Review of Proppant Behavior and Fracture Conductivity Preservation in Deep Geothermal Systems

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ABSTRACT

The long-term performance of Enhanced Geothermal Systems (EGS) depends greatly upon the ability to maintain fracture conductivities long enough to allow for extraction of heat from the deep subsurface at economically viable rates. Hydraulic stimulation is an important tool used to create the conductive pathways required for this purpose. However, in the absence of proppants, hydraulic fractures will close as the in-situ stress increases. Proppant injection is important because proppants are used to create a permanent channel for fluids to flow through the created fractures so that they remain open, and the reservoir will continue to produce. Compared to other conventional oil and gas operations, there are some significant differences in using proppants for geothermal systems. First, the proppant has to maintain its mechanical strength and hydraulic performance at temperatures higher than 200°C. Second, the geochemical environment of geothermal reservoirs can be very aggressive and corrosive, which can cause the proppant to crush, undergo chemical changes and generate fines, all of which result in a progressive reduction of the fracture's ability to conduct fluids. To provide a comprehensive reference for the selection of proppants in geothermal systems, researchers have integrated experimental data from laboratory scale tests with field data and new technologies to provide a full scope of proppant selection criteria. The focus of this study is to evaluate how proppants behave mechanically and chemically when subjected to high temperature conditions that are representative of EGS and super-hot rock (SHR) projects. Combining experimental data with practical field experience will support the decision-making process for selecting proppants to sustain the conductivity of fractures over the life of geothermal energy production.

This paper provides an overview of the current knowledge regarding the behavior of proppants under geothermal conditions, emphasizing the major factors contributing to the degradation of the fracture's ability to conduct fluids. Special emphasis has been placed on the development of new methods for testing proppants in SHR environments, where the temperature of the reservoir could be greater than 375°C. Additionally, the study explores the potential for developing more flexible and stronger proppants and/or operating practices that would extend the time that the fracture's conductivity remains stable in deep geothermal reservoirs.

1. INTRODUCTION

Several methods, technologies and testing procedures for the oil and gas industry including horizontal drilling, hydraulic fracturing, proppant technology and proppant crush-resistance tests have been adopted adapted for use in geothermal systems [1-5]. Proppants consist of particulates or particles added to the fracturing fluids used to stimulate fractured wells. The purpose of the proppant is to provide mechanical support to fracture apertures, so they do not collapse when the stimulation pressure is removed and the stresses of the surrounding rock are reapplied [2,3,5-7]. Their successful application in geothermal systems is hindered by several technical challenges associated with deep geothermal reservoirs. These challenges include extreme operating conditions such as temperatures in excess of 200°C, fluid flow issues like early thermal breakthrough, very aggressive geochemical environments containing alkaline and silica-rich fluids, induced seismicity and expected long operational lifetimes [2,3,6-8]. So, they require more advanced models, simulations and experimental techniques for heat extraction, fluid flow and proppant behavior [8-11]. Additionally, geothermal systems involve coupled thermal, mechanical, and chemical (TMC) processes. These TMC processes are unique to geothermal systems and can cause significant degradation of both proppant properties and fracture conductivity [3,6,10-12].

This study involves combining laboratory scale experimental investigation of proppant behavior in deep and super-hot geothermal systems, field-based case studies and recent technological advancement to assess current scientific knowledge of proppant behavior in deep and super-hot geothermal systems. As geothermal developments continue to move into deeper and hotter reservoirs, particularly those involving Enhanced Geothermal Systems (EGS) and super-hot rock (SHR) concepts [13,14], the long-term stability of proppant supported fracture conductivity has become one of the most important technical challenges for successful operation [1,7-11]. A major focus of this study is on the determination and characterization of proppant degradation mechanisms in geothermal environments. Degradation mechanisms of interest include thermal weakening, mechanical crushing (due to high closure stress), chemical dissolution, stress corrosion and generation of fines [10-12]. It should also be noted that many of these processes are amplified by the TMC effects present in geothermal reservoirs. These effects lead to a gradual reduction in fracture permeability and corresponding reductions in

geothermal system performance over time. So, it is important to identify more resilient, flexible and stable proppants for sustainable solutions [11-13,15,16].

This paper evaluates a variety of proppant materials for their suitability in varying geothermal conditions and applications. Proppant materials evaluated in this review include conventional proppants (natural sands), high strength proppants (sintered bauxite and ceramic composites), and engineered proppants that are resistant to extreme temperatures. An emphasis is placed on determining how the physical properties of the proppant material (composition, grain shape, density, strength, and chemical resistance) influence its performance at extremely high temperatures. Although natural sands are available and economical, they have limitations due to thermal degradation and chemical reactions in EGS and SHR environments. On the other hand, advanced ceramic and composite proppants have superior thermal and mechanical properties compared to natural sands, but they may introduce higher operating costs and constraints [12,15,16].

The study also investigates advanced laboratory testing methods suitable for simulating super-hot reservoir conditions (i.e., temperatures above 374°C and stresses like those found in deep geothermal reservoirs). These testing methods go well beyond conventional API/ISO proppant testing and include long duration exposure to fluids, fluid circulation and cyclic thermal loading to simulate real world geothermal reservoir environments [3,17]. This type of testing is essential to predict long-term changes in fracture conductivity and proppant durability in SHR environments.

Lastly, this research will also look at the potential of new models, technologies and operations to improve the long-term stability of fractured conductivity over the course of long-term production at geothermal sites. Such technologies include optimum proppant selection, customized stimulation design, chemical stabilization of proppants, advanced mathematical models and alternative proppant support concepts which can be used in extreme geothermal environments [11,12,16-18].

Several experiments were documented in literature using a variety of testing techniques including high-temperature conductivity and material integrity testing. Many of these testing techniques have been detailed in the paper along with all testing protocols and analysis procedures. The inclusion of such details would help facilitate reproducibility and comparison of results from other studies conducted under different testing conditions.

2. GEOTHERMAL SYSTEMS AND PROPPANT REQUIREMENTS

Previous studies in hydrocarbon reservoirs indicate significance of factors like proppant size, strength and concentration as well as fracture closure stress on fracture conductivity [5,19,20]. Geothermal systems exhibit a unique set of extreme thermal, mechanical, and geochemical conditions that are detrimental to the performance and durability of conventional proppant materials that were originally designed for use in oil and gas applications [11]. The extreme conditions present in geothermal systems are significantly different than those present in petroleum reservoirs and therefore impose severe restrictions on the strength, thermal resistance and chemical stability of proppant materials.

2.1 Temperature Ranges

The temperature range encountered in geothermal systems affects the physical and chemical properties of fluids and the behavior of proppants. Conventional hydrothermal geothermal systems generally operate in a temperature range of about 200°C to 275°C. To achieve commercially viable heat extraction rates, EGS aim to extract heat at higher temperatures in the range of 200°C to 375°C by employing artificially created fracture networks instead of naturally permeable formations, while SHR systems represent the most extreme conditions and are planned to operate at temperatures greater than 374°C in order to develop new high-power-density geothermal resources [2,3,5,11].

At or above 375°C, and when pressures are more than 22 MPa, water enters a super-critical state. Super-critical water has certain distinct characteristics compared to sub-critical fluids, including lower viscosity, increased diffusivity, a modified dielectric constant, and increased ability to act as a solvent [3]. The differences in physical and chemical properties of super-critical water enhance the rate of mineral dissolution, precipitation and other fluid-solid reactions that can severely affect proppant integrity. As a result of these chemical reactions, proppants in super-critical water are exposed to rapid chemical degradation, surface deterioration and the generation of fine particles, which can rapidly reduce the fracture conductivity. The extreme temperature, fluid pressure and closure stress conditions in deep geothermal systems affect both the mechanical integrity and chemical stability of geothermal proppants.

2.2 Mechanical Stresses

The mechanical properties of a deep geothermal reservoir are characterized by high in situ stresses. Typical ranges for confining stresses at 3-4 km depths including fracture face normal stresses after stimulation are 80-120 MPa. Due to high stress levels, there is a significant likelihood that the proppant will be crushed into the fracture walls and lose its permeability over time as a result of prolonged degradation of the proppant caused by stress. It is not only the magnitude of stress that affects geothermal systems, but the expected life span of geothermal systems is also a significant factor. Geothermal proppants can expect to be subjected to both static loads as well as cyclic thermal and mechanical loading from injection/production cycles, temperature cycling and changes in reservoir pressure/depletion over their expected 20−30-year design life [1,6,7,15]. If geothermal proppants fail to maintain their mechanical integrity when subjected to such extreme conditions, then the likelihood that they will gradually become plugged off and thus lead to a reduction in the injectivity and productivity of the geothermal reservoir over time will increase. To ensure that geothermal proppants will maintain their mechanical integrity (resistance to crushing, creep and stress corrosion) over extended periods of time, geothermal proppants need to be mechanically stable to prevent these forms of mechanical failure.

2.3 Geochemistry of Geothermal Fluids

Geochemical characteristics of geothermal fluids differ considerably from those present in hydrocarbon reservoirs and may also impact the operation of geothermal proppants. Dissolved silica concentrations in geothermal fluids typically exist at concentrations ranging from about 50 to 400 mg/L and have pH levels that are generally near-neutral to slightly basic (i.e., pH = 7−9). Also, geothermal fluids are typically very reactive due to their presence of many ions available to react with other substances; these include Na+, K+, and Cl- among others [9,10]. Mineral dissolution and precipitation reactions caused by geothermal fluids, especially those which occur at elevated temperatures, increase the occurrence of reactions like silica deposition, scaling, and secondary minerals forming on proppant surfaces.

In contrast to hydrocarbon reservoirs, which may include organically rich brines that can partially buffer chemical reactions, geothermal fluids promote a wide range of rock-fluid-proppant interactions. These interactions can lead to chemical weakening of proppant grains, surface roughening, bonding between grains and blocking of pores within the proppant pack. Over long durations of production, these interactions can lead to irreversible reductions in fracture conductivity, as well as complex predictions of long-term reservoir performance.

2.4 Performance Criteria for Geothermal Proppants

Proppants being utilized in geothermal reservoirs need to have performance standards that are far stricter than what has been historically established with conventional oil & gas production. Typical API Recommended Practices (API RP 19C) include sieve analysis, sphericity, turbidity, acid solubility, density and crush resistance, among others [20]. The temperature of the fluids, the stress level imposed on the fluid flow from closure stresses and the chemically aggressive nature of the fluids along with expected long-term production lives in geothermal systems all contribute to rapid degradation of conventional proppant materials. Although standardized testing methods of proppant materials for geothermal reservoirs (e.g. API RP 19C and ISO 13503) were developed for hydrocarbon reservoirs [5], they can serve as a basis for evaluating the strength of proppant materials, their particle size distributions, and how they generate fines for use in geothermal applications [1,3].

2.4.1 Thermal Stability

The most significant requirement for proppant materials to operate in geothermal reservoirs is thermal stability, particularly for EGS and SHR reservoirs which may experience temperatures exceeding 374°C. A qualified proppant material must retain at least 95% of its original mechanical strength after extended exposure to such elevated temperatures. At elevated temperatures, time-dependent creep, microstructural damage, embrittling of grain boundaries and phase transformations occur, which are negligible in hydrocarbon reservoirs [3,10,12]. Even though the standardized testing protocols for proppant qualification and degradation mechanisms (API/ISO) under TMC conditions with moderate temperatures (e.g. at 200°C or less) were also performed [2,6,7,11], it is essential that extended high-temperature testing be employed to compare and qualify proppant materials for EGS and SHR geothermal applications. Moreover, proppant placement with TMC effects should take uncertainties in the brittle-ductile transition zone uncertainties when approaching to supercritical temperatures [21].

2.4.2 Mechanical Integrity and Stress Resistance

Effective fracture closure stresses in deep geothermal reservoirs (3 – 4 km) are typically in the range of 50 – 80 MPa, and proppants must have crush resistance greater than 10,000 psi (approximately 69 MPa) to resist mechanical failure due to crushing and embedment over long production lifetimes. Frac-sand proppants experience significant levels of crushing at stress levels above 35 MPa. Although crush testing of proppants provides a basic evaluation, geothermal proppants must also resist sustained load and stress corrosion at elevated temperatures to improve long-term EGS heat extraction [15,16].

2.4.3 Chemical Stability in Geothermal Fluids

Geothermal fluids are typically composed of silica-rich, slightly alkaline (pH 7 – 9) brines containing high concentrations of dissolved salts (Na+, K+, and Cl-) [1]. At high temperatures, these brines increase the rate of mineral dissolution and precipitation reactions, which weaken geothermal proppants chemically and bond them together in the proppant pack [10,11]. Proppants must therefore be resistant to chemical dissolution or surface reactions in hydrothermal environments to preserve the shape of the grains and the permeability of the proppant pack. Standardized testing protocols (API/ISO) for determining solubility of proppants are limited and do not assess their chemical stability for long duration of exposure in geothermal fluid environments.

2.4.3 Permeability Preservation and Fine Generation

The primary measure of performance of geothermal proppants, like those used in enhanced oil and gas recovery, is the preservation of fracture conductivity over time. For example, a common goal of laboratory experiments in the field of geothermal research is to determine whether the fracture conductivity of a proppant can be preserved to a level at least 80 % of the initial conductivity after extended exposure (e.g. 40 hours at 400°C under stress) [3]. Similarly, the amount of fines generated should remain at most 1% by weight, consistent with the API/ISO recommendations, since small amounts of fines generated can produce disproportionate decreases in fracture conductivity due to the blocking of pores and the migration of fines. Fine generation in geothermal environments is further enhanced by thermal cracking and chemical corrosion of proppants and is a key discriminant of the performance of various proppant materials.

2.4.3 Comparative Evaluation of Proppant Materials for Geothermal Reservoirs

Proppants can be in various sizes, shapes and strength levels with also of different materials. Their selection on an application may depend on reservoir/TMC conditions, fluid type, in-situ stresses and the overall cost [10,20]. A brief description of commonly used proppant types with focus on natural quartz sand, ceramic proppants and sintered bauxite is given below:

Natural Sand: Natural quartz sand is inexpensive and readily available, but it performs poorly in geothermal environments. At temperatures above 200 – 250°C, natural sand is susceptible to chemical dissolution, stress corrosion, and thermal weakening. Due to its relatively low crush strength, natural sand is generally only suitable for shallow or low-stress geothermal reservoirs and is therefore not generally applicable to EGS or SHR applications, regardless of the cost advantage. Rasin-coated sands (RCS) and polymeric proppants may be subject to similar degradation mechanisms under such thermal conditions, too [11].

Ceramic Proppants: Ceramic proppants are mechanically stronger and thermally more stable than sand, and they come with an exact grain size distribution as well as rounded grain shapes. Ceramic proppants can withstand crush forces under moderate to high stress levels, making them a viable option for EGS applications. However, conventional ceramic proppants experience either chemical or phase changes at temperature ranges similar to those for SHR, particularly if the silica rich geothermal fluid impacts the proppants. Ceramic proppants are typically denser and heavier than most proppants and thus are generally less efficient for transporting and placing them into wells.

Sintered Bauxite Proppants: Sintered bauxite is the strongest of commercially available proppants and it exhibits the best level of resistance to crushing and embedment at the highest levels of stress. In addition, sintered bauxite is one of the most thermally stable commercially available proppants and it performs well in geothermal environments at elevated temperatures. However, because of its high density, sintered bauxite proppants are difficult to transport and place, and as such, they are likely to be used in only select intervals of SHR reservoirs. Some coating options are considered to improve their strength (against degradation) and density properties.

Several experimental, numerical and field studies and tests have been conducted to study the performance of these proppants along with various size and coating considerations [1,3,6,7,11,12,15-18]. Table 1 illustrates that no single commercial proppant meets all geothermal performance requirements without some compromise. For example, while natural sand may be acceptable for shallow or low-temperature geothermal systems, ceramic and sintered bauxite proppants are generally more suited to EGS and SHR systems, where maintaining long-term conductivity at extreme TMC conditions is crucial. Future research is anticipated to focus on developing advanced, composite proppants that combine the thermal and mechanical strengths of high-strength materials with the transportability and chemical stability of conventional proppants.

Table 1. Performance Ranking of Proppant Materials for Superhot Rock (SHR) Applications

Criterion	*Natural Sand*	*Ceramic Proppant*	*Sintered Bauxite*
Thermal stability (>375–400°C)	Poor	Moderate	Excellent
Crush resistance (>10,000 psi)	Low	High	Very High
Chemical resistance (silica-rich fluids)	Poor	Moderate	High
Permeability retention	Low	Moderate–High	High
Fines generation resistance	Poor	Good	Excellent
Placement efficiency	Excellent	Moderate	Challenging
Overall SHR suitability	Unsuitable	Conditional	Preferred

3. TEMPERATURE EFFECTS ON FRACTURE CONDUCTIVITY

3.1 Experimental Findings from Laboratory Testing

Proppant performance is being studied at laboratory scales using fracture conductivities that consider the unique combinations of elevated temperature, high stress, and complicated fluid-rock interaction in geothermal reservoirs. Laboratory experiments are important as they provide a means to isolate and study each of the combined thermal, mechanical and hydraulic factors affecting the permeability of fractures. Therefore, laboratory testing of conductivity at high temperatures will help to understand the evolution of the fracture's ability to conduct fluid through temperature effects on fracture surface geometry and the flow regime as it relates to EGS and SHR applications. Laboratory experiments conducted on bauxite-filled fractures in granite at normal closure stress levels (2,000-3000 psi) showed a strong dependency of the fracture's hydraulic properties on the temperature and the utility of proppants to improve transmissivity [6,7]. These studies have demonstrated the importance of thermal sensitivity and the surface characteristics of fractures. The effects of water chemistry and closure stress in elevated temperatures (230°C) as well as proppant dissolution/precipitation observations were discussed in [10]. Low temperature (25°C), low-pressure (2000 psi or less) experiments using deionized water and gaseous nitrogen as the testing fluid, the experiments in [22] showed a low-density ceramic proppant was effective in improving conductivity several times compared to fractures without proppant. Conductivity experiments with varying concentrations of sintered bauxite ceramic proppants at temperatures below 130°C in [23] also confirmed this type of proppants sustained fracture conductivity but proppant crushing and embedment issues gradually decreased permeability. Laboratory results for long-term hydraulic conductivity and embedment in [24] indicated relatively large concentrations of high-strength proppants were needed in the stimulated fractures.

3.1.1 Temperature-Dependent Hydraulic Properties Results

The measured values of fracture hydraulic conductivity in [6] are characterized by significant variability among different temperatures but the results were not conclusive regarding the types of fractures (e.g. saw-cut versus wedge-split samples). For example, at room temperature (approximately 22°C) both fracture geometries have high hydraulic conductivity; however, as temperature increased, hydraulic conductivity decreased substantially, likely due to the thermal expansion of the rock and proppant. Moreover, some embedment and brokage of proppant were observed, potentially due to the chemical effects and confining stresses in addition to an increase in temperature. Despite loss of permeability at higher temperature, stress and chemical exposure, the transmissivity with bauxite proppant

was observed to be much better than that without proppant in laboratory experiments [7]. The hydraulic conductivity of the sand at 90°C is 65 – 85 % less than that obtained under ambient temperature conditions. In addition to being the largest absolute reduction in hydraulic conductivity, it was also the greatest relative reduction. Moreover, as temperature increased, hydraulic conductivity appeared to show much greater variability compared to its behavior at lower temperatures.

3.1.2 Key Experimental Observations

Several major trends emerge from the laboratory data. In high temperatures with SHR conditions, ceramic proppants resist degradation better than natural sands for long-term thermal and compaction stability [3]. Moreover, a significant drop in conductivity is found as the temperature moves from room temperature to approximately 90°C, indicating that early-stage thermal effects govern the mechanisms of conductivity degradation [6]. The non-linear behavior of the temperature dependence of conductivity degradation indicates that conductivity degradation is instead driven by threshold-based processes, such as rapid rearrangement of proppant grains, redistribution of interfacial stresses, and early geochemical reactions [6].

Further, saw-cut fractures (smooth, planar surfaces) usually experience larger drops in conductivity than wedge-split fractures as they tend to be more easily compacted, while wedge-split fractures retain the natural surface roughness and asperity-controlled aperture variability of the fractures. This improved surface roughness and variability in aperture diameter improves resistance to temperature induced conductivity degradation and also preserves preferred flow channels under thermal stress [6]. A similar result is reported in [21].

Moreover, an increase in conductivity is observed at high temperatures when flow rates increase to 15–30 mL/min. This conductivity increase is due to the reorganization of the proppant pack due to the increased hydrodynamic forces generated by the flow rates and results in grain rearrangement, localized dilation, and reopening of previous flow-paths that were restricted due to the initial compaction of the proppant pack. Importantly, this effect is due to changes in the structural characteristics of the fractures and not to any improvement in the inherent material properties of the proppant [6].

In addition to the observed temperature effects, there are also test sequence effects that produce local increases in conductivity. For example, in some of the tests conducted at 150°C, measured conductivity has been found to exceed the measured conductivity at ambient conditions. These increases are considered artifacts of testing sequence effects and/or the reconfiguration of the proppant pack and are not indicative of actual increases in fracture conductivity. Therefore, caution must be exercised in interpreting experimental results, especially when attempting to extrapolate short term laboratory results to long term field performance [6].

Similar results of conductivity gains and losses with use of proppants at different temperature, mechanical stress and geochemistry are reported in literature. One can also refer to [3,10,11,12] and the references there for the loss of mechanical stability, chemical stability and strength of proppants even with resin coating in the presence of higher temperatures and aggressive chemistry.

3.2 Batch Reactor Experiments

While the short-term laboratory tests provide good insight into fracture conductivity with proppants and the temperature-induced loss of conductivity, longer term batch reactor experiments (e.g. around 4-10 week durations) are needed to analyze the performance and stability of proppants under varying geothermal conditions including exposures to different temperatures. More insight into proppant degradation issues due to adverse chemistry are discussed in the next section.

Modified API/ISO crush tests for thermal and geochemical impact on proppants were conducted in [1] using Raft River geothermal fluids at 250°C for a period of two-months. Four different types of proppant combinations were used: Reservoir (granite) rock, reservoir rock + sintered bauxite, reservoir rock + quartz proppant and reservoir rock + kryptosphere proppant. They compared the proppant crushing results for unreacted case and a fixed set of reacted conditions. Mechanical degradation of kryptospheres (hollow ceramic spheres) occurred at a greater extent than bauxites though the specific thermal and chemical effects wouldn't be explicitly determined.

The batch reactor experiments for proppant selection in [10] compared sintered bauxite and quartz sand using several trials using geothermal conditions in periods of 4-11 weeks. The experiments were implemented using deionized water, deionized water with silica and a sample from Raft River at 200-230°C. Even though water leakage in some trials affected the results, proppant dissolution and some precipitations were observed.

A few other batch reactor studies include [11] on chemical stability and microstructural dynamics of four proppant types at 130°C over a duration of 25 days, and [12] on thermal stability of CO_2 - responsive light-weight bauxite proppants using geothermal fluid from Raft River at 250°C and at low temperatures about one month. The results of [12] showed that the thermal stability of bare bauxite as well as polymer-coated versions.

3.3 Some Causes of Temperature-Induced Conductivity Loss

As stated earlier, the observed decrease in fracture conductivity with increasing temperature is caused by the concurrent operation of multiple interacting mechanisms, rather than a single mechanism [6,7,10,11,12]. These mechanisms interact with each other and can often support each other during geothermal conditions. Even though additional details will be given in the next section (results from batch reactor experiments), potential causes of temperature-induced conductivity loss are summarized below:

Proppant Pack Compaction: Thermal loading causes proppant grains to settle and rearrange themselves within the fracture, resulting in the progressive compaction of the proppant pack. With decreasing pore volume, the tortuosity and restriction of flow-paths increase. Once

compacted, the proppant pack is capable of limited elastic recovery, but most of the conductivity loss is typically irreversible, even if the temperature and stress conditions become stable again [3, 10,12].

Thermal Expansion Mismatch: The difference in thermal expansion coefficient between the host rock, proppant grains and pore fluid generates localized stress redistributions at grain-grain and grain-rock interfaces. Stress concentrations generated at these locations cause grain reorientation, the growth of contact areas and, in some instances, the localized crushing of grains. All these actions contribute to the degradation of permeability and the reduction in effective fracture aperture [5].

Geochemical Precipitation: Between approximately 100°C and 200°C, precipitation of secondary minerals, such as silica, can occur on the surface of proppant grains and within pore throats. Even though the amount of precipitation is very small, the reduction in pore connectivity would be significant enough to produce measurable reductions in conductivity, without necessarily producing large amounts of mechanical damage to the individual proppant grains [1,10,11,12].

Effects of Two-Phase Flow: Under near-boiling conditions and low-flow testing, the formation of steam and entrained gas phases within the fracture is common. This leads to the formation of a two-phase flow regime in which the relative permeability of the fractured system to liquid water is reduced. Thus, the observed conductivity losses during laboratory measurements and possibly during field operations are underestimated compared to what would be expected during single phase flow [18].

Acceleration of Proppant Embedment: Higher temperatures accelerate time dependent deformation mechanisms, including creep and viscoelastic flow of the rock at fracture surfaces. This produces a faster proppant embedment into the surrounding rock matrix, thereby producing a continued reduction in effective fracture aperture and thus in conductivity over time [15,16,17,18,23,24].

4. GEOCHEMICAL DEGRADATION IN LONG-TERM BATCH EXPERIMENTS AND FIELD STUDIES

4.1 Geochemical Degradation in Long-Term Batch Experiments

In addition to the short-term laboratory tests about the mechanisms of proppant degradation, long-term batch reactor experiments are needed to understand how the proppant degrades chemically in geothermal fluids. Tests conducted using Raft River geothermal brine at 250°C for a two-month duration in [1] showed specific mechanisms of degradation of different types of proppants. Bauxite proppant specimens exposed to geothermal conditions in the laboratory tests demonstrated evidence of silica leaching from the surface of the proppant specimens. In addition, the bauxite proppants subjected to a modified API crush test exhibited an increased crushed fraction (i.e., 5–10%), which suggests that the bauxite proppant specimens underwent some form of chemical weakening. However, the overall structural integrity of the bauxite proppant specimens remained intact. However, kryptosphere proppants exhibited a significant loss of strength (approximately 20–30%). Since there was minimal visually detectable alteration to the surface of these proppants, the significant mechanical weakening is indicative of degradation mechanisms occurring internally to the proppants. Therefore, hollow ceramic materials may be significantly more susceptible to hydrothermal environments than solid, dense proppants like bauxite [1].

The results of the experiments in [10]-[12] and some other reports in [2] also indicate geochemical effects under relatively moderate temperatures including dissolution of bauxite proppants and quartz sand (though not necessarily reducing permeability) as well as precipitation (with negative impact on fracture porosity and permeability) although such effects were reduced by using suitable coating options. These findings clearly demonstrate that short-term exposure periods can initiate degradation processes that are likely to increase over the operational life of geothermal systems. Furthermore, the observed damage at 250°C indicates that degradation rates will be greatly increased in deeper EGS and SHR reservoirs that operate at temperatures of 350–400°C or greater. Therefore, the long-term geochemical stability of proppants should be considered along with thermal resistance and mechanical strength in designing geothermal proppants.

4.2 Field Case Studies and Operational Experience

While operational concerns, such as thermal draw-down, induced seismicity and low fracture continuity were still present, the Fenton Hill tests demonstrated that fracture conductivity supported by proppant was superior to pure shear dilation in the context of geothermal reservoirs. The test results have become the foundation for later research on EGS stimulation techniques and materials [1,2,13,14].

Le Mayet, France (HDR System, 1980s–1990s): The goal of the Le Mayet HDR-System Project was to simulate and extend the Fenton Hill experience in a geological environment typical for Europe (basement rock, medium tectonic stress) by conducting several stimulation campaigns to compare wells treated with and without proppants. According to the field-testing results, wells injected with proppants reached significantly higher injectivity indices than wells injected without proppants, which confirms the laboratory-measured fracture conductivity based on the properties of proppants [1,2].

Further investigations of pressure responses suggested that proppants help maintaining the fracture aperture during shut-in conditions especially in zones subjected to relaxation due to stress and thermal contraction. Unfortunately, there is a lack of well-documented operational data for this project covering only about five years of injection/production history; therefore, no definitive conclusions could be drawn regarding the long-term stability of fractures, the embedding of proppants into the surrounding rock, and chemical degradation. Consequently, while Le Mayet has identified the potential for short- to medium term proppant assisted stimulation in EGS systems, it has also revealed an urgent need for longer term monitoring campaigns to evaluate how sustainable these stimulations can be during geothermal cycling operations.

Utah FORGE (2018–Present): The Utah Frontier Observatory for Research in Geothermal Energy (Utah FORGE) is the largest and most thoroughly instrumented EGS field laboratory to-date. The objective of this project has been to investigate stimulation mechanisms, fracture development and flow stability within a crystalline granitic reservoir. Unlike earlier HDR projects, Utah FORGE includes both controlled proppant injection tests with various sizes, densities and types of proppants, as well as a large number of diagnostic tools, such

as micro-seismic monitoring, distributed temperature sensing (DTS), tracer studies and geochemical sampling [17,25]. Therefore, Utah FORGE will allow the researchers to establish correlations between proppant placement, fracture activation and fluid flow paths directly.

Early results show that proppant assisted fracturing has increased injection rates and decreased pressure drops when compared to water only stimulated wells which were primarily caused by shear dilatation. However, this project is in an early stage of operation and long-term data on retention of fracture conductivity, proppant transport efficiencies, and thermal effects will need to be collected over time to validate more advanced proppants and stimulation techniques in field operations.

Newberry Volcano Enhanced Geothermal Systems Project (2010-Present): The Newberry Volcano project takes EGS to the extremely high temperature and near supercritical states where stimulation depths exceed 3km and the reservoir temperature exceeds temperatures from all previous HDR projects. This project takes place in a geological environment consisting of volcanic and crystalline rocks that have been subjected to high stress and several sources of uncertainty. Some experimental tests for suitable proppant selections [3] and stochastic thermal-poroelastic models [26] are developed to address permeability dynamics and proppant selection under similar SHR environments with thermal-hydra-mechanical interactions. However, there is limited operational field experience along with many uncertainties for the long run chemical stability of these materials, thermal cycling effects, and how potential proppants interact with fractures under the supercritical fluid conditions of SHR. The Newberry Volcano project highlights both the potential and the challenges of using proppants in supercritical geothermal systems.

Some other EGS sites for stimulation attempt with proppants include Groß Schönebeck in Germany [2,24], Rosemanowes in UK [13], and Blue Mountain site in the USA [4,11,27] as well as in hydrocarbon reservoirs like Caney Shale in the USA [5].

5. EMERGING TECHNOLOGIES: TEMPERATURE-SENSITIVE PROPPANTS AND TUNABLE CONDUCTIVITY

Some recent advancements in materials science and numerical/mathematical modeling may provide alternative solutions for addressing many of the long-standing issues with EGS and SHR [8,11,12,15,18,20,22,26,28]. The development of temperature sensitive proppant is intended to provide dynamic adjustment of fracture permeability based on changes in reservoir temperature that occur during geothermal operations. As opposed to traditional proppants that provide a constant level of fracture conductivity, temperature sensitive proppant seeks to control fracture permeability through active management of fluid flow paths between injection and production wells.

5.1 Concept of Fracture Conductivity Tuning

Fracture conductivity tuning is defined as the ability to control fluid flow through fractures without mechanically intervening in the fracture network. Temperature sensitive proppants are being developed to change some physical property such as stiffness, volume or contact behavior because of a change in local temperature within the fracture network [8,16,20]. Early in the injection process, cold fluids injected into high temperature geothermal reservoirs produce large thermal gradients in the vicinity of the injection point. Temperature sensitive proppants would use this gradient to change the fracture's aperture and permeability in a controlled and reversible fashion.

Some operational benefits of fracture conductivity tuning techniques are summarized below:

Delayed Thermal Breakthrough: Maintaining higher conductivities in cooler fractures on the injection side and lower conductivities in hotter fractures on the production side will help create a more uniform heat sweep and delay the occurrence of premature thermal breakthrough.

Passive Flow Redistribution: The system is passive, redistributing flow automatically between fractures based upon their localized temperatures. There are no down-hole valves or changes required at the surface to adjust the flow distribution between fractures.

Reversible Conductivity Modulation: As the reservoir conditions evolve, temperature sensitive proppants may reversibly expand or soften as they are exposed to cooler fluids, thereby restoring fracture conductivity in areas where it was previously restricted. The reversible nature of the conductivity modulation allows for an adaptive response to the evolving thermal and hydraulic conditions present throughout the life of the reservoir.

In summary, the fracture conductivity modulation technique provides an additional self-regulatory mechanism by which fluid flow can be controlled to meet thermal management objectives of the reservoir, and this cannot be accomplished using traditional proppant systems.

5.2 Potential Material Classes for Development of Temperature-Sensitive Proppants

Three basic material classes and their several coated, sintered, low-density, lightweight and surface modified versions have been identified through current studies. Some of them may serve as potential temperature responsive proppants [1,3,5,6,7,10,11,12,20,28], and each employs a unique physical mechanism to modulate conductivity.

Polymeric Composite Proppants: Most of these materials are made from engineered polymers or composite materials, and they have variable properties depending on their temperature range. As a result, at higher temperatures, the material becomes softer, which can cause partial closure of fractures and a decrease in conductivity, while a drop in temperature will allow the material to become stiffer or expand, which will restore the flow capability of the fractures. Some benefits to using these types of materials are that their temperature responses can be easily manipulated, and the materials are lightweight. However, there are many concerns regarding their longevity due to chemical and thermal degradation in geothermal environments.

Shape Memory Polymer (SMP) Proppants: SMPs (also called shape memory alloy proppants) are materials that change shape or stiffness based on how hot they get, thus creating a change in the dimensions or stiffness of the alloy. Once cooled, the SMA returns to its initial state. If used as a proppant for hydraulic fracturing, SMAs can open or close fracture apertures as the temperature varies. A major advantage of this type of proppant is the mechanical strength, but some disadvantages of using SMAs as proppants are the high cost of the materials, limitations in manufacturing at the size of a proppant, and the unknown corrosion potential of SMAs in geothermal fluid. Although conceptually attractive, precise control of reaction kinetics and long-term cycling behavior remain technically challenging.

5.3 Current Research Status and Modeling Insights

Since hydraulic stimulation involves THM processes with complex geometry, it is challenging to model thermal stresses pressures and temperatures. A discrete fracture model based on displacement discontinuity method and a flow simulator were utilized in [29]. The discrete element modeling (DEM) coupled with thermal and flow models were introduced in [15], showing proppants sensitive to temperature could improve the evolution of fracture conductivity and also the distribution of fluids in EGS reservoirs. As such, model studies have shown the potential to enhance heat recovery efficiency, reduce pressure drop and extend the life of the reservoir.

Although there are positive model study outcomes, the development is still in its infancy. Up until now, most research has involved conceptual designs, laboratory scale testing of material properties and numerical simulations rather than their direct field trial/pilot scale applications. Major barriers to further development are the survivability of the proppant material under extreme temperature and stresses, and lack of understanding of long-run cyclic performance.

Proppants sensitive to temperature represent a new paradigm for fracturing design based on adaptability rather than passivity for geothermal systems. While the current technology readiness level is low, continued advancements in materials science/engineering, coupled modeling and experimental validation should ultimately allow for deployment of this technology in high temperature EGS and SHR systems. Ultimately, field demonstrations will be critical to transform these conceptual possibilities into operational realities.

6. PROPPANT SELECTION GUIDELINES FOR GEOTHERMAL AND SUPERHOT ROCK SYSTEMS

6.1 Current Best Practices for Proppant Selection

Proppant selection for geothermal stimulation must follow a formal and cautious process which will consider temperature of the reservoir; in-situ stress; chemical composition of the fluid being used; and duration of operational life of the system. Data from HDR and EGS field application studies, supplemented by laboratory high-temperature testing data, suggest that proppant performance in geothermal applications is influenced not only by its mechanical properties, but also by its thermal and chemical stabilities.

For most geothermal reservoirs operating at temperatures ranging from 200-275°C, and for EGS reservoirs at temperatures up to about 375°C, current best practice emphasizes the utilization of materials that have a documented track record of successful operation [1,3,6,7,10,11,12,20,22,23]. High-quality sintered bauxite proppants in the 30/60 or 20/40 mesh range, preferably with a ceramic coating, continue to be the primary choice for the majority of geothermal stimulation treatments. Bauxite has demonstrated consistent field performance, providing crush resistance greater than 12,000 psi; better resistance to chemical alteration than naturally occurring silica sand; and a favorable cost-to-performance ratio for typical geothermal treatment volumes. Therefore, sintered bauxite with suitable coating options represents a solid base-line solution for the majority of geothermal wells [1,3,6,7,10,11,12,20].

However, in the case of more challenging environments (such as deep EGS wells, or those characterized by higher closure stresses, lower productivity, etc.) additional optimization measures may be necessary. In addition to using premium ceramic proppants having high alumina content, or composite formulations, to provide assurance of sustained fracture conductivity, various additional optimization methods are available. Examples include pre-heating bauxite proppants before injecting them into the formation, to minimize retained moisture, thus reducing thermal shock and embedment effects resulting from exposure to high reservoir temperatures. Blending of different mesh sizes (i.e., combinations of 20/40 and 30/60) may be used to increase the density of the proppant pack, and retain conductivity, under cyclic thermal and mechanical loads. However, there are mixed results from literature about their effectiveness [20].

There are certain materials that have been consistently shown to be ineffective in geothermal applications and, therefore, should generally be avoided. For example, naturally occurring silica sand does not possess the requisite mechanical strength for high-temperature, high-stress applications, and exhibits significant creep and dissolution behavior. Hollow ceramic materials, including kryptospheres, exhibit strength loss and structural failure when exposed to stress and temperature conditions present in geothermal environments. Additionally, utilizing unqualified or experimental materials in an operational project poses an unreasonable level of risk, and should be avoided [1,20].

In SHR systems, operating at temperatures above about 375°C, and often in supercritical fluid conditions, a fundamentally different approach to proppant qualification is needed. Conventional oil and gas testing methodologies are inadequate in these environments. Materials for potential SHR use must be tested in SHR-specific laboratory experiments that simulate exposure to temperatures of around 400°C, confining pressures of around 50 MPa, and supercritical fluid chemistry over extended periods [3]. Although there are no currently qualified proppant materials for long-term SHR applications, research indicates that several advanced commercial ceramic proppants, sintered composite materials, and thermally stable coated proppants may offer suitable alternatives [20]. These materials seek to integrate high compressive strengths with enhanced fracture toughness and resistance to thermal cycle-damage. Since SHR is still a relatively new technology, it is essential that all SHR development programs utilize dedicated test sections, equipped with extensive pressure, temperature, and flow monitoring capabilities, to permit direct evaluation of long-term proppant behavior in SHR reservoir conditions.

6.2 Reservoir-Specific Considerations

Reservoir Specific Factors: The final decision on what type of proppant will be used is based upon the unique characteristics of each geothermal reservoir as well as the goals that need to be met during its operational phase [1]. The temperature gradient of a geothermal reservoir has a significant impact on the decision of which proppant to choose. For example, a relatively shallow geothermal reservoir that is at moderate temperatures does not warrant the use of an expensive high-temperature resistant proppant. On the other hand, if there is a deeper and hotter zone within a reservoir, then a more durable type of proppant would be considered. In addition to the temperature gradient of a reservoir, the in-situ stress state (closure stress) of the fractures in the reservoir plays a major role in the selection of a proppant. If the closure stresses are high enough to crush a low strength proppant, then a crush resistant ceramic proppant must be used. As noted earlier, the chemical composition of the fluids in a geothermal reservoir can affect how the proppant will perform over time. This is especially true when the system is undersaturated because there are increased risks of dissolution and chemical alterations occurring.

Additional operational aspects such as stimulation duration, stimulation size and the overall life of the reservoir also contribute to the proppant selection process. For example, repeated stimulation events or cyclic injection schemes require the consideration of cumulative thermal damage to the proppant. Moreover, large-scale development projects must weigh the performance of the proppant relative to the economic feasibility of the project. Short-term pilot projects may allow for the use of more expensive materials to minimize the level of technical risk. However, for long-life geothermal systems designed to operate for multiple decades, the selection of a proppant should focus on the durability and ability of the proppant to retain conductive properties over time rather than selecting a proppant solely based on the initial cost savings. These factors all demonstrate the need for a reservoir-specific, life cycle-based approach to select a proppant for geothermal or superhot rock systems, as demonstrated in Table 2 below. For additional details, one can refer to [13,14,24].

Table 2. Key reservoir factors influencing proppant selection are summarized below:

Reservoir Factor	Consideration	Selection Impact
Temperature gradient	Shallow warm zones vs. deep superhot zones	Use temperature-appropriate materials; avoid premium proppants in cooler zones
Fracture stress state	Moderate vs. high closure stress	High stress conditions require crush-resistant ceramics
Fluid chemistry	Silica-rich vs. undersaturated fluids	Undersaturated fluids increase dissolution risk
Treatment duration	Single stimulation vs. repeated treatments	Repeated treatments require assessment of cumulative thermal damage
Treatment scale	Pilot tests vs. full-field development	Pilot projects may justify premium materials; large-scale projects require cost optimization
Reservoir lifetime	Short-term demonstration vs. 30-year operation	Long-term projects prioritize durability over upfront cost

7. RESEARCH GAPS AND FUTURE DIRECTIONS

7.1 Outstanding Uncertainties

Despite advancements for understanding proppant behavior in geothermal and enhanced geothermal systems, several issues of uncertainty continue to exist. One of the largest areas of concern is regarding long-term stability of proppants when subjected to super-hot and supercritical conditions. Most of laboratory and field evaluations of SHR proppants that have been conducted to date include an operational period of no more than three years. This is not sufficient time to evaluate the long-term performance of SHR proppants in geothermal applications where project lifetimes typically are multi-decades.

There are many uncertainties of both the proppant longevity and the fracture integrity (i.e., the interaction of proppants with the surrounding rock) that can be traced back to the lack of a well-established method of accelerated aging of proppants in addition to a lack of sufficient duration of field monitoring of proppant performance under combined thermomechanical and geochemical environments. Laboratory test methods typically evaluate one parameter at a time (e.g., thermal, mechanical or chemical), while fractured geothermal reservoirs experience all three TMC parameters simultaneously. Consequently, the coupling of these mechanisms can have significant impacts on proppant crushing, dissolution and weakening. As a result, future research will need to develop test methodologies, models and numerical methods that can accurately capture the complexities associated with multiple interacting mechanisms.

Another area where there is very little quantitative information is the impact of the production of fine grains from crushed proppant and surface degradation on the long-term hydraulic properties of fractured geothermal reservoirs. Moreover, laboratory testing of proppants typically employs simplified fracture geometries characterized by smooth surfaces, constant apertures and no stress heterogeneities, whereas actual geothermal fractures exhibit rough surfaces, variable apertures and stress heterogeneities. All these characteristics of fracture geometry can potentially affect proppant placement, pumping schedules and long-term flow properties.

Finally, the economic consequences of selecting proppant types, sizes and concentrations in geothermal reservoirs should be considered. In addition to evaluating the technical performance of materials, other factors like comprehensive techno-economic evaluations of proppant costs, stimulation scale, well designs with multiple stages, operational life and heat recovery efficiencies need to be estimated. Therefore, it is very difficult to determine optimal proppant selections, pumping schedules and concentrations for economic efficiency among various geothermal reservoir development options [2,9,27].

7.2 Future Research Priorities

While there is room for new testing schedules for laboratory and batch experiments as well as more advanced models, the future research focus should be on long term, field-based validations of proppant performance in actual geothermal settings. Controlled field tests with several candidate proppants should be developed to include monitoring periods of at least five to ten years to monitor the direct relationship between the proppant's ability to retain fractures' conductivity, changes in injectivity, and its thermal performance. Such data sets are critical to closing the gap between laboratory test results with a duration of less than one year and the field test requirements for long-term operation. At the same time, the expansion of access to facilities capable of high-temperature, and supercritical testing is needed. Currently, only a few laboratories world-wide have the capability to conduct experiments at supercritical geothermal conditions, which limits the rate at which new materials can be developed. The availability of standardized testing methods for SHR proppant testing would provide for an increased participation in SHR proppant research and enhance the comparative nature of the various studies.

Batch experiments, utilizing accelerated aging in high pressure, high temperature vessels may provide a mechanism for simulating the long-term durability of materials. In addition to combining the effects of TMC stressors, these batch experiments should be closely linked to computational modeling frameworks. This approach would permit laboratory scale measurements to be scaled up to field relevant time frames. Moreover, sensitivity analysis and numerical modeling advances will play an important role in future research. Calibration of fully-coupled TMC models with laboratory and field data will be necessary to predict the evolution of fracture conductivity and reservoir performance in geothermal operations. The use of these models will enable both the evaluation of different proppant options and the optimization of stimulation designs through the quantification of uncertainty and trade-offs between performance.

In addition to continued research into adaptive technologies (e.g. temperature sensitive, tunable or high-strength proppants) and evaluations of proppant dynamics within naturally fractured networks, innovative methods should be developed to manage fracture networks by passively controlling fluid flow and achieve improved thermal sweep efficiencies.

8. IMPLICATIONS FOR EGS COMMERCIALIZATION

8.1 Project Economics and Sensitivity to Proppant Selection and Performance

The cost of selecting and maintaining a good proppant will directly affect whether an EGS can operate economically as long as it exists. The difference in cost between using the low-cost sintered bauxite proppant, and the high-end ceramic proppant, may potentially be a significant amount in the overall cost of completing a well and stimulating a reservoir. In addition to the initial cost of the proppant, the long-term ability of the proppant to retain its original fracture conductivity will greatly determine how much revenue a well will generate over its lifetime. If a proppant loses 50 percent of its original fracture conductivity over a ten-year time frame, then it will likely lose half of the fluid flow through the fracture during the same time frame, resulting in a loss of production. This will also lead to a decrease in the total amount of energy generated by the well over the course of its operating life (a factor that can be modeled as a reduction in the cumulative energy output of the well). Over the 30-year duration of most EGS projects, the effects of gradual degradation mechanisms on fracture conductivity and subsequently on production rates can significantly reduce the net present value of the project.

Further adding to the financial risks associated with EGS development is the lack of reliable information about the long-term behavior of proppants in geothermal environments. Since there are no established records of proppant performance in commercial-scale ESG or SHR geothermal operations, the developer must make conservative assumptions regarding long-term performance. Consequently, developers typically model future performance conservatively, and often at the expense of higher hurdle rates or lower valuation of the project. In some cases, the uncertainty associated with long-term proppant performance can act as a deterrent to investment in new EGS projects.

When SHR applications become more common and cost/benefit analyses justify the use of premium, high-performance proppants in project economics, these materials will become more attractive. While the initial costs of the premium proppant can be expected to be $200,000 to $500,000 per well, the potential to maintain a fracture conductivity of greater than 90 percent for the life of the well (as opposed to less than 70 percent for standard proppants) could allow for longer productive lifetimes, more stable production, and better overall project economics in extreme temperature and stress conditions.

8.2 Standards, Regulation, and Policy Implications

As the EGS technology moves closer to commercial deployment, the conversations about standardizations and regulatory framework for proppant qualification are becoming increasingly active. Organizations such as the API Standard 19 committee have been actively working on adapting established oil & gas proppant testing methodologies to the TMC specificities of geothermal applications. These methodologies are expected to evolve into formalized geothermal application-specific testing protocols defining minimum qualification thresholds for proppant performance. Furthermore, government agencies are increasing their involvement in this area. The US Department of Energy's Geothermal Technologies Office has incorporated proppant selection and qualification guidance into its best practices documents for EGS development. These documents are to provide guidance on reducing technical risk associated with selecting proppants for EGS development so that common evaluation criteria can be used by developers to help facilitate the reduction of project development time and costs. Additionally, national regulatory requirements for EGS proppants are emerging. Countries such as Germany and Australia require documentation of proppant qualification testing prior to permitting for EGS development projects. These regulatory requirements are designed to ensure reservoir integrity, reduce potential environmental risks and improve the chances of successful long-term operation of such EGS projects. As geothermal energy increases in importance in national decarbonization strategies, it is likely that regulatory expectations will continue to expand.

Looking ahead, broader deployment of EGS as a clean energy source may bring new rules to supply chain sustainability and environmental performance of proppants. These regulations could include requirements to evaluate the lifecycle carbon footprint of proppant material,

verify the responsible sourcing of proppants, and encourage the recycling or reuse of proppants when possible. Developing standards and regulatory requirements will be essential to guiding both technological development and commercial rollout of geothermal proppants.

9. CONCLUSIONS

Geothermal energy and especially EGS depend heavily on the proper implementation of proppant technology for successful application. As demonstrated by numerous experiments and EGS projects, propped fractures have better injection and production capabilities than unpropped fractures. Therefore, the added expense associated with using proppants can be justified technically and establish proppant technology as a major contributor to commercialization of geothermal energy.

The high-temperature environment of geothermal fields imposes several restrictions on proppant materials used in geothermal operations. Silica sand, which is a natural product, suffers unacceptable loss of strength, creep, and dissolution in the high-temperature EGS conditions, making it generally unsuitable for use in virtually all geothermal applications. Bauxite proppants that are sintered perform well up to about 250-275°C. However, there is also a significant amount of laboratory and field data showing that the physical and chemical properties of sintered bauxite proppants degrade significantly as the temperature approaches 300°C. At present, the suitability of sintered bauxite proppants for super-hot rock environments greater than 375°C is still unknown and emphasizes the need for new materials/coating options and more comprehensive qualification processes.

Losses in fracture conductivity resulting from temperature-induced effects are among the largest contributors to reduced performance of geothermal systems. A variety of laboratory studies have shown that increasing temperature will result in a significant reduction in fracture conductivity—usually by 50% to 85%—resulting from a combination of proppant compaction, thermal stress redistribution, and geochemical precipitation within the fracture network. These data emphasize the need for temperature-specific proppant selection and support the conclusion that material performance in geothermal conditions cannot be inferred from room-temperature testing.

Recent developments in SHR testing procedures mark a significant step forward in the development of qualification procedures for geothermal proppants. Initial SHR test results of advanced ceramic proppants are promising, indicating excellent structural integrity, very low creep deformation, and retained meaningful permeability under extreme temperature and stress conditions. While these early results suggest that engineered ceramic and composite materials may provide solutions for next-generation geothermal systems, further validation is necessary.

One of the main conclusions of this review is that laboratory measurements of material properties at ambient conditions do not accurately predict how those same materials will behave in geothermal environments. In some cases, materials that are determined to be weak under mechanical testing at room temperature remain stable under super-critical conditions, while other materials that are strong at ambient conditions exhibit unexpected failure due to creep or thermally activated deformation. This observation emphasizes the need for geothermal-specific testing frameworks that simulate the coupled TMC conditions experienced during geothermal operation.

While laboratory testing and field deployment of geothermal proppants continue to evolve, much uncertainty still exists relative to the long-term durability of proppants throughout the operational lifetime of geothermal projects. The current understanding of long-term proppant performance is based largely on short duration laboratory tests, usually conducted at elevated temperatures for periods of weeks to months, and relatively short-term field observations (i.e., five to ten years). Extrapolation of such data into predictions of performance over extended operational lifetimes (i.e., 25 to 30 years) introduces uncertainty and risk, emphasizes the need for long-horizon field trials and validated accelerated aging methodologies.

Therefore, proper proppant selection for geothermal applications depends on the needs of each project. Factors that influence the optimum selection of a proppant include the conditions of the reservoir, the goals of the project, the operating parameters of the project, and the budgetary constraints of the project. Thus, no one proppant solution is appropriate for every geothermal project. As such, comprehensive reservoir-specific testing of potential proppant candidates should precede large-scale deployment to ensure both the technical performance of the selected proppant and the economic viability of the overall project.

REFERENCES

[1] Mattson, E. D., Neupane, G., Plummer, M., Jones, C., & Moore, J. (2016). Long-term sustainability of fracture conductivity in geothermal systems using proppants. Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22-24, 2016, SGP-TR-209.

[2] Shiozawa, S., & McClure, M. (2014). EGS design with horizontal wells, multiple stages, and proppant. Proceedings, Thirty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 24-26, 2014, SGP-TR-202.

[3] Alcantar, J., Dhanjal, S., Boitnott, G. N., & Hender, S. (2025). Geothermal proppants: Qualification for use in superhot reservoirs. Proceedings, Stanford Geothermal Workshop, Stanford University, Stanford, California, February 10-12, 2025, SGP-TR-229.

[4] Norbek, J., Latimer, T., Gradl, C., Agarwal, S., Dadi, S., Fercho, S., Lang, C., Mcconville, E., Titov, A., Voller, K., & Woitt, M. (2023). A review of drilling, completion, and stimulation of a horizontal geothermal well system in North-Central Nevada. Proceedings, Stanford Geothermal Workshop, Stanford University, Stanford, California.

[5] Katende, A., Allen, C, Rutqvist, J., Nakagawa, S., & Radonjic, M. (2023). Experimental and numerical investigation of proppant embedment and conductivity reduction within a fracture in the Caney Shale, Southern Oklahoma, USA. Fuel, 341, 127571.

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[6] Stoddard, T., McLennan, J., & Moore, J. (2011). Fracture conductivity of a bauxite-propped geothermal system at in-situ conditions. Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 31 - February 2, 2011, SGP-TR-191.

[7] Stoddard, Trevor, McLennan, J.D., and Joseph Moore. "Residual Conductivity of a Bauxite-Propped Geothermal System-Influence of Self-Propping, Time, And Closure Stress." Paper presented at the 46th U.S. Rock Mechanics/Geomechanics Symposium, Chicago, Illinois, June 2012.

[8] Zhang, Q., Taleghani, A.D. (2023). On tunable fracture conductivity to enhance heat extraction from enhanced geothermal systems. Proceedings, Stanford Geothermal Workshop, Stanford University, Stanford, California, February 5-9, 2023.

[9] Hu X., Song, X., Wu, K., Shi, Y., Li, G. (2021). Effect of proppant treatment on heat extraction performance in enhanced geothermal system. Journal of Petroleum Science and Engineering, 207.

[10] Brinton, D., McLin, K., & Moore, J. (2011). The chemical stability of bauxite and quartz proppants under geothermal conditions. Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, California, January 31-February 2, 2014, SGP-TR-191.

[11] Mutume, B., Ettehadi, A., Dhanapala, B., Palisch, T., Radonjic, M. (2025). Multiscale Characterization of Thermo-Hydro-Chemical Interactions Between Proppants and Fluids in Low-Temperature EGS Conditions. Energies.

[12] Childers, M. I., Endres, M., Burns, C., et al. (2017). Novel highly dispersible, thermally stable core/shell proppants for geothermal applications. Geothermics, 70, 1–10.

[13] Tester, J.W., Anderson, B. J., Batchelor, A.S., …, Veatch, R.W. (2006). The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. MIT Report.

[14] Brown, D.W., Duchane, D. V., Heiken, G., Hrisca, V.T. (2012). Mining the Earth's Heat: Hot Dry Rock Geothermal Energy. Springer

[15] Bandara, K. M. A. S.; Ranjith, P. G.; Zheng, W.; Tannant, D. D.; De Silva, V. R. S.; Rathnaweera, T. D. (2022). Grain-scale analysis of proppant crushing and embedment using calibrated discrete element models. Acta Geotechnica, 17, 4837–4864.

[16] Al Balushi, F., Zhang, Q., & Taleghani, A. D. (2023). Autonomous fracture conductivity using expandable proppants in enhanced geothermal systems. SPE Journal, 28(5).

[17] Chen, C., Torres-Verdin, C., Miskimins, J., et al. (2024). Utah FORGE 5-2419: Temperature Testing of Proppants for EGS and Stimulation of Electromagnetic Fracture Mapping Using Electrically-Conducive Proppants - 2024 Annual Workshop Presentation.

[18] Chen, Y., Wang, H., Li, T., Wang, Y., et al. (2020). Evaluation of geothermal development considering proppant embedment in hydraulic fractures. Renewable Energy, Elsevier, vol. 153(C), pages 985-997

[19] Fredd, C. N., McConnell, S. B., Boney, C. L., & England, K. W. (2001). Experimental study of hydraulic fracture conductivity demonstrates the benefits of using proppants. SPE Production & Facilities, 16(02), 84–90.

[20] Ramazanov, V., Matovu, S., Al Shafloot, T. *et al.* Enhancing Fracturing Proppant Performance: Methods and Assessment. *Arab J Sci Eng.* 50, 4477–4503 (2025). https://doi.org/10.1007/s13369-024-09679-y

[21] Jenna, H., Rogers,T & Sever, M. (2025). Gaps, challenges, and pathways forward for superhot rock geothermal: summary report. Proceedings, 50th Workshop on Geothermal Reservoir Engineering, Stanford University, California, SGP-TR-229.

[22] Li, Z., Guo, R., …, Chen, C. (2025). Experimental and numerical investigation of fracture conductivity between non-smooth rock surfaces with and without proppant. Geoenergy Sci. and Eng., 246, 213582.

[23] KC, B., Ghazanfari, E., McLennan, J., Frash, L. & Meng, M. (2024). Evaluation of sintered bauxite proppant for binary enhanced geothermal systems. Geomech. Geophys. Geo-energ. Geo-resour., 10(21). https://doi.org/10.1007/s40948-023-00719-9

[24] Zimmermann, G. & Reinicke, A. (2010). Hydraulic stimulation of a deep sandstone reservoir to develop an Enhanced Geothermal System: Laboratory and field experiments. Geothermics, 39(1), 70-77.

[25] Xing, P., England, K., Moore, J. & McLennan, J. (2025). Analysis of the 2024 Circulation Tests at Utah FORGE and the Response of Fiber Optic Sensing Data. Proceedings, 50th Workshop on Geothermal Reservoir Engineering, Stanford University, California, SGP-TR-229.

[26] Wang, X. & Ghassemi, A. (2013). A three-dimensional thermal-poroelastic model for natural fractured geothermal reservoir stimulation. GRC Transactions, 37, pp.871-877.

[27] KC, B., Frash, L.P. & Ahmmed, B. (2024). Minimum propped fracture permeability for economic multi-stage enhanced geothermal systems. Proceedings, 50th Workshop on Geothermal Reservoir Engineering, Stanford University, California, SGP-TR-227.

[28] Taleghani, A., Shojaei, A., & Li, G. (2018). Shape Memory Polymer Proppants, Methods of Making Shape Memory Polymer Proppants for Application in Hydraulic Fracturing Treatments. Retrieved from https://repository.lsu.edu/engineering_patents/46

[29] McClure, M.W. & Horne, R.N. (2010). Discrete fracture modeling of hydraulic stimulation in enhanced geothermal systems. Proceedings, 35th Workshop on Geothermal Reservoir Engineering, Stanford University, California, SGP-TR-18.