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Future of Geothermal Wells in Superhot Context

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INTRODUCTION

Geothermal well technology is based on oil and gas well industrial technology. 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 more challenging conditions, including higher temperatures. To enable successful harnessing of energy from superhot resources, new technology must be developed that addresses these issues specifically to the geothermal sector. The aim of the Horizon Europe COMPASS project (No. 101084623), led by ON Power and Reykjavik Energy, 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 were established, research was made into solutions to mitigate or solve identified challenges and results were published in project reports available at the project website. 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 CHARACTERISTICS OF THE INTENDED ENVIRONMENT

To establish the basis for discussion on deep well development, relevant environmental characteristics and their relation to testing within the COMPASS project are summarized. The testing regime focuses on flexible foam cement design and casing corrosion mitigation.

Conditions in Hengill deep wells:

- Temperature & Pressure: Target formations lie at 2–3.5 km depth, with the upper 2–2.5 km cased. Expected temperature is 400–550 °C and pressure 150–250 bar. Fluids are superhot with enthalpy >2800 kJ/kg.
- Lithology: Bedrock consists mainly of basaltic lavas and hyaloclastites, with intrusives rare above 800–1000 m but common below.
- Fluid Chemistry: Limited data exist, but fluids are likely vapor-like with low density. Chlorine may partition as HCl, and SiO_2 concentrations range 25–200 mg/kg. Condensation produces highly acidic liquid and amorphous silica dust, which can erode casings and flow lines.

The testing regime uses these conditions to design foam cement and corrosion control solutions such as cladding. Chemical characteristics are excluded from preliminary cement testing because exposure to the corrosive fluid from the well occurs only if casing fails or leak-off happens. Laboratory tests focus on thermo-mechanical properties under bottomhole temperature and pressure.

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.

	Estimates from prior reports	Thermal stress mitigation tests			Cladding for corrosion mitigation tests		
		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	SiO2: 25–200 mg/kg	The superhot fluid is not in direct contact with cement sheaths			Simulating service brine (pH<3)		

2 CHALLENGES ADDRESSED IN RECENT RESEARCH

2.1 Challenges in superhot geothermal energy

Superhot formations in Iceland occur as shallow as ~2100 m. “Superhot” refers to water with enthalpy >2800 kJ/kg, remaining in steam phase during isenthalpic decompression. These fluids form by complete boiling of geothermal liquid. There are a variety of issues that can arise during extraction of fluid from such conditions including acid manifesting due to condensation and scaling due to mixing with conventional geothermal water. Silica (SiO_2) poses erosion and scaling risks and its state is highly dependent on depth and pressure. Targeting shallower formations and carefully selecting production conditions helps minimize these issues.

Producing from superhot zones requires isolating the conventional reservoir with a long cased off area (~2–3 km) to prevent fluid mixing. High temperatures, corrosive fluids, and casing length create challenges including thermal expansion which can compromise integrity, causing tensile rupture or collapse. Collapse often results from poor cementing and water pockets that expand under heat. Cementing is difficult due to extreme temperatures, phase segregation, and premature curing; proper composition, retarders, and testing under real conditions are essential. Thermal stress between steel casing and rigid cement also increases failure risk.

Drilling into superhot geothermal reservoirs presents unique challenges. Experience from wells like IDDP-1 and IDDP-2 shows that conditions can be highly corrosive due to condensation of acidic species such as HCl and HF, making corrosion mitigation essential. Dissolved SiO_2 also causes erosion and scaling; its solubility increases with depth and pressure, while depressurization leads to silica dust or scale. Mixing superhot fluids with conventional geothermal fluids in the well bore is not feasible because it heightens corrosion and scaling risks. Therefore, the conventional system must be isolated from the superhot zone using a long casing (~2–3 km).

The COMPASS project proposes further solutions: (1) Flexible casing system with couplings to reduce deformation and rupture. (2) *Extra-High Speed Laser Application* (EHLA) clad method cladding for internal corrosion protection. (3) *Annular Pressure Build-up Relief system* (APB-relief) and *flexible foam cement* to prevent collapse and reduce axial stress, improving well integrity and longevity.

2.2 Key lessons

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

- Choosing a shallow superhot target to mitigate the problem of precipitated SiO_2 because the solubility of SiO_2 is lower at shallower depths due to lower pressure. Shallower depths result in lower thermal and pressure gradients within the well bore and thus lowers the risk of SiO_2 precipitation.

- Condensation in superhot geothermal fluids will cause severe corrosion when dissolved Cl in the steam goes entirely into the first droplets leading to low pH. Thus, it is crucial to prevent any condensation within the well bore. This is mainly done by preventing inflow of colder geothermal fluid into the well, above the utilisation zone.

- Corrosion control is crucial due to highly corrosive conditions that can occur in superhot geothermal wells and also in surface equipment. Appropriate materials and methods are needed to mitigate these problems. Novel cladding solutions are under development and first results are promising. COMPASS work exceeded the state of the art by providing a cost effective and high-performance solution cladding based on selective application of high performance CRA via laser-cladding, specifically EHLA (Extreme High-speed Laser Application). Standard carbon steel casing was used as a substrate and coated with selected CRAs (Inconel 625 and stainless steel 316L) based on state-of-the-art results and testing within the project. Within the project a productive, flexible EHLA cladding machine was designed and integrated with the application of geothermal pipe cladding as a chief performance measure.

- Addressing thermal expansion and contraction is paramount in design of geothermal wells, particularly when casing length extends 2-3 km and is exposed to high temperatures. Lessons learned from IDDP-1 and IDDP-2 demonstrate that such long casings are prone to failure due to thermal expansions and high temperature gradient under the intense typical operational conditions of superhot wells.

- A flexible casing and cementing system are essential for mitigating the stresses on the casing in extreme temperatures which ensures proper well integrity and prevents casing failures.

- An essential part of a flexible casing system is a proper cementing job and quality of the cured cement downhole. Geothermal well cementing needs to endure to more severe conditions than traditional cementing. Segregation of the cement, formation of water pockets and premature curing of the cement are defects that can affect the lifetime and efficiency of the well. The cement placement should be carefully designed to not only ensure the cement stability but also to avoid lost circulation and water pocket in cement sheaths. Mechanically, cement has to be flexible to be able to withstand the thermal expansion and expand with the steel casing when the well heats up or contract when it cools down. Chemical composition of the cement has to ensure that curing is not occurring before cement arrives at the target depth. Chemical retarders in the cement, that can extend the curing time of cement at high temperatures must be applied. Moreover, the cement integrity has to withstand the high temperature 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, well integrity and lifetime of geothermal wells.

- 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 collapse failures of the casing when temperature increases during warm up which can result in loss or lower production performance of the well. An APB Relief system is designed to ventilate and release high water pressure in the cement to prevent collapse of the steel casing.

In addressing these issues, novel technologies were explored and developed further in the COMPASS project to utilize and develop state of the art technologies and experiences from previous well designs.

3 FUTURE RESEARCH INTENTIONS

Iceland offers ideal conditions for superhot geothermal (SHG) demonstration, with high thermal gradients, accessible >400 °C resources, and advanced infrastructure. The Nesjavellir field in the Hengill volcanic system has been chosen for the SHiFT project ("SuperHot geothermal – Integrated demonstration and Flow Testing"), leveraging decades of exploration and existing facilities of the 120 MWe/300 MWt power plant. Wells NJ-11 and NJ-32 already encountered superhot zones (>350–380 °C at ~2 km), enabling low-cost testing of production and reinjection. SHiFT builds directly on the legacy of the Iceland Deep Drilling Project (IDDP), which pioneered the exploration of SHG. The first well in the SHiFT project will be designated as the third IDDP well, thereby extending and advancing the achievements of this landmark initiative. In the first well at Krafla (IDDP-1), drilling intersected magma at 2.1 km, producing record-breaking superheated steam. The second well, (IDDP-2) at Reykjanes reached 4.6 km and 427 °C, confirming supercritical conditions but exposing challenges in casing integrity and material performance. These pioneering projects proved that superhot geothermal systems could yield up to ten times more energy per well than conventional resources, highlighting their transformative potential for baseload renewable power. However, previous wells in the IDDP program and elsewhere globally, whether highly superheated or supercritical, have failed prematurely due to compromised well integrity. To address these barriers multiple EU-funded initiatives have targeted the critical enabling technologies for superhot geothermal systems. Most recently, the COMPASS project advanced well design and completion technologies, tackling the fundamental causes of earlier SHG well failures such as casing collapse, cement degradation, and material corrosion. Through laboratory and pilot-scale testing, COMPASS matured flexible couplings, advanced cements, cladding solutions, and annular pressure build-up (APB) relief systems to TRL 4–5, demonstrating their ability to withstand conditions exceeding 400 °C. Yet COMPASS also identified the next critical step: the full-scale field demonstration of integrated SHG wells. A research project planned to be launched in the autumn of 2026 is designed to take that step where some of COMPASS validated individual components will be investigated further. Reykjavik Energy will lead SHiFT to integrate the newest research results into operational sup and test components under real reservoir conditions. Building directly on these learnings, the research plans to advance well designs, drilling strategies, and surface systems to demonstrate for the first time sustainable power generation from superhot reservoirs. Success will not only unlock vast new energy potential in volcanic regions but also open the door to geothermal exploitation in many more settings worldwide, positioning geothermal as a truly global, large-scale, and competitive clean energy source.

CONCLUSIONS

The goal of a superhot well is to produce fluid with very high enthalpy (>2800 kJ/kg). In the Hengill area, target formations lie at 2–3.5 km depth, with the upper 2–2.5 km cased. Expected conditions: 400–550 °C, 150–250 bar. Bedrock consists mainly of basaltic lavas and hyaloclastites, with intrusives common below 1 km. The fluid is likely vapor-like, containing HCl and 25–200 mg/kg SiO_2. Condensation creates acidic liquid and silica dust, causing corrosion and erosion. Mixing with conventional geothermal fluid must be avoided, requiring a long casing (~2–3 km). Cementing such casing is challenging due to extreme temperatures and thermal expansion, which can compromise integrity. Flexible foam cement design focuses on thermo-mechanical properties under bottomhole conditions. The COMPASS project addressed these challenges by: (1) Corrosion mitigation via EHLA cladding of casing, (2) Thermal stress control using flexible couplings and foam cement, and (3) Pressure management with an Annular Pressure Build-up (APB) relief system. Continued research into the utilisation of superhot resources is planned within the IDDP project in the Hengill volcanic system where favourable conditions exist for further development.

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