Department Petroleum Engineering

Master's Thesis

Pulsed plasma coiled tubing drilling in crystalline rock environment

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May 2022

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Master Thesis 2022

Petroleum Engineering

Pulsed plasma coiled tubing drilling in crystalline rock environment

Supervisor: Univ.-Prof.Dr. Mikhail Gelfgat

Chair of Petroleum and Geothermal Energy Recovery

I dedicate this master thesis to my girlfriend and my family for giving me all the necessary support in finishing my long-lasting studies.

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Abstract

Geothermal energy is related to the thermal energy stored in the Earth's crust and it originates from the radioactive decay of materials and from the planet's formation. There are a couple of ways of utilizing geothermal energy. The most common classification is deep and shallow geothermal systems. The feasibility of such systems depends mostly on the geothermal gradient and accessibility of the aimed reservoir. Due to the high temperatures in greater depths (which are mostly aimed at geothermal projects), a well construction can be challenging. This challenge is highly affected by the thermal effects, chemical properties of the circulated fluid, and production rate. The heat which is contained in such depths is necessary to bring to the surface, that is why, there is a special emphasis on the well design and well integrity, as well as the materials being used.

Before designing the well, it is needed to describe what kind of the geothermal system is going to be approached. Otaniemi project, which is going to be discussed in this thesis, is an Enhanced Geothermal System (EGS). This kind of system needs to be stimulated in order to make a fracture system, because of enhancing the permeability of the same. Afterward, the circulated medium (water or CO2) is pumped from the injection well through the fractured system, where the fluid extracts the heat from the rock, and it migrates towards the production well.

In order to utilize such projects, very often it is needed to reach great depths, where the drilling cost takes the biggest amount of the financing part. That is why there is a desire to reduce the cost of drilling in order to reach such depths and make the deep geothermal projects financially acceptable.

Pulsed plasma drilling is a new developing technology utilizing the coiled tubing concept, which aims to reach such great depths with lower costs in order to utilize various geothermal projects around the world. The working principle of this technology is using a contactless plasma bit, which develops electrical discharges in order to disintegrate the rock in the subsurface. This method will be discussed as a possible technology to enable the more economically viable geothermal energy production. The advantage of this drilling method is a higher rate of penetration and reduced tripping time. The latter is explained by using coiled tubing (continuous pipe) drilling technology compared with the separated pipes in the conventional drill string. Another potential benefit could be the increased running time of the

bit, compared to the conventional ones, due to the avoidance of the mechanical impact on the formation.

Zusammenfassung

Geothermie ist verwandt mit der in der Erdkruste gespeicherten Wärmeenergie und entsteht durch den radioaktiven Zerfall von Materialien und durch die Entstehung des Planeten. Es gibt verschiedene Möglichkeiten, Erdwärme zu nutzen. Die gebräuchlichste Klassifizierung sind tiefe und flache geothermische Systeme. Die Machbarkeit solcher Systeme hängt hauptsächlich vom geothermischen Gradienten und der Zugänglichkeit des angestrebten Reservoirs ab.

Aufgrund der hohen Temperaturen in größeren Tiefen (die meist auf Geothermieprojekte abzielen), kann ein Brunnenbau eine Herausforderung darstellen. Diese Herausforderung wird stark von den thermischen Effekten, den chemischen Eigenschaften des umgewälzten Fluids und der Produktionsrate beeinflusst. Die in solchen Tiefen enthaltene Wärme muss an die Oberfläche gebracht werden, weshalb besonderes Augenmerk auf das Brunnendesign und die Brunnenintegrität sowie auf die verwendeten Materialien gelegt wird.

Vor der Planung des Bohrlochs muss beschrieben werden, welche Art von geothermischem System angefahren werden soll. Das Otaniemi-Projekt, das in dieser Arbeit diskutiert wird, ist ein Enhanced Geothermal System (EGS). Diese Art von System muss stimuliert werden, um ein Fraktursystem herzustellen, da die Permeabilität desselben verbessert wird. Anschließend wird das umgewälzte Medium (Wasser oder CO2) aus der Injektionsbohrung durch das Kluftsystem gepumpt, wo die Flüssigkeit dem Gestein die Wärme entzieht und in Richtung Produktionsbohrung wandert.

Um solche Projekte zu nutzen, müssen sehr oft große Tiefen erreicht werden, wo die Bohrkosten den größten Teil der Finanzierung ausmachen. Aus diesem Grund besteht der Wunsch, die Bohrkosten zu senken, um solche Tiefen zu erreichen und die Tiefengeothermie-Projekte finanziell tragbar zu machen.

Das gepulste Plasmabohren ist eine neu entwickelte Technologie, die das Coiled-Tubing-Konzept nutzt, das darauf abzielt, so große Tiefen mit geringeren Kosten zu erreichen, um verschiedene geothermische Projekte auf der ganzen Welt zu nutzen. Das Arbeitsprinzip dieser Technologie ist die Verwendung eines berührungslosen Plasmameißels, der eine hohe Temperatur entwickelt, um das Gestein im Untergrund zu zerkleinern. Dieses Verfahren wird als mögliche Technologie diskutiert, um eine wirtschaftlichere geothermische Energieerzeugung zu ermöglichen.

Der Vorteil dieser Bohrmethode ist eine höhere Eindringgeschwindigkeit und eine reduzierte Auslösezeit. Letzteres erklärt sich aus der Verwendung von Coiled Tubing (Endlosrohr)-Bohrtechnologie im Vergleich zu den getrennten Rohren im herkömmlichen Bohrstrang. Ein weiterer potenzieller Vorteil könnte die längere Laufzeit des Meißels im Vergleich zu herkömmlichen Meißeln sein, da mechanische Einwirkungen auf die Formation vermieden werden.

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Chapter 1

Introduction

Geothermal energy is showing more often, by the technology development, that it is taking a place in energy transition from fossil fuels system towards a sustainable one. To take a bigger part, it is inevitable to move forward with many sorts of technologies. (D. Moya 2018) The biggest advantage of this kind of energy is its continuity throughout a great period of time, because of its independence of the meteorological conditions. Another advantage is a relatively small footprint in comparison to other renewable energy sources, such as wind and sun power plants.

The energy by itself is contained in the Earth's crust. That heat is generated by the decay of radioactive isotopes of uranium (U^{238}, U^{235}), thorium (Th^{232}) and potassium (K^{40}) which are present in the Earth. (M.H. Dickson 1995) Therefore, geothermal energy is considered as a renewable source of energy. Throughout the geological setup of Earth's subsurface, the heat, contained in the same, varies. It mostly depends on the phenomena named geothermal gradient, which briefly describes the potential of the geothermal energy utilization. In the other hand, geothermal potential is mostly defined by the cost efficiency, of the heat extraction. This generally depends on the temperature, depth, fluid flow, geothermal system which is in use and the surface processes. (Huenges, Geothermal Energy Systems: Exploration, Development, and Utilization 2010)

The upper mentioned criteria are a technical, environmental, and economic point of view. In the other hand geothermal reservoirs can be seen as highly pressurized and heated water and/or vapor accumulations, which can be extracted from the subsurface and used as a source of energy. To extract the geothermal energy, it is necessary to understand certain phenomena. First of them is a heat conduction, where accordingly to the second law of thermodynamics, the heat moves through the material from the hotter to the cooler zone (Huenges, Geothermal Energy Systems; Exploration, Develeopment and Utilization 2010). The second phenomena are the heat convection of the transported hot material to the surrounding. These two phenomena are the first order of importance in exhibiting high gradient reservoirs. The other important reservoir properties are porosity and permeability of the rock. They are directly connected to the ability of the fluid to flow through the pores and fractures within the reservoir.

Therefore, three properties which directly influence the potential to extract the geothermal energy from the Earth's subsurface are: the permeability, the heat content and heat carrier fluid. Among these parameters, only the fluid flow and the permeability of the rock can be enhanced or engineered.

The nature of mentioned properties is the basis for the distinction between the conventional and unconventional geothermal systems. To utilize geothermal energy, it is necessary to have a formation with the sufficient permeability, high heat content and the fluid that will carry out that heat to the surface. Conventional geothermal systems are types of systems that naturally have the necessary properties. Therefore, the heat is carried out of the system with the naturally occurring fluid in the porous and permeable reservoir. Based on the temperature of the reservoir, the conventional geothermal systems are divided into seven groups (grades). Non-electrical grade (<100°C), very low temperature (100°C to <150°C), low temperature (150°C to 190°C), moderate temperature (190°C to <230°C), high temperature (230°C to <300°C), ultrahigh temperature (>300°C), and steam fields (approximately 240°C with steam as the only mobile phase). Whereas in the first four groups, only the liquid is the mobile phase and in the last two, the mobile phase can be a mixture of the vapor and the liquid. These systems, like oil and gas ones, occur on specific locations. In that manner, they are economically and technologically possible to reach, but not everywhere in the world. (M.Y. Gelfgat 2021)

In the other hand, there are unconventional geothermal systems, in which at least one of the necessary properties (permeability, heat content, heat carrier) is missing. These systems are not limited to the specific location, but they are rather expensive and hardly feasible, due the current deficiency of necessary technological solutions. Such deep subsurface systems are high pressure and temperature environments. Because of the deficiency of some parameters these systems can be Hot Dry Rock (HDR) or Hot Wet Rock (HWR) formations. Hot-Dry Rock is a geothermal concept, as its name states, is a type of a high temperature reservoir containing a small quantity of fluids or no fluids at all. The thermal energy is contained within hot, but essentially dry and impervious crystalline basement rocks found almost everywhere, deep beneath Earth's surface. Hot Wet Rock is a hydrothermal system, unlike the HDR. It is a high temperature subsurface sedimentary or metamorphic, low permeability formation, which is containing fluid. (M.Y. Gelfgat 2021) .Oil and gas society, has an experience in reaching such depths, but the utility of these projects, is most of the time questionable. Therefore, it is necessary to investigate the scalable geothermal concepts, in order to enable a sustainable energy production anywhere. Furthermore, it is necessary to explore new drilling technologies. Concepts such as Enhanced (Engineered) Geothermal Systems (EGS) require deep drilling practises. That is why the support of new drilling technologies is needed. The problem arises when the word is about the hard formations which are overlaying the aimed targets with the wanted properties.

As there is a common need in the world, to go after the clean and green sources of energy, oil and gas companies started to be interested in such goals. Especially in Europe, mainly because of new policies of becoming resource-efficient, green, and competitive low-carbon economy (European Comission 2020). The new course gives an opportunity for developing new technologies to reach requested goals. Geothermal energy for sure, can contribute to reach such goals, mostly because it has a potential to be present anywhere and can be continuously productive.

Over past couple of decades, geothermal industry, as well as oil and gas industry, strived to answer how to reach geothermal sources more easily and efficiently exploit these energy sources. Some of the solutions which might be the answer to make geothermal energy more efficient are Enhanced Geothermal Systems, where the heat is extracted from deep impervious formations. Even tough, the construction of a geothermal well is like the oil and gas ones, the problem occurs when drilling into deeper zones. As going deeper, the pressure and temperature arises, and the current technology cannot cost effectively follow such demands.

Furthermore, the most geothermal reservoirs include hard rock types such as granite, quartzite, greywacke, basalt, rhyolite, and volcanic tuff. These types of rock are hardly penetrable, with a low permeability, and with no or with a very low quantity of fluid which can be produced. In the other hand, comparing to sedimentary formations the temperatures, are considered high. Also, they are abrasive, with high compressive strength and may be fractured. All these issues are making the drilling process of geothermal wells rather difficult and expensive. (J. Finger 2010)

Therefore, the policy of many countries in the world is to aim for the sustainable and green energy. Geothermal energy can be found anywhere, but there are still many questions to be asked and many answers to be given. It is inevitable, between many scientific disciplines, to cooperate. Still many geothermal systems are unconventional, in other words, not ready to be used commercially. Many of those are hardy reachable, and as already mentioned very expensive, which directly influences the feasibility of that kind of energy consumption. In the other hand, there is a great will within the scientific society, to utilize geothermal energy in much wider spectrum and finally to provide it anywhere.

There is a wide variety of benefits, by using the geothermal energy. Its utility depends on the amount of energy stored in a reachable location, whether the energy will be used directly or for electricity production (or combined). According to the Geothermal handbook developed by the Energy Sector Management Assistance Program (ESMAP), the World Bank Group (WBG), eight stages of developing the geothermal project have been established (*Figure 1)*. (D. Moya 2018)

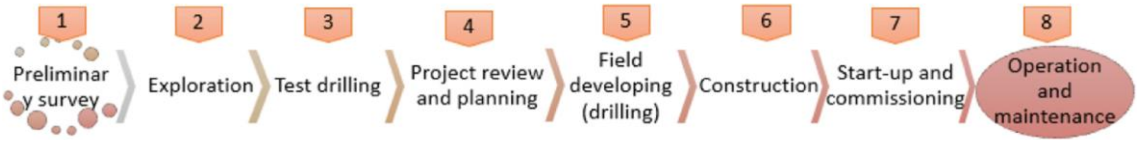

Figure 1 Schematic representation of the eight stages of geothermal development by ESMAP-WBG (D. Moya, 2018)

Based on the amount of energy stored and its availability, when the word is about the electricity production, there are five power plant configurations, classified into two groups. Steam cycles, which are extracting energy from the higher well enthalpies and binary cycles for lower enthalpies. The mentioned powerplant configurations are: 1. Dry steam, 2. Single flash, 3. Double flash, 4. Binary and 5. Advanced geothermal energy conversion systems. All the power plant configuration systems, differ themselves based on the energy conversion schemes. Some of them are more efficient than the others, which mostly depends on the enthalpy stored in the heat carrier. Except the electric power generation, there is a direct use of geothermal energy in the terms of heat. There is a wide spectrum of direct utilization, from geothermal heat pumps, space heating, greenhouse heating, aquaculture pond heating, industrial uses and others. In the following *Figure 2,* is a diagram of direct geothermal applications, based on the stored temperature and phase ratio

1.1 Unconventional geothermal systems

Unconventional geothermal systems are considered as those which do not contain enough heat carrier fluids or sufficient permeability, or both. Therefore, in order to extract the energy, certain engineering system modifications are needed. The design parameters and criteria for a certain system, are determined by the economic objectives. Hence, these objectives are then tailored by taking into consideration the in-situ field conditions. Before creating the reservoir, parameters which should be addressed are the reservoir temperature, geology, stress regime and in-situ fluid. In the first row of engineering parameters, when the word is about unconventional geothermal systems is the fracturing process. This process directly influences the reservoir creation and, in those terms, should provide the enhancement of the energy extraction (R. Baria 1999). Systems, with such reservoir parameters can be found more often than the conventional ones, but the economical accessibility becomes questionable. Therefore, the potential of the unconventional geothermal systems is great, but further research is needed in order to fulfil that potential.

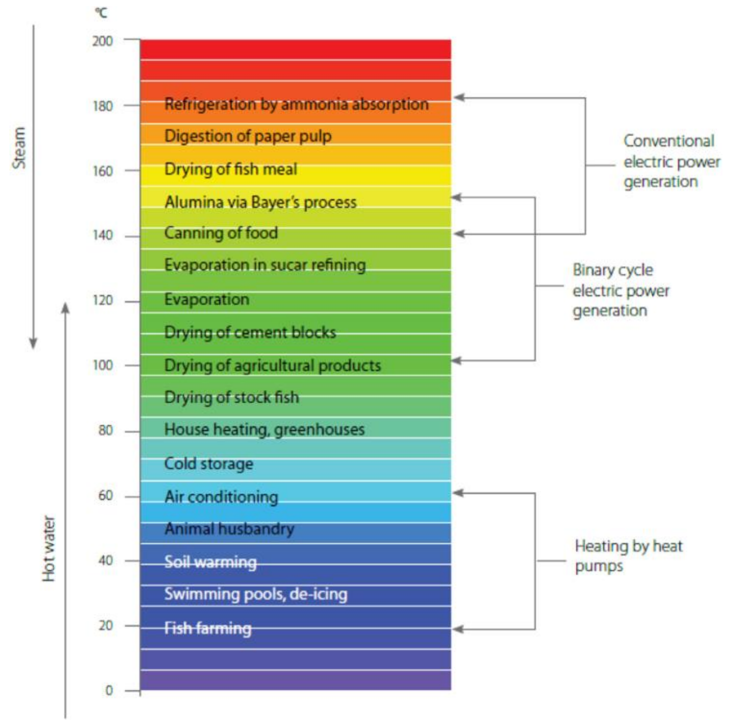

Figure 2 Lindal diagram for direct geothermal applications (D. Moya, 2018)

1.1.1 Supercritical (deep volcanic) hydrothermal systems

Supercritical conditions, in this term, is the aim to achieve for these kinds of systems. This involves drilling into greater depths than the two-phase systems are, with the fluid temperature above 373°C and 220 bars, which are supercritical water properties. Supercritical geothermal systems are attractive, due the power output which they can give, due to the high enthalpy (>3000 kJ/kg) they contain. The power potential of such wells will be in the order of 50 - 70 MWe, which is much higher than any conventional geothermal well. With these properties the difference between the liquid and steam phase disappears, the fluid becomes single-phased with high enthalpy.

The only project of such scope was held in Iceland, better known as the Icelandic Deep Drilling Project (IDDP). The target of the research well (RN-15/IDDP-2) was reached in 2017, at a depth of 4.5 km, with the measured bottomhole temperature of 426°C and the fluid pressure of

34 MPa, after six days of heating. This project was extremely challenging because of the extreme formation configuration. However, the purpose of this project was to find out if it is economically feasible to extract energy and chemicals out of hydrothermal systems at supercritical conditions. Therefore, the first milestone has been reached by completing the IDDP-2 well. Because it is the first well which has successfully encountered the supercritical hydrothermal conditions, with high-power output. The project is, by the time of writing this thesis, carrying out the flow testing and fluid sampling in order to determine the chemical and thermodynamic properties of the formation fluids. (G.Ó. Friðleifsson 2017). *Figure 3* is illustrating the IDDP.

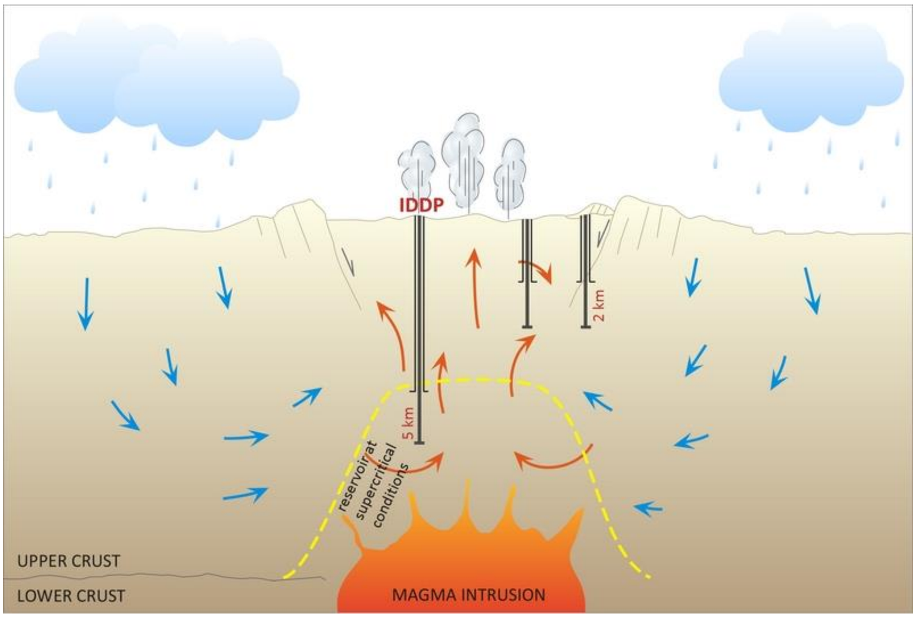

Figure 3 Iceland Deep Drilling Project (Orkustofnun, 2022)

1.1.2 Enhanced geothermal systems (EGS)

The concept of the enhanced geothermal system is of a big interest for a further development due to its high energy production potential. This kind of the geothermal system consists of a hot dry rock (HDR), with a very low permeability, which was not fractured naturally. Therefore, it is needed to fracture the rock, in order to enhance the permeability of the system. The main aim is to extract the heat from the rock with the working fluid. The working fluid (mainly water or CO_2) is then pumped from the injection well, through the before made fractures of the hot rock. While migrating, the fluid extracts the heat from the rock, and moves further towards the production well, where is going to be produced.

To utilize an EGS project, it is needed, first, to find a suitable location where the temperature is as high as possible. Also, unlike the other geothermal systems, the aim of the EGS is not to find an appropriate reservoir, but to find a site with a sufficient temperature. Except the temperature, it is inevitable to analyze the depth of the targeted rock, because the well must be constructed, which is the biggest stake of the financial part of the project. The fact that, it is not of the biggest importance to find an appropriate reservoir, but to find the rock with the high temperature, grows the worldwide geothermal potential exponentially. The next step should be to drill the exploratory well to examine the downhole properties. This well can afterwards be repurposed for an injection or a production well, which depends on the results which have been summoned. The next step is to conduct the tests, which will determine the rock properties of the aimed reservoir. Among these tests, the most important is the “mini-frac”, i.e., a small hydraulically created fracture which should show the surface tension on the given spot. Afterwards it is important to obtain the data about the rock’s permeability and potential productivity.

Once, all the data have been collected, it is possible to start drilling the injection well. After reaching the wanted point of the reservoir, the stimulation can start. In order to fracture the reservoir, it is important to pump the specific fluid at the high pressure and high flow rate. During the stimulation, the well should have a high-quality seismic monitoring system to monitor the stimulation stages constantly. The main purpose of rock fracturing is to create pathways so the working fluid can circulate through the fracture network. When the fracture network is finally completed it is necessary to construct the second well and its fracture network, which will be interconnected with the previous one. By circulating, the fluid extracts heat, and migrates to the production well. (P. Olasolo 2016) When it is brought up to the surface through the production well, the heat carrier fluid usually goes through the sand removers in order to prevent potential scaling and erosion pipe problems. Then it is directed through the evaporator and preheater, where the working fluid (with the lower boiling point) is heated. The working fluid is heated to the boiling point in the preheater and afterwards emerges as a saturated vapor while in contact with the evaporator. Afterwards, the saturated vapor expands in the turbine, condenses, and returns to the evaporator. The initial carrier fluid in the meantime is injected back to the rock and is being re-heated The explained heat extraction process is known as the Organic Rankine (binary) cycle, and is mostly used for lower enthalpy resources, with the temperatures ranging from 85°C – 170°C. (D. Moya 2018) The working fluid is used because of its corresponding properties, with lower boiling point and high vapor pressure (*Figure 4*).

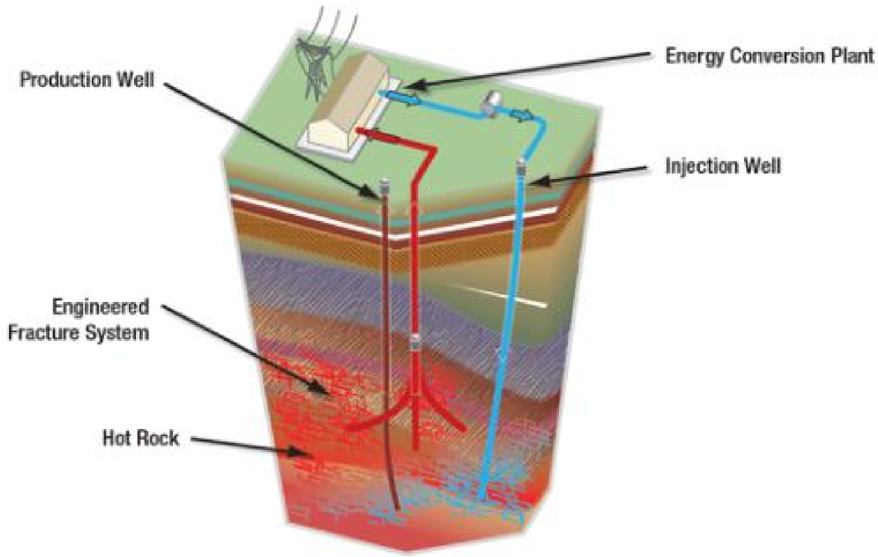

Figure 4 Basic layout of an EGS type geothermal plant purposes for being used (P. Olasolo, 2016)

The better understanding of enhanced geothermal systems has begun after completing the Soultz-sous-Forêts project in France, in 2008. The reservoir is drilled in a Paleozoic granite formation, with three 5000 m deep wells where the temperature has reached 200°C. The main goal of this project was to show the potential of this energy source retrieved from different geological conditions in Europe, and therefore attracting investors (*Figure 5*).

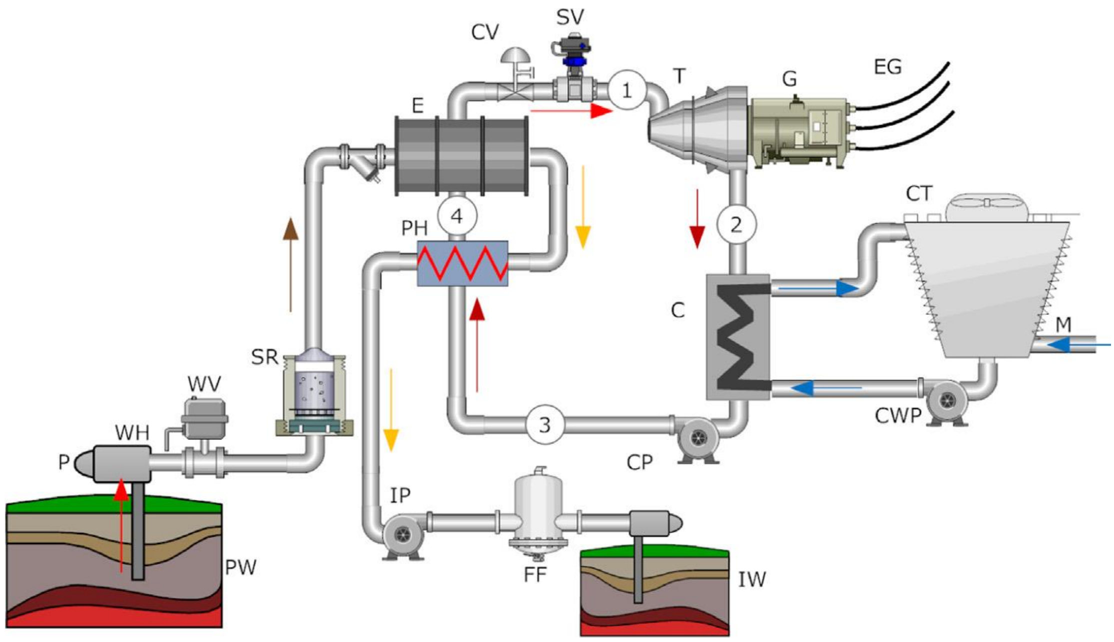

Figure 5 Basic binary geothermal power plant (D. Moya, 2018)

1.1.3 Closed-loop systems

The complexity of constructing the enhanced geothermal system, first from finding an acceptable subsurface environment, then to satisfy the legislative, can postpone the project finalization. The systems can be expensive, mostly because of the power input which need to be considered. Furthermore, the reservoirs need to be stimulated and therefore need to accept certain requirements. Also, the working fluid in that manner, through the circulation process in small quantities can be lost. In the other hand, there is another known system, which needs more research and development efforts for commercialization. The closed-loop system (CLG) overcomes the permeability and flow issues of the circulating fluid. This technology presumes working fluid continuous circulation (water or carbon dioxide), through the sealed pipes in the wellbore, and therefore collects the heat from the subsurface formation, from which the power can be produced. Something similar is commercially used within ground source heat pump geothermal applications, but there is no possibility to produce electricity by using this system.

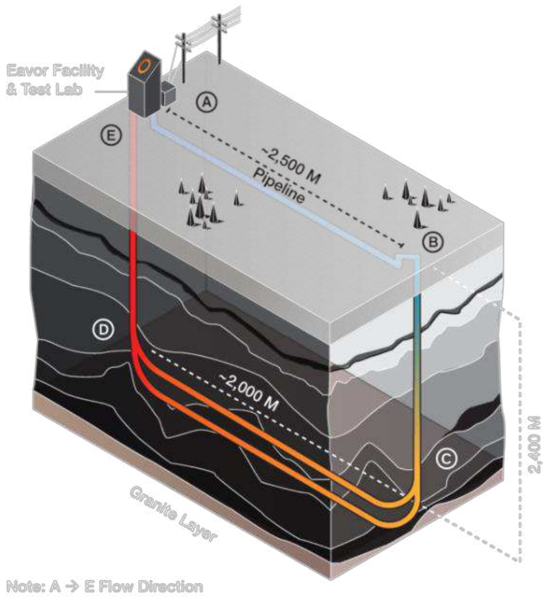

Figure 6 Eavor-loop system (Eavor technologies 2020)

The fact that the structure of this technology is closed and sealed gives an opportunity to operate within the big variety of temperatures. The application by itself can vary from low temperature sedimentary rocks to hot-dry rock formations. Even to extremely high temperatures, which can provide supercritical values for the working fluid. As it is already known, these conditions increase the final power output. Furthermore, there is no direct contact between the rock and the working fluid, nor production directly from the rock, and therefore there is no production of greenhouse gasses. This makes operating expense with lower value, as there is no need of installing necessary surface facilities to purify the produced fluid. (Horn 2020). Different concentric pipe-in-pipe and multilateral, sealed, U-loop configurations can be used to optimize site specific costs and performance.

Closed-loop geothermal systems, as already mentioned, allow using supercritical carbon dioxide (CO_2) as a working fluid. Supercritical CO_2 becomes desirable as the physical properties, at this state change, and become extremely convenient for this purpose. With the critical values of 31°C and 73.8 bar, CO_2 expands like gas with the density of a liquid. The demonstration of a closed-loop geothermal system with the supercritical CO_2 was made by the company GreenFire Energy. They showed how a down borehole heat exchanger (DHBHX) can extract enthalpy from deep wells in hot dry rock environment. They have made a simple tube-in-tube assembly installed in the existing well. (A. Amaya 2020). By using CO_2 as a medium there is no need to instal the external pump as its application is based on creating a strong thermosiphon effect and therefore eliminating the potential parasitic power input which needs to be considered.

Furthermore, there is also a closed-loop multilateral-pipe energy system developed by a Canadian company Eavor (*Figure 6*). They are developing systems to produce both power and heat supply. This technology is based on circulating the added fluid into the closed-loop system where it has been circulated and heated through the system. Unlike the previous mentioned types, this Eavor-loop consists of two pairs of horizontal wells, joined by horizontal branches connected and sealed by the pipeline on surface. First the two horizontal boreholes need to be drilled and connected, by shaping the “U” well. The multiple laterals are drilled, connected, and sealed, from the existing “main” horizontal boreholes. To increase the efficiency of the whole system, another symmetrical pair needs to be made. The loop is finally made on the surface, by connecting the wellheads of the vertical parts of the system. With this final stage, it is succeeded to achieve the thermosiphon effect, which excludes the need of external pumps, and therefore reduces the parasitic load. The following table 1 shows some of the differences between the use of the closed-loop geothermal system and the enhanced one in risk manner. It is consisted of three columns, where the first one is showing the risk element, where the following geothermal system can have.

Risk Element	EGS	CLGS / DCLGS
Induced seismicity	Reported at some sites. Can be under control without environment damages (e.g., Basel, Switzerland and Pohang, South Korea)	None expected
Natural seismicity (energy plants can be fragile, e.g., Fukushima, Japan)	Plants are simple and robust (e.g., geothermal plant in Fukushima survived earthquake and tsunami)	Robust
Surface subsidence	Reported at some sites, but most likely not at HDR fields. Effect is common for the gas fields and considered for every of Underground Gas Storages. With proper monitoring not critical for operations	None expected
Fluid use / losses	Potentially high losses if open system leaks into fracture system (could be a way to sequesterCO2 if used as circulating, heat exchanging fluid)	Small for H2O-based systems, none for sCO2
Water pollution	Reported at some sites	None/small (depending on completion)
Surface gas emissions (H2S, CO2)	Significant with flash tanks and measurable in binary cycles	None/minor potential of H2S, CO2 leaks (depending on cased hole or open hole completion)
Mineral scaling in pipes	Well integrity and flow assurance often compromised. Can be improved by tubing material(coating) selection	None/small (depending on cased hole or open hole completion)
Permeability maintenance, fracture network plugging	Rendering energy extraction less efficient	Not applicable
Prediction of energy production over time	High uncertainty due to fracture plugging, geomechanical changes, etc.	Highly calculable operation, reliable over long time periods

Table 1 Comparison of risk profiles of EGS vs. CLGS (M.Y. Gelfgat, 2021), (E. van Oort, 2021)

Chapter 2

Pulsed plasma coiled tubing drilling technology

To start with the well design, it is needed to collect a big variety of information. Regardless, sometimes it is not possible to have all of them. The desirable information includes the following parameters. First, it is needed to distinguish what is the purpose of the well, whether it is a production, injection, or an exploration well. Because the well design in the end is influenced by its purpose. Second, what are the subsurface conditions. It is of great importance to know, lithological and stratigraphic wells sections, including the shallow formations, temperatures and where the targets are. Furthermore, the information of reservoir conditions is of the big importance for planning the well design. The temperatures, pressures and especially the fluid chemistry influence the decision of picking up the proper material. The utilization of such projects is challenging, as the aimed depths are very deep (6-10 km), where the lower horizons are impermeable crystalline basement rocks.

All the mentioned criteria affect only the technical challenges that in the end have an impact on the final cost of the well. Another impact on the final project price are the large diameters of both, the hole and the casing which are required to provide the sufficient flow rate on the surface. Another issue which makes the cost of the geothermal projects higher is that, for especially enhanced geothermal systems, as well as closed loop ones are additional drilling activities. Directional drilling in this case is a big cost driver as it is dictated by the unexplored geological setup. Drilling hazards can also be considered as one of additional cost drivers These issues can be minorized, but can affect the drilling time (cost), and can also be very challenging in such way that the tools can be lost. Another aspect which has a great cost impact is the rate of penetration, as the cost is directly attributed to the drilling time, so anything that speeds up the hole deepening progress is beneficial. Of course, without compromising the safety, well stability and directional path. To sum up, any of technological advancements, can provide lower capital cost of the drilling part and hence the project.

Usually, the mentioned cost rises exponentially comparing to the drilled meter, and that is why in many cases geothermal projects, especially, those which are deeper, are not economically feasible. One of the main characteristics of measuring the success of a drilling project is the value of the non-productive time (NPT). It represents the time when, for various reasons, the drilling operation is interrupted. To reduce the NPT, it is necessary to conduct thorough well construction planning, to pick the corresponding tools, and to have the experienced crew. The drilling process of a geothermal well is time lasting and expensive. The same as in case of the oil and gas exploration phase, but still gaining necessary information ensures steep learning curve. (M.Y. Gelfgat, 2021).

One of the potential technologies, which can contribute to the lost time reduction, is pulsed plasma drilling technology, developed by the company GA Drilling, with the headquarters in Slovakia. The use of this technology is a great example of the multidisciplinary collaboration between different engineering fields. Its main advantage is the increasing rate of penetration, by applying plasma for rock destruction, and therefore reducing time spent to reach certain depths.

2.1 Pulsed plasma drilling technology

This technology uses contactless drilling method, by applying enormously high temperatures, and therefore thermo-mechanically breaking the rock without melting the formation and, therefore making hole cleaning much easier. Regardless to that, the most important goal of the pulsed Plasmabit™ technology is to increase the rate of penetration, from an average of 3 m/h to 10 m/h or even more. While using coiled tubing as a transfer line, with the mentioned bottomhole assembly (see *Figures 7 and 8*), it is intended to achieve faster tripping time and the continuous mud circulation while drilling. (GA Drilling 2020)

Figure 7 Pulsed plasma bit (GA Drilling, 2019)

When drilling with Plasmabit™, the determinants of the rate of penetration change regarding to the conventional (mechanical) drilling methods. In this case, thermal characteristics such as: boiling point, melting point and thermal conductivity define the penetration ability of the plasma bit. The electrical arc from this bit provides the temperatures up to tens of thousands of degrees Kelvin, which also generates pressure and shock waves. With this electrohydraulic phenomenon, the bit disintegrates and moves the destroyed material away from the bottomhole assembly area. (I. Kocis 2015) The heat is directly applied to the rock surface without the intervening medium between the electric arc and the rock. The rock disintegration is based on applying the generated electric arc upon the rock surface. The electric arc is created from the electric arc generator and is directed into the area where it can be further shaped and moved around near the rock by action force modules. By direct heat exposure of the rock, it gets intensively heated, which causes further disintegration. So, it is needed, continuously to clean the bottomhole from the cuttings and to keep no materials between the aimed rock and the arc, because it is needed to achieve the direct contact between the arc and the rock surface. Also, it is needed to keep the arc close to the rock surface and push it continuously towards the rock surface. It is succeeded in such way by placing the conductive channel of the electric arc in a spiral form with the action of fluid and/or magnetic stream forces. (Kočiš 2017)

The disintegration by itself is made by providing extreme heat flow from the electric arc and the second fluid flow which cools down the rock. The combination of these two flows, stresses the rock, which leads to its weakening. By increasing the heat intensity, the arc is being pushed down, closer to the rock and at the same time pushes the destroyed rock away. Therefore, making space for further rock disintegration. The second (cooler) fluid stream enters between

Figure 8 Pulsed plasma drilling surface facility (TASR, 2018)

the arc and the rock, which leads to the enhancement of the pressure shock wave applied on the bottomhole and advances the disintegration process. (Kočiš 2017) There are several modes of rock disintegration. The according mode can be selected based on the geological condition of the formation. These modes are spallation, melting and evaporation. They all differ, on the energy which needs to be provided, and the heat which needs to be applied. The most energy consuming mode is evaporation, as the rock needs to be heated above the boiling point. Therefore, the preferred mode is spallation. The heat flow, by applying the combination of these modes, causes the change of rock's mechanical properties, by changing its physic-chemical properties. The most significant properties changed are the mechanical strength and flexibility, which are lowered due to the action of the heat flow. The heat flow causes intensive and rapid heating of the rock which leads to changing its mechanical properties. This includes several physio-chemical reactions such as recrystallization, dehydration and finally fragmentation. (Kočiš 2017) – see *Figure 9*.

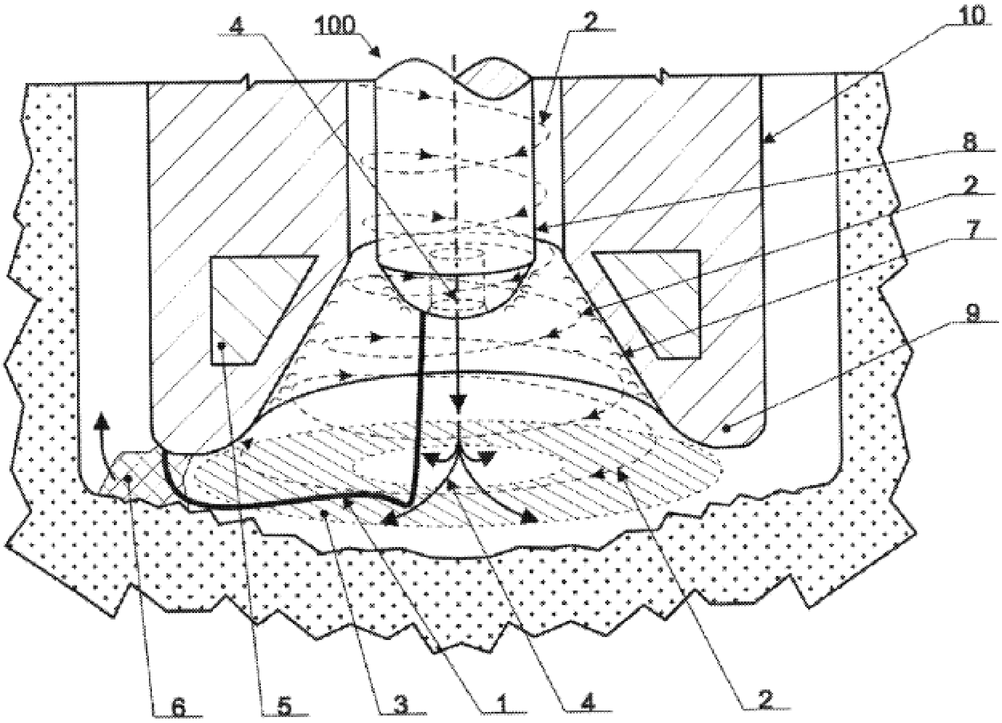

Figure 9 Schematic layout of the part of the arc extending radially beyond the contours of the device (USA Patent No. US 9 , 822 , 588 B2, 2017)

Reference signs:

1. Electric arc inside the active surface zone
2. Fluid stream force action module — first fluid stream
3. Zone of heat flow action
4. Fluid stream force action module second fluid stream
5. Magnet force action module
6. Module for guidance and raising of crushed rock
7. Module of reflecting surfaces guiding the heat flows
8. Electric arc generator electrode
9. Electric arc generator electrode
10. Device contours (Kočiš 2017)

Based on the experimental work done on 23 rock types by GA Drilling, there is no need of changing so many input parameters in terms of energy supply. This means that different rock types do not need to be drilled with different drilling modules, as the case is with the conventional drilling techniques. The Plasmabit™ prototypes used while testing was using around 200 kW of energy. It is assumed that in the real case, the energy consumption would have been around 500 kW. When drilling with the Plasmabit™ 10m/h, it is assumed that it would consume around 50 kWh per drilled meter. Furthermore, it is needed to have the plasma forming fluid supply of around 1l/min, cooling fluid of around 50 l/min and the drilling fluid of around 3000 l/min. The drilling fluid is then circulated and afterwards reused. (GA Drilling a.s. 2021)

The surface facility is intended to have a hybrid rig, which would have been possible to use for both running the conventional drill strings with separated drill pipes and the coiled tubing for drilling purposes. The shallow formations are usually softer and easy to drill, as well as the different borehole and casing diameters need to be placed. That is why, the conventional drill strings would've been more convenient to use in that stage.

Plasmabit™ technology with its high-speed hard rock drilling capabilities can be an optimal solution for enhanced and closed-loop geothermal systems. The engineered (controlled) reservoir brings an advantage of a longer lifetime than a reservoir created using fracturing. With this technology combined with others, there is a great potential to penetrate hard formations more effectively. The biggest potential, of the geothermal energy lies in mostly deep formations, where supercritical water conditions enhance the power production efficiency. To reach those depths, it is mainly needed to break through hard metamorphic/igneous formations. With today's conventional technologies, to perform such projects it is hardly reachable, firstly, as it is time consuming, secondly because it is hardly profitable. That is why most of deep geothermal project fail to be utilized. With pulsed plasma drilling technology, it is intended to overcome the project profitability gap, and therefore by making geothermal energy more accessible anywhere.

2.2 Coiled tubing drilling

Coiled tubing in general relates to a continuous length small diameter steel pipe and related surface equipment. It (Figure 10) consists of the coiled tubing unit, a reel where the flexible continuous steel pipe is spooled on. In order to deploy the unit downhole, it needs to be spooled off and led to the gooseneck, which directs the coiled tubing to the injector head. At the other end of the coiled tubing, there is a high-pressure swivel joint that enables pumping fluids through the pipe. Furthermore, beneath the injector head, there is a stripper assembly, which ensures the proper dynamic sealing of the unit. In order to assure an additional security in the terms of the pressure control, the blowout preventer needs to be installed between the stripper and the wellhead.

The tubing by itself is made of the low-carbon alloy steel. The usual sizes of the coiled tubing range between 0.45 inch and 4.5 inch whereas the 2-inch pipe outside diameter is the most

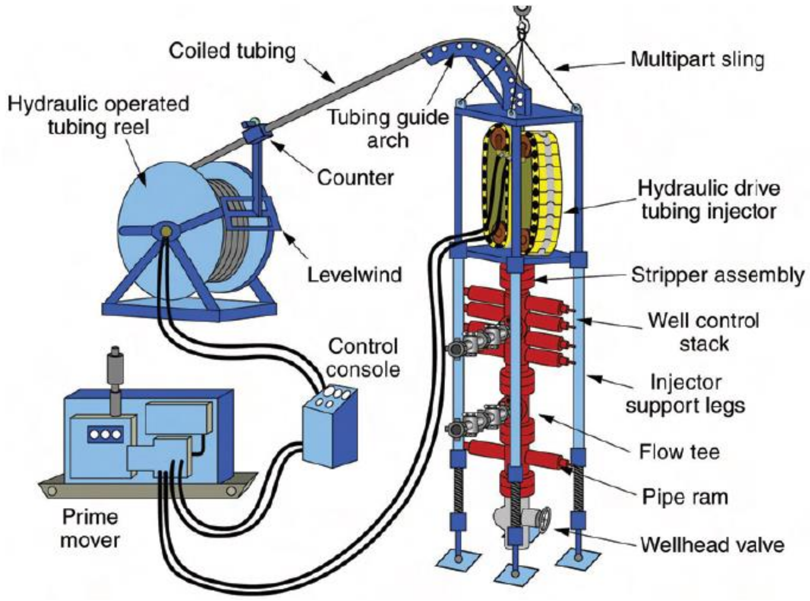

Figure 10 Mechanical elements of a hydraulic CT unit (courtesy of SAS Industries Inc.). (R.F. Mitchel, 2006)

common type. The range it can cover in length is between 600 m and 9000 m. The manufacturing process of the coiled tubing starts at the mill, where the steel sheets are cut into skelps. Each skelp is then typically cut at 45° on a bias. The bias edges are welded together to form a continuous strip. Next, the strip of sheet steel is roll formed into a tubular shape. In the meantime, the high-frequency machines connect its two edges into a form of a continuous longitudinal seam. The 45° bias weld (Figure 11), winded helically around the tubing is removed from the external side by the welding flash, in order to make the smooth outside diameter of the tubing. In the end the excessive scale and other loose material is flushed away and removed from the inside of the tubulars. (R. Christie, 2015)

The mentioned approach of the manufacturing process, by welding the bias in such way is due to the stress distribution which is spread over the length of the helix rather than concentrated within a narrow band as would been in the butt-welding case.

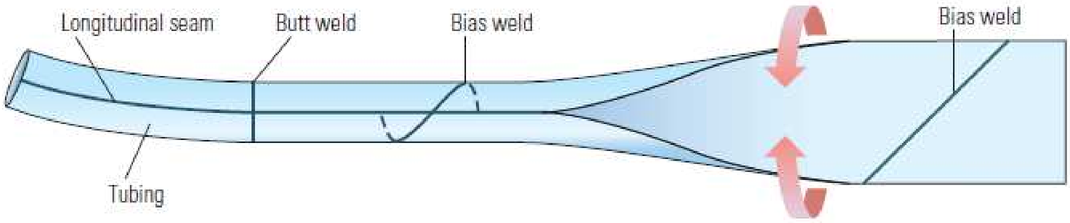

Figure 11 Welding of coiled tubing (R. Christie, 2015)

The most common application of the coiled tubing is in matter of deploying tools and materials through the production tubing. These kinds of activities mostly happen during remedial works when performed in producing wells. Furthermore, coiled tubing finds its applicability in fishing practices, especially in highly deviated or horizontal wells. Its strength and rigidity combined with the continuous circulation capability are a great advantage in workover operations. It is also used in cementing activities when the accurate placing of cement downhole is needed. Disregarding its mobility, there are also some permanent installations of coiled tubing.

Coiled tubing applications in drilling are used for specific situations. Mostly it carries out the open hole operations in both, directional and non-directional wells. The drilling part by itself is ran by the downhole motor. The whole technique ensures the higher speed and lower weight on bit. In directional wells, the steering device is needed. Its application also can be found in both, over and underbalanced drilling cases.

Another advantage of using coiled tubing while drilling, is the shorter tripping times. Due to its continuity, as already mentioned before, there is no lost time for connecting or disconnecting pipes while tripping in and out of the well. Furthermore, due to the same reason, the problems and fatigues which might happen to other drill pipes, are avoided. Therefore, by reducing the tripping time, it gives an opportunity for this technique to be more cost effective. Also, in the benefit of the cost, there is a potential to use less service personnel. Except, its tripping speed, and less crew members, coiled tubing might provide a smaller footprint and a better mobility (R.F. Mitchel, 2006).

This technology has a continuous improvement over two previous decades. It has been established as a standard practice for re-entry drilling operations in the Middle East. The need and application of this technology has spread, because it has proved as a reliable technology especially in terms of enhancing the production in older fields. Also, it is a cost effective and highly economic tool. Disregarding that, the problems which encounter when using coiled tubing in drilling operations is that the material, of which the coiled tubing is made, provides a small percentage of the weight on bit (WOB). When the case is about the conventional drilling techniques, the drill pipe weight is regulated via the rig brake, coiled tubing needs a mechanical injector at the surface to push the tubing inside the borehole and therefore provide the adequate weight transfer. Furthermore, due to its properties, when pushing the tools, the compressive forces get increased. In that case the tubing buckles into a sinusoidal shape. If increasing these forces more, the CT forms a helical shape, which can cause a helical lockup. This happens when the tubing is pushed against the wall, and the friction opposes to movement in the hole. (SPE Baker Hughes; SPE Saudi Aramco; SPE Schlumberger, 2010)

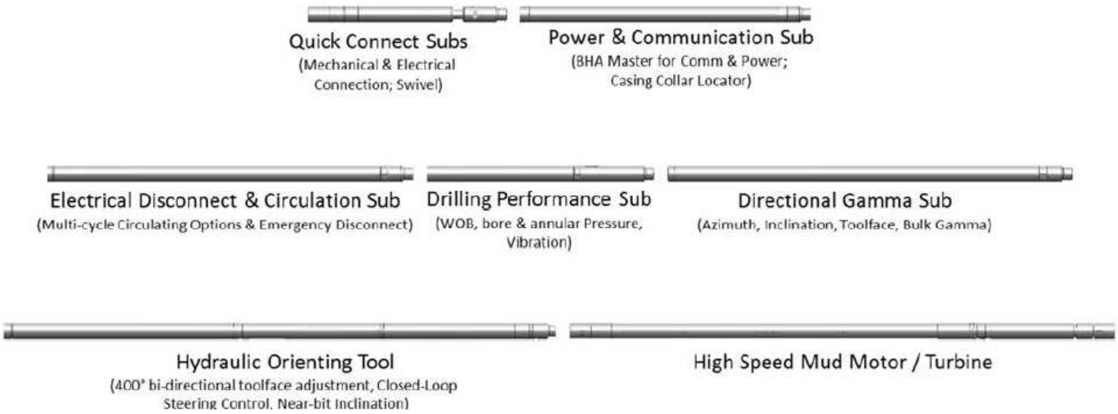

Figure 12 New high-temperature coiled tubing bottomhole assembly (Baker Hughes, 2020)

To address the above-mentioned issue of gaining the weight on bit a certain quantity of heavy-weight drill pipes is usually added to the BHA. Due to its inability to rotate, it is inevitable to add the orienting device in a combination with the downhole motor or the turbine, which can provide a high torque rotation of downhole tools. The orienting device allows the adjustment of the motor bend subs to control the well path deviation. In order to control the rotation, it is needed to add the „measuring while drilling" tool. (Zaharova, 2017)

When addressing these problems occurring with coiled tubing drilling, such as WOB, with the Plasmabit™, it can be avoided. There is no need of applying any weight on the bottomhole as this is a non-contact method, using thermal energy to disintegrate the rock. Except the heavy weight drill pipes, which are needed to maintain the vertical tensile force in order to avoid the above-mentioned helical buckling, it is also needed to have the pulse plasma drilling head for the rock disintegration, the downhole control system, which controls the power and fluid transmitted to the head. Furthermore, it is needed to have the efficient cooling system, logging device and the transfer line connector. (GA Drilling a.s., 2021).

While using pulsed plasma drilling technology, the coiled tubing is used as a transfer line. While coiled tubing as it is said by itself is a continuous steel pipe without joint connections. The use of this advantage has led to have the ability to maintain the continuous pressure while tripping into and out of the well. Tubing's continuity allows to maintain the underbalanced conditions above the reservoir and is of the greatest importance of reducing the potential damage on the sensitive formations. There is a closed working cycle which ensures significant ecological and cost benefits when using this method. Also in safety terms, the wellhead integrity is supported during all stages of well head interventions.

The continuity of the coiled tubing allows to use continuously the hardwired telemetry and conduits, which is of the great importance for the pulsed plasma drilling method. Coiled tubing can have electric logging line or other signal telemetry options installed while tripping. (R.F. Mitchel, 2006). Also, there is a possibility of installing the wires inside of the umbilical needed for telemetry or providing the necessary energy for the parts of bottomhole assembly. Even though, the installation of the umbilical can reduce the effective inner diameter of the tubing but provides necessary safeness to the wires inside of it. Furthermore, the survey activities, are solved with the real time monitoring equipment installed within the Plasmabit™ BHA (Bottom hole assembly). Also, reaming is less needed, because when applying plasma on the bottomhole the well gets more unified shape, so there is less probability that the equipment will get stuck.

Chapter 3

Otaniemi geothermal heat project

St 1 Deep Heat Oy energy company decided to build the enhanced geothermal system power plant in Espoo, Finland. It was planned to build a 40 MW energy system in order to provide heating for Espoo's district Otaniemi, in the vicinity of Helsinki. This was a pilot project with the support of the Finnish Ministry of Employment and Economy. The main goal of this project was to enhance the knowledge of exploring and utilizing the production of geothermal energy in the crystalline rock conditions of Finland to power up the district heating network. As the fossil energy is still the present source of energy for district heating, Finnish, as well as European plan, is to enhance the use of the renewables. Therefore, the Otaniemi project is one of the key parts of a plan to shift the district heating network to carbon-neutral in the city of Espoo, by 2030. (St1 Deep Heat Oy, 2016)

The project is consisted of building two wells with a depth to 6.2 – 6.4 km, which are the deepest ones of geothermal kind in the world. By the time of writing this thesis, the pilot hole (OTN-1) was drilled to the depth of 2 km and two deep wells, OTN-2 with 6.2 km and OTN-3 with 6.4 km depth. The extreme depth of the last two wells is due to the low geothermal gradient of 18.75°C/km. The subsurface formation is typical for this part of Finland. It is consisted of the Precambrian bedrock, which is overlain by a thin layer (0-20 m) of Quaternary sediments. This geological structure makes drilling activities, especially deeper ones more complex. Furthermore, crystalline rock environment has a low porosity (< 0.5 %), which limits the fluid only to flow through the deformations, shear zones and fractures. In the other hand, hard formations due to their low porosities make a good physical insulator, which gives a space to hydraulically stimulate the reservoir to make the passages (fractures) for the working fluid. (I.T. Kukkonen, 2021).

Before the hydraulic stimulation, it was inevitable to do the preliminary work. In 2018, around 18,000 m³ has been pumped into OTN-3 well to monitor and control the seismic events. The seismicity was monitored with 14 satellite seismic stations in the vicinity of the stimulated well. This phase was monitored with the traffic light system (TLS) which was set at the magnitude of M2.1, which means that the occurrence of the event with the higher seismic value would immediately stop the stimulation.

The OTN-III drilling program has been based on the experience of OTN-II monitoring vertical well, reached 3325 m depth in 104 days. The advanced air hammer drilling techniques have been used in OTN-III to reach 4200 m, then hydraulic hammer used until 4520 m followed with mud motor and Roller Cone bits for directional part of the well including completion section from 5440 until 6400 m. The total time estimate for this well was 210 days. The final depth of 6.4 km has been reached in April 2018, by using the combination of water-hammer and the conventional rotary drilling techniques. The OTN-2 well was drilled to the depth of 3 km. Firstly, it was intended to be the monitoring well, for the stimulation process. When the monitoring process was over and the data has been obtained, the OTN-2 well has been deepened to 6.2 km depth. Afterwards, in 2020 the stimulation phase has begun. In the end the EGS reservoir has been made, with the intersected fracture network of the OTN-2 and OTN-3 well. (I.T. Kukkonen, 2021) – see Figure 13.

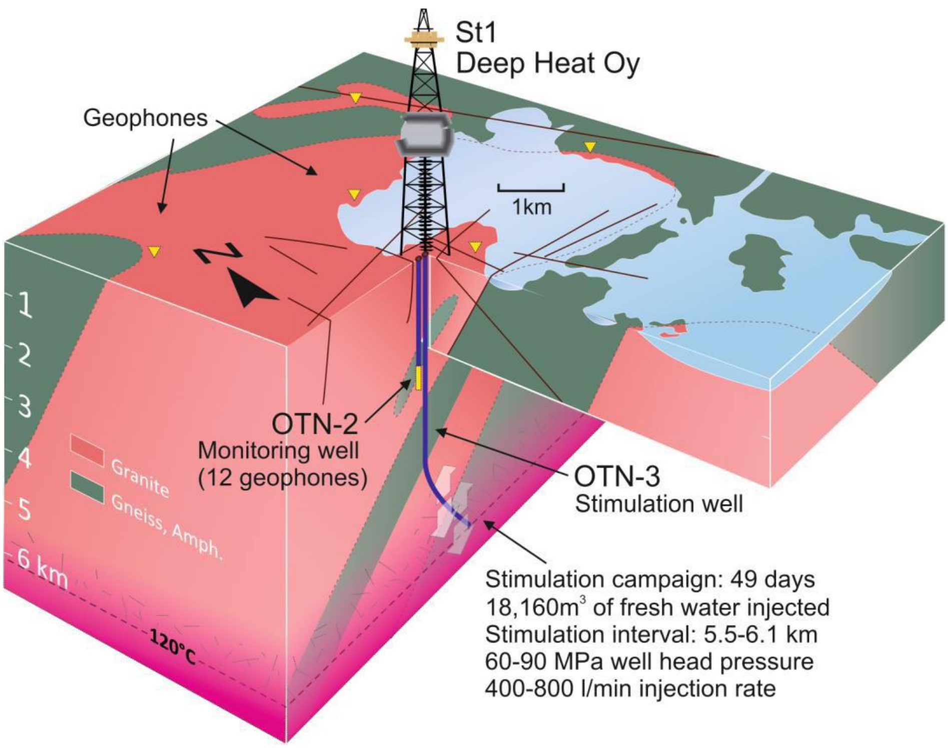

Figure 13 Deep Heat Oy project model (I.T. Kukkonen, 2021)

The project has been further proceeded by installing the production pumps and testing the production phase. The final thermal power is yet to be analyzed but is more likely not to reach the initial estimate of 40 MWt. However, the lessons learned from this project will provide the priceless experience in reaching the final goal of placing the production of the geothermal energy towards a technically and economically viable industrial scale concept.

3.1 OTN-III case study

3.1.1 The basis for Plasmabit™ application evaluation

After finalising the OTN-I well and drilling the first part of the OTN-II well, the construction of the OTN-III well has started in April 2016. The drilling program has been made based on the experience from the 3325 m deep OTN-II monitoring well, for which was needed 104 days in total. In the first phase, the depth of 4520 m has been reached with the air hammer technology for 83 days. (Figure 14) This technology is based on using the airflow to hammer the bit against the rock. That airflow is afterwards used to carry the cuttings out of the well. Afterwards the water hammer drilling technology has been used to proceed - with reaching the final depth. This method is then proved to be financially unreasonable, which led to 6 months break of any drilling activities on this project. In total, to complete the whole OTN-III well, 288 days was needed.

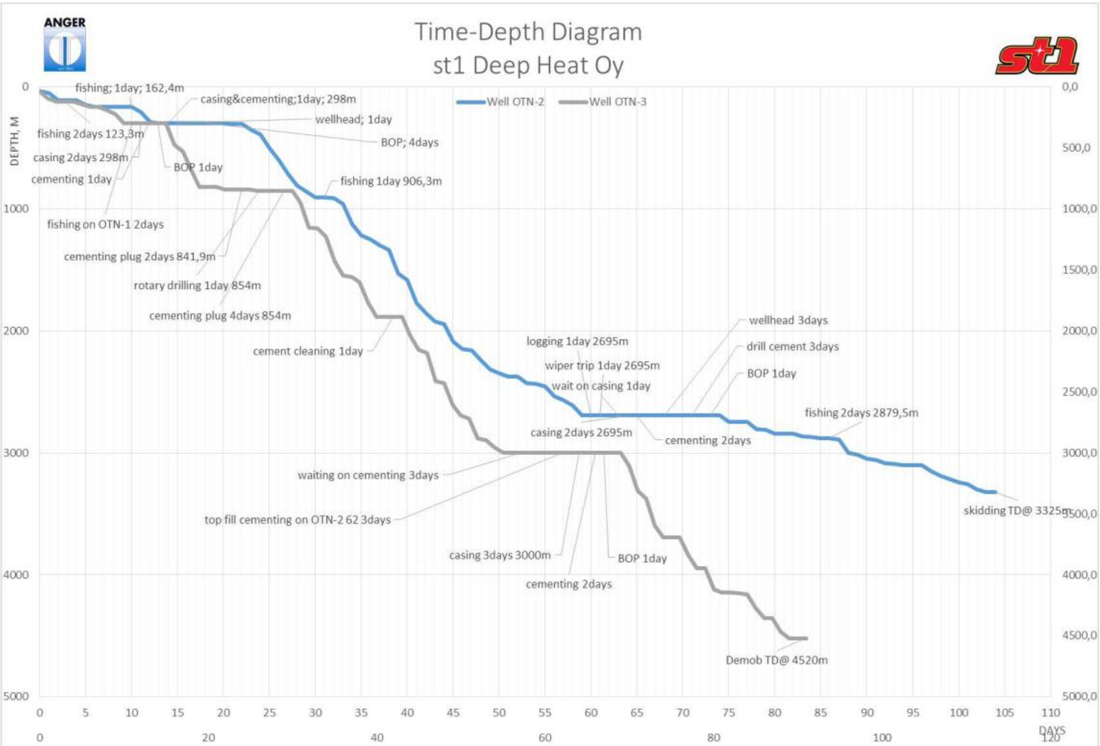

Figure 14 Time-depth Diagram st1 Deep Heat Oy (Saarno, 2018)

For the purpose of this analysis the last interval between 5442.90 m and the final depth of 6400 m has been considered. Firstly, this interval was chosen to be analyzed due to the availability of information through the daily drilling reports. Furthermore, this interval's rock structure is hard and abrasive, which makes a good basis to compare the Plasmabit™ and the conventional drill bits. Finally, the idea behind using the Plasmabit™ is to penetrate into depth as far as possible, disregarding the formation hardness.

Daily drilling reports (DDR) are a vital part of any drilling operations team. It has to contain all the necessary information happened on a rig within two shifts in a 24-hour rate. Mostly the reports contain the basic data from the location, date, and the personnel present on the site during two shifts. Furthermore, there are information about the progress, daily activities, bottomhole assemblies, mud material, drilling bits, casing data, drilling data and mud pumps. The accurate and timely spread of information on DDRs can keep operations and budget on track. Also, it helps to organize data if needed to be distributed to the parties who are interested in such record.

The total length of 957.10 m of OTN-III well has been drilled with 11 drill bits. While completing this part of the well, the drilling operator decided to use bits from two producers, Baker Hughes and Smith (Schlumberger group). All of them are tricone drill bits. The Smith bits series used are from the FH line (Figure 15). This line is made with a single metal seal with

Figure 15 Smith FHI tricone drill bit series (Smith Bits, 2017)

tungsten carbide inserts. These inserts have the conical shape, geometrically optimized to reduce the breakage possibility. The IADC bit code (7-3-7) refers to the hard formation drilled with the tungsten carbide teeth, where the bit body is sealed with a metal protection. (Smith

Bits, 2017) The drilling operator also used the tricone drill bits made by Baker Hughes. There were two types of them. Both of those types are of Vanguard VM series bits (Figure 16). These kinds of bits have the journal bearing. According to the producer, these bits have a successful application in directional wells, with good thermal stability. While drilling the first part of the last interval, the DS line of VM series have been used. Those bits have shirttail compacts enhanced with diamonds, which makes them applicable in abrasive formations. The IADC code in this case (6-4-7) stands for a medium hard formation, drilled with the bit which has inserted tungsten carbide teeth, sealed with the metal protection. The bit used to reach the final point of the OTN-III well was of DX line, which is used in directional applications in hard and abrasive

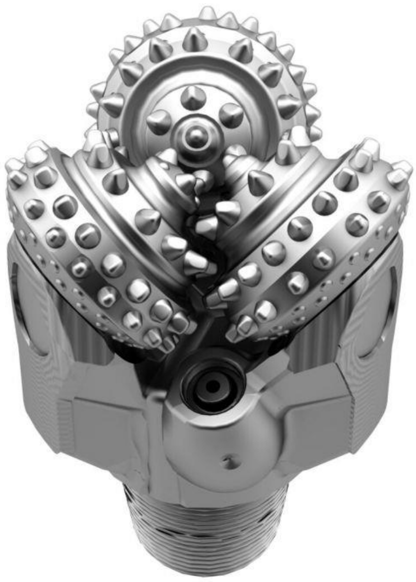

Figure 16 Vanguard VM series tricone drill bit (Baker Hughes, 2021)

formations, due to their diamond gauge compacts. According to the IADC code (8-3-7), the last interval is referred as an extra hard formation drilled with the tricone drill bit with tungsten carbide inserts with metal body sealing. (Baker Hughes, 2021)

In the following table 2 are shown the bits used while drilling the interval between 5442.9 m and 6400.0 m in the OTN-III well and the performance each bit made. The drilling time is referred as the time spent to drill the following interval in the next column. The third column shows the overall progress measured in drilled meters of each bit. Finally, the fourth column shows the average rate of penetration of each bit.

Drill bit types	Drilling time (h)	Interval (m)	Penetration (m)	ROP = (4)/(2)
1	**2**	**3**	**4**	**5**
Smith FHI 70Y, RA 4643, 7-3-7	43.75	5442,9 - 5546,0	103.10	2.35
Smith FHI 70Y, RA 3791, 7-3-7	38.00	5546,0 - 5636,0	90.00	2.37
Baker VMD DS, 5280797, 6-4-7	39.25	5636,0 - 5708,7	72.70	1.85
Baker VMD DS, 5281949, 6-4-7	43.25	5708,7 - 5802,0	93.30	2.16
Baker VMD DS85, 5279256, 6-4-7	26.66	5802,0 - 5880,0	78	2.93
Baker VMD DS85, 5279255, 6-4-7	6.28	5880,0 - 5907,3	27.30	4.35
Smith FHI 70Y, RJ 3795, 7-3-7	43.50	5907,3 - 6004,0	96.70	2.22
Smith FHI 70Y, RJ 3794, 7-3-7	12.14	6004,0 - 6067,0	63.00	5.19
Baker VMD DS68, 5281906, 6-4-7	15.71	6067,0 - 6186,0	119.00	7,57
Baker VMD DS68, 5282057, 6-4-7	33.50	6186,0 - 6292,0	106.00	3,16
Baker VMD - 95DX2, 5285307, 8-3-7	36.96	6292,0 - 6400,0	108.00	2.92
TOTAL	**338.99**		**957.10**	**2.82**

Table 2 Drill bit performance

The analysis has been based on daily drilling reports (DDR), between 13th of March of 2018 when the drilling of the last interval started and 22nd of April of 2018 when the final depth has been reached. The purpose is to compare the drilling performance of conventional drill bits to two scenarios of the pulsed plasma, coiled tubing drilling method.

To fulfil the purpose of the analysis, the methodology was following. The data has been retrieved from the daily drilling reports. The daily drilling reports are consisted of all the events, which took place on a drill rig. These events are described and marked in a timely manner (hours) e.g., as showed in *Figure 17*. The corresponding activity time has been divided as follows: the first 3.5 hours, the same as changing the rotary slip and inserts were considered as the tool manipulation (NP), whereas running into hole (RIH) is considered as a productive time. In the other hand installed rotary hose and top drive time is accounted under tool manipulation (P). Time spent for mud circulation has happened from 19:15 and 21:30. Time spent to de-ice the unit is considered as a complication and accident. Finally, 6.75h have been spent for drilling. Their purpose is to show the progress and used for analysis from the side of the supervisor and the top management. In addition, it is used in case of an investigation in order to restore the chain of events happened on the rig. After retrieving the information from DDR, the breakdown of the activities has been made. These activities are separated into two groups: the necessary ones, which had to be done and cannot be avoided. The second group is the one with all the activities, which could have been avoided, if some other technologies have been introduced. Furthermore, these two groups, afterward led to a clear distinction between the productive and non-productive time.

Operational Sequence

From:	To:	Duration	Operation
06:00	07:00	1,00	POOH to from 4614 m to 4500 m (doubles)
07:00	08:00	1,00	Changed inserts on rotary drill pipe slip
08:00	09:30	1,50	POOH to from 4500 m to 4165 m (doubles)
09:30	10:30	1,00	RIH from 4165 m to 4300 m (single joints)
10:30	12:15	1,75	Changed rotary slip and inserts
12:15	18:30	6,25	RIH from 4300 m to 5350 m (single joints)
18:30	19:15	0,75	Installed rotary hose to top drive
19:15	21:30	2,25	Broke circulation, circulated with 500 l/min, observed high pump pressure of 130 bar,
			rotated with 20 RPM and reciprocated string up and down to break gel
			Increased pump rate in increments to 1900 l/min. Total circulation volume 400 m³
21:30	22:45	1,25	Due to frozen make-up unit, unable to break top drive connection. De-iced unit, broke
			connection
22:45	23:15	0,50	Made connection, RIH with circulation, tagged bottom @ 5374,30 m
23:15	06:00	6,75	Time drilling with max. 3 t WOB, ROP 1 m/h, tool face orientation by 300 degree
Total Hrs.		**24,00**	

Figure 17 Example of an operational sequence part of the DDR

The first group of activities as mentioned was consisted of those activities, which could not be avoided. One of those activities is drilling, which is mainly the base of this analysis. With the drilling activity, there was a special emphasis on the time spent to drill a certain interval, and the progress made. Except, the drilling process, within the first group of activities there is also running the tools into (RIH) and pulling it out of the hole (POOH). It is of a big importance to follow up on this activity due to the comparison with the coiled tubing part of the technology, which this thesis main goal is. The other necessary activities are the mud circulation, surveys, (back)reaming and tool manipulation (Change of handling equipment related to drilling and reaming).

The second group of activities withdrawn from the daily drilling reports, are consisted of those which could have been avoided by using some other drilling techniques, better formation understanding and/or better engineering part. Those activities have been put under a group called rig equipment services and inspections and those activities are cementing, milling operations, rig equipment services and inspections, complications and accidents, unnecessary tool manipulations (RIH and POOH, change of equipment related to complications and accidents) and others.

Rig activity	**Time spent [h]**
Drilling (rotating and sliding)	338.99
Mud circulation	55.65
RIH	208.93
POOH	212.04
Tool manipulation (P)	27.01
Surveys	20.25
Reaming	19.00
Rig equipment services and inspections (NPT)	50.87
Other (NPT)	1.25
Productive time (PT)	881.88
Non-Productive time (NPT)	52.12
TOTAL	**934.00**

Table 3 Conventional drilling activities breakdown

This table 3 shows the ratio between the productive (PT) and the non-productive time (NPT) spent on this rig. Unlike *table 2*, which follows the drilling parameters of each drill bit, *table 3* shows the overall summary of the work done while constructing the last interval of the OTN-III well. Even though, the calculations are showing that the ratio between the PT and the NPT, is favourable, the other parameters which are presenting drilling the 957.10 m long well section, are showing less convenient results.

In order to present the results as convincingly as possible, the following calculations have been made. First, it was necessary to follow the daily progress in terms of the drilled meters and therefore, to follow the daily average rate of penetration (m/h). Furthermore, it was also intended to state the time spent for tool manipulation. Therefore, it was needed to calculate the average speed of pulling out and running the tools into the hole.

To make this analysis more convenient, the term of “clean rate of penetration” (1) has been introduced. With this term it is wanted to be stated the direct correlation between the interval drilled until the point of the true measured depth (TMD) to the drilling time spent for the rock destruction in the same interval.

$$clean\ ROP\ [m/h] = \frac{(\text{TMDi+1} - \text{TMDi})\ [m]}{\text{Drilling time of the interval i [h]}} \tag{1}$$

Therefore, it is calculated that, with the conventional drilling methods the clean rate of penetration is 2.86 m/h. The average rate of penetration of 11 mentioned drill bits is 2.82 m/h (*table 2*). To add up the average running into the borehole speed is 277.99 m/h and pulling out of the borehole speed is 322.96 m/h. This is important because there were 11 round trips, in order to substitute the drill bits. To demonstrate the average drilling speed per roundtrip, another formula (2) was introduced. The rate of roundtrip (RORT) is the ratio between the corresponding drilled interval within one roundtrip and the time spent for one roundtrip. In these terms, the roundtrip also consists of the drilling time, not only the operation of removing the drill string from the wellbore and running it back to the borehole.

$$RORT\ [m/h] = \frac{Total\ penetration\ per\ bit\ [m]}{Time\ spent\ for\ a\ roundtrip\ [h]} \tag{2}$$

This value can be a convenient measure of the performance of a drill bit. It integrates the progress made by the bit and time the same bit spent in that roundtrip. Time spent for a roundtrip consist of all the necessary and unnecessary activities, mentioned above. That means, it consists of both the productive and non-productive activities. The average RORT of all drill bits within the last interval of the OTN-III well is 1.09 m/h. The following *table 4* shows the average RORT value of each bit used to drill this section. This value depends in total of the drilling process, efficient cuttings transport, the selection of the drilling parameters, various drilling interruptions, surface equipment malfunctions and others. In total 45 % of the time has been spent for tripping the tools in and out of the borehole whereas 36% of the time has been spent for pure drilling activities in total. For the conventional drilling methods in general, in such metamorphic formations, shows that this is the average speed of reaching the wanted depth.

934 hours have been spent in order to reach the final depth. This means that the limits of the conventional technology have been reached. In other words, the time has come to introduce new technologies and reconsidering already existing ones.

Drill bits	**RORT (m/h)**
Smith FHI 70Y, RA 4643, 7-3-7	1.44
Smith FHI 70Y, RA 3791, 7-3-7	1.26
Baker VMD DS, 5280797, 6-4-7	0.87
Baker VMD DS, 5281949, 6-4-7	0.82
Baker VMD DS85, 5279256, 6-4-7	1.13
Baker VMD DS85, 5279255, 6-4-7	0.68
Smith FHI 70Y, RJ 3795, 7-3-7	1.01
Smith FHI 70Y, RJ 3795, 7-3-7	0.88
Baker VMD DS68, 5281906, 6-4-7	1.65
Baker VMD DS68, 5282057, 6-4-7	1.14
Baker VMD - 95DX2, 5285307, 8-3-7	1.06
Average	**1.09**

Table 4 Rate of roundtrip for each drill bit

3.2 Pulsed plasma, coiled tubing drilling

The combination of pulsed plasma and the coiled tubing drilling method may be an answer in time reduction of above-mentioned drilling activities, which have taken place in Otaniemi, Finland. By achieving extremely high temperatures, with the pulsed plasma drilling method it is possible to easily penetrate even the hardest formations. Furthermore, by solving the issue of bottomhole cleaning, as it disintegrates the rock, and therefore forming very small particles. (*Figure 18)*. These particles are then removed with the circulated mud out of the borehole, to the surface. This fluid is then filtered, recycled and injected back to the borehole.

In the other hand there is the coiled tubing plasma drilling method, which provides the higher ROP, necessary borehole stability and reduces tripping times. When using coiled tubing, there is no need to manipulate and connect the pipes, as the tubing is continuous. This means that RORT in each case can be increased, as well as the overall drilling efficiency. Due to the continuity of the coiled tubing, it is possible to continuously circulate the fluid.

The use of pulsed plasma drilling technique, as it is experimentally proved by GA Drilling, increases the clean rate of penetration, comparing to the conventional drilling methods, in a pessimistic scenario, to 5 m/h and in a base scenario to 10 m/h. Even though, it was also proved

Figure 18 Cuttings from plasma-based drilling (GA Drilling a.s., 2021)

in an optimistic scenario that the clean rate of penetration can reach up to 20 m/h. However, for the purpose of this analysis, only the pessimistic and the base scenarios were used. To add up, the tripping time, because of the use of coiled tubing, has also been decreased. The average tripping speed for the pessimistic and base scenario is different. The average value of running into the hole for the pessimistic scenario is 600 m/h, which is assumed the same for pulling out of the hole. And the average speed of tripping in and out, for the base scenario is 1200 m/h. These tripping speeds are considered as the lower and upper boundaries for coiled tubing tripping times.

The workflow of reconstructing the daily drilling reports, in a manner that the OTN-III well has been drilled with the coiled tubing pulsed plasma drilling method, is as follows. The main premise is the term of the clean rate of penetration of 5 m/h for the pessimistic scenario and 10 m/h for the base scenario. Afterwards, the correlation of the average rate of penetration and the clean rate of penetration (3) has been made, which was assumed to be the same for all three scenarios (conventional, pessimistic, and base).

$$x = \frac{Average\ ROP\ [m/h]}{Clean\ ROP\ [m/h]} \tag{3}$$

Based on that constant, the average rates of penetration, for both scenarios, have been calculated. In order to assume how much time is spent for a certain rig activity for the specific scenario, it is needed to compare the referent values of the average rate of penetration, and tripping speed of the coiled tubing plasma drilling method to the conventional one (4). In the following equations the index p,b stands for drilling with the Plasmabit™ and index c stands for conventional drilling technology.

$$y_{p,b} = \frac{Average\ ROP_{p,b}\ [m/h]}{Average\ ROP_c\ \ [m/h]} \tag{4}$$

The same correlation has been made regarding the tripping speeds between the conventional method and the plasma drilling scenarios (5). For both, pulling out and running into the hole.

$$z_{p,b} = \frac{Avg.tripping\ speed_{p,b}\ [m/h]}{Avg.tripping\ speed_c\ [m/h]} \tag{5}$$

Once all the correlations are known, it is needed to calculate the time spent for a particular activity. First, the average daily rate of penetration for each plasma drilling scenario needed to be calculated by multiplying the constant $y_{p,b}$ with the daily average rate of penetration of the conventional method for each day. The index i in the following equations, stands for the specific day, that value refers to.

$$daily\ avg.ROP_{p,bi}[m/h] = y_{p,b} \times\ daily\ avg.ROP_{ci}[m/h] \tag{6}$$

Once the daily average rates of penetration have been obtained, it was necessary to determine the values of the drilling time for each day. It was decided that the activities related to conventional drilling case are going to happen in the same way in the cases of drilling with the Plasmabit™. This assumption does not affect the daily tripping and drilling times, as they have been determined with before-mentioned average speeds. As the daily drilling reports are 24 hours based, the daily drilling time has been assumed as following.

Tool manipulation (P)	0.75 h
Reaming	0.5 h
Total	**1.25 h**

Table 5 DDR data from day 2

Afterwards, the daily drilling time has been calculated as follows:

$$daily\ drilling\ time_{p,b2}[h] = 24\ h - 1.25\ h = 22.75\ h \quad (7)$$

When the daily drilling time has been determined it was simply assumed that the daily progress is a product of the daily avg. ROP and the drilling time spent for each day.

$$daily\ progress_{p,bi}[m] = daily\ avg. ROP_{p,bi}\ [m/h] \times daily\ drilling\ time_{p,bi}[h] \quad (8)$$

When considering both Plasmabit™ drilling scenarios, it is considered that the tool retrieval happened when the tool inspections and rig equipment services were scheduled in the real case scenario. The tripping times for each day are based on the average coiled tubing tripping speed and the depth the tools reached at the given moment.

$$Daily\ avg. tripping\ time\ [h] = \frac{Tripping\ distance\ [m]}{Avg. coiled\ tubing\ tripping\ speed[m/h]} \quad (9)$$

Once, the daily values of the drilling and tripping time are calculated, it was needed to summarize them and compare the values with the real data obtained from the DDRs.

3.3 Scenario for OTN-III well

The latter explained method has been applied in the OTN-III well case. The purpose of the whole analysis was to compare the conventional technologies that have been applied while constructing the last interval of the OTN-III well, to the coiled tubing pulsed plasma drilling method, within the interval between 5442.9 m and 6400 m depth. It is considered that the interval, until the depth of 5442.9 m has been drilled with the combination of hydraulic hammer and steerable mud motor with the tricone roller bit in the directional part of the well.

Furthermore, there have been created two case scenarios as already mentioned, with two different clean rates of penetration, and with two different tripping speed. The pessimistic scenario with the clean rate of penetration of 5 m/h and 600 m/h tripping speed. The other one is the base case scenario with the clean rate of penetration of 10 m/h and 1200 m/h tripping speed in both directions. These values were the main prerequisites, in order to get the corresponding times for the certain activity.

In the pessimistic case scenario, the final depth has been reached at 31st of March 2018. Which is in total 22 days earlier, than in the case of the real scenario, drilled with the conventional methods. The plasma drilling method with higher rates of penetration, can easily break through harder formations. Also as mentioned this method is contactless and there is a lower probability that the bit would get defected due to the mechanical reasons. Furthermore, the bottomhole cleaning can be more effective, because of the coiled tubing continuity and easier cuttings removal. The cuttings by themselves are much finer, and therefore easier to remove. In addition, the tripping times are much faster.

In the base case scenario, the target has been reached at 21st of March 2018. The average penetration per roundtrip was 478.55 m. This assumption is based on the before-mentioned calculation of the daily drilling progress. As the average daily progress when drilling with conventional methods is 24.54 m, with drilling in Plasmabit™ pessimistic case scenario is 53.17 m whereas in the base case scenario is 119.64 m. The tools are assumed to be pulled out of the borehole, when the inspections and tool services are intended. This follows up to the conclusion that only two roundtrips happened in the base case scenario. The average rate of penetration is 7.24 m/h. The handling equipment in both plasma cases are not needed as the coiled tubing has been applied.

3.4 Conventional vs Plasma drilling time analysis

When comparing mentioned case scenarios to the conventional drilling method there are clear advantages concerning the time of reaching final depth. This is mostly due to the velocity of execution of certain activities, which is reduced for a significant time. Thankfully to the increase of the clean rate of penetration in hard rock formations. Also, pulsed plasma drilling technology provides a more unified shape of the borehole which reduces probability of tools to get stuck. Therefore, there is a less need to additionally ream the borehole. Furthermore, the coiled tubing technology in this manner has a great impact in reducing tripping times, as well as bottomhole cleaning.

The equipment services and inspections are also significantly reducing because this drilling method is contactless. Because of this fact, there is a less chance for the bottomhole assembly to get broken as there is no danger of mechanical impact on the bit. Also due to the real monitoring which also introduced in this technology the time spent for surveying is reduced as well. The ration between the non-productive time and productive time is not relevant in this case as, the coiled tubing pulsed plasma drilling method aims the activities which affect mainly the productive time. In addition to that, the non-productive time reduced for 41% in the pessimistic case scenario and 74% in the base case scenario.

Rig activities	Conventional	Plasma	
	Real scenario [h]	Pessimistic [h]	Base [h]
Drilling (rotating and sliding)	338.99	312.46	150.79
Mud circulation	55.65	33.56	5.00
RIH	208.93	20.09	5.26
POOH	212.04	30.74	10.60
Tool manipulation (P)	27.01	15.88	6.00
Surveys	20.25	12.25	2.50
Reaming	19.00	8.00	0.50
Rig equipment services and inspections	50.87	29.12	13.50
Other	1.25	1.25	0.00
Productive time	881.88	432.99	180.64
Non-Productive time	52.12	30.37	13.50
TOTAL	934.00	463.36	194.14
Date of reaching final depth	22.4.2018	31.3.2018	21.3.2018

Table 6 Breakdown of activities for all three scenarios

These data are based on the assumed progress made by each Plasmabit™. The dates of reaching the final depth of 6400 m, are the ending point of summing up the activities made. For an example, the date of reaching the final depth in the pessimistic case Plasmabit™ scenario is the 31st of March 2018, which is 17 days from start of drilling. The time spent for the activity is assumed as following:

$$rig\ activity\ time\ [h] = \sum_{i=1}^{i=17} rig\ activity\ time_i\ \ [h] \tag{10}$$

The operating time of the Plasmabit™ is around 500 hours. In the pessimistic case scenario, there have been two roundtrips in total until reaching the final depth. The average rate of a roundtrip is 2.21 m/h, whereas in the base case scenario is 5.30 m/h. Hence comparing to the conventional case, where the calculated rate of roundtrip is 1.09 m/h with 11 roundtrips in total. With this data, it can be clearly seen, how much progress can be made with this drilling technique.

In the following table 6 the total performance of each bit can be seen comparing to the pulsed plasma bit.

Drill bit types	Drilling time (h)	Penetration (m)	ROP (m/h)	Avg. ROP/run	RORT
Smith FHI 70Y, RA 4643, 7-3-7	43.75	103.10	2.35	2.04	1.44
Smith FHI 70Y, RA 3791, 7-3-7	38.00	90.50	2.37	2.25	1.26
Baker VMD DS, 5280797, 6-4-7	39.25	72.20	1.85	1.40	0.87
Baker VMD DS, 5281949, 6-4-7	43.25	94.00	2.16	1.74	0.82
Baker VMD DS85, 5279256, 6-4-7	26.66	77.30	2.93	2.05	1.13
Baker VMD DS85, 5279255, 6-4-7	6.28	27.30	4.35	2.05	0.68
Smith FHI 70Y, RJ 3795, 7-3-7	43.50	96.70	2.22	2.78	1.01
Smith FHI 70Y, RJ 3794, 7-3-7	12.14	63.00	5.19	2.74	0.88
Baker VMD DS68, 5281906, 6-4-7	15.71	119.00	7,57	5.71	1.65
Baker VMD DS68, 5282057, 6-4-7	33.50	106.00	3,16	2.88	1.14
Baker VMD - 95DX2, 5285307, 8-3-7	36.96	108.00	2.92	2.28	1.06
TOTAL	338.99	957.10			
Plasmabit™, ROP: 5 m/h	234.58	957.10	5.00	2.98	2.21
Plasmabit™, ROP: 10 m/h	132.25	957.10	10.00	6.59	5.30

Table 7 The total drill bit performance

The drilling time in the pessimistic case has been reduced for 30% and in the base case scenario even for 60% comparing to the real case scenario.

In the following figures, the time versus depth is plotted for all three scenarios, where the benefits can be clearly seen of the coiled tubing plasma drilling scenarios.

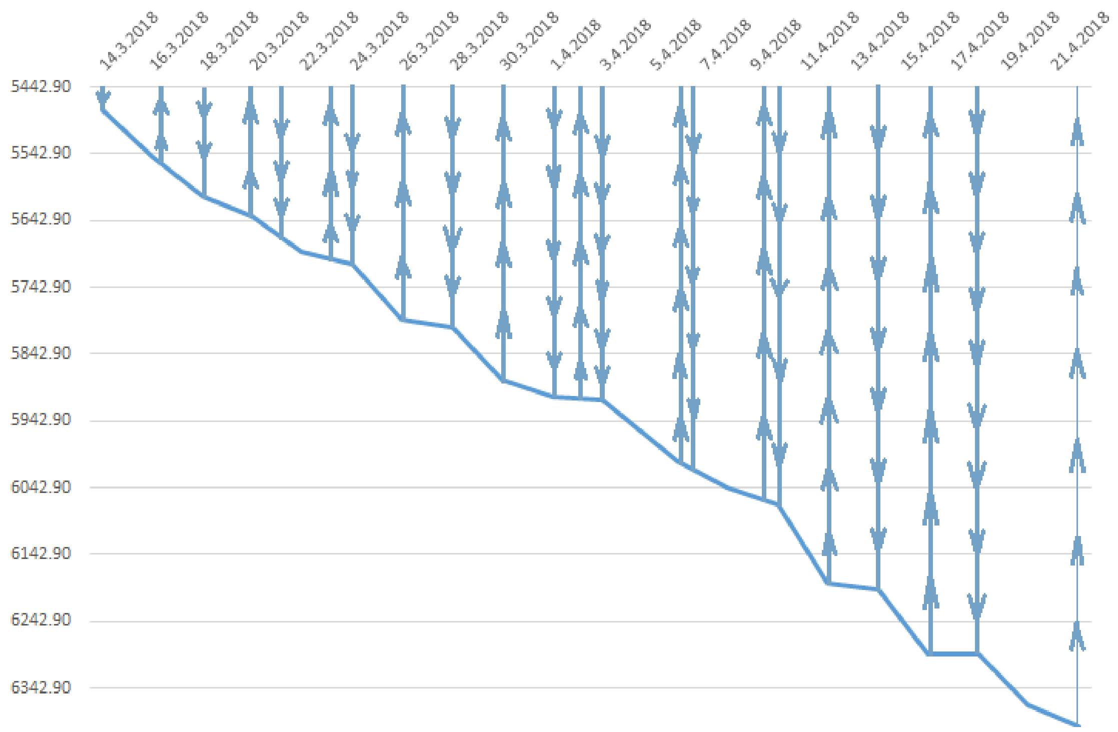

Figure 20 Time [days] vs. depth [m] plot with corresponding roundtrips for drilling with the conventional drilling methods

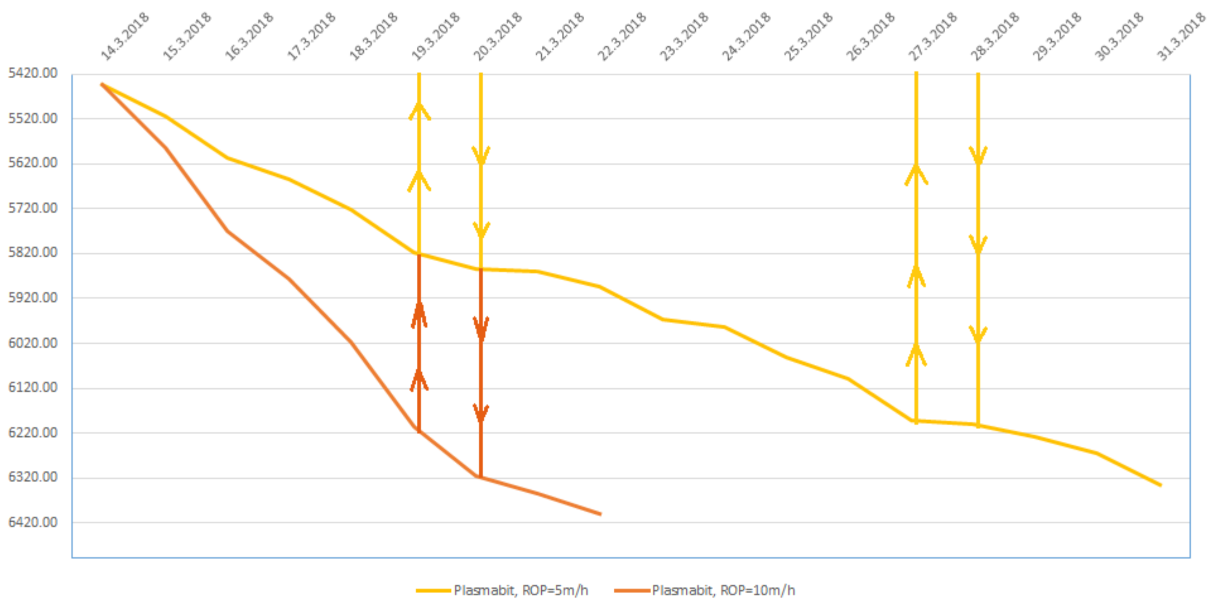

Figure 19 Time [days] vs. depth [m] plot with corresponding roundtrips for drilling with the Plasmabit™

3.5 Cost Analysis

As mentioned before, the benefits of using coiled tubing pulsed plasma drilling method can be clearly seen in a substantial time reduction while reaching such depths, especially when it is the word about geothermal wells. In the case of the pessimistic scenario with the clean ROP of 5 m/h, the final depth of 6400 m has been reached in 234.58 hours which is in total 100 h earlier than it has been drilled with the conventional methods. In the other hand with the base case scenario the final depth has been reached almost 200 hours earlier comparing to the conventional methods. This is especially important in the terms of the cost. The prerequisites were that the cost of the spread rate per day is 75 000 € and the casing and cementing cost for the cased part until the depth of 4000 m is 4 400 000€. This means that the rest of the borehole until the depth of 6400 m would be open hole. The methodology of the total drilling cost (TDC) estimation is as following:

$$TDC[€] = The\ number\ of\ hours\ taken\ to\ drill\ 1000\ m \times €75{,}000/day\ [h] \qquad (11)$$

When using pulsed plasma drilling method, the deepening rate changes. While that rate for the conventional case is 1.09 m/h, for the pessimistic case scenario is 2.21 m/h and for the base case scenario is 5.30 m/h.

Total drilling cost (TDC) = (The number of hours taken to drill the 1,000m section = 1000/1.09=917.4) x €75,000/24 spread rate/day/hour = €2,867,000 for the 1,000m open hole section.

Total drilling from 5442.90m MD to 6,400m MD	Conventional	Pessimistic	Base
Total drilling cost (TDC) in EUR per 1000 m	2,867,000	1,217,000	467,000
Total drilling cost (TDC) in EUR for 957.1 m	2,744,005	1,164,790	446,965

Table 8 The total cost breakdown for all three cases

The cost estimation above applies to drilling in hard rock from the depth of 5442.9 m to final depth. The reductions will vary according to the geology and at what depth the basement lies. Compared to conventional drilling and based on current test and development data, pulsed plasma drilling technology combined with coiled tubing can save 20 – 30% in well construction time and a total cost reduction on well construction 15 –22% in the case of drilling well similar to OTN-III in Finland.

Chapter 4

Conclusion

The complete utilization of geothermal energy production is still theoretical. Today's technology cannot fully use its whole potential. Most of the reservoirs are hidden in deep and economically unreachable depths. Due to the material resistance to its harsh environment in terms of extremely high pressures and temperatures, as well as the unhostile fluids. This gives the focus on the technological development, where the oil and gas industry meet the geothermal. The other focus is how to make these projects economically feasible. This raises the question of a much broader spectra, because geothermal energy can provide clean, green, and reliable source of energy worldwide. The only question is how to use its full potential in an economically feasible way, when it is known that drilling takes up to 50% of the cost to the complete geothermal project.

Plasma drilling in this case can provide an answer to previous mentioned problems. Its increased rate of penetration, with the combination of using coiled tubing, which provides faster tripping speed with the continuous mud circulation, might be the solution. Also, it can be used in directional drilling, which automatically expands the use of this drilling method. Furthermore, it is proven that this technology can withstand extremely high temperatures and pressures even until the depth of 10 km. By summarizing all of these facts, all the features if implemented can decrease the final cost of the well construction in total.

Nevertheless, plasma drilling technology might help to bring geothermal energy sources to a more commercial scale. So far, this source of energy is not possible to utilize worldwide, only in high enthalpy areas, where it is not needed to dig into big depths. In addition, this question also arises when addressing the efficiency of geothermal systems. For the given amount of funds, some other energy projects could be more cost effective. Science and engineering in cooperation can provide many answers to today's problems, especially when it is the word about geothermal energy, and give the opportunity to bring it anywhere.

4.1 The objectives for Plasma drilling - a typical well in the CLGS project

The expertise at this moment is developing new systems that can increase the efficiency of the geothermal system. One of those are deep closed loop geothermal systems. This innovative solution is different from the enhanced geothermal systems. It also uses the hot dry rock, but there is no fluid injection nor extraction and most importantly there is no fracturing, which can rise some questions from the society. The permeability in this case is overcame, by simply conducting the pipes through the connected wells, and therefore forming a heat exchanger. This means, also that there is no direct communication between the circulated fluid with the subsurface environment. In that way, closed loop systems can reach into wide variety of reservoirs where the temperature exceeds 300°C. This means that the power output increases in large amount. Also, it provides the possibility make such systems more viable for a broader use.

Hence, some modelling works has shown that this system can provide the similar power output to the enhanced geothermal system, while it can overcome some issues, which come with EGS, such as induced seismicity, emissions, mineral scaling, etc. (E. van Oort 2021). Yet, the problem is the well construction, where the wells have to meet in a certain point. According to Eavor (company which develops solutions for closed loop systems), another way of utilizing this system is to drill two vertical wells next to each other. These two wells, in that way would reduce the footprint. Also, it would be possible to use the magnetic ranging and to keep them uniformly apart. The lateral wells will in the end meet at a certain point, breaching out of the vertical ones. There is another concept, where the two vertical wells are more distant (around 6 km) than in the before explained one. These two wells are simultaneously drilled vertically and are connected horizontally in order to create a U-shaped configuration. After that a series of 10 laterals are drilled from each side which are connected within the two vertical wells by shaping the closed loop. This system would provide 2 MW_e on each side. The biggest issue with this concept is that around 100 km of wells must be drilled, as there are 20 laterals. At the moment this concept is still not economically feasible as the drilling costs would have been too high.

Plasma drilling technology in this case, combined with some other technologies, can provide a solution addressed to the directional drilling issue and well construction part, as well as to the cost of the whole project. Firstly, due to its high speed of reaching wanted targets. As it is already known, plasma drilling provides much faster rates of penetration. Because of its capability to easily break through hard formations. Second, it can also provide easier directional control, as it is stated by GA Drilling, the bottomhole assembly is equipped with intelligent directional maneuverability. Furthermore, the assembly contains smart sensors, which are allowing artificial intelligence sensing and 3D mapping (Ga Drilling 2019). In the other hand, when introducing coiled tubing during the drilling process as a transfer line, with its high tripping speeds, it can immediately decrease the time of drilling.

The concept of deep closed loop geothermal system (DCLGS) should provide the better efficiency regarding the power production from geothermal sources. Some analysis proves that the certain concepts of DCLGS are more cost effective comparing to other geothermal systems. The problem in this case is of technical nature. It arises when the word is about the well construction part, more specifically directional drilling. The introduction of plasma drilling in this case, combined with other technologies, should make the utilization of such projects easier. As this drilling method can reduce the drilling time, and therefore reduce the capital cost of the project. If the concept of DCLGS and pulsed plasma drilling method meet at the certain point, it can change the perspective of the geothermal energy in general. The energy cost reduction and the availability of geothermal energy worldwide would be inevitable.

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Nomenclature

T	temperature	[°C]
r	radius	[inch]
P	power	[MW_e]
l	length	[km] [m]
p	pressure	[bar], [MPa]
t	time	[h], [min]
E	energy	[kWh]
v	speed	[m/h]
U	enthalpy	[kJ/kg]

Abbreviations

BHA	Bottom hole assembly
CLGS	Closed-loop geothermal system
CO_2	Carbon dioxide
CT	Coiled tubing
DCLGS	Deep closed-loop geothermal system
DDR	Daily drilling report
EGS	Enhanced geothermal system
ESMAP	Energy Sector Management Assistance
H_2O	Water
H_2S	Hydrogen sulfide
HDR	Hot Dry Rock
HWR	Hot Wet Rock
IADC	International Association of Drilling Contractors
IDDP	Icelandic Deep Drilling Project
K^{40}	Potassium-40 radioactive isotope
NPT	Non-productive time
POOH	Pulling out of the hole
PT	Productive time
RIH	Running into the hole
ROP	Rate of penetration
RORT	Rate of the roundtrip
TDC	Total drilling cost
Th^{232}	Thorium-232 isotope
TMD	True measured depth
U^{235}	Uranium-235 isotope
U^{238}	Uranium-238 isotope

WBG	World Bank Group
WOB	Weight on bit