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Case Study of a Multilateral Closed-Loop Geothermal System

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ABSTRACT

Results from a full-scale demonstration project of a multilateral closed-loop geothermal system are presented. The project is located near Sylvan Lake, Alberta, Canada and consists of two 2.5 km long multilateral horizontal wellbores connecting two 2.4 km deep vertical wellbores to create a U-tube shaped closed-loop geothermal system. The horizontal wellbores are intersected using magnetic ranging technology, and sealed with a novel completion technique "Rock-Pipe™", resulting in a giant subsurface heat exchanger. It is an entirely closed system with no flow into or out of the formation. A water-based working fluid is then circulated through the system, entirely driven by the thermosiphon effect created by the density difference between the inlet and outlet wells.

Design and execution of the project is described, along with important results. Key performance indicators are drilling execution, operational leak-off rate, solids production, and thermodynamic performance. Thermodynamic output of the system is modeled and forecasted prior to the start of circulating operations. Pilot results are scaled-up to a realistic commercial project to demonstrate that a closed-loop multilateral system is technically and economically feasible. This technology is unconstrained by formation permeability and enables projects in areas without hydrothermal flow capacity.

1. INTRODUCTION

Closed-loop geothermal systems, also known as wellbore heat exchangers, rely only on conductive heat transfer and have been investigated for many years due to their inherent business advantages including massive scalability, no water use, no fracking, no induced seismicity, no corrosion/erosion/scaling, no fluid disposal, and low environmental footprint. The advent of a true closed-loop system mitigates the exploration risk involved in searching for rare geological areas with both high temperatures and high flow capacity. Therefore, this type of system has potential to become globally scalable and open entirely new markets. Several key technical and economic hurdles must be overcome:

- **Limited by conductive heat transfer through rock.** Unlike traditional geothermal which utilizes convective heat transfer and production of hot brine, closed-loop systems extract heat only by conductive heat transfer which is a slow physical process.

- **Installed costs of drilling, completions, and surface facility relative to output.** Drilling and completion is the majority of the cost for a closed-loop system. With pure conductive heat transfer the power output per effective well length is lower than traditional open systems so capital efficiency ($/KW capacity) is a challenge.

- **Depletion.** Maintaining energy production for an economically viable timeframe (30+ years), and mitigating heat-losses in the wellbore

Many prior closed-loop systems have been predicated on a concentric tubing approach. Due to the limited borehole length in contact with hot rock, these designs must overcome the above challenges by focusing on very deep, extremely hot formations to be economically viable. This paper describes the field demonstration of a closed-loop technology, "Eavor-Loop™", that provides solutions to the above challenges. The main differences with Eavor-Loop™ are:

1. **Multilateral wells.** Multilaterals increase the volume of rock that is harvested for heat. In the commercial-scale Eavor-Loop™ system, 10+ multilaterals are used to generate 10x+ higher energy output relative to a single lateral. Drilling multilaterals is inherently cheaper since the fixed costs (vertical wells, access, land, etc.) are spread over more energy-mining laterals. In addition, multilaterals generate economies of scale by increasing the scope of repetitive drilling operations. This is a brute-force solution to the relative slowness of conductive heat transfer. For context, a typical Eavor-Loop™ would have 50,000m of wellbore in contact with hot rock, where other concepts involving concentric tubing had only ~500m.

2. **Multilateral Completions.** The vertical sections of Eavor-Loop™ are cased and cemented, identical to standard geothermal or oil and gas practice. However, the horizontal multilateral sections are drilled open-hole and completed in a unique fashion using a chemical setting agent combined with a tailored working fluid that contains reactants. This technique allows for repetitive, standardized open-hole drilling and avoids the use of complicated and expensive multilateral junctions and casing.

3. **Repurposing Drilling Technology from the North American Shale Industry.** Drilling speeds have increased by more than 50% in the last several years, driven by technology and the manufacturing-style operations of the North American Shale Industry. Figure 1 shows the time required to drill long horizontal wells in Canada, compared to the LCOE of Wind

and Solar (rooftop commercial and industrial), normalized to 2013. It is possible to re-purpose this trend to a new application in geothermal energy.

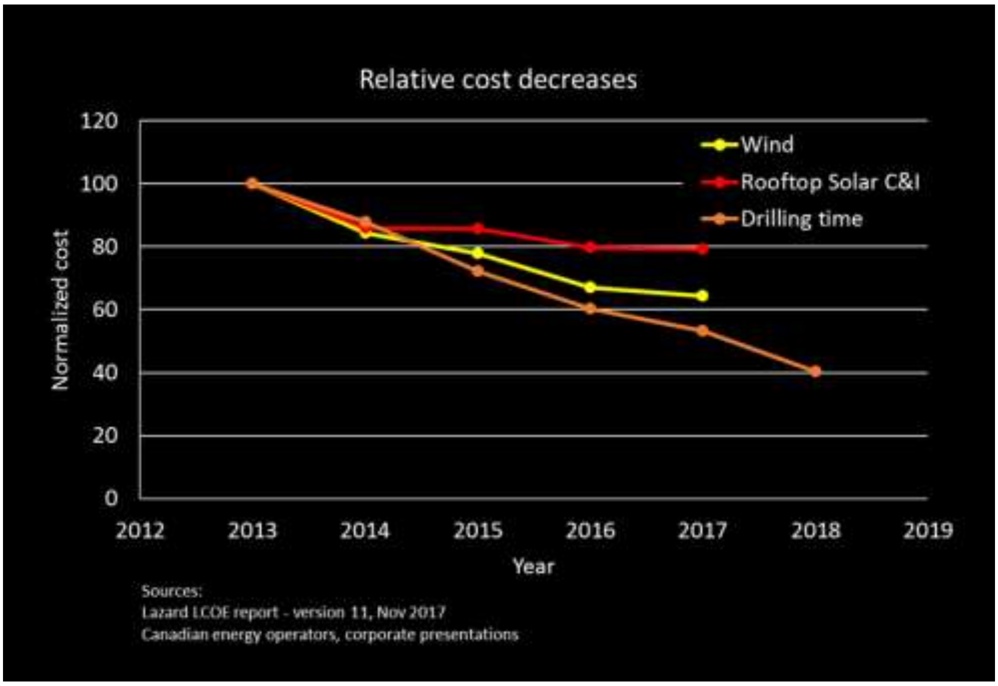

Figure 1 - Relative decreases of Wind and Solar LCOE and NA drilling time, normalized to 2013

4. **Standardization.** Eavor-Loop™ has been purposefully designed to be standardized, repeatable, consistent, and able to take advantage of incremental efficiency gains and economies of scale. This is also the same strategy that wind and solar have used so successfully over the last decade to drop costs – they rely on manufacturing-style production and implementation, unlike nuclear, hydro, or traditional geothermal. Recently in North America, oil and gas resource plays have applied this same strategy with compelling results. Figure 2 illustrates the normalized cost for these manufactured energy systems as economies of scale are realized.

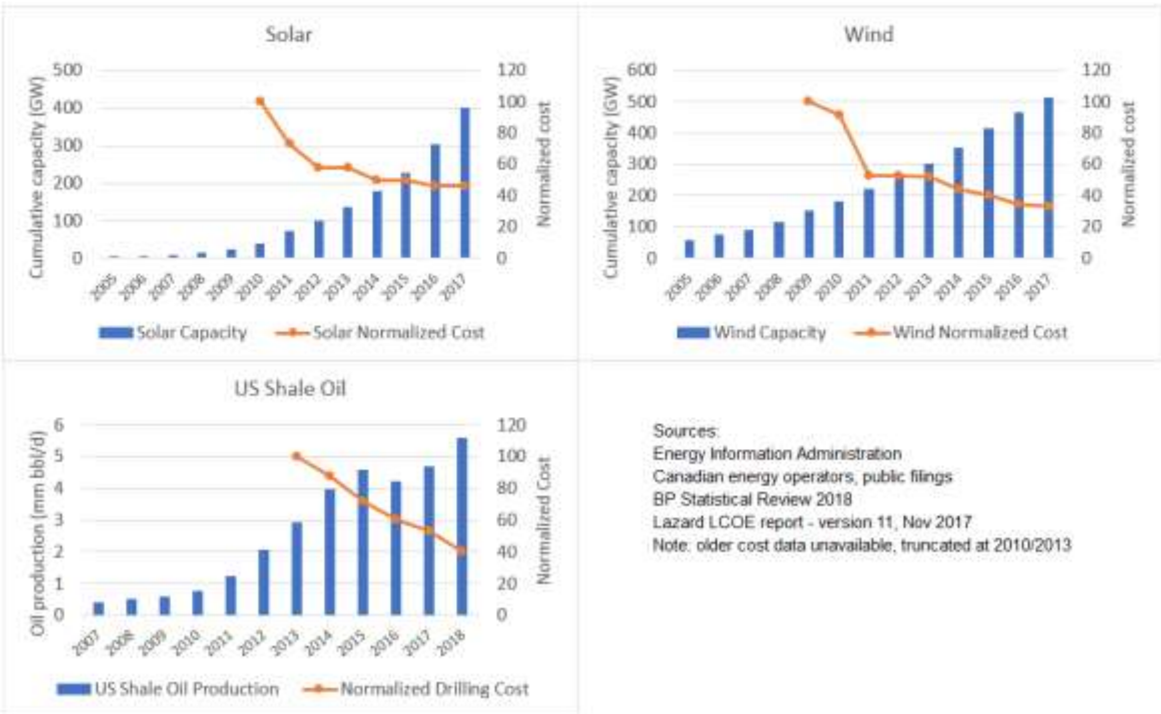

Figure 2 - Cost decreases with scale for manufactured energy systems

5. **Enhanced Fluids.** Thermodynamic and mechanical efficiency can be improved by deploying novel working fluids and additives.

2. PROJECT DESCRIPTION

The Eavor-Loop™ Demonstration Project ("Eavor-Lite"), is a full-scale prototype of the technology intended to de-risk the key technical components. The closed-loop system, shown in Figure 3 below, consists of a large U-tube shaped well at 2.4km depth, with two parallel ~2000m multilateral horizontal wellbores, and a pipeline connecting the sites on surface. Two drilling rigs are operated simultaneously from both sites and used to intersect the multilateral wellbores at depth. A water-based working fluid is circulated in the inlet well, through the parallel wellbores to recover heat by conductive heat transfer with the rock, and rises in the outlet wellbore at a higher temperature. The density difference between the inlet well and outlet well creates a thermosiphon which completely drives the flow, without any pumping power. A test facility on surface is designed to remove solids, measure all relevant performance data, and cool the water for re-circulation into the inlet well.

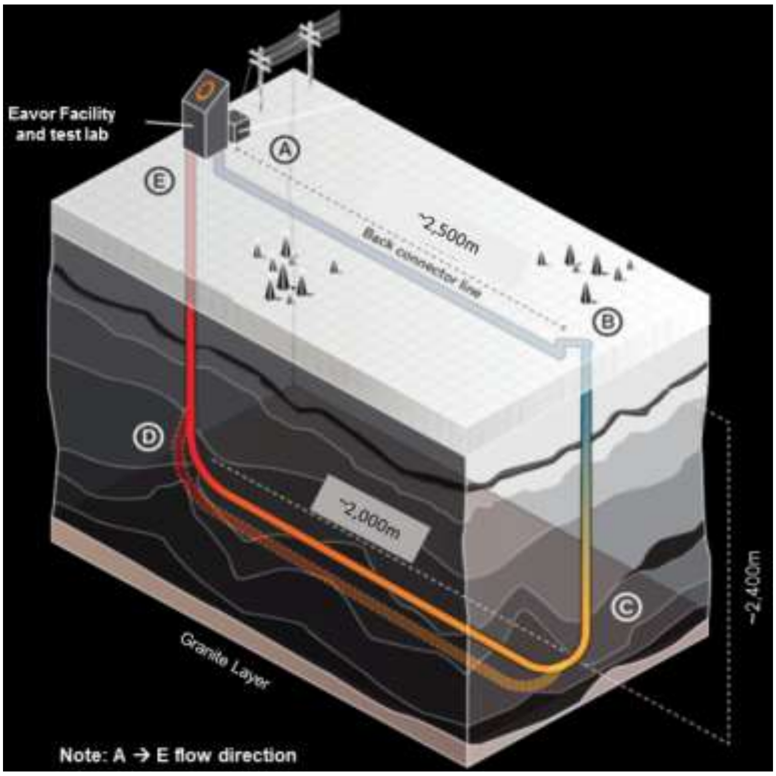

Figure 3 - Eavor-Lite Schematic

The key technical objectives of the Eavor-Lite project are outlined in Table 1 below.

Table 1 – Eavor-Lite Technical Objectives

Technical Objective	Success Criteria
1. Drill and intersect a multilateral Eavor-Loop with two laterals	•Successfully execute drilling program
2. Create a closed system by chemically sealing the Eavor-Loop (Rock-Pipe™ completion)	•Pressure test to 5000 kPa •Maintain circulation operations with < 1 m3/d leak off rate •Maintain low solids production and > 90% uptime
3. Validate thermodynamic performance and demonstrate thermosiphon	•Meet or exceed expected performance of 900 kWth •Demonstrate thermosiphon control and operation

A summary of the implementation milestones is shown in Figure 4 below.

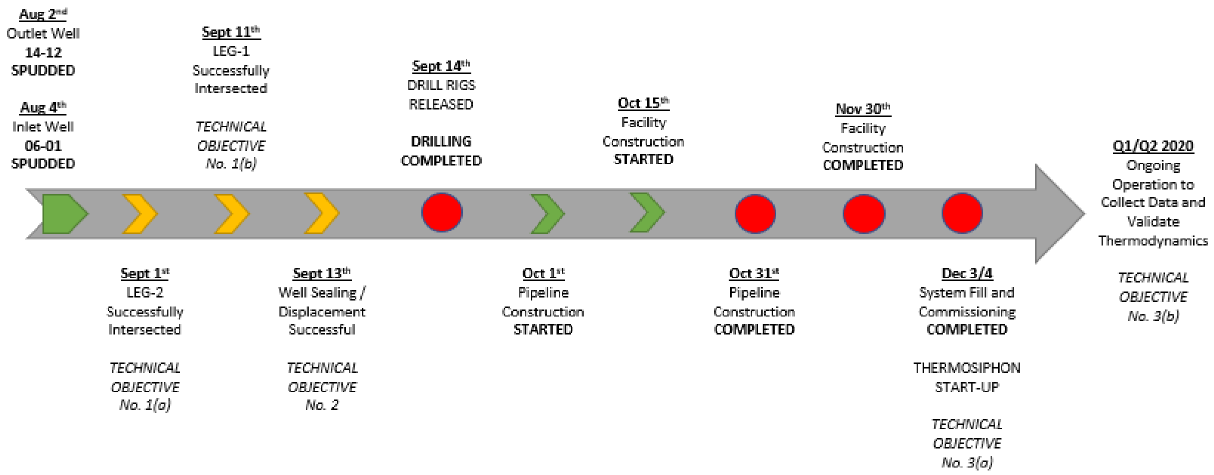

Figure 4 - Key Milestones for Eavor-Loop Demonstration Project

The goal of the project is to demonstrate and mitigate key technical risks, thus enabling commercial projects. Although Eavor-Lite has lower bottom hole temperatures, the wellbore layout, sealant design, multilateral junctions, multilateral wellbore intersections, and thermodynamic modelling are the same as a commercial project (see Table 1).

Table 2 - Comparison between Eavor-Lite and Commercial Scale Projects

Parameter	Eavor-Lite	Commercial Project
Number of Laterals	2	10+
Depth, TVD [m]	2400	1500 - 4500
Site-to-site distance [m]	2500	5000+
Vertical casing size [in]	7	7 or 9 5/8
Multilateral wellbore size [in]	6 1/8	6 1/8 to 8 1/2
Rock Type	Quartz/Calcarenite Sandstone	Quartz sandstone, siltstone, igneous
Formation Temperature [ºC]	78	>100ºC
ΔT Inlet to Outlet well [ºC]	30	>40ºC
Multilateral completion	Rock-Pipe™	Rock-Pipe™

The rationale for this design is to build a demonstration project that achieves the most cost-effective and quickest path to commercialization of the technology – or, in other words, the quickest path to failure. A commercial project has many more laterals but since each lateral has the same design, demonstrating two parallel laterals proves 10+ laterals. Other technical requirements of a commercial project, such as generation of electricity using a heat engine, are commercial off-the-shelf (COTS) items and have been proven in similar commercial environments.

2.1. Project Location

The project is located west of Sylvan Lake, near the town of Rocky Mountain House, Alberta, Canada (Figure 4). The North surface location hosts the outlet well on an existing inactive oil and gas site, 14-12-38-5W5, and the inlet well is at 6-1-38-5W5. The target formation is the Rock Creek, a fine-grained sandstone in an area with a typical sedimentary basin geothermal gradient of 30°C/km. The Rock Creek between the sites averages 2400m TVD, therefore the bottom hole temperature is expected to be ~78°C. A detailed description of Geology can be found in Vany et al (2019).

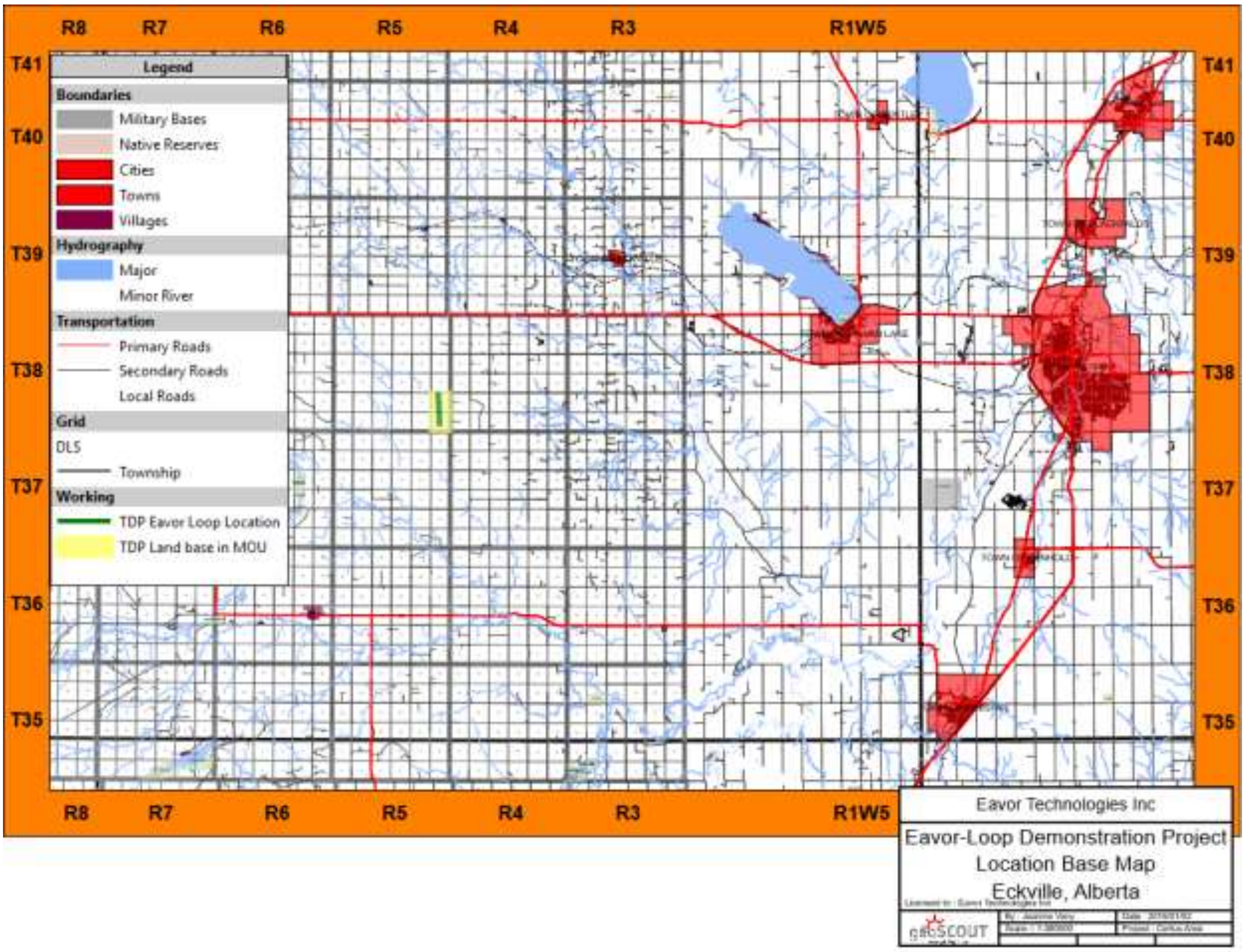

Figure 5 - Eavor-Lite location map

2.2. Well Design

A simplified wellbore schematic is shown in Figure 5 (note only one lateral is depicted). 244.5mm surface casing is installed below groundwater, with 177.8mm intermediate casing landed at 90° in the Rock Creek formation. The horizontal laterals were drilled with a 156mm bit and spaced 50m apart, after a short spreading section.

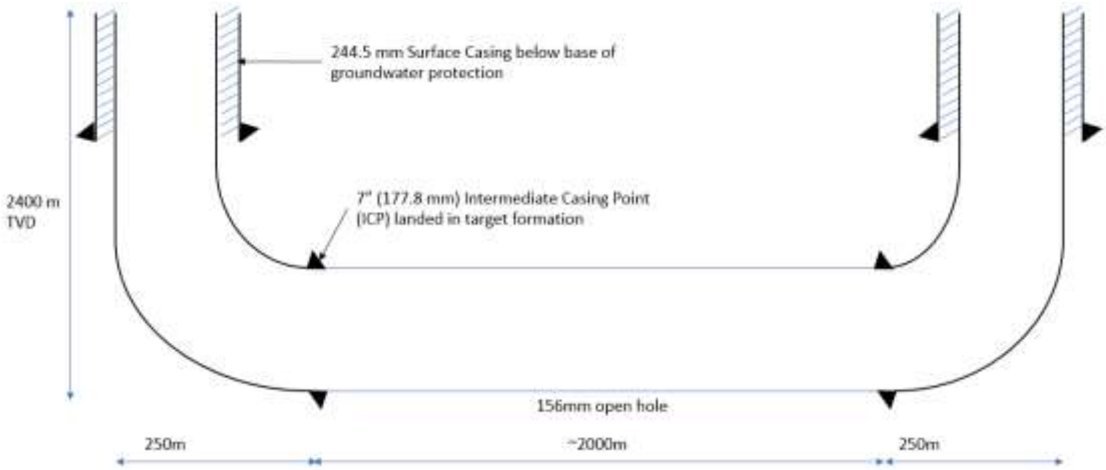

Figure 6 - Eavor-Lite Wellbore Schematic

2.3. Surface Facilities

The Surface Facilities for the project are illustrated in the Process Flow Diagram shown in Figure 6. The outlet well site (14-12) facilities consists of a water storage tank, solids removal, centrifugal pump, and aerial cooler. The hot water from the outlet well, which has been heated downhole, enters a water storage tank to drop out solids and manage volume changes (thermal expansion and subsurface leak-off). The water is circulated by thermosiphon or centrifugal pump and cooled in a forced draft aerial cooler with a variable frequency drive on the fan motor to control the outlet water temperature. The water flows into a buried pipeline and returns to the inlet well to be re-injected downhole to be re-heated. The water is initially trucked into the water storage tank to fill the loop, and corrosion inhibitor and other additives are added in a batch treatment. The hydrostatic head due to the water level in the tank also sets the pressure at the inlet to the circulation pump when operating in pumping-mode.

The flow rate of water through this closed loop system is measured by a magnetic flow meter downstream of the outlet well and controlled by a main control valve. A thermosiphon effect is generated by the density difference between colder (higher density) water flowing to the inlet well relative to the hotter water (lower density) returning from the outlet well. The pump is turned off and bypassed during thermosiphon mode. The main control valve downstream of the outlet well is used to set the thermosiphon flow rate.

There are multiple transmitters to measure the pressure and temperature at the outlet well, the inlet to the pipeline and the inlet well. Flow meters on the outlet and inlet wells, in addition to redundant radar level transmitters on the water storage tank are utilized to measure any loss or gain of water through the closed loop system. This information is used to quantify loss/gain of water to the sub-surface formation.

Overall the surface facility has a relatively small footprint, and there is no flaring, no venting and no ground water usage / disposal requirements.

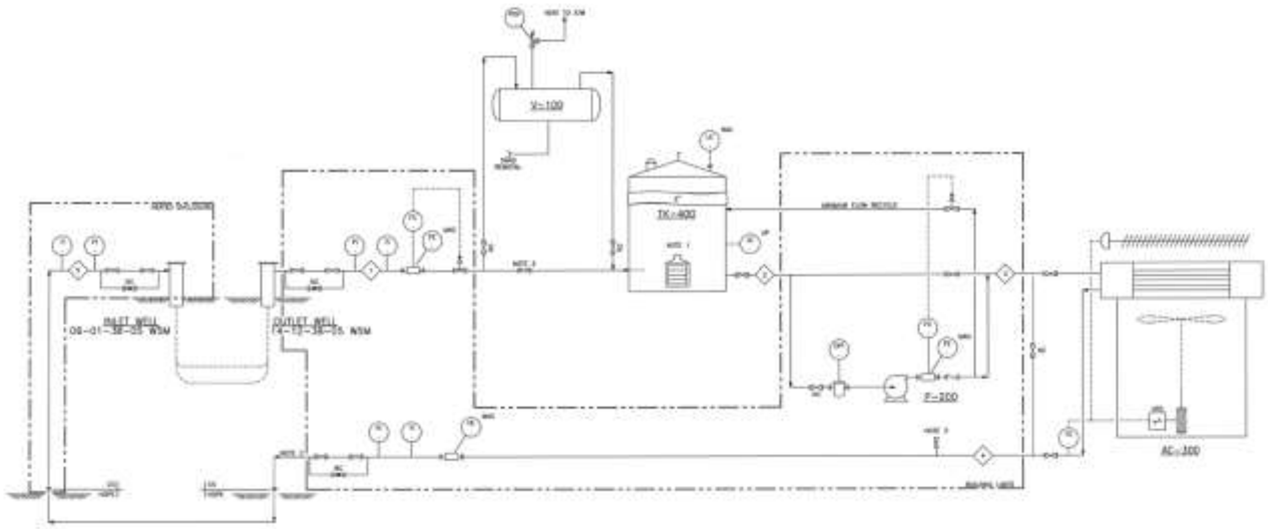

Figure 7 - Facilities Process Flow Diagram (PFD)

3. TECHNICAL OBJECTIVES AND RESULTS

The technical objectives of the project are listed above in Table 1.

Wellbore Intersection

After setting and cementing intermediate casing, both the inlet and outlet wells had a gyroscope run to refusal. This information is compared to the MWD measurements to calibrate absolute trajectories and reduce error. The horizontal laterals are then drilled with standard MWD equipment until ranging operations. The wellbores were planned to make a “y-connection” – rather than hitting each other head-on, the subject well gradually merges with the target well. The geometry is designed so that the flow direction (Inlet well to Outlet well) is not into the deadleg section, to prevent unnecessary turbulence, pictured in Figure 7 below.

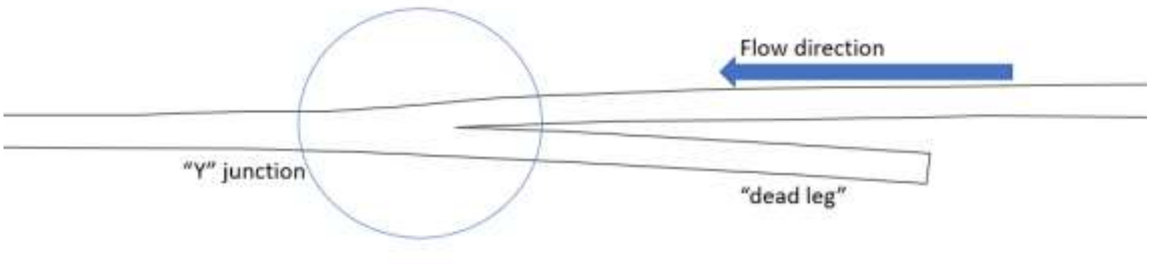

Figure 8 - Wellbore Intersection Schematic

Both legs were successfully intersected. The second intersection occurred at 3,783.11m(MD) on Sept. 11, 2019. Significant learnings with a host of valuable optimization and remedial techniques were devised and deployed.

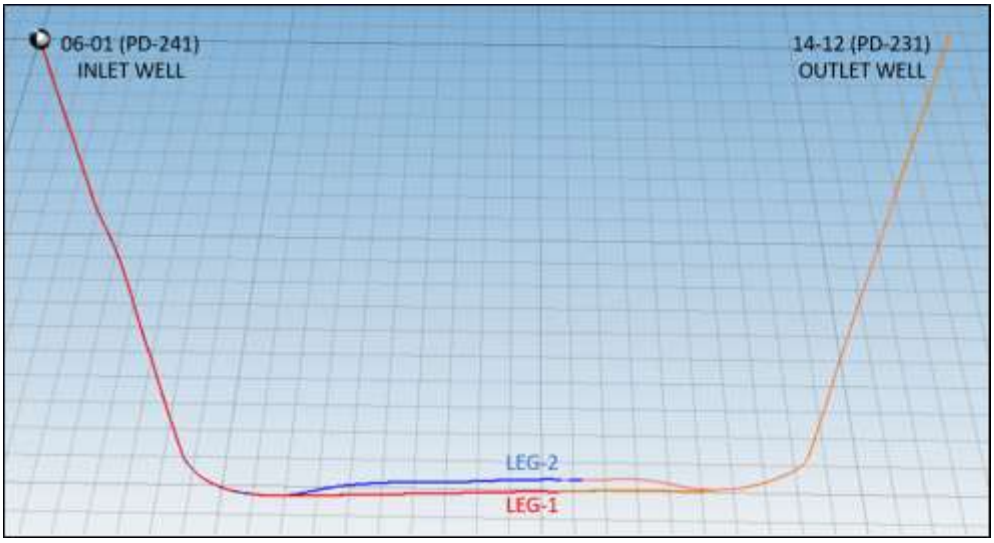

Figure 9 – As-drilled final schematic (fully intersected laterals)

3.1. Create and maintain seal

The Eavor-Loop™ system is unique in that the horizontal multilateral wellbores are sealed without casing. Instead, a setting agent is applied to the formation with the drilling rigs on site. After drilling, the entire well volume is displaced over to the working fluid, which has a chemistry designed to interact with the setting agent and to maintain a closed-loop, sealed system. The working fluid is mostly water, with additives to assist in maintaining wellbore integrity, maintaining a seal, and to improve thermodynamic performance.

The sealing effectiveness was monitored and validated during drilling operations based on negligible mud losses. Formation integrity tests (FITs) were also carried out at specified intervals throughout the drilling program to test the effectiveness of the sealant through application of 5 MPa pressure (measured at surface) for a period of 15-75 minutes per test. These FITs were carried out systematically to validate the near-term sealing integrity of the wellbores on nine separate occasions at various intervals as horizontal drilling progressed, including tests pre-intersection, following the initial intersection, and following completion of both intersections and drilling fluid displacement. Overall, the completed system was able to maintain over 90% of the applied 5 MPa pressure.

In addition to the FITs, the initial sealing integrity was further validated upon execution of the Post-Drilling Mud-Displacement program. The full volume of this drilling mud (218 m3) was displaced from the entire loop with the working fluid without minor apparent losses to the formation. Eavor developed and implemented a dual verification method for this mud displacement exercise; (i) viscous dye pill spacer for visual confirmation; (ii) real-time pH analyzer for higher resolution chemical composition verification. The initial displacement return was pumped from 06-01 and received at 14-12 within four (4) minutes of the calculated 174 minute displacement pumping duration, indicating that the subsurface wellbore geometry is consistent with the expected geometry given the bit dimensions and measured distances, and the flow split between the two lateral legs is approximately equal.

Following start-up of the system on December 4, samples were taken of the outlet well produced fluid (upstream of the water storage tank) as well as downstream of the aerial cooler to visually assess any solids production. There was no evidence of solids in the samples – a photo is shown in Figure 10. Solids production is also monitored by measuring the pressure drop across the filter upstream of the circulation pump. During the commissioning phase of operation on December 3 while the pump was operational no change to this dP was observed.

Figure 10 - Outlet Well and Aerial Cooler Outlet Fluid Sample - December 4, 2019

The sealant performance will continue to be monitored during normal operation. Leak off is straightforward in that this is a closed loop system, so leaks will be detected if a reduction in the total mass of the system is observed. The primary means of monitoring ongoing leak off is through tank level measurement, where the steady state leak-off rate observed since January 1 is 0.72 m3/d.

Part of the Rock-Pipe™ completion system is to include additives within the circulating fluid itself that enhance and maintain the downhole seal. This can be seen since the leak-off has dropped significantly from commissioning to current state, and chemistry continues to be refined to further control leak-off into the formation.

3.2. Thermosiphon Demonstration

The switch to thermosiphon mode was done on December 4, following the fluid fill and system commissioning that was completed on December 3-4. The system had been operating for ~ 24 hours using the circulation pump while system commissioning was being completed. The final step in commissioning was to test the emergency shut down (ESD) functionality of the system, which would shut off the pump, isolate and drain the aerial cooler, and close the main flow valves to stop circulation.

The ESD test was performed on December 4 at 11:15 AM. The system remained offline with no circulation for a period of approximately 20 minutes while the auto drain sequence on the aerial cooler was tested. Following completion of this test, the main flow valves were re-opened to see if the thermosiphon could reestablish circulation. Over the course of 5 minutes, the flow gradually increased to the set point flow rate of 35 m^3/h, at which point the throttling valve on the outlet well began to close to maintain the desired flow. This data is shown in Figure 9, with the pump discharge pressure shown in 'blue' and the circulation rate shown in 'orange'.

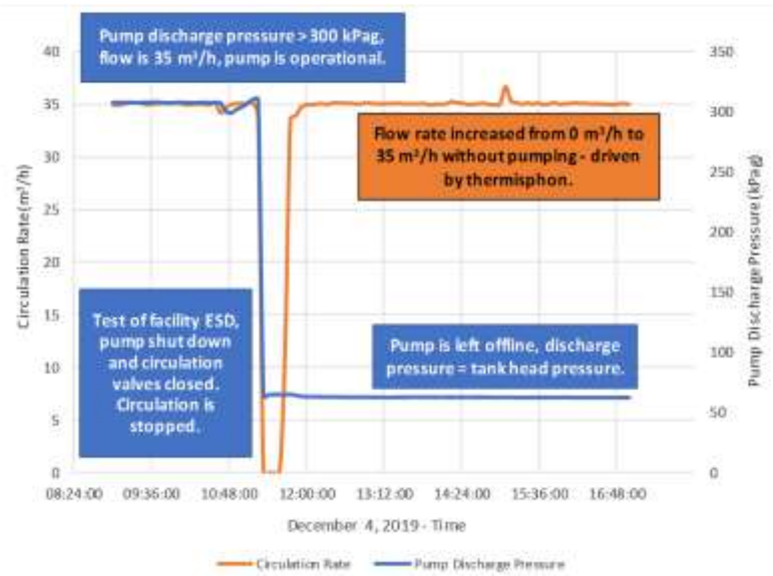

Figure 11 - thermosiphon demonstration

Overall, this test successfully proved the ability of the thermosiphon to start up an Eavor-Loop™ system without the use of a circulating pump within 1 day of operation. The facility has been stable and operating consistently in thermosiphon mode since December 4.

3.3. Validate Thermodynamic Performance

Eavor-Loop™ thermodynamic performance is best estimated using a transient numerical wellbore model with radial coordinates. The advantages of this type of model are the quick computational run-time, relative simplicity, and ability to handle transient data such as shut-in periods, changing flow rate and inlet temperature, and variable fluid properties.

Fourier's Law of Heat Conduction, i.e. $q = k\, A\, \nabla T$, and the conservation of energy equation can be combined to derive the Partial Differential Equation (PDE) that governs the transient conduction of thermal energy in radial coordinates:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{1}$$

where:

T is the temperature field

r is the radial position relative to the well bore centerline

z is the axial position relative to the well bore inlet

k is the thermal conductivity of the rock

ρ is the density of the rock

C_p is the specific heat of the heat.

The circumferential variation in temperature is assumed to be negligible, i.e. $\frac{\partial T}{\partial \theta} = 0$

Integrating eqn. (1) over a finite control volume, $dV = 2\pi\, dr\, dz$ and over a fixed period of time, dt, yields a linear, algebraic equation for the discrete local temperature, $T_{i,j}$, along with it's neighboring radial temperatures: $T_{i+1,j}$ and $T_{i-1,j}$, and neighboring axial temperatures: $T_{i,j+1}$ and $T_{i,j-1}$:

$$\rho C_p \frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t}\pi(r_{i+1}^2 - r_i^2)(z_{j+1} - z_j) = 4\pi k(z_{j+1} - z_j)\left(r_{i+1}\frac{T_{i+1,j}^{n+1} - T_{i,j}^{n+1}}{r_{i+2} - r_i} - r_i\frac{T_{i,j}^{n+1} - T_{i-1,j}^{n+1}}{r_{i+1} - r_{i-1}}\right)$$
$$+\ 2\pi k(r_{i+1}^2 - r_i^2)\left(\frac{T_{i,j+1}^{n} - T_{i,j}^{n}}{z_{j+2} - z_j} - \frac{T_{i,j}^{n} - T_{i,j-1}^{n}}{z_{j+1} - z_{j-1}}\right) \tag{2}$$

Note that the radial derivatives on the R.H.S. of eqn.(2) are implicitly calculated at the new time step (n+1) whereas the axial derivatives are explicitly calculated at the previous time step (n).

This system of algebraic equations for all of the control volumes or grid points can be solved to compute the temperature field at the new time step,

$$T_{i,j}^{n+1} \tag{3}$$

The momentum and energy equations for water flow in the horizontal well bore can be solved along with the algebraic equations for transient heat conduction in a coupled solution method to predict how the pressure and temperature of the water flow in the well bore changes over time. In a steady-state scenario without variable input parameters, the transient numerical approach aligns well with the analytical approach of Ramey, 1962, and Kutun, 2015. The key input parameters in the modelling are thermal conductivity of the rock, k, and rock temperature. Thermal conductivity has been estimated using the mineralogy approach of Jorand et al, 2015, and described in Vany et al, 2019.

The temperature distribution of the rock is illustrated after 1 year of circulating operations in Figure 13 and 5 years in Figure 14, with radial distance on the y-axis, axial position along a single lateral on the x-axis, and temperature represented with the color bar.

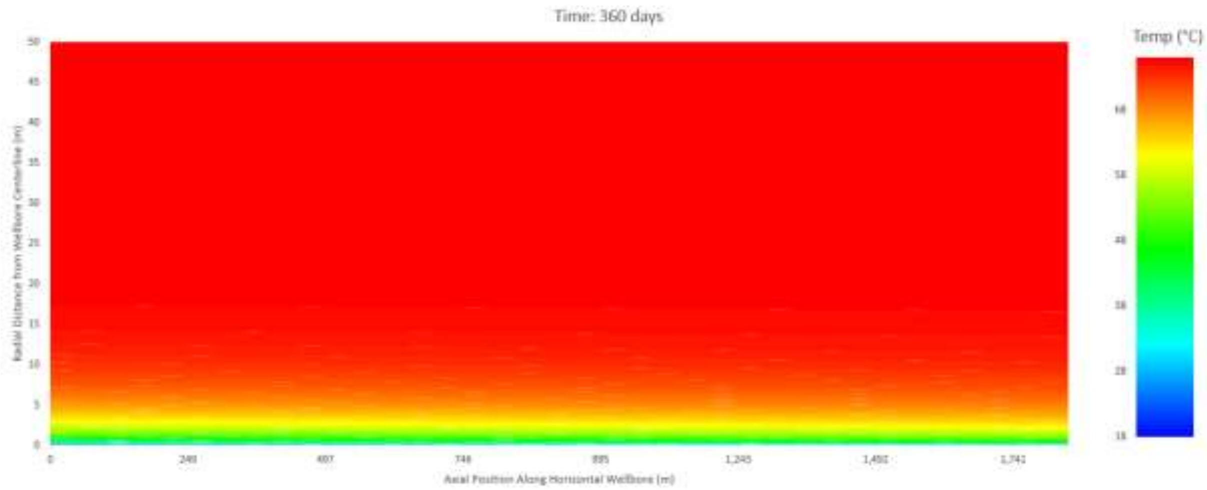

Figure 12 - Rock temperature distribution, 1 year

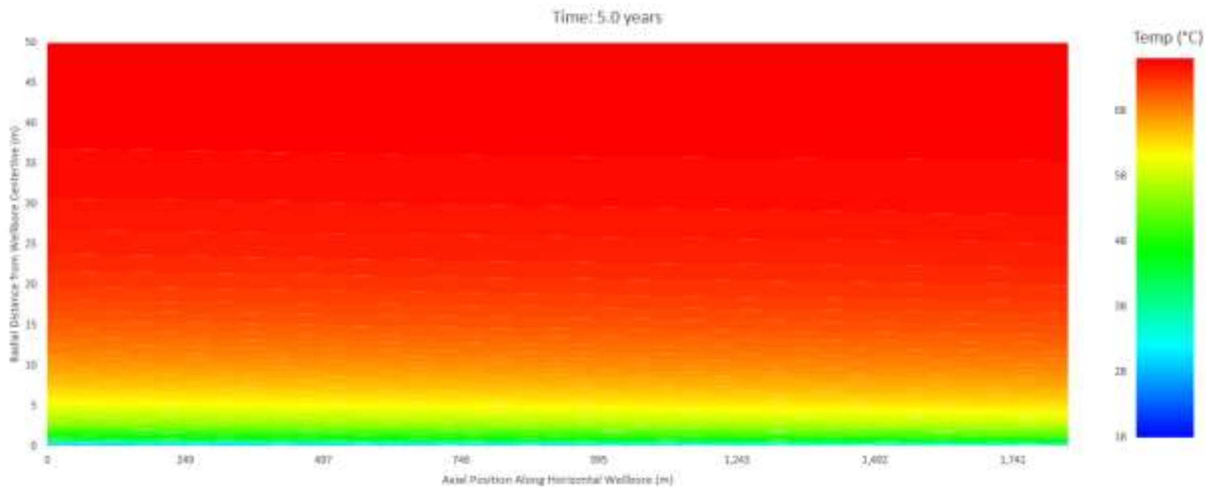

Figure 13 - Rock temperature distribution, 5 years

Measured performance of the Eavor-Lite project was compared to the simulated performance. Data has been collected since start-up on December 3, which is then imported into this transient model. The key input parameters for the model are the inlet well pressure, temperature, and flow rate. Cumulative energy recovery is compared to the measured data for a single lateral, shown in Figure 14. There is good agreement between the predicted and calculated cumulative recovery, with the measured recovery approximately 2% higher than predicted at the end of this 33-day period.

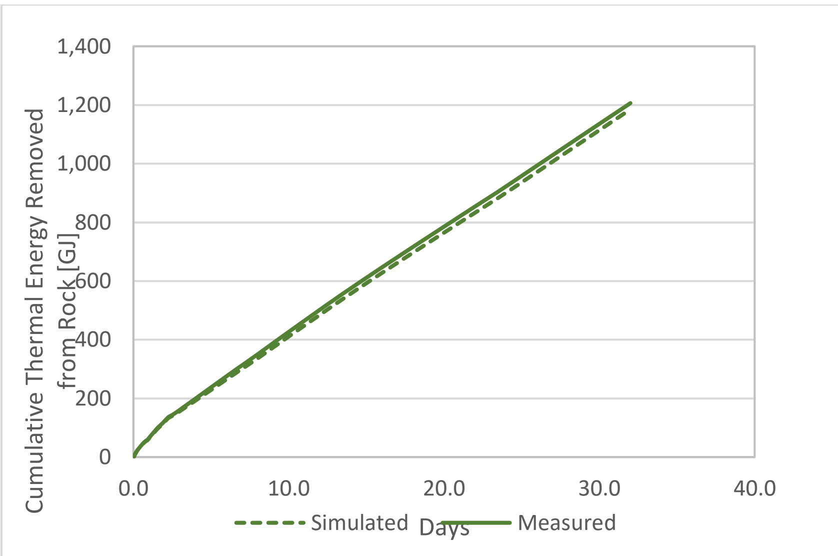

Figure 14 - Eavor-Lite Simulated vs. Measured Cumulative Energy Recovery

Figure 14 shows the difference between field measurements and the original simulation model that was developed *prior to spud*. Critically, the results show that Eavor-Loop performance can be estimated accurately in the design phase – this factor is the main business advantage of Eavor-Loop over traditional geothermal; Eavor-Loop removes exploration requirements and performance uncertainty. By removing the exploration/delineation phase, projects can be completed with a shorter cycle-time (18 months) and with lower risk.

The next step for thermodynamic evaluation of the transient model will be to use the measured data to history match the empirical data. Since the match is already close to pre-spud expectations, only minor changes will be required in simulation parameters. However, the history match will provide the corresponding rock thermal conductivity to minimize the least-squares error between the measured and predicted values and indicate the accuracy of the rock thermal conductivity estimation methodology.

Data collection and model validation will be ongoing over longer operating periods as Eavor-Lite continues to operate. Following the baseline testing, the operating parameters will be adjusted to better demonstrate the transient capabilities of the model. Testing of enhanced working fluid additives is planned to take place in Q2-Q4 2020.

4. SCALING RESULTS TO COMMERCIAL PROJECTS

The purpose of the Eavor-Lite project is to de-risk commercial deployment of the closed-loop multilateral system. Wellbore intersection operations and sealing technology are being demonstrated at the same unit scale as a commercial project, the only difference is a commercial project would have more multilaterals.

Regarding thermodynamics, the purpose of the Eavor-Lite project is to prove the simulation and modelling methodology, and also to validate the geological workflow to estimate input parameters. Therefore, the thermodynamic performance of any commercial project can be reliably estimated with this same methodology, regardless of location, geology, rock temperature, or conductivity.

By scaling the results from Eavor-Lite, a typical commercial project in a low enthalpy scenario would generate up to 2 MW electric or 20 MW thermal. It is also possible to stack closed loop systems vertically within the rock volume as well as arrange the laterals in various 3D configurations. A steep learning curve is expected to apply to construction costs, as seen in all standardized repetitive industrial processes, and the technology is well suited to benefit from manufacturing efficiencies and economies of scale.

5. CONCLUSION

The design of a near-commercial scale demonstration project of a multilateral closed-loop geothermal system has been presented. The key technical objectives required to de-risk the system for commercial deployment are wellbore intersection operations, creating and maintaining a sealed closed wellbore loop, and validating thermodynamic performance. Initial execution and performance data from the project show that all technical objectives have been successfully achieved.

The system is now poised for commercial deployment in suitable markets. This technology is unconstrained by formation permeability and enables projects in areas and formations without hydrothermal flow capacity, and thus opens large new markets for geothermal energy.

REFERENCES

Horne, R.N. "Design Considerations of a Down-hole Coaxial Geothermal Heat Exchanger, *Geothermal Resources Council Transactions*, 4, 569 (1980).

Jorand, R., Clauser, C., Marquart, G., Pechnig, R., Statistically reliable petrophysical properties of potential reservoir rocks for geothermal energy use and their relation to lithostratigraphy and rock composition: The NE Rhenish Massif and the Lower Rhine Embayment (Germany), *Geothermics*, Volume 53, Pages 413-428, (2015)

Kutun, K., Tureyen, O., Satman, A., Analysis of Wellhead Production Temperature Derivatives, *Proceedings*, Fortieth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2015)

Morita K., M. Tago and S. Ehara. Case Study on Small-scale Power generation with Downhole Coaxial Heat Exchanger, *Proceedings*, World Geothermal Congress, Antalya, Turkey, 24-29 April (2005)

Nalla, G., Shook, G.M., Mines, G.L. and Bloomfield, K.K., Parametric sensitivity study of operating and design variables in wellbore heat exchangers, *Geothermics*, 34(3), pp.330-346, (2005)

Oldenberg, C., Pan, L., Muir, M., Eastman, A., Higgins, B.: Numerical Simulation of Critical Factors Controlling Heat Extraction from Geothermal Systems Using a Closed-Loop Heat Exchange Method, *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2016)

Ramey Jr, H.J. Wellbore Heat Transmission, *Journal of Petroleum Technology*, pp 427-435, 14, 04, (1962)

Vany, J., Hirschmiller, J., Toews, M., Subsurface Characterization Methods for Multilateral Closed Loop Geothermal Systems. Case Study of Field Scale Technology Demonstration Project in Alberta, Canada, *Proceedings*, World Geothermal Congress 2020, Reykjavik, Iceland (2020)