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# Enhancing Thermal Efficiency in Super-Hot Geothermal Systems: Optimizing Premium Connections for Advanced Vacuum Insulated Tubulars

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## ABSTRACT

As the geothermal industry progresses towards developing and dispatching next generation technologies to exploit this form of renewable energy, maintaining thermal efficiency within wellbores becomes increasingly critical. One critical aspect of ensuring thermal efficiency in next-gen geothermal wells is Vacuum Insulated Tubing (VIT). Based on existing literature, an area of significant knowledge gaps and uncertainty is the impact of heat loss at the connections of VIT, where the lack of vacuum insulation enables non-desirable heat transfer. This issue becomes more pronounced in extreme temperature environments, where the materials used for insulators in connection points are not rated for the elevated temperatures encountered. In response to this challenge, the focus has been placed on decreasing the length of the premium connection, a crucial component in preserving the structural integrity of VITs. By shortening the connection length, the surface area exposed to non-insulated conditions is minimized, thereby reducing thermal losses. This technical enhancement is vital for maintaining the overall efficiency of geothermal systems, particularly in super-hot rock applications, where even minor inefficiencies can result in significant operational challenges. This paper covers the existing literature and current state of knowledge on this topic, presents the laboratory testing performed coupled with validatory numerical simulations, in addition to field-scale coupled reservoir and wellbore simulations highlighting the impact of VIT on the performance of closed loop geothermal systems. The findings indicate a substantial improvement in the ability to maintain higher temperatures within the wellbore, ultimately contributing to more efficient energy extraction and extending the operational lifespan of geothermal systems in high-temperature environments.

## 1. INTRODUCTION

Geothermal energy is one of the many sustainable energy sources gaining traction in the last decade. Unlike other green energy resources, geothermal energy offers a commodity that is not found, which is its baseload nature, and is very useful given the dynamics of the energy demand which varies significantly throughout the day, week or month (Sfeir et al., 2024). It is recognized as a sustainable and reliable source of renewable energy providing baseload power. There are many types of geothermal systems varying from conventional hydrothermal systems (e.g. Geysers in California) dating centuries, to next-gen unconventional systems such as closed loop geothermal (hereafter referred to as CLGS) and enhanced geothermal systems (EGS). CLGS have gained considerable attention due to their adaptability in diverse geological conditions with minimal direct interaction with the reservoir and their ability to minimize environmental impacts. A typical CLGS is a co-axial single well configuration: A cold fluid (e.g. $H_2O$) is injected in the annulus, it extracts heat from the surrounding rock primarily through conductive heat transfer as it travels downhole (Figure 1), the heated fluid is then transported back to the surface via a return tube, enabling continuous heat recovery from the geothermal reservoir.

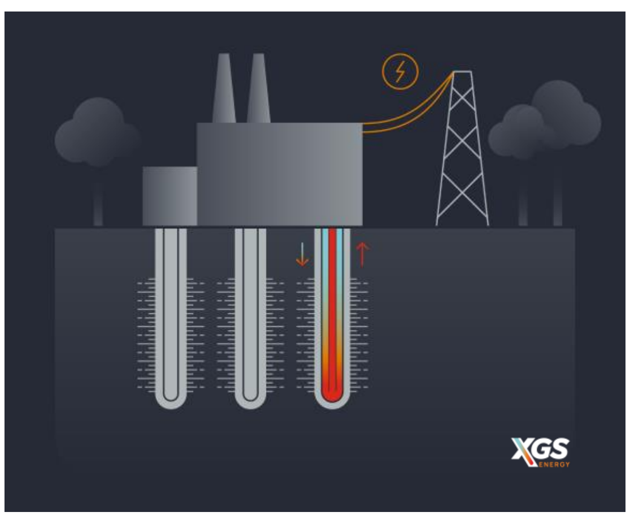

**Figure 1. Example of a Closed Loop Geothermal System (CLGS) (XGS Energy, 2024)**

The insulation efficiency of this return tube is crucial to maximize the heat recovered at the surface. Vacuum Insulated Tubing (hereafter referred to as VIT), widely used in the oil and gas industry, has emerged as a promising solution to address thermal loss issues in geothermal applications. VIT consists of two coaxial steel pipes with a vacuum media in-between, forming an ultra-low thermal conductivity pipe, targeting to minimize the heat loss between the produced working fluid in the VIT and the colder fluid circulating in the annulus. This paper provides a comprehensive overview of the use of VIT in CLGS: literature review, knowledge gaps, research performed via laboratory experiments, manufacturing advancements, and numerical simulations.

## 2. OBJECTIVES

The objective of this study is to evaluate the thermal performance of VIT in geothermal applications through a combination of laboratory experiments and numerical simulations. The study aims to quantify the heat transfer mechanisms, with special emphasis on understanding and mitigating heat losses at VIT connections, which are identified as critical points of inefficiencies. Laboratory experiments replicate real-world operational conditions to measure thermal conductivity and assess the impact of varying operating conditions (flow rates, temperatures, etc.). Also, advanced numerical simulations, coupling reservoir and wellbore processes to simulate and analyze a CLGS using VIT and the effect of the thermal performance of the VIT on the full-scale system.

## 3. LITERATURE REVIEW

### 3.1 Definition

VIT consists of two coaxial steel pipes, mostly of different steel grades. The air between the inner and outer pipes is evacuated using a vacuum pump during the manufacturing process. Once the vacuum is established, the pipes are sealed and welded to ensure long-term integrity under extreme pressures and temperatures (Figure 2).
In CLGS, the return tube is subject to heat loss mechanisms primarily driven by the temperature differential ($\Delta T$) between the warm produced fluid inside the tube and the cooler injected fluid in the annulus. The insulation efficiency of the produced fluid/heat depends on factors such as the thermal conductivity of the tube material, the effectiveness of insulation, and the temperature difference between the two media. Minimizing these losses is critical for maximizing the thermal energy produced from the system.

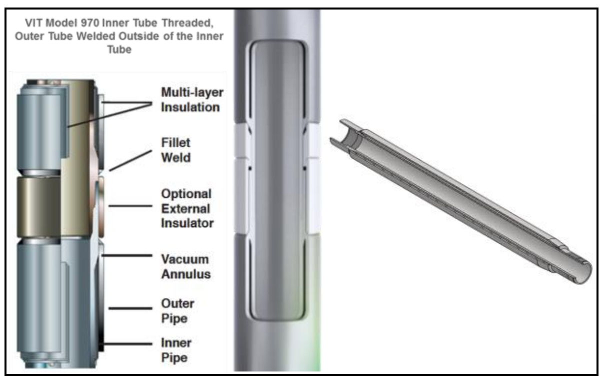


**Figure 2. VIT cross section (Vallourec, 2024)**

Depending on loading conditions, the sizes of the two VIT pipes vary as well as the metals used. Very often the inner tube is pre-stressed during the manufacturing process to accommodate variances in thermal expansion behavior of the inner and outer tube. The annular space often contains reflective materials, such as multilayer foil or low-emissivity coatings, to mitigate radiative heat transfer. Furthermore, coatings and anti-hydrogen permeation barriers, as described by Zhang et al. (2015) and Zhou et al. (2015), are frequently applied to protect steel pipes from corrosive environments and extend their operational lifespan. The result is a system capable of achieving thermal conductivity values as low as 0.001-0.005 W/m.K, which minimizes heat exchange between the vacuum pipe and the annulus, significantly enhancing energy efficiency in geothermal wells (Sliwa et al., 2017; Kaiser et al., 2015). Additional features such as getter materials are often included to absorb residual gases and maintain the vacuum over time (Ayres et al., 1985)
The analysis of thermal conductivity in VIT systems involves multiple heat transfer mechanisms: conduction, convection, and radiation. While conduction and convection dominate heat transfer in conventional systems, radiation is present in the vacuum chamber. VIT systems used in oil and gas applications were originally designed with a static annulus in mind while, in geothermal wells, especially co-axial CLGS, fluid flows in the annulus. This phenomenon has not been extensively studied and represents a critical gap in understanding VIT performance in dynamic geothermal environments. Numerical simulation approaches such as computational fluid dynamics (CFD) analysis, combined with laboratory testing, is necessary to quantify the impact of convective heat transfer in the annulus. Other considerations that need to be addressed regarding the heat transfer of VIT technology from oil and gas to geothermal applications are the temperature ratings, the expected lifetime for the VIT performance, and larger stresses may be applied in geothermal systems due to larger thermal stresses.

### 3.2 Current advancements and limitations in VIT

The thermal conductivity of a VIT is a critical performance metric, as it directly influences energy efficiency in geothermal applications. It is typically analyzed for its two primary components: (1) Main Body, with reported values as low as 0.005 W/m·K (Sliwa et al., 2017; Ferreira et al., 2012) (2) Connection, with significantly higher values than for the main body due to the presence of metallic threads and the discontinuity of the vacuum insulation at the joints. Figure 3 shows the combined thermal conductivity by percentages of pipe body and connection contributions, for oil and gas applications. As highlighted by Zhou et al. (2015), connections remain a critical area for further research to optimize thermal performance and reduce energy losses. Numerical investigation on that topic, such as those performed by Ferreira et al. (2012), for annular pressure buildup applications, suggests that connections can contribute disproportionately to overall heat loss in systems with frequent joint spacing. Currently, no comprehensive numerical simulation data exists to detail the heat transfer mechanisms within VIT systems under operational CLGS conditions, specially accounting for the connections in the simulation. Chen and Wright (2024) used FEFLOW to replicate a field test performed. Dufrene et al. (2024) referenced numerical modeling tools, including Vallourec's proprietary in-house software, designed for coaxial CLGS analysis using the experimental thermal conductivity results to enhance the accuracy of these numerical simulations, providing better predictive capabilities for geothermal applications. However, a lot of effort is still required to address this problem accurately and comprehensively via numerical simulations.

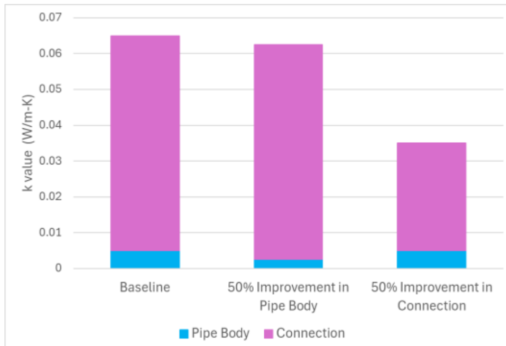


**Figure 3. Combined thermal conductivity comparisons of baseline case, 50% reduction of pipe body thermal conductivity and a 50% reduction of connection thermal conductivity (Adapted from Ceyhan and Vasantharajan, 2021)**

A lot of work has been done on laboratory experiments, where the majority of the focus has been for oil and gas applications, such as steam injection. For example, a study by Satchwell and Johnson (1992) concluded that heat loss was reduced by 98% at the pipe body and 6% at the connection. Tests requiring a vacuum of 0.1 torr in the annulus were not achieved because of leaks, whereas vacuum of larger pressures were not effective in reducing the heat loss, consistent with the literature. Azzola et al. (2007) showed that VIT has been used successfully to mitigate the potentially harmful effects of annular pressure buildup (APB) in an offshore well, while deploying external coupling insulators. A large scale experiment was built with two in-ground connected VIT joints. Test results correlated with numerical simulation showed a 61% reduction in heat loss with the external coupling insulators.

A study by Dufrene et al. (2024) utilized a dedicated VIT test bench to measure the thermal performance of a VIT in a controlled environment simulating geothermal conditions. A 4.5” x 3.5” VIT with premium connections was tested using hot oil circulated within the inner annulus of the VIT and water circulated in the outer casing annular space. This experiment is explained in detail in section 6 of this paper. The study also emphasized that heat loss at connections contributes to over 75% of the total heat loss, underscoring the need to evaluate connection insulation. This laboratory setup is described in more detail in later sections. Ceyhan et al. (2021) presented a novel experimental method to determine the thermal performance of VIT used in oil and gas, where the experimental setup involved placing one or two VIT joints in an ice-water bath, with heated air flowing through the VIT. The temperature difference between the inlet and outlet of the VIT was measured, and the heat loss was calculated using the effectiveness-number of transfer units (ε-NTU) approach. This setup allowed for the measurement of both single-joint and double-joint VIT performance, capturing heat loss at connections and pipe bodies. The experiments revealed that approximately 80% of the total heat loss occurs at the connections between VIT joints, highlighting their critical role in overall insulation performance. Azzola et al. (2004) emphasized the importance of laboratory testing for the coupler and inner-to-outer column welds, where axial heat loss dominates. Future testing should aim to evaluate the thermal conductivity of an entire VIT assembly under varying operational conditions, including simulated geothermal environments with high pressure, temperature, and flow dynamics.

Limited data is available for field tests on VIT’s, however a study by Aeschliman (1985), showed that the presence of annulus water in injection well annuli introduces a real and economically important heat loss mechanism, however as mentioned this application differs to the annular conditions expected in geothermal systems. Another study by Gosch et al. (2004) provides valuable insights on a field performance evaluation using advanced fiber optic monitoring systems. Fiber optic technology was successfully employed to evaluate the performance of VIT systems in real time. The study showed significant heat losses at VIT connections, even with the use of insulation inserts and thermal coatings (Figure 4). These areas remain critical weaknesses in VIT systems, as thermal bridging at the joints undermines overall performance. Fiber optic data highlighted that the connections require advanced design improvements, such as better coating or alternative insulation methods, to mitigate these losses.

Another challenge faced with VIT’s is hydrogen permeation. This issue has the potential to significantly impact the long-term thermal performance of VIT systems. The process, described by Fick's law, involves hydrogen molecules contacting the outer steel surface, dissociating into atomic hydrogen, and diffusing through the steel. These hydrogen atoms recombine into molecular hydrogen inside the vacuum chamber, increasing its thermal conductivity and compromising insulation performance (Zhou et al., 2015). While hydrogen permeation has been tudied in oil and gas environments, its behavior under geothermal conditions remains uninvestigated. Mitigation efforts focus on the use of getter materials to absorb hydrogen or anti-permeation coatings to reduce hydrogen ingress.

Utilizing an alternative working fluid, such as $CO_2$, offers the possibility to mitigate hydrogen permeation by diminishing the presence of the hydrogen atom in the well; however, studies have demonstrated that water ($H_2O$) exhibits superior heat transfer properties compared to $sCO_2$, particularly in enhanced geothermal systems (Sfeir et al., 2024), however its applicability in CLGS remains to be tested and validated.

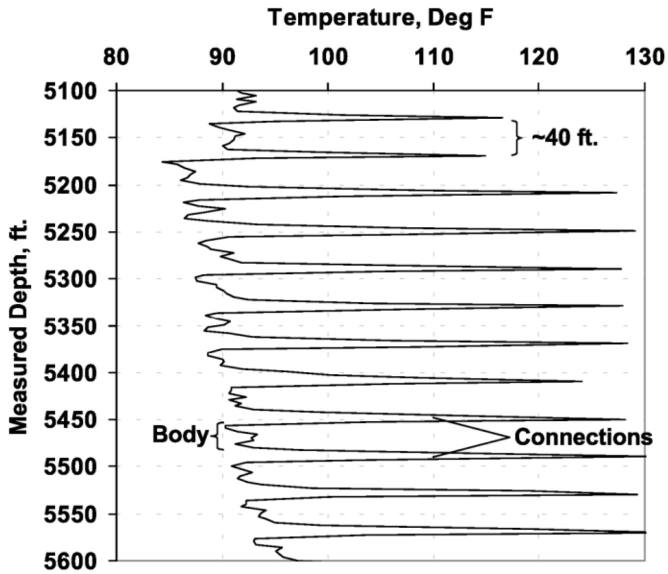


Fig. 5—Expanded view of a portion of Marlin Well A-6.

**Figure 4. Heat loss through connection – Marlin Well – fiber optic measurement (Gosch et al., 2004)**

### 3.3 Impact on geothermal systems performance

VIT enhances the thermal performance of geothermal systems by minimizing heat loss through its advanced insulation design, addressing all three primary heat transfer mechanisms: conduction, convection, and radiation. The evacuated annular space between the inner and outer tubes eliminates convective heat transfer, while the vacuum significantly reduces conductive losses. For conduction, the heat transfer rate is governed by Fourier's law, where the heat loss is directly proportional to the thermal conductivity of the material. VIT materials are engineered to have low thermal conductivity. The thermal energy production is also directly proportional to the temperature differential between the injected fluid and produced fluid. Therefore, reducing the thermal losses in the return tube proportionally increases the energy production (i.e. for a fixed injection temperature, a 10% decrease in the temperature drop, induces approximately a 10% increase in thermal energy production). This analogy highlights the importance of VIT performance on the global geothermal system performance.

## 4. KNOWLEDGE GAPS

As described in the literature review section above, several knowledge gaps are still limiting the broader application of VIT in geothermal systems. While significant research has focused on reducing thermal conductivity in the VIT main body, the connections between VIT joints remain a critical area of concern, as proved for oil and gas applications (annular pressure buildup, steam injection, permafrost prevention, etc.), but not yet proved for geothermal applications, where the physics and system conditions are different. Studies indicate that connections contribute disproportionately to overall heat loss, accounting for up to 70-80% of total thermal losses, in oil and gas applications, yet comprehensive numerical models and experimental data to fully characterize these losses under operational geothermal conditions are limited. Additionally, most VIT designs have been optimized for static applications, such as oil and gas wells, where the annular fluid is stationary. As Damour and Orberg (2018) highlighted, there are a lot of challenges in properly testing the thermal integrity of VIT when it comes to laboratory settings or field measurement. The VIT thermal performances can significantly vary in function of the external environment. In geothermal systems, particularly in coaxial CLGS configurations, dynamic fluid flow in the annulus introduces convective heat transfer effects that have not been extensively studied. The limited availability of field data hinders the ability to validate and refine existing models.

## 5. ADVANCES IN VIT DESIGN

Since the initial development of VIT by General Electric (Brown et al., 1980), VIT design has gone through many iterations. Many of these advancements have been aimed at increasing the effectiveness of the vacuumed annulus to improve the life of the VIT. One improvement was the addition of multiple layers of insulative wrap (MLI) around the inner pipe prior to assembly, added to mitigate radiative heat transfer. Another important advancement was the inclusion of getters to the vacuum annulus, as mentioned in the literature review. The following sections detail the current status of VITs, along with the new developments underway.

### 5.1 VIT connections

Connections are required for VITs, as with any tubing or casing joint, to form the entire tubing string. It is typically not feasible nor standard practice to use a single coiled tubing, or to weld every joint together for many reasons (operational, safety, and economic). This same industry standard applies to VITs, which are typically constructed of Range 3 standard pipe (~36-45 ft length). For standard applications (temperatures below 180°C), there are multiple connection options that can be used – from API buttress type threads to premium connections using metal-to-metal sealing surfaces and specialized threadforms to handle a different loading conditions. Applications requiring performance at temperatures higher that 180°C (typically expected in geothermal wells) must rely on a different type of connection validated and rated to such conditions. Another connection testing protocol, ISO/PAS 12835:2013, defines a testing program for higher temperature applications, the Thermal Well Casing Connection Evaluation Protocol (TWCCEP). At the time of writing this paper, the only VIT-applicable connections validated under such conditions are "premium" type connections. These connections were initially designed to withstand stresses expected to be seen in extreme conditions of some of oil and gas wells; however, not expected in geothermal applications, making these connections mechanically "over-engineered" for geothermal wells. The following sections present the required advancement and needs.

### 5.2 VIT mechanical considerations

The main mechanical failure mode of concern for VIT is in tension. The construction of VITs requires double-walled pipes, making them much heavier than a standard tubing string. Additionally, next-gen geothermal wells are expected to be drilled to larger depths (especially for superhot rock reservoirs), increasing the tensile loads on the connections. VIT can be constructed with a threaded connection on either the outer pipe or the inner pipe (Figure 5). Although the tensile load capacity is traditionally higher with the VIT configuration using an outer pipe threaded connection, this configuration is not typically preferred for geothermal applications due to the geometry of the connection. An outer-pipe threaded connection requires a female-female coupling, which increases the overall OD of the tubing string, leading to flow restrictions, undesired turbulences and heat losses (Figure 6). To increase the tensile capacity for an optimized VIT connection, the metal-to-metal sealing area is removed and replaced with additional threads.

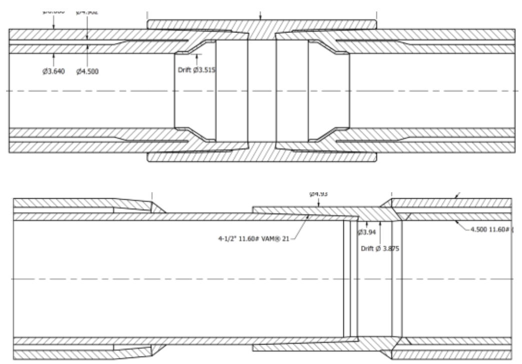

**Figure 5. Comparison between VIT models, with outer pipe threaded (upper) and inner pipe threaded (lower)**

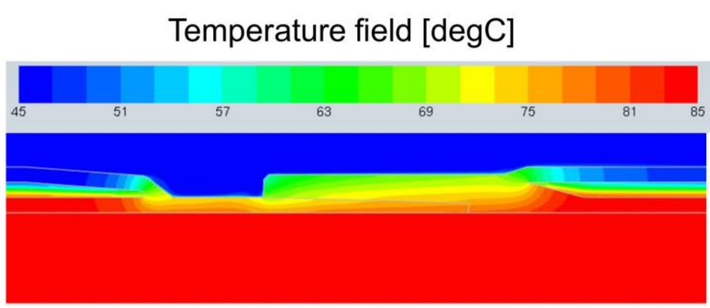


**Figure 6. Temperature distribution simulation using computational fluid dynamics (CFD) analysis**

For the improved VIT connection under investigation, this load flank contact area is higher than "premium" threaded connections, which require a metal-to-metal sealing surface to meet extreme sealing requirements for gases. This problem was studied via the Finite Element Method using the computer software Abaqus. The models use a 2D axis-symmetry hypothesis and include non-linearities regarding contact management and elastoplastic material behaviors. The simulated geometries include the threaded connection and two sufficiently long sections of VIT pipes. The simulations include a step for the assembly (make-up) of the connection, which is followed by a tensile step up to failure. To apply the tension, the end of the VIT pipe on the right side is fixed axially while an imposed displacement is applied on the end of the VIT pipe on the left side. The models allow to quantify the tensile resistance of the products and to monitor the progression of stress concentration and plastic strains in the cross critical sections. The increased support contact area is analyzed comparing the VIT optimized connection (red) with the standard premium threaded connection (blue), resulting in an estimated 40% increase of tensile capacity (Figure 7). Although the tensile limit of the connection is improved, the inner pipe is still restricted by its own geometrical limitations. To fully utilize the improvements to the connection, the tension loading must also be distributed between the inner and outer pipes. During typical construction of the VIT, the threaded connection is a separate component that is welded to both the inner and outer pipes at each joint end. By configuring the assembly with the intention of balancing load, a total capacity beyond the tensile limit of the inner pipe can be achieved.

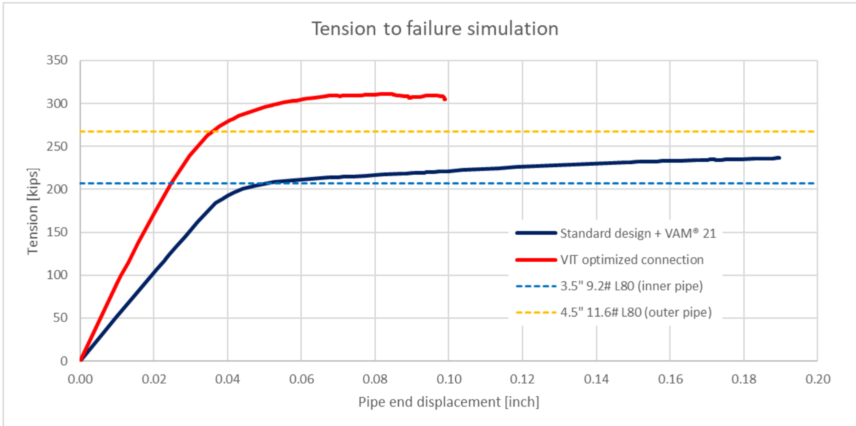


**Figure 7. Tensile load capacity comparison between standard premium connection (blue) and VIT optimized connection (red)**

### 5.3 VIT thermal considerations

The main objective of VIT is to provide thermal insulation between production and annular fluids. When comparing the average thermal conductivity values between carbon steel grades and VIT pipes (average of pipe body and joint), there is a huge difference in the values, 35 vs 0.04 W/m.K, highlighting the benefits VIT provides over standard steel tubing. The thermal conductivity of a VIT joint is the combination of the thermal conductivity of two VIT components: the double-walled vacuumed pipe and the connection. As discussed in the literature review section, the connection exhibits a much higher thermal conductivity than the rest of the pipe. To improve the thermal insulation of the connection area, the first option is to reduce the size of the heat loss window, i.e. the non-vacuumed area of the VIT pipe. In standard premium connection applications, this length is about 8 inches. As previously mentioned, this unvacuumed length equates for the majority of heat loss in the VIT system. Optimizing this window significantly reduces the overall thermal conductivity. For standard, low-temperature applications a PTFE sleeve can be installed over the connection to insulate this non-vacuumed length, usually gives a 50% reduction in thermal conductivity. However, this solution is unfeasible for deep geothermal applications. Which leads to the development of the "*geothermal-optimized design*", reducing the non-vacuum length from 8" for standard VIT connections to 1" for the *geothermal-optimized* connection design. The testing performed to quantify improvements in thermal performance are detailed in the following section.

## 6. LABORATORY AND NUMERICAL VALIDATION

This section presents the laboratory and numerical experiments performed on the new *geothermal-optimized design* for VIT connections, including methodology, data processing and results.

### 6.1 Laboratory testing

A dedicated test bench was constructed at the Vallourec R&D facility in Houston, TX, for the specific purpose of characterizing the thermal performance of VITs. The primary objective of this test bench was to be able to measure the impact of the connection on overall VIT thermal performance (Figure 8).

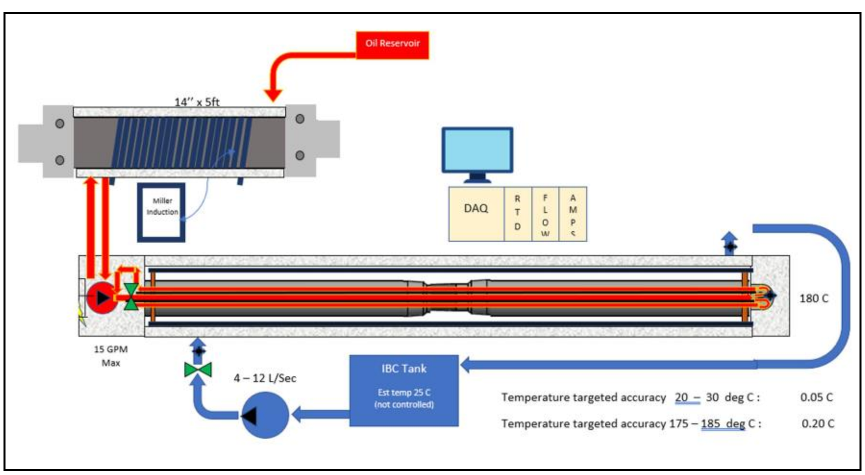


**Figure 8. VIT Test Bench Setup (Dufrene et al., 2024)**

Measurements included temperature differentials between the inlet and outlet of both fluids to calculate heat transfer and thermal conductivity. Tests were conducted across multiple flow rates (20 gpm to 50 gpm), with stabilized temperatures reaching 180°C. Results demonstrated consistent thermal conductivity calculations, highlighting the system's ability to replicate realistic conditions and accurately measure VIT performance. The testing apparatus and flow mechanism are shown in Figure 8 and Figure 9, respectively. Hot oil is circulated through the inner annulus (red annulus) of the VIT in a closed loop, acting as the heat source. The oil is pumped into the system via an inner shaft (installed inside the VIT annulus), down the length of the VIT joint, then circulates back outside the shaft. On the outside of the VIT (blue annulus), water flows along the length of the sample, tested at different flow rates, being the fluid under investigation for heat transfer (ΔT measurements).

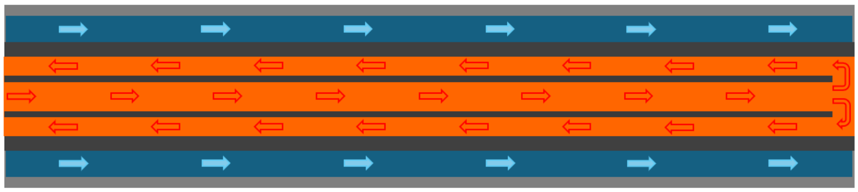

**Figure 9. Fluid flow in VIT test bench - Oil inside the VIT annulus (red) and water outside the VIT (blue)**

The test compared the two different connections in the same VIT configuration (4.5" 11.6# x 3.5" 9.2# L80). Each specimen consisted of two 20-ft (6.1m) segments that were made up for a total VIT length of 40ft (12.2m). Each connection configuration underwent testing at multiple different flowrates (2, 5, 10, and 20 gpm) to measure the impact of heat transfer between the VIT and the water (Table 1). The dominant heat transfer mechanism in this test is conduction, which is known for its transient nature. Therefore, water flowrates were chosen to impose enough residence time for adequate heat transfer; via an iterative trial-and-error process until the flowrates were large enough and heat transfer occurred (due to minimal residence time). The smaller flowrates, less than what is normally experienced in geothermal wells (within geometric proportions) provide an extreme case for scientific and contextual reasoning, allowing substantially more relative residence time than could be expected, and yet ascertain the thermal conductivity of the connection and the overall VIT joint.

Figure 10 shows the temperature drop measured at different flowrates, showing (1) decreased ΔT for the new geothermal-optimized design (red and purple), compared to the standard (blue), by around 40% for smaller flowrates, and down to 20% for larger flowrates (2) the measured ΔT decreases with increasing flowrates, until there is no difference due to minimal conductive heat transfer.

**Table 1. Testing program for VIT thermal test bench**

| Connection | Flowrate (gpm, kg/s), each flowrate tested twice | | | |
|---|---|---|---|---|
| Standard VIT | 2 gpm (0.13 kg/s) | 5 gpm (0.32 kg/s) | 10 gpm (0.64 kg/s) | 20 gpm (1.26 kg/s) |
| VIT geothermal optimized | 2 gpm (0.13 kg/s) | 5 gpm (0.32 kg/s) | 10 gpm (0.64 kg/s) | 20 gpm (1.26 kg/s) |

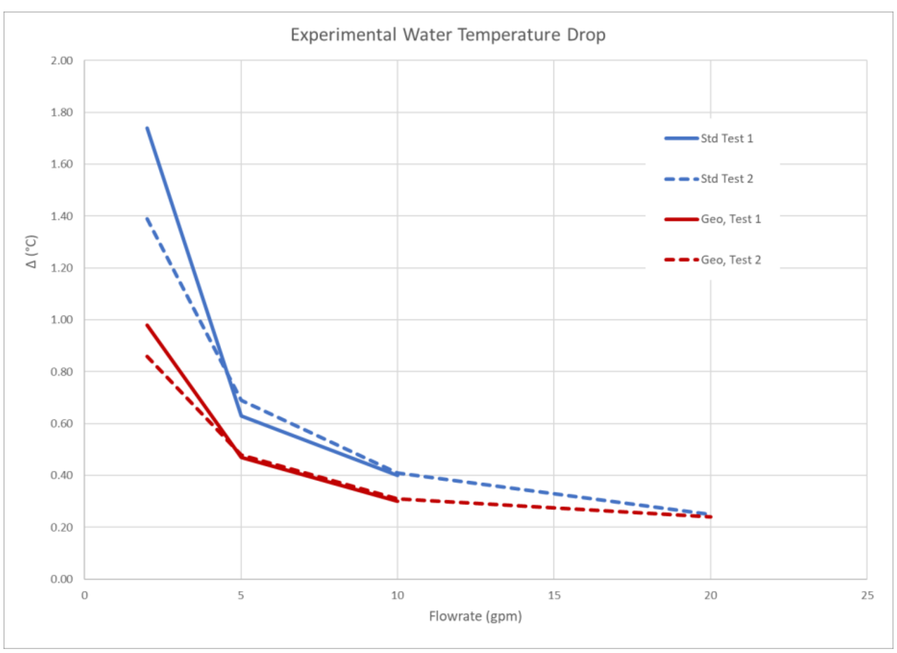


**Figure 10. Comparison of lab tests of standard connection (blue) with VIT optimized connection (red)**

### 6.2 Computational Fluid Dynamics (CFD) analysis

Simultaneously, a numerical investigation of the same problem was conducted. Computational Fluid Dynamics method was employed to this problem, replicating the laboratory setting to predict the results. The tool used for the CFD analysis is ANSYS Fluent 2024R1, using a 2D axisymmetric geometry approach. Although the physical geometry is not perfectly axisymmetric due to the positions of the water inlet/outlet in the annular section, this assumption has a minor impact on the overall fluid and thermal behavior. The flow was considered to be in a steady state, allowing for the analysis of the system's behavior over time without transient effects. To capture the effects of turbulence, the k-omega Shear Stress Transport (SST) model was employed, providing a robust and reliable approach for predicting turbulent flows. The inputs of the model were as replicative as possible to the properties of the physical testing bench, initial and boundary conditions. Figure 11 shows the 2-D temperature profile of the standard connection and geothermal-optimized connection. As predicted, reducing the non-vacuumed length of the connection reduces the heat loss window, leading to a decrease in the ΔT, improving the overall thermal insulation.

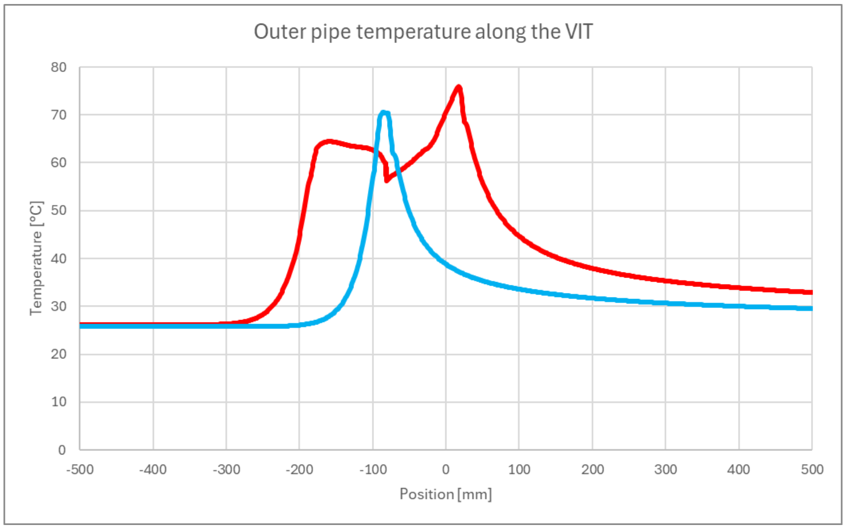


**Figure 11. Temperature profile comparison between standard connection (red) and geothermal optimized connection (blue)**

### 6.3 Comparisons between laboratory and numerical methods

The results obtained in the two methods are correlated in this subsection. Due to the instrumentation of the laboratory setting and the possible post-processing methods of the CFD simulation, the average ΔT was obtained at each connection and plotted in Figure 12. The results show that the two tests are within an acceptable agreement, with all but one data point (geothermal optimized connection at 2gpm) within 0.1°C. Even the outlying data point only shows a difference of 0.3°C, which will be further studied with more testing. Also comparing the standard and new VIT connection, it can be seen that there is no big difference at the 20 gpm datapoint, which will need to be further investigated in future experiments.

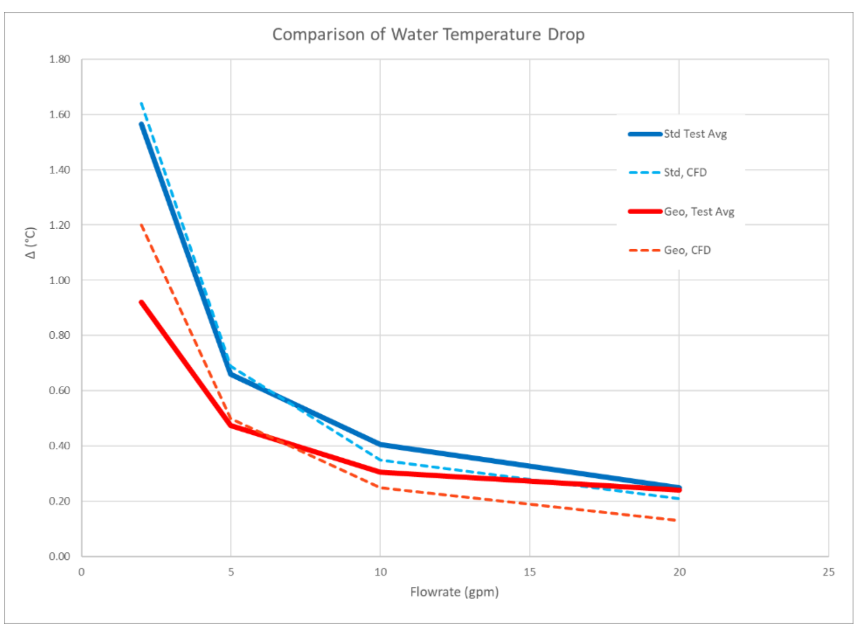


**Figure 12. Comparison of physical test results to CFD simulations**

The next step in this research is full calibration and validation of these tests in order apply such physics to a full-scale system. Numerical modeling of actual field measurement will be performed and matched, coupled with the data measured from the laboratory setting (VIT test bench), to verify the predictive performance of the lab testing and CFD modeling, for further future research and development efforts.

## 7. COUPLED RESERVOIR WELLBORE SIMULATION

Numerical simulation is a vital component of any technological development and advancement path, including evaluating the impact of VIT on the performance of CLGS. As mentioned earlier, VIT is designed to mitigate heat losses as the produced working fluid travels upward. A coupled wellbore-reservoir thermo-hydraulic simulation is one of the most effective and reliable approaches for studying such a problem. This section presents the work done as part of this research to investigate the impact of the VIT thermal properties on the overall performance of a single well co-axial CLGS. As this paper focuses on VIT's performance only, the most suitable evaluation metric is to compare the temperature drop from the bottom of the VIT to the surface ($\Delta$T).

### 7.1 Simulation overview

**Numerical Simulator -** This coupled wellbore-reservoir simulation employs Intersect, also known as Ix (SLB, 2024). Ix leverages modern numerical techniques, parallel computing, and advanced physics to simulate complex reservoir dynamics. It is particularly well-suited for handling highly heterogeneous reservoirs, advanced well configurations, and complex physics, including thermal and compositional processes. One of the tool's key capabilities is its Multi-Segment Wellbore module, which enabled the researchers in this study to employ user-defined Python scripts to model the co-axial CLGS (i.e. pumping cold fluid down the annulus, directing it through the VIT at the bottom of the well, and returning the heated fluid to the surface).

**Model Definition & Geometry -** The examined system comprises a single vertical well centered in a 3-D rectangular reservoir. The model is a 400x400x3000 (x-y-z) system composed of 425,556 gridblocks, with uniform size distribution in the reservoir and local grid refinement (LGR) within 25-m radius of the wellbore. Conservation of energy and mass is solved at every gridblock in a coupled manner between the reservoir porous media and the wellbore. The gridblocks size range from less than a meter in the vicinity of the wellbore to 20-m near the reservoir boundary. The simulation spans a period of 30 years, covering the expected lifespan of the geothermal well.

**Reservoir & Wellbore Properties -** The properties of the rock matrix are configured to replicate those of typical hot dry rock (HDR) environments, typically ultra-tight media, having low porosity and permeability. This translates into having conductive heat transfer as the dominant mechanism in transferring heat from the rock to working fluid in the sealed wellbore, with some convective heat transfer, and zero radiation. **Error! Reference source not found.** and **Error! Reference source not found.** provides in-depth information on reservoir rock and wellbore properties, in addition to relevant initial and boundary conditions. The well is 3-km deep vertical well, with a 12.25-in hole inner diameter, standard 9⅝-in casing, and 4.5-in tubing. Since heat transfer is mainly controlled by the solids material properties, the thermal conductivity of the cement plays a significant role in the results of the simulation and the output of the system. This parameter varies from wellbore to wellbore and is affected by many parameters related to the wellbore completion method. As this is beyond the scope of this study, a conceptual sensitivity simulation was performed to show the impact it can have on the system.

**Table 2. Reservoir properties, initial & boundary conditions**

| Reservoir Properties, Initial & Boundary Conditions | | |
|---|---|---|
| Reservoir Properties | Reservoir Thickness | 3 km |
| | Reservoir Permeability | 1 mDarcy |
| | Reservoir Porosity | 3% |
| | Natural Fractures | N/A |
| | Rock Thermal Conductivity | 3 W/m.K |
| | Rock Specific Heat Capacity | 900 J/kg C |
| Initial Conditions | Saturation | 100% H2O |
| | Pressure (hydrostatic) | 29,400 kPa @ 3000m |
| | Temperature | 25°C at surface |
| | | 100°C at 450m |
| | | 225°C at 1000m |
| | | 350°C at 3500m |
| Boundary Conditions | Flow | No Flow Boundary (impermeable) |
| | Pressure and Temperature | Far field constant P & T |

**Table 3 Wellbore properties**

| Wellbore Properties | | |
|---|---|---|
| Tubulars | Casing Thermal Conductivity | 44 W/m.K |
| | Casing Specific Heat Capacity | 460 J/kg.°C |
| | Tubing OD | 4.5 in |
| | Tubing ID | 3 in |
| | Tubing Insulation | VIT |
| Completion | Cement OD | 12 ¼ |
| | Cement Thermal Conductivity | 0.1-10 W/m.K |
| Geometry | Orientation | Vertical |
| | Depth | 3000 m |
| Initial Conditions | P & T | Same as reservoir |

**VIT thermal conductivity –** This parameter is the main purpose of this numerical investigation. There are 2 sets of analysis conducted. The first analysis is to showcase the role of VIT in such CLGS, i.e. comparing the performance of the system if a standard steel tubing (35 W/m.K thermal conductivity) were used, compared to a VIT (0.06 W/m.K). The second analysis assesses how the improvement of VIT thermal properties can affect the performance of the CLGS, by running simulations of VIT thermal conductivity values ranging from 0.02 to 0.08 W/m.K, at 0.02 increments.

**Operating Conditions –** This simulated duration is for 30 years, constantly injecting 2 kg/s of 50°C at the top of the annulus.

### 7.2 Simulation results

The first set of results in this subsection highlights the effect of the thermal conductivity of the cement outside the casing on the temperature of the produced fluid, i.e. on the overall performance of the system. This sensitivity is included to highlight the potential impact of this parameter on the overall CLGS performance. The three (3) simulated cases correspond to different cement thermal conductivities of 0.1 W/m.K, 1 W/m.K, and 10 W/m.K. For the case with a thermal conductivity of 10 W/m.K, the outlet temperature was the highest among the three scenarios, producing 198°C fluid after 30 years of circulation (blue curve in Figure 13). Then, the 1 W/m.K case had a lower outlet temperature of 186°C (green curve), a 6% drop when the thermal conductivity of the cement was decreased tenfold. However, when the cement thermal conductivity was reduced to 0.1 W/m.K, a greater difference was seen unlocking the non-linear relationship between the cement thermal conductivity and the heat mining mechanism in CLGS, where the temperature of the produced fluid at the surface was 123°C (red curve), a 33% drop after reducing the thermal conductivity of the cement by tenfold (from 1 to 0.1 W/m.K). These findings briefly show the impact of the cement thermal conductivity on the performance of a CLGS as this is a separate topic, but used to justify the input used in the next set of results where the impact of the VIT thermal conductivity was investigated, as a mediating case, a 1 W/m.K cement thermal conductivity was selected for the upcoming investigation.

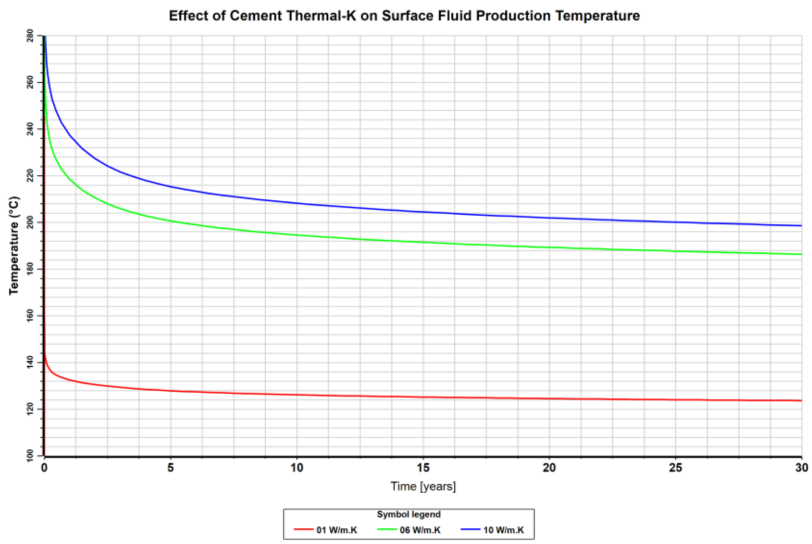


**Figure 13. Effect of cement thermal conductivity on surface fluid production temperature**

The second set of results focuses on the impact of the VIT on the performance of the CLGS by comparing temperature drops along the VIT from the bottom of the well to the surface. In the results shown in Figure 14, a simulation was performed assuming a non-VIT return tube, standard steel pipe with a thermal conductivity of 35 W/m·K (black curve). This case is used to highlight the importance of VIT on the success of CLGS. When comparing the black curve, to the colored curves (blue, green, purple and red), corresponding to different VIT return tubes, the difference between VIT and non-VIT is substantial, in terms of temperature drop from bottom to top, highlighting significant heat loss to the surroundings due to the high conductivity of steel. A temperature drop of around 122°C from bottom to top was calculated for the non-VIT tube, compared to values not exceeding 15°C for VIT return tubes. These values play a huge role in the feasibility and profitability of geothermal systems, underscoring the necessity of using VIT to maintain thermal efficiency in CLGS, and in most cases the technoeconomic sustainment of a project.

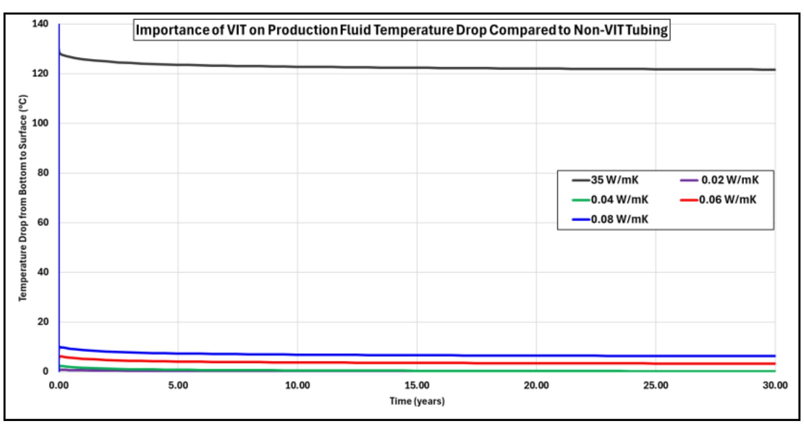


**Figure 14. Importance of VIT on production fluid temperature drop compared to non-VIT**

Figure 15 focuses on the thermal performance of VIT by analyzing cases with varying thermal conductivity values, excluding the non-VIT case to isolate the effects of VIT. The investigated range of 0.02–0.08 W/m·K represents current industry capabilities and potential advancements. The results reveal a progressive reduction in temperature drop along a 3-km vertical well as the thermal conductivity decreases. For the 0.08 W/m·K case, the temperature drop from the bottom of the well to the surface is 6°C, which is minimal but still impactful for production. Reducing thermal conductivity to 0.06 W/m·K halves the temperature drop to 3°C, showing a 50% improvement in temperature drop with a 25% reduction in VIT thermal conductivity. For 0.04 and 0.02 W/m·K cases, the temperature drop asymptotically approaches zero. These results emphasize the importance of reducing VIT thermal conductivity for energy efficiency, as even modest improvements significantly enhance system performance. However, asymptotic behavior indicates practical limits, beyond which further reductions may yield negligible benefits, guiding engineering efforts toward optimizing materials and manufacturing techniques.

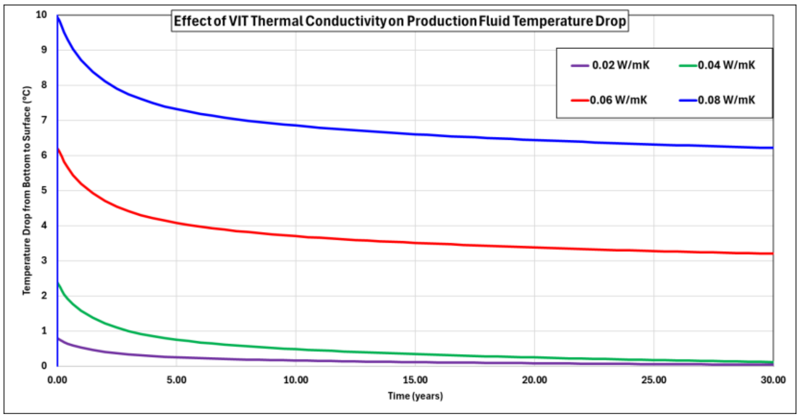


**Figure 15. Effect of VIT thermal conductivity on production fluid temperature drop**

As discussed in the literature review section, the overall thermal performance of the system may be compromised by the thermal properties at the pipe connections, which introduce thermal bridging effects and elevate the effective thermal conductivity of the entire pipe assembly. The VIT pipe body has a thermal conductivity value of around 0.002 W/m.K, however, the overall thermal conductivity value of the tubing along the well is increased, accounting for much higher values at the connection. The numerical investigation presented in this subsection highlights the critical benefits of addressing these challenges. By minimizing or eliminating the thermal inefficiencies at connections, the overall thermal conductivity of the pipe system can be significantly reduced, thereby enhancing its ability to retain heat over long distances. This aligns with the trends observed in the analysis of thermal conductivity reductions in Figure 15, where even incremental reductions in thermal conductivity yield substantial performance gains. Overcoming these connection-related challenges would allow the system to approach the near-ideal performance of the VIT. This model does not model explicitly model the connections, but accounts for it implicitly in the overall thermal conductivity value selected. Future work will include developing a modeling methodology to include the connection as part of the modeling process.

## 8. CONCLUSION

This paper emphasized the important role played by VIT in geothermal systems, specifically in next-gen systems such as CLGS. The existing literature on the properties of VITs, current state of art, limitations and challenges were covered. This paper's objective was to highlight the role that the VIT connections may or may not play in next-gen geothermal systems. These components were initially developed for applications where the annular area would be in static condition the majority of the time. Whereas this is not the case for next-gen geothermal, where a dynamic annulus is expected, convective heat transfer may play a role at the connection. For this reason, current R&D efforts at Vallourec are tackling this phenomenon via analytical, numerical, laboratory, and field measurements in order to create a better understanding of this phenomena and assess its relevance. This paper showed that in an experimental setting, validated by numerical simulations (CFD), the improvements in VIT connections have been validated, demonstrating significant enhancements in thermal performance. In addition to this, coupled reservoir-wellbore thermo-hydraulic simulations showed the impact of the overall VIT thermal properties on the thermal performance of co-axial CLGS. These promising results will be further corroborated by full-scale testing, ensuring the reliability and effectiveness of the new connection in real-world applications. The successful validation of this innovative connection technology establishes a highly efficient VIT solution, which is poised to potentially play a crucial role in the deployment of next-gen geothermal systems, especially in superhot rock reservoirs.

## ACRONYMS

CFD – Computational Fluid Dynamics
CLGS – Closed Loop Geothermal System
EGS – Enhanced Geothermal System
ε-NTU – Effectiveness-Number Transfer Units
FEA – Finite Element Analysis
SST – Shear Stress Transport

VIT – Vacuum Insulated Tubing

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