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# Heat Extraction from SuperHot Rock - Technology Development

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## ABSTRACT

SuperHot Rock (SHR) Engineered (or Enhanced) Geothermal Systems (EGS) is one of the most promising paths to scale clean, firm, cost-competitive geothermal electricity production worldwide, but significant scientific and development uncertainty surrounds these potential high-value resources. In this paper, we discuss the technologies needed to create SHR reservoirs and describe critical gaps where targeted public and private investment can break down roadblocks.

Creation and operation of superhot engineered geothermal systems involve risks and opportunities that need to be further evaluated by lab testing and field demonstrations, such as a) well and tool integrity, b) fluid-rock-casing interactions, c) reservoir management and longevity, and d) the possibility of felt or damaging injection-induced seismicity. The technology development and testing needed to plan for, drill to, characterize, and mine heat from SHR include a) numerical models, b) laboratory studies of rock geomechanics, fluid dynamics, and fluid-rock interaction at SHR conditions, c) SHR materials and equipment – drill bits, drill string, proppants, diverters, sealants, instruments, and zonal isolation tools, and d) for SHR EGS reservoir creation, stimulation tools, and methods, tested at wellbore and reservoir scales.

The scope of the challenge invites collaboration between geothermal and oil and gas operators, and those with broader expertise in deep, higher-temperature geologic systems, such as economic geologists and metamorphic petrologists, or engineers and laboratories that routinely work in superhot and supercritical conditions.

## 1. INTRODUCTION

Recovery of just 2% of the thermal energy stored in hot rock 3 to 10 km below the continental US is equivalent to 2000 times the primary US energy consumption (Tester et al., 2006). By developing these resources, clean, firm renewable geothermal power becomes possible virtually anywhere. Over the past few decades, most engineered geothermal system (EGS) R&D and deployment has focused on resources less than 200 °C. However, the goal of economic EGS anywhere may not be achievable unless power production per well can be significantly improved. There are three ways to increase power production per well: increase flow rate, increase flow temperature, or both. Cladouhos et al. (2018) proposed that drilling into superhot rock (SHR) resources and producing super high-enthalpy fluids (>2100 kJ/kg) is one of the most promising potential paths to scale clean, firm, cost-competitive geothermal electricity production worldwide. Cladouhos and Callahan (2023) provides a comprehensive review of previously drilled superhot wells, reservoir analogs, and the status of technologies and geoscience needed to create SHR EGS reservoirs. In this shortened version we provide an update from papers presented at the 2023 Geothermal Rising Annual Conference and with a specific focus on start of the art technologies and gaps.

We use the term superhot rock (SHR) to refer to systems with formation temperatures above 375 °C (Cladouhos and Callahan, 2023). SHR may host or produce supercritical water, however, that would also require a pressure of greater than 22 MPa and pure water, two conditions that will seldom be the case in the real world. The most complete description of the energy of a geothermal fluid is enthalpy. As steam fraction, pressure, and temperature change in the journey from formation into and up the well, enthalpy will only be reduced by minimal heat loss to the formation along the wellbore. Superhot rock will produce super high enthalpy fluid which has a specific enthalpy of greater than 2100 kJ/kg (Banks and Ball, 2023). Theoretical wellbore modelling by Rivera, Carey, and Chambefort (2023) shows that the optimal wellhead pressure for energy production is 12 MPa, thus superheated steam rather than supercritical fluid would be produced at the surface. The higher enthalpy of the produced fluid results in much higher thermal-to-electricity conversion efficiency and less parasitic load (Moon and Zarrouk, 2012) as a steam power plant would be connected to the SHR wellfield rather than a binary power plant (Figure 1).

SHR resources, rock hotter than 375 °C, occur everywhere on the planet, at depths dependent on the local temperature gradient. Therefore, to achieve the goal of scalable, clean, firm, cost-competitive geothermal electricity production worldwide, developing the technologies to create engineered superhot rock geothermal systems in low permeability rock could prove transformative and worth the additional effort and investment.

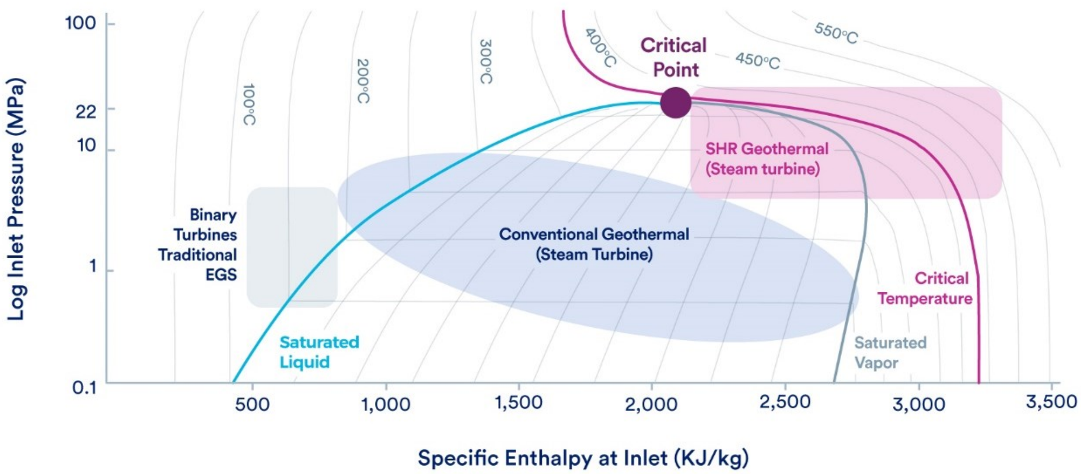


**Figure 1: Pressure vs Enthalpy graph for pure water showing conditions at the wellhead or inlet to the power plant typically encountered in lower temperature EGS, conventional hydrothermal fields, and the promise of SHR geothermal.**

### 1.1 Goals of SHR EGS development

The goals of an "n$^{th}$ of a kind" (NOAK) SHR EGS project (Cladouhos & Callahan, 2023) will be:

1. Net electricity generation of greater 20 MW per well,
2. Produced fluid with specific enthalpy over 2100 kJ/kg,
3. Sustainable field operation projected for over 20 years,
4. Levelized cost of electricity of less than $50 MW/hr, and
5. Low risk of impacts from induced seismicity.

The "first of a kind" (FOAK) project and its immediate successors will not reach the first four goals as SHR EGS developers learn-by-doing. The fifth goal must always be achieved to maintain local support.

Achieving the generation, production, and sustainability goals of SHR EGS will require a large surface area for heat exchange. Pending published SHR-specific models, we adopt an estimation from Kennedy et al. (2021) for lower temperature EGS that about 4 million m$^2$ of surface area is needed for sustainable EGS production given reasonable rock and fluid thermal properties. As an example, to achieve this amount of surface area would require 200 fractures along a 2 km long lateral (assuming a 10 m fracture spacing), 200 m well spacing, and 100 m high fractures. McClure (2021) calculates that modern shale wells achieve a flowing fracture surface area of 9 million m$^2$, so this surface area goal is attainable at lower temperatures and in weaker rocks. What technologies are needed to do the same in hotter, stronger rocks?

## 2. DEVELOPING A SHR RESOURCE – STATE OF THE ART AND GAPS

Independent of the SHR site to be developed or even the specific design of heat extraction, new technologies, designs, and ideas will need to be developed and tested, involving laboratory research, numerical modeling, materials selection, development of best practices, and risk analysis. In the next sections, we review the state-of-the-art in multiple disciplines and identify gaps in knowledge or technology that require investment and should be addressed by research and development to increase Technology Readiness Level (TRL) to succeed with SHR resource development. Although the list below is broad, the focus is on aspects related to what is needed for reservoir development.

### 2.1 Modelling of fracture propagation and reservoirs in superhot rock

There is a broad array of models needed to design, create, and manage an engineered SHR reservoir: geodata models, geophysical models, numerical reservoir models, coupled THMC (thermo-hydraulic-mechanical-chemical) models, fracture propagation models, power plant models, and techno-economic models.

Geochemical geothermal models have begun pushing into supercritical pressure-temperature space (e.g., Magnusdottir and Finsterle, 2015; Battistelli et al., 2020; O'Sullivan et al., 2020; Lamy-Chappuis et al., 2021; Sonnenthal et al. 2021; Feng et al., 2021; DePaolo et al., 2022; Altar et al., 2023; Xu et al., 2023) but an integrated model for brittle deformation in superhot reservoirs with the influence of natural fractures does not yet exist. The challenges of modeling fracture propagation and fluid flow in a SHR reservoir include rapidly changing physical properties of water, such as density and viscosity, in the vicinity of the critical point (±75 °C and ±5 MPa) . For example, during both the stimulation and operational phases of an SHR EGS, the same water could undergo multiple phase changes, 10x changes in viscosity, and 5x changes in density. Another critical issue for THMC models of SHR EGS operations is the role of mineral dissolution and precipitation on fracture transmissivity. In particular, quartz, which has retrograde solubility, may precipitate and seal fluid pathways unless countermeasures can be developed (Saishu et al., 2014; Watanabe et al., 2021a). This is an uncertainty that can be further investigated in the lab, as discussed in the next section. The geomechanical behavior of rocks in the brittle-ductile transition (BDT) and the influence of thermal cracking due to the large temperature contrast between rock and injected fluid are also not included in most models.

Scott et al. (2023) used CSMP++ to perform a reconnaissance study of EGS with modeled well depths of 15.5-17 km and rock temperatures above 400 °C. A rationale for a bulk permeability increase from a native state of less than $10^{-18}$ $m^2$ to an injection-stimulated bulk permeability of $10^{-15}$ – $10^{-14}$ $m^2$ was provided by experimental evidence that permeability enhancement due to fluid injection may be highly efficient in nominally-ductile crystalline rock at high temperatures (Watanabe et al., 2017; Watanabe et al., 2019, Watanabe et al., 2020; Goto et al., 2021, Goto et al., 2023). This first-ever published numerical simulation of ultra-deep SHR EGS can be extended through more realistic geomechanics, hydraulic discrete fracturing, and the inclusion of chemical equilibrium solvers.

More robust numerical reservoir models and coupled THMC models that can simulate the equations of state for supercritical water, phase changes, mixed steam-water flow, and geochemistry will be necessary to predict the longevity of SHR EGS due to permeability changes and thermal decline. However, there is a gap in thermodynamic and kinetic data needed for modeling fluid-rock interaction within the P-T conditions of the supercritical regime that will require further laboratory experiments to derive.

Finally, code comparisons like those performed at lower temperatures (Molloy et al., 1980; White and Phillips, 2015; Kennedy et al., 2021) have not been performed on code developed for SHR EGS. The need for data from field experiments for history matching to validate SHR EGS codes is even more critical.

Gaps

- A comprehensive survey is needed of the capabilities of existing modeling packages at SHR and BDT conditions and the upgrade pathways.
- Fracture propagation in diverse lithologies with unpredictable structural relationships. Hydraulic fracturing software was designed to predict hydraulic fracture apertures, dimensions, and propagation direction in a layer-cake stratigraphy of sedimentary rocks.
- Development of appropriate stress conditions and rock property parameters for these systems.
- There is a lack of thermodynamic and kinetic data needed for modeling fluid-rock interaction within the P-T conditions of the supercritical regime.
- Models that can test ideas for creation of sufficient surface area and flow paths to maximize heat extraction from the rock volume in a sustainable manner.
- Physics-based models for fracture propagation that account for geomechanics in rock approaching the BDT, with abundant and unpredictable natural features, using near-critical point water that will experience rapid changes in pressure, viscosity, and density.
- Inclusion of impacts of phase transition (esp. through critical point) on geomechanics and flow properties within models.
- Reservoir modeling – heat conduction from rock to fluids and supercritical thermodynamics of fluid in reservoir.
- Coupled DFN and Reservoir Model – upscaled discrete element modeling of entire systems for analysis and planning.
- Models are also needed for projection of long-term operations of sustainability (thermal and pressure changes) and geochemical effects such as dissolution and precipitation along fractures and proppants.
- Until reliable data is available for model validation, comparison of results between different codes can be used to evaluate results.

### 2.2 Laboratory testing at reservoir conditions

Currently available laboratory test equipment is generally limited to temperatures of 300 ºC or below, most often at temperatures below 200 ºC. The geomechanics lab at EPFL (Violay et al., 2010; Violay et al., 2015; Acosta et al., 2021) has been running experiments (strain, elastic properties, and compressive strength) through the BDT on a variety of rock types up to 800 °C. A higher upper-temperature limit is needed in laboratory experiments to account for faster strain rates in experiments than EGS operations and especially tectonics.

State-of-the-art geomechanical testing has also been performed at labs in Japan (Watanabe et al., 2017a, b; Goto et al., 2021a; Goto et al., 2021b), New Zealand (Rendel et al., 2021), and Iceland (Nono et al., 2020). Hydraulic fracturing experiments have been performed in granite samples at temperatures of 200-450 °C using water (Goto et al., 2021b) and $CO_2$ (Pramudyo et al., 2021). These experiments showed cloud or distributed brittle deformation at the grain-scale near the BDT.

There have also been a number of relevant geochemical experiments conducted to develop a suite of mineral-fluid thermodynamic properties for supercritical systems, fluid properties (Schultze, et al., 2022), and geochemical constraints (Hermanska, Kleine, and Stefansson, A., 2020). Quartz solubility in supercritical fluids is of great concern (Dobson et al., 2021) and has been investigated in the lab by Rendel and Mountain (2023), Saishu, Okamoto, and Tsuchiya, (2014), and Watanabe et al. (2021a).

A key component of state-of-the-art laboratory testing is monitoring of acoustic emissions (AE). For example, Ko et al. (2023) used AE to determine packing strength and crush resistance of proppants at temperatures of 320 °C. Goto et al. (2021b) used AE to measure the onset of rock failure difficult to observe by other means.

The durability of well construction materials at SHR conditions has been a concern since on-site testing at IDDP-1 was found to contain highly corrosive HCl and HF (Karlsdottir et al., 2014). Thorhallsson et al. (2020) performed a corrosion study of steels and alloys by testing materials in a simulated superheated geothermal environment (SSGE) in flow-through reactors. Vendors and service providers often test or certify their own equipment but are unlikely to test at SHR conditions until there is an identifiable market opportunity.

Most other lab tests have not been performed at SHR conditions, thus there are many gaps.

Gaps

Several types of test apparatus will be needed for the measurement of properties of rock, cement, and other downhole materials at SHR conditions (375-600 °C) as outlined by Petty et al. (2023):

- A comprehensive, worldwide survey is needed of the capabilities of existing laboratories and upgrade pathways to reach SHR conditions. Clean Air Task Force recently issued a nine-question survey to start this task (CATF, 2024).
- Lab measurements of fracture toughness and the effects of thermal shock on rock weakening.
- Robust measurement of the geomechanical properties of various rock types at high temperatures and pressures.
- Porosity, density, and permeability of various rock types as a function of temperature and pressure.
- Thermal properties – thermal conductivity, thermal diffusivity, thermal expansion, and heat capacity – of various rock types at high temperatures and pressures.
- Fluid/rock interactions – dissolution and precipitation in rocks and cements.
- Material properties - solubility, stability, strength, and thermal properties for materials such as cements, proppants, diverters, drilling fluids, tracers, and additives such as corrosion and scale inhibitors, treatment chemicals, friction reducers, foaming agents, and others.
- Mechanical properties of casing materials and casing components at very high temperatures and under stresses produced with thermal cycling.
- Downhole instrumentation and tools, such as logging instruments and cables, as well as methods for conveying and deploying downhole tools and instruments.
- Further laboratory study of the behavior of rock near the BDT. For instance, will the cloud fracturing reported by Goto et al. (2021b) have an impact on rock strength and fracture propagation in the field? What laboratory scale (if any) tests can be done to investigate?
- Quantification of the impact of phase transition (esp. through critical point) on flow properties of EGS fluids.

### 2.3 Site selection and characterization

Initial SHR EGS technology testing and pilot projects will be in known geothermal areas and developed fields that have significant geological, geophysical, and geothermal data and the potential to use wells of opportunity for technology testing at lower temperatures or deepening. Another advantage is that the local depth to SHR in a geothermal area could be shallower than 5 km, which is easily reached with conventional drilling methods.

Regional and global expansion beyond natural geothermal areas can start from global heat flow and depth to temperature maps (e.g. Figure 2). The resolution of continental or global maps will be necessarily coarse (~100 x 100 km), at a scale that does not even capture the shallow heat at many geothermal resources. Thus far more detailed geoscience site assessment will be required once a general area of favorable subsurface temperature has been selected.

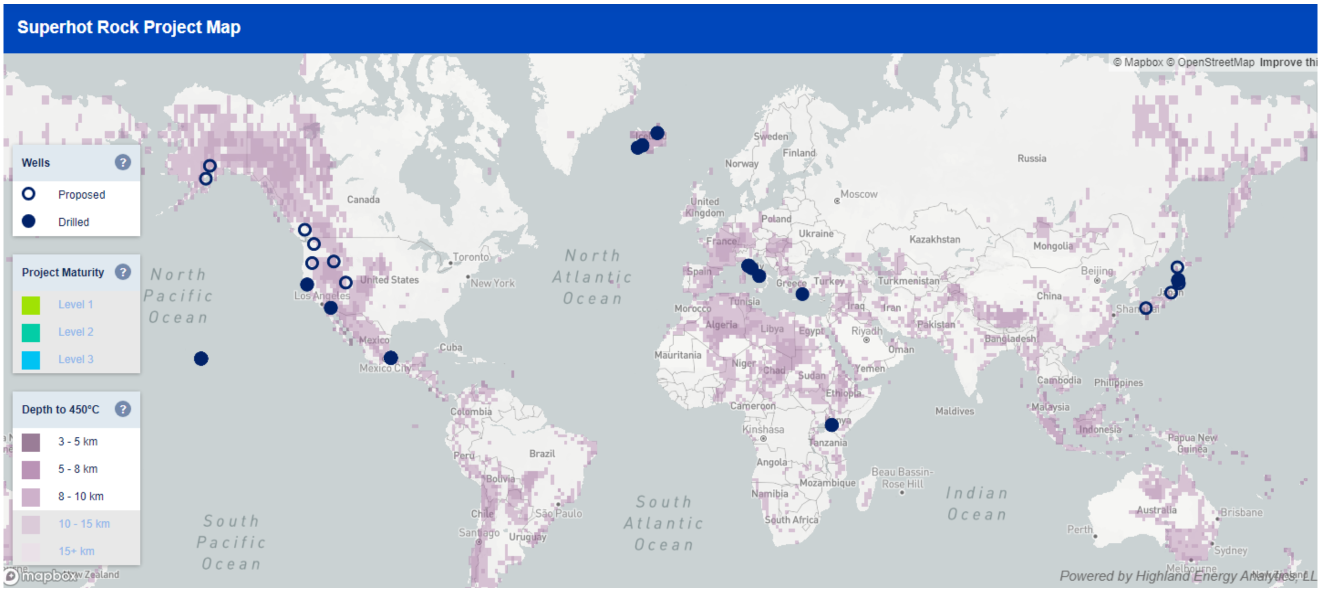


**Figure 2: Global map of areas with 450 °C rock at less than 10 km depth highlighted (Ball, 2022). Grid size is 1 degree x 1 degree (110 km N-S, 80 km E-W at 45° latitude)**

Geologic mapping, exploratory and offset wells, historical seismic data and tools like magnetotellurics, electromagnetic induction tomography, and active & passive seismic surveys will be used to find and characterize targets for SHR EGS projects. These geoscience surveys will provide the data for technical synthesis, seismic risk analysis, induced seismicity mitigation plans (Majer et al., 2016), geo-models, play fairway analysis (Kolker et al. 2022; Hjörleifsdóttir et al, 2023; Taverna et al, 2024), and fracture and reservoir models. Also important for SHR EGS project siting will be market analysis, off-taker identification, transmission, and community benefits.

Identifying supercritical fluids, magma, and other hazards before drilling remains challenging. For example, at Larderello, 2D and 3D active seismic survey data highlighted a deep seismic marker named the “K-horizon” that was hypothesized to be supercritical fluids based on the offset well San Pompeo 2 (Baccarin et al., 2019). However, this seismic marker was not found to be supercritical fluids when intersected by the deepened Venelle-2 well.

Passive microseismic arrays can be used for exploration, well siting, and stimulation monitoring of superhot and supercritical resources (also see §3.9). Ambient seismic noise tomography is being used to site the next IDDP (Iceland Deep Drilling Project) target in the Hengill geothermal field, SW Iceland (Sanchez-Pastor et al., 2021; Goertz-Allmann et al, 2023). In New Zealand, there have been a number of studies of the roots of the existing geothermal system in the Taupo Volcanic Field using 3D seismic tomography (Bannister et al., 2015) and MT (Bertrand et al., 2015). In Mexico, studies conducted as part of the GEMex project have characterized the architecture of the Los Humeros geothermal system (e.g., Norini et al., 2019).

Characterizing SHR EGS reservoirs after hydraulic stimulations will use the same geophysical methods (e.g., passive seismic monitoring, seismic tomography, etc.) used pre-drilling; therefore, collecting baseline data is critical for later data collection and interpretation.

Gaps

- Geophysical surveys and seismic monitoring continue to need validation through drilling.
- Reliable, drilling-validated geophysical signatures of SHR targets will reduce risk of SHR development and well targeting.

### 2.4 Directional drilling in SHR - Summary of current technologies

Drilling into SHR resources has already been accomplished by pushing the limits of existing geothermal drilling and well completion technologies. Drilling a vertical or near vertical well into rock above 500 °C has been accomplished with PDC or roller cone bits (Kruszewski and Wittig, 2018) without monitoring while drilling (MWD) or rotary steerable systems (RSS). The Prati 32 well at The Geysers was drilled to a bottom hole temperature of 400 °C using air drilling, but the final tricone bit only lasted 30.5 m, with reduced penetration rates (< 3 m/h), due to the extreme temperature conditions of the well, as air drilling does not cool the wellbore (Garcia et al., 2016). The DESCRAMBLE project on the Venelle-2 well reached a BHT of 507-517 °C at 2.9 km using fluids and rotary drilling (Baccarin et al., 2019). The last two drill bits were Stingblades, PDCs with conical diamond elements, that drilled at 4.0 and 9.2 m/hr and lasted 101 and 179 m (Baccarin et al., 2019).

Past casing failures in SHR wells have often been related to thermal cycling and cold-water quenching. For example, in Iceland, IDDP-1 and Hellisheidi-45 sustained damage to the shallow portion of the wells caused by emergency injection of cold water to prevent blowouts (Ingason and Árnason, 2022). IDDP-2 failed due to an incomplete cement job at 2300 m (Ingason and Árnason, 2022). Well completions that can withstand thermal cycling, either planned or unplanned, will be critical for constructing SHR wells that will last.

Compared to the SHR hydrothermal wells, such as IDDP-2, in which corrosive and abrasive fluids were encountered (Kruszewski and Wittig, 2018), SHR EGS wells are not expected to encounter significant volumes of harsh native fluids, so drilling may be somewhat easier. However, pressures in the BDT may be greater than in traditional hydrothermal wells (Fournier, 1991; Dobson et al., 2017), a knowledge gap that needs to be explored.

For SHR EGS reservoir creation, a key challenge for current technology is directional drilling at SHR conditions to maximize well length and fracture intersections in the resource. The well in the IDDP-2 project in Iceland was directionally deepened from 2500 to 4659 m in 168 days to a maximum measured temperature of 426 °C (Stefánsson et al., 2021). The project deployed a 300 °C directional drilling system developed by Baker Hughes using DOE funds (Dick et al., 2012) that employed MWD, and all-metal mud motor (M2M) (Baker Hughes, 2020). The well was deepened vertically to 2750 m, then inclination was built to and held at about 30° (Baker Hughes, 2020), although the plan had been to hold at 20° (Stefánsson et al., 2021). Unfortunately, this particular M2M technology has not been further developed or used.

In SHR EGS, there may not be a source lithology to follow. Instead, the reason for directional drilling of the first well will be to maximize lateral reach of a well in order to intersect or create more vertical fractures. For EGS development, various trajectories and inclinations have been proposed and drilled for EGS wells to maximize the number of fracture stages, increase connectivity, and minimize thermal breakthrough. These well geometries include subvertical (Cladouhos et al., 2016; Cladouhos et al., 2018), horizonal toe to heel (Shiozawa and McClure, 2014), and horizonal heel to heel (Norbeck et al., 2023a).

Fully horizontal wells may not be the most cost-effective and there is no requirement that wells be drilled along an isotherm, rather a well that gets hotter with depth may be preferable. But inclinations greater than 30° from vertical will likely be necessary. Directional drilling, MWD, and navigation will be critical in the second and third wells of a triplet in order to maximize intersection of permeability created in the first well.

Another recent demonstration is the use of Insulated Drill Pipe (IDP) at the Eavor-Deep well in New Mexico (Brown et al., 2023). IDP and mud coolers can be used to cool the well bore of a 350 °C well to 150 °C, allowing for the use of ordinary (elastomer dependent) MWD and mud motors (Ando and Naganawa, 2020). The Eavor-Deep well only reached 250 °C formation, so IDPs full advantage has yet to be tested in SHR (Eavor, 2023b). IDP will be even more effective when paired with continuous circulation and cooling systems at the surface as downhole temperatures spike quickly when circulation is broken for any reason.

Gaps

- Directional drilling in SHR has been demonstrated just a few times and is likely to be expensive and time-consuming. Serious investment and learn-by-doing will be needed to further reduce risks, costs, and drilling time.
- Due to the great risk to drillers and project success, measures to contain extreme pressures must be developed and implemented.
- Well completions that can withstand extreme thermal cycling from SHR production to cold-water quenching will need to be designed and tested.

**2.5 Well logging**

The most important downhole borehole logs in EGS are temperature, image logs, and sonic velocities. Active and passive seismic data collection in boreholes is discussed in section 3.9.

Measuring temperatures in the 375-500 °C range will be possible provided appropriate tools are selected. The HiTI project (Asmundsson et al., 2014) developed several new high-temperature downhole instruments, including a DTS system, a downhole analog wireline temperature tool, and a multisensory (T, P, spinner) downhole memory tool. In the DESCRAMBLE project, temperature logs were collected up to 517 °C (Baccarin et al., 2019).

Image logs, Acoustic Borehole Imagers (ABI) and/or Microresistivity Borehole Imagers (MBI), are used to characterize natural and induced fractures (depth, orientation, aperture, filling, etc.), and borehole stress indicators (breakouts and drilling-induced tensile fractures). These logs are critical to wellbore stability, wellbore trajectories, and stimulation design. The commercial versions of these logging tools can reach 175-180 °C. The Sandia BHTV (ABI) can reach 280 °C (Davatzes and Hickman, 2011), but the gain in temperature has a tradeoff in resolution. For wireline deployments, injection during logging or circulation through drill pipe in advance of logging can be used to cool a well hotter than these limits. Another option is to use LWD (logging while drilling or tripping) to cool the well, which resulted in a successful run of a full suite of logs down to a formation temperature of 500 °C in IDDP-2 (Stefánsson et al., 2021; see also Nabors , 2023). Interpretation of borehole images for *in situ* tectonic stresses must be taken with care as drilling and cooling wells will cause thermally enhanced drilling-induced damage to the wellbore walls (Permata and Tutuncu, 2019; Wallis et al., 2020a, 2020b).

Measuring stress magnitudes, specifically the minimum principal stress magnitude and orientation, is also important for stimulation design. This is done through an XLOT (extended leak-off test), which should be possible at SHR conditions but has not been performed.

Another challenge of measuring stress is that any one stress measurement may be nonrepresentative of the rock volume due to mechanical heterogeneities or structures. It is common in geothermal fields with critically stressed faults to observe large stress rotations across faults (Hickman et al., 2000). In low permeability EGS fields, this may not be an issue; however, so few stress measurements have been taken at depth that this risk is unknown.

Other traditional geophysical surveys such as dipole sonic logs, spectral gamma ray, compensated density, and neutron are typically limited to 260 °C.

Gaps

- Tools and methods to gather fracture and stress data (XLOT, image logs, etc.) must be extended to superhot conditions (i.e., 450 °C).
- The potential for variability of stress orientations at depth has not been evaluated due to limited stress measurement data at depth.

### 2.6 Hydraulic stimulation overview - Application

To maximize the chance of EGS success in all geologic and tectonic settings, the default plan for hydraulic stimulation should include zonal isolation and high-pressure stimulations. Whether the stimulation mechanisms expected are tensile fracturing or hydroshearing, zonal isolation provides the best chance for maximizing surface area and connectivity between two wells. The technologies needed for creation or enhancement of permeability in all rock formations can be divided into:

1. Wellbore completion, which can be subdivided into
    a. Zonal isolation on the outside of casing, and
    b. Zonal isolation on the inside of the casing.
2. Hydraulic stimulation, which can be subdivided into
    a. Fracture initiation,
    b. Fracture growth, and optionally
    c. Proppant emplacement

The technologies and tools used in O&G stimulations from these operations are generally designed for maximum temperatures of less than 200 °C so SHR stimulations will require different approaches. A potential exception to the 200 °C limit in O&G would be steam floods for EOR (i.e., as practiced in the Central Valley of CA and Alberta) (Zerkalov, 2015; Settari et al., 2018).

#### 2.6.1 Zonal isolation outside casing allows for multistage stimulation.

The current practice in O&G wells and recently demonstrated in geothermal operations at 230 °C at FORGE (Cariaga, 2023) and 190 °C at Project Red (Norbeck, et al., 2023) is to cement casing in the production interval to provide zonal isolation outside of the casing. At temperatures less than 200 °C, Ordinary Portland Cement (OPC) is sufficient; however, above 300 °C, advanced cements will be needed (Sugama and Pyatina, 2022). Calcium aluminum (CAC) or phosphate-based (CAP) cements have been lab-tested up to 400 °C (Sugama and Pyatina, 2022; Pyatina and Sugama, 2023; Sakuma et al., 2021) but have not yet been field-tested above 350 °C (Petty, 2022). A variety of cement blends were exposed to actual downhole conditions for 3-9 months in the Newberry 55-29 well. Analysis of the samples showed that OPC formulations suffered severe carbonation and weakening, while CAC and CAP performed well at 350 °C (Pyatina et al, 2023).

Even if cements can be developed to withstand superhot temperatures there will be challenges and disadvantages of cemented completions. A disadvantage of cementing may be the flow constriction at the well bore since fluid will only be able to flow into or out of wells past perforations. Another risk is that the cement slurry will invade fractures away from the well, effectively destroying the fracture permeability needed for EGS. A good cement job in conventional geothermal wells is notoriously difficult (Finger and Blankenship, 2012). A bad cement job will not provide zonal isolation, increasing the risk of drilling a useless well.

Conventional packers and bridge plugs that use polymer sealing elements will not be suitable in SHR wells. At FORGE, these tools failed at 200 °C (EGI, 2020). Liners and serial all metal external casing packers have been designed for 330 °C and 6000 psi with plans for 10,000 psi and >400 °C (Esquitin and Vasques, 2021). The most cost-effective approach to well isolation may be to develop methods that do not require steel and cement. Open hole stimulations have been performed up to 320 °C (Cladouhos et al., 2015; Cladouhos et al., 2016), although a perforated liner (uncemented) was eventually needed. Other approaches to eliminating liner installation include mineral coating, such as RockPipe (Eavor, 2023a) or vitrification (Houde et al., 2021), installed after or during drilling.

Gaps

- Development and testing of cements and steel designed to withstand SHR conditions.
- Advanced cements need to be used and evaluated in SHR wells.
- Test alternative methods to provide zonal isolation behind casing, such as mineral coating, or advanced materials to fill annular space.
- Further development and testing of external casing packers for T >400 °C

2.6.2 Zonal isolation inside casing

In addition to zonal isolation outside of the casing or liner as described above, there must be methods to isolate zones on the inside of the casing to focus flow rate and pressure to a selected treatment zone. In O&G well stimulation, this is provided by plugs and balls or sliding sleeves. In principle, there is no reason that these tools cannot also be used at SHR conditions if all metal tools can be designed.

Other methods to isolate inside the casing include sequential filling of the casing with sand (sanding back) to temporarily block already stimulated zones, or diverters such as TZIM (Cladouhos et al., 2016).

Vendors and service providers often test or certify their own equipment but are unlikely to test at SHR conditions until there is an identifiable market opportunity.

Gaps

- Testing of all methods and tools at SHR conditions, first in labs (see §3.2) and then in the field.

2.6.3 Fracture initiation

Plug-and-perf hydraulic stimulation has been demonstrated up to 190 °C (374 °F) (Norbeck and Latimer, 2023), however, this is expected to be near the maximum operational temperature for this approach using current off-the-shelf technology. Therefore, a different approach may be needed for SHR, at least until service companies develop tools for SHR and cements are developed for these temperatures (see above).

Using a high-pressure stream of water and abrasive, hydro-jetting can be used to perforate holes into hard formations which will create a weak point in the well for fracture initiation (Bour and Petty, 2016). This tool is SHR-ready because there are no temperature-vulnerable components and the jetting keeps the tool and well cool.

Other approaches to fracture initiation and growth include thermal shocking, acids (Lucas et al., 2020), chelating agents (Watanabe et al., 2021b), and targeting natural fractures.

Gaps

- Due to the importance of scale, it will be difficult to test any fracture initiation methods anywhere but in SHR wells and SHR EGS demonstration projects.

2.6.4 New fracture growth

Hydraulic stimulation and tensile fracture growth in rock below 200 °C is a complex but relatively well-understood process. Modern shale wells typically have flowing fracture surface areas at the scale needed for sustainable heat mining (i.e., $9 \times 10^6$ $m^2$) (McClure, 2021). With successful zonal isolation and fracture initiation as described above, the new fracture growth stage of a hydraulic stimulation relies on the hydraulic pumping power provided by pumps, and proppant to keep the main fractures open after the pressure is removed. Additional permeability enhancement and connectivity may be achievable using lower-pressure hydraulic stimulation, aka, hydroshearing (Cladouhos et al., 2011; Cladouhos et al., 2016). The goal of all of the above is to maximize fracture length, well spacing, and total surface area of fractures, all of which have a direct impact on power generation and sustainability.

For EGS projects, a reservoir length or well spacing goal of 500 m has been commonly adopted. To date, much smaller well spacing has been achieved, such as 120 m (Fercho et al., 2023). Yet this is the most important input to calculate thermal breakthrough times and well-pair sustainability.

Gaps

- No one has performed hydraulic stimulations at high or moderate pressures in SHR, thus the geomechanics of rocks near the BDT, thermal cracking, and the effect of the unusual properties of supercritical fluids have not been field tested.
- Maximum fracture length induced by stimulations in SHR EGS represents a critical knowledge gap due to the impact of supercritical fluid, BDT, thermal fracturing, and intragranular fracturing. Results from models and lab testing (see above) may

provide useful predictions; however, until field tests in actual SHR wells are performed and documented, potential fracture size in SHR EGS reservoirs will remain one of the most important unknowns.

2.6.5 Fluids, proppants, and fracture transmissivity

Like hydraulic fracturing in O&G, the fluid most likely to be used to create hydraulic fractures in SHR EGS stimulation will be water. The water need not be potable and can be re-used for circulation once the EGS reservoir is created. Additives commonly used in conventional geothermal fields and hydraulic stimulations, such as acids, friction reducers, and scale inhibitors, will likely be needed. Given the extreme temperatures, the additives will likely not be the same as those in current use. In the first author's experience in the geothermal industry, the use and composition of any additives pumped into the subsurface during geothermal drilling, stimulation, or long-term injection are disclosed and reviewed by both federal and state regulators, which may not be the case in the O&G industry.

In some cases, salts such as NaBr and NaCl might be useful to increase the density of the water column and, thus, the downhole fluid pressure (Hogarth and Holl, 2017) during fracturing.

Alternative fracturing fluids such as compressed, supercritical $CO_2$ may be effective in the stimulation of very hot rock. Hot wet $CO_2$ would be very corrosive and could help to dissolve and etch the rock to preserve open fractures without proppants (Petty et al., 2020). However, care would need to be taken as hot wet $CO_2$ would also be detrimental to any steel casing.

Proppants must be strong, resistant to crushing, and chemically stable at SHR conditions. Quartz sand, sintered bauxite, resin-coatings, and ceramics have been tested up to 320 °C (Jones et al., 2014; Lisabeth and Norbeck, 2020; Ko et al., 2023) but not in SHR conditions. Based on basic mineralogy, it is expected that these proppants will alter at SHR conditions, resulting in significantly reduced fracture permeability. However, the right material selection (Ko et al., 2023), and/or adjustment of working fluid composition (Jones et al., 2014) may provide a solution for proppant longevity in fractures. Diverter materials in the slurry, including thermally degradable zonal isolation materials (TZIM), may be useful to prevent leak-off, extend fractures, and facilitate proppant transport and placement (Petty et al., 2022). An alternative to the use of proppants would be to operate at fluid pressures high enough that fractures are hydro-propped; that is, the operating injection pressure would be significantly greater than the magnitude of the minimum horizontal stress. The economics of hydro-propping at resource temperatures from 175-350 °C were modeled by Frash et al. (2023a; 2023b). Technically, operating at high pressures is feasible; for example, the Habanero well pair in the Cooper Basin, Australia, produced 19 kg/s of 215 °C water with a production wellhead pressure of 32 MPa and an injection well pressure of 43 MPa (Hogarth and Bour, 2015).

Related to proppant and alteration is the initial fracture transmissivity (often called fracture permeability, which is not technically accurate) and its evolutions with time and flow. Very little is known about this topic at SHR conditions so it represents a large gap for both laboratory and field studies.

Lastly, tracers are key tools to characterize pathways between wells. Napthalene sulfonates, a standard conservative tracer used at lower temperatures, are thermally unstable above 350 °C (Sajkowski et al., 2021); therefore, SHR-durable tracers will need to be developed.

Gaps

- Research and development of non-toxic additives to prevent scale, reduce friction, and enhance flow rates at SHR conditions.
- Proppant placement and chemical, thermal, and mechanical durability at SHR conditions. A wide range of proppants and fluids should be tested in flow-through reactors developed for SHR testing (also see section 3.2).
- If proppants cannot be developed to withstand the heat, are there other methods (high-density fluid, hydropropping, chemical treatments, or others) to create and maintain permeability?
- Will fracture permeability increase or decrease with time? Factors causing a decrease will include fracture closure, proppant dissolution, and precipitation. Factors causing an increase will include thermal cooling, host rock dissolution, and fluid channeling.
- What tracers can be used at SHR conditions?

### 2.7 Induced seismicity

Induced seismicity has been a major concern for EGS for decades (Majer et al., 2007; Cladouhos et al., 2010). The DOE has developed a robust Induced Seismicity Mitigation Protocol (ISMP) for US projects (Majer et al., 2012; Majer et al., 2016), and operators have experience implementing them in EGS projects since the ISMP was developed and tested (Cladouhos et al., 2016; Norbeck and Latimer, 2023). Expertise in minimizing induced seismicity has also been developed in the Rhine Graben projects (Shapiro, 2015; Richard et al., 2016) where some projects initially caused felt events at Basel (Baisch et al., 2009) and Soultz-sous-Forêts (Dorbath et al., 2009). A notable exception to the progress in preventing induced seismicity occurred in 2017 in Pohang, South Korea, when a Mw 5.4 earthquake was likely caused by injection in a critically stressed fault (Kim et al., 2018). Possibly the most important lesson is that EGS projects in urban areas like Pohang and Basel should be avoided until a method to identify blind, critically stressed faults in advance of well stimulations is developed.

It has been suggested that reservoir creation near the brittle-ductile transition will reduce seismic risk (i.e., Japan Beyond Brittle, Muraoka et al., 2014), and areas with high temperature gradients (>100 °C/km) where the first SHR projects will be tested, correlate with areas of low seismic risk due to thinner brittle crust and high heat flow. It is documented that the Ridgecrest earthquake swarms of 2020 were suppressed in the Coso geothermal area (Kaven, 2020). However, seismologic observations and numerical models suggest many earthquakes nucleate at depths of 7-10 km in rocks near the BDT (i.e., Chen and Molnar ,1983; Lapusta and Rice, 2003) and others argue that SHR EGS may be prone to enhanced seismicity (Parisio et al., 2019a), so this idea needs further testing.

Gaps

- Better understanding the geomechanics in the brittle-ductile transition. Given that the zone does not transmit S waves as readily will it have an impact on reducing seismic risk?

- Investigating whether induced seismicity due to cold fluid injection migrates downward as modeled by (McClure, 2023b). Can seismic data from geothermal injection programs (i.e., Hartline, Walters and Wright (2019)) be used to test the hypothesis?

### 2.8 Diagnostics and characterization

To model, target, and manage a SHR enhanced geothermal system, the native state and final state of the rock volume must be well-characterized. Not only will this result in a higher likelihood of success, but it will also reduce hazard and investment risk and increase public confidence. There are many geothermal, geophysical, and well engineering methods for measuring properties and changes in the earth's crust and geothermal reservoirs. This is a very large subject worthy of another full report; we present some highlights of the state-of-the-art and no gaps.

Microseismic monitoring has been used since Fenton Hill to image EGS reservoirs and fracture systems (Majer and Doe, 1986; Fehler et al., 1991). Since then, a wide variety of microseismic monitoring techniques have been used in geothermal field characterization and EGS projects. Seismic data is used for well targeting, induced seismicity mitigation plans, determining stress from focal mechanisms, and tomography to measure changes in elastic moduli.

At the Newberry Volcano EGS Demonstration, the microseismic array (MSA) deployed 8 shallow (~250 m deep) BH sensors to reduce surface noise and increase coupling to saturated bedrock and 7 surface sensors to provide focal sphere coverage for moment tensor analysis (Cladouhos et al., 2016). Another approach to surface and near-surface MSAs is a large-N nodal array to stack time data and create coherent signals (Edwards et al., 2021; Zhang et al., 2022).

Downhole geophone arrays commonly used in O&G hydraulic fracturing jobs have had limited success in geothermal fields due to the relatively low temperature tolerance of geophones and high shallow temperatures in geothermal fields. At FORGE Utah, a distributed acoustic sensing (DAS) fiber optic (FO) array installed in a 985 m deep monitoring well outperformed borehole geophones for locating microseismic events (Lellouch et al., 2020). An even more effective approach is to install DAS-FO sensing arrays in multiple wells (injectors, producers, and monitoring wells) at reservoir depth (Norbeck and Latimer, 2023; Titov et al, 2024). An extra benefit of installation of fiber optics in reservoir or near-reservoir depths is the ability to also perform distributed strain sensing (DSS) (Norbeck and Latimer, 2023; Ward-Baranyay et al., 2023; Titov et al, 2024). While distributed acoustic sensing fiber optic arrays have only been used up to 200 °C, AFL has recently developed a 500 °C gold-coated FO cable (AFL, 2023) which could be used in SHR wells in the near future.

Other geophysical methods that may be useful for EGS characterization are INSAR (Mellors et al., 2018), gravity modeling (Bonneville et al., 2017), and magnetotellurics (Pauling et al., 2023). Finally, well testing will be crucial to the characterization of any EGS, including pressure monitoring, pressure transient analysis, circulation testing, tracer testing, etc. (Horne, 1995).

## 3. PROPOSED PATHS FORWARD

The gaps in technology and knowledge for SHR EGS reservoir creation listed in Section 2 are broad and multidisciplinary. Part of the solution to solving the challenges of producing SHR is one of system integration. Many of the pieces may be out there, but scientists, engineers, and service providers around the world may not yet know that they hold knowledge and technology that can transform geothermal energy. Two obvious examples where outreach and education could provide new insights for SHR geothermal are earth scientists and engineers in the O&G industry and academic institutions.

The tools of the shale revolution, horizontal drilling and multistage fracturing, proppants, and microseismic monitoring, are now being applied to geothermal projects at temperatures below 230 °C. Extending those tools and methods to SHR conditions will be one pathway to filling some of the gaps needed for SHR geothermal. However, many innovations needed for SHR geothermal may come from groups not working on hydraulic fracturing; for example, service companies working on steam floods, in situ pyrolysis, and deep-water fields may have the needed technology.

Geologists and geophysicists have been studying rocks on both sides of the BDT for many years and can bring many insights to the challenges likely to be encountered in SHR development. To identify geochemical and geomechanical nuances of fluid-rock interaction at the BDT, Cladouhos and Callahan (2023) briefly reviewed the extensive literature on magmatic and metamorphic systems that have been very well studied due to the occurrence of ore deposits and orogenesis. Professional and academic economic geologists, metamorphic petrologists, volcanologists, and structural geologists contain a deep knowledge of SHR systems, but relatively few have engaged in geothermal or SHR research. In the US, more collaboration between researchers normally funded by NSF (National Science Foundation) and those normally by DOE would yield tremendous benefits.

One of the most effective approaches to system integration is public investment in demonstration projects. In countries with strong geothermal industries and government support (Iceland, Italy, New Zealand, and Japan), there is ongoing support for superhot geothermal both at the system integration and targeted funding levels. The latest funding opportunity for EGS pilot projects (which includes funding for a SHR EGS demonstration) from the US DOE (DOE, 2023), summarizes the learnings and objectives of pilot demonstrations as follows:

- "exemplars, proving reliability and performance ultimately de-risking the technologies,"
- "experiments from which to learn, because upscaling typically identifies new problems that are not apparent at smaller scales and allows the community to settle on a 'dominant' design," and
- "opportunities for collaboration, such that best practices can be established, and processes can be standardized and improved."

In planning and executing demonstration projects, gaps not anticipated during the proposal writing phase will be revealed. It is important that funding agencies recognize that to maximize successes and learnings from demonstration projects, additional secondary funding for data analysis, tools development, and new collaboration will be necessary. For example, a gap discovered during a demonstration project on one continent might be best solved by a collaborator on a different continent.

Public investment will be essential to bring SHR geothermal projects to fruition in a timeframe that could be useful to address issues such as greenhouse gas mitigation and energy security. Bridging the gaps identified in this paper will require significant financial commitments globally to support investigations at academic institutions, national laboratories, and public-private partnerships. Such investment will result in reducing risk for further investment of venture capital. Moreover, early projects will need to occur where the heat is relatively shallow. This will inherently be a global endeavor. Projects in Iceland, Italy and elsewhere funded under the European Union's Horizon 2020 program provided foundational groundwork in the drilling of supercritical geothermal systems and spurred several drilling projects that resulted in significant learnings and technologies in turn. The Iceland Deep Drilling Project (IDDP) has drilled two superhot wells, IDDP-1 and IDDP-2, and is planning a third. The learnings from this two-decade-long project on drilling, well completion, corrosion, etc., have been immense, and the extensive published literature will be invaluable for future SHR projects worldwide. The DEEPEN project is an EU-funded project with a global team with the goal of developing a methodology to explore and characterize superhot and supercritical geothermal plays (Kolker et al. 2022; Hjörleifsdóttir et al, 2023; Taverna et al, 2024). International collaborations like these should be encouraged and continued. For example, an annual international workshop with a narrow focus on SHR geothermal with a broad invite list to include scientists and engineers with expertise across the gaps would serve to facilitate the interdisciplinary and international collaboration needed to develop solutions and fill gaps. Ideally, these workshops would be hosted at potential SHR sites (i.e., in Japan, Iceland, Italy, New Zealand, Oregon, California).

Public funding for geothermal field projects commonly requires public and technical outreach to share results and build support for geothermal. Recent US examples being the FORGE project (https://utahforge.com/outreach/), and the latest funding opportunity for EGS pilot projects from the DOE (DOE, 2023). In New Zealand, a new research program highlighting supercritical geothermal resources has an excellent public-facing website (https://www.geothermalnextgeneration.com/)(Chamberfort, 2023). Even privately funded companies are sharing their results publicly and transparently (Eavor, 2023b; Norbeck and Latimer, 2023), a notable change compared to traditional geothermal operators who often treat internal data as proprietary. Many online tools are now available for paper, internal report, and data sharing such as the USDOE's Geothermal Data Repository (https://gdr.openei.org/); however, the US focus leaves out the many advances in the EU and Japan (which have their own data sharing sites).

## 4. CONCLUSION

High enthalpy superhot rock EGS presents a promising path to scale clean, firm, cost-competitive geothermal electricity production worldwide, but significant scientific and development uncertainty surrounds these resources. In this paper, we discussed the technologies needed to create SHR reservoirs and describe critical gaps ripe for public and private funding necessary to break down potential roadblocks.

A key conclusion is that solving the challenges of creating and producing SHR geothermal reservoirs will require international and multidisciplinary collaboration, system integration, and demonstration projects. The scope of the challenge invites partnership, not just between geothermal and oil and gas operators, but also with those that offer broader expertise in deep, higher temperature systems, such as economic geologists and metamorphic petrologists, and engineers and labs that routinely work beyond the critical point of water.

Although superhot rock geothermal will push the limits of many subsurface tools and is beyond the bounds of current hydrothermal and EGS projects, it should be noted that humans safely and routinely operate equipment that contains materials above 375 °C. Coal power plants burn at 550 °C, nuclear power plants at 700 °C, and pizza ovens at 400 °C. That is, we can engineer equipment to access, contain, and extract energy from the global SHR resource - engineers and scientists need the incentive to do so.

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