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Key lessons and characterization for deep geothermal well exploitation: insights from the COMPASS project

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ABSTRACT

Geothermal well technology comes mainly from the oil and gas industry. This technology transfer has generally been very beneficial for the geothermal sector. There are, however, issues, specific to geothermal, that have not been addressed properly that have led to incidents resulting in casing failures, especially in hot, powerful wells. The conditions when producing from superhot formations are challenging; the temperatures are higher, the casings longer, and the fluid chemistry can be corrosive. Thus, it is foreseeable that conventional geothermal well technology, with its origins in oil and gas technology, will not suffice as the geothermal sector pushes the border towards higher temperatures. To enable successful harnessing of energy from superhot resources new technology must be developed that addresses these issues specific to geothermal.

The aim of the COMPASS project is to address technical issues regarding drilling into and producing energy from superhot formations with special focus on well design. Within the COMPASS project a basis of key lessons learned from previous deep drilling projects was established. The challenges were analyzed and solutions presented. This paper comprises the results of this investigation and aspires to be a piece in the puzzle to form a useful basis for discussion of further solutions for deep well drilling into superhot conditions.

1. INTRODUCTION

The challenges of drilling into superhot geothermal reservoirs are unique. According to the experience from wells that have been drilled into superhot formations, such as IDDP-1 in Krafla and IDDP-2 in Reykjanes, the conditions in the well can be highly corrosive. Superhot formations can be found as shallow as ~2100 m below the surface (Ingason et al., 2014; Friðleifsson et al., 2015; Hermanská et al., 2019; Fridriksson et al., 2022; Gunnarsson et al., 2022). The term superhot means that the energy content of the water, i.e., its enthalpy, is higher that ~2800 kJ/kg. That means that the superhot fluid does not form condensate upon isenthalpic decompression. The superhot fluid is likely formed by complete boiling of geothermal liquid from the conventional reservoir (Hermanská et al. 2019).

The superhot target can be in the depth-range of 2.0-3.5 km and even deeper. The temperature range is expected to be 400–550°C and the pressure 150–250 bar. When drilling into such a target the conditions can become corrosive, the longer-than-usual casing can be problematic resulting in problems with casing and cementing. Also, high temperature causes extreme thermal expansion/contraction. In this paper, we identify the main challenges of superhot geothermal drilling and discuss possible solutions to overcome them. These include the development of high-temperature-resistant materials and improved cementing and casing technologies. By addressing these issues, we aim to support safer and more efficient access to supercritical geothermal resources, which hold significant promise for sustainable energy production.

2. CHARACTERISTICS OF THE INTENDED ENVIRONMENT

The current plan for IDDP-3 is to target superhot formations at <3 km depth. The experience from IDDP-1 and other wells in Krafla as well as from two wells in Nesjavellir has shown that superhot fluids exist at relatively shallow depths in those two fields. Under these conditions the fluid can be expected to be similar to the fluid produced from IDDP-1. The fluid can be expected to be derived from complete boiling of subcritical geothermal fluid. By analogy to IDDP-1, the non-volatile components can be expected to be quantitatively removed from the "steam-like" superhot phase, the volatile components to be in similar concentrations to what is observed in the subcritical geothermal fluids, and finally the silica concentration is likely to be in the range from 50 to 100 mg/kg (Ármannsson et al. 2014; Fridriksson et al. 2015; Hermanská et al. 2019).

The preferred pressure, temperature and enthalpy regime is shown in Figure 1. To set the basis for the discussion on deep well development the relevant information on the characterization of the intended environment is described. Temperature, pressure, fluid composition and fluid phase are at first described based on existing documents and data for deep wells in the in Iceland:

- Temperature and pressure – The preferred target formations are at the depth of 2-3.5 km. The uppermost 2-2.5 km of the well will be cased off. The expected temperature is 400°C-550°C and the pressure 150-250 bar. The fluid will be superhot with enthalpy higher than 2800 kJ/kg.

- Lithology – The bedrock in Hengill is predominantly composed of lavas and hyaloclastites of basaltic composition, with minor amounts of more evolved rocks. Intrusives are rare in the uppermost 800 to 1000 m but become increasingly common below that depth (Franzson, 2000; Franzson et al., 2005; Níelsson and Franzson, 2010; Galezcka et al., 2022)

- Fluid chemistry – Exact knowledge of the chemical composition of the fluid in superhot formations in Hengill is limited. The superhot fluid is expected to be "vapor-like", i.e., with relatively low density, at the temperature and pressure conditions expected. Based on limited experimental and theoretical data and empirical data from Krafla and Nesjavellir, we anticipate that Cl will behave as a volatile component and partition into the superhot fluid and be present in the form of HCl°. We also expect SiO_2 to be present in the fluid in concentrations ranging between about 25 and 200 mg/kg. Condensation of the superhot fluid will result in the formation of highly acidic liquid phase, and therefore condensation inside the well should limited as possible. Depressurization of the fluid will result in the formation of amorphous silica dust that can cause erosion inside the casing and erosion and/or clogging on the flow line.

A testing regime utilising these characteristics for the intended environment has been developed for use in tests for flexible foam cement design and for pre-screening and design of testing regimes for cost-effective casing corrosion control solutions such as cladding.

The condensation of the superhot fluid can occur and be in contact with cement if casing is damaged or there is a leak-off along the cement sheath creating pathways for the subcritical geothermal fluid to migrate upwards to the shallower sections where the temperature is lower. Thus, chemical degradation of cement by geofluids does not seem to be a real threat while the mechanical well integrity is ensured. As a result, the chemical characteristics of geothermal fluids will not be used as testing parameters for preliminary foam cement selection and design. The main characteristics as used for flexible foam cement design in the laboratory are thermo-mechanical parameters under bottomhole temperature and pressure, namely temperature and pressure variations of the wellbore and downhole environment at different well-life events.

COMPASS will go beyond the state of the art by providing a cost effective and high-performance solution cladding based on selective application of high-performance CRA (corrosion resistant alloys) via laser-cladding, specifically EHLA (Extreme High-speed Laser Application). Traditional carbon steel casing will be used as a substrate and will be coated with selected CRAs based on state-of-the art results and testing within the project. Within the project a bespoke machine was designed and integrated with the application of geothermal pipe cladding as a chief performance measure.

Table 1 shows how the estimated properties were expected to be used within the experiments in thermal stress mitigation solutions and cost-effective cladding for corrosion mitigation.

In addressing these issues, novel technologies are being explored in the COMPASS project which will utilise the state-of-the-art technology and experience from previous well designs.

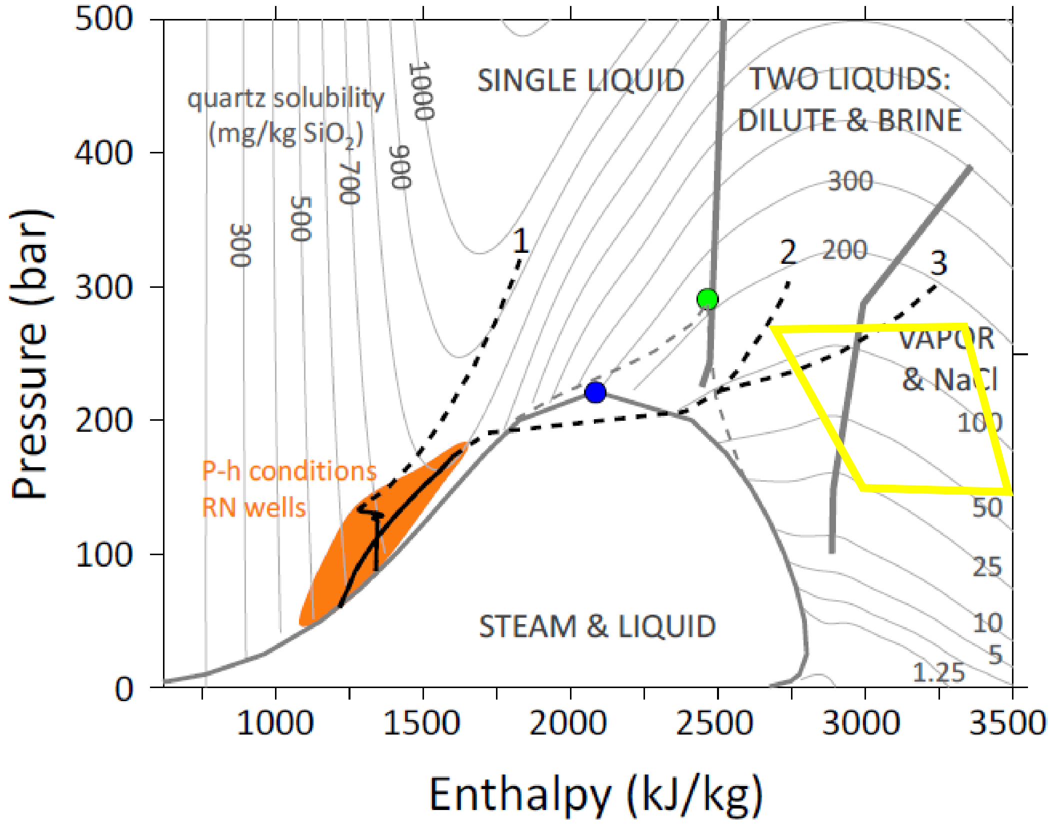

Figure 1. Silica solubility at sub- and supercritical conditions. The figure is from Fridriksson et al. (2015) and was constructed to show the expected silica concentration and the state of the H_2O-NaCl system in the Reykjanes field before drilling IDDP-2. Note that the thick gray lines representing transitions between the different fields in the H_2O-NaCl system are based on conditions in the saline Reykjanes geothermal system and do not apply to the dilute systems in the Hengill Volcano. The thin, light-grey lines, representing silica solubility are, however expected to apply to the solubility of quartz the Hengill systems. The preferred pressure and temperature regime is highlighted by the yellow tetragon.

2. CHALLENGES IDENTIFIED AND PROPOSED SOLUTIONS

The challenging conditions encountered at superhot geothermal reservoirs, i.e., high temperatures, corrosive environment, dissolved SiO_2 in the steam and long casing create unique technical challenges in designing a deep superhot production well. The main challenges and proposed solutions are:

2.1 Thermal expansion/contraction in high temperatures.

Challenge: Thermal expansion/contraction in casings is known to compromise well integrity. This problem increases with higher temperature. The primary causes of casing failures have been identified as tensile rupture and collapse (Thorbjornsson et al., 2019). Tensile rupture occurs when the casing material, under high temperatures, undergoes permanent deformation that upon cooling leads to high tensile stress and potential fracturing, especially if the material becomes brittle.

Proposed solution: Addressing thermal expansion and contraction is paramount in geothermal wells, particularly when casings extend 2-3 km and are subjected to high temperatures. Lessons learned from IDDP-1 and IDDP-2 demonstrate that such lengthy casings are prone to failure under the intense operational conditions typical of superhot wells.

A flexible casing system is essential for mitigating the stresses on the casing due to extreme temperatures, and ensuring proper well integrity and preventing casing failures. Flexible couplings which are a patented solution for thermal expansion issues of casings that are confined in cement, have been considered as a key aspect for increased well integrity. The flexible couplings have been deployed and are currently being tested in the newest production well NJ-37 in Nesjavellir, Iceland, and the solution therefore an emerging technology.

Corrosive environment. Chemical challenges arise when the super-hot fluid condenses again. Cl will partition quantitatively into the liquid phase, if condensation occurs, forming HCl rich, acidic and highly corrosive droplets. Similarly, if the super-hot fluid and the conventional geothermal fluid mix, HCl will be scrubbed into the liquid phase to form hydrochloric acid, which is highly corrosive.

Proposed Solution: First, the conventional geothermal system needs to be cased off to prevent the mixing of the supercritical fluid with the conventional reservoir and thus preventing the formation of acidic fluid. Therefore, a long casing is required, 2-2.5 km – which leads to new problems with the thermal expansion of the material in the casing.

Secondly, it is crucial to minimize condensation of the super-hot fluid within the well bore to prevent the formation of HCl rich droplets.

Appropriate materials and methods are needed to mitigate corrosion if such HCl rich droplets were to form. Novel cladding solutions are being investigated and indicating promising results.

Nevertheless, the exact chemical properties of the superheated steam at Hengill geothermal system remain uncertain. Therefore, the deep, superheated steam in the Hengill geothermal system will be further characterized by collecting deep downhole samples at selected depths in 3-4 wells in the Hengill area. The results of this downhole sampling will test the validity of using chemical analysis of IDDP-1 steam as a proxy for deep fluids in Hengill. The testing regime will then be reviewed to accommodate the results of the analysis

Erosion and scaling due to dissolved silica in steam. Challenge: Under superhot conditions the solubility of silica (SiO_2) in the vapour-like phase increases with higher pressure and thus, greater depth. Depressurization as the fluid flows from the formation into the well bore causes SiO_2 to form silica dust in the steam.

Proposed solution: Choosing a shallow superhot target will mitigate the problem of dissolved SiO_2 because the solubility of SiO_2 is lower at shallower depths due to lower pressure.

Cementing Challenges.

Challenge: Since the conventional geothermal system needs to be cased off, the casing will be unusually long – 2-2.5 km. Cementing long casings in geothermal wells is particularly challenging due to extreme temperatures and chemical aspects. Also, cementing flexible casings needs to be addressed. Accurate testing of cement properties under real conditions is vital to avoid failures. Lessons from previous geothermal projects highlight that successful cementing is critical to prevent costly and environmentally damaging outcomes.

Casing collapse often results from poor casing quality and improper cementing which can cause high water content and water pockets in the cement. The water will expand with heat making temperature a significant factor.

Proposed solution: An essential part of a flexible casing system is a proper cementing job. Geothermal well cementing exhibits more severe conditions. The cement placement should be carefully designed to not only ensure the cement stability but also to avoid the lost circulation and water pockets in cement sheaths. The cement must be flexible to be able to withstand the thermal expansion. Moreover, the cement must withstand the high temperature expected in the well. Foam cement solutions have been used in the oil and gas industry and adapting this technology for geothermal could potentially make groundbreaking advancements to improve geothermal cementing technologies.

Even though improved technology is implemented in the well design, failures in the cementing can occur resulting in water pockets between casings. These pockets can cause detrimental failures of the casing when temperature increases during warm up. APB relief system is designed to be a ventilation system in the well design to release this excessive pressure.

Annular pressure build up (ABP).

Collapse due to APB in a cemented annulus is one of the major problems in operation of geothermal wells. High pressures build up in fluid trapped between casings when the well heats up causing casing collapse. APB is created by expansion of excess annular fluids, e.g., excess water in cement or trapped water. When circulation and/or injection is stopped after drilling is finished, the well warms up and thermal expansion generates stresses in casings. Fluid pressure builds up until, in the worst case, it leads to a failure of the part with the least resistance, i.e., the casing collapses.

Proposed solution: APB relief systems designed to release excessive pressure. A potential solution to solve APB of cemented annulus is to introduce a pressure-relief through the casing wall. A prototype will be demonstrated in relevant environment in a simulated full-scale experiment. A patent application has been filed for the annular pressure relief technology with a working title “Casing Collapse Protector” that has been in development at ÍSOR within the COMPASS project.

Table 1: Estimated properties of the intended environment and planned inclusion in experiments performed

	Estimates built on previous reports	Tests for thermal stress mitigation solutions			Tests for cost effective cladding for corrosion mitigation		
		Equipment restraints	**Value tested**	**Method to correlate**	**Equipment restraints**	**Value tested**	**Method to correlate**
Depth	2 – 3.5 km	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Temperature	400–500°C	200°C-300°C	<300°C	Modelling /simulations	200°C	Susceptibility to SCC in sour environment	High pressure high temperature testing
Pressure	150–250 bar	250 bar	n.a.	n.a.	150–200 bar	General corrosion and localised corrosion resistance	High pressure high temperature testing
Enthalpy	Superhot, h> 2800 kJ/kg	n.a.			n.a.		
Lithology	lavas and hyaloclastites of basaltic composition, with minor amounts of more evolved rocks						
Fluid chemistry*	SiO_2: 25–200 mg/kg	The superhot fluid is not in direct contact with cement sheaths			Simulating service brine (pH<3)		

*to be updated after downhole sampling

3. CONCLUSIONS

The aim of a superhot well is to produce superhot fluid – i.e., a fluid that has high energy content/enthalpy. There are few interesting sites for drilling such a well in the Hengill volcanic complex. The characteristics of a superhot formation in the Hengill area can be briefly described as follows.

- The preferred target formations are at the depth of 2-3.5 km. The uppermost 2-2.5 km of the well will be cased off. The expected temperature is 400-550°C and the pressure 150-250 bar. The fluid will be superhot with enthalpy higher than 2800 kJ/kg.

- The bedrock in Hengill is predominantly composed of lavas and hyaloclastites of basaltic composition, with minor amounts of more evolved rocks. Intrusives are rare in the uppermost 800 to 1000 m but become increasingly common below that depth.

- Exact knowledge of the chemical composition of the fluid in superhot formations in Hengill is limited. The superhot fluid is expected to be "vapor-like", i.e., with relatively low density, at the temperature and pressure conditions expected. Based on limited experimental and theoretical data and empirical data from Krafla and Nesjavellir, we anticipate that Cl will behave as a volatile component and partition into the superhot fluid and be present in the form of HCl°. We also expect SiO_2 to be present in the fluid in concentrations ranging between about 25 and 200 mg/kg. Condensation of the superhot fluid will result in the formation of a highly acidic liquid phase. Condensation of the superhot fluid inside the well should therefore be limited as possible. Depressurization of the fluid will result in the formation of amorphous silica dust that can cause erosion inside the casing and on the flow line.

Condensation of the superhot fluid can take place and come into contact with cement under two key scenarios: either when the casing is compromised or when there's a leakage through the cement sheath, forming pathways for subcritical geothermal fluids to migrate towards shallower sections with lower temperatures. In light of this, it appears that the risk of chemical degradation of the cement due to geofluids is not substantial, provided that the mechanical integrity of the well is maintained. The primary considerations for designing flexible foam cement in laboratory settings revolve around assessing thermo-mechanical parameters under bottomhole temperature and pressure conditions.

This compiles the current state of knowledge within this project on the preferred target for a superhot well and subsequent testing regime. The chemical properties of the deep, superheated steam in the Hengill geothermal system will be further characterized by collecting deep downhole samples at selected depths in 3-4 wells in the Hengill area. The results of this downhole sampling will test the validity of using chemical analysis of IDDP-1 steam as a proxy for deep fluids in the Hengill area.

The intended environment has thus been preliminarily characterized. When drilling into such a target the conditions can become corrosive, especially when the well is heating up after drilling. Moreover, the steam at those temperatures will contain dissolved silica that will condense from the steam during depressurization. Mixing of the deep fluid with conventional geothermal fluid should be avoided at all costs as such will cause corrosion and scaling. Therefore, the conventional system should be cased off by long (~2-3 km) casing. The length of the casing causes increased challenges in cementing and the high temperatures will cause extreme thermal expansions when the well heats up.

The COMPASS project tackles the corrosive environment by developing methods for cladding standard casing materials with corrosive resistant materials. The challenges related to high temperatures that the COMPASS project addresses are thermal expansions/contractions in long casings and high pressures that build up in fluid trapped between casings when the well heats up. The COMPASS project contributes towards developing flexible cement solutions that work with available flexible couplings for reducing stresses due to thermal expansions/contractions in long casings. Annular Pressure Build-up (APB) relieve system was further developed to release pressure that builds up in fluid trapped in the cemented annulus between casings.

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