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IDDP-3 and development of superhot geothermal resources at Hengill, Iceland

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INTRODUCTION

The modern interest in superhot geothermal resources in Iceland began with the unexpected encounter of a superheated zone during drilling of well NJ-11 at Nesjavellir in 1985. At a depth of only ~2.1 km, the well intersected formation temperatures exceeding 380°C and unusually high pressures, far beyond the design envelope of the well. This discovery showed that Icelandic volcanic systems can host extremely hot and energetic environments at shallow depth, raising new questions about their extent and feasibility from utilization point of view. The NJ-11 experience ultimately motivated the formation of the Iceland Deep Drilling Project (IDDP) in the year 2000, a national collaboration between Reykjavík Energy (OR), Landsvirkjun, HS Orka, the Icelandic government, and several international partners. The goal of IDDP was to drill into superhot and supercritical formations and assess whether these resources could be utilized for power production and whether such projects are technically feasible. The first two IDDP wells greatly expanded understanding of superhot geothermal resources in Iceland. IDDP-1 at Krafla encountered magma at 2.1 km and produced the hottest geothermal steam recorded globally (~450°C). Well IDDP-2 at the Reykjanes field reached 4.6 km and confirmed supercritical formation temperatures above 500°C. Although both wells were ultimately shut down due to integrity or equipment limitations, they demonstrated that accessible superhot resources exist within Iceland's active volcanic zones. More recent drilling, including NJ-32 at Nesjavellir and similar wells at Hellisheiði and Hverahlíð, has strengthened this picture by confirming the presence of shallow superheated zones (~350–400°C at 2.1–2.3 km depth). These findings support the view that the Hengill central volcano contains a shallow, drillable superhot resource suitable for targeted development. Building on this foundation Reykjavik Energy has initiated a three-year superhot geothermal development plan (2026–2028). The plan moves beyond scientific exploration and focuses on field-scale demonstration: including drilling of IDDP-3 as a superhot production well, a second well for field testing of superhot reinjection, stimulation experiment of low-permeability superhot zones and pilot-scale power generation from >400°C steam. Unlike earlier deep-drilling attempts, the strategy around IDDP-3 deliberately targets the known shallow superhot zone to reduce costs, limit uncertainty, and accelerate technology development.



Figure 1. Locations of IDDP wells in Iceland

1 TECHNOLOGY READINESS OF SUPERHOT RESOURCE DEVELOPMENT

1.1 Targeting superhot geothermal resources in volcanic environments

The general framework for the formation of geothermal systems in volcanic regions is well understood, yet the specific conditions that give rise to superhot fluids remain difficult to predict without drilling. Such systems are typically fueled by deep-seated magma bodies or intrusive complexes that supply heat to circulating groundwater. Traditional geothermal systems commonly host saturated fluids, following the boiling point curve of water down to 2–3 km depth until the permeability structure changes or heat input increases sharply. Superhot

fluids (>400°C) however tend to occur at the interface between the shallow hydrothermal system and the underlying intrusive heat source, typically at depths of 2–5 km. In this transitional zone, permeability, heat flow, and fluid chemistry are far less understood. As a result, drilling remains the only reliable method for confirming the presence, depth, and characteristics of superhot reservoirs.

The IDDP program has provided the clearest insights into these environments. IDDP-1 encountered a rhyolitic intrusion at ~2.1 km (Friðleifsson et al., 2024), producing superheated steam from a narrow zone at around 500°C between magma and overlying hydrothermal formations. IDDP-2 drilled much deeper, reaching 4.6 km, and documented supercritical conditions (>500°C) through mineral equilibria and hypersaline fluid inclusions recovered in core samples (Friðleifsson et al., 2018). These observations show that superhot conditions can occur both very shallow and very deep, depending on local intrusive architecture, fracture networks and permeability.

At Nesjavellir, wells NJ-11 (Steingrímsson et al., 1990) and NJ-32 (Friðriksson et al., 2022) confirmed superheated feed zones (~350–400°C) at only ~2.1–2.3 km depth. The sharp thermal gradient observed in these wells suggests the presence of a shallow intrusive body or the top of a focused deep upflow or a combination of both. Understanding these geological controls on the thermal conditions of the fluids is essential for effectively targeting and utilizing superhot reservoirs. Integrating drilling results with geophysical imaging, thermal modeling, and structural analysis will be key to improving future targeting of superhot zones and enabling the expansion of high-enthalpy geothermal development in the Hengill area.

1.2 Technical Constraints for Superhot Geothermal Development

While evidence increasingly confirms the presence of superhot reservoirs at drillable depths in Iceland, the ability to develop and operate such systems remains limited by current technical capabilities. The experiences from IDDP-1 and IDDP-2 demonstrated that the primary challenges are not related to locating superhot fluids, but to safely constructing and maintaining wells and surface systems exposed to >400°C temperatures, rapidly changing thermodynamic conditions, and corrosive chemistry of the superhot fluids.

The most critical limitation is well integrity. Conventional carbon-steel casings lose mechanical strength above ~300–350°C and are highly susceptible to corrosion when exposed to HCl-bearing superheated steam (Karlsdóttir et al. 2015). IDDP-1 experienced casing deformation and eventually structural failure as thermal cycling and acidic condensate weakened the steel (Kaldal et al., 2022) while IDDP-2 encountered serious cementing problems. These issues highlight the need for improved casing alloys, flexible couplings to absorb thermal expansions, high-temperature cements and cementing methods, and operational strategies that minimize the impact of these conditions on the well integrity and surface equipment.

Fluid chemistry at superhot conditions adds further complexity. Transient formation of HCl in dry steam, as seen in IDDP-1 and NJ-11 and NJ-32 at Nesjavellir, can cause rapid corrosion during warmup and if the well is shut in. Highly superheated steam may also carry silica in the vapor phase, which can precipitate during pressure drop and cause erosion or scaling of surface equipment (Markusson and Hauksson, 2015). Managing this chemistry requires maintaining high wellhead pressures, controlling heat-up rates, and using corrosion-resistant materials at critical locations.

Surface equipment presents another constraint. Standard valves and wellhead components are not designed for sustained operation at >400°C and experienced corrosion, erosion and leakage in earlier tests, mainly in IDDP-1 (Ingason et al., 2014). High-temperature qualifications of valves and flowlines are therefore essential before long-term superhot production can be considered.

Together, these constraints define the current engineering boundary of superhot geothermal development. Overcoming them—through improved materials, revised operational procedures, and dedicated field testing in IDDP-3 is essential for enabling safe, sustained, and scalable utilization of superhot resources. All these challenges have been the subject of decade long research collaborations through multiple projects, such as the COMPASS project. These challenges are not bound to the unique conditions in volcanic geothermal systems in Iceland and do apply in general to all geothermal systems where superhot fluids are utilized at >400°C.

1.3 Scaling up of Superhot Geothermal technology for power production

Scaling up superhot geothermal production requires understanding how superhot reservoirs behave under sustained flow and how the produced fluids can be harnessed for power generation in a stable and predictable manner. Field experience provides important clues. IDDP-1 and the superheated feed zones of NJ-11 and NJ-32 showed that initial flow can deliver extremely high enthalpy steam. To date, the longest flow test of such a well

is the intermittent test carried out on IDDP-1 from 2010 to 2012, but comprehensive knowledge will only emerge through dedicated testing of future wells, including controlled long-term flow tests, monitoring of enthalpy evolution, and detailed observation of reservoir response. Understanding these competing effects is essential for designing scalable SHG operations.

Production from superhot wells offers superior enthalpy and power density but requires careful control of pressure, temperature, and flow transients. The long-term reservoir response is governed by fracture-dominated flow, thermally induced permeability changes, and mineral reactions that may either enhance or restrict flow paths over time. These dynamics form a key focus of upcoming IDDP-3 testing and the broader 2026–28 development program.

2 THE SUPERHOT GEOTHERMAL DEVELOPMENT PLAN FOR HENGILL (2026-2028)

2.1 The superhot development plan

Reykjavík Energy and ON Power have established a three-year development plan to transition superhot geothermal utilization from a research concept into a field-validated, scalable technology. The program is structured to build on the known shallow superhot conditions at Nesjavellir while creating a practical pathway toward future 4–5 km deep wells. The overall strategy combines conservative well design, rapid learning cycles with new technological approachs and targeted field experiments aimed at elevating the technology readiness level of SHG operations for scale up. The plan is organized into four interconnected phases:

1. The first phase focuses on drilling and testing the first >400°C production well in the Hengill area (IDDP-3)
2. The second phase introduces reinjection into 400–500°C formations and testing whether fluids can be injected safely into superhot rocks.
3. The third phase focuses on permeability enhancement and hybrid superhot-EGS, evaluating whether thermal and mechanical stimulation can increase connectivity in the low-permeability superhot domain.
4. The final phase demonstrates pilot-scale power production using wet-scrubbed >400°C steam.

Together, these phases form a structured development pathway designed to identify risks early, test technical solutions under real SHG conditions, and build the knowledge required for future commercial-scale operation.

2.2 Direct production of superhot fluids - Drilling of IDDP-3

IDDP-3 will be the first operational step in the superhot development plan and is designed to directly access and flow-test the shallow superhot zone previously confirmed at Nesjavellir. Earlier wells, NJ-11 and NJ-32 encountered superheated feed zones of ~350–400°C at depths of only ~2.1–2.3 km, along with high formation pressures, strong cross-flow, and indications of corrosive HCl-bearing steam.

The design philosophy for IDDP-3 is deliberately conservative. The goal is to construct a simple, robust, and controllable well capable of sustained testing at >400°C rather than a complex scientific well with high technical risk. The principal design modification relative to standard production wells is the use of deep production casing to ~2 km, isolating the upper two-phase reservoir and exposing only the deeper superheated zones. This aims to enable production of 400-500°C fluids with enthalpies of 3100–3300 kJ/kg while reducing risks of corrosive condensate during steady operation. The well will incorporate improved construction methods and equipment selection, potentially including corrosion-resistant casing alloys where required, flexible couplings to accommodate thermal expansion, and upgraded cement and cementing methods. Following drilling and completion, IDDP-3 will undergo a structured flow-testing program to characterize production capacity, fluid properties, enthalpy evolution, and the stability of superheated discharge.

A critical operational requirement is that IDDP-3 must not be shut in once superhot flow is reached, except in emergencies. Lessons from IDDP-1 showed that shut-in of superhot wells leads to rapid acidic condensation and damages to the casings. To prevent this, IDDP-3 will be equipped with multiple discharge lines and paired valve systems, enabling continuous flowing even during maintenance of surface equipment. High wellhead pressure (>100 bar) will be maintained to prevent silica precipitation to avoid erosion of surface equipment.

2.3 Reinjection into superhot reservoirs

Reinjection of fluids into superhot formations is the second major step of the development plan. The goal is to confirm whether water can be injected into formations at 400–500°C, how these formations respond to injection,

and whether permeability can be maintained to support long-term production. This phase will determine whether a downward expansion of the reservoir is achievable and whether superhot wells can operate as part of a balanced production–reinjection system or to support the shallower produced system.

Injection tests will primarily use condensate or separated brine in liquid form. Upon entering superhot formations, these fluids may boil or remain liquid depending on the local temperature, pressure, and injection rate. In either case, the extreme thermal contrast is expected to induce strong thermo-mechanical stresses. Similar effects at lower temperatures in Icelandic fields have shown that injecting cooler fluids opens existing fractures and can enhance injectivity (Gunnarsson et al., 2013), at superhot conditions, these effects are expected to be even stronger.

A comprehensive monitoring program will track the reservoir response. Fiber-optic cables will give direct insight into temperature propagation and strain. Dense seismic arrays will record microseismicity associated with fracture formation. Tracer testing will reveal connectivity between wells and identify the shape and velocity of the injection plume. Additional methods will also be applied to understand changes in the thermal and hydraulic structure of the reservoir as well as intensive monitoring of nearby wells.

2.4 Stimulation of permeability in superhot reservoirs

The third phase of the development plan focuses on the feasibility of stimulating superhot geothermal formations to increase permeability and establish the basis for hybrid superhot–EGS operation. Although Icelandic volcanic systems are generally highly fractured, the deeper superhot zones are often less so with limited open fracture networks. This low natural permeability could pose a major constraint on long-term production of superhot systems. Stimulation at superhot conditions relies primarily on thermal effects. Injecting cooler water into formations exceeding 400–500°C produces significant thermal contraction in the surrounding rock, causing fractures to dilate and potentially creating new fractures due to the rapid thermal shock. If thermal stimulation alone does not achieve the desired connectivity, hydraulic stimulation may be applied.

Depending on the outcomes of IDDP-3 and the superhot reinjection well, stimulation may target creating a connected pair between these two wells or improving connectivity with existing production wells. The key objective is to determine whether permeability enhancement at superhot conditions can support stable production as one of the approaches for the utilization of the superhot reservoirs at the Hengill field.

2.5 Pilot power production from IDDP-3

One key objective is to demonstrate pilot-scale power production from >400°C superheated steam. This builds directly on the experience from IDDP-1, where corrosive HCl-bearing vapors were successfully treated in a wet-scrubbing pilot system (Hauksson et al. 2014), removing both acidic components and silica solids. Although wet scrubbing is not the most thermodynamically efficient approach, because it partially quenches the steam and reduces the available enthalpy, it offers clear advantages during early SHG development. It provides robust mitigation of acidic species, minimizes corrosion risk, and relies on equipment that is already well established in geothermal operations. For these reasons, wet scrubbing is the safest and lowest-risk method for the first demonstration of power production from superheated fluids at Nesjavellir.

The pilot wet scrubbing system planned for IDDP-3 will operate at modest flow rates (5–10 kg/s), enabling evaluation of scrubbing performance, material durability, scaling behavior, and overall system response under controlled conditions. The primary goal is not maximum efficiency, but to establish operational stability, validate corrosion-control strategies, and generate the data required to develop future high-efficiency superhot power cycles.

2.6 The economy of SHG power production

The economic potential of superhot geothermal resources stems from the exceptionally high enthalpy of fluids produced at >400°C. A single successful SHG production well could deliver energy outputs comparable to several conventional wells, reducing drilling footprints, surface infrastructure, and per-MW development costs. However, realizing this potential depends heavily on the cost and durability of wells and equipment capable of withstanding such extreme conditions and fluids. Experience from IDDP-1 and IDDP-2 shows that the greatest economic risks are not related to the resource itself but to well integrity, material performance and equipment design. Equipment failure can erode the value proposition rapidly if wells fail prematurely or require extensive workovers. For IDDP-3 and future wells, improved casing alloys, flexible couplings, and high-temperature cement represent higher upfront capital costs but are essential investments for enabling long-term operation.

The 2026–2028 development plan is structured to quantify this balance by testing upgraded designs under real conditions.

On the power-conversion side, pilot testing at 5–10 kg/s of wet-scrubbed superhot steam will provide empirical conversion efficiencies for >400°C fluids at Nesjavellir. Even small improvements in efficiency could translate into materially lower levelized cost of electricity. The key economic question is whether the high productivity and energy density of SHG wells can offset their increased drilling and material costs. Demonstrating stable operation, predictable maintenance, and reliable power-conversion performance in IDDP-3 will provide the basis for estimating long-term economics and assessing the viability of larger-scale SHG developments.

SUMMARY AND CONCLUSIONS

The development of superhot geothermal resources cannot be achieved through theory, lab testing or modeling alone. It requires structured field experiments. Although IDDP-1, IDDP-2, and numerous research projects such as COMPASS have greatly advanced understanding, the most critical unknowns such as well integrity at >400°C, reservoir behavior under sustained flow, reinjection feasibility, and power-conversion performance can only be resolved through dedicated, full-scale field testing as presented here.

IDDP-3 and the associated three-year development program represent the next decisive step toward making superhot geothermal a scalable baseload energy option. IDDP-3 is designed to be operated in safe, continuous flow at high wellhead pressure, providing a controlled platform for evaluating fluid properties, material performance, and long term production stability. Downstream pilot power production using wet scrubbing will establish the first operational benchmarks for handling and converting >400°C steam. In parallel, reinjection trials will determine whether fluid injection into superhot resources can provide pressure support and enhanced permeability at depth, supporting both long-term superhot production and improving the sustainability of the existing fields in Hengill.

The success of this program depends on learning from each test, continuously improving well and equipment design and operational procedures as well as integrating results into next field test. Through iterative experimentation and continuous adaptation, the technological barriers surrounding superhot geothermal can be progressively reduced. The IDDP-3 well will not provide the final solution, but it will hopefully be the enabling step toward many more.

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