# Review of Experimental and Numerical Approaches to Wellbore Material Performance under Supercritical Geothermal Conditions

Meng Meng[1], Tatiana Pyatina[2], William Kibikas[3], Eva Schill[4], Nicole Taverna[5], Scott Mello[5], T. Broadhurst[3,6]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545

[2]Brookhaven National Laboratory, Upton, NY 11973

[3]Sandia National Laboratories, Albuquerque, NM 87185

[4]Lawrence Berkeley National Laboratory, Berkeley, CA 94720

[5]National Laboratory of the Rockies, Golden, CO 80401

[6]University of New Mexico, Albuquerque, NM 87106

* mengm@lanl.gov

**ABSTRACT**

Advanced testing and verification tools for supercritical geothermal well materials are critical for successful well construction and operation, as they enable the effective selection of appropriate materials. Through reviewing existing methods, published results, and insights into material behavior from public literature and expert interviews, we identified the primary challenges, knowledge gaps, and recommendations for future tools and methods development. Major challenges include replicating high-temperature (>375 °C) and high-pressure (>22 MPa) conditions in laboratory environments while accommodating realistic material dimensions and dynamic fluid flow, performing in-situ measurements, and validating newly developed simulation tools. Here, we focus on tools and methods for characterization of experimental capabilities including fluid-rock interactions and material mechanical testing, and the modeling capabilities including wellbore multiphase flow dynamics, fluid chemistry prediction, corrosion prediction, borehole stability, and well integrity. The existing studies found that corrosion is critical in subcritical regions and casing materials exhibit pronounced plasticity at high temperatures. Material corrosion and degradation are being investigated but more experiments and data are needed. Advanced devices for testing the complex brittle-to-ductile transition for cement and rock are rather limited. Overall, the testing and validation overview highlights the critical research priorities for advancing the understanding and performance of well construction materials in supercritical geothermal environments.

## 1. INTRODUCTION

Superhot rock geothermal energy (SHR) offers orders-of-magnitude improvements in energy density and efficiency, enabling low-cost, firm, clean power and long-duration energy storage at scale. By definition, superhot systems can be >374 °C but not necessarily at pressures above the critical point of the relevant brine, and saline fluids exhibit different critical points than pure water. The supercritical point of pure water is 374 °C (647 K) and 22.1 MPa (221 bar, 3,206 psi), while the IDDP-2 well (Iceland Deep Drilling Project) reported the seawater's critical point around 406 °C and 29.8 MPa (Friðleifsson et al. 2017). Table 1 summarizes the comparison among superhot, supercritical, and subcritical conditions.

**Table 1: Comparison among superhot, supercritical, and subcritical conditions for pure water**

| Terminology | Temperature | Pressure | Fluid State |
|---|---|---|---|
| Superhot | ≥374 °C | Any | Steam or supercritical |
| Supercritical | ≥374 °C | ≥22.1 MPa | Supercritical fluid |
| Subcritical | < 374 °C | <22.1 MPa | Liquid / steam |

At present, multiple countries have explored superhot geothermal systems across the world, including but not limited to IDDP-1 and IDDP-2 projects in Iceland (Friðleifsson et al., 2014; 2017), Kakkonda field in Japan (Kato et al., 1998), Larderello field in Italy (Gherardi et al., 2025), Menengai field in Kenya (Kipyego et al., 2013), Los Humeros in Mexico (Espinosa-Paredes & Garcia-Gutierrez, 2003), and Salton Sea in the United States (Kaspereit et al., 2016). Despite the current progress, no project has yet fully commercialized superhot systems. The limited survivability of drilling and well construction materials at high temperatures and downhole chemistries has been the main hindrance to developing productive wells. Early failures of constructed superhot wells have prevented full utilization of the superhot

resources and caused significant financial losses, since each superhot geothermal well could cost up to $20 million. It is more challenging or even impossible to remediate these failed wells. Table 2 summarizes some types of well failures in several superhot systems.

**Table 2: Materials issues in representative supercritical geothermal wells (x represents existence of issues, no represents no issues, and N/A represents no relevant information was found)**

| Country | U.S. | | | Iceland | | | Italy | Japan | Kenya | New Zealand |
|---|---|---|---|---|---|---|---|---|---|---|
| Area | Salton Sea | Geyser | Puna, Hawaii | Krafla Field | Reykjanes field | -- | -- | -- | -- | -- |
| Well number | State 2-14 | Prati 31/32 | KS-13 | IDDP-1 | IDDP-2 | KJ-39 | Venelle-2 | WD-1A | MW-4 | SC-1 |
| Depth (m) | 3220 | 3396 | 2528 | 2104 | 4650 | 2848 | 2900 | 3729 | 2500 | 2800 |
| Temperature (°C) | 355 | 400 | 1050 | 450 (wellhead) | 427 | 386 | >500 | >500 | ~400 | 500 |
| Pressure (MPa) | N/A | N/A | N/A | 14 (wellhead) | 34 | 23 | 45 | N/A | 14 | 26 |
| Drill bit issue | x | x | N/A | x | No | N/A | x | x | N/A | N/A |
| Casing damage | x | x | x | x | x | x | x | x | x | x |
| Liner failure | x | x | x | x | x | x |  | x | N/A | N/A |
| Cement failure | N/A | N/A | N/A | x | x | N/A | x | x | N/A | N/A |
| Drilling fluid degradation | X | N/A | N/A | x | x | x | x | x | x | N/A |
| Lost circulation | X | x | X | x | x | N/A | x | x | X | N/A |
| Wellhead failure | N/A | x | N/A | x | x | x | N/A | N/A | N/A | N/A |

In SHR environments, materials and drilling systems must withstand not only elevated temperatures and pressures but also supercritical-phase corrosion, thermal shock, hydrothermal alteration, extreme brine chemistry, rapid mineral precipitation, and strong thermo-mechanical gradients that affect every part of the wellbore, from the drill bit and BHA to casing, cement, elastomers, and completion hardware. Relevant materials and technologies are actively being developed to advance superhot geothermal well construction, including novel high-temperature cement formulations, flexible and thermally tolerant couplings, advanced casing and liner materials, corrosion- and scale-resistant coatings, and enhanced zonal isolation systems. Despite promising material designs and conceptual advantages, these emerging technologies require rigorous validation to demonstrate their performance, reliability, and long-term durability under representative downhole conditions.

However, the majority of the current materials validation and drilling-technology qualification practices were developed for hydrocarbon reservoirs with typical temperature limits of 150-180 °C and do not capture the degradation mechanisms relevant to supercritical geothermal temperatures, pressures, and fluids. New validation techniques for SHR well materials must be achieved through a combination of controlled laboratory experiments and advanced numerical simulations to establish both fundamental material behavior and system-level performance. At present, both advanced experimental facilities and high-fidelity numerical simulators capable of reproducing superhot geothermal conditions remain limited in availability and scope. This limitation presents a significant bottleneck for the systematic evaluation and deployment of new well construction technologies.

In this work, we conduct a comprehensive review of existing experimental methodologies and numerical modeling approaches used to validate well construction materials and technologies under high-temperature and high-pressure conditions. The review summarizes the current state of the art, highlights key achievements, and evaluates the applicability of these techniques to superhot geothermal environments. This study is conducted in parallel with Schill et al. (2026) and Kibikas et al. (2026): the former focuses on geochemistry of supercritical geothermal fluids, while the latter provides a broad review of resource characteristics, drilling experience, and technological gaps in superhot geothermal wells.

## 2. EXPERIMENTAL CAPABILITIES AND ADVANCEMENT

Experimental techniques are essential for superhot geothermal systems because material behavior under extreme temperature, pressure, and chemical conditions cannot be reliably extrapolated from conventional geothermal or oil-and-gas data. Laboratory experiments provide the only means to directly observe degradation mechanisms, phase-dependent interactions, and non-linear material responses that emerge under superhot and near-critical conditions.

### 2.1 Fluid-solid interactions

Fluid-solid interactions encompass a broad range of processes relevant to geothermal systems, including tubular corrosion, cement degradation, and fluid chemistry evolution. Geothermal fluids, particularly under superhot and supercritical conditions, can be highly corrosive with presence of acids, dissolved salts, reactive gases (e.g., $H_2S$ and $CO_2$), and transient chemical intermediates. Accurate characterization of the chemical composition of superhot geothermal fluids is a prerequisite for reliable assessment of both tubular corrosion and cement integrity. Autoclaves are the primary experimental devices used to investigate fluid-solid interactions and are widely

employed in subsurface research. However, the majority of existing autoclave systems are limited to temperatures of 300 °C and pressures of only several tens of megapascals, reflecting their historical use in oil and gas, energy storage, and carbon sequestration research.

### 2.1.1 Fluid Chemistry

The most common method for analyzing supercritical fluid chemistry involves periodic sampling of effluent from high-temperature, high-pressure autoclaves, followed by ex-situ analysis of key parameters, including pH, major ion concentrations, trace metals, total dissolved solids, non-condensable gases, secondary minerals, and transient chemical species.

A central challenge in supercritical fluid chemistry analysis is in-situ sampling, as rapid depressurization and cooling typically induce immediate silica precipitation. To address this challenge, Zhong et al. (2024, 2025) investigated quartz dissolution in pure water under conditions of 300 to 500 °C and 25-50 MPa, and employed a dilution-based sampling technique in which the high-temperature, high-pressure fluid was immediately mixed with a large volume of cold, silica-free water at a 50:1 dilution ratio. Although this procedure necessarily cools and depressurizes the sample to ambient conditions, the dilution dramatically reduces the dissolved silica concentration. As a result, by the time the sample cools, the silica concentration is already too low for measurable precipitation to occur, ensuring that the diluted sample faithfully preserves the dissolved silica content present at the moment of in-situ extraction.

In addition to bulk chemical analyses, cross-scale molecular characterization techniques, including Raman spectroscopy, infrared (IR) spectroscopy, X-ray scattering, Brillouin scattering, and high-resolution optical imaging, can be applied to supercritical fluids when experimental cells incorporate transparent, high-temperature, high-pressure windows. These methods offer valuable insight into molecular structure, speciation, and fluid-solid interactions under extreme conditions.

### 2.1.2 Tubular Corrosion

The University of Iceland (UoI) built one high-pressure, high temperature autoclave capable of operating at temperatures up to 500 °C and pressures up to 30 MPa (Kalsdottir et al., 2023; 2025). The system allows controlled introduction of salinity, $CO_2$, $H_2S$, and $N_2$, and includes mechanical stirring to approximate flow dynamics encountered in geothermal wells. The device has been used to test the corrosion of multiple tubular materials, including L80 carbon steel, L80-13Cr stainless steel, and titanium alloy Ti-475, under conditions of 350 °C and 400 °C at pressures of 16.5-16.8 MPa.

Experimental results showed that corrosion was generally more severe under 350 °C compared to 400 °C, suggesting complex temperature-dependent corrosion mechanisms. Both L80 and L80-13Cr suffered localized pitting corrosion, whereas Ti-475 maintained structural and chemical integrity. The superior performance of Ti-475 is attributed to the stability of its $TiO_2$ passive layer, which resists breakdown even in the presence of aggressive gases. Complementary field-based evidence was reported by Thorbjornsson and Kalsdottir (2015) and Thorbjornsson et al. (2020), who examined tubular materials retrieved from the IDDP-1 wellhead, which had experienced maximum temperatures of ~452 °C at pressures of ~14 MPa. Their findings also confirmed that carbon steel is unsuitable for high-temperature geothermal wells, reinforcing the need for advanced alloys in superhot applications.

### 2.1.3 Cement degradation

The UoI autoclave was also used to evaluate cement degradation under conditions of 350 °C and 16.2-17 MPa, with $CO_2$ and $H_2S$ included during a 3-day exposure period (Peciarová, 2024). A Dyckerhoff cement (65% cement and 35% silica by weight of blend, equivalent to 54% silica flour by weight of cement) maintained or increased its strength after the autoclave test. However, this short-term result does not necessarily indicate long-term survivability under true supercritical downhole conditions. Cement performance over extended operational timescales in geothermal wells remains uncertain.

Brookhaven National Lab (Pyatina et al., 2024) conducted a field study by exposing 9 cement formulations into the Newberry geothermal well (Fig. 1), with a temperature of ~325 °C and pressure ~26 MPa. Supercritical $CO_2$ is expected at the bottom of the well. After 3 months of exposure, the Portland cement and silica flour blend (60/40 by weight of cement blend) exhibited a 13% increase in their mechanical strength. However, after 9 months, this cement experienced an 86% dramatic strength loss. This highlights the importance of testing duration, which is difficult to achieve in the laboratory. Theoretically, early-stage carbonation leads to calcium carbonate formation and strength gain, whereas prolonged exposure results in calcium leaching via carbonation and subsequent dissolution of calcium-depleted silica phases, causing severe strength degradation.

Field exposure tests conducted in two high-temperature geothermal wells producing brines with different salt content at 293 °C and 277 °C in Baca, NV and Imperial Valley CA demonstrated variable performance of Portland cement-based slurries placed into non-treated or bentonite mud-pretreated Berea sandstone cylinders and lowered into the wells for up to a year (Gallus, et al. 1979). The results underline importance of validating cement formulations under relevant well conditions, including relevant compositions of geothermal fluids. Well-exposure tests are generally expensive and not always feasible. An alternative option is samples exposure to the steam/brine coming from a well at the surface. This type of experiments was done in Iceland for metal corrosion testing with a test chamber connected to a throttled steam, flowing in the exhaust pipe from the well at a pressure of 12-13 bar and temperature of about 350-360 °C (Karlsdottir et al., 2015).

**Fig. 1 Photographs of sample exposure tools (baskets) with cylindrical cement samples inside (Pyatina et al., 2024)**

Additional experimental challenges under supercritical conditions were highlighted by Pyatina and Sugama (2023), who reported rapid corrosion of rupture disks in a Parr autoclave rated to 500 °C and pressures of 34.46 MPa. Some high alkalinity tested systems caused fast corrosion of rupture disks under supercritical conditions and resulted in premature disk failures in less than 24 hours. Inconel steel disk replacement with corrosion resistant Hastelloy steel did not resolve this problem. The autoclave was modified by fabricating an extended attachment that repositioned the rupture disk further away from the high temperature zone (Fig. 2). Such engineering workarounds and experimental adaptations are likely to be necessary for many laboratory investigations under supercritical conditions.
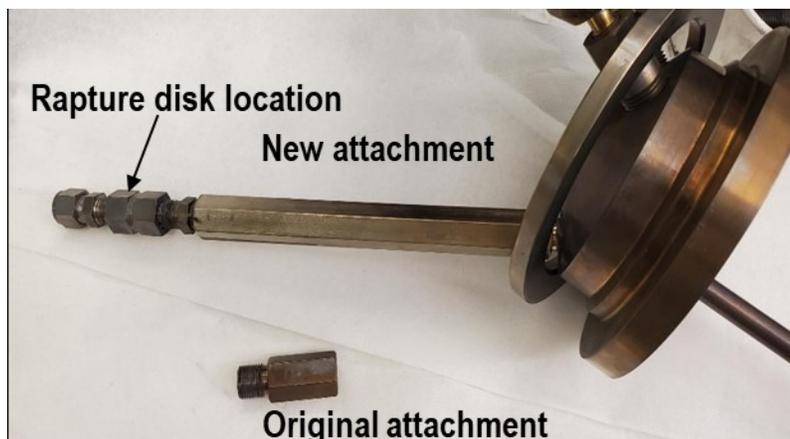


**Fig. 2 Photographs of extended attachment for rupture disk**

Despite the experimental challenges involved, cement testing under "wet" conditions, using autoclaves that allow direct or limited fluid access to the samples (Roy, 1980), is highly desirable for geothermal applications. Sustained "dry" conditions are unlikely to exist in geothermal reservoirs, even in systems initially classified as dry-steam dominated. The Geysers field in California, one of the few historically dry-steam geothermal systems, ultimately required large-scale water injection due to reservoir depletion (Pyatina et al., 2025). In addition, natural formation humidity arising from connate water, adsorbed moisture, and residual pore fluids implies that truly anhydrous conditions rarely, if ever, occur in the subsurface.

In enhanced geothermal systems (EGS), water injection is fundamental to reservoir stimulation and heat extraction, further intensifying the coupled thermal, hydraulic, chemical, and mechanical (THCM) loading experienced by the wellbore system. Even for cement slurries placed between casings, water is inherently present as part of the cement formulation and cannot dissipate in the manner assumed under "dry" test conditions. Consequently, adopting dry conditions for cement testing, material selection, or well design is not only unrealistic but also poses a direct risk to long-term well integrity and operational reliability. Experimental evidence highlights the importance of accounting for moisture effects. DiMartino and Ruch (2018) demonstrated pronounced differences in cement behavior when comparing dry exposure at 450 °C to partially wet exposure at 550 °C. Under dry conditions, both ordinary Portland cement (OPC)/silica and calcium-aluminate phosphate (CAP) cements exhibited amorphization and extensive cracking, whereas CAP cement maintained good structural integrity under the partially wet, higher-temperature conditions. These results underscore the necessity of wet or partially wet testing environments to accurately assess cement performance in geothermal systems.

In addition to the devices mentioned above, several organizations are developing new core-flooding systems and autoclaves for SHR-related applications. For example, the Fractured Earth Lab at LANL (https://www.lanl.gov/engage/collaboration/feynman-center/tech-and-capability-search/fractured-earth-lab) is constructing four core-flooding devices rated for operation up to 500 °C and 138 MPa to investigate fluid-solid interactions. Future research outcomes and publications are anticipated.

## 2.2 Mechanical testing

Mechanical testing is essential for assessing the integrity of tubulars, rock, and cement under the extreme temperature and pressure conditions expected in SHR wells. Elevated temperatures fundamentally alter material strength, ductility, and time-dependent deformation mechanisms, which need to be quantified to support reliable well design and long-term operation.

### 2.1.1 Tubular testing

Tubular materials (e.g., casing string, connectors, and tubing) maintain high strength under low temperatures, and their mechanical failure is therefore less critical compared to cement failures in conventional oil and gas wells. However, SHR well features with high-temperature up to 500 °C under which casing strength could be significantly reduced and materials may transition toward highly ductile behavior.

As shown in Fig. 3, Gruben et al. (2021) conducted systematic mechanical testing on different types of metallic materials, including carbon steels, nickel-based alloys, austenitic stainless steels, and titanium alloys, over a temperature range from ambient conditions to 550 °C. For carbon steels, both yield and tensile strength decrease substantially with temperature. Specifically, at 350 °C, yield and tensile strengths were reduced to 80% and 85% of their room temperature values, respectively, while at 500 °C both strengths decreased to approximately 60%. Notably, K55 retained only 45% of its room temperature tensile strength at the highest test temperature. Elevated temperatures therefore promote yielding at lower stress levels, and when combined with pre-stress induced by downhole pressure and thermal expansion, plastic deformation of casing becomes unavoidable and must be incorporated into well integrity analyses.
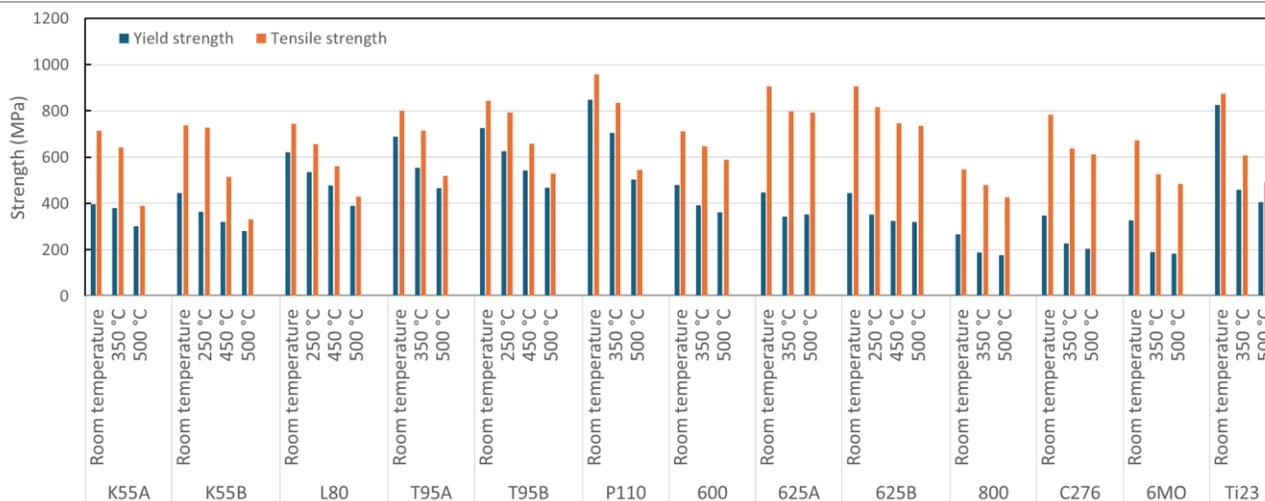


**Fig. 3 Yield strength and tensile strength for different types of casing materials, replotted from Gruben et al. (2021)**

Gruben et al. (2021) also found the nickel-based alloys display serrated curves due to the Portevin-Le Chateliers effect (PLC). PLC occurs with dynamic strain ageing that could potentially reduce ductility and can accelerate low-cycle fatigue damage, particularly under repeated thermal or pressure cycling, conditions that are common in geothermal wells. As a result, despite their excellent corrosion resistance, nickel-based alloys may be less suitable as primary structural casing materials in SHR applications. In contrast, the tested titanium alloy retained high strength at 500 °C and did not exhibit PLC behavior. However, titanium alloys possess an elastic modulus approximately 50% lower than that of carbon steel, which may significantly influence load transfer, casing deformation, and interactions with cement and surrounding rock. The implications of this reduced stiffness for overall well integrity warrant further investigation.

In a subsequent study, Gruben et al. (2022) demonstrated that creep deformation becomes a critical consideration for casing materials exposed to temperatures between 350 °C and 500 °C under sustained load. For both steels and Ti-23 alloys, creep rates at 500 °C were found to be two to three orders of magnitude higher than those at 350 °C. In deep geothermal environments characterized by high in-situ stresses and elevated temperatures, creep may lead to axial permanent elongation, radial expansion, wall thinning, and localized necking, all of which pose significant risks to long-term casing integrity.

Field experience indicates that most casing failures occur at connections rather than along the casing body (Zahacy, 2018). Maintaining casing connection integrity is therefore critical for safe and reliable geothermal well operation (Droessler et al., 2021). High-temperature geothermal conditions can generate severe thermally induced axial loads, which may exceed the yield strength of the casing material. The high-temperature conditions in geothermal wells can create severe thermally-induced axial loads that may exceed the yield strength of the

casing material. Post-yield thermal loads impose additional challenges for casing strings and connections and must be explicitly accounted for during geothermal casing design (Droessler et al., 2021). While Droessler et al. (2021) reported thermal cycling tests on casing strings with connections up to 290 °C, comparable testing above the critical temperature of water (375 °C) has not yet been reported, representing a critical knowledge gap for superhot geothermal wells.

2.1.2 Rock and Cement testing

Evaluating the constitutive and failure behavior of rocks under supercritical geothermal conditions, across a range of confining pressures, is essential for developing constitutive models and predicting failure modes in superhot reservoirs. Compared to well cement, high-temperature and high-pressure mechanical testing of rocks have been more widely performed due to broader applications in geoscience and engineering. Nevertheless, even for rocks, the maximum temperatures achieved in reported triaxial experiments are typically limited to ~300 °C, reflecting current facility limitations (Kumari et al., 2017). Some publications conducted triaxial high pressure tests on thermal treated rocks may not be able to reflect their mechanical behavior under both high pressure and high temperature.

Meyer et al. (2024) measured stress-strain behavior and permeability of Lanhélin granite over a temperature range from 200 °C to 800 °C (Fig. 4) with a confining pressure of 150 MPa, and pore pressure of 50 MPa. The tested granite exhibited predominantly brittle behavior between 200 °C and 600 °C, with peak strength decreasing modestly from 624 MPa at 200 °C to 588 MPa at 600 °C. At 800 °C, however, the strength dropped sharply to 272 MPa, and no distinct peak strength was observed, indicating a transition toward ductile deformation. These results highlight that the brittle-to-ductile transition is strongly dependent on mineralogy. High-silica, low porosity rocks such as granite and rhyolite are less prone to ductile behavior below ~500 °C, whereas softer sedimentary rocks (e.g., shale), carbonate rocks, and many metamorphic rocks transition to ductile behavior at below 200 ° C.
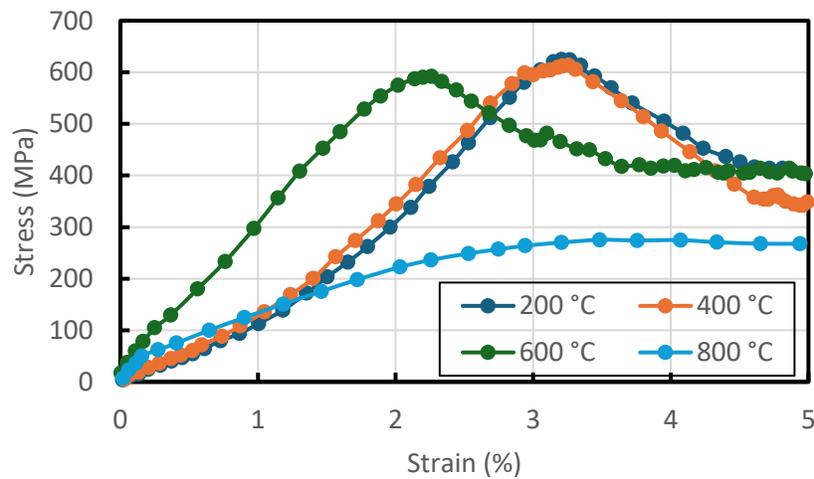


**Fig. 4 Stress strain curve of Lanhélin granite, replotted from Meyer et al. (2024)**

Similar considerations apply to well cement, although cement mechanical behavior under geothermal conditions is much less well understood. Pyatina et al. (2024) demonstrated that testing conditions strongly influence measured cement properties, with significant discrepancies observed between uniaxial compressive strength (UCS) and triaxial test results. For example, the novel geothermal cement formulation CAP#71/FAF exhibited elastic moduli of 3.6–4.2 GPa in UCS tests, compared to 14.6 to 20 GPa under triaxial conditions. Likewise, the #80/Silica formulation showed moduli of 2.1–3.1 GPa in UCS tests and 14.4–15.1 GPa in triaxial tests following exposure. Consistent with these findings, our own experiments on Class G cement blended with silica flour revealed that testing conditions can lead to more than 100% differences in measured strength. In general, an elastic modulus exceeding ~10 GPa is indicative of brittle cement behavior, whereas moduli near ~5 GPa correspond to more ductile behavior. Increased ductility is advantageous in geothermal wells, as it reduces stress concentrations and lowers the risk of cement cracking and debonding.

Beyond stress-strain characterization, wellbore-scale mechanical testing provides additional insight into failure mechanisms. As shown in Fig. 5, Goto et al. (2022) conducted true triaxial wellbore failure experiments on granite at temperatures ranging from 200 °C to 450 °C. Their high-temperature true triaxial apparatus, originally developed for hydraulic fracturing and hydrothermal flow-through studies, was adapted to assess wellbore stability by (1) drilling a 10 mm diameter borehole in a 100 × 100 × 100 mm cubic granite specimen and (2) progressively reducing the minimum horizontal stress while holding the maximum horizontal and vertical stresses constant. Under these conditions, non-catastrophic tensile and shear failures were observed, and fracture initiation was reasonably predictable using existing brittle failure criteria for granite. However, additional investigation is needed, as the applied stresses were hydrostatic at 53 MPa, which may not fully represent realistic in-situ stress anisotropy. Moreover, the imposed stress path differs from that encountered during drilling, where far-field stresses remain fixed while wellbore pressure and temperature evolve dynamically. Importantly, fluid pressure and thermal cooling, both of which are major contributors to wellbore instability, were not included in the experiments.
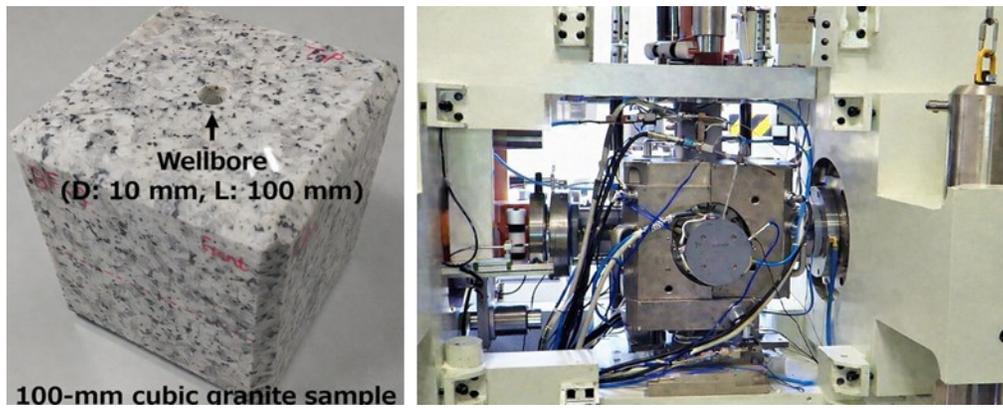
**Fig. 5 Granite sample and high temperature true triaxial cell, adapted from Goto (2022)**

2.1.3 Flow and permeability testing

Flow and permeability testing are typically performed on rock samples, but similar methodologies can be applied to cement, cement-casing interfaces, and cement-formation interfaces. Permeability measurements are particularly valuable when integrated with mechanical testing, as they provide insight into damage evolution, fracture connectivity, and leakage risk.

Meyer et al. (2024) measured permeability during triaxial compression tests on granite; however, the induced shear fractures were not aligned with the imposed flow direction. Consequently, the measured permeability primarily reflected transport through the damaged rock matrix, rather than through a well-connected fracture network. To better capture fracture-dominated flow, triaxial direct shear experiments or tests on pre-fabricated fractures are preferable, as they allow alignment of fluid flow with fracture planes and provide more representative permeability measurements for geothermal reservoir and wellbore applications. The coupled thermal, hydraulic, mechanical, and chemical (THMC) processes could be investigated through long-term flow tests under simulated geothermal conditions (Meng et al., 2022;2026).

## 3. MODELING CAPABILITIES AND ADVANCEMENT

Advanced modeling capabilities are essential for understanding and managing the coupled THMC processes that govern the performance and integrity of superhot geothermal wells. Modeling supports both design-stage decision-making and real-time operational risk mitigation.

### 3.1 Wellbore multiphase flow dynamics

Wellbore multiphase flow modeling is critical for predicting transient temperature and pressure (T-P) profiles during drilling, circulation, shut-in, restart, injection, and production. These transient conditions strongly influence well integrity, corrosion, cement performance, and non-productive time (NPT). Battistelli et al. (2020) developed the EOS2H module, coupled with T2Well, to model coupled wellbore-reservoir flow of $H_2O$-$CO_2$ mixtures under supercritical, steam-like conditions. This model was validated using data from the IDDP-1 well, demonstrating its ability to reproduce observed pressure and temperature behavior. Lamy-Chappuis et al. (2022) introduced a comprehensive well hydrodynamics model capable of handling pressures from 0.1 to 500 MPa, temperatures from 5 °C to 1000 °C, and salinities up to 100 wt% NaCl. This model was verified against IDDP-2 well data, making it one of the most robust frameworks available for superhot geothermal applications. Wei and Chen (2025) developed a single-phase supercritical flow model to investigate hazardous operational scenarios that threaten wellbore integrity, with particular emphasis on rapid temperature fluctuations during initial circulation following extended shut-ins. Their work highlights the vulnerability of casing and cement to thermal shock under supercritical conditions. Zhou et al. (2025) demonstrated that the commercial transient multiphase flow simulator OLGA can accurately model fluid dynamics and heat transfer in supercritical geothermal wells. OLGA is capable of handling lost circulation, feed zones, and explicit wellbore–reservoir coupling, and its predictions were validated using IDDP-2 data. These results indicate strong potential for guiding field operations and real-time decision-making.

### 3.2 Corrosion prediction

Corrosion has been found as a major challenge for supercritical geothermal wells, and reliable prediction of casing corrosion rates is essential for material selection and well design. Yanagisawa et al. (2021) developed a corrosion prediction model applicable to casing materials under conditions up to 500 °C and 60 MPa. Their results indicate that transient temperatures in the 300–350 °C range are potentially most corrosive for low-alloy steels, consistent with experimental observations reported by Kalsdottir et al. (2023; 2025).

The basic steps are predicting temperature and pressure profile of a wellbore, considering volcanic gases (e.g., $H_2S$ and $CO_2$) composition, calculating the temperature and pressure dependency of pH based on geochemical simulations, and predicting the material corrosion rates. Yanagisawa et al. (2021) used a predictive equation for the material corrosion rate based on the temperature of thermal water as a single phase, pH and the Cr equivalent of the elemental composition of a material. The equation is based on the empirical results of autoclave

and field tests. They have highlighted the importance of prediction accuracy of the fluid pH using geochemical simulations and more experimental data.

$$\log(C.R.) = 6.696 - 1930\left(\frac{1}{T}\right) - 0.622(pH) - 0.085(Cr_{eq})$$

Where, C.R. is the corrosion rate (mm/y), and Creq is the Cr equivalent, which is an indicator of the corrosion resistance of the material.

### 3.3 Fluid chemistry prediction

TReactMech (Sonnenthal & Spycher, 2023) is a numerical simulation framework designed to model THMC processes in fractured and porous media. It has been applied to predict the behavior of $CO_2$-water systems in geological environments, focusing on fluid-rock interactions and resulting geochemical evolution.

It is important to note that TReactMech does not model the fundamental thermodynamics of supercritical fluids directly. Instead, it predicts changes in fluid composition resulting from reactions with the host rock. For superhot geothermal systems, this capability must be coupled with accurate thermodynamic property calculations for $H_2O$-NaCl systems, spanning 0-1000 °C, 1-500 MPa, and 0-100 wt% NaCl, to fully capture fluid behavior across subcritical and supercritical regimes.

### 3.4 Borehole stability

Maintaining borehole stability improves drilling efficiency, reduces operational risk, and supports long-term injection and production. Porlles et al. (2024) performed a borehole stability analysis for a cold-water injection scenario in a hypothetical superhot well using both elastic Kirsch solutions and thermo-plastic Abaqus modeling. For the specific scenario evaluated, borehole instability was not identified as a limiting factor. However, the study highlighted several important limitations. First, accurate prediction requires realistic thermal and mechanical properties of reservoir rocks at high temperature, which in turn demands high-temperature triaxial testing facilities. Second, the analysis assumed intact rock, whereas geothermal reservoirs commonly contain pre-existing natural fractures. These fractures are likely to respond very differently to thermal and mechanical loading and may represent preferred failure planes. Furthermore, pore pressure effects were not explicitly addressed. If the formation is saturated, the coupled response of pore fluids under supercritical or superheated conditions and the implications for effective stress and borehole stability remain largely unreported in the literature.

### 3.5 Well integrity

While borehole stability concerns the openhole section, well integrity focuses on the performance of casing, cement, and their system response with bonded interface. The investigations of well integrity in superhot wells are also limited. Unlike oil and gas wells, where pressure cycling dominates, geothermal wells are primarily challenged by thermal cycling. As shown in Fig. 6, our recent investigations (Thakur et al., 2026) found that cement plasticity is important for pressure cycling, while in temperature cycling, both casing and cement plasticity are important to be considered.



**(a) Pressure Cycling: cement plasticity**

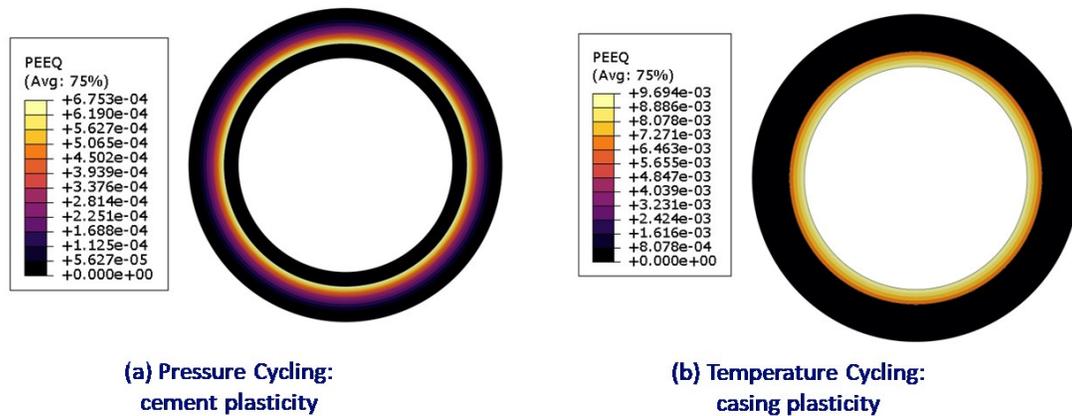**(b) Temperature Cycling: casing plasticity**

**Fig. 6 Plastic deformation of cement and casing under pressure and temperature cycling (adapted from Thakur et al., 2026). Cement plasticity is the primary concern for pressure cycling, while casing plasticity cannot be neglected for temperature cycling.**

In addition, high-temperature geothermal wells routinely exceed elastic limits during heat-up; post-yield/strain-based design is therefore standard, accepting compressive plasticization on heat-up and protecting against tensile failure on cooldown, such as Holliday-type methodologies (Suryanarayana and Krishnamurthy, 2018). Casing connections represent a particularly vulnerable component (Droessler et al., 2021). Thermally induced axial loads may exceed casing yield strength, and traditional stress-based design methods are often inadequate. Droessler et al. (2021) proposed a strain-based design framework that explicitly accounts for cyclic thermal loading and post-

yield material behavior, which appears better suited for geothermal applications. Overall, significant work is needed to understand well integrity for superhot wells.

## 4. DISCUSSION AND RESEARCH GAPS

This review highlights that the primary challenges facing superhot geothermal systems are not driven by peak reservoir temperature alone, but by coupled effects from thermal transients, multiphase behavior, material response, and time-dependent degradation.

### 4.1 The subcritical window as the critical corrosion regime

Both experiments and models show that corrosion does not increase monotonically with temperature. Instead, it is controlled by fluid chemistry and phase state, with peak corrosion for low-alloy steels commonly occurring in the 300-350 °C subcritical regime. In SHR wells, where flashing and condensation can occur during transients, the most severe corrosion may occur just above or below the critical point depending on gas content and the presence of an aqueous phase. Materials selection must therefore account for thermo-hydraulic transients and local phase conditions, not simply peak reservoir temperature.

Corrosion peaks just below the critical point for several reasons: (1) slightly subcritical conditions promote intermittent flashing and condensation, producing acidic condensate films enriched in $CO_2$, $H_2S$, $O_2$, and concentrated salts; (2) near-critical fluid properties (density, compressibility, heat capacity) enhance convection and mass transfer, accelerating delivery of corrosive species to the metal surface; (3) changes in water chemistry near the critical point, such as increased auto-dissociation and reduced dielectric constant, alter speciation and electrochemical kinetics, often increasing aggressiveness; (4) Protective $Fe_3O_4$ or $FeCO_3$ scales on carbon steel become unstable, enabling localized attack; and (5) flashing also concentrates salts and promotes scale deposition, creating crevice conditions that intensify pitting.

Overall, the subcritical regime just below the critical point often combines the most damaging conditions: two-phase condensation with acidic films, enhanced near-critical transport, unstable protective scales, and salt concentration. Once conditions transition fully into a single-phase supercritical regime, corrosion mechanisms may change and, in some systems, corrosion rates may decrease, provided condensation and salt deposition are avoided. Nevertheless, supercritical water can remain highly aggressive if oxidants or dissolved salts are present, underscoring the need for integrated THMC modeling, targeted experiments, and transient-aware materials design.

### 4.2 Both transients and extremes govern well integrity

The extreme temperatures encountered in superhot geothermal systems fundamentally alter material behavior, promoting ductile and time-dependent deformation mechanisms that are rarely relevant at ambient or moderately elevated temperatures. Under these conditions, both casing steels and well cements exhibit reduced elastic moduli, lower yield strengths, enhanced creep, and increased susceptibility to plastic strain accumulation. As a result, materials respond not only to instantaneous loads but also to thermal history, loading rate, and cyclic exposure, leading to mechanical behavior that departs significantly from that observed in conventional geothermal or oil and gas wells.

At the same time, field experience and modeling studies indicate that some of the most damaging conditions do not occur during steady-state production, but rather during non-steady operational phases, including drilling circulation, extended shut-ins, restart operations, lost circulation events, and cold-water injection. Multiphase wellbore flow modeling shows that these transient operations can induce rapid and spatially localized fluctuations in temperature and pressure, driving sections of the wellbore into subcritical, two-phase regimes, even when the surrounding reservoir remains fully supercritical.

Taken together, these observations fundamentally reframe well integrity in superhot geothermal systems. Rather than a static design problem governed by peak temperature or pressure, well integrity emerges as a dynamic, transient-dominated challenge controlled by the interaction of multiphase flow, evolving material properties, and operational practices.

### 4.3 Difficulty to mimic realistic geothermal environments

Most Standard API and proprietary tests rely on benign aqueous systems, often NaCl brines with low ionic strength, whereas real geothermal fluids contain high concentrations of dissolved silica, alumina, $CO_2$, $H_2S$, boron, alkali metals, and trace elements (Mroczek et al., 2020; Arnórsson, 2015). These chemistries, particularly at supercritical temperatures, dramatically accelerate cement degradation, casing corrosion, and elastomer failure (Kruszewski & Aiken, 2016; Sugama et al., 1999). When materials are qualified under benign conditions, degradation mechanisms such as hydrothermal alteration, carbonation, sulfide attack, and scaling are not adequately captured.

Equally important is the absence of realistic flow and phase conditions. Very few tests simulate continuous two-phase water flow, supercritical water-steam transitions, or flashing events, all of which are common in SHR wells and strongly influence material integrity (Reinsch et al., 2017). Similarly, existing protocols do not address thermal cycling (Kibikas et al., 2025), despite well-documented rapid temperature cycling in superhot wells during circulation interruptions and shut-ins. Field data from IDDP-1 and IDDP-2 show that wellbores can reheat from ~100 °C to >350–400 °C within hours to days once circulation ceases (Elders et al., 2014; Friðleifsson et al., 2017). This rapid reheating induces extreme thermo-mechanical stresses that API tests never attempt to simulate.

Because these qualification tests systematically exclude the key drivers of material degradation in SHR environments—extreme temperature, supercritical fluid chemistry, two-phase flow instability, and thermal shock—they routinely underpredict degradation rates. As a result, cements, drilling fluids, spacers, elastomers, casings, and completion elements may pass laboratory qualification but fail in the field within months, leading to compromised well integrity, unplanned workovers, and long-term operational risk (Reinsch et al., 2017; Kruszewski & Aiken, 2016).

## 4.4 Plasticity and post-yield behavior needs to be considered

Ongoing mechanical testing and numerical modeling consistently demonstrate that casing and cement in SHR wells routinely exceed their elastic limits during thermal cycling. Unlike conventional oil and gas or moderate-temperature geothermal wells, SHR systems experience extreme temperature excursions and repeated heating–cooling cycles that induce large thermally driven strains. Under these conditions, elastic assumptions break down, and both metallic and cement materials exhibit irreversible plastic deformation, stiffness degradation, and evolving damage states. To accurately characterize this behavior, advanced mechanical testing facilities capable of operating at temperatures up to 500 °C and pressures exceeding 22 MPa are essential. Such facilities need to support uniaxial, triaxial, and true triaxial loading paths while enabling control of confining pressure, pore pressure, temperature, and loading rate. High-temperature, high-pressure mechanical testing of casing materials, cement formulations, and reservoir rocks is critical for capturing yield behavior, post-yield response, creep, and cyclic degradation under conditions representative of SHR wells. The resulting datasets form the foundation for constitutive models that are required to reliably analyze wellbore stability and well integrity during all operational phases, including drilling, cementing, injection, shut-in, restart, and long-term production.

For casing and casing connections in particular, these findings underscore that traditional stress-based design approaches are inadequate for superhot geothermal applications. Stress-based criteria implicitly assume elastic behavior and do not account for post-yield deformation, which is unavoidable in superhot conditions. Instead, strain-based, post-yield design frameworks are required. Such approaches explicitly accommodate controlled compressive plastic deformation during heat-up while ensuring that tensile strain limits are not exceeded during cooldown, when casing and cement are most vulnerable to cracking and debonding. This design philosophy aligns with both observed material behavior and established field practices in high-temperature applications.

Furthermore, time-dependent deformation mechanisms, including creep, low-cycle fatigue, and thermal ratcheting, are suggested to be incorporated into well integrity assessments and requires further investigations. At temperatures above ~350 °C, creep rates increase dramatically, allowing significant strain accumulation under sustained or cyclic loads. Repeated thermal and pressure cycling can further accelerate fatigue damage and ratcheting, particularly at casing connections and cement interfaces. Neglecting these mechanisms may lead to premature failures, even if short-term integrity appears acceptable.

## 4.5 Modeling as the Integrating Framework

Advanced modeling capabilities, particularly wellbore multiphase flow, corrosion prediction, wellbore stability, and well integrity, serve as the integrating framework linking materials behavior, fluid chemistry, and operational decisions. The integrated model needs to anticipate hazardous transient scenarios, guide real-time operational adjustments, inform materials selection and cement design, and reduce non-productive time and failure risk.

## 5 CONCLUSION

In this work, we have done a review of the experimental and modeling achievements relevant to well construction materials for superhot geothermal wells. The experimental capabilities include fluid-rock interactions and mechanical testing, and the modeling capabilities include wellbore multiphase flow dynamics, fluid chemistry prediction, corrosion prediction, borehole stability, and well integrity. Collectively, these findings suggest that the technology readiness of superhot well construction is constrained by the testing and validation methods. Bridging this gap requires expanded supercritical-capable experimental infrastructure, long-duration and field relevant materials testing, and an integrated modeling framework that links the tested material behavior and life-cycle operations. The critical corrosion regime within the subcritical window highlights the importance of understanding transient pressure and temperature profile across the wellbore. Combined with fluid chemistry and corrosion prediction, guidelines for material selection should be generated. Existing testing on casing and cement materials revealed that the tendency of brittle-to-ductile transition, and much more testing is required to achieve a good understanding. Addressing these challenges will enable SHR systems to realize their promise of order-of-magnitude higher power density, transforming geothermal energy from a niche baseload resource into a scalable, dispatchable pillar of future energy systems.

## ACKNOWLEDGEMENTS

## REFERENCES

Arnórsson, S. (2015). Geochemistry of Geothermal Fluids.

Battistelli, A., Finsterle, S., Marcolini, M., & Pan, L. (2020). Modeling of coupled wellbore-reservoir flow in steam-like supercritical geothermal systems. Geothermics, 86, 101793.

Di Martino, G., & Ruch, A. (2018). Non-Portland cement slurry development and application for ultrahigh-temperature geothermal well with supercritical conditions. *Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference, APDT*, *2018-Augus*. https://doi.org/10.2118/190974-ms

Droessler, M., Tao, G., Hamilton, K., Skelton, B., & Yoshikawa, M. (2020, April). Casing Connection Evaluation for High-temperature Geothermal Applications–A Case Study. In World Geothermal Congress (Vol. 1). Iceland: Reykjavik.

Elders, W. A., et al. (2014). Scientific results from Iceland Deep Drilling Project well IDDP-1. Geothermics, 49, 1–23.

Eslami, M., Choi, Y. S., Nesic, S., & Breining, R. (2024). Effect of formic acid (HCOOH) on the corrosion protectiveness of magnetite ($Fe_3O_4$) at elevated temperature. Corrosion Science, 229, 111868.

Espinosa-Paredes, G., & Garcia-Gutierrez, A. (2003). Estimation of static formation temperatures in geothermal wells. Energy conversion and management, 44(8), 1343-1355.

Feng, P., Xu, D., Yin, G., Song, K., Wang, R., Li, Z., & Wang, P. (2025). Synergistic Corrosion Mechanisms of Supercritical Water and Na2SO4 Deposition Layer: Austenitic Stainless Steels 316 L and 304. The Journal of Supercritical Fluids, 106663.

Friðleifsson, G. Ó., Elders, W. A., & Albertsson, A. (2014). The concept of the Iceland deep drilling project. Geothermics, 49, 2-8.

Friðleifsson, G. Ó., Elders, W. A., Zierenberg, R. A., Stefánsson, A., Fowler, A. P., Weisenberger, T. B., ... & Mesfin, K. G. (2017). The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target. Scientific drilling, 23, 1-12.

Gallus, J. P., Watters, L. T., & Pyle, D. E. (1979). Performance of Oilwell Cementing Compositions in Geothermal Wells. Society of Petroleum Engineers Journal, SPE 7591, 233–241.

Gherardi, F., & Magro, G. (2025). Geochemistry of geothermal well gases from superhot zones of Larderello, Italy. Applied Geochemistry, 106480.

Goto, R., Sakaguchi, K., Parisio, F., Yoshioka, K., Pramudyo, E., & Watanabe, N. (2022). Wellbore stability in high-temperature granite under true triaxial stress. Geothermics, 100, 102334.

Gruben, G., Dillingh, B., Kaldal, G. S., Hoang, N. H., Wollenweber, J., Rørvik, G., ... & Nyhus, B. (2021). Thermo-mechanical tensile testing of geothermal casing materials. Geothermics, 89, 101944.

Gruben, G., Nyhus, B., Hoang, H. N., & Rorvik, G. (2022). Creep behavior of casing materials. GRC Transactions, 46.

Kaesche, H. (2003). Corrosion of Metals: Physicochemical Principles and Current Problems. Springer.

Karlsdottir S.N., Ragnarsdottir K.R., Thorbjornsson I.O., Einarsson A. (2015). Corrosion testing in superheated geothermal steam in Iceland, Geothermics, 53, 281-290

Karlsdóttir, S. N., Boakye, G. O., Wallevik, S. Ó., Alexandersson, K. F., Přikryl, J., Straume, E. O., & Ásbjörnsson, S. (2023). Material Testing and Challenges for Casing Materials for Superhot Geothermal Wells. In Proceedings World Geothermal Congress 2023 Beijing, China, September 15-17, 2023.

Karlsdottir, S. N., Boakye, G. O., Straume, E., & Ijegbai, D. A. (2025). Corrosion Behavior of L80-Carbon Steel and 13 Cr Casing Materials at 400° C in Simulated Superhot Geothermal Well Environment. In CONFERENCE 2025 (pp. 1-12). Association for Materials Protection and Performance.

Kato, O., Doi, N., Sakagawa, Y., & Uchida, T. (1998). Fracture systematics in and around well WD-1, Kakkonda geothermal field, Japan. Geothermics, 27(5-6), 609-629.

Kaspereit, D., Mann, M., Sanyal, S., Rickard, B., Osborn, W., & Hulen, J. (2016). Updated conceptual model and reserve estimate for the Salton Sea geothermal field, Imperial Valley, California. Geothermal Resources Council Transactions, 40(11).

Kibikas, W., Pyatina, T., Dewers, T., Bauer, S., Sugama, T., & Meng, M. (2025). Thermal shock resistance of lightweight cements developed for geothermal conditions. Geothermics, 130, 103340.

Kibikas, W., Pyatina, T., Meng, M., Schill, E., Taverna, N., Mello, S., Broadhurst, T., (2026). Supercritical Geothermal: Resources, Drilling Experience, and Technological Gaps. Stanford Geothermal Workshop, Stanford, CA.

Kipyego, E., O'Sullivan, J., & O'Sullivan, M. (2013, November). An initial resource assessment of the Menengai caldera geothermal system using an air–water TOUGH2 model. In Proceedings, 35th New Zealand geothermal workshop, Rotorua, New Zealand.

Kruszewski, M., & Aiken, C. (2016). Cement behavior in high-temperature geothermal wells. Geothermal Resources Council Transactions.

Kumari, W. G. P., Ranjith, P. G., Perera, M. S. A., Shao, S., Chen, B. K., Lashin, A., ... & Rathnaweera, T. D. (2017). Mechanical behaviour of Australian Strathbogie granite under in-situ stress and temperature conditions: An application to geothermal energy extraction. Geothermics, 65, 44-59.

Lamy-Chappuis, B., Yapparova, A., & Driesner, T. (2022). Advanced well model for superhot and saline geothermal reservoirs. Geothermics, 105, 102529.

Meng, M., Frash, L. P., Li, W., Welch, N. J., Carey, J. W., Morris, J., ... & Kneafsey, T. (2022). Hydro-mechanical measurements of sheared crystalline rock fractures with applications for EGS Collab Experiments 1 and 2. Journal of Geophysical Research: Solid Earth, 127(2), e2021JB023000.

Meng, M., Wigand, M., Frash, L. P., Thakur, M. M., Xiong, Q., Welch, N. J., ... & Carey, J. W. (2026). A novel hydro-mechanical-chemical coupled experiment for unconventional hydrocarbon production evaluation. International Journal of Rock Mechanics and Mining Sciences, 198, 106362.

Meyer, G. G., Shahin, G., Cordonnier, B., & Violay, M. (2024). Permeability partitioning through the brittle-to-ductile transition and its implications for supercritical geothermal reservoirs. Nature Communications, 15(1), 7753.

Mroczek, E., et al. (2020). Geothermal fluid chemistry and scaling in high-enthalpy systems. Geothermics.

Owen, J., Barker, R., Straume, E., & Karlsdóttir, S. N. (2025, April). Magnetite Formation and Localized Corrosion of Carbon Steel in a Simulated Geothermal Environment at Elevated Temperature and Pressure. In AMPP CORROSION (pp. AMPP-2025). AMPP.

Peciarová, M. M. (2024). Mechanical Properties and Microstructure of Well Cement Blends for Superhot Geothermal Wells (Doctoral dissertation).

Porlles, J. W., Houde, M. D., Yao, J., Batir, J., Soroush, H., & Madayarov, A. (2024, June). Borehole Stability Analysis for an Injection Well in Superhot Rock Drilled with Millimeter Wave Technology. In ARMA US Rock Mechanics/Geomechanics Symposium (p. D042S059R010). ARMA.

Pyatina, T., & Sugama, T. (2023). Cements for Supercritical Geothermal Wells at 400 C. Proceedings of the Geothermal Rising Proceedings, Reno, NV, USA, 1-4.

Pyatina, T., Sugama, T., Moghadam, A., Naumann, M., Skorpa, R., Feneuil, B., ... & Godøy, R. (2024). Assessment of Cementitious Composites for High-Temperature Geothermal Wells. Materials, 17(6), 1320.

Pyatina T., Petty S., Devoe M., Liu S., Sugama T. (2025)"Cementitious Materials for High-Heat-Content Geothermal Wells – Challenges and Advancements" GRC transactions, vol 49.

Reinsch T., Dobson P., Asanuma H., Huenges E., Poletto F., & Sanjuan B. (2017). Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. Geothermal Energy, 5(1), 1-25.

Revie, R. W., & Uhlig, H. H. (2025). Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering (5th ed.). Wiley.

Roy, D. M. (1980). New High Temperature Cementing Materials for Geothermal Wells: Stability and Properties. Brookhaven National Laboratory.

Schill, E., Kibikas, W., Pyatina, T., Meng, M., Mello, S., Taverna, N., Broadhurst, T., Dobson, P., 2026. Sub- and Supercritical Geothermal Fluids – A Global Database. Stanford Geothermal Workshop, Stanford, CA.

Sogaard, E. (2014). Chemistry of advanced environmental purification processes of water: fundamentals and applications. Newnes.

Sonnenthal, E., Smith, J., & Spycher, N. (2023). TReactMech v4. 217. Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA United States.

Sugama, T., et al. (1999). Durability of geothermal cements under hydrothermal conditions. Cement and Concrete Research.

Suryanarayana, P. V., & Krishnamurthy, R. M. (2018, February). Post-Yield Tubular Design and Material Selection Considerations for Improved Geothermal Well Integrity. In Proceedings, 43rd Workshop on Geothermal Reservoir Engineering (pp. 12-14). Stanford, California: Stanford University.

Thakur, MM, and Meng, M., Zhang, W. (2026) Thermomechanical Modeling of Wellbore Integrity for Enhanced,and Superhot Rock Geothermal Systems. Available at SSRN: https://ssrn.com/abstract=6153959 or http://dx.doi.org/10.2139/ssrn.6153959.

Thorbjornsson, I. O., Karlsdottir, S. N., Einarsson, A., & Ragnarsdottir, K. R. (2015). Materials for geothermal steam utilization at higher temperatures and pressure. In Proceedings of the World Geothermal Congress.

Thorbjornsson, I. O., Kaldal, G. S., Krogh, B. C., Palsson, B., Markusson, S. H., Sigurdsson, P., ... & Jonsson, S. S. (2020). Materials investigation of the high temperature IDDP-1 wellhead. Geothermics, 87, 101866.

Wang, G. X., Almara, L. M., & Prasad, V. (2024). Thermodynamic analysis of anomalous region, critical point, and transition from subcritical to supercritical states: Application to van der Waals and five real fluids. Physics of Fluids, 36(2).

Wei, C., and Chen, Y., (2025) Thermal Cycling-Induced Wellbore Integrity Risks in Super-Hot Geothermal Drilling: Identifying Hazardous Operational Scenarios. GRC conference. Reno, NV, USA.

Yanagisawa, N., Masuda, Y., Asanuma, H., Osato, K., & Sakura, K. (2021). Estimation of casing material corrosion rates for supercritical geothermal development. Geothermics, 96, 102149.

Zahacy, T. A. (2018). Application and Value of Geothermal Well Reliability Data. Geothermal Resources Council Transactions .

Zhang, X., Gao, L., & Wang, Y. (2024). Handbook of Corrosion Engineering: Modern Theory, Fundamentals and Practical Applications. Elsevier.

Zhong, C., Xu, T., Yuan, Y., Gherardi, F., & Feng, G. (2024). An experimental study on quartz solubility in water under supercritical geothermal conditions. Journal of Hydrology, 630, 130663.

Zhong, C., Xu, T., Yuan, Y., Gherardi, F., & Feng, G. (2025). An experimental study on quartz dissolution kinetics in water under supercritical geothermal conditions. Journal of Hydrology, 134229.

Zhou, L., Liu, Y., Meng, M. and Anfinsen, B.T., 2025, October. Advanced Numerical Analysis of Well Integrity and Thermal Dynamics in Superhot Geothermal Reservoirs. In SPE Annual Technical Conference and Exhibition (p. D031S031R007). SPE.