECT DESCRIPTION

Objectives:

Geothermal energy production can significantly contribute to sustaining the energy supply during the current fossil energy transition. The University of North Dakota (UND) developed a geothermal consortium in 2021, led by UND's Dr. Gosnold, to add a sustainable, renewable, and ecologically sound sector to North Dakota's economy to respond to the new green energy requirements. This consortium was formed by industries, faculty, graduate students, and researchers from various disciplines, combining scientists and engineers in geothermal, petroleum, and electric production. To further the goal of the development in geothermal engineering in North Dakota, this proposed project will investigate if heat flow sweep efficiency and geothermal energy recovery from heterogeneous or fractured reservoirs can be significantly improved by using green-viscous polymer gels to selectively reduce the unfavorable flow capacity of fractures that cause the most severe channeling to further the goal of geothermal engineering development in North Dakota.

Geothermal water extraction from hot formations in a sedimentary basin uses technology similar to secondary oil and gas extraction with injection and production wells connected by a fracture network. A critical difference is that injected fluids can cool the hot formation and devalue and shorten the geothermal resource's lifetime if the wells are too close or if short circuits exist in the fracture network. This project seeks a solution to the short circuit problem by injecting biopolymer gels that will increase hot water flow and improve sweep efficiency.

Methodology:

Existing Sweep Improvement Methods

Cement and mechanical devices often work well for problems that occur directly at the wellbore if the developed fracture orientations can 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 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).

The DOE recently (2021-2022) funded a project by the Missouri Technology and Science University to attempt heat recovery enhancement using smart gel particles. ***We are unaware of any other peer-reviewed journal articles, research, or applications using biopolymers to treat severe fracture or channeling issues for geothermal reservoirs; therefore, this proposed research is a new endeavor.***

Methods Proposed

This project is directed at four scenarios, including:

(1) Long-term stability studies of potential gels to identify formulations that will be sufficiently stable for reservoir temperatures up to 130°C.

(2) Geothermal reservoir fracture system characterization.

(3) Testing the flow behavior of promising gels in severe fractures and porous media under conditions representative of the low temperature and low permeable geothermal formations (~130°C, 10-md rock).

(4) Geological and numerical model building to determine the optimal means for applying polymer treatments in low temperatures for heat flow (~130°C). The models will integrate with structural geology and simulations for field application predictions.

UND will develop biopolymer gels based on IP-H anionic polymers to block severe fractures, taking into account rock formation lithologies, including variations in permeability, especially for low permeable zones (Brzonva *et al.,* 2017). The biopolymer should have a cross-linking function and form a gel when passing through the severe fractures or channels to block the most conductive water pathways but not jeopardize the other pathways so the water can be produced.

An important mechanism for our method is that certain fixed pressure gradients are required to extrude the biopolymer gels through fractures. The effective viscosity of the gel extruding through the fractures is typically 10^3 to 10^6 times greater than gelants (Seright and Liang, 1995); however, useful biopolymer gels must not show progressive plugging during extrusion through the channels. A minimum pressure gradient is required to extrude a given treatment agent through a channel. The pressure gradient during polymer extrusion is insensitive to flow rate once this minimum pressure gradient is exceeded.

We do not suggest steam injection or CO_2 injection for geothermal reservoir sweep improvement due to the Williston Basin's reservoir conditions and cost-effectiveness since the oil viscosity is low in the Bakken, at 2 to 4 cp, and steam injection is better for a heavy oil reservoir. The cost-effectiveness of CO_2 injection will be discussed in a later section (**Ultimate Technological and Economic Impacts**). We also do not suggest using regular gels for fracture treatments if the geothermal reservoir has a low permeability zone (<10 md).

Scope of Work:

PHASE 1 /Budget Period 1
Task 0 *- Project Management and Planning (01/01/2023-03/31/2023)*

The Recipient shall work with the Award Project Officer upon approval to develop a Project Management Plan (PMP). The PMP shall be discussed and implemented within 30 days of the project's kick-off.

Task 1.0 – *Biopolymer Development and Stability Study (02/01/2023-12/31/2023)*

This task's objective is to develop and evaluate green/biopolymer gel formulations based on the current biomass- or cornstarch-based biopolymer developed at UND. Polymer gel stability at the temperature ranges for target geothermal energy reservoirs (~130ºC), various permeable zones (low to 10 md), and rheology behaviors will be studied through laboratory experiments. Other polymer stabilities related to mechanical degradation and oxidation will be investigated at a later date. Two commercially available green polymers or biopolymers (scleroglucan or diutan) will be compared for temperature/oxygen or microbe degradation stability behaviors. Task 1.0 will be completed in the Green and Renewable Energy Material Lab in the Department of Chemical Engineering at UND. Liquid and gas chromatography, Scanning Electron Microscope (SEM) analysis, Fourier-Transform Infrared Spectroscopy (FTIR), and UV-VIS will be used for stability testing.

We will also investigate how long the polymer gel needs to be stable, considering the heat flow in the evaluated geothermal reservoir.

Polymer properties, especially their stability and ability to penetrate porous rock, are important for other sweep improvement and conformance methods, such as in-depth conformance improvement. 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. The following two paragraphs discuss why the current, mature materials may or may not be suggested for this proposal.

a. Partially Hydrolyzed Polyacrylamide (HPAM). The most common polymer used for sweep efficiency enhancement in the energy industry is HPAM; however, HPAM is unstable at elevated temperatures if divalent cations are present (Davison and Mentzer, 1982; Moradi-Araghi and Doe, 1987; Ryles *et al*., 1988). Acrylamide groups within the HPAM polymer experience hydrolysis to form acrylate groups in temperatures greater than 60°C. HPAM polymers can precipitate if the fraction of acrylate groups, or the degree of hydrolysis, in the polymer becomes too high and when significant concentrations of divalent cations (especially Ca^{2+}) are present. These facts limit HPAM polymer utility for many potential applications in warmer reservoirs. Dissolved oxygen is a concern for the stability of all polymers at elevated temperatures. HPAM solutions are projected to lose their original viscosity after 100 days at 150°C, two years at 120°C, and eight years at 100°C (Seright, 2010). We will not use HPAM due to the temperature tolerance and green energy requirements from a global standpoint; however, we will test it for comparison during this project.

b. Biomass-derived biopolymers 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). We successfully used fungal treatments at UND to break down the highly cross-linked lignin fraction, with a delicate balance between the cross-linking polymerization and degradation to produce the desired biopolymers and hydrogels. This cross-linked polymer is stable, biodegradable, and highly soluble in water at a neutral pH due to partial oxygenation of the phenolic rings as long as it remains in permanent contact with water (Brzonova *et al.,* 2017). Lignin biopolymers can become pH-sensitive anionic hydrogel/polymers in either aqueous or organic solvents by changing the treatment conditions.

c. Commercial biopolymers.

Xanthan is one bio-type and the second most common polymer used in enhanced hydrocarbon energy recovery. This polymer has incredible resistance to mechanical degradation and is a much more effective viscosifier than HPAM in high-salinity, high-hardness brines (Seright *et al.,* 2011); however, Xanthan solutions will experience a viscosity half-life of approximately five years at ~80°C under the ideal conditions of no dissolved oxygen and a pH ranging between 7-8 (Seright, and Henrici, 1990). Stability at higher temperatures will be lower, in accordance with the Arrhenius relation.

Two other biopolymers could be considered for this work: Scleroglucan and Diutan. **Scleroglucan** has promising high-temperature stability (https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/scleroglucan). This polymer is produced by a filamentous fungus. Fungal debris would allow Scleroglucan to be used commercially for geothermal recovery purposes. **Diutan** is a more promising new biopolymer (Seright *et al.,* 2009) and is produced by carefully controlled aerobic fermentation. Diutan has the same viscosifying power as Scleroglucan at 2-3 times that of Xanthan; excellent tolerance of salinity and hardness, similar to that of Xanthan and Scleroglucan; has a resistance to mechanical degradation that rivals Xanthan; is very clean, providing filterability tests comparable to clean HPAM and Xanthan polymers; and has the potential to be priced competitively as a polymer used in the energy industry for enhanced recovery (Seright *et al.*, 2009). Diutan has a thermal stability of 5 to 150ºC based on the studies of Liang et al. (2019).

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 our biopolymer gel, which will be developed and tested at UND, will be sufficiently stable for geothermal applications. We will test Scleroglucan and Diutan at the same time for stability comparisons.

***Task 2.0** – Fluid-Flow Behaviors in Low-Permeability Rocks (07/01/2023-03/31/2023)*

This task's objective is to evaluate the flow/blocking ability of the green/biopolymer formulations in fractures using core flooding tests. ISCO syringe pumps and Hassler cell fluid-flow systems will be used in the Advanced Energy Recovery Lab at the Harold Hamm School of Geology and Geological Engineering.

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(a); Seright, 2010.). Information on the biopolymer 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.

PHASE 2 /Budget Period 2

***Task 3.0** – Fracture System Characterization (02/01/2023-12/31/2023)*

This task's objective is to characterize the fracture development and temperature profile description in potential geothermal reservoirs, such as the Lodgepole Formation and carbonate formations down to the Deadwood Sandstone in the Williston Basin (Gosnold *et al.*, 2012; 2020). This task's goal is directed at fractures or channels that are severe enough to jeopardize hot water production. Task 3.0 will be executed by the "Development Geothermal Consortium" and Dr. Wang's group.

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 (Figure 1).

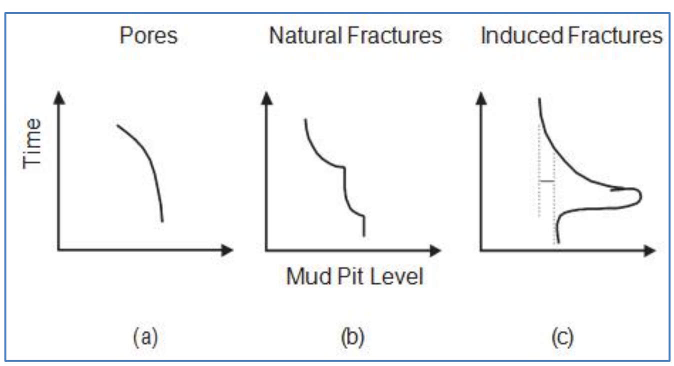


Figure 1. Mud loss indication and pit level behavior in pores, natural fractures, and induced fractures: (a) gradual buildup in loss ratio with pressure, (b) sudden start and exponential decline, and (c) loss that can occur with an increase in ECD as pumps are turned off and on (Dyke, et al. 1992)

Fracture detection using well logs and borehole images can provide a reliable indication of the presence of significant features; however, the full complexity of many of the smaller-scale fracture systems will not be visualized (Tiab and Donalson, 2012). A combination of core analysis, pressure transient test analysis, and various fracture-finding logs is suggested for detecting and locating fractures, including fracture orientation. This combined approach will be executed first for geothermal wells in this project.

We will also use the injectivity or productivity index from wells to examine these parameters during the water production stage.

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

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

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).

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

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

Where, $k_f w_f$ is in µm^2-m.

In these equations, k_f is the effective fracture permeability, q is the total fluid injection or production rate, μ is the fluid viscosity, Δp is the well-formation pressure difference, h_f is the fracture height, L_f is the fracture half-length, k_m is the effective permeability of the porous rock, r_e is the external drainage radius, and r_w is the wellbore radius. We assume that fracture widths greater than 1 *mm* may qualify as severe fractures.

This method has been applied to 25 Daqing wells and the Tambaredjo field in Surname (Wang *et al.*, 2008(b); Moe Soe *et al.*, 2012).

***Task 4.0** – Geological and Numerical Modelling (05/01/2023-11/30/2024)*

This task's objective is to establish geological models based on the potential of severe fracture profiles of geothermal reservoirs and structural geology in Williston Basin, 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 well records. A high-performance tool, *tNavigator*, which was developed by *Rock Flow Dynamic* with multiple functions of geology design, structural design, PVT design, and numerical simulations for geothermal reservoirs, will be employed in this project. *CMG* numerical software, which was developed by the *Computer Modelling Group*, will be used to simulate polymer flooding during heat flow. These tools are already installed on Harold Hamm School of Geology and Geological Engineering computers and are currently used by students and faculty.

The proposed project will focus on three goals based on the geothermal reservoir's geological features:

(1) Establish an actual model of 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) Create an optimal model of well spacing and well configurations to take advantage of 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. This design will be determined using reservoir simulation models to assess the potential of the polymer imbibition process in existing wells in the fracture zones and evaluate if alternative well completion/fracture configurations might provide higher sweep efficiencies and heat recoveries.

(3) Design a trial case for field implementation. A well pattern or development strategy involving layer perforation/blocks and the injection of polymer gel formulations will be developed based on optimal numerical simulation results, followed by an economic evaluation of the proposed method. This field test design step is necessary before implementing a full field-scale test.

Anticipated Results:

This proposed project's anticipated results will positively impact sustainable energy in North Dakota. 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.

The University of North Dakota has studied the potential for electric power generation from low-to-intermediate temperature (90-150°C) fluids in sedimentary formations (Gosnold *et al.*, 2013). Energy could be extracted from many geothermal reservoirs using co-produced fluids and Organic Rankine Cycle (ORC) power generation systems. *Stage II* of the Development Geothermal Consortium (Contract No. R-046-057) project states that the ORC "*system could yield 1 MW with the100 °C at 51 l* s^{-1} *resource available at the UND-CLR site. They have a new system coming online that will deliver power at $2,000 per KW"*. Approximately 10 *KW* more geothermal energy production is anticipated if 1% of the sweep efficiency is enhanced using the proposed technology. Gosnold and Crowell (2013) also mention that the potential resource estimates for the Williston Basin are 1,020 *Joules*, which implies a resource potential of several *GW* of electrical power. The power production for the top ten producing wells in the Madison and Red River formations based on an exit temperature of 160 °F (71.1 °C) and an ambient air temperature of 60 °F (15.6 °C) for an ORC with 6 percent efficiency is approximately 671 to 814 *kW*. We are confident that at least 5 to 10% sweep increments can be achieved, assuming our biopolymer gel is stable at 90 to 130ºC for one year with at least a 1% enhancement in heat flow.

Facilities, Techniques to Be Used, Their Availability, and Capability:

UND has excellent facilities and support staff for hosting the project, managing the budget, and coordinating all project elements. In-person and online remote meetings will be held between the research teams periodically.

The following laboratories will be used for the proposed project, including the Advanced Energy Recovery Laboratory (Leonard Hall, Rooms 13 and 314A), Geothermal Laboratory (Leonard Hall, Rooms 114 and 11), and Green Material and Bio-treatment Research Laboratory (Harrington Hall, Rooms 260, 360, and 304). These laboratories have high functional testing systems with ISCO syringe pumps for fluid flow observations, high precision thermal conductivity and temperature logging for heat flow testing, and high pressure, high temperature reactors and bioreactors for bio-polymer manufacturing.

A robust geologic modeling software, "*JewelSuite*," donated by *Baker Hughes* will be the dominant tool used to identify the geologic features for simulation improvement, allowing us to describe the geological settings and predict the potential of the sweep efficiency improvement by polymer injection. Two other software suites will be used for geology and structural design to develop numerical simulation models for geothermal production zones.

Resources:

The Williston is a vast geothermal resource, with laterally extensive, permeable formations that have temperatures ranging from 60 °C to greater than 150 °C at depths ranging from 1,000 m to 4,500 m (Gosnold, 2011,2012,2013,2020). We will focus on analyzing the research target's resource for the potential for natural fractures in deep geothermal formations, which is one of the outcomes from the project "Contract No. R-046-057". We are focused on the existed resource of low temperature (90 °C to 130 °C) geothermal resources. The potential channeling by fracture development is this project's primary goal. The lithologies, structural geology, well-logging data, petrophysical properties, Pressure-Volume-Temperature (PVT) data, and other reservoir characteristics in the targeted zones will be used for this research. We will access well production history if any oil/gas wells exist in the analyzed formation to determine the geothermal sweep effectiveness before and after polymer treatment.

Environmental Influences While Project is Underway:

Geothermal energy is more vital today than ever: it supplies clean, baseload renewable energy, emits little or no greenhouse gases, and has a very small environmental footprint. Our project could facilitate a substantial favorable environmental impact. No negative environmental impacts will result from this research project. The University of North Dakota and Baker Hughes fully comply with all EPA requirements.

Ultimate Technological and Economic Impacts:

The technology developed during this project will apply to any low-temperature geothermal reservoir where polymers or gels may improve sweep efficiency. The results from our proposed work will lead to a substantially improved sweep in geothermal formations. Recovery factors are less than 10% (Colin, 2010) 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 (Wang et al., 2008(a); 2008(b)), and a potential 6% efficiency increase of approximately 3 to 4 *MW* in a low temperature geothermal formation, such as the Madison and Red River formations. Our technology should be of value to any hot reservoir where sweep is a problem.

Our biopolymer is lignin-based. The cost of lignin in 2022 is approximately $650 per tonne for each tonne of polymer synthetic. The cost of using CO_2 is much higher, with an average weighted cost of US $58 per tonne (Policy and carbon pricing are critical to incentivizing investment:

https://www.woodmac.com/news/the-edge/the-coming-carbon-capture-and-storage-boom--we-have-lift-off/).

The cost of the polymer is $0.65 per *kg* once the weight mass is converted; however, the polymer mass should be diluted into solution for field application purposes: 1,000 parts per million (ppm) or 1,000 *mg/L*. The polymer cost is 100 times lower than CO_2 if we consider the same slug size for water production per barrel. Most of the polymer treatment usage is approximately 0.1 Pore Volume (PV) for water production (Wang *et al.*, 2008(b)), and CO_2 usage is 0.4 PV (Chen et al., 2020). Using CO_2 as an agent for increasing sweep results in a cost 400 times higher than using biopolymers. We did not consider the water cost for the polymer solution in our cost estimation.

STANDARDS OF SUCCESS

Our deliverables for the four proposed scenarios include:

- A quantitative report on the biopolymer formulation's stability study for geothermal use, developed in UND's Green Energy Lab, for selected permeable formations in the Williston Basin, including the graphs of polymer/gel thermal stability and polymer gel rheology behavior in fractures at various temperatures (90 ~ 130ºC) and rock types (sandstone and carbonate).
- A quantitative report on fluid-flow behavior analysis using the developed bio-polymer formulation (lignin-based) compared to at least one other commercial green polymer. We will test these formulations using selected permeable formations in the Williston Basin, including the polymer gel's plugging capability in low permeability strata.
- A database of the geological and structural geology models with target formation lithologies for selecting geothermal wells in the Williston Basin.
- A database of numerical simulation models with geothermal sweep efficiency predictions at various temperatures (90 ~ 130ºC), depths, and thermal conductivities.
- A recommendation plan for the well conditions for geothermal sweep efficiency improvement in the Williston Basin.

Value to North Dakota and Environment:

- Long-term energy stability and security.
- Initiation of a new high-employment industry and continual support for the current fossil energy industry.
- Education and outreach through research and community communication.
- Increased job transition opportunities from the oil and gas field to renewable energy.
- Increased green energy sustainability.
- Increased environment sustainability using wood by-products (cellulose-based polymer).

BACKGROUND/QUALIFICATIONS

Dr. Dongmei Wang (PI) is an Associate Professor at UND's Harold Hamm School of Geology and Geological Engineering. Dr. Wang (PI) has been involved in technological investigations to enhance oil recovery from the Bakken Formation using formulated surfactants coupled with gravity drainage, sponsored by the Department of Energy Research Partnership to Secure Energy for America /DOE-RPSEA (RPSEA 09-123-09). She has also led projects related to enhanced oil recovery from heavy oil using polymer flooding through an *Alaska North Slope* grant from the DOE (DE-FE0031606). Dr. Wang has been the PI for seven other research projects funded by EPSCoR and the oil and gas industry regarding surfactant imbibition methods to stimulate oil recovery.

Dr. William Gosnold (Co-PI) is a Chester Fritz Distinguished Professor in the Harold Hamm School of Geology and Geological Engineering at the University of North Dakota. Dr. Gosnold's career spans forty-two years of research in heat flow, geothermal energy, tectonics, and climate change. He was a member of the team that developed the United States National Geothermal Data System for the US Department of Energy. He served as chair of the Department of Geology and Geological Engineering (2006-2010), interim chair of the Department of Petroleum Engineering (2015-2016), and is currently the Graduate Director for the Harold Hamm School of Geology and Geological Engineering. He was the PI or Co-PI on nine different geothermal and energy resource projects during the past decade, totaling $7,869,503.

Dr. Yun Ji (Co-PI) is an Associate Professor in the Department of Chemical Engineering at the University of North Dakota. She is an expert in chemical and biochemical engineering process design. Dr. Ji is also an expert in biopolymer material manufacturing using lignocellulosic biomass and other renewable sources such as agriculture residue and industrial wastes. She will oversee Task 1.0 and identify and quantify polymer stability and characterization using different analytical instruments.

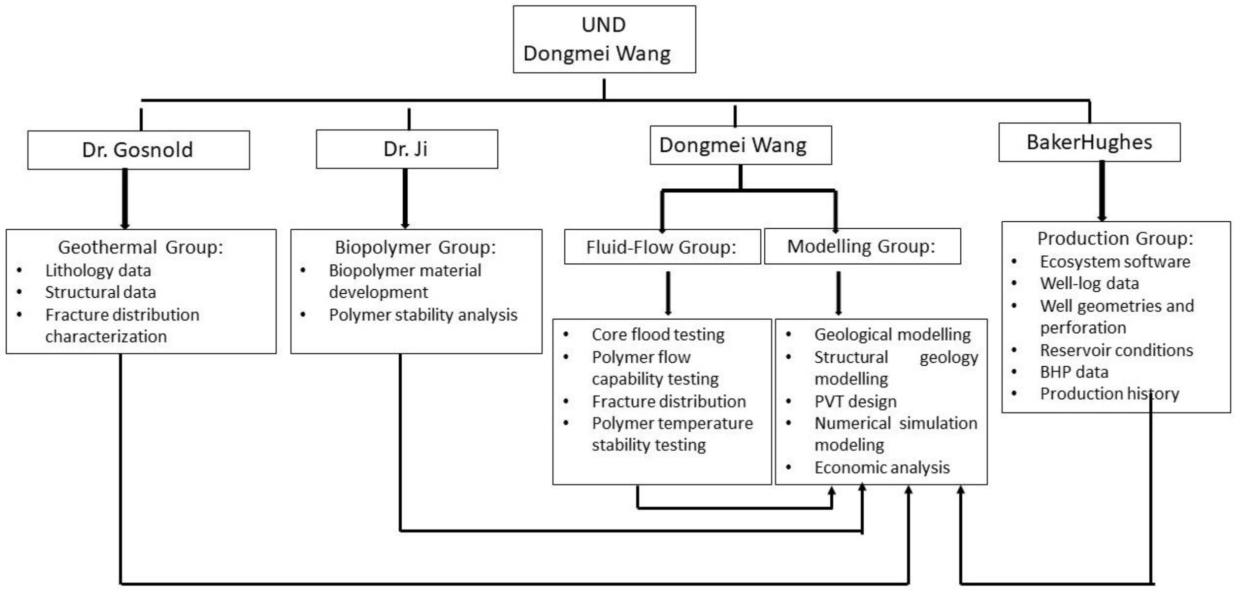
MANAGEMENT

The project will be based at the University of North Dakota, and the PI and Co-PIs will manage the collaboration with Baker Hughes. The following management actions will be executed:

- All team members will develop a Project Management Plan (PMP) consisting of a work breakdown structure and supporting narrative that concisely addresses the overall project as outlined in the agreement within 30 days.
- A kick-off meeting will be held at UND with all PIs and research group members.
- The PMP will provide a concise summary of the objectives and approaches for each Task and, where appropriate, for each subtask. The PMP will provide schedules and planned expenditures for each Task, including any necessary charts and tables, and all major milestones and decision points.
- The PMP will identify key milestones that must be met before proceeding to the project's next phase.
- The graduate students will write and submit bi-weekly laboratory research reports to the PIs every other Friday.
- The quarterly reports on project progress and the final report will be submitted to the NDIC for review and approval. The PI's meeting agendas will be set and circulated one week before the monthly group meeting, which will be held in person or through Zoom or Microsoft TEAMS.
- We will also regularly hold progress review meetings and workshops with other producers interested in applying our technology.

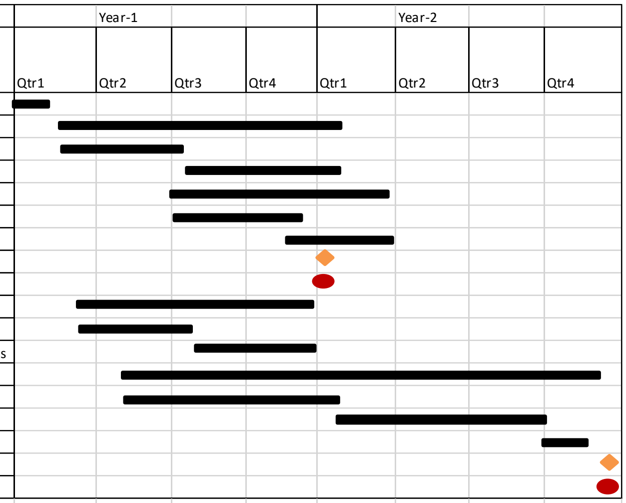
- We will attend project review meetings and conferences held by entities such as the Geothermal Rising Conference (GRC), the American Clean Power Energy (ACP), and other renewable energy conferences or workshops since these venues are the best environments for transferring and exchanging technical ideas.
- We plan to visit field sites to discuss the project with coal mining engineers and scientists for technology transfer. Periodic and final research reports will be widely distributed through the University of North Dakota's website database. We will also hold regular progress review meetings and workshops with local producers interested in applying our technology.
- The budget will be managed by staff in the College of Engineering and Mines at UND and the UND Grants and Contracts Office. Budget expenditures and actions relative to the project will be discussed at team meetings and approved by the PIs.

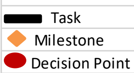
Organizational Chart:



TIMETABLE

Task Name	Assigned Resource
Task 0 Project Management and Planning	All team members
Task 1.0 Biopolymer Development and Stability Study	
Subtask 1.1 Biopolymer material development	Ji's group
Subtask 1.2 Polymer stability testing	Ji's group
Task 2.0 Fluid-Flow Behavior Laboratory Experiments	
Subtask 2.1 Core flooding test on polymer rheology in porous media	Wang's group
Subtask 2.2 Core flooding test on sweep effeciency	Wang's group
Milestone 1	All team members
Decision point 1	PI,CO-PIs
Task 3.0 Fracture System Characterization	
Subtask 3.1 Geothermal temperature profile discription	Gosnold's groups
Subtask 3.2 Fracture profile of geothermal formation discription	Gosnold's and Wang's groups
Task 4.0 Geological & Numerical Modelings	
Subtask 4.1 Geological modelling	Wang's group
Subtask 4.2 Numerical Simulation Modelling	Wang's group
Subtask 4.3 Economic Evaluation	Wang's group
Milestone 3	All team members
Decision point 3	PI,CO-PIs





BUDGET

Table 1 is a detailed budget for this proposed project followed by budget justification.

Table 1 – Detailed budget estimation

BUDGET OUTLINE F&A (INDIRECT COST) RATE 41.00%

Enhanced Sweep Efficiency for Geothermal Renewable Energy Using Bio-Polymer Supplement

DESCRIPTION	Year 1	Year 2	TOTAL
PI - WANG	23,627	24,336	47,963
CO-PI - Gosnold	20,148	20,753	40,901
CO-PI - JI	17,696	18,227	35,923
Post-Doc	4,500	4,635	9,135
GRAD -1	24,707	24,707	49,414
GRAD -2	24,707	24,707	49,414
GRAD-3	24,707	24,707	49,414
Fringe Benefits:			
PI - WANG	5,907	6,084	11,991
CO-PI - Gosnold	5,239	5,396	10,634
CO-PI - JI	4,424	4,557	8,981
Post-Doc	2,250	2,318	4,568
GRAD -1	0	0	0
GRAD -2	0	0	0
TOTAL PERSONNEL	157,911	160,425	318,337
TRAVEL for Field Work	6,000	6,000	12,000
COMMUNICATIONS-PHONE	0	0	0
COMMUNICATIONS-POSTAGE	50	50	100
INSURANCE	0	0	0
RENTS/LEASES-EQUIPMENT & OTHER	0	0	0
RENTS/LEASES-BUILDING/LAND	0	0	0
OFFICE SUPPLIES	0	0	0
PRINTING-COPIES, DUPLICATING	50	50	100
REPAIRS	0	0	0
UTILITIES	0	0	0
SUPPLIES-IT SOFTWARE	0	0	0
SUPPLY/MATERIALS-PROFESSIONAL	1,000	1,000	2,000
SUPPLIES-MISCELLANEOUS	0	0	0
IT EQUIPMENT <$5,000	0	0	0
OTHER EQUIPMENT <$5,000	0	0	0
FEES-OPERATING FEES & SERVICES	0	0	0
FEES-PROFESSIONAL FEES & SERVICES	0	0	0
FEES-SUBCONTRACTS (see Note 1 below)	0	0	0
PROFESSIONAL DEVELOPMENT	0	0	0
FOOD AND CLOTHING	0	0	0
WAIVERS/SCHOLARSHPS/FELLOWSHPS	0	0	0
TOTAL OPERATING	7,100	7,100	14,200
EQUIPMENT >$5,000	0	0	0
IT EQUIPMENT >$5,000	0	0	0
TOTAL EQUIPMENT	0	0	0
TOTAL DIRECT COST	165,011	167,525	332,537
			0
F&A (INDIRECT COST) *	67,655	68,685	136,340
TOTAL COST requested from NDIC	**232,666**	**236,210**	**468,877**
Cost Share- Baker Hughes in kind			474,000
TOTAL COST			942,877

* F&A is applied to modified total direct costs, consisting of all salaries and wages, fringe benefits, materials, supplies, services, travel and subgrants and subcontracts up to the first $25,000 of each subgrant or subcontract (regardless of the period covered by the subgrant or subcontract). Modified total direct costs (MTDC) shall exclude equipment, capital expenditures, charges for patient care, tuition remission, rental costs of off-site facilities, scholarships, and fellowships, as well as the portion of each subgrant and subcontract in excess of $25,000.

This two-year research project (requesting $468,877 from NDIC, which is 49.7% of project total of $942,877) is proposed by the Harold Hamm School of Geology & Geological Engineering, Department of Chemical Engineering of University of North Dakota (UND) in the College of Engineering and Mines of University of North Dakota. If awarded, the funding will be used to support three graduate student stipends, purchase laboratory equipment and supplies, attendance of technical conferences, presentations, and some faculty summer salaries for research involved. The details are described below.

Among the estimated budget, faculty support is for three faculty researchers covering the academic disciplines in the project: geothermal energy, geological and petroleum engineering, and chemical engineering. Student support is for three graduate students and one post-doc from Material Manufacturing Initiation (MMI) of UND who will work in the laboratory. Fieldwork is for travel for temperature logging. UND F&A is 41% of Total Direct Cost. The student field and laboratory work will include temperature profile and fracture analysis on core samples and core flooding tests, as well as biopolymer gel stability measurement, geological modeling and numerical simulation modelling. Baker Hughes will contribute a robust geological modeling software "JewelSuite" of $474K (50.3% of total) for the project along with their engineer working times.

UND is requesting $468,877 from NDIC for the following contribution times.

The PI (Wang) will work on this project about 22.5% time during the two budget periods (1/1/2023 to 12/31/2024) and oversee project planning and management, laboratory experimental schematic design, and gel forming efficiency studies. The PI will work on Tasks 0, 2, 3, and 4.

The Co-PI (Gosnold) will on this project about 15% of his time during the two budget periods (1/1/2023 to 12/31/2024) and be in charge of project planning and management, laboratory experimental result analysis, and reaction structure analysis. The CO-PI will work on Task 0 and Task 2.

The Co-PI (Ji) will work on this project about 15% of her time during the two budget periods (1/1/2023 to 12/31/2024) and be in charge of project planning and management, laboratory experimental result analysis, and reaction structure analysis. The CO-PI will work on Task 0 and Task 1.

A Post-Doctoral Researcher will work on this project about 10% of her time during the two budget periods (1/1/2023 to 12/31/2024). The post-doc will be responsible for laboratory facility maintenance, supply purchasing, student monitoring, and guiding. She will work on Tasks 0 through 5.

Three graduate students will work on this project about 50% of their time during the two budget periods. Their work will involve tasks related to laboratory work during Tasks 2 to 4.

Table 2 lists a budget summary for the project research.

Table 2 – Budget summary

Project Associated Expense	NDIC's Share	Applicant's Share (Cash)	Applicant's Share (In-Kind)	Other Project Sponsor's Share
UND Faculty support	$156,392			
UND Student support	$161,944			
UND F & A	$136,340			
Field Work	$12,000			
Laboratory Supplies	$2,200			
Baker Hughes				$474,000

STATE PROGRAMS AND INCENTIVES

Dongmei Wang (PI) participated: (1) as a Principal Investigator for "Enhanced Oil Recovery from the Bakken Shale using Surfactant Imbibition Coupled with Gravity Drainage," which was sponsored by the NDIC from 3/11/2011 to 3/10/2014. Contract: G-020-44. Total amount: $125,000. (2) As key personnel for the "Geothermal Development Consortium" project, is currently sponsored by the NDIC, 6/1/2021- 5/30/2023

William Gosnold (Co-PI) is participating as a Principal Investigator for the **"**Geothermal Development Consortium" project, currently being sponsored by the NDIC from 6/1/2021 to 5/30/2023. Total amount: $865,791.

Yun Ji (Co-PI) is participating: (1) as a Principal Investigator for the **"**Greener Routes to Corn Valorization: Corn and Corn Process Waste into Value Added 'Green' Surfactants and Lubricants" project, currently being sponsored by the ND Corn Council from 7/1/2022 to 6/30/2023. Total amount: $68,520. (2) As a co-Principle Investigator for the **"**Design and Commercialization of Next Generation Corn based Customizable and Transformational Functional Products" project, currently being sponsored by the ND Corn Council from 7/1/2022 to 6/30/2024. Total amount: $101,480. (3) As a Principle Investigator for the "Design and Commercialization of High Value Functional Products from Soybean Meal" project, which was sponsored by the ND Soybean Council from 7/1/2022 to 6/30/2024. Total amount: $61,251.

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Grand Forks, ND 58202-8358

Karlene Fine, Executive Director
North Dakota Industrial Commission
State Capitol – 14th Floor
600 East Boulevard Ave Dept 405
Bismarck, ND 58505-0840

This project is proposed by the Harold Hamm School of Geology & Geological Engineering at the University of North Dakota requests $468,877 from NDIC which we will match 50:50 with funding from our industry partner – Baker Hughes.

During fossil energy transition time, geothermal is one of great opportunities to sustain energy supplement. To further the goal of the development in geothermal engineering in North Dakota, we aim to investigate whether sweep efficiency of heat flow and geothermal energy recovery from heterogeneous or fractured reservoirs can be significantly improved by using green-viscous polymer solutions to selectively reduce the unfavorable flow capacity of fractures that cause the most severe channeling. The anticipated results of this proposed project will have positive impacts on the energy sustaining for North Dakota. For a sedimentary crystalline formation with heterogeneous strata and appropriate permeable zones, aqueous polymer solutions can expand the streamlines of heat flow to increase heat extraction without excessive pressure depletion. In addition, this blocking agent (Biopolymer) can reduce/eliminate channeling through the most conductive fractures, while diverting aqueous fluids through less conductive fracture pathways. If cold aqueous solutions (water phase) is injected into a formation to collect geothermal energy, the subsurface pathway would be quickly cooled if it followed the most direct fracture pathway. By selectively plugging part of that fracture pathway, water can be diverted to contact hotter rock and give better sweep of the hot-water reservoir.

Our team of industry partner enthusiastically supports the project and we hope to have a positive response to our proposal from NDIC. We are happy to answer any questions NDIC and its proposal reviewers may have.

Sincerely,

Dongmei Wang

Dongmei Wang, Ph.D., Associate Professor
Harold Hamm School of Geology and Geological Engineering, Stop- 8358
Leonard Hall 313
University of North Dakota
Grand Forks, ND 58202-8358
Phone: 701-777-6143
E-mail: Dongmei.Wang@und.edu

From:	Leddige, Anna
To:	Wang, Dongmei
Cc:	West, Elizabeth; Laudal, Daniel
Subject:	RE: $100 Application fee
Date:	Tuesday, July 19, 2022 8:58:32 AM

I have submitted this for payment and will follow up with Payment Services asking them to include the proposal. Thanks.

Anna Leddige, MBA
Chief Business Officer, College of Engineering and Mines
University of North Dakota

Upson II Room 165D
243 Centennial Drive, Stop 8155
Grand Forks, ND 58202-8155
701-777-3412

From: Wang, Dongmei
Sent: Monday, July 18, 2022 3:56 PM
To: Leddige, Anna <anna.leddige@und.edu>
Cc: West, Elizabeth <elizabeth.o.west@und.edu>; Laudal, Daniel <daniel.laudal@und.edu>
Subject: $100 Application fee

Anna,
Please see attached proposal to NDIC that was approved to submit by UND. If I could have a copy of $100 application can be insert to the document for submission, that would be appreciated.
Please let me know if you need more information.

Thank you,
Best regards,
Dongmei

Dongmei Wang, Ph.D
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July 18, 2022

Karlene Fine, Executive Director
North Dakota Industrial Commission
State Capitol – 14th Floor
600 East Boulevard Avenue
Bismarck, ND 58505-0840

Subject: Tax liability pertaining to UND's proposal, "Enhanced Sweep Efficiency for Geothermal Renewable Energy Using Biopolymer Supplement""

Dear Ms. Fine:

I am writing to you regarding the Tax Liability Statement which is a requirement for the University of North Dakota's proposal to the NDIC's Renewable Energy Program. Dr. Dongmei Wang is the Principal Investigator for this proposal entitled "Enhanced Sweep Efficiency for Geothermal Renewable Energy Using Biopolymer Supplement." As an Authorized Official of the University of North Dakota, I affirm that the University of North Dakota is a State entity and has no tax liability.

Please feel free to contact me at (701) 777-2505 or Karen.katrinak@und.edu with any questions.

Thank you for the opportunity to propose this project to the Renewable Energy Program.

Sincerely yours,

Karen Katrinak

Karen Katrinak, Ph.D.
Proposal Development Officer
Research and Sponsored Program Development

Baker Hughes

Date: June 13, 2022

Dr. Dongmei Wang, PhD
Associate Professor, Harold Hamm School of Geology & Geological Engineering
Leonard Hall, Room 313
81 Cornell Street, Stop-8358
University of North Dakota
Grand Forks, ND 58202

Re: Letter of Support for the Renewable Energy Program of North Dakota Industrial Commission

Dear Dr. Wang:

This letter expresses our support for the proposed project titled "*Enhanced Sweep Efficiency for Geothermal Renewable Energy Using Bio-Polymer Supplement*". This proposal is in direct alignment with Baker Hughes's company goal to facilitate the development of geothermal technology and application into sedimentary basins. We are anxious to see the subject technology implemented successfully for geothermal sweep efficiency enhancement. If successful, we anticipate that this technology can be applied to increasing geothermal recovery not only for North Dakota geothermal reservoirs, but also for other formations and sedimentary basins in the other states. As a result, we look forward to working with the UND team on this exciting opportunity and understanding the outcomes of the project.

Baker Hughes is pleased to provide three licenses of our JewelSuite Subsurface Modeling package & 3 years of maintenance and support as a subsurface modeling tool to optimize field development planning. The software will provide the research staff to improve subsurface geology & structural understanding to develop a numerical simulation model for geothermal production zones. The cost share of the software licenses is estimated $474K in US dollars.

If you have questions or require additional information, please do not hesitate to contact me.

DocuSigned by:
Martin Brudy
78D0FC7BD2544B0...

Dr. Martin Brudy
Commercial Lead