

Supercritical Geothermal: Resources, Drilling Experience, and Technological Gaps

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Keywords: Supercritical geothermal, drilling and well construction materials, high temperature degradation, data science

ABSTRACT

Maximizing geothermal energy potential will benefit from the ability to drill and produce heat from greater enthalpy resources than are currently utilized. Supercritical geothermal wells (>373 °C and 22 MPa) have the potential to produce 5 to 10 times as much heat as traditional hydrothermal resources. However, attempts at supercritical drilling have in the past encountered near catastrophic issues during drilling and well construction, such as IDDP-1/2 and Venelle-2, which have prohibited successful utilization. To understand the current limitations in supercritical drilling and well construction, a multi-laboratory collaboration is underway to identify supercritical wells drilled, their downhole chemistries, materials used in their drilling and well constructions, and identify technological and testing gaps of drilling/well construction materials for supercritical conditions. An industry and literature review of these resources was conducted to identify 45 wells where bottomhole temperatures exceeded 373 °C. These resources are all hydrothermal and have typically been found in volcanically active regions such as Hawaii and the western United States, Iceland, Mexico, Italy, Japan, and Kenya. Most supercritical wells were drilled with conventional methods and materials employed by the geothermal industry, with only a few wells drilled with the intent of reaching supercritical conditions and producing such as Venelle-2, IDDP, and WD-1. Collected data assembled for the project will be made publicly available on the Geothermal Data Repository (GDR) to guide future supercritical drilling efforts and materials R&D.

1. INTRODUCTION

Supercritical geothermal is a class of high temperature geothermal resources separate from conventional hydrothermal resources, ground source heating, enhanced geothermal systems (EGS) in hot dry rock (HDR), and other proposed geothermal resources such as closed loop operating at temperatures ranging from 30 °C. These existing geothermal resources typically involve extracting heat from near-surface lithologies, either through extraction of existing fluids or steam or re-circulation of fluids to enable continuous production. Supercritical geothermal involves accessing conditions above the supercritical point of water: ~373 °C and 22 MPa for freshwater (Bischoff, Rosenbauer, and Pitzer 1986). Above the supercritical point, water has potentially ideal properties for heat extraction, along with other useful benefits including:

- Supercritical water has much higher enthalpy and can transport substantially more heat at comparable mass flow rates (Fridleifsson and Elders 2005), and are estimated to provide on the order of 5 to 10 times the thermal output of typical hydrothermal wells, which translates directly into higher power density and potentially lower levelized cost of energy (Figure 1).
- Beyond power density, supercritical geothermal development opens access to deep, high-enthalpy reservoirs that are geographically widespread in volcanic and high-heat-flow regions, expanding the technically recoverable geothermal resource base (Watanabe, Numakura, et al. 2017).
- In systems such as the Salton Sea, these deep reservoirs may host elevated concentrations of dissolved critical minerals (CM) like lithium, so supercritical wells can enable coupled clean electricity generation and strategic mineral recovery from the same infrastructure (Dobson et al. 2023).

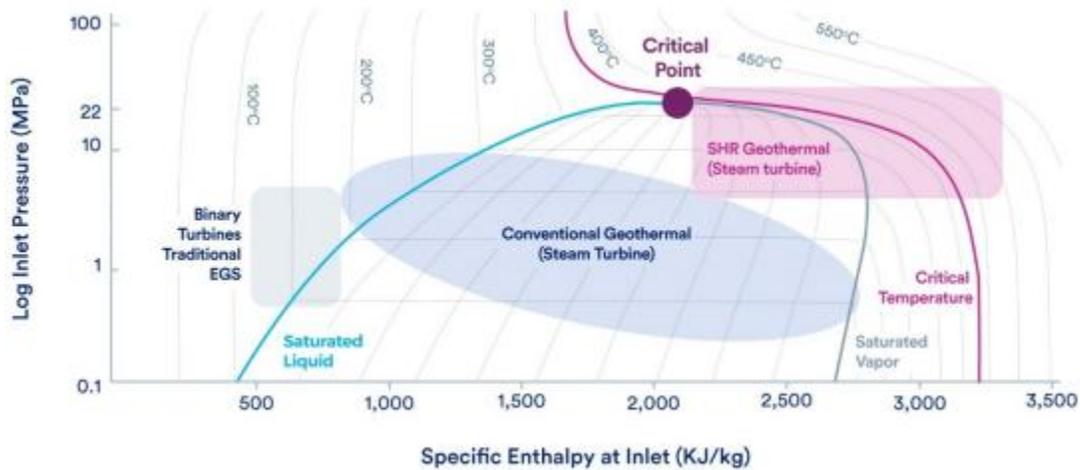


Figure 1: Pressure vs Enthalpy graph for pure water showing conditions at the wellhead or inlet to the power plant typically encountered in different geothermal production styles. Adapted from Cladouhos and Callahan (2024).

The potential for enhanced heat and CM extraction offers good incentive to develop supercritical geothermal wells and the concept has been discussed for since 1980s (see review by Kruszewski and Wittig (2018)). However, to date there remains only a few wells intentionally drilled and constructed under supercritical conditions. A major contributor to this is the upfront costs; geothermal wells typically run very high drilling and construction costs (Blankenship et al. 2005) that increase financial risk in case of well failure or non-productivity. The paucity of wells at supercritical or near-supercritical conditions makes evaluating the techno-economic feasibility difficult to ascertain. Fridleifsson and Elders (2005) suggested that based on the costs of Intercontinental Deep Drilling Project-1 (IDDP-1), the costs of drilling would be 1.5 to 3 times conventional geothermal wells in Iceland, but the heat extraction over the well lifecycle would be sufficient to offset the initial costs.

Wells with temperatures above 350 °C have been drilled in Iceland, Italy, Japan, Mexico, USA (California and Hawaii), Greece, and Kenya (Reinsch et al. 2017). Drilling costs considerations have previously limited existing supercritical wells to volcanic regions with relatively shallow (2-5 km) supercritical conditions. These resources have different geologies, stress conditions, and aqueous chemistries. However, a consistent limitation in supercritical drilling projects has been the extreme temperatures (>350 °C) and corrosive fluid conditions (ex., high salinity, low pH, etc.). These conditions lead to rapid degradation of metals, cements, and fluids used for drilling and well construction that can result in everything from casing collapse (e.g., IDDP-2) to drill bit degradation (e.g., Prati-32). A stark example of this is the fact that prior to the 2000s, supercritical wells have generally been drilled unintentionally and drillers were unprepared for the adverse conditions reached, leading to well failures. Due to geothermal drilling and well construction being adapted from petroleum exploration technologies, there is a scarcity of materials developed that have been shown capable of handling supercritical or even >300 °C conditions for geothermal lifecycle timelines. For example, Pyatina et al. (2023) showed that cements exposed in a Newberry well to ~300 °C and geothermal fluids chemically and mechanically degraded including various commercial and state-of-the-art cement blends designed for conventional geothermal conditions. To add to that, the ability to evaluate degradation/durability of materials at supercritical conditions even at a laboratory-scale is lacking – as few laboratories have the capability to combine the needed thermal, mechanical, and chemical conditions in a single setup – and there exists today no standard practice for material selection/usage in geothermal wells at such conditions.

To better enable supercritical drilling in the future, the Supercritical Drilling Material Analysis project was undertaken as a collaboration by Sandia National Laboratories, Brookhaven National Laboratory, Los Alamos National Laboratory, the National Laboratory of the Rockies, and Lawrence Berkeley National Laboratory to:

- Identify all existing supercritical or near-supercritical (e.g., 350-375 °C) wells globally and evaluate the specific conditions at each site.
- Characterize the geochemical and fluid composition of fields where supercritical conditions exist and potential correlations.
- Document materials used in the construction of different wells and material limitations/failures that were observed at each site.
- Survey experimental and numerical methods employed by academia and industry to evaluate material failure at supercritical conditions to provide insight on needed capabilities.
- Collect the gathered data and report in a publicly accessible database to inform the geothermal community on supercritical drilling limitations and needs.

This paper provides an overview of the projects findings on supercritical wells, material failure/degradation, R&D capabilities globally, and the developed data repository. More detailed geochemical data for the supercritical resources are documented in Schill et al. (2026) while a review of supercritical testing capabilities and needs are documented in Meng et al. (2026). The dissemination of these results will benefit the geothermal community and industry by documenting the needs from micro- to meso-scale for enabling successful drilling and construction of supercritical wells.

2. SUPERCRITICAL AND SUBCRITICAL GEOTHERMAL RESOURCES

Below we provide an overview of the various wells that have been drilled to supercritical or near-supercritical conditions. A map of supercritical regimes identified globally is shown in Figure 2. Notably, a large supercritical resource is currently under exploration in New Zealand but has not actively been drilled yet, so was not included in our assessment (Solms et al. 2025). Given a general lithostatic and hydrostatic gradients of ~22.6 MPa/km and 10.6 MPa/km, it can be predicted that the minimum supercritical pressure of 22 MPa would occur at least below 2 km. Due to limited bottomhole pressure (BHP) measurements, it is difficult to identify if many resources meet the pressure condition for “supercritical” water. Therefore, we consider in this effort only resources where bottomhole temperatures (BHT) were measured or are predicted to reach or exceed 373 °C. An overview from the final database is provided in Figure 3.

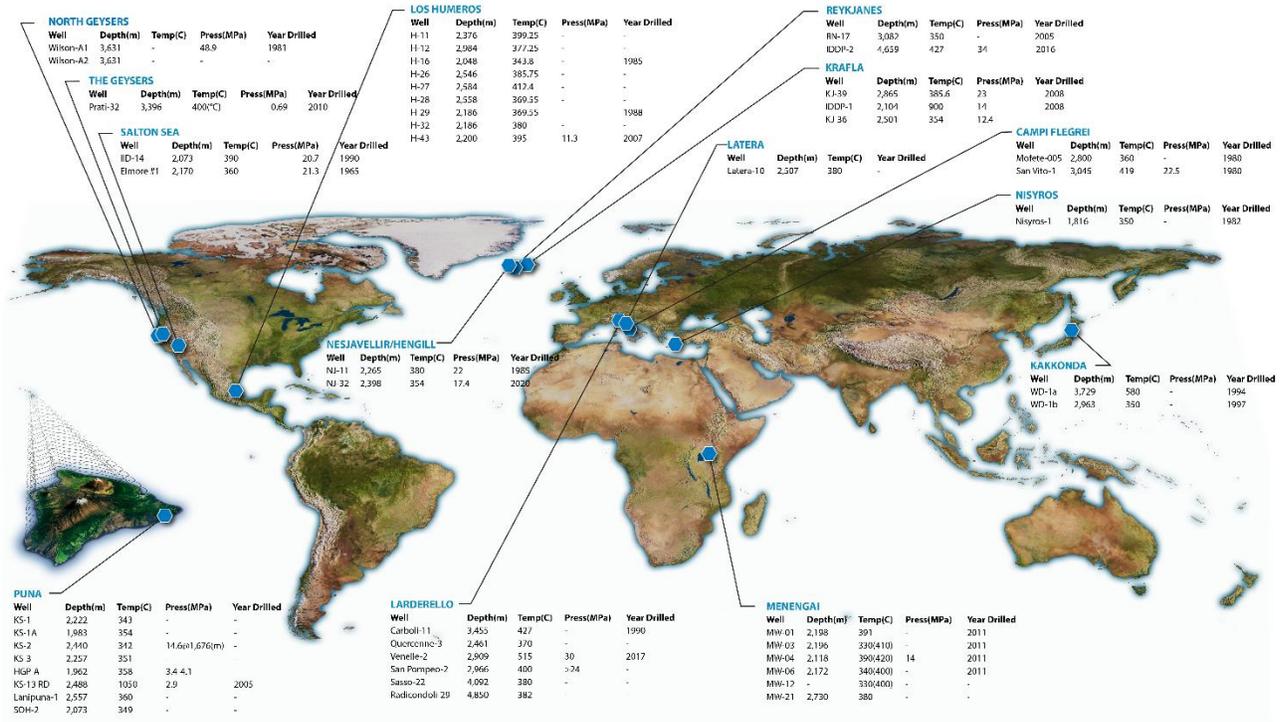


Figure 2: Map of all supercritical or near-supercritical wells drilled globally with attendant locations, depths, and temperatures either measured or inferred via secondary measurements. Illustration by Josh Bauer/NLR. Parentheses around temperature values indicate extrapolated BHT measurement due to instrument limitation. Links to all datasets collected can be found in Kibikas et al. (2025).

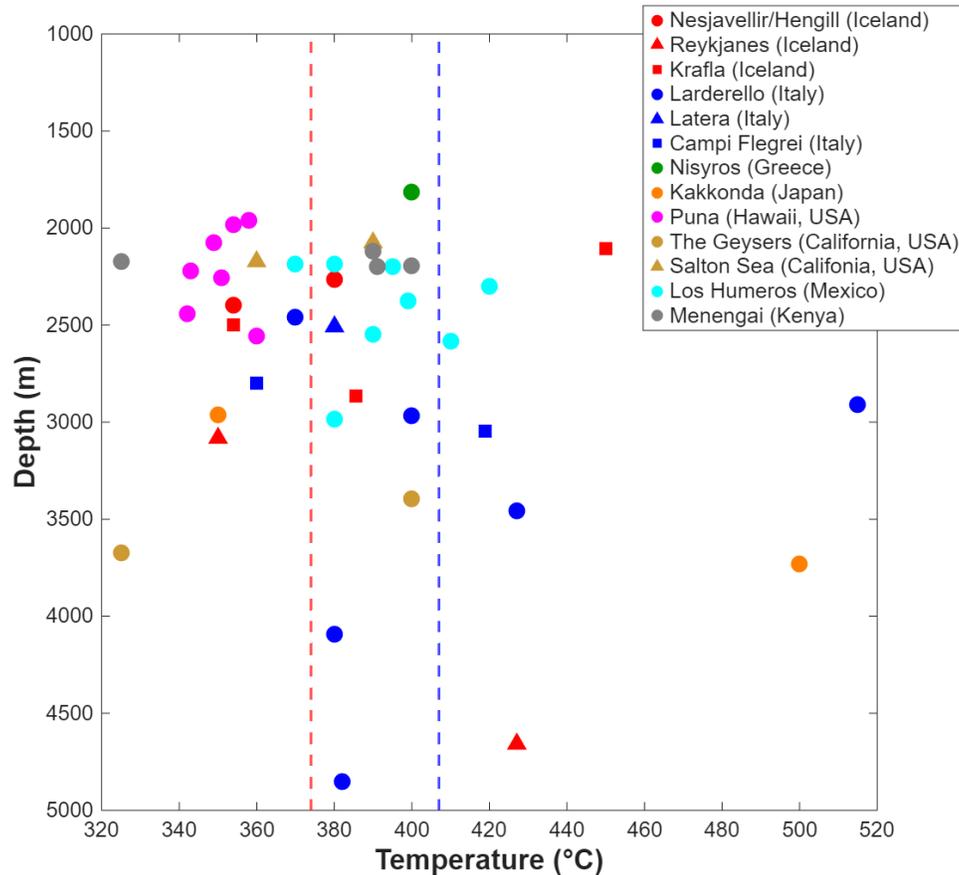


Figure 3: Plot of available depth and temperature profiles based on literature for different supercritical wells globally. Red and blue lines represent the minimum temperature for a supercritical system with freshwater (373 °C) and seawater/3.5% NaCl brine (407 °C). Pressures were not included as they are often not measured downhole.

2.1 Iceland

Given the high volcanic activity in Iceland and the well-developed geothermal energy sector, there have been several wells that exceed the temperature threshold drilled in the last 40 years, primarily in high-enthalpy volcanic systems at Krafla, Hengill (Nesjavellir/Hellisheiði), and Reykjanes, where active rift volcanism and shallow magma intrusions in young basaltic crust create very high geothermal gradients (Friðleifsson and Elders 2017) (Figure 4). At Krafla, supercritical conditions were intersected unintentionally at the KJ-36 and KJ-39 wells, and intentionally intersected during the drilling of IDDP-1 (Mortensen et al. 2010). IDDP-1 was drilled at Krafla to explore drilling and construction of wells at supercritical conditions (Elders, Fridleifsson, and Albertsson 2014). During the drilling of IDDP-1, rhyolitic magma was intersected at 2.1 km and >900 °C beneath a hydrothermal system with an overlying liquid-dominated zone (190 to 220 °C) and deeper high-enthalpy steam and mixed fluids (Elders, Fridleifsson, and Albertsson 2014). At Reykjanes, a heavily altered, seawater-fed geothermal system was indicated to exhibit supercritical conditions during the drilling of the RN-7 well in 2005 (Marks et al. 2010). The high alteration of the geothermal system – with rock types encountered including hyaloclastites, tuffs, breccias, marine sediments, basalts, and diabases – and the seawater-recharged, hypersaline, H₂ rich brine have made both drilling and long-term production difficult. Because of the potential supercritical conditions identified, RN-15 was re-drilled to create IDDP-2 in the Reykjanes field in 2016. IDDP-2 was successfully drilled to 4.65 km depth and measured temperatures above about 426 °C in the fractured basalt system, implying supercritical or near-supercritical saline fluids (Fridleifsson et al. 2014). However, serious issues during drilling – primarily complete circulation losses for significant sections of drilling – and well construction/operation – particularly cement job failure, casing collapse due to thermal stresses, and corrosion throughout the well – led to high costs and eventually quenching and sealing the well (Friðleifsson et al. 2017). At Hengill, the drilling of NJ-11 in 1985 and NJ-32 in 2020 revealed the existence of a supercritical geothermal system could be accessed at ~2 km, but that the high HCl and H₂ bearing system lead to extreme corrosion and pitting of the liner and casing of both wells that raises challenges for successful utilization of the system (Fridriksson et al. 2022). Due to the conditions, Hengill is currently being considered for the next supercritical drilling effort in IDDP-3.

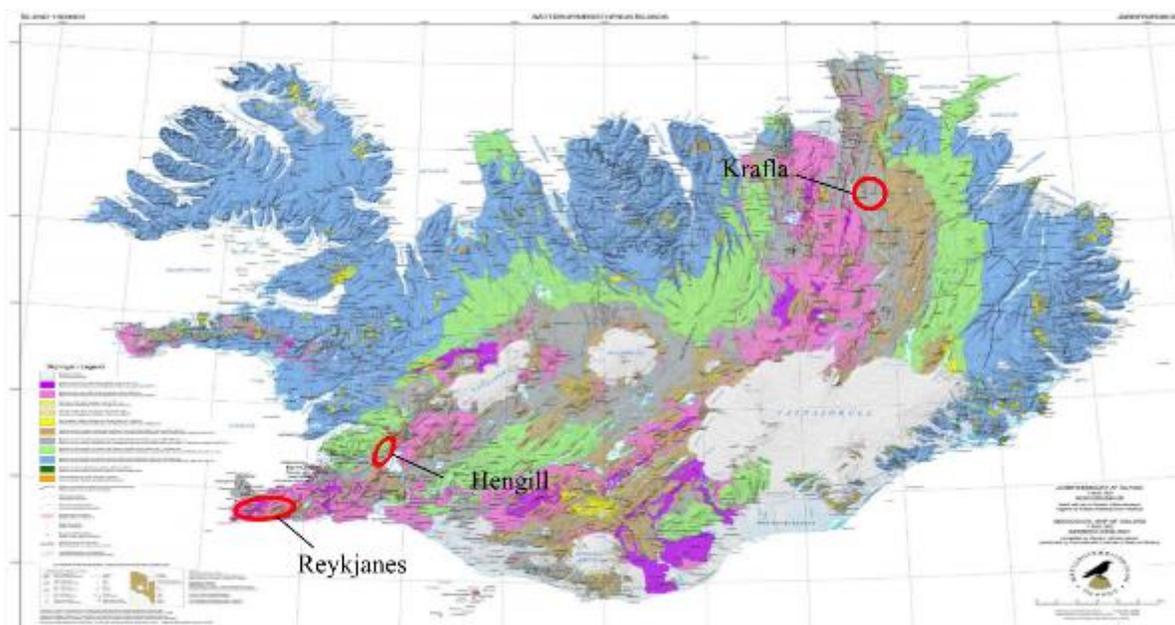


Figure 4: Locations of various supercritical systems drilled or planned for drilling in Iceland. Map based on Geological map of Iceland, Iceland, 1:1.000.000 (Icelandic Institute of Natural History).

2.2 Italy

In Italy, several supercritical or near-supercritical wells have been drilled at Larderello, LATERA, and Campi Flegrei. Several wells were drilled at Larderello in the 1980s and 1990s establishing the high temperatures of the geothermal system there. The Larderello geothermal system is broadly described as a series of clay-rich sediment acting as a caprock, overlying the primary geothermal reservoir system of arkosic sandstones, massive carbonates, and anhydrites, with underlying metasediments and gneisses making up the crystalline basement (Bertini, Giovannoni, and Stefani 1980). Early attempts to exploit higher temperature resources were attempted at wells such as Sasso-22 and San Pompeo-2 (Baron and Ungemach 1981; Batini et al. 1983). However, early attempts at reaching these abrasive conditions revealed serious challenges for both drilling and well construction. Serious lost circulation and stuck pipe issues led to irreconcilable issues at both wells, while H_2 and CH_4 encountered during drilling led to serious corrosion of drill strings and bits that led to collapse and abandonment of the wells (Batini et al. 1983). More recently the DESCRAMBLE program for enabling high-enthalpy geothermal drilled Venelle-2 in Larderello with the intent of reaching supercritical conditions using state-of-the-art drilling and well construction materials (Bertani et al. 2018). The well recorded bottom-hole temperatures of nearly $500^\circ C$ at ~ 4 km depth, sampling or approaching supercritical vapor-dominated reservoirs with CO_2 -rich, saline steam and gas phases derived largely from crustal sources. However, due to the instability of the well and potential for blowout the well was sealed.

Campi Flegrei and LATERA are both caldera-hosted magmatic-hydrothermal systems where shallow crustal magma drives very high temperatures at a few kilometers depth, creating structural conditions favorable for supercritical fluids (Belkin, McAleer, and De Vivo 2024). At Campi Flegrei, supercritical conditions were encountered at the San Vito-1 and Mofete-005 wells (Baron and Ungemach 1981). The San Vito-1 well was able to reach temperatures of $\sim 400^\circ C$, though the well was not able to produce much fluid due to encountering low fractures/permeability past temperatures of $\sim 380^\circ C$ and high CO_2 and favorable mineralization conditions. Issues with heating of the surface and downhole equipment required the well to be sealed quickly after drilling as the well components were not developed to handle the elevated temperatures (Baron and Ungemach 1981). At LATERA, the deepest exploration well LATERA-10 encountered temperatures of $\sim 400^\circ C$ at only 3.3 km, though the magmatic origin and carbonate-rich reservoir rocks produces large amounts of H_2S , H_2SO_4 , and HCO_3 that could lead to long-term production difficulties in wells accessing the deep supercritical zones of LATERA (Cavarretta et al. 1985).

2.3 Japan

In Japan, the Kakkonda field in northeast Honshu hosts a well-documented supercritical geothermal system. The system exists in the fractured Quaternary Kakkonda granite beneath a shallower convective reservoir of sedimentary rock. The NEDO Deep Geothermal Resources Survey drilled the exploratory well WD-1a in two main campaigns between 1993 to 1995 to a total depth of 3729 m, penetrating an 800 to 900 m section of the Kakkonda granite below Miocene and pre-Tertiary formations (Muraoka et al. 1998). The well intersected an entire shallow hydrothermal convection zone above ~ 2.1 km depth and then a deeper, relatively impermeable contact metamorphic aureole and granitic pluton. Temperature measurements and fluid-inclusion microthermometry show a boiling-point-controlled profile up to about $279\text{--}280^\circ C$ at ~ 2100 m, transitioning downward into a conduction-dominated regime with extremely high gradients in the underlying granite (Saito, Sakuma, and Uchida 1998). Using high temperature logging methods, static formation temperatures near the bottom of WD-1a were approximated at $500^\circ C$.

The inflection in the WD-1a temperature-depth profile at ~2100 m and ~280 °C is interpreted as the brittle-ductile transition in the surrounding crystalline rocks, which also marks the base of pervasive hydrothermal convection and the top of a deep conductive boundary layer above the pluton (Doi et al. 1998). Below roughly 2.2 to 2.5 km, fluid-inclusion data and borehole sampling document a transition to hypersaline, metal-rich brines and abundant CO₂ and H₂S, consistent with phase-separated magmatic fluids trapped in and released from the granite. Reverse-circulation sampling near the base of WD-1a yielded a brine with ~28 wt% total dissolved solids and very high Fe, Mn, Zn, and Pb concentrations, while mud-logging during drilling recorded continuous influxes of CO₂ below ~2.3 km and H₂S below ~2.5 km. These observations, together with pressures near the critical curve for a ~9–10 wt% NaCl equivalent brine at the 2.1 km inflection, indicate that WD-1a approached or intersected deep conditions where circulating fluids evolve toward supercritical or near-supercritical states relative to hydrostatic boiling curves (Sawaki et al. 2000).

WD-1a failed to intersect a productive deep reservoir at the top of the granite (Muraoka et al. 1998). The sidetrack well WD-1b was drilled from ~2.2 to 2.3 km depth to ~3.0 km during 1996–1997 to specifically target fractures near the sediment/granite contact, guided by microseismic, resistivity, and structural data (Kamenosono et al. 1997). WD-1b encountered significant lost circulation and several productive fractures near the projected plutonic rim, including a major drilling break at ~2816 m and direct intersection of the granite boundary at ~2839 m, confirming the presence of deep, fracture-controlled permeability at the base of the convective system. The close spatial separation of WD-1a and WD-1b bottoms (within ~200 m) but contrasting intersection of large fractures underscores the strong lateral heterogeneity of deep permeability and highlights the need for precise structural targeting in future supercritical-oriented drilling at Kakkonda.

2.4 Mexico

The Los Humeros geothermal system in Mexico currently hosts the largest cluster of superhot and supercritical-adjacent wells reported for any single field, including wells H-8, H-11, H-12, H-16, H-26, H-27, H-28, H-29, H-32, and H-43 in the high-enthalpy northern and Central Collapse sectors (Gutiérrez-Negrín et al. 2021). Mexico's superhot resources at Los Humeros are associated with nested caldera complexes high-silica pyroclastic volcanism, andesitic-dacitic volcanism, and a thick volcanic–intrusive pile that includes andesitic sequences, basaltic intrusions, and metamorphosed limestones, which collectively host a vertically extensive two-reservoir system (Elders et al. 2014). Initial temperature reconstructions from static formation temperature analyses show a liquid-dominated reservoir between about 1000 to 1650 m elevation with 290 to 330 °C fluids, and a deeper, mostly vapor-dominated reservoir between ~0 to 900 m elevation where formation temperatures reach ~350 to 400 °C, particularly in the northern sector where wells such as H-8 and H-26 intersect the hottest zones (Garcia et al. 2000).

Production wells at Los Humeros mainly discharge high-enthalpy, excess-steam fluids from andesitic formations between roughly 1000 to 2800 m depth, with typical enthalpies above 2500 kJ/kg and reservoir temperatures commonly exceeding 300 °C; in the northern steam-dominated reservoir, measured or reconstructed temperatures of ~350–400 °C above 2 km depth imply a superhot zone extending to at least 2.5 to 3 km where pressures transition from hydrostatic to steam-static conditions (Kruszewski and Wittig 2018). In and around the Central Collapse of Los Potreros Caldera/La Antigua structural system, deep feed zones NW-SE oriented that acts as a primary conduit for heat and fluid flow, tapped by wells such as H-11, H-16, H-28, H-29, H-32 and H-43 encounter very high-temperature, low water fraction steam with HCl-rich, NaCl brines at depth (pH: ~2 to 4; temperature: up to ~300–395 °C) (Magaly et al. 2010). These conditions generate extreme casing corrosion (e.g., API L-80 steel), calcite/silica scaling, and frequent well abandonment or recompletion (Kruszewski et al. 2018). These corrosive fluids have driven progressive changes in drilling and completion practice, including the move to TN80-3%Cr corrosion-resistant casing, refined cement designs, and in the case of H-43, successful in-well NaOH neutralization to raise produced fluid pH to ~6.5–6.7 and enable commercial exploitation of otherwise unusable acid production from the northern Central Collapse sector (Kruszewski et al. 2018).

2.5 USA

In the USA, supercritical geothermal conditions have been observed or inferred to occur at 3 locations: the Puna Geothermal Venture (PGV) in Hawaii and The Geysers and the Salton Sea in California (Kruszewski and Wittig 2018). At the Salton Sea (e.g., IID-14, Elmore #1) geothermal field, hypersaline NaCl brines rich in dissolved metals, including elevated lithium, are produced from a sedimentary-hosted reservoir roughly 1 to 3 km deep (Dobson et al. 2023). Thermal models coupled with deep well temperature data suggest that supercritical or near-supercritical conditions may exist at greater depths within the same system, above and around young intrusive bodies that act as both heat sources and loci for magmatic fluid input (Stimac et al. 2017). The IID-14 exploration well was drilled at Red Hill, a very young rhyolite dome, to a depth of 2073 m in 1990, with a reported temperature of 390 °C, but was plugged and abandoned due to the elevated pressures encountered (Stimac et al. 2017). At The Geysers (e.g., Wilson-A1, Wilson-A2, Prati-32), compilations of deep exploration and step-out production wells (e.g., Wilson-A1, Wilson-A2, Prati-32) and thermal models indicate rock and fluid temperatures exceeding the critical point of water at depths of approximately 4 to 5 km, associated with high temperature intrusive bodies beneath the main vapor-dominated reservoir (Stimac et al. 2017). Although produced fluids are primarily superheated or saturated steam at the wells currently on line, aggressive acidic condensate and chloride-bearing brine phases generated by boiling and condensation within the reservoir and along wellbores have led to severe casing corrosion (Farison 2017; EPRI 2020), required the use of corrosion-resistant alloys, and motivated extensive condensate treatment and reinjection management even under subcritical wellbore conditions.

At Puna, on the Kilauea Lower East Rift Zone, deep wells such as Lanipuna-1, KS-1, KS-1A, KS-2, KS-3, KS-13 RD, SOH-2, and HGP-A intersect a high temperature basalt-hosted system where downhole temperatures up to about 360 °C and pressure data indicate supercritical to near-supercritical conditions at depth within a fracture- and dike-controlled reservoir (Kitamura 1980). Shallow to intermediate depths (roughly the upper 1 to 2 km) host a complex groundwater system in which cold to warm dilute waters mix with heated, saline fluids of largely seawater origin; thermal wells and anchialine ponds near the coast discharge warm (30 to 40 °C), brackish to saline waters with chloride concentrations from about 1,000 to more than 4,000 mg/L and seawater-like Cl/Br ratios (Sorey and Colvard

1994). Several wells at Puna have encountered hot, highly saline brines above and within the main production interval that are interpreted as conductively-heated seawater modified by water-rock interaction, with reservoir chloride concentrations of order 7,000–30,000 mg/L and temperatures near 300–320 °C in the deeper brine zones. These fluids are strongly corrosive and locally acidic (pH ~2–3 in separated liquid from KS-1A and KS-3), and have caused significant casing and liner damage in earlier wells, leading to design changes that include high-alloy casing, foam cements, careful thermal cycling management, and reinjection of condensate into deeper brine zones to limit scaling and corrosion even where flowing conditions in the wells themselves are subcritical (Sorey and Colvard 1994). Later drilling of KS-13 and the redrilling effort of KS-13 RD led to drilling into an active magmatic body, indicated by the production of quenched glass (Spielman, Rickard, and Teplow 2006; Teplow 2009).

2.6 Greece

In Greece, near- to supercritical geothermal conditions were encountered only at Nisyros-1 within the Nisyros volcanic caldera, making this the key deep probe into the Nisyros high-enthalpy system. Nisyros lies on the active South Aegean volcanic arc and hosts a composite andesitic-dacitic stratovolcano and nested caldera built on Mesozoic limestones and Neogene sediments, with active fumaroles, steaming ground, and hydrothermal explosion craters that record repeated phreatic activity and demonstrate a vigorous magmatic-hydrothermal system beneath the caldera floor (Mendrinis et al. 2010). Deep exploration wells Nisyros-1 and Nisyros-2 penetrate this structure and show a stratified hydrothermal system in which shallow 120–170 °C mixed groundwater and dilute brines overlie a deep, overpressured, liquid-dominated reservoir of very saline, magmatically influenced brine at 275–350 °C or higher (Mendrinis et al. 2010).

Nisyros-1 was drilled in 1982 to 1816 m, intersecting a shallow ~100 °C aquifer in altered volcanics at 400–1000 m and a deep productive interval in fractured marbles and intrusive diorite below ~1450 m that yields brine with salinities around 80–100 g/kg total dissolved solids and measured temperatures of about 330–350 °C; wax-strip measurements at the wellhead and subsequent interpretations indicate fluid and formation temperatures approaching or exceeding 400 °C at total depth, implying near- or supercritical conditions for NaCl-rich brine at this depth. During the first production test from the deeper zone, a predominantly vapor flow deposited on the order of 100 tons of solid chloride salts in roughly 6 hours, and a second test produced an extremely saline brine containing about 100 to 300 g/L chloride. Reservoir engineering and regional heat flow analyses suggest that this deep, overpressured brine body beneath the caldera could support on the order of ~50 MWe of high-enthalpy generation if drilling, completion, and corrosion challenges can be managed, and that Nisyros is one of the shallowest known sites globally where supercritical or super-hot conditions are accessible in a continental arc setting (Mendrinis et al. 2010).

Operationally, Nisyros-1 experienced severe well integrity problems once deep production from the high-salinity reservoir was attempted (Chiotis and Vrellis 1995). The original 9 5/8-inch J55 production casing suffered multiple zones of buckling and collapse between ~150 m and ~1235 m during the first production test and subsequent well-killing with cold seawater, with failures concentrated at several discrete intervals where poor primary cementing and fractured formations left the casing weakly supported and potentially with microannuli. Post-test remediation involved milling through collapsed sections and installing a 7-inch tie-back casing down to ~1258 m, but the tie-back string itself later collapsed and buckled, again attributed primarily to large thermally induced axial stresses from rapid heating during flow initiation and rapid cooling during quenching, superimposed on external overpressure and non-uniform annular support. Analyses of the Greek high-enthalpy wells show that in Nisyros-1 the combination of overpressured, self-sealed cap-rock, high undisturbed temperatures that closely follow a boiling-to-depth profile in a saline system, a shallow seismically controlled seawater invasion zone that perturbs the thermal profile, and extremely corrosive, high-chloride, CO₂-H₂S-rich brine (Mendrinis et al. 2010) produces a worst-case environment where thermal cycling drastically reduces burst and collapse resistance in casings and cements (Chiotis and Vrellis 1995).

2.7 Kenya

Menengai is a high temperature caldera-hosted geothermal system in the Central Kenya Rift, part of the East African Rift System, where several deep wells (MW-01, MW-03, MW-04, MW-06, MW-12 and MW-21) intersect extremely high temperature hydrothermal resources with measured or inferred temperatures up to ~390 °C. The fairly shallow depth of these resources indicates that the hydrothermal systems here are at lower pressures and some may not be truly supercritical (Reinsch et al. 2017). The system is hosted in a Quaternary trachytic caldera whose floor is infilled by post-caldera lavas and pyroclastics and structurally controlled faults associated with the volcanic axis and graben formations (Mutonga and Mungai 2017). Subsurface alteration in the vicinity of the supercritical wells indicates transitioning from oxidized shallow assemblages to high-temperature epidote-actinolite-wollastonite below ~1400 to 1500 m, consistent with reservoir temperatures exceeding 250–300 °C.

Temperature and geochemical data reveal a vertically stratified system with a cooler upper aquifer (≤170–200 °C) and cold inflows above ~1000–1300 m, overlying a deep reservoir where measured and equilibrium temperatures range from ~280–390 °C in MW-01, MW-03, MW-04, MW-06, MW-09, MW-12, MW-19 and MW-20. Deep static and flowing logs record >390 °C in MW-01 and MW-04 and ~320–340 °C in MW-03, MW-06 and MW-12, while fluid chemistry shows high enthalpy, steam-rich discharges with elevated H₂ and H₂S in the driest wells, indicating superheated or near-supercritical vapor feeding the deepest perforated intervals (Malimo 2013). Despite the variable well conditions and highly corrosive conditions, a standard drilling and well construction approach was employed for all wells to maximize efficiency: K55 casing standard for all section – 30" conductor, 20" surface casing at ~60-80 m, 13 3/8" anchor casing at ~400 m, 9 5/8" production casing at ~850-1300 m and 7" slotted liners to 2100 to 3000 m with casing depths chosen to isolate the cold upper aquifer and preserve connection to the deep vapor-dominated reservoir (Khaemba 2014).

Drilling into this reservoir presents severe operational challenges: very hard trachytic cap rocks generated strong vibration and bit damage, highly fractured formations cause massive and total loss of circulation, and high pressures/temperatures below ~1000 m led to frequent stuck pipe, drill string failures, and extensive fishing operations (Okwiri and Cherutich 2013). Drilling in several geothermal wells was significantly complicated by magma encounters, which pose both operational and safety challenges. For example, in wells MW-04 and

MW-06 (previously MW-05), fresh glass-bearing magma was encountered at depths of 2,082 m and 2,174 m, respectively (Mibei 2012). Significant corrosion occurred downhole in MW-01, MW-03, and MW-04 that were indicated by high amounts of reddish outflow and FeO produced, and in the case of MW-04 leading to failure of the well after 6 to 7 months. Calcite scaling occurred for MW-01, MW-03, MW-04, and MW-06, with flashing occurring in MW-06 prior to calcite scaling. To mitigate some of these problems, operators progressively adopted air-hammer top-hole drilling, widespread use of aerated water and foam for hole cleaning under loss conditions, directional “build-hold-drop” trajectories (e.g., MW-01 and the MW-09 pad wells) to cut multiple structures while maintaining wellbore separation, and deeper production casings (to ~1400 m) combined with improved inner-string cementing and tie-back strings with external casing packers to re-isolate cold inflows (Mibei 2012).

3. DRILLING AND WELL CONSTRUCTION IN SUPERCRITICAL GEOTHERMAL CONDITIONS

3.1 Casings, Liners, and Connections

Casings in geothermal wells are a series of metal pipes with inner diameters ranging from 36” to 7” that act in geothermal wells as pathways to inject or extract heated fluids while isolating these fluids from other permeable zones between the bottom hole and the well head. In general, wells are constructed of a series of casings in the following order: a conductor casing (26 to 36”) for shallow poorly consolidated soil/sediment and well stabilization; a surface casing (26 to 36”) to prevent fluid escape and add pressure resistance; anchor/intermediate casings (9 5/8 to 13 3/8”) to stabilize well in less competent formations above production zone; the production casing (7 to 9 5/8”) to provide a pathway for the recovered or injected fluid; a liner (5 1/2” to 7”) to provide isolation from rock/sand production at the base of the well and cover potentially damaged sections if needed. An example schematic is shown in Figure 5.

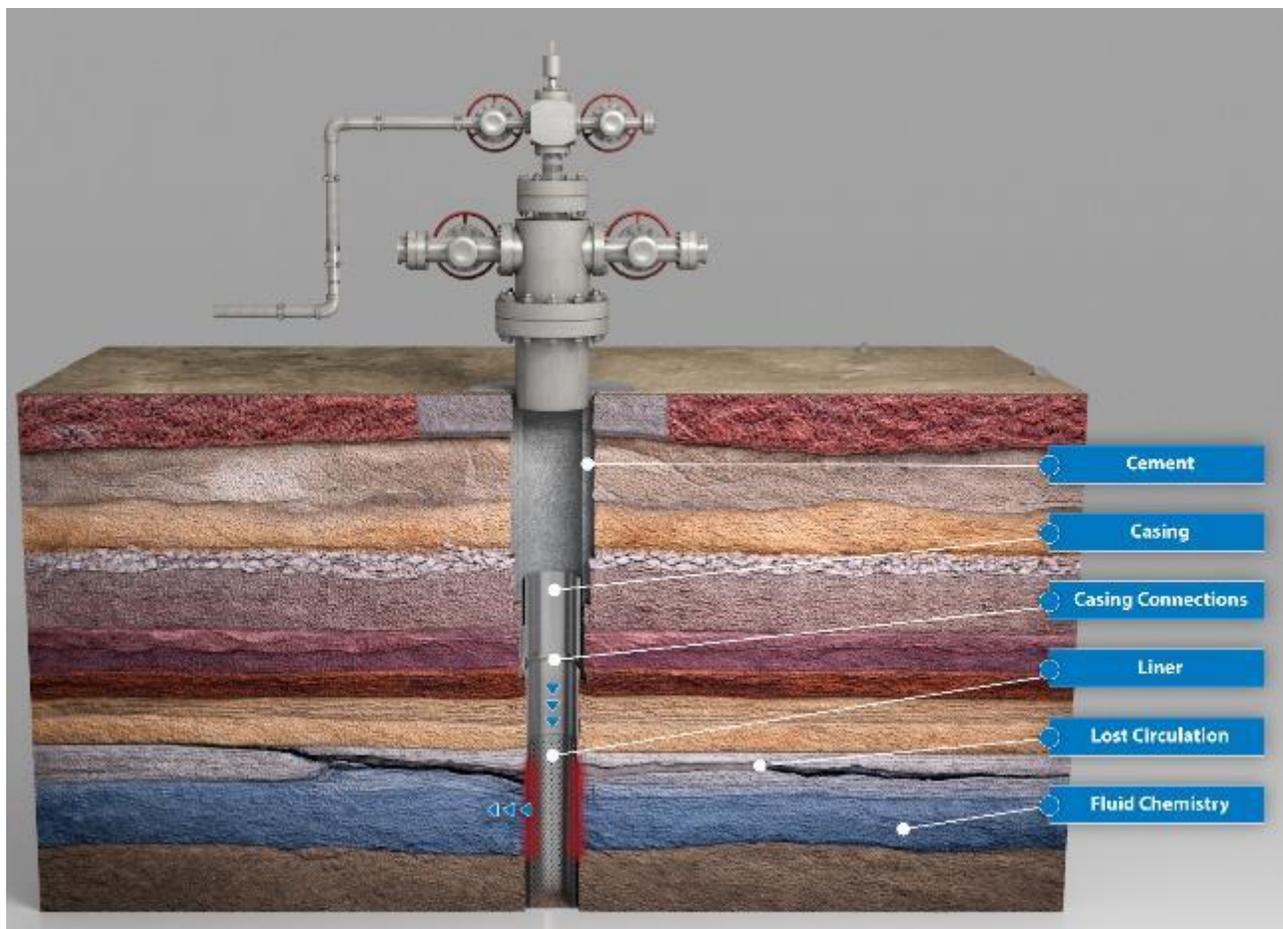


Figure 5: Example of well construction materials in use in a geothermal well.

In general, casings are typically composed of a series of alloy steels designed for different abrasive conditions. These include K55, J55, C75, N80, and P110 steels, with more recent wells incorporating L80, designed for sour gas conditions, for production casings and liners. More recent attempts at reaching supercritical conditions in wells such as at IDDP-1/2 and Venelle-2 have led to implementations of more resilient casing materials and connections. Titanium alloy casings were employed in these wells to allow for enhanced resilience in either the intermediate/production casings or the liners to stabilize the wells. Prior experience with replacement of corroded casings or using sacrificial casings at the Salton Sea, a location notable for the highly corrosive brines and rapid degradation of well materials, with titanium and nickel alloys has demonstrated the efficacy of these materials for improved well durability (MacDonald and Grauman 2014; Pye et al. 1989).

In well construction, the casings – particularly the production casings and liner – are the most critical component of the well and arguably the most likely point of material failure. As pointed out by Kruszewski and Wittig (2018), casing failures are typically the main reason for failure of supercritical wells, combined with the failure of the primary cementing job to achieve its intended function, if not being used as an injector well like KJ-39 or Prati-32. In geothermal wells, casings are subjected to a combination of thermal stresses – due to the elevated heating and possibly temperature cycling from injection cycles – and exposure to highly corrosive brines and gases, including low pH, high salinity, and the presence of H₂S and HCO₃. Both conditions are present below supercritical temperatures and pressures, but the relative impact may differ for fluids that are brought from supercritical to subcritical conditions during fluid extraction.

The vulnerability of supercritical and near-supercritical wells is illustrated starkly by Nisyros-1 in Greece, where multiple collapse failures affected both the original 9 5/8" J55 production casing and a later 7" tie-back. In Nisyros-1, a combination of 1) overpressurization, 2) ultra-saline brine at ~330 to 350 °C, 3) poor primary cementing along several casing intervals, and 4) thermal cycling during seawater quenching generated large axial thermal stresses and external overpressures that drove localized buckling and collapse over hundreds of meters of the casing string (Chiotis and Vrellis 1995). High formation temperature, overpressure, trapped annular fluids, non-uniform cement support, and abrupt cold-water quenching clearly demonstrated the capacity limit of at-the-time geothermal well construction materials and methods, such that future supercritical wells would require specialized methods to enable production. More modern attempts at supercritical drilling have experienced similar problems with casing-temperature related failures. At IDDP-1 at Krafla, an 18 5/8" surface/anchor casing failed by local collapse at ~610 m because of a defective cement job, and the 13 3/8" production casing suffered multiple breaks below ~1600 m in intervals that were either uncemented below ~1490 m or only poorly supported, after the well was heated from <100 °C during cementing to >300 °C during recovery and then cooled again during quenching (Friðleifsson et al. 2015) (Figure 7). At IDDP-2 at Reykjanes, during early recovery a >100 m section of uncemented casing below ~2300 m experienced sufficient thermally-induced stress and buckling that the casing collapsed and access to the deepest ~1.5 km of the hole was permanently lost before even flow testing could be conducted (Friðleifsson et al. 2017).

The impacts of temperature on casings are relatively consistent between different supercritical wells, but the high variability of geochemistry and gas phases produced in different supercritical systems (see Schill et al. (2026)) has produced significant variations in corrosion and scaling issues for casings. In ultra-saline, metal-rich systems such as the Salton Sea, the primary issue has been extreme uniform and localized corrosion of casings and surface equipment, driven by high Cl brines (typically 200–300 g/kg TDS with Cl⁻ often >150 g/kg) at 260–340 °C and low to moderately acidic pH (Williams and Mckibben 1989). Numerous field and lab exposure tests have led to incorporating high-Ni-Cr-Fe alloys, cladding, heavy wall sections, and surface treatments such as boriding specifically to slow casing and tubing wastage and maintain integrity of wellheads and production strings, especially in wells which reach supercritical temperatures or greater. At Los Humeros, deep production from the Central collapse sector has repeatedly shown that even relatively low salinity NaCl waters can become highly corrosive when magmatic HCl is partitioned into high enthalpy steam (Magaly et al. 2010; Elders et al. 2014). In H-16, the 7" liner in the deep production interval corroded at an average rate of ~0.75 mm/year, with intense Fe-sulfide and silica scaling over ~20 m between ~1410 to 1430 m where HCl-bearing deep steam mixed with shallower H₂S-rich fluids; the well ultimately had to be repaired by plugging the deep zone with cement and abandoning the most corrosive interval (Gutiérrez Negrín and Viggiano Guerra 1990). In H-43, completed open-hole from 1243-2200 m into a deep superheated zone with measured temperatures up to ~395 °C, the produced brine initially had pH ≈ 5.2 but dropped to 4.4 in 10 days of test production while Fe in the separated water rose to ~23 ppm, clearly indicating active casing corrosion (Magaly et al. 2010). To keep H-43 and similar high-enthalpy acid wells on line, CFE has implemented continuous deep neutralization by injecting a 47 % NaOH solution at ~1350 m (≈100 m below the 9 5/8" shoe) at ~260–320 mL/min, which raises produced-fluid pH to ~6.5–6.7 and reduces Fe to ~0.35 ppm (Magaly et al. 2010).

Menengai provides a recent comparison with traditional geothermal casing programs utilized at supercritical temperatures, as the entire casing string for all wells at Menengai utilizes K55 stainless steel with traditional buttressed thread couplings (BTC) (Khaemba 2014). MW-01, MW-03, MW-04, and MW-06, MW-12, and MW-21 each encountered supercritical temperatures. During drilling MW-01, MW-03, MW-04, and MW-06, each of these wells experienced stuck pipe incidents within the deep zones where fresh glass (magma) was encountered. At these locations, total loss of circulation was also experienced. While attempting to free the drill string and re-establish circulation, a reddish outflow was observed, indicating high levels of FeO and reflecting accelerated corrosion of steel components over just a few days. During flow tests in MW-06, a dry-steam well and with high enthalpy, scale around the wellhead and fragments throughout the well were collected and analyzed. The scales contained high iron content, along with significant calcite and silica, suggesting elevated rates of corrosion accompanied by scaling in the wellbore. The well has since totally collapsed after less than 7 months of flow tests with corrosion and scaling identified as a significant operational issue. MW-01, MW-03, and MW-04 also faced significant operational challenges of calcite scale precipitation and corrosion. MW-01 has since required extensive mechanical workover while MW-03 and MW-04 ran dry and production was halted. Interestingly, MW-12 and MW-21 reached conditions like the other wells but did not experience significant corrosion or scaling, despite the use of the same casing materials. However, these wells are not producing from supercritical conditions but midsections of the originally drilled well (which were drilled to supercritical temperatures), avoiding issues of elevated temperatures and corrosive fluid content. These observations suggest that fluid and gas phase chemistry in supercritical systems is the most variable and critical factor and must be carefully considered in casing selection and well string design.

3.2 Cements

Well cementing is one of the most critical components of well construction, serving several essential functions: ensuring zonal isolation, providing mechanical support to the casing, and offering protection against corrosive and mechanical stress. Well failures are difficult to attribute to a single factor, “casing failure” is generally accompanied by cement failure (or cement absence behind the casing due to poor primary cementing job). Only geothermal wells failures have been previously directly attributed to cement failure (Nelson 1990). Field experience from superhot and near-supercritical geothermal wells demonstrates that cement performance is a critical and often limiting factor in well integrity. Unlike conventional geothermal wells, supercritical wells impose extreme thermal gradients, aggressive fluid

chemistries, and repeated thermal and pressure cycling on the cement sheath, frequently exceeding the operational envelope of conventional Ordinary Portland Cement (OPC)-based systems, commonly used for well cementing. Moreover, cementing problems in superheated and supercritical wells often result from drilling with significant losses, poor well cleaning, and poor slurry stability. All these can create water pockets behind casing, sustained pressure buildup, casing and well damage. Successful well operations must rely on proper execution of the primary cementing and cement material durability under the well conditions.

Casing failures often coincide with problematic drilling intervals, including those with incomplete removal of cuttings, stuck bottom-hole assemblies, formation instability, and lost-circulation zones. The same intervals cause complications during primary cementing operations, necessitating remedial cementing to achieve adequate zonal isolation. A well-documented example is the IDDP-1 well, where most casing failure depths coincided with intervals that experienced significant drilling difficulties and subsequent cementing challenges (Holmgeirsson et al. 2010). Interpretation of CBL log showed several uncemented intervals. Casing collapse during the initial flow test at ~620 m was near the intersection of two cementing operations (inner string cementing planned up to 420 m and then filling up the annulus from top through the kill-line) that encountered losses (Holmgeirsson et al. 2010; Pálsson et al. 2014). Similarly, in the case of Nysiros-1 well, casing buckling and collapse in several places above the perforation were linked to poor cementing along with very fast well heating and cooling during the kick-off and well killing. Cementing tools failure at high temperatures (a packer in the case of IDDP-1 cementing) may further complicate primary cementing and later well integrity.

In addition to operational challenges during cement placement, slurry performance in superheated and near-supercritical geothermal wells is fundamentally constrained by the limited thermal stability of the organic additives commonly used to control the behavior of drilling fluids, spacers, and cement slurries. Retarders, dispersants, fluid-loss agents, and stabilizers developed for oil and gas applications typically lose effectiveness or degrade at temperatures above 200–250 °C (Nelson 1990). In geothermal wells, particularly those targeting superheated conditions, degradation of these additives can result in premature setting, segregation, sedimentation, free-fluid development, or uncontrolled rheological changes during placement (Pyatina et al. 2025). These issues directly affect not only cement slurries but also drilling fluids and spacers, compromising well cleaning and annular displacement efficiency (Mohamed, Salehi, and Ahmed 2021).

Slurry optimization in volcanic formations presents an additional challenge due to severe lost circulation and the resulting uncertainty in downhole temperature. In wells with significant losses, bottom-hole circulating temperature (BHCT) is difficult to estimate and can vary rapidly depending on circulation conditions, loss severity, and formation permeability (Southon and Knight Mertz 2005; Capuano 2016). Underestimating BHCT can lead to premature setting and plugging, whereas overestimating it can cause excessive retardation, instability, or water separation. This narrow and uncertain operational window is particularly problematic in superheated volcanic environments, where static temperatures may be reached within hours of circulation interruption, as observed in IDDP-1 (Pálsson et al. 2014). As a result, slurry stability issues are often linked not only to formulation limits but also to fundamental uncertainties in thermal conditions during cement placement.

While most superheated and near-supercritical geothermal wells have relied on OPC-based cement systems, field and laboratory experience indicate that only calcium aluminate-based cement systems have demonstrated durable performance under highly corrosive, high-temperature geothermal conditions (Martino and Ruch 2018; Pyatina et al. 2025). Calcium aluminate cement-based formulations show superior resistance to acidic fluids, aggressive gases, and repeated thermal cycling compared to OPC-based blends. However, these systems present practical limitations. They are significantly more expensive than OPC-based systems and are incompatible with Portland cement, requiring either dedicated surface equipment or extremely careful cleaning to prevent cross-contamination. Even small amounts of OPC contamination can induce flash setting of calcium aluminate cement, increasing operational risk during field deployment (Martino and Ruch 2018; Pyatina et al. 2025).

The OPC blend of Portland cement with silica, that is most used in well cementing today, originated in the oil and gas HT well cementing in the 70th to prevent cement strength retrogression due to the conversion of calcium-silicate-hydrate (C-S-H) phase to highly crystalline alpha dicalcium silicate (α -C₂SH) at calcium-to-silica ratios above one and temperatures above ~ 110 °C (Nelson 1990). The recommended amount of silica was 35 to 40% by weight of cement. Formulations with up to 80% OPC substitution by silica were tested with the results showing continuous silica reactions at temperature reaching 343 °C. Based on the consumption of crystalline silica it was concluded that 40% silica may not be sufficient at these temperatures (Iverson, Maxson, and Bour 2010). When sufficient silica is added (Ca/Si~1) calcium-silicate hydrate, xonotlite, that is stable up to 600 °C should form (Taylor 1997). In practice, formation of various calcium silicate and carbonates along with the persisting lower-temperature hydrate, tobermorite, has been observed along with xonotlite during hydration of OPC-based blends (Eilers, Nelson, and Moran 1983; Iverson, Maxson, and Bour 2010; Pyatina et al. 2018). Nevertheless, the thermal stability of OPC-based formulations should not be of significant concern under hydrothermal non-corrosive environments. The 60/40 OPC/Silica blend was shown to be mostly stable with minor increase in porosity and decrease in strength, under supercritical conditions for 30 days (Pyatina and Sugama 2023; Pyatina et al. 2025; Pyatina et al. 2023). Rapid degradation of OPC-based cement formulations occurs under high-temperature acidic conditions often encountered in young volcanics (Pyatina et al. 2024).

Thermal shock-related degradation is another concern in superheated wells. In young volcanics the upper parts of the wells have low fracturing gradient. To avoid formation damage and lost circulation problems light-weight blends of OPC and silica are often employed. For example, Icelandic blends used for the upper parts of the wells include 2% perlite and 2.5% Wyoming bentonite; similarly, the Venelle-2 well deepened to supercritical temperature in the frame of DESCRAMBLE project and partially cemented with calcium phosphate ThermaLock at depth, was cemented with Norcem I/II blend of Portland cement class A with bentonite and 2% perlite at the upper parts of the well. Similarly, 2% bentonite was used in cementing Los Humeros high-temperature wells (communications with Abraham III Molina Martinez, department head, Federal Electricity Commission, government of Mexico). Investigations of the Icelandic blend after autoclaving for 3 days at 350 °C showed loss of the strength (Peciarova 2024). Likewise, analysis of the top 300 m cement conducted by Gerosion on IDDP-1 well demonstrated non uniform density and strength loss of the perlite-containing Icelandic blend after 2 years of

flow testing and research operations on the well. The degradation was likely the result of thermal shocks imposed on the upper parts of the well.

There have been a few exceptions to using OPC/silica blend for cementing superheated wells. The Kakkonda WD-1a well employed a high-belite (high-C₂S) Class J oil-well cement, rather than standard API Class G/H. This cement, which is no longer manufactured, was specifically formulated for high-temperature geothermal use and was successfully placed under aggressive wellbore cooling. The project demonstrated that a well can be drilled and completed at very high temperatures. This was achieved by an active circulation of cold fluids that allowed keeping the well temperature at 200 °C, while its static temperature was estimated to be above 500 °C. It should be mentioned that despite successful drilling and completion at superhot conditions WD-1a did not achieve commercial production due to loss of permeability and formation instability at depth.

At the Salton Sea geothermal field, calcium phosphate cement systems (ThermaLock) were deployed in wells including Elmore #1 and IID test wells for high-temperature remediation, demonstrating improved stability under extreme thermal and chemical conditions compared to conventional Portland cement systems (Susan Petty, personal communications). The remediation was required due to the quick degradation of the OPC-based blends used during primary cementing. Calcium phosphate cement was also used in Italy (Larderello field). Optimized cement formulations were designed and tested for superhot geothermal applications, long slurries stabilities were achieved at elevated temperatures (Martino and Ruch 2018), and the Venelle well was successfully completed with calcium phosphate cement. The well was dry and was not produced.

Hawaiian Puna wells (Figure 1) were cemented with OPC-based blends, however, wells constructed later at lower bottom hole static temperatures were completed with calcium aluminate cement-based blend, ThermaLock, at the deeper parts exposed to aggressive volcanic gases, suggesting realization by the industry of the need for more durable cementing solutions. Lately, a hot well at Newberry was cemented with a blend based on calcium aluminate cement (Gabrijel Grubac, Mazama, Daniel Bour, Bour consulting, personal communications, 2025).

Long-term well integrity is further complicated by the evolving nature of geothermal reservoir environments during exploitation. As production progresses, pressure decline, cooling, fluid injection, and changes in permeability can alter subsurface fluid chemistry, often increasing concentrations of non-condensable and corrosive gases such as CO₂, H₂S, and acidic condensates (Garcia et al. 2012; Soltis and Lichti 2010). Field observations from The Geysers, Coso, and New Zealand geothermal fields show that corrosive conditions may intensify years after well completion, leading to accelerated degradation of casing and cement, particularly in zones affected by steam migration and perched condensate (Pyatina et al. 2025). These evolving conditions highlight the need to consider not only initial drilling and completion environments, but also the long-term chemical and thermal evolution of the reservoir when selecting cement systems and designing well construction strategies.

Successful cementing of super-heated, near-supercritical, and supercritical geothermal wells requires optimized cementing solutions, including tailored slurry designs, long-term cement durability under relevant and evolving conditions, and robust execution of the cementing operation with well-defined contingency plans. Success is strongly dependent on drilling practices, particularly effective well cleaning, mitigation of lost-circulation issues, and the performance of drilling fluids and spacer systems.

3.3 Drill Bits

In general, 3 types of bits have been employed in the drilling of supercritical wells. Tricone or roller-cone bits have been employed in most supercritical wells from Italy to Menengai to Puna. Composed primarily of steel or tungsten-carbide, different variants such as milled tooth bits and tungsten-carbide inserts (TCI) can be employed for soft rocks or hard rocks depending upon the situation (ex., drilling of KS-3 at Puna). Rotary coring bits, typically diamond impregnated or roller cone bits, are employed for recovery of critical intervals of core for above ground analysis, though typically these bits exhibit lower rate-of-penetration (ROP). Finally, polycrystalline diamond compact (PDC) bits are bits with fixed-cutter bits that composed of steel, tungsten-carbide, and diamond that shear rock. PDC bits have been shown to have the highest ROP of any bit and need fewer replacements and well tripping. Tricone bits dominate supercritical drilling, though in the case of wells such as SOH-2 and IDDP-1/2 where lithological characterization was a critical need for the project coring bits were utilized as well (Olson 1993). PDC bits have been shown to have optimal performance in homogenous formations, while in formations that are highly fractured, heterogenous, and have large lithological variability they show reduced performance. PDC bits are highly sensitive to impact and vibration, and fractured hard rock with lost circulation events causes significant bounce and break of PDC cutter bits faster than would occur in homogenous formations. Experiments with PDC bits when drilling a well at Menengai revealed the PDC bits handled torque poorly and abraded too quickly when drilled through the highly variable trachytic rocks. However, innovative approaches have been explored to overcome the limitations of PDC bits. At Venelle-2, one of the first supercritical wells conducted primarily with PDC bits, a special type of PDC bit called the StingBlade was employed to withstand the high temperatures and heterogenous basement rocks (Bertani et al. 2018). At IDDP-2, although tricone roller bits were exclusively used, a novel elastomer-free tricone and hybrid bit was utilized along with high temperature grease rated for up to 300 °C (Fridleifsson et al. 2014). New solutions will be needed to enable the effective use of PDC bits in the highly heterogenous and abrasive conditions that are ubiquitous in supercritical geothermal systems.

Beyond the impacts of heterogeneity on drill bit survival, supercritical systems pose several other issues that hamper drilling. The high temperatures and hard rocks increase the rate of bit degradation and teeth abrasion, leading to a large number of bit replacements and non-productive time (NPT). Figure 6 shows the average bit degradation during the drilling of the Prati-32 well after 300°. Higher temperatures increase the rate of bit wear, and thus rapid cooling via drilling fluid is a necessity to ensure bit life and reduce NPT. However, the extreme amount of severe lost circulation events in most supercritical wells leads to a loss of fluids before sufficient cooling can occur, leading to

enhanced degradation of bits. This was a major issue at IDDP-1/2, where the rapid bit replacement even with state-of-the-art equipment led to elevated drilling costs. Even modern StingBlade PDC bits utilized at Venelle-2 degraded under the high heat downhole partly due to the fluid losses and partly due to the relatively narrow drill pipe in the deepest sections (3 ½") (Bertani et al. 2018). Indeed, long periods of heating can lead to other issues, such as stuck bit from hardening mud as was observed during a halt in operations at Sasso-22 (Baron and Ungemach 1981).



Figure 6: Bit appearance after drilling 300' into normal temperatures in The Geysers field reservoir (left) and bit condition after drilling 100' into high temperature zone at depth 11134' at Prati-32 (right). Adapted from Garcia et al. (2012).

Another issue with supercritical well drilling is the potential for drilling into magma. At IDDP-1, drillers encountered rhyolitic magma as indicated by the production of silicate glass from the hole (Elders, Fridleifsson, and Albertsson 2014). A similar situation was seen at the sidetrack well KS-13 RD at Puna encountered a dacitic lava (Teplow 2009) and Menengai trachytic glass in MW-06 (Mibei 2012). In both cases, encountering lava reaching $>800\text{ }^{\circ}\text{C}$ led to a stuck and degraded bit that needed to be either removed via explosives or abandoned and sealed to enable production. A major issue was the rapid rate of temperature change – at IDDP-1 the temperature rose more than $400\text{ }^{\circ}\text{C}$ over 10s of meters before the bit reached the lava, far too quick for conventional temperature monitoring techniques to effectively detect the high thermal gradient. In order to economically drill to supercritical conditions, active monitoring of temperature such as measurement-while-drilling may be necessary to prevent trapping of the bit and expensive hole clearing operations.

3.4 Lost Circulation Materials

Lost circulation materials (LCM) are a general category of materials that are mixed with drilling fluids that can potentially plug and seal zones of high permeability – including fracture/shear zones, highly porous formations, and cavities/vugs – where drilling fluids escape the borehole (e.g., lost circulation). Lost circulation is a pervasive issue in geothermal drilling, representing up to 30% of drilling costs in some cases. As such, the effectiveness of different materials in treating lost circulation is critical for reducing risks and costs in geothermal. In general, a variety of different granular, flaky, fibrous, and slurry type materials are employed to treat lost circulation. The first three are a mix of organic, degradable materials (ex., microcellulose, cotton fibers, sawdust, sugar cane) and rigid inorganic materials (ex., calcium carbonate, graphite, mica flakes, diatomaceous earth), while the slurry materials are a category of chemical compounds designed to chemically harden around loss zones and are typically polymers in makeup (Alsaba et al. 2014).

Outside of a few studies (Kibikas et al. 2024; Vivas and Salehi 2022, 2021; Kibikas and Ingraham 2025), there is a paucity of information on the durability of different LCM at traditional hydrothermal system conditions (e.g., 150 to $250\text{ }^{\circ}\text{C}$) and essentially no research on the durability of LCM at near-to-supercritical temperatures/pressures or fluid chemistries in supercritical systems. Kibikas et al. (2024) showed that most LCM degrade by $>30\%$ in the first 24 hours when exposed to $>200\text{ }^{\circ}\text{C}$, so it can be expected that supercritical conditions would quickly degrade any LCM emplaced in the system without sufficient cooling downhole and neutralization of downhole acidic fluids (Figure 7).

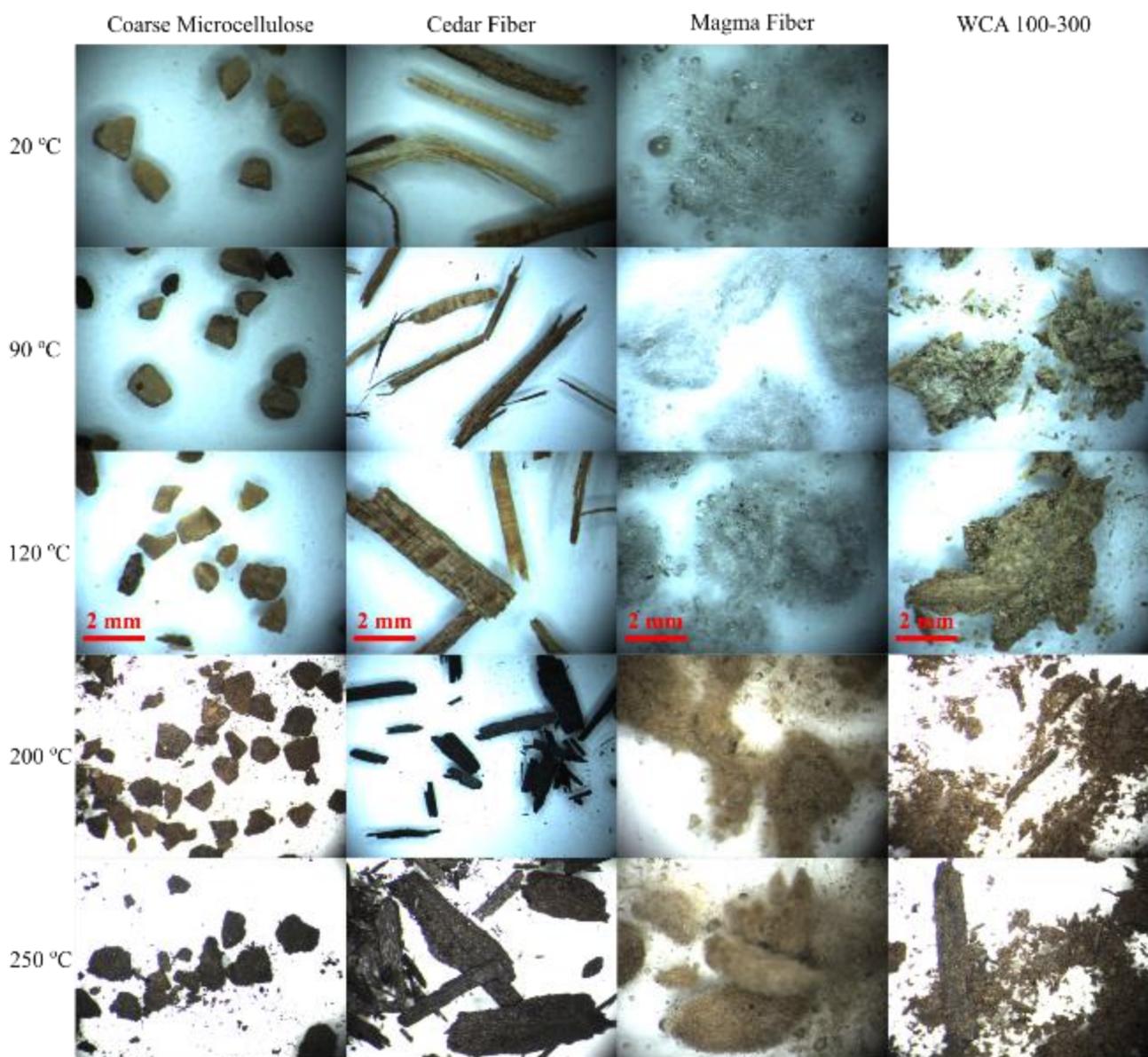


Figure 7: Examples of several LCM after exposure to 90, 120, 200, and 250 °C for a period of 3 days. Adapted from Kibikas et al. (2024).

Though knowledge of LCM degradation at supercritical conditions is limited, lost circulation and attempted treatment methods have been applied in supercritical wells such that useful information can be gleaned on the effectiveness of LCM in these wells. At Puna in Hawaii, lost circulation was encountered at all supercritical wells drilled there. Commonly moderate-to-severe losses (>50 bbl/hr) occurred in the shallowest sections (<600 m) as would be expected in near-surface fractured basalts (Winn et al. 2023). In the earliest drilled wells at Puna – Lanipuna-1, HGP-A, KS-1, KS-1A, KS-2, KS-3 –lost circulation was treated by a variety of materials including walnut shells, calcium carbonate, sugar cane, and cotton. LCM were generally ineffective at treating major losses, thus cement jobs were applied which were generally able to reduce fluid loss rate if not seal the zones. Lost circulation was also extreme for the SOH-2 hole, where major losses were untreatable between 460 and 1370 m depths, resulting in high bit wear and low returns (Olson 1993). More recent drilling at KS-13 RD in the 2000s showed that microcellulose (e.g., ground walnut shells) proved effective at treating fluid losses in multiple sections of the subaerial basalts at Puna (Spielman, Rickard, and Teplow 2006). Similar experiences in drilling at Iceland reveal the difficulty in treating fluid losses in supercritical wells in fractured basalts. At IDDP-1, major losses began after drilling past ~2063 m and encountering permeable feed zones, beyond which neither LCM nor cement were able to halt losses and drilling continued without returns or mud (Friðleifsson et al. 2015). IDDP-2, noted for being in the highly heterogeneous Reykjanes system, after drilling below 2500 m losses were near total and multiple treatments, including 12 separate cement squeezes, were totally unable to halt losses (Friðleifsson et al. 2017).

Other non-basaltic supercritical systems have shown variable success with different LCM in treating losses. At Menengai, though LCM are used relatively sparingly, treatment is exclusively done through the combined injection of microcellulose and white mica flakes which has been demonstrated to be effective in nearly all wells drilled. At Japan while drilling into hard rock, severe losses occurred between

1600 and 2150 m depth during drilling of WD-1a (Saito, Sakuma, and Uchida 1998). Treatment used 97 of the 340 days spent on the drilling program, representing a significant loss, and treatments were ultimately only partially effective. Similarly, the sidetracking of WD-1B at the same site encountered severe losses around ~2488 m (Kamenosono et al. 1997). Blind drilling was required below this depth as the losses were essentially untreatable in WD-1B despite multiple cement squeezes. At Larderello, near supercritical wells like San Pompeo-2 and Sasso-22 typically encountered major lost circulation events throughout the well drilling - especially between 2500 and 3000 m depth – that were not treatable with LCM pills (such as “bento blocks”) or cement squeezes (Baron and Ungemach 1981). At Sasso-22, the lack of circulating fluid led to corrosion and damage of the drill bits and pipes as well as pipe breakage and collapse due to the mud drying downhole. More recently, at Venelle-2 near total losses began below 2334 m, where treatment was unable to halt any losses despite past experience in the field. The high losses, especially below 2600 m, led to the need to use water as a drilling fluid/cleaning agent and weighting agents (Bertani et al. 2018). It is speculated that the untreated loss zones eventually led to the partial loss of cement around the liner and production casing, which required extensive efforts to repair including modification of the 9 5/8” liner and partial milling of the cemented section below 1205 m (Bertani et al. 2018). From these experiences, it can be seen that lost circulation is a pervasive problem in most supercritical wells that have been drilled to-date. The highly fractured nature that makes many volcanic systems attractive for producing supercritical geothermal seems to enhance the difficulty of drilling due to 1) the need to seal certain fractured zones but not others and 2) the need to seal relatively large fracture or shear zones in highly heterogeneous lithologies.

3.5 Drilling Fluids

Geothermal drilling fluids are typically water-based but now range from bentonite-rich muds in cooler intervals to low bentonite or bentonite-free polymer/clay systems and even water-only (ex., IDDP) or air (ex., The Geysers) systems with periodic high-temperature sweeps in hotter sections. The primary purposes of the drilling fluid are (1) to cool and hydraulically support the bit and BHA to reduce bit wear and extend bit life and (2) to transport cuttings and clean the hole. To achieve these goals at geothermal conditions, a suite of additives is used to adjust density, viscosity, filtrate loss, wellbore strength, lubricity, and corrosion behavior (Table 1), with particular emphasis on minimizing solids content and maintaining rheology at elevated temperature (Tuttle and Tate 2025).

For supercritical and near-supercritical drilling, the key drilling-fluid concerns are: 1) severe or total loss of drilling fluid into large fractures; 2) high-temperature gelation or irreversible setting (solidification) of clays and polymers; 3) thermal breakdown of drilling mud, polymers, lubricants, and LCM that can compromise both hole cleaning and wellbore integrity. In response, recent geothermal practice has shifted toward low-solids, high spurt-loss fluids and water drilling with high temperature viscous sweeps, where cuttings are carried intermittently by temperature-stable biopolymers (stable at temperatures up to ~200 °C for short exposures) and mechanical sweep materials, and conventional clay-rich mud is restricted to cooler, non-productive intervals. To avoid bentonite-type mud clay collapse and solidification the fluid temperature is kept below 60 °C with mud coolers and the fluids pH is carefully controlled to remain above 8.

Table 1: Examples of different components in geothermal drilling fluids and their intended purposes.

Fluid Component	Purpose	Example Materials
Working fluid	Base for carrying additives through drill pipe.	Water, oil, foam
Weighting agents	Increase fluid density to control formation pressure and maintain well control.	Barite, hematite, magnetite, ilmenite, manganese tetroxide
Viscosifiers	Build and maintain viscosity and gel strength for cuttings suspension and hole cleaning at elevated temperature.	Bentonite, high-T polymers (e.g., THERMA-VIS, diutan-type polymers), rectorite-based systems, modified natural polymers;
Fluid-loss reducers	Control filtration into formations, protect wellbore stability, and reduce formation damage under HTHP.	PAC-type polymers, POLYAC PLUS, THERMA-CHEK, acrylamide-based high-T filtrate reducers
High temperature dispersants	Maintain dispersion of solids and prevent flocculation or gelation of clays and polymers at high T and salinity.	Mixed-metal hydroxides (MMH/MMO), lignosulfonate- or humic-based stabilizers, synthetic dispersants
Lubricants	Reduce friction, torque, and drag in high-angle/hard-rock wells, especially with high WOB and temperature.	High-T synthetic lubricants, ester- or glycol-based lubricants formulated for WBMs; e.g., LUHE-H in high-T WBM formulations.
Lost-circulation materials (LCM)	Bridge fractures and vugs, reduce or stop seepage/partial/severe losses.	Inorganic LCM (CaCO ₃ , mica, silica/diatomite), fibrous/cellulosic materials (microcellulose, cotton), LCM pills, cement/silicate systems

Corrosion inhibitors	Protect drillstring, casing, and surface equipment from CO ₂ /H ₂ S and oxygen-induced corrosion at high T.	Filming amines, sulfite or bisulfite oxygen scavengers
pH and alkalinity control agents	Maintain alkaline pH to stabilize clays and polymers and reduce CO ₂ -related corrosion.	NaOH, KOH, soda ash, lime

The issue of drilling fluid loss is covered in Section 3.4. However, drilling fluid programs in high loss environments are often modified well beyond adding LCM to a base mud, including changes in flow direction (e.g., reverse-circulated cement and plugs), temporary drilling with water or aerated fluids (ex., Menengai, Puna), and deliberate reductions in mud weight to mitigate induced fractures and improve lost circulation treatments (Winn et al. 2023). Generally, mud weight needs to be adjusted to maintain the right balance between formation pressure control and wellbore stability, preventing kicks if it's too light and losses or formation damage if it's too heavy. Control of overpressurized fragile formations can pose problems due to a very narrow window of acceptable mud weight (e.g., history of drilling in Theistareykir field, Iceland has shown overpressure from 50 to 300 m in some areas, the same intervals experienced loss circulation problems. Increased mud weight is required to control overpressured formations. Mud weight is adjusted with weighting materials, such as barite, hematite, etc.). The major losses in various supercritical wells across the world will require novel innovations of various elements of drilling fluids to mitigate fluid losses from highly fractured zones (Tuttle and Tate 2025).

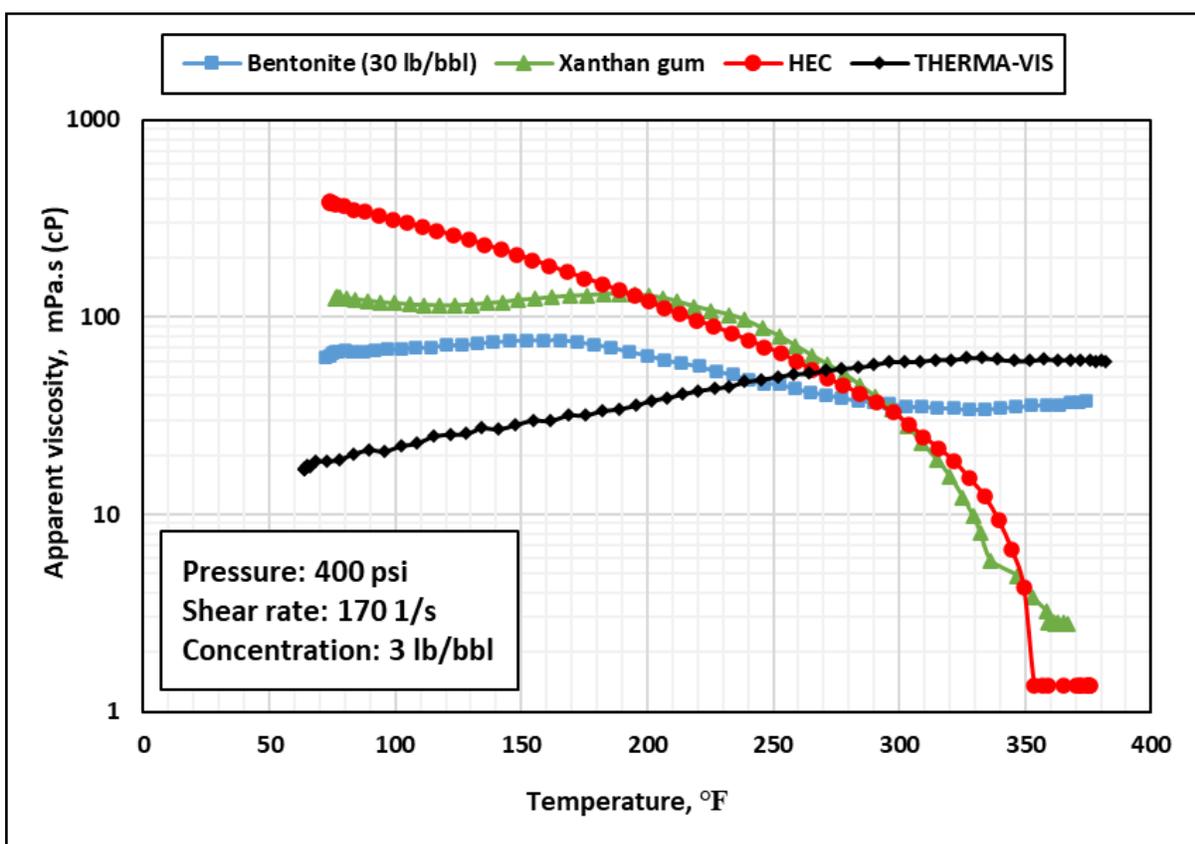


Figure 8: Effect of increasing temperature on the apparent viscosity of different drilling fluid additives. Adapted from Mohamed, Salehi, and Ahmed (2021).

High temperatures are a potentially major hurdle for use of drilling fluids in supercritical drilling. Bentonite has been shown to be rheologically stable to at least 204 °C (Vivas and Salehi 2021), though clays can dehydrate and degrade between 150 and 220 °C, and most polymers breakdown between 110 and 220 °C (Figure 8). Because of the theoretical limit of mud stability, novel attempts have been made to drill without mud such as KS-1, KS-2, and KS-3 at Puna where water was used in deeper sections due to potential losses or at Sasso-22 in Larderello where steam from a nearby geothermal plant was used as working fluid (Baron and Ungemach 1981). Using water provides a fluid to effectively cool the drill bit and partially clean the bottomhole and using steam avoids concerns of the breakdown of bentonite and many polymers (Tuttle and Tate 2025). In general, drilling in many supercritical systems has deviated in the last few years to using a bentonite-water system in shallower depths, then switching to either water/aerated foam as is done for wells at Menengai and Los Humeros (Lorenzo-Pulido 2008) or switching to use of a gel-water system by adding high temperature polymers as at Venelle-2 (Bertani et al. 2018). High temperature gelation or hardening of many swelling clays can lead to issues such as stuck pipes and drill bits, potentially compromising the bottomhole assembly (BHA). This occurred at the San Vito-1 well at Campi Flegrei, where an interruption

of circulation led to mud gelation and loss of the BHA despite attempts to restore circulation by perforating the drill string with explosive charges (e.g., charges decomposed at the high temperatures downhole) (Baron and Ungemach 1981).

Several approaches exist to prevent high temperatures from degrading drilling fluids in supercritical systems. During the drilling of WD-1a at Kakkonda, a novel top-drive system was employed to effectively cool (e.g., mud cooler) the temperature below 200 °C downhole, despite the measured temperature at depth being >500 °C (Saito, Sakuma, and Uchida 1998). WD-1a demonstrated improved drill bit durability by employing their novel cooling system, even with significant losses of drilling fluids in several sections (Saito, Sakuma, and Uchida 1998). Mud coolers were also employed at IDDP-1 in the upper sections of the well to maintain cooling downhole (Elders, Fridleifsson, and Albertsson 2014). Mud cooling has been widely cited for its potential to enable supercritical drilling (Khaled et al. 2023), and potentially in combination with concepts such insulated drill pipes could enable drilling with conventional drilling muds that maintains the ability to both cool and clean downhole simultaneously (Reinsch et al. 2017).

4. MATERIAL VALIDATION AT SUPERCRITICAL CONDITIONS

4.1 Lab Scale

Lab testing of the above well construction materials is important for the selection of proper materials, design of the wellbore structure, and integrity of the wellbore. Most of the current testing standards and equipment are designed for below 300 °C or even room temperature, which do not meet the requirement of supercritical conditions. Among the limited supercritical testing facilities, autoclaves (or reactor vessels) are available in multiple organizations. University of Iceland (Karlsdottir et al. 2022) holds one autoclave capable of handling temperature up to 500 °C and pressure up to 30 MPa. The autoclave is mainly used for corrosion testing of different casing materials and Titanium material has shown better corrosion resistance compared to carbon steels. Brookhaven National Lab (Pyatina et al. 2024) has one modified Parr autoclave with an extended attachment for holding rupture disk, and it is rated to 500 °C and pressure up to 34.46 MPa. The autoclave has been applied in evaluating performance of a variety of geothermal cement systems as mentioned in the prior sections. Jilin University from China (Zhong et al. 2024) reported one reactor rated to 500 °C and 50 MPa, and has been using it to analyze quartz dissolution in pure water. Overall, these autoclaves are useful in evaluating fluid-solid interactions and potential material degradation, including tubular material, cement, LCMs, and drilling fluids.

Mechanical strength testing on casing has been performed by Gruben et al. (2021) under dry heat conditions up to 500 °C. They found that both yield and tensile strength of metallic materials drop under elevated temperatures, among which K55 only retained 45% of its room temperature tensile strength when tested under 500 °C. These materials also show creep deformation when temperatures were between 350 °C and 500 °C. Mechanical testing on cement under supercritical conditions has not been reported, Meyer et al. (2024) performed triaxial compression tests on Lanhélin granite over a temperature range from 200 °C to 800 °C. The device could be used to measure cement performance as well. The brittle-to-ductile transition depends on mineralogy, compositions, and microstructures. It will be important to understand how different types of well cement perform mechanically under supercritical conditions.

Researchers from Japan (Watanabe, Egawa, et al. 2017) have developed one true triaxial cell with primary focuses on hydraulic fracturing of rocks under supercritical conditions. Longer, fewer fractures were created under 200 °C, while a greater number of shorter fractures were created under 450 °C. The breakdown pressure also decreased significantly under 450 °C compared to 200 °C. Goto et al. (2022) later used the facility to investigate wellbore stability under 200–450 °C. Non-catastrophic tensile and shear failures were observed, and fracture initiation was reasonably predictable using existing brittle failure criteria for their tests.

4.2 Numerical Modeling

While the development of experimental facilities capable of supercritical conditions is technically challenging and resource intensive, numerical modeling provides a complementary and scalable framework for investigating coupled thermal, hydraulic, mechanical, and chemical processes in superhot geothermal systems. The wellbore flow dynamics has been relatively widely investigated, and multiple codes have been successfully applied in predicting temperature and pressure profile during well constructions and circulations, including EOS2H coupled with T2Well (Battistelli et al. 2020), well hydrodynamics model by Lamy-Chappuis, Yapparova, and Driesner (2022), and transient multiphase flow simulator OLGA (Zhou et al. 2025). For corrosion prediction, Yanagisawa et al. (2021) predicted corrosion rate of casing materials under conditions up to 500 °C and 60 MPa. Key inputs are temperature profile in a well, fluid pH, and the Cr equivalent of the elemental composition of the casing material. TReactMech (Sonnenthal, Smith, and Spycher 2023) could be used to predict changes in fluid composition resulting from reactions with the host rock. Some simulations have been performed on wellbore stability and well integrity as well, but more work is needed.

4.3 Field-Scale

Laboratory-scale experiments are cost-effective and offer a high degree of control. However, they struggle to replicate the complexity of realistic geothermal environments, and long-duration exposure tests are often impractical. As a result, field-scale testing becomes both valuable and necessary for validating material performance under true geothermal conditions. Thorbjornsson et al. (2015) exposed a series of metallic materials to superheated steam in the IDDP-1 well (452 °C, ~140 bar, mass flow rate ~12 kg·s⁻¹) and found that the N06625 nickel-based alloy and the R52400 titanium alloy exhibited the greatest resistance to corrosion. Similarly Pyatina et al. (2023) deployed multiple cement formulations in the Newberry geothermal well at temperatures of approximately 325 °C and pressures of ~26 MPa. Their results showed that conventional Portland-based cement experienced an 86% loss in mechanical strength after nine months of exposure, degradation far more severe than has been observed in laboratory testing.

5. SUPERCRITICAL RESOURCE DATABASE FOR FUTURE R&D

To support the storage and dissemination of supercritical geothermal well information, all data gathered in this study were compiled into a publicly accessible database on the Geothermal Data Repository (GDR) (Kibikas et al. 2025). The database houses information from published literature, well reports, expert interviews, and laboratory tests, with a focus on materials used for different well construction components (i.e., drilling and completion), and issues encountered by these materials at specific temperatures, pressures, and geochemistries. The underlying goal is to summarize how these materials perform in supercritical and sub-supercritical conditions, illuminating where gaps may exist, and informing future materials R&D for well construction components in superhot wells. Additional data was gathered on material validation and testing as supplemental information to what has been tested in the field in actual wells.

Data was assembled for 48 wells drilled into superhot conditions, across seven countries, including Iceland (Nesjavellir, Reykjanes, Krafla), Italy (Larderello, Latera, Campi Flegrei), Greece (Nisyros), Japan (Kakkonda), United States (Puna, North Geysers, Salton Sea), Mexico (Los Humeros), and Kenya (Menengai). The most significant data gaps exist for Los Humeros and Italian wells, where we were unable to locate complete and shareable information. Casing connections was the most challenging well construction component to locate data on, and therefore that component is the least complete.

The database was designed to balance human readability with machine usability. Data are organized into a collection of basic, topic-specific CSV files (e.g., overview, drill bits, casing, cement, drilling fluids, and fluid chemistry), each structured around consistent identifiers including well_name, geothermal_field, and country_region to allow simple cross-referencing. Figure 9 provides a high-level schematic of the database structure and the general categories of information contained in each file. Many fields contain text descriptors, reported ranges, or notes reflecting uncertainties and observational context from original sources. This flat-file structure allows users to easily inspect the data in spreadsheet software, text editors, or load it directly into analysis environments like Python.

The dataset is distributed through the GDR, and includes a README file that documents file structure, column definitions, and usage notes. All references are embedded in the data using APA-formatted citations. The database is hosted on the GDR to ensure long-term accessibility, versioning, and discoverability for the geothermal community, while allowing the dataset to be expanded and refined as additional data is made available.

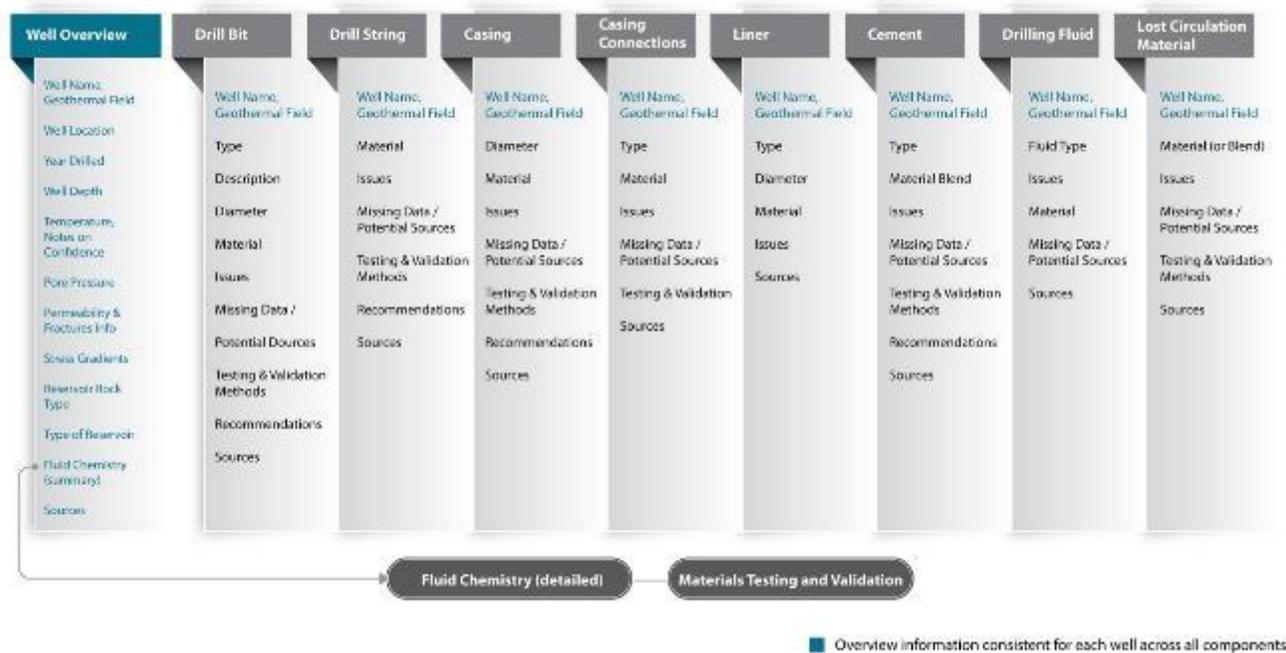


Figure 9: Overview of the supercritical drilling materials database layout. Blue text indicates overview-type information and metadata (e.g., well ID, depth, temperature, pressure, location, etc.). All well construction component tables are linked via a unique identifier consisting of well ID, geothermal field, and country. This also applies to fluid chemistry, but materials testing and validation information is not tied to specific wells. Illustration by Josh Bauer/NLR.

Each well component table can be connected to the overview information via a well ID, enabling analysis of materials and their performance at high temperature and pressures. Here we provide an assessment of the current material limitations for each well component based on the data and issues summarized in the database. Data are filtered to wells with no documented issues for a given well construction component, and then the material (or equivalent) is documented for the highest temperature and pressure well. The results are presented in Table 2.

Table 2: Table providing a summary of the contents of the supercritical drilling materials database, including, for each well construction component: most commonly used material, max temperature without documented issues, max pressure without documented issues, max depth without documented issues, and most common issue.

Well Construction Component	Most Commonly Used Material	Max Temperature without Documented Issues (Well)	Max Pressure Without Documented Issues (Well)	Max Depth without Documented Issues (Well)	Most Common Issue
Drill Bit	Tungsten Carbide	900 °C (IDDP-1)	48.9 MPa (Wilson-A1)	4,850 m (Radicondoli-29)	Low ROP, corrosion, wear out
Drill String	G-105 or S-135	900 °C (IDDP-1)	48.9 MPa (Wilson-A1)	4,850 m (Radicondoli-29)	Stuck drill string
Casing	Carbon steel, K55 (above reservoir), Alloy steel, L80, Grade Type I, API 5 CT (production)	580 °C (WD-1a)	30 MPa (Venelle-2)	4,850 m (Radicondoli-29)	Corrosion, severe scaling
Casing Connections	Blue (metal-to-metal seals, premium threaded, dope-free), ER	580 °C (WD-1a)	34 MPa (IDDP-2 (RN-15))	4,850 m (Radicondoli-29)	Casing collapse, thermal expansion
Liner	L80	515 °C (Venelle-2)	48.9 MPa (Wilson-A1)	4,850 m (Radicondoli-29)	Corrosion and pitting
Cement	Class G with Silica	427 °C (Carboli-11)	22.5 MPa (San Vito-1)	4,850 m (Radicondoli-29)	Corrosion, problems cementing cause by lost circulation zones
Drilling Fluid	Bentonite	1050 °C (KS-13 RD)	48.9 MPa (Wilson-A1)	4,850 m (Radicondoli-29)	Total fluid loss, hardening of mud
Lost Circulation Material	Cement	380 °C (NJ-11)	48.9 MPa (Wilson-A1)	4,850 m (Radicondoli-29)	High or total losses, LCM not successful

As stated in Meng et al. (2026), geothermal well integrity is a dynamic, transient-dominated challenge controlled by the interaction of multiphase flow, evolving material properties, and operational practices. It is not a static design problem governed by peak temperature or pressure. Geochemical aspects are also crucial in categorizing material behavior in these conditions. Therefore, Table 3 does not capture the full picture. It does however help to illuminate the gaps in field testing for certain materials and well construction components. While not yet incorporated into this summary table, we recommend the reader see Meng et al. (2026) for an examination of experimental and numerical approaches to wellbore material performance under superheated and supercritical geothermal conditions, and Schill et al. (2026) for additional discussion of the geochemical data collected as part of this effort and its implications on well construction material performance.

6. CONCLUSIONS

We provided a significant overview of all known attempts at drilling to supercritical temperatures for the purposes of geothermal energy extraction. 45 wells have been identified in over 7 countries where such conditions have been reached, with different issues or limitations observed at each site. Importantly, both temperature and subsurface chemistry profiles are very different for each supercritical system, such that the difficulties of supercritical drilling must be addressed depending upon the local geological conditions.

In general, it has been observed that traditional materials such as drill bits, casings, and cement that have been applied for conventional hydrothermal systems are insufficient to maintain long term heat extraction at supercritical conditions. The highly abrasive temperatures and fluid/gas chemistries in these systems, often near or in volcanically active areas, leads to rapid degradation and corrosion of all drilling and well construction materials. Addressing these issues requires state-of-the-art experimental and numerical modeling capabilities to simulate and design materials for resisting the high corrosivity of supercritical conditions. However, to date there is a paucity of research on the survivability of different materials, such that there are not even sufficient standards or general knowledge on what materials can handle at supercritical conditions.

Addressing this requires detailed R&D focused on identifying and overcoming the limitations of supercritical drilling and well construction. The gathered data from this effort was incorporated into a novel database in the GDR, where information on existing supercritical systems, drilled/constructed wells, material failures, and experimental simulation capabilities are collected. This database provides a valuable contribution to the geothermal community in that it provides information on what has been tried and what is further needed to enable high-enthalpy geothermal in different systems.

ACKNOWLEDGEMENTS

We would like to thank various reviewers – Estefanny Davalos Elizondo, Geoffrey Mibe, Jiann Su – for evaluating our manuscript and recommending needed changes. We would like to thank Josh Bauer and the NLR creative team for development of several figures in this manuscript. We would also like to thank the Geothermal Technologies Office – particularly Alex Prishjatschew and Pamela Daitch – for funding this work under AOP 4.3.1.8 “Supercritical Drilling Material Analysis: Current Practices, Technological Gaps, and Recommendations.” Finally, we thank CFE for sharing detailed information on their superhot geothermal wells at the Los Humeros geothermal field as an important contribution to this data collection and analysis effort.

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