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White paper on Orkuveitan's deep utilization plans

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ABSTRACT

Orkuveitan has been a participant in the Iceland Deep Drilling Project (IDDP) from its commencement in 2000. Our partners in the project are Landsvirkjun, HS Orka, Iceland Energy Authority and Equinor. The main goal of the project is to drill a superhot production well in a traditional geothermal area. Through the years this project has sparked many other ideas related to deep heat utilization and the expansion of geothermal energy usage worldwide. In this paper we will present the goals of Reykjavik Energy in our deep utilization journey, identify knowledge gaps and go through the key parts of our plans to go deeper and to make geothermal energy more accessible.

Orkuveitan's approach is threefold. Firstly, a deep injection well will be drilled to support our current production by injecting into superhot geological formations below our current production zone. With this deep injection we hope to unlock the energy below our current production zone. Secondly, a deep production well will be drilled in our current production area, in line with the goals of the IDDP. Thirdly, we are researching the potential for deep superhot EGS in Iceland. Mapping of potential locations is ongoing. The ultimate goal of Orkuveitan's deep utilization efforts is to unlock geothermal potential in many untapped locations in Iceland and perhaps spark a geothermal revolution worldwide.

1. INTRODUCTION

The demand for green and sustainable energy has grown immensely in the past few years, due to the current geopolitical landscape and the growing focus on the conclusion of the reliance on fossil fuel (IEA (1), 2024). Geothermal has excellent potential to meet a large portion of that demand (IEA (2), 2024). Orkuveitan has been a large player in the development and operation of geothermal resources since its first drilling in Reykjavik in the 1930s. Orkuveitan made a breakthrough in the use of geothermal for district heating by developing a district heating network for the city of Reykjavik and its neighboring communities, a geothermal district heating system that was for a long time the largest in the world. The start of geothermal utilization by Orkuveitan was in low temperature geothermal fields (T<150°C) and the usage was mainly in district heating. Ideas on electricity production were present from the outset. With the harnessing of energy from the Nesjavellir geothermal field, Orkuveitan started electricity production in combination with the production of heat for district heating. Added effort was put into the geological research of the field in the 1980s and heat and power production commenced in the 1990s. The idea of deep superhot utilization was sparked by the drilling of well NJ-11 in Nesjavellir in 1984. Well NJ-11 was unexpectedly drilled into a very hot formation at the depth of 2.1 km. The temperature measured in the well reached the upper limit of the measuring range of the probe; 380°C. The downhole pressure was estimated to be 220 bar. For several reasons the well was deemed impossible to control with the technology available at the time and the bottom 500 m of the well were filled with gravel (Steingrimsson et al., 1990).

The drilling of NJ-11 sparked the idea of producing energy from the superhot formation encountered in the well, to advance geothermal energy production beyond traditional geothermal power plants in high temperature fields. The three largest power companies in Iceland; Orkuveitan, HS Orka and Landsvirkjun formed the Iceland Deep Drilling Project, in a consortium with the Iceland Energy Authority and international partners, with the goal of drilling into superhot formations at supercritical conditions to produce fluid for power generation.

The first well of the project, IDDP-1, was drilled in the Krafla field in northern Iceland in 2008. The well was originally planned to reach a depth of approximately 4.5 km but unexpectedly encountered magma at a depth of 2.1 km (Hólmgeirsson et al., 2010). The production casing was 2000 meters long, leaving about 100 meters of open well above the magma. Despite encountering magma, a flow test was successfully conducted, revealing that the open section of the well was permeable. During the test, the wellhead temperature reached 452°C, with a well head pressure of 142 bar. The estimated power output of the well was about 30-40 MWe. Significant challenges arose in the handling of the fluid, as it was highly corrosive, and the steam condensed silica either as dust or scale in pipes (Hauksson et al., 2014). The primary issue, however, was the integrity of the production casing. Thermal expansion and contraction, caused by the extreme temperature variations when the well was heated after drilling and shut in for maintenance, led to casing failure. As a result, the well had to be abandoned (Friðleifsson et al., 2021).

The next well of the IDDP project was drilled in the Reykjanes field in 2017. This well reached its planned depth of about 4.6 km, and core samples were obtained from the deepest part. At the bottom of the well, the highest recorded temperature was 426°C and the pressure was 340 bar, conditions above the critical point of water (Friðleifsson et al., 2021). Unfortunately, the production casing failed shortly after, preventing access to the lower sections of the well. It is believed that the failure resulted from a combination of poorly cemented casing and thermal expansion.

Through IDDP the partners have gained important information and learned valuable lessons on locating and drilling into superhot formations as well as designing wells and equipment to handle superhot conditions and fluids. The idea of how to harness superhot conditions has developed and broadened throughout the project. At Orkuveitan these lessons have resulted in the plan for deep utilization that is presented in this paper.

2. ORKUVEITAN'S DEEP UTILIZATION PLANS

The goal of Orkuveitan's deep utilization journey is to produce energy from superhot formations. The strategy is to drill wells into superhot formations in three separate projects. In the first project an injection well will be drilled, in the second project a production well will be drilled within our currently utilized hydrothermal fields, and in the third project a duplet will be drilled outside our current fields, into superhot dry rock.

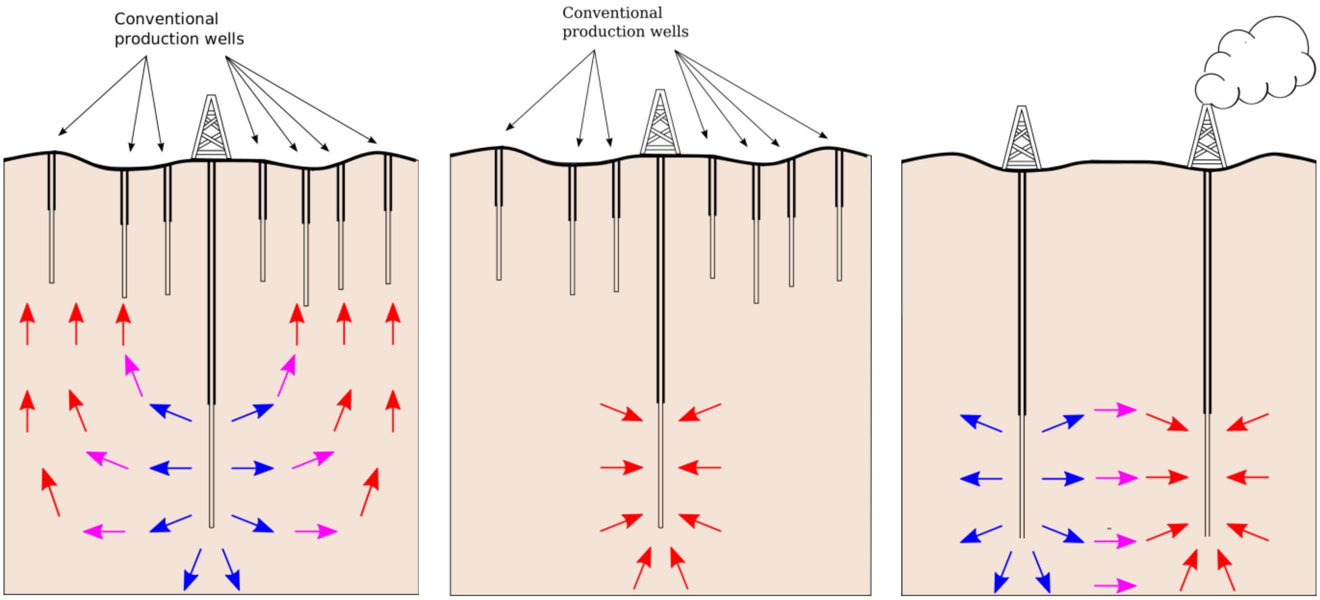

Figure 1: Three different scenarios of deep heat utilization. A. Deep injection into a superhot formation, B. Deep production from a superhot formation, and C. A superhot dry rock injector and producer.

2.1 Deep Injection

Drilling a deep injection well into superhot formations is technically feasible with current technology. The goal of such a well will not only be to provide pressure support to the current production field, as the current reinjection wells do, but also to provide more heat into the system by unlocking heat from superhot formations. Injecting cold water into superhot formations can create permeability through the formation and opening of existing fractures. This process has been described by Lister (1974) and Halldórsdóttir et al. (2023). A cold front travels through hot ductile rock resulting in fracture formation and opening as the rock cools and quickly contracts. Water flows through these new fractures, transporting heat from the superhot formation to the nearby traditional hydrothermal system. Some modeling was done within the GEOPRO project that suggested that deep injection could be beneficial and operational experience from Hellisheiði suggests that deep injection could positively impact the current production from the field. Well HE-40 is drilled directionally below production well HE-06. Injection with cold water (around 50°C) into well HE-40 significantly increased the permeability in the bottom feed zones without thermal breakthrough to HE-06.

2.2 Deep Production (IDDP)

The original goal of the IDDP was to drill a deep well into superhot formations to produce supercritical fluid from the well. As the participants in the project have gained experience the goal has been adjusted based on the information now available. Rather than targeting supercritical conditions the goal is now to drill a well that produces fluid with a high enthalpy; higher than 2800 kJ/kg. The pressure-enthalpy diagram in Figure 2 depicts this quite clearly. Going beyond the supercritical point of water and reaching superhot conditions does not necessarily mean that the produced fluid has a higher enthalpy than fluid below the critical point as the temperature lines in the graph curve towards lower enthalpy at higher pressures. The shaded yellow area in the graph shows what we have chosen to call the superhot region. In this region the enthalpy is above 2800 kJ/kg, a high enough enthalpy so that fluid in this region remains in the vapor/supercritical phase as it goes through isenthalpic depressurization upon rising to the top of a well. This is critical to minimize the potential corrosion in the well due to highly acidic droplet formation.

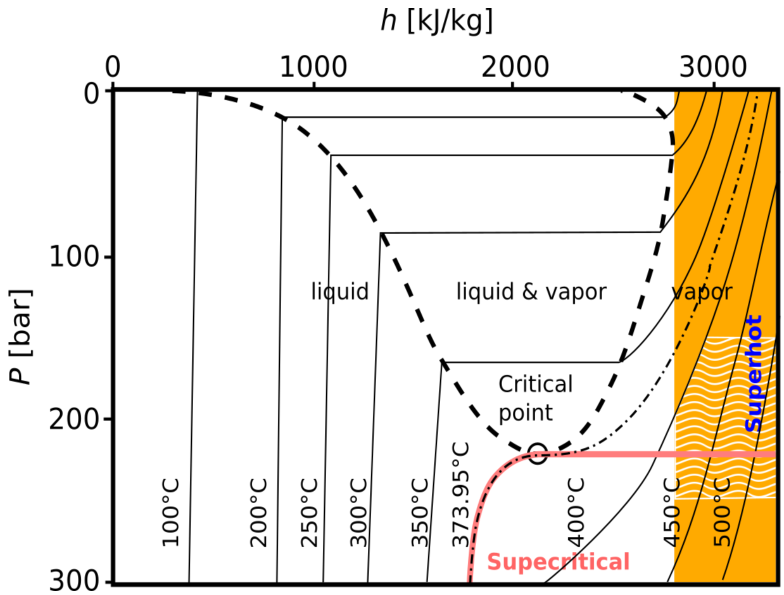

Figure 2: A pressure-enthalpy diagram of water with the pressure axis reverted to represent well depth. The shaded yellow area in the graph represents the region where the enthalpy is higher than 2800 kJ/kg.

In our first attempt at drilling a deep production well the target formation will not be very deep; or 3-3.5 km. The goal is to drill right below our current production zone with a long casing, casing of the formation we currently produce from. There are practical reasons for this related to the drilling operation and well design. Drilling into superhot formations is a challenge when it comes to controlling the well during drilling. It is also a challenge to design a well with a long casing that can handle the thermal expansion necessary to heat up a superhot well. Limiting the depth of the well to 3-3.5 km enables us to derisk the drilling and design as much as possible at this stage of the overall deep utilization journey to optimize the chance of success. Limiting the well to 3-3.5 km also enables us to limit as much as possible the potential for silica scaling in the well and surface equipment. The solubility of silica in the superhot region is pressure dependent and by limiting the depth of the well the pressure is kept as low as possible without compromising the high enthalpy and thus, silica scaling is kept to the lowest possible level. The target for the first superhot production well is therefore a superhot formations at about 3-3.5 km depth to produce fluid with an enthalpy above 2800 kJ/kg.

2.3 Superhot Dry Rock

Deep injection and deep production represent great potential within our current production fields. But as we look further into the future more energy is needed to supply the population of Reykjavik and neighboring communities with water for district heating and to meet the growing demand for sustainably produced electricity. There is a lot of potential for geothermal energy production outside of the traditional hydrothermal fields in Iceland. Superhot dry rock (or superhot EGS) presents an opportunity to utilize superhot formations wherever they can be found in Iceland. The graphic in Figure 3 shows the temperature at 1000 m depth in Iceland (°C). A lot of potential for superhot dry rock is available in Iceland and Orkuveitan and ÍSOR (Iceland Geosurvey) are currently working on mapping the general potential for superhot dry rock as well as targeting specific locations.

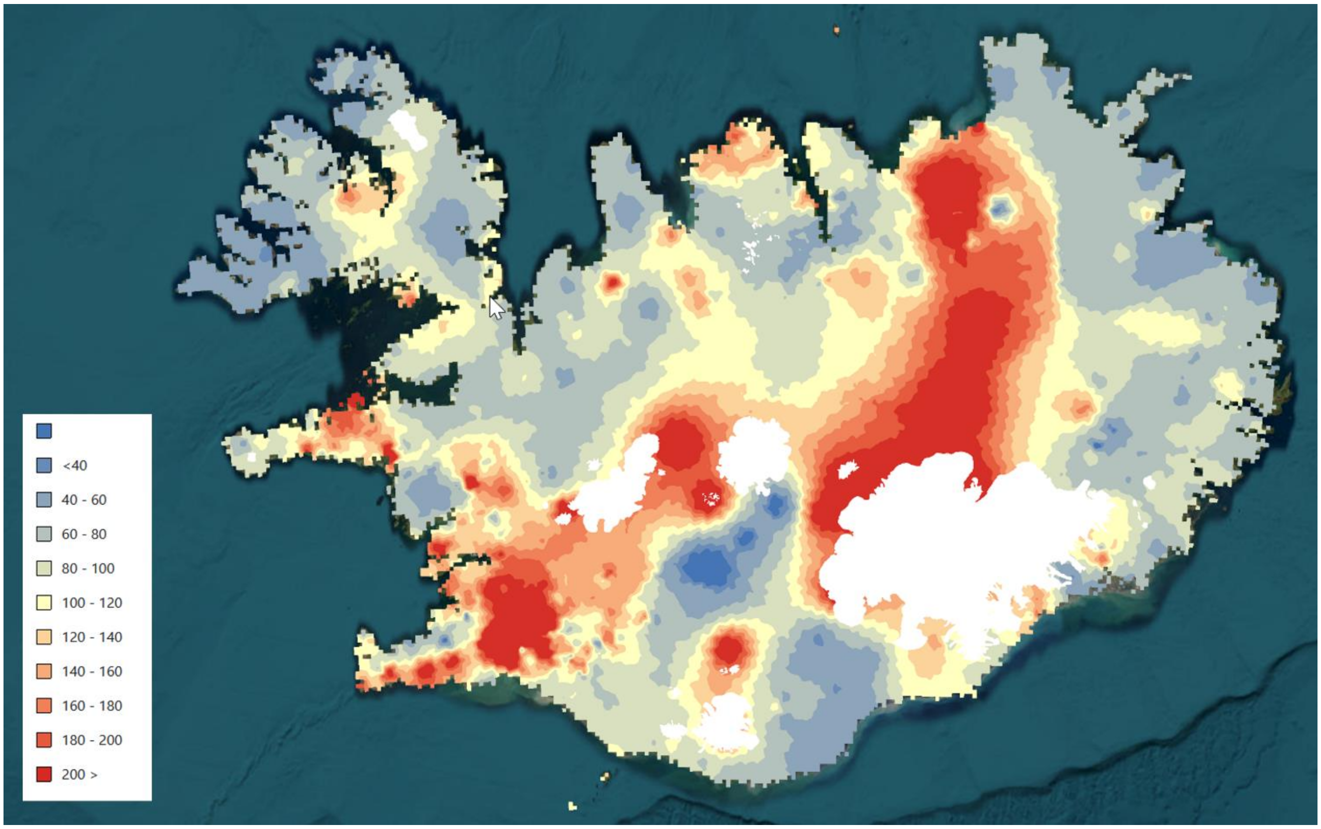

Figure 3: A map of Iceland showing the formation temperature (°C) at 1000 m depth. The data is extrapolated in 2 km x 2 km squares from wells with downhole temperature measurements. Assembled in 2017 for the NagTec Atlas (Hopper et al., 2017).

3. CHALLENGES

There are four factors that present specific technical challenges in superhot utilization for Orkuveitan; the chemistry of the produced fluid, the high temperature of the formation and fluid, the long casing, and energy production.

3.1 Chemistry of the Produced Fluid

The chemistry of the fluid is purely dependent on the physical processes it has undergone in the subsurface. As the fluid heats up to superhot or supercritical conditions it goes through chemical and physical processes that result in a high chloride and silica content. When the fluid is brought to the surface HCl rich droplets form if any condensation occurs. It is therefore key to target formations with an enthalpy above 2800 kJ/kg to prevent condensation during isenthalpic depressurization. Some condensation is always likely to happen during the heat up of the well and thus highly corrosive conditions will be present in the well for at least a short period of time. One way to face this challenge is to use corrosion resistant materials in the casing, such as titanium or corrosion resistant steels. Another way is to clad traditional casing material with corrosion resistant materials. Cost effective laser cladding procedures for casings are being developed within the Orkuveitan led EU funded COMPASS project (Gunnarsson et al., 2024). Dissolved silica can also cause significant issues. As was detailed before, silica solubility is pressure dependent in the supercritical region. By limiting the depth of the first production well to 3-3.5 km, silica scaling in the well or surface equipment can be kept at a controllable level.

3.2 Temperature and Casing Length

The high temperature and long casing together cause thermal stress on the casing. A novel technology developed by ÍSOR through several EU funded projects (GeoWell, CeoConnect, DEEPEGS); flexible couplings; is intended to address a part of that problem. The flexible couplings allow for axial thermal expansion of casing segments within the couplings to reduce the risk of plastic deformation and casing failure (Thorbjornsson and Kaldal, 2021). This is essential for the heating up of a superhot well with a long casing. It also enables superhot wells to be serviced with a lower risk of casing failure due to thermal stresses. Flexible couplings are currently being put down into well NJ-37 in Nesjavellir, to test their effectiveness in a traditional hydrothermal well before using them in a superhot well.

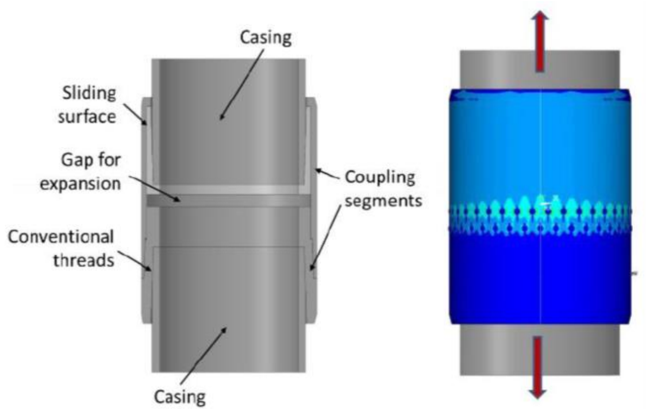

Figure 4: A diagram showing the functionality of flexible couplings (Lipus et al., 2022).

Cementing has also been a challenge in deep and superhot wells. The cementing procedure is critical and cementing in segments is recommended for long casings. A key concern is the existence of water pockets in the cement which can result in the casing buckling. ÍSOR is currently developing a pressure relief system to prevent buckling within the COMPASS project which Orkuveitan intends to use for deep superhot wells. The properties of the cement are also of critical importance. Limited flexibility of traditionally used cement can result in casing failure due to thermal stresses. In the COMPASS project a novel foam cementing solution is under development. A key feature of the foam cement are enhanced flexibility due to a gas-liquid dispersion that incorporates bubbles in the cement matrix resulting in a low density. This better accommodates expanding casings and reduces the risk of casing rupture and other similar failures due to thermal expansion.

3.3 Energy Production

Producing a fluid with high enthalpy from a superhot well is not the final goal, it is extracting energy from the fluid. Energy production from a highly corrosive fluid with a high silica concentration will likely be quite challenging although the technical solutions are all currently available. A key aspect in choosing the right equipment and processes is to ensure that the enthalpy of the fluid is maintained through the fluid processing necessary to enable its use in a power and heat production process. A good overview of this can be found in a recently published report by Clean Air Task Force (Brown et al., 2024).

4. CONCLUSION

Reykjavik Energy's deep utilization efforts represent an exciting step forward in expanding the potential of Iceland's geothermal resources. Through the ambitious goals set out in our deep utilization strategy, we aim to unlock previously untapped energy by drilling into superhot formations and pushing the boundaries of traditional geothermal energy production. Our approach, which includes the development of deep injection and production wells, as well as exploring superhot dry rock (EGS), is designed to harness the vast energy stored beneath Iceland's surface. The integration of these technologies will not only improve the sustainability of our current geothermal operations but also provide a blueprint for expanding geothermal energy access worldwide.

Despite the promising potential, several technical challenges remain, particularly with fluid chemistry, high temperatures, and the mechanical integrity of well casings. However, through continued collaboration with our partners and investment in innovative solutions such as corrosion-resistant materials and flexible coupling technologies, we are steadily overcoming these obstacles. The next step is the drilling of a deep injector. The drilling is currently planned in 2026/2027. For the deep production well we will focus on testing innovative technologies, e.g. from the COMPASS project and mitigating risks related to silica scaling and fluid handling in surface equipment with a focus on maintaining the fluid enthalpy as high as possible. Next in superhot dry rock utilization is resource mapping in collaboration with ÍSOR.

Ultimately, the success of Reykjavik Energy's deep utilization strategy holds great promise, both for Iceland's energy future and as a model for global geothermal development. As we continue to explore and unlock the full potential of deep geothermal resources, we anticipate that these efforts will not only contribute to our own energy needs but will also play a critical role in the global transition to clean, sustainable energy.

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