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Ultra Hot - Supercritical Geothermal - IEA Geothermal Collaboration

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ABSTRACT

Several member countries of the International Energy Agency Geothermal Technology Collaboration Program are actively undertaking research into the deep, high-temperature roots of geothermal systems, which potentially host supercritical or 'ultra-hot' geothermal fluids. The work is focused on: delineation and identification of locations of ultra-hot geothermal resources that might be prospective and accessible by drilling; advancing technology to enable reliable energy production from the high temperature prospects; and the evaluation of the energy that might be available long term in support of the low carbon energy futures that member countries are actively pursuing. This paper discusses these aspects, in relation to some of the ultra-hot projects, seeking to share knowledge acquired, inform interested parties and direct future enquiry.

The large energy in place in these 'deep roots' is undisputed. The aspects that remain to be worked through, apart from resource identification and delineation, are developing reliable technology that can be used in the energy production infrastructure and developing appropriate regulatory regimes that provide adequate certainty to support the investment needed.

Work on this topic undertaken by Working Group 12 of the Geothermal Technology Collaboration Programme is described in the paper, including how the activity of the group is helping advance this area of novel geothermal energy technology development. Recent advances have seen significant improvements in knowledge of the geochemical and physical conditions to be expected in these ultra-hot settings through experiments in fluid-rock interactions and advanced simulation models.

1. INTRODUCTION

'Ultra-hot' temperatures above the critical point temperature of 374 ºC have been encountered in deep drilling projects in several countries, including Iceland, Italy, Japan, Kenya, Greece, USA and Mexico, and some have even drilled into molten rock or magma, but few drilling projects have confirmed both fluid pressure and temperature conditions that are higher than the critical point (22 MPa and 374 ºC for pure water). The International Energy Agency Geothermal Technology Collaboration Program (IEA-Geothermal, Working Group 12, Bromley et al, 2020) has members actively collaborating and undertaking research into the deep, high-temperature roots of geothermal systems, which potentially host either supercritical or 'ultra-hot' (at subcritical pressures, but temperatures > 374 ºC) geothermal fluids (Figure 1).

Issues and questions to be considered when assessing the potential for exploration and development of the 'deep roots' of geothermal systems containing these supercritical or ultra-hot fluids include :

a) Reservoir properties: What temperature range, permeability range (seismicity & ductility), recovery factor range, cut-off values, and fluid chemical properties (e.g., acidity, mineral concentration) are appropriate for an ultra-hot resource capacity assessment?

b) Geophysics data: What role do the following geophysical methods play in an assessment: MT (resistivity), magnetics (Curie Point depth), gravity (density and topographic stress), seismic (reflections, P /S wave velocity tomography and attenuation), and geodetics (creep, inflation & deflation)?

c) Resource modelling: At a conceptual level, what knowledge is required for planning sustainable operations (>100 years)? What resource volume is required per 100 MWe development project? What heat input is needed into the base of the reservoir, and heat output from the wells at the surface? What assumptions most strongly affect sustainability including: heat in place per unit volume, acceptable temperature change over the project life (perhaps -10 ºC), and appropriate recovery factors (perhaps 20%)?

d) Development strategies: What options might there be, for example, production of the hottest deep supercritical fluid then injection into shallow and peripheral sub-critical aquifers, or fluid injection at ultra-hot reservoir depths with enhanced production from shallower depth aquifers?

e) Engineering challenges: Including: appropriate materials for pressure containment that achieve adequate well and plant longevity, procedures for cementing well casings, managing well expansion with temperature change, how to initiate well flow, well bore geochemical deposition and the appropriate process plant for energy transformation.

f) Regulatory issues: How do regulators adjust policies, without inadvertently imposing excessive compliance costs, for: 1) diffusive (or fuzzy) 3D resource boundaries, 2) the need for flexibility so learnings through time can lead to adaptation, 3) management of land access over desirable resource volumes, and 4) management of possible resource interference between users (proving cause and effect when there are multiple tappers).

In the following subsection (1.1) we high-light and summarize some recent "ultra-hot" and related deep geothermal projects around the world, and then in sections 2, 3 and 4, we share and discuss information on development aspects and the main challenges associated with resource delineation, appropriate regulations, engineering challenges, and geochemical issues.

1.1 Recent and Current Projects

a) The IDDP Iceland Deep Drilling Project (Iceland, 2000 – ongoing) aims to find out if it is economically feasible to extract energy and chemicals out of hydrothermal systems at supercritical conditions. Advanced drilling technology has been applied (Fridleifsson et al, 2017) and novel fluid handling and evaluation systems designed (Einarsson et al, 2015). The IDDP-2 well was able to go beyond the critical point for the saline geothermal waters deeper in the Reykjanes reservoir encountering a temperature of 427°C at depth of approximately 4600m (Ingason et al, 2020, Weisenberger et al, 2019).

b) The DEEPEN project (USA, Icelandic and European partners, 2021-2024) aims to DErisk Exploration for geothermal Plays in magmatic ENvironments, that is, increase the probability of success when drilling for geothermal fluids in magmatic systems, through the development of improved exploration methods and frameworks for the joint interpretation of exploration data using a Play Fairway Analysis methodology (www.or.is/en/about-or/innovation/deepen/).

c) The FORGE (Frontier Observatory for Research in Geothermal Energy, Utah, USA) program is designed to assist in enabling the building of large-scale, economically sustainable Enhanced Geothermal System (EGS) systems for heat extraction from underground formations. This project is now into phase three at the Milford site in Utah, with well drilling a significant part of the work. Near term goals aim to perfect drilling, stimulation, injection-production, and subsurface imaging technologies required to establish and sustain continuous fluid flow and energy transfer from an EGS reservoir (Moore et al, 2021).

d) The Clean Air Task Force (USA), operating for over 25 years, has a focus on decarbonising the energy system. They have recently commenced activity in super-hot rocks and deep geothermal, and are looking to have three phases to their super-hot rocks activity: Phase 1 is developing technology, including drilling 3 to 7 km wells; Phase 2 is commercial deployment, whilst also extending the reach of drilled depths to 10km; and Phase 3 aims to unlock super-deep geothermal across the globe at depths of 10-20 km.

e) Development of Subduction-Origin, Supercritical Geothermal Resources (Japan), has been progressing since 2017, through the New Energy and Industrial Technology Development Organization (NEDO). They are seeking to utilize 400 to 500°C supercritical fluid at a depth shallower than 5km. Earlier work suggested supercritical geothermal resources may exist in/around many of the volcanic zones in Japan, with the potential of possibly several tens of gigawatts. 2040 is targeted for the operation of a pilot plant. The first phase of the project was completed in 2020 and the second phase began in 2021 to select a region for deep drilling in the third phase (Asanuma et al, 2020).

f) Newberry Super-Hot EGS Project (USA) proposes an EGS proof of concept at a location where very hot rocks are close to the surface (~5 km). Drilling into the brittle-ductile transition aims to test the efficiency of thermally induced fracturing and reservoir creation as well as the development of drilling techniques and borehole instrumentation adapted to high temperature (Bonniville et al, 2020).

g) The Krafla Magma Testbed (KMT, Iceland) project aims to establish research infrastructure able to access a magma chamber and initiate a 30-year scientific programme for observations and experiments in magma dynamics, volcanic risk, and "extreme" geothermal energy (Hersir et al, 2020).

h) GEMex (EU, Mexico), a collaboration effort between Europe and Mexico (2016-2020), was funded by the European Commission through Horizon 2020, and worked to research the potential use of two types of "unconventional" geothermal resources in Mexico; an Enhanced Geothermal System (EGS) at Acoculco, and the Super-hot Geothermal System (SHGS) at Los Humeros.

i) DESCRAMBLE (Italy) was an international project (2015-2018), undertaken within the Larderello geothermal field in Italy, which aimed to encounter supercritical geothermal conditions. The Venelle-2 well, a dry well drilled to 2200m was extended as part of the project to 2810m encountering temperatures of more than 500°C. (Bertani et al, 2018)

j) DEEPEGS (EU) was a European Horizon 2020 project (2015-2020) aimed to demonstrate the feasibility of EGS for delivering energy from renewable resources within Europe (Bruhn et al, 2018). Three different resource systems were selected to represent different locations and geological formations in Europe.

k) Geothermal: The Next Generation (GNG, New Zealand, 2019-2024) is a research project that strives to explore and understand New Zealand's supercritical geothermal resources by addressing geological, geophysical, geochemical and technological challenges, and integrating this knowledge to decarbonize industry and power sustainable economic growth opportunities for future generations, The tasks include modelling reinjection of non-condensable gases, investigation of high-temperature tracers, laboratory studies of super-critical fluid-mineral equilibria and modelling the interface between molten rock and circulating super-critical fluids (www.geothermalnextgeneration.com).

In addition to the above selection of projects, there are a range of international collaborations and consortia based on shared research and development interests:

• The EU GEOTHERMICA conglomerate with activity now incorporated into the European Partnership on Clean Energy Transition (CETP).

• The Geothermal Research Cluster (GEORG) which aims to promote research and development of geothermal resources in a sustainable way and contribute to reducing the world's dependence on carbon-based energy sources.

• The International Energy Agency – Geothermal Implementing Agreement (IEA Geothermal, Working Group 12) 'Deep roots of volcanic geothermal systems' which annually produces reports that document activity in ultra-hot geothermal.

• The International Partnership for Geothermal Technologies (IPGT) which aims to accelerate the development of geothermal technology through international cooperation.

2. SUPER-CRITICAL GEOTHERMAL RESOURCE ASSESSMENTS

Methods for super-critical resource identification and delineation are under development through ongoing research. They rely on fluid and host rock properties that can be imaged remotely using geophysical tools, combined with local geochemical, geological information and well-bore data where available. The resource depth and thickness accessible by drill-holes is dependent on drilling technology development. Knowledge acquired through international collaboration and sharing of information on depth and delineation parameters is discussed below.

2.1 Depth extent

In the United States, the results of deep drilling into superhot conditions (deep roots) were summarized in Stimac et al (2017). Using current drilling technology, Uddenberg (2020) assessed that the depth limit for superhot resources (>374 ^{o}C) is about 7 km. New technology would be required to drill viable boreholes below this depth. In other countries, such as New Zealand and Japan, a depth limit for drilling of about 5 - 6 km has been assumed (Bignall & Carey, 2011, Okamoto et al, 2020). Where permeability can exist naturally, such as above or beside magma chambers, or within tectonically active regions, then the thickness of the potential ultra-hot resource is limited only by the temperature range over which the rock can sustain fractures (i.e., extending down into the brittle-ductile transition zone) as discussed, for example, in Watanabe et al (2017). Where natural permeability is not present, then EGS technology to stimulate or create new fractures is required.

2.2 Resource delineation

Where there is limited information from drilling, one approach to superhot resource delineation has been to undertake a prioritization exercise, wherein the most favorable sites for further exploration are identified using probability maps. A layered GIS method, incorporating all the key parameters (e.g., heat, permeability and fluid) collectively increases the chances of a successful deep drilling project. In some areas, this is undertaken using the "Play-Fairway" approach (e.g., within the USA at Mt Baker and Mt St Helens, Washington State (Steely et al, 2021), and in Hawaii (Lautze et al, 2020)). Several key geo-scientific databases are used to incorporate information about resistivity, density, and stress-state with respect to depth, that are then used in the probability formulations. Magneto-telluric resistivity models (to about 10 km depth) are interpreted to indicate the presence of geothermal fluids and/or partial melt zones. Interpreted models of density and magnetic susceptibility from gravity and magnetic survey data (e.g., analysis of Curie Point Temperature versus depth) are combined with 40Ar/39Ar geochronology for relative ages of intrusive and extrusive volcanics, to constrain fault locations, stratigraphy and geometry of potential heat sources and their surrounding fluid convecting systems. Passive seismic arrays help with detection of active fracturing (permeability creation) linked to seismicity, in accordance with the local critical or non-critical stress state. A combination of 3D active seismic surveys, natural seismic tomography and ambient noise tomography provides data to help develop detailed seismic velocity (Vp, Vs, Vp/Vs), and seismic attenuation models. These have helped constrain cross-sections and conceptual models of other physical properties, which, in turn, are used to identify and delineate likely supercritical fluid resources.

In Europe, a similar probability approach is described in Manzella et al (2019) as part of the IMAGE project. Although regional in scope, the best information originated from Italy and Iceland. Favorable indicators for the presence of super-critical or superhot resources include the assumption that these resources surround magmatic intrusions in the shallow crust that are still hot enough. The most likely tectonic settings are subduction zones, mid-ocean spreading ridges, and volcanic rifts or extensional basins (zones of crustal thinning). Identifying areas where super-hot temperatures are likely, involves constructing crustal thermal models. The main indicators are:

a) the depth to the 400 ^{0}C isotherm (largely from borehole temperature data but also, in places, magnetic data revealing the Curie Point depth);
b) crustal thickness (largely from seismic data, indicating the depth of the MOHO discontinuity, i.e., the boundary between the Earth's crust and the underlying mantle);
c) earthquake density; and
d) the estimated depth to the brittle ductile transition (BDT).

A combination of BDT depth and earthquake density provides an indication of geodynamic conditions favorable to shallow magmatic emplacement. Using GIS layers, a "favorability" map of geothermal resources at super-critical conditions was then obtained. The authors found that other geophysical data, such as resistivity, gravity and seismic velocity tomography are useful for local studies but tend to be too sparse for the Europe-scale regional mapping study.

In Mexico, an assessment of the potential high temperature roots (super-hot reservoir conditions) was addressed in the GEMEX project, in particular at the Acuculco and Los Humeros geothermal systems (Guerrero-Martínez et al., 2019). Lucci et al (2020) analyzed the anatomy of the Los Humeros magmatic plumbing system using petrological and thermo-barometric studies which suggested magma transport between multiple interconnected magma storage layers within the crust. These occur between about 30 km and 3 km depth. Rather than the previously assumed single voluminous chamber of magmatic melt, deeper chambers of molten basalt are inferred to feed up into progressively shallower and smaller (ephemeral) magma chambers within the shallow crust. This has implications in terms of heat transfer, ductility and permeability of rocks, particularly those surrounding the smaller and shallower chambers, which might host super-critical fluids.

In Japan, the results of a supercritical and ultra-hot geothermal resource assessment research project have recently been reported in a Special Issue of Geothermics Journal (Asanuma and Bromley, 2022). Geophysics (especially MT resistivity and seismology) has played a major role in determining the likelihood of successfully encountering super-hot resources. In addition, geochemical studies have addressed the issues of gas content in the supercritical vapor and the potential for silica deposition to provide a permeability cap for containing the supercritical reservoirs.

3. APPROPRIATE REGULATIONS

As noted in annual reports from several IEA Geothermal partner countries (www.iea-gia.org) there is a need to develop appropriate regulations that support and deliver permits that enable exploration and then ultimately facilitate reservoir production and injection operations. Environmental effects and social impact assessments will address relevant environmental issues, similar to effects associated with conventional geothermal projects, along with relevant volcanic aspects that may be associated with tapping into ultra-hot reservoirs located closer to magma bodies. Individual site-specific aspects of a supercritical resource project, both surface and sub-surface, are expected to influence the degree of complexity in obtaining exploration and development permits.

4. ENGINEERING CHALLENGES

Challenges ahead for wide-scale deployment of these ultra-hot resources include engineering issues. The aspects relate to drilling, setting and cementing casing, downhole measurements of the fluid and rock stress state under the high temperature reservoir conditions, and constructing wells that produce reliably and achieve an economic operating life.

Some of these challenges were partially addressed in the DESCRAMBLE project at Larderello (Bertani et al 2018) and the IDDP drilling in Iceland (Ingason et al 2020). Reservoir simulation and conceptual modelling challenges were discussed in, for example, Scott et al (2015), Driesner et al (2020), Ingason et al (2020) and Yapparova et al (2020).

As part of the recent Japanese research effort (see Asanuma et al, 2022) corrosion rates of casing materials during supercritical geothermal development were predicted and compared with observations. The corrosion rate at subcritical conditions (300 ^{o}C) was found to be higher than at >374 ^{o}C, but corrosion-resistant materials are still needed for long-life performance. Improved corrosion simulators capable of dealing with supercritical environments are also needed. A separate Japanese study reports on a novel tool to measure supercritical rock stress state using a mechanical device to record the shape of a core extracted by a two-stage core drilling method. In addition, a numerical study concluded that the creation of artificial supercritical geothermal reservoirs by hydraulic fracturing with a radial extent of hundreds of meters was feasible (Tsuchiya et al, 2020). The initial crustal stress state (orientation and magnitude) was found to have a major impact on reservoir creation (Watanabi et al, 2020), hence the importance of continuing to improve tools to measure the downhole stress state of rock at high temperature.

5. GEOCHEMICAL CHALLENGES

Laboratory-based studies have recently been investigating the geochemical processes involved in fluid-rock interaction at various supercritical conditions and fluid mixtures (brine and gas). An example from New Zealand is the work undertaken at the Wairakei GNS laboratory by Bruce Mountain and colleagues (see the GNG website for presentations by Mountain and Rendel). These studies are a recognition of the need for better geochemical solubility data at ultra-hot reservoir conditions in order to improve simulation software designed to predict the performance of plant and supercritical/ultra-hot reservoirs under exploitation. Fluid flow is controlled by permeability and phase state which is, in turn, influenced by deposition and dissolution of minerals from the margins of fractures and from the rock matrix. Changes in dissolved or exsolved gases (H_2S, SO_2, HCl, CO_2) and consequential changes in pH under various energy extraction scenarios are also critical to long term production and reinjection performance. The ideal development strategy would see all gases reinjected with the other fluids, in order to minimize carbon and other gas emissions. To achieve this requires further experimental investigations and simulations. CO_2 and H_2S gas reinjection studies are currently underway in New Zealand and have been successfully demonstrated in Iceland and elsewhere at conventional geothermal power plants, with the challenge now to develop appropriate methods for supercritical reservoirs.

6. ULTRA-HOT RESEARCH SYMPOSIA

A virtual symposium was held on the 14th-16th of February 2022 as a contribution towards international research collaboration on this topic. This was a joint symposium between IEA Geothermal (Working Group 12), 'Geothermal-Next Generation', and the International Partnership in Geothermal Technology (IPGT reservoir modelling group). A link to the 22 presentations from this seminar titled "Ultra-Hot Supercritical Symposium" is available on the IEA-Geothermal website (IEA-Geothermal, 2022). The symposium was subdivided into three main topics: 1) 'Modelling', 2) 'Geochemistry' and 3) a 'Smorgasbord', covering a variety of subjects, including case studies, exploration, drilling, environmental and social aspects).

Another collaborative symposium on a similar topic was held in Rotorua, New Zealand, on the 6th of December 2022. It was jointly organized between 'Geothermal- Next Generation' research participants and IAPWS (International Association of the Properties of Water and Steam) as part of their annual meeting and workshops. A link to the presentations from this seminar titled "IAPWS 2022 Symposium on Supercritical Geothermal" is available at: Geothermal-Next Generation (2022). The symposium was subdivided into three main topics: 1) 'Volcanism in the Taupo Zone and Geophysics, 2) 'Geochemistry- laboratory experiments' and 3) 'Resource Assessment Methods and Modelling' and covered a wide range of supercritical or 'ultra-hot' topics that are currently under investigation in New Zealand.

7. CONCLUSIONS

There is a large amount of energy in place in these 'deep roots' containing super-critical or ultra-hot fluids.

There is an active collaborative, collegial community sharing ideas, outputs and future investigative activities. The work discussed in this paper is the result of part of that collaboration between members of the IEA Geothermal Working Group 12 focusing on 'Deep roots' of geothermal systems.

Overall the work is focused on: delineation and identification of locations of supercritical geothermal resources that might be prospective and accessible by drilling; evaluation of the energy that might be available long term; advancing technology to enable reliable energy production from the high temperature prospects; and developing appropriate regulatory regimes that provide adequate certainty to support the needed investment in supercritical geothermal as a part of a global low carbon energy future.

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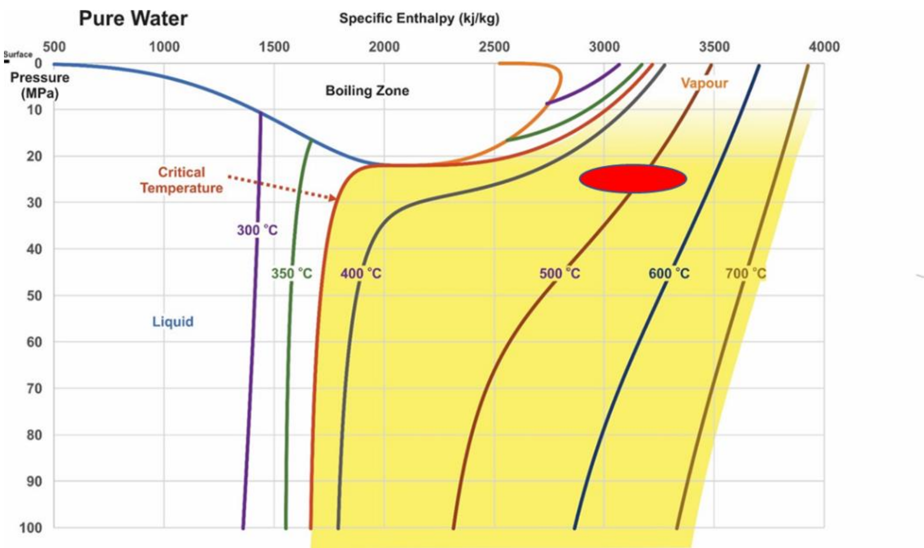

Figure 1. Simplified representation of the super-critical region (shaded yellow), and main area of interest (red oval) in 'enthalpy-pressure' phase space for pure water. "Ultra-hot" vapour develops at lower pressure and shallower depths.