U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SAND2022-4321C

2022 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
GEOTHERMAL TECHNOLOGIES OFFICE

Closed Loop Geothermal Working Group

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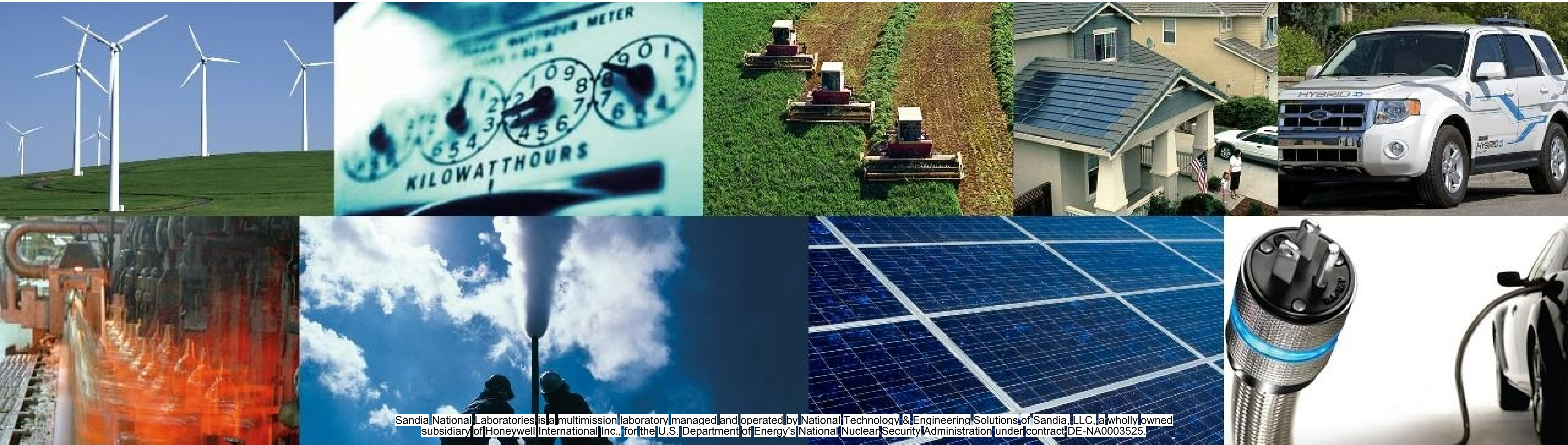
Giorgia Bettin, Total Project Funding $548K, May 26, 2022



“This presentation does not contain any proprietary, confidential, or otherwise restricted information”

Section 1: Program Policy Factors

Relevance to Geothermal Technologies Offices' (GTO) Objectives

- Recent advances in directional drilling technology has opened the possibilities for advanced borehole configurations, and has prompted a renewed interest in the use of closed loop geothermal systems (CLGS) at both GTO and industry.
- Numerical simulation tools developed and validated in this project will enhance GTO's body of knowledge on the expected performance of CLGS in terms of thermal power production and heat quality for a variety of borehole configurations, geothermal reservoirs, working fluids, and enhancement technologies.
- Potential auxiliary outcomes from the project will be quantifying efficiencies of conversions to electrical energy and of system economics as a result of power output estimations.
- The simulator is general and can be used by GTO to evaluate/assess new proposed designs and enhancement technologies.
- The simulator can also be extended to evaluate both environmental impacts and CLGS longevity impacts (e.g. geomechanics, loss of circulation and contaminant transport).

Relevance to Industry Needs

- Numerical simulation tools developed and validated in this project can assist the geothermal industry to predict the expected performance of proposed CLGS.
- The simulation tools can be adapted to perform “what if” scenarios to evaluate/assess new proposed designs and enhancement technologies.
- Proposed CLGS configurations can be optimized for performance by coupling the simulator to the Sandia National Laboratories (SNL) Dakota optimization package.
- The simulator can coupled with techno-economic software to perform economic studies.
- Potential auxiliary outcomes from the project will be quantifying efficiencies of conversions to electrical energy and of system economics as a result of power output estimations.
- The simulator can also be extended to evaluate both environmental impacts and CLGS longevity impacts (e.g. geomechanics, loss of circulation and contaminant transport).

Resilience to COVID-19

Being a numerical simulation project reduced the potential impact from the pandemic. Weekly SNL team meetings and bi-weekly working group meetings were conducted virtually. There are challenges from entirely virtual interactions, which cannot replace occasional in-person meetings. The COVID-19 restriction on live conferences has perhaps stifled collaborations with similar projects and interests in the geothermal community.

Diversity, Equity, and Inclusion

This project models SNL values to promote and nurture a thriving, inclusive and supportive culture. Inclusion and diversity are defining elements of Sandia. They foster multiple perspectives, promote acceptance of different learning and working styles, and encourage the innovation for which we are known. Through our commitment to inclusion and diversity we strive to attract, retain and develop a thriving workforce. One of our Sandia's core values is to work together for great results. We share this common vision by fostering an attitude of mutual respect. The competencies model being deployed at SNL through workforce and talent acquisition training include cultivating inclusion, understanding dimensions of diversity, listening, and being an ally.

Section 2: Technical Review

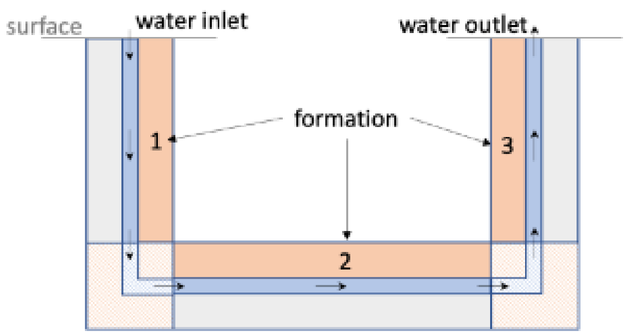
Methods/Approach

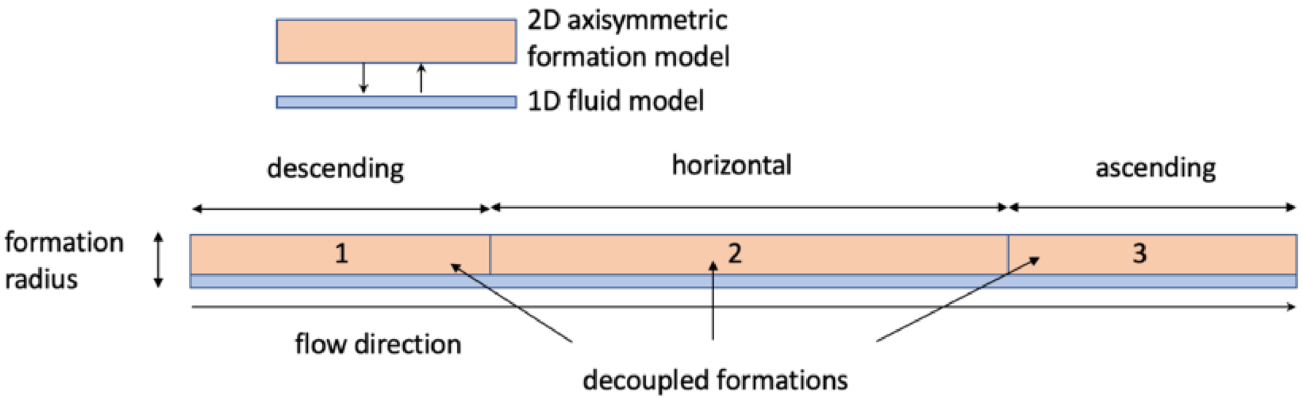
Objective: This project numerically investigates the potential of closed-loop geothermal systems (CLGS) considering variations in borehole configurations, geothermal reservoirs, working fluids, and enhancement technologies. The principal quantitative questions addressed are the mechanical (electrical) and thermal power generation, heat quality yields and comparative system economics. This project is structured as a working group, including PNNL, INL and SNL.

Technical Approach:

- Working group discussed and specified the CLGS configurations anticipated, reservoir types (e.g. geothermal gradient, dry and wet rock), The working group has engaged an advisory panel of experts from academia, national laboratories and industry to guide the direction, scenarios, and technologies that have been studied.
- Develop a CLGS simulator based on the Sandia National Laboratories (SNL) Sierra/Aria parallel-processing computational framework. The Dakota optimization software couples with Sierra/Aria to enable optimization and parameter sensitivity studies, a distinguishing feature of our approach. Validate the simulator against available data and literature.
- Working group specified the progression of CLGS studies involving U-tube and coaxial systems based on the FORGE site and the HGP-A well in Hawaii.
- FY21 results presented at GRC21

Methodology for SNL Closed-Loop Simulator





1. Heat transfer is through heat conduction (hot dry rock), also natural convection (hot wet rock).
2. Water has been the main working fluid, scCO2 studies in progress
   - 1D area-averaged thermal energy balance
   - Coupled to formations through a convective boundary condition with Gnielinski heat transfer correlation
3. 2D axisymmetric formations
   - Heat transfer between Region 1 – 2 and Region 2 – 3 is ignored
   - Heat transfer in “elbow” regions is negligible
   - Region 2 has constant initial temperature
4. Pressure computation can be segregated or implicit
   - Incompressible fluid w/ properties as functions of temperature and pressure
   - Steady momentum balance w/ Darcy-Weisbach friction factor used to model wall shear stress
5. Thin layer of insulation modeled as in series thermal resistance added to heat transfer coefficient

Simulator Validation

- Comparison to Song et al. (2018) and Stanford solution for u-tube placed in Xinji thermal reservoir w/ water as the working fluid

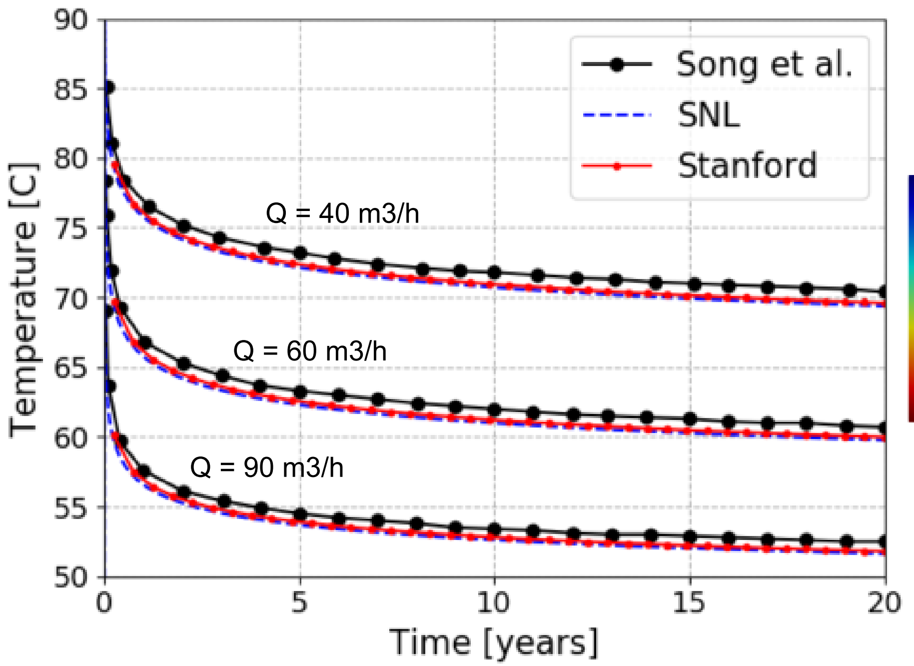
- Formation thermal characteristics

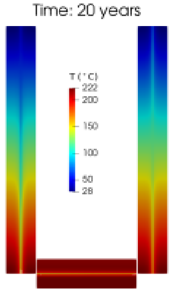
Rock density [kg/m3]	Rock specific heat [J/kg-K]	Rock thermal conductivity [W/K-m]	Surface temp [C]	Formation gradient [C/m]
2200	850	3.0	25	30

- Insulation is neglected in our model here (results in slight underprediction)

Flow rate [kg/s]	Formation gradient [C/m]	Depth [km]	Horizontal length [km]
varied	30	3.5	6

- Heat transfer coefficient is effectively infinite, any sufficiently large value will produce a similar solution

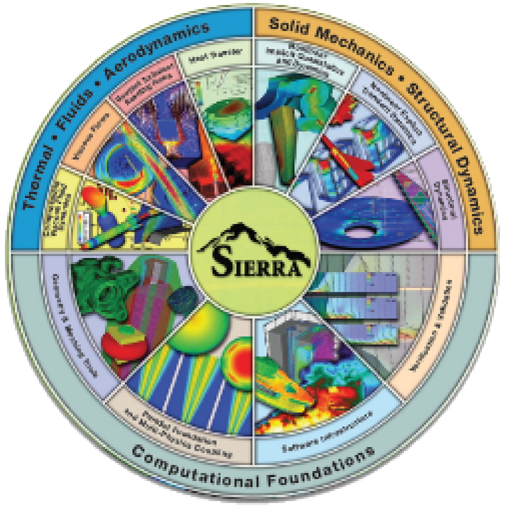




Gradient-Based Optimization Strategy

Multi-physics PDE solver

Optimization / Uncertainty Quantification / Sensitivity Analysis



DAKOTA
Explore and predict with confidence

- Weak form of coupled PDEs is discretized using linear (1D fluid) and bilinear elements (formation)
- Meshed biased to resolve radial gradients
- SUPG stabilization
- Adaptive time stepping w/ predictor-corrector
- Nonlinear system of equation solved using Newton iterations w/ preconditioned GMRES for linear systems

- Used to drive SIERRA
- Gradient-based optimization of the objective function w/ central differences

$$F_{\mathrm{mech}} = \int_0^T \left(\dot{m} \Delta h_f \eta - \frac{1}{\eta_p} \max(\dot{W}_p, 0) \right) dt - \frac{CL}{C_e}$$

- Parametric sweep of design space

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Technical Accomplishments and Progress

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Development of water working fluid scenarios, problem descriptions	A water-filled U-tube scenario and problem description was defined and simulated using SNL Sierra code. An optimization algorithm was initiated.	January 2021
Development of parameter space for U-shape borehole configurations with water as the working fluid.	U-tube model was coupled with Dakota for exploring configurations and operating conditions for optimal thermal and electrical energy output. An initial coaxial tube model was successfully implemented.	March 2021
Completion of U-shaped borehole configuration simulations with water as the working fluid.	U-shape problem descriptions were have solved for a hot-dry-rock scenario based on the Utah FORGE site. Two papers and presentations submitted to GRC 2021.	June 2021

Parameters for optimal mechanical (electric) energy

- FORGE site approx. thermal characteristics (225 °C bottom borehole temp)

Rock density [kg/m3]	Rock specific heat [J/kg-K]	Rock thermal conductivity [W/K-m]	Surface temp [C]	Formation gradient [K/km]
2750	790	3.05	25	78.8

- Emplace 8.5" diameter u-tube heat exchanger w/ water as the working fluid
- Thin-layer of insulation 0.01 m thick w/ conductivity .025 W/K-m added to the ascending well bore

Injection temp [C]	Pipe Diameter [m]	Well depth [km]	Flow rate [kg/s]	Horizontal length [km]	Insulation length [km]
27	0.2159	2.5	Varied [1-60]	Varied [1-10]	Varied [0-2.5]

- Optimization

$$F_{\text{mech}} = \int_0^T \left(\dot{m}\Delta h_f \eta - \frac{1}{\eta_p} \max(\dot{W}_p, 0) \right) dt - \frac{CL}{C_e}$$

drilling cost $C = 1640$ \$/m

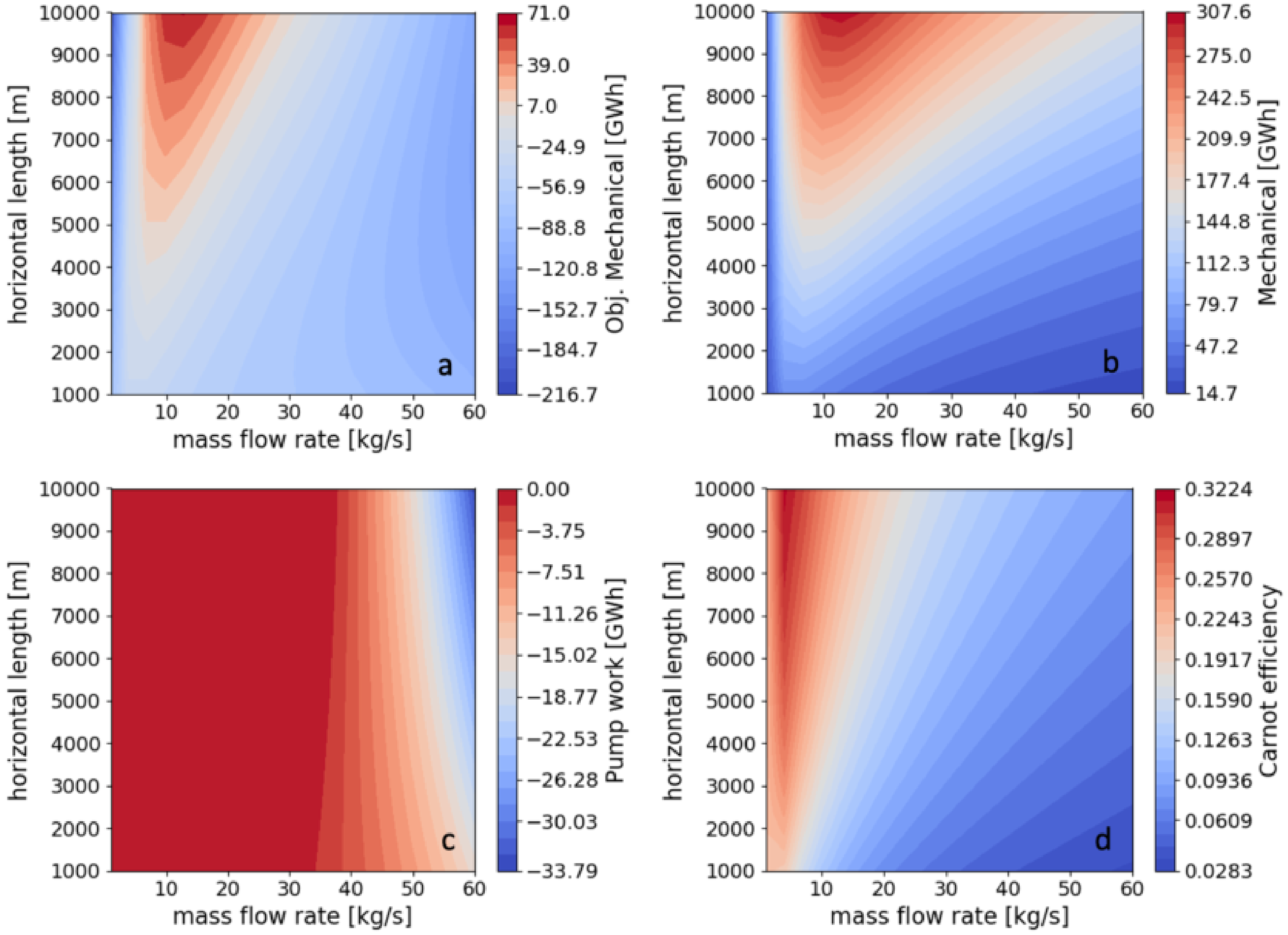
electricity price $C_e = 104500$ \$/GWhe

Flow rate [kg/s]	Horizontal length [km]	Insulation length [km]	Obj. function [GWhe]	Mechanical Output [GWhe]
10.8	10	1.4	88	324.6

U-tube performance over flow rate & loop length

- Feasibility envelope is narrow, depends strongly on drilling costs (Fig. a)
- Optimal mass flow rate exist for each horizontal length, no true optima in 1-10km (i.e., increasing length still increases obj.) (Fig. b)
- 8.5" diameter pipe has wide thermosiphon envelope (Fig. c)
- Carnot efficiency peaks around narrow band, does not correspond to max output, chosen design corresponds to plant efficiency of 0.18 (Fig. d)

Mass flow rate – horizonal length plane (no insulation)



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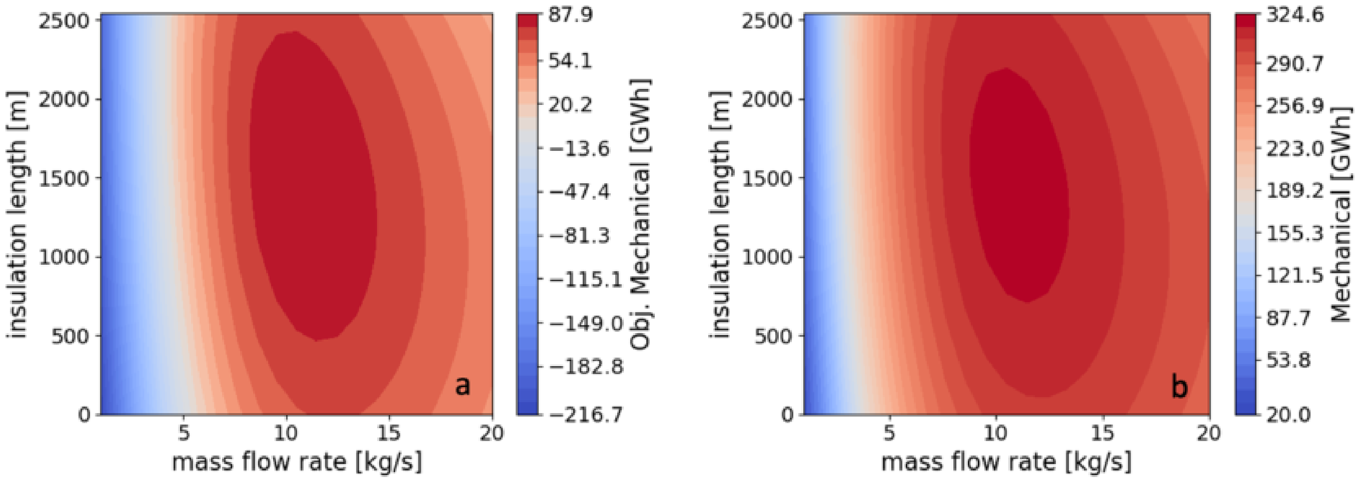
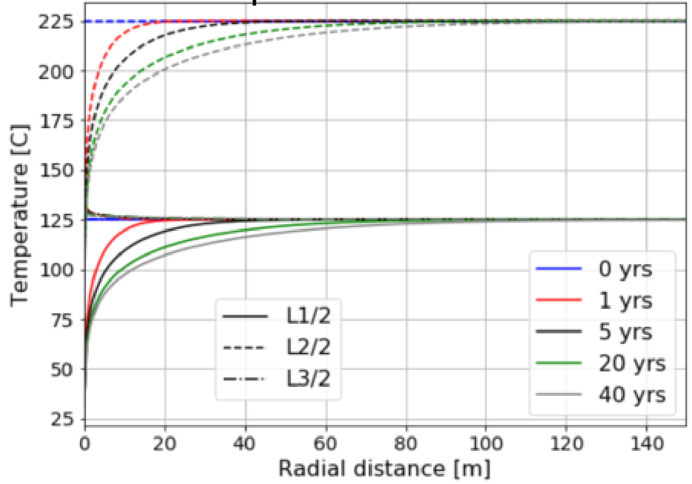
U-tube performance over flow rate & insulation length

Mass flow rate – insulation length plane
(max. horizontal length)



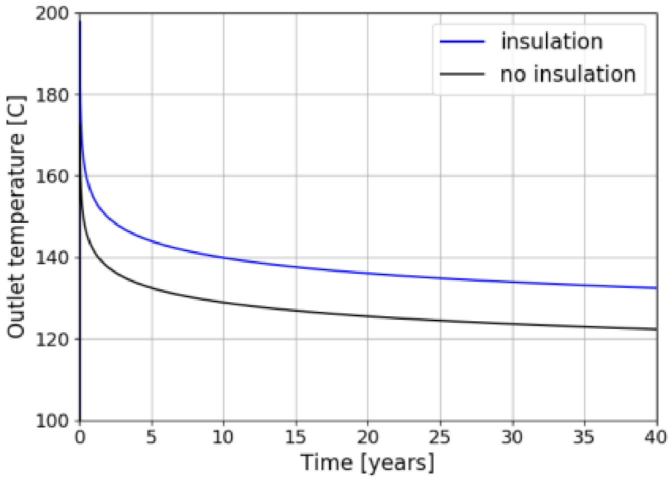
Thermal drawdown of HDR reservoir at optimal conditions



- Insulation increases mech. output by less than 6% at optimal conditions, increases outlet temp by about 10 C
- Thermal drawdown is contained to 100 m radius at 40 years
- Increasing diameter to 15” results in less than 10% increase (penalties on diameter not considered)

Flow rate [kg/s]	Horizontal length [km]	Insulation length [km]	Mechanical Output [GWhe]
12.26	10	1.38	355.1 GWhe

Insulation impact on outlet temperature at optimal conditions



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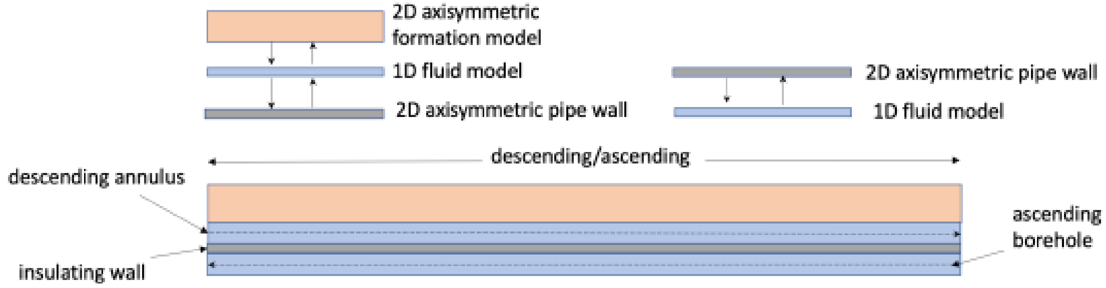
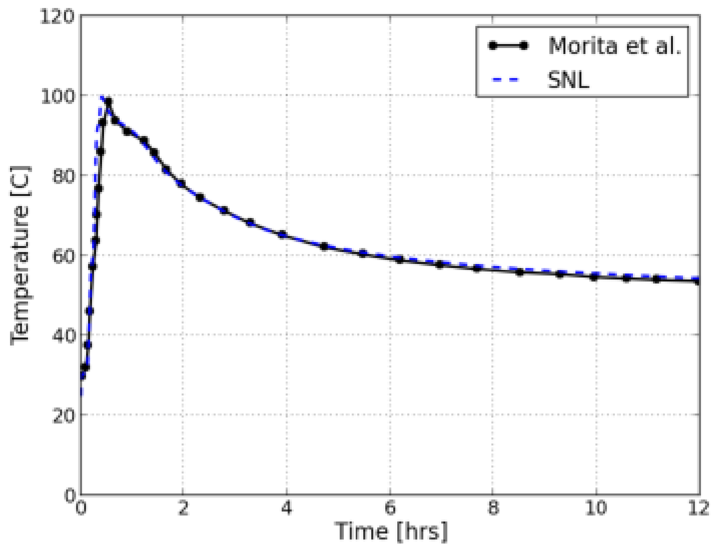
Technical Accomplishments and Progress (cont'd)

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Development of a parameter space for coaxial borehole configurations with water as the working fluid.	Coaxial problem descriptions have been developed and solved for a hot-dry-rock scenario based on the Utah FORGE site. Milestone extended for Dakota optimization and comparison of coaxial with u-tube.	March 2022 (FY22 Funding delayed to January 2022)
Development of collective alternative scenarios, with at least one scenario led by each lab, and review by the technical panel of experts.	Group presented alternate scenarios . SNL proposed to consider alternate site characteristics (natural and manufactured), and working fluids to enhance performance of current and proposed CLG systems.	In progress

Coaxial Model Validation

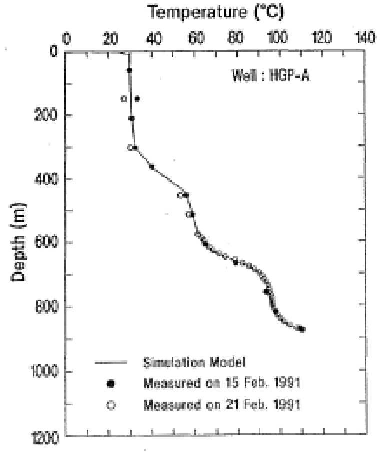
- Comparison to HGP-A Downhole Coaxial Heat Exchanger (DCHE) experiments in Hawaii (Morita et al. 1992)





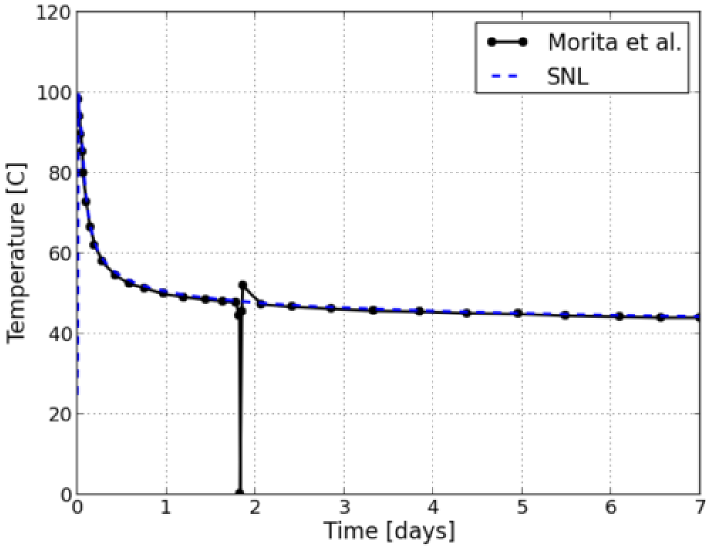
- Formation thermal characteristics

Rock density [kg/m3]	Rock specific heat [J/kg-K]	Rock thermal conductivity [W/K-m]
3050	870	1.6

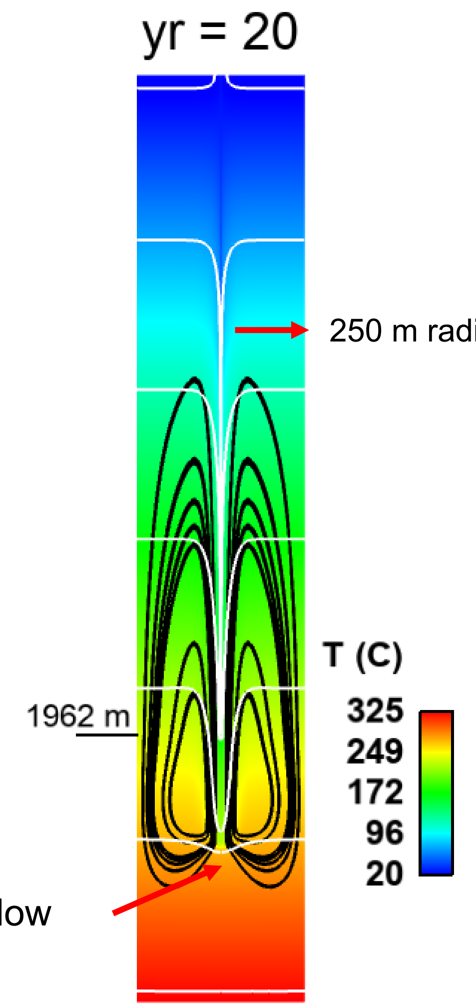


- HGP-A DCHE params

Injection temp [C]	Flow rate [kg/s]	Well depth [m]	Insulation [W/K-m]
30	1.33	876.5	0.06

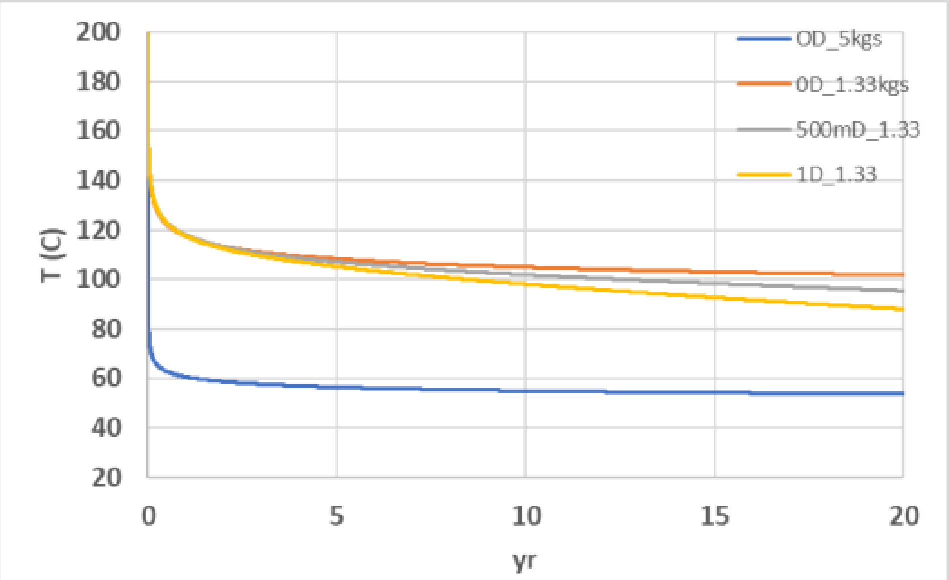


HPG-A Closed-Loop Coaxial System in Wet Rock



Temperature and path lines for 1.33 kg/s co-axial mass flow rate in 500 mD reservoir

HPGA: Perfect Insulation



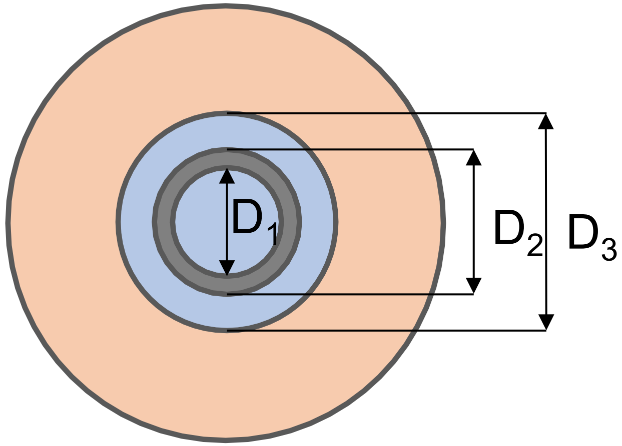
Buoyant convection is detrimental

Power at 20 yrs (Carnot)

Mdot (kg/s)	kWth	kWe	kWh/yr
1.33	414	79	696
5.0	547	40	348

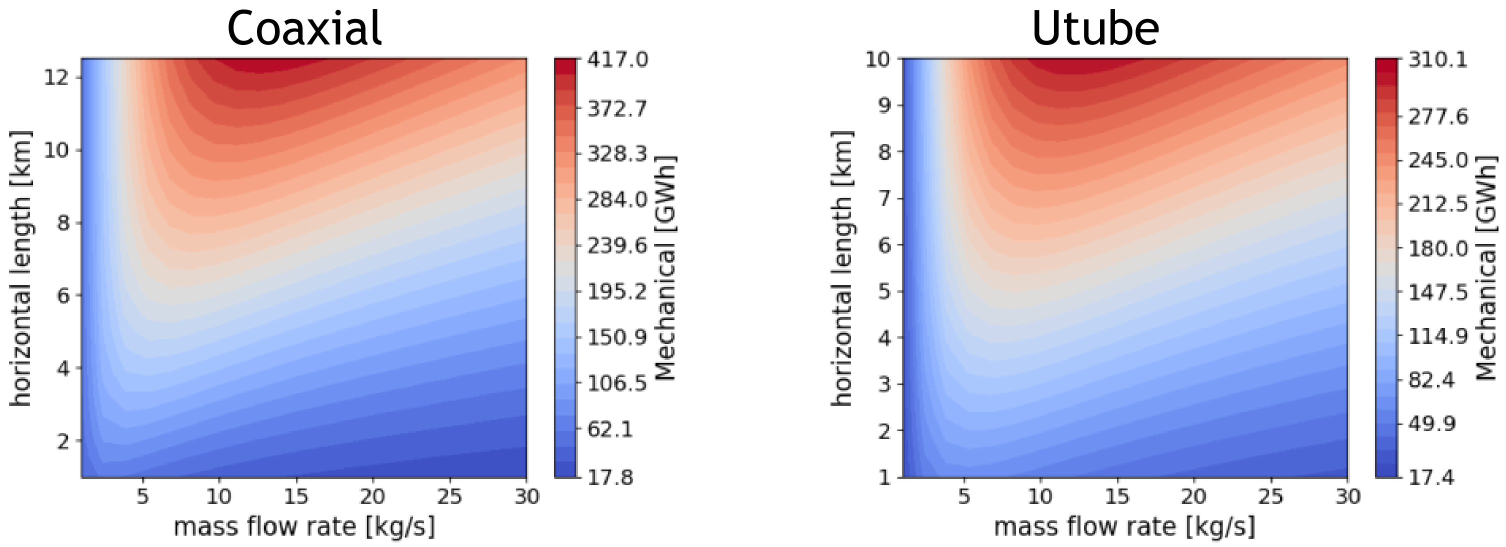
Performance Comparison between Coaxial and U-tube

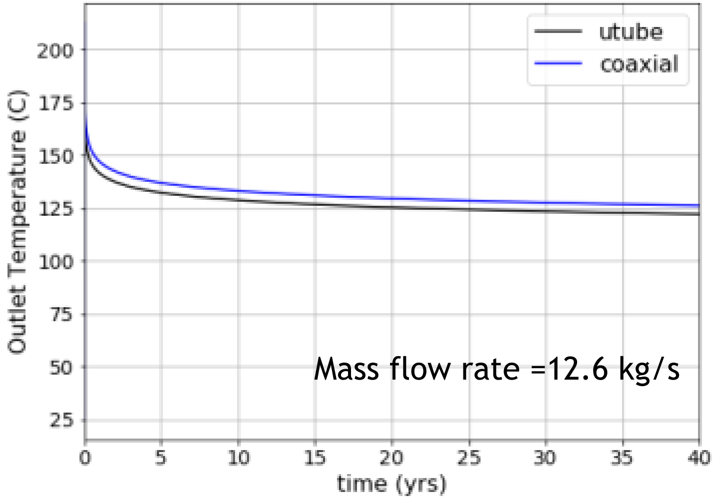
- Equal borehole volume achieved by increasing coaxial horizontal length from 10 km to 12.5 km
- Area ratio was set to 1
  - Equal inner tube and annual tube cross-sectional



$$\text{Area ratio} = \frac{\text{Annular Area}}{\text{Pipe Area}} = \frac{\pi D_3/4 - \pi D_2/4}{\pi D_1/4}$$

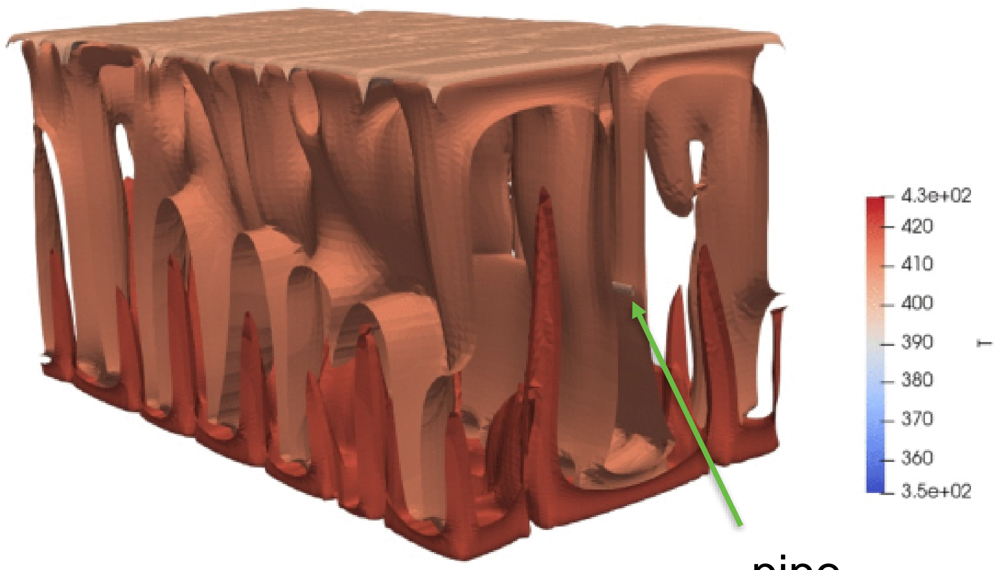
Mass flow rate – horizontal length plane



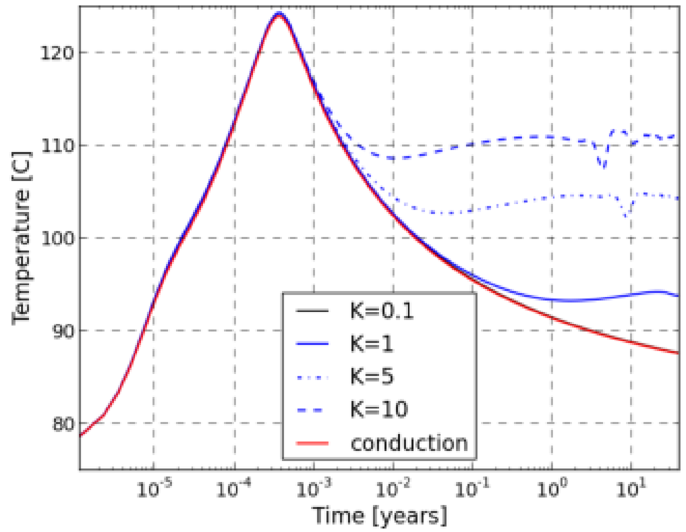


Hot wet rock – preliminary result

Porous natural convection



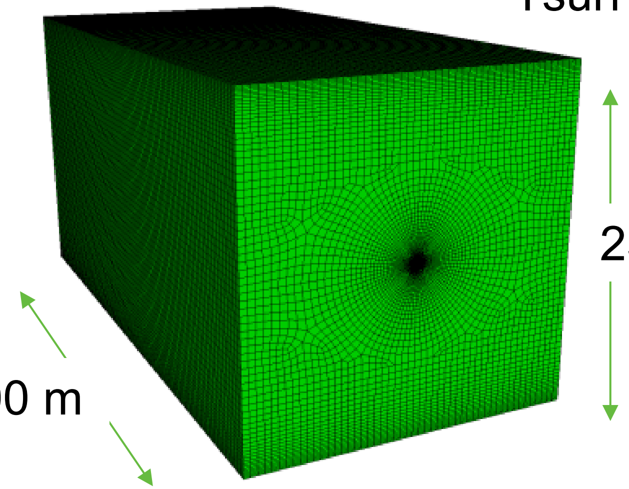
pipe



- Water working fluid w/ temperature dependent properties
- Only modeled horizontal region and assumed pipe embedded in 500 [m] x 250 [m] x250 [m] uniformly permeable domain

Tsurf = 400 K

injection temp of 350 K



250 m

500 m

Mass flow rate (kg/s)	Inj temp at depth (K)	Thermal gradient (C/km)	Pipe Diameter [m]	Time period (years)	Solid Density (kg/m3)	Solid specific heat capacity (J/kg-K)	Solid thermal conductivity (W/m-K)	Porosity	Permeability (1e-12 m2)
2	350	110	0.2159	40	3000	850	3.1	0.133	Varied

Technological Advancement and Data Dissemination

- The CLGS simulator developed for this project brings a general parallel-processing framework for enabling CLGS optimization and other coupled multiphysics (geomechanics, multiphase flow) for advanced analysis of related geothermal technologies.
- A distinguishing feature is the optimization capability allowing to find the optimal performance of each studied system.
- Throughout the project, the CLGS working group has engaged an advisory panel of experts from academia, national laboratories and industry to guide the direction, scenarios, and technologies that have been studied.
- Predictions of u-tube and coaxial performance under variations in mass flow rate, borehole configurations, tube length and ascending well insulation have been presented at GRC21.
- A funded proposal (*L. Pyrak-Nolte (PI,Purdue) et al., Role of Fluid and Temperature in Fracture Mechanics and Coupled THMC Processes for Enhanced Geothermal Systems, DOE/EERE Frontier Observatory for Research in Geothermal Energy – Milford Site, Utah*) will utilize the Sierra framework for parts of this work.

Future Directions

Milestones	Status and Expected Completion Date
Investigate impact of scCO2 as a working fluid	In progress, expected completion June 2022
Investigate the impact of natural convection in hot wet rock	In progress, expected completion June 2022
Investigate the impact of alternate site characteristics (enhanced conductivity, fractured rock)	In progress, expected completion September 2022

Summary

- We have developed a general purpose simulator for CLG systems that can analyze current system configurations, reservoir sites, alternate fluids and enhanced technologies, and which utilizes optimization to find a parameter set that maximizes energy production.
- For the same horizontal length, the U-tube and coaxial systems perform similarly; for the same total borehole length (and cost) the coaxial system can outperform the U-tube owing to a longer horizontal length in the former.
- Each horizontal leg length has an optimal mass flow rate (i.e., there is a balance between increasing residency time versus increasing enthalpy flux)
- Insulation length and diameter (8.5 vs 15”) have modest impact on output at optimal mass flow rate and horizontal leg length
- Current CLGS configurations for 8.5” diameter pipe, can provide electrical energy (~325 GWhe over 40 years) for roughly 700-800 homes (~1MWhr per year). However capital costs can only be recovered for drilling costs below present averages.
- Other mechanisms are needed to enhance heat transfer

Acknowledgement

- This work was funded by the U.S. Department of Energy, Office of Efficiency and Renewable Energy (EERE), Office of Technology Development, Geothermal Technologies Office.

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