# International Partnership for Geothermal Technology

# Stimulation Procedures Whitepaper

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# INTRODUCTION

The International Partnership for Geothermal Technology (IPGT) has defined seven technology focus areas:

1. Lower Cost Drilling
2. Zonal Isolation/Packers
3. High Temperature Tools
4. Stimulation Procedures
5. Modeling
6. Exploration Technologies
7. Induced Seismicity

A whitepaper has been written for each of these focus areas that gives a concise summary of the state-of-the-art and provides recommendations as to how to advance the technology in that area. This document is the whitepaper on "Stimulation Procedures." It has been jointly developed by Working Groups formed in Iceland, Australia, Switzerland and the United States. In addition, the stimulation working groups includes members from Germany, and Japan. In late 2009, a draft Stimulation Procedures whitepaper, authored by Charles F. Visser of the US National Renewable Energy Laboratory was circulated to all working group members for comments on its contents. Suggestions received were consolidated and blended into the current re-write of that original draft document.

This whitepaper summarizes the current state-of-the-art in stimulation and makes recommendations on advancing the technology for application to stimulation of EGS[1] reservoirs as well as single well stimulation and stimulation of hot, low permeability regions of otherwise productive geothermal systems. As a whitepaper, it remains current only for a relatively short time that depends on the rate of technology advancement. This document should, therefore, be reviewed and updated from time to time.

In this document, we define **hydraulic stimulation**[2] to mean the process of injecting fluid into a rock mass at, or below the fracture opening pressure (or far-field minimum principal total stress). Hydraulic stimulation, therefore, seeks to induce shear deformation on favorably oriented natural fractures in the rock mass, and through the process of shear-induced dilation, increase the permeability of the rock mass. We define **hydraulic fracturing** to mean the process of injecting fluid into a rock mass at a rate and pressure sufficient to form and propagate opening mode fractures.[3] Shearing will also occur in the rock mass around the opening mode fracture in response to fluid loss and stress changes associated with the main fracture. The pressure to extend a hydraulic fracture must therefore be above the minimum principal stress. Proppant may or may not be used. The Habanero wells in Australia are examples of application of "hydraulic stimulation"[4] methods (Wyborn, 2010).

[1] EGS includes both "Enhanced" as well as "Engineered" Geothermal Systems. Discussion continues within the industry about what to infer from the use of "Enhanced" or "Engineered" in the EGS label. No consensus exists and in this whitepaper they are considered synonymous.
[2] In the petroleum industry, this may sometimes be referred to as "matrix stimulation."
[3] Other modes of fracturing can occur concurrently with mode I (tensile fracturing).
[4] In most (all?) instances of high flow-rate stimulations (i.e. up to 50 l/s), downhole wellbore pressures reach what is believed to be the level of the minimum principal stress component. At sufficient distance from the wellbore however, the pressure will decline to lower levels, suggesting hydraulic stimulation to be the dominant

Experience in high temperature geothermal fields in New Zealand (Siega et al., 2009), Iceland (Bjornsson, 2004), Mexico (Flores-Armenta and Tovar-Aguado, 2008), Indonesia (Pasikki et al., 2010) and elsewhere has shown that permeability can be effectively increased by cold water injection. Significant volumes of cold water are pumped into the well, resulting in increased injectivity. We define this as **thermal stimulation.**

The term **stimulation**, as used here, may refer to hydraulic stimulation, hydraulic fracturing or thermal stimulation or some other stimulation process.

## HYDRAULIC STIMULATION - ISSUE DESCRIPTION

Reservoir stimulation is the single most critical research area for enabling the development of commercial EGS technology. Stimulation also provides a method to increase production in conventional geothermal wells and low permeability regions of otherwise productive geothermal systems. Effective stimulation should produce a permeable reservoir volume through which the injected water can be circulated to extract heat energy from the rock mass. The circulation must occur at rates sufficient to yield an adequate commercial return on the sale of the extracted energy, which is helped by low parasitic losses.[5] Furthermore, the flow within the reservoir should sweep a sufficiently large surface area to minimize the risk of early thermal breakthrough. For example, swept areas of the order of 2-5x$10^6$ $m^2$ are required to give operational lifetimes of 20-25 years (Batchelor, 1987; Kruger et al., 1992). Early thermal breakthrough has been observed at several prototype EGS sites where injector and producer were separated by less than 200 m (Nicol, 1989; Richards et al., 1994; Tenma et al., 2001; Zyvoloski et al., 1981). Well spacings significantly greater than this are required to avoid premature cooling of the production fluid and a progressive reduction in energy production. Alternatively stated, a larger and more uniformly stimulated reservoir volume will result in a significant increase in heat extraction rate and useful life of the wells. To avoid early breakthrough of cool fluids, the flow should occur through a large volume of the reservoir without localization into a few channels or fractures. However, if flow is localized in fracture channels, then enough of them must be present (or created) so that the swept area is sufficient to allow heat to be extracted at economic rates over the design life of the well-reservoir system. By stimulating the reservoir in a more uniform way (as opposed to only at a specific depth) or by creating multiple conductive fractures connecting the injection and production wells, the fluid movement from the injector to the producer wells becomes more uniform and, for the same energy extraction rate, involves slower fluid velocities and less differential pressure. This will also require wellbore completion that allows management of the flow at the multiple injection and production horizons. Flow localization is a function of the conductivity of the pathways (and their distribution) and the injection rate-viscosity product. For a given

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mechanism beyond that distance. Consequently, there is no consensus as to what the pressure field in a crystalline EGS reservoir undergoing stimulation looks like. Flow usually enters at a few narrow horizons corresponding to fractured zones; and so, velocities are high. In some cases, the flow may become turbulent, resulting in high pressure gradients near the well. In many ways, this is a problem for the modelers; hence, close collaboration with this Working Group is recommended.

[5] Parasitic losses refer to the total losses taken away from the heat energy available at the bottom of the borehole. These include overall inefficiencies in the flash or binary plants at the system converting steam to electricity, or heating some intermediate heat exchange fluid. They also consider the compression energy necessary to circulate water from one well to the other, and to the surface. These last ones are a function of the stimulated conductivity of the reservoir flow paths and the proper placement of the injecting and the producing wells, which is similar to a typical oilfield waterflood problem where “sweep efficiency” needs to be optimized. The stimulation and reservoir engineers need to work in concert here.

distribution of conductive pathways (fractures) a limit for the injection rate-viscosity product can be determined above which localization will start to become dominant.

The key technical challenge in reservoir stimulation is to achieve sufficient productivity from the reservoir for commercial EGS power generation without requiring an excessive pressure gradient across the reservoir, or resulting in excessive localization of flow. To this end, a viable stimulation procedure must (1) produce new, pervasive permeability rather than enlarging a few existing fractures, or (1a) stimulate a number of fracture zones through the reservoir to provide sufficient conductivity and swept area to allow economic heat extraction, (2) avoid the formation of a localized high conductive pathway that leads to early cold water breakthrough, and (3) maintain the conductivity of fractures in a variety of stress, temperature and geochemical regimes.

In the case of the stimulation of single hydrothermal wells which have poor productivity after drilling, the emphasis may be somewhat different as the stimulation of a few existing fractures may actually be the main purpose in order to connect the well in question to more permeable structures or reservoir volumes. Propellant fracturing is noted here as a method that has been proven to be useful in creating multiple radiating fractures from the wellbore to distances of approximately 5 m (Cuderman and Northrop, 1986). Increasing the penetration distance and conductivity of fractures formed by this means should be investigated. Propellant fracturing methods that work at high temperature are also needed.

The processes involved in natural fracture permeability enhancements are not well understood, and thus are not as yet amenable to control. Research and field projects have demonstrated that hydraulic stimulation can produce an increase in the rock mass equivalent permeability. However, to date there has been only limited progress in demonstrating the procedures required to stimulate large volumes of naturally fractured rock on the scale needed to produce a commercial reservoir (the Soultz 3.5 km reservoir was certainly progress although it was unfortunately never adequately tested (Genter et al., 2010)). Whereas large fractured rock mass volumes (several $km^3$) have been created in full-scale, in-situ experiments, circulating fluid through these conductive fracture systems at commercial flow rates of 50 l/s or more has not yet been accomplished, with the possible exception of Landau,[7] at least for an Engineered Geothermal System. Experience has also highlighted the potential problem of induced seismicity.

Zonal isolation (see Working Group 2 whitepaper) is essential for many stimulation activities and subsequent flow management, whether single well operations or EGS formation. Furthermore, the degree of zonal isolation that can be achieved will constrain the type of stimulation that can be carried out. Packers, cased and cemented completions, or other zonal isolation methods are required to allow focusing the stimulation into multiple discrete zones. Zonal isolation is important during production/injection and to target individual fractures or fracture networks for characterization of the reservoir and for validating models.

## HYDRAULIC STIMULATION AND HYDRAULIC FRACTURING - KNOWLEDGE GAP ANALYSIS

The petroleum industry’s treatment procedures are used routinely to create fracture half-lengths of 300 m or more. It is likely that a viable EGS heat exchanger can be made in sedimentary rocks using methods developed for stimulating petroleum wells, but this technology will need to be demonstrated for naturally fractured reservoirs under geothermal conditions. Hydraulic fracturing was applied to attempt to improve the productivity of hydrothermal wells as long ago as the 1980s under the US DOE-sponsored Geothermal Reservoir Well Stimulation Program (Campbell et al., 1981; Entingh, 2000), and produced mixed results. The reasons are difficult to evaluate, in part because of inadequate characterization of the host rock (including the stress state at the location, direction, and permeability of pre-existing fractures). Hydraulic fracture growth through a naturally fractured rock mass remains an issue of active research, but stimulations are routinely carried out in the petroleum industry, mostly in sedimentary naturally fractured rock, with good results. For the case of crystalline rock, the field data are more limited. High-rate viscous hydraulic fracture treatments with and without proppants have been performed in several EGSs including the Fenton Hill Phase 1 reservoir, (Brown et al., 2012), the Rosemanowes Phase 2A (CSM-Circ-15, 1984) and Phase 2B (Pine, 1989) reservoirs, and in the relatively shallow test facility at Le Mayet in France (Cornet, 1989). Results are mixed. Experience of hydraulic fracturing of crystalline, naturally fractured rock in mining settings, which included mine-through data, has demonstrated that single, opening-mode hydraulic fractures are formed when a short interval is isolated and pressurized at the wellbore (Jeffrey et al., 2009). The experience in the petroleum industry[6] suggests that if specific zones can be isolated, then hydraulic fracturing of EGS wells, or conventional hydrothermal wells, will result in a significant stimulation effect. Methods to apply hydraulic fracturing rather than hydraulic stimulation to an EGS reservoir should be developed.

Projects underway in France and Australia currently define the state-of-the-art in hydraulic stimulation technologies in crystalline geothermal reservoirs. The first phases of the project at Soultz-sous-Forêt, France, created a reservoir in a 165°C granite at 3,500 m depth that was then circulated at 25 l/s and produced at 140°C for four months without signs of thermal depletion (Genter et al., 2010). The circulation impedance of the system was 0.1 MPa/l/s, the first and only time this commercial target has been reached. For comparison, the target production rate for some commercial, deep EGS injection wells in Australia is approximately 100 l/s at 250°C. At the Habanero well site, circulation testing gave an injectivity for Habanero 1 of approximately 1 liter/MPa/s (Xu et al., 2012) which is equivalent to an impedance of 1 MPa/l/s, significantly higher than the impedance measured at Soultz. In 1998, the production well at Soultz was extended to 5,000 m depth, where a predicted rock temperature of 200°C was verified. Hydraulic stimulation in 2000 produced a 1.1 $km^3$ reservoir that has since been extended through the stimulation of two further boreholes to create a triplet circulation loop. The comparison of Soultz and Habanero demonstrates the strong affect of site conditions on the success of hydraulic stimulation and this is further reinforced by the experience at Landau, described below.

Another project in the Rhine Graben at Landau,[7] Germany, used hydraulic fracturing techniques to improve the injectivity of a well which intersected a fault system (Schindler et al., 2010). The production well also intersected a fault but needed no stimulation to produce at the circulation rate of 70 l/s. The system now produces 3 MWe+5MWth. This project serves to highlight the need to understand the processes underpinning the improvements in injectivity

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[6] Usually, in low permeability sedimentary and moderately metamorphosed reservoirs that are naturally fractured. Mechanical characteristics of some of these ultralow permeability shaley reservoirs (i.e. less than $10^{-18}$ $m^2$ absolute permeability) are significant (relatively large tensile and compressive strengths and low bulk compressibilities).

[7] Landau is an example of an Enhanced Geothermal System inasmuch as it is a conventional geothermal system whose performance was improved to commercially viable levels by a very high flow rate (190 l/s) stimulation of the injection well.

achieved by high-rate, high-pressure stimulation of open hole sections that include faults and major fracture zones. Experiments and analysis that include coupling of the Hydraulic-Thermal-Mechanical-Chemical processes are needed to fully understand the inherent mechanisms and ideally to optimize the various parameters.

Hydraulic stimulation of an injection well at Salak (West Java, Indonesia) resulted in an injectivity increase from , 8 kg/MPa/s to 38 kg/MPa/s, although some of this improvement may be due to thermal effects (Pasikki et al., 2010). In contrast, in a second well there was no increase in injectivity, but an improvement in well performance, conjectured to result from establishing a connection to a lower pressure fracture network[8].

General-purpose open-hole packers that have been demonstrated to work reliably do not exist for geothermal environments, with the primary performance-limiter being the poor stability of elastomeric seals at high temperatures. Existing borehole packers are incapable of handling temperatures above 175°C and do not seal effectively in the enlarged, broken-out wellbores often encountered in geothermal wells. Experimental packer systems have been developed for geothermal environments, but they currently only operate at low pressures, and they are not retrievable. Cased-hole isolation tools suitable for high-temperature environments are emerging. These tools have the advantage of metal-to-metal seals, but they still rely on packers to affect the zonal isolation. A fully cased and cemented completion would facilitate individual hydraulic fracturing treatments into perforated or slotted intervals along the well. The zonal isolation white paper contains a detailed discussion of the current status of packer technology.

## THERMAL STIMULATION

In thermal stimulation, injectivity increases with injection time (often approximately proportional to $\sqrt{t}$), and with the temperature contrast between reservoir and injection temperature (Lim et al. 2011, Grant 2012). Injectivity can be increased by up to a factor of ten, and averages around a five-fold increase (Axelsson and Thórhallsson, 2009). Comparison with productivity shows that permeability-thickness has increased by more than 10-fold. The effect is, at least in part, reversible, because if the well is allowed to warm injectivity decreases again. The change is considered to be caused by thermal contraction of the rock, and opening of the fractures. On occasion it may be necessary to pump at high pressure to open the fracture sufficiently to accept some flow. Once this has happened, further improvement is created by the cooling of the fracture.

It is not clear what portion of the permeability increase achieved by cold water injection will remain after the well is allowed to reheat. If there is thermal stress cracking and spallation and/or self propping when the fractures are cooled, a permanent increase in permeability of a production well may be possible. Occasional trials of thermal stimulation in production wells have shown variable results, with an improvement being sometimes achieved (Tulinius et al. 2000, Kitao et al. 1990, Zúñiga 2010).

Chemical stimulation methods have proven to be effective in the case of single hydrothermal well stimulation operations, particularly in carbonate reservoirs (Schumacher and Schulz, 2012). More generally, there is considerable variability in the efficiency of the treatments applied in different geothermal fields (Portier et al., 2009), and the factors underlying this variability are poorly understood. There is currently little experience in applying chemical stimulation methods to EGS wells. Chemical stimulation processes therefore require further study.

## CURRENT LIMITATIONS TO STIMULATION PRACTICE

Three main limitations to stimulation practice should be addressed to enable commercial development of EGS reservoirs as well as improved productivity of conventional geothermal wells or low permeability regions of otherwise productive geothermal systems:

1. Hydraulic fracturing, as used in the oil and gas industry, has been tried at several EGS reservoirs in both sedimentary and crystalline rock. However, results have been generally poor and the lack of zonal isolation has posed a significant obstacle. These data should be examined in the light of the current understanding of fracture growth mechanics and current practice in shale gas stimulation to try to understand why these previous attempts were not effective. Hydraulic fracture stimulation will always include considerable hydraulic stimulation as the rock volume around the hydraulic fracture channel is pressurized, inducing shearing.
2. Better zonal isolation should be developed and tested to enable effective hydraulic fracture stimulations. Cemented casing completions with slots or perforations should be tested in an EGS well.
3. Hydraulic stimulation has been shown to enhance the permeability of the rock mass in some cases, but creation of sufficiently uniform or sufficiently low injection impedance flow paths has not been demonstrated.
4. Incomplete knowledge about the process of thermal stimulation and the factors influencing it.

## STIMULATION OBJECTIVES

Stimulation procedures should be designed to:

1. Induce new, pervasive fracture systems rather than enlarging a few existing fractures, except in the case of single hydrothermal well stimulation (see above),
2. Stimulate sufficient fracture zones through the reservoir to allow efficient economic heat extraction,
3. Avoid formation of a localized high conductive pathway that leads to early cold water breakthrough,
4. Create commercial-scale fractured rock volume and water-accessible fracture area,
5. Maintain conductive fractures in a variety of stress, temperature and geochemical regimes.

The capability to achieve reliable zonal isolation (see whitepaper on this subject) is a key technology that must be implemented to enable improved reservoir stimulation technology.

### POTENTIAL APPROACH

A database of case histories of stimulation operations in EGS and conventional geothermal reservoirs should be developed that will allow methodologies to be evaluated. Lessons learned can be tested for each type of reservoir and in different geological settings in field demonstration projects, possibly located in Australia, the United States, and Iceland.

Possible tasks for demonstrating fracturing methodologies include:

- Set technical objectives for improvement of geothermal stimulations. The objectives will differ for EGS development, conventional geothermal wells or low permeability regions of otherwise productive geothermal systems.
- Develop methods to assess the risk of injection-induced seismicity and methods to control the identified risk in conjunction with the IPGT Working Group on induced seismicity.
- Develop recommended stimulation procedures for various reservoir types and conditions.
- Demonstrate the ability to characterize and then consistently and predictably achieve sufficient stimulation within large volumes of naturally fractured hard-rock lithologies and in different geological environments.
- Conduct experiments under the controlled in-situ conditions afforded by underground rock laboratories or mines to better understand the stimulation process and basic parameters such as the area swept by forced fluid flow in fractured hard rocks.
- Develop and verify models for predicting fracture surface area, flow impedance, fracture spacing and stimulated rock volume in conjunction with the IPGT Reservoir Modeling Working Group.
- Design and implement innovative reservoir stimulation methodologies using existing and new fracture and reservoir/geomechanics models that consider the coupled fluid-thermal-mechanical system to predict fracture shear and opening displacement and reservoir conductivity change.
- Develop improved-resolution stimulation monitoring tools and analysis methods for application to real-time treatment control and post-treatment reservoir evaluation.
- Investigate the application of pressure-transient concepts in analyzing the induced fracturing system, i.e. primary vs. secondary permeability enhancements.

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