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# Literature Survey of Stimulation Techniques in Geothermal Wells WP 2.05

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# 1 INTRODUCTION

## 1.1 STIMULATION TECHNIQUES IN GEOTHERMAL WELLS

The report is part of the activities planned in the work project of WP 2.05: Hydro-Fracturing and Acidizing. The activity documented in this report based on **Activity 2.05 b**: literature review, summarizing data on well stimulation, and to study the results of previous geothermal stimulation jobs in worldwide and Indonesia. What was done and what was the result.

Two main types of stimulation technologies can be considered (Combs et al., 2004):

1. Mechanical techniques can be:
   - Hydraulic fracturing due to massive fluid injection in the wells
   - Thermal stress fracturing due to temperature reduction
   - Explosive fracturing
   - Well mechanical treatment: re-deepening, jetting, scraping
2. Chemical techniques include:
   - Matrix acidizing or chemical stimulation
   - Clay shrinking and/or stabilization
   - Scale inhibitors

According Combs et al. (2004), the stimulation procedure considered in most of the geothermal well stimulations to date is hydraulic fracturing of the potential producing formation. A fracture are created by increasing the pressure inside a wellbore until the formation surrounding the wellbore fails in tension and separates either at the site of a pre-existing fracture or via a new fracture. The resultant fractures are intended to enhance the flow into the well by increasing the fracture surface area in the producing formation or by connecting it to existing fractures that will supply reservoir fluids to the wellbore

In addition to hydraulic fracturing techniques, thermal and explosive fracturing techniques have been experimented with in geothermal reservoirs. Although thermal fracturing is not perfectly understood, temperature cycling in geothermal wells is known to cause fractures in subsurface rocks. Temperature limitations, emplacement problems, and safety aspects for both equipment and personnel severely limit the use of explosive fracturing in geothermal wells.

Chemical reactions between stimulation fluids and solids are the basis for some types of well stimulation techniques such as matrix acidizing and acid fracturing. The solids to be attacked may be either native to the formation (such as clays and cementation materials) or those subsequently deposited in the pore channels (such as scale or solids from drilling fluids). The effectiveness of chemical stimulation methods in geothermal applications has been limited because the complex physical and chemical reactions involved are not well understood under geothermal conditions.

This report provides an overview of stimulation techniques used in the past, classify them and define associated mechanisms. This review compiles information and results obtained stimulation campaigns performed for hydrothermal systems and HDR/EGS.

# 2 LITERATURE REVIEW

## 2.1 HYDRAULIC FRACTURING

Reservoir stimulation mechanisms in geothermal reservoir are quite closed to mechanisms described in the petroleum reservoir (Economides and Nolte, 1989), although a major difference exists between their purpose. Petroleum reservoir stimulation aims at increasing the permeability of a reservoir in order to allow the maximum oil recovery, which stands in rock pores, as geothermal reservoir stimulation aims at optimizing heat recovery, which is stored in the rock matrix.

### 2.1.1 Hydraulic Fracturing Experiences

Kohl and ClémentIt (2006) provides an overview of hydraulic fracturing stimulation techniques used in the past, classify them and define associated mechanisms, summarize as following.

As many stimulation campaigns have been performed on various hydrothermal and EGS site all over the world, the purpose of this section is not to give an exhaustive index of the results of each test. The authors want to try to classify the main stimulation phases performed on geothermal reservoirs and the conclusions they led to, according to the considered reservoir properties (stress field, open or closed reservoir etc.) and to the type of stimulation realized (injected fluid, use of proppant, packers, flowrate etc.).

***Hydraulic stimulation with a proppant agent***

Three stimulation with a proppant agent were performed in Urach, Germany, in 1978 (Jupe et al., 1993). The Urach reservoir faces a normal faulting stress field ($\sigma_v > \sigma_H > \sigma_h$), characterized by a very low minimum horizontal stress, and a maximum horizontal stress nearly equivalent to the overburden. Proppant agent concentrations are related to be of 90 and 240 g/l of bauxite sand, in water or viscous gel. No results were obtained concerning the well injectivity, but the connection between wells could be increased after the last stimulation with proppant agent.

Three stimulations with proppant agent are also reported in le Mayet-de-Montagne, in France, in 1988 and 1989. This reservoir is quite an open system, with a normal faulting stress regime ($\sigma_v > \sigma_H > \sigma_h$). Each time, between 100 and 200 $m^3$ of water were injected, with a volume of proppant agent (sand) of 2, 7, and 40 tons of sand injected. If the first stimulation with proppant result was not significant, the second stimulation led to a great improvement of the recovery factor between wells, going from 20%, decreasing, to 58%, stable. Though, no improvement of the well injectivity was observed during any of the three stimulation campaigns (Jupe et al., 1993).

Proppant injections also occurred in Rosemanowes, UK. This geothermal reservoir is characterized by a strike-slip stress regime ($\sigma_H > \sigma_v > \sigma_h$). Proppant injections in production well RH15 are related to have had a good influence on the Rosemanowes reservoir responses, increasing the recovery factor from 70% to 85% (Willis-Richards et al., 1995). Proppant injections also took place in the Gamma project reservoir, Japan (Jupe et al., 1993) and in the Fjallbäcka reservoir, Sweden (in combination with viscous gel injections) (Willis-Richards et al., 1995), that is characterized by an inverse faulting stress regime ($\sigma_H>\sigma_h>\sigma_v$) or a strike slip regime, but few literature was found to conclude on the positive or negative effect of these stimulations.

One could here notice that proppants injections with viscous gels can be performed in sedimentary reservoirs, like in the Rotliegend well situated in the eastern part of Germany (Legarth et al., 2003).

### *Hydraulic stimulation with a viscous gel*

Viscous gels injections are often realized in combination with proppant injections. Low and high viscosity gels injections were performed in le Mayet-de-Montagne; these injections, when realized with a high viscosity gel, are reported to help jacking of fractures connected to the well, but finally quite low results were reported after these injections. High viscosity gels were also used in Rosemanowes, UK (Baria and Green, 1986), in order to increase chances of jacking and opening of fractures in tensile mode more than shearing, but recorded focal mechanisms were in fact consistent with strike-slip shear.

As geothermal conditions are most of the time extreme conditions –high temperatures, high stresses and highly corrosive fluids, there is a great need of material and techniques development. In that purpose, new gels and stimulation fluids based on saponite and smectite clays are tested (Hirano et al., 2000)

### *Hydraulic stimulation in a limited section of the well*

Stimulation injection in perforated casing was performed in well Habanero 1 in the EGS of Cooper Basin, Australia (Wyborn et al., 2005). This geothermal field is characterized by an inverse faulting regime ($\sigma_H>\sigma_h>\sigma_v$). Following stimulation 1 (realized in the entire well open section), packers were introduced at the top of the well open section, and perforations of the casing above the casing shoe were made. This technique allowed showing up fractures in which inflow could reach 25 l/s during injections phases.

Hydraulic stimulation performed in Falkenberg, Germany took place in a 3 m long packed-off interval, which had previously been identified by core and BHTV logging as the center of a 50m long joint free interval, at 250m depth (Jupe et al., 1993). Falkenberg stress regime changes from an inverse faulting regime above 100 m, to a strike slip regime between 100 and 200 m, and to a normal faulting regime below. This technique allowed the creation of a new hydraulic fracture in the packer interval.

Packers were also tested on the injection well of the Hijori site, Japan, but, as packer rubbers were found to be damaged because of reservoir very high temperatures, no conclusion could be deduced from tests performed in that site. Packers were also used in le Mayet-de-Montagne, France, but their use combined with the injection of proppant makes any conclusion very hazardous.

The technique of injections in perforated and cemented casing was also used during phase 1 of the Fenton Hill project, and packers were used during phase two of the project, with relatively good results after several tests, as injectivity of the wellbore was 2 l/s/MPa and recovery factors was evaluated to 60%. Literature also reports (Jupe et al., 1993) stimulations in perforated casings and using packers in Urach, Germany, and the use of perforated casings was in that case thought to be responsible of high friction losses in the casing.

Another technique that could here be described is well plugging or well sanding/reaming/fracturing. This technique consists, in case of low inflow possibilities in the open section of the well, to sand up the well open section and then to ream out a part of the casing, in order to perform hydraulic stimulation in the reamed part of the casing. Its application is independent of evaluated stress regime of the reservoir. Such experiments were successfully performed at very small scale (flowrates lower than 3 l/s) in the Akinomiya site, Japan (Jupe et al., 1993). This technique of well sanding was also used in the Ogachi EGS, Japan and is very precisely described in literature (Kaieda et al., 2005). In this site, two reservoirs were successfully created at depth of 719 and 1000 m.

*Hydraulic stimulation with water or brine only*

As the cheapest fluid available in high quantity on earth is water, most of hydraulic stimulation phases in EGS were performed using fresh water, or with heavy brines, i.e. NaCl saturated water, reaching a density of 1200 kg/m$^3$ at 20°C. If quantities of available brine are often limited to the capacity of external tanks, one can find evidences that the injection of such a fluid into the reservoir before fresh water injection during stimulation phases can be established (Baujard and Bruel, 2005). Water injections offer the possibility of injecting great volumes of fluids in order to improve well injectivities, productivities or the recovery factor between wells. Another advantage of long-term fresh water injections in the reservoir is that this injected water can temporarily cool down the rock temperatures, leading to a thermal stimulation, due to contraction of rocks.

Though water injections allow high rate injections over long time periods, many uncertainties remain concerning the way of optimizing such injection in order to obtain good stimulation results.

The 5-km depth EGS reservoir of Soultz-sous-Forêts, France, has been developed using essentially fresh water and heavy brine injections, and some acid injections more recently (Baria et al., 2006). Thanks to these operations, connection could be achieved between two wells GPK2 and GPK3, the connection with the last well-being problematic for the moment. Massive hydraulic stimulations were also performed in well Habanero 1 of the Cooper Basin EGS, Australia (Asanuma et al., 2004; Wyborn et al., 2005), in the Ogachi geothermal reservoir (Kaieda et al., 2005; Tenzer, 2001) , in the Hijori EGS (Matsunaga et al., 2005), and in Fenton Hill (Robertson-Tait et al., 2000).

A long-term massive cold water injection program has also been utilized as an effective hydraulic stimulation method for low capacity injectors in the Salak geothermal field taking advantage of the large temperature difference between the injecting fluid and the formation (>167 $^{o}$C) and relatively high coefficient of thermal stress (Yoshioka et al., 2008, and Pasikki et al., 2010). Three massive water injection stimulation treatments have been conducted on a well drilled within the proven reservoir boundary but exhibiting relatively low permeability characteristics. These stimulations included injection of 3.3 billion pounds of water and successfully increased well injectivity by more than 150%.

Hydraulic stimulation phases are planned in the Desert Peak reservoir, Nevada (Robertson-Tait et al., 2005) and probably in the Coso geothermal field, where low pressure stimulation experiments were realized (Rose et al., 2006) and stimulation test on shear of the fractures were done on site (Rose et al., 2005).

Cold water (condensate fluid) injection into geothermal reservoirs of Wayang Windu has been experienced (Mulyadi, 2010). The objective of this injection is to document production improvement by creating hydraulic fracturing due to cold water injection. To test this conclusion an injection program to initiate hydraulic fracturing was conducted in two wells. A series of multiple injection rate followed by fall off tests gives the parameters for designing the hydraulic fracturing jobs to improve well performance. An injection program to produce hydraulic fracturing was then conducted. The choice of the maximum injection rate is the critical aspect in initiating fracture opening. Post test treatment shows that new fractures were created and production improvements were achieved. Average steam mass flow production improved by 50 – 100 %.

### 2.1.2 Review of Application on Hydraulic Fracturing in Geothermal Fields in Indonesia

In geothermal fields, drilling of geothermal is aimed to intersect body of the fractures or faults. Sometimes, however, the drilling operation failed to meet fractures. Wells may intersect high temperature formation but no total loss of circulation occuring during drilling, indicating failed to meet fractures. A number of wells in Tompaso geothermal fields, for example, shows that the wells intersect formation up to 250-275oC, but failed to meet fractures. Hydraulic fracturing is needed to create hydraulic induced-fracture which will connect wellbore with natural fracture. Well candidates suitable for hydraulic fracturing in geothermal formations may also geothermal field with existing high temperature, but low in permeability.

Application of hydraulic fracturing in high temperature hydrothermal reservoirs, however is still very rare. The temperature of geothermal reservoir is considerably high compared to those at oil reservoir. From a review on the the reservoir temperature of several geothermal field in the world, including Indonesia, the temperature of geothermal reservoir could be as high as 350°C (Table 1).

Tabel 1. Reservoir Temperature in Two-phase Geothermal Field in Indonesia (Suryadarma et.al.. 2010).

| Field | Reservoir Temperature |
|---|---|
| Salak | 235-310 $^{o}$C |
| Bedugul | 280-320 $^{o}$C |
| Dieng | 240-330 $^{o}$C |

| Field | Reservoir Temperature |
|---|---|
| Hulu Lais | 250-280 °C |
| Karaha Bodas | 250-350 °C |
| Kotambagu | 250-290 °C |
| Lahendong | 250-350 °C |
| Lumut Balai | 260-290 °C |
| Sarulla | 250-310 °C |
| Sibayak | 230-280 °C |
| Sungai Penuh | 230-240 °C |
| Tompaso | 240-260 °C |
| Ulubelu | 240-260 °C |
| Wayang-Windu | 240-300 °C |

The past five years there is growing interest to apply hydraulic fracturing in geothermal field in Indonesia, such as in Salak geothermal field (Yoshioka and Pasikki et al., 2009; Yoshioka and Jermi et.al, 2015) and the Wayang-Windu geothermal field (Mulyadi, 2010). Both fields are high temperature water dominated reservoir in volcanic formation.

An application of fracturing treatment for enhancing well injectivity in Gunung Salak geothermal field, Indonesia has been described by Yoshioka and Pasikki et al. (2009) and Yoshioka and Jermi et.al. (2015). The Salak field is a water dominated geothermal field producing up to Salak geothermal field has been generating 110-377 MW of power generation for more than 20 years. The treatment was brought to low capacity injectors in order to achieve improvements in well injection capacity. The fracturing treatment did not include use of proppant, hence the method applied is more thermal fracturing, which utilized high coefficient of thermal stress and temperature difference between the injected fluid and the temperature of reservoir fluid - at about 300°F (149°C) of temperature difference. These differences in thermal stress and temperature will then lead to rock failure. Comparison between PTS before and after fracturing treatment showed that more feedzones identified after hydraulic stimulation and injection above fracture gradient pressure during hydraulic stimulation has developed new fractures. According to Pasikki (2015), after stimulation the Injectivity Index improved by 180%, WHP at zero flow has declined from 400 psia to 100 psia, injection capacity of Awi 18-1 has improved up to tenfold. He suggested that when planning a well stimulation project, collecting information from different sources and doing an integrated interpretation makes possible a better characterization of the process. Combined use of Hall plot, MEQ events, Injectivity test and Pressure Fall-off can give consistent picture of progress and effectiveness of stimulation.

Similarly, fracturing treatment applied in the Wayang-Windu geothermal field (Mulyadi, 2010), is more thermal fracturing because it did not include use of proppant. The Wayang Windu geothermal field has been generating 227 MW electricity. It is interpreted as transitional between vapor- dominated and liquid-dominated conditions. The enthalpy of the fluid ranges from 1300 kj/kg until 2788 kj/kg. Fracturing was conducted by injecting cold water (condensate fluid) to the reservoir with multiple step injection rates. Comparison between pressure transient analysis before and after stimulation confirm the improvement of productivity of the well.

### 2.1.3 Review of Previous Study at ITB on Hydraulic Fracturing Application in High Temperature Geothermal System

Researches to study hydraulic fracturing application in high temperature geothermal system has been conducted at the Institut Teknologi Bandung (ITB) since 2010, among others by Rachmat and Winarno (2010), Saptadji and de Jong (2015), Rachmat and Prihatmaka (2015) and Rachmat and Asri (2015).

*Summary of a Study on Water Fracturing and Proppant Fracturing Treatment Applied on High Temperature Water Dominated Hydrothermal System (Rachmat and Winarno, 2010)*

Rachmat and Winarno (2010) conducted a study of water fracturing and proppant fracturing treatment applied on high temperature water dominated hydrothermal system, with the folllowing objectives:

1. To study the potency of applying hydraulic fracturing treatment in geothermal well of hydrothermal system, to analyse the obstacles of its field operational procedure, and to find optional solutions to it.
2. To build a model of hydraulic fracturing operation in geothermal well of hydrothermal system by conducting simulation using hydraulic fracturing simulator.
3. To find optimum condition of hydraulic fracturing operation by conducting a sensitivity study on both given and changeable parameters such as reservoir temperature, rock type, porosity, permeability, fracture gradient, fluid system, pumping rate, and proppant size.
4. To compare the cost of water fracturing and proppant fracturing, and to study the economy of proppant fracturing.

Regarding the obstacles, they concluded that there will be many design considerations if a proppant fracturing technology is selected to be brought on a high temperature geothermal well. The most vulnerable component of a proppant hydraulic fracturing treatment regarding the formation temperature is the hydraulic fracturing fluid system, as its properties will decay as it is exposed in higher temperature. The early thermal degradation of the fluid system will reduce the efficiency of the hydraulic fracturing treatment. Among the properties of the fluid system (i.e. compatibility with formation fluid, fluid loss, breaking (viscosity reduction), proppant-carrying capacity), the capacity of the fluid system to carry proppant is likely to be damaged by the high formation temperature. Additives - crosslinked fluid – which is used to form a highly viscous solution so that the fluid system is able to suspend and carry proppant could only withhold a maximum temperature of 400°F (204°C), much lower for geothermal fields in Indonesia.

They described that important components in design hydraulic fracturing treatment, are including selection of the fracturing fluid, the proppant, the pumping schedule, and the fracture geometry model, as the following:

1) Fracturing fluid holds important role in a hydraulic fracturing treatment. The fluid is used to open the fracture, and at the same time to transport proppant along the fracture length. Regarding these two main functions, the important parameters a fracturing fluid should acquire are viscosity, fluid breaking, fluid loss, and friction pressure. The fracturing fluid should have proper viscosity to suspend proppant so that the proppant is transported and well distributed through the length of the fracture. The fluid should also acquire low fluid loss so that the designed fracture geometry could be achieved. It should also break and clean up rapidly once the treatment is over. Friction pressure exerted during pumping is yet another important parameter regarding the fracturing fluid since the higher the friction pressure, the higher the surface treating pressure will be, imposing threat to the well's tubular of which pressure rating is limited.Among several types of fluid used in hydraulic fracturing treatment, which are water-base fluid, oil-base fluid, acid-base fluid, and multiphase fluid, water-base fluid is the most commonly used since it is low in cost and easy to handle. Oil-base fluid is more expensive and more difficult to handle, and only used in a highly water sensitive formation. Acid base fluid is used in an acid treatment, which is a different version of hydraulic fracturing treatment utilizing acid injection, while multiphase fluid (e.g. foams and emulsions) is the fluid type made in order to incorporate the properties of standard water-base fluid, oil-base fluid, or acid-base fluid.

2) Proppant Selection. The use of proppant in a hydraulic fracturing treatment of geothermal formation is still debateable. In conventional hydraulic fracturing method, proppant is injected along within proppant slurry with one objective of keeping the fracture open after the injection has ceased. In case of water fracturing, the proppant is not used. In this case, the fracture is kept open if shear slippage exerted during the treatment is sufficient, so that one rough rock surface can slide over/atop another. Thus, the joint opening and permeability are irreversibly increased even if the pressure treatment is suddenly ceased.
3) Pumping Schedule. Designing a hydraulic fracturing treatment starts with the design of desired fracture geometry. The geometry of the fracture includes fracture half length, fracture height, and fracture width. For example, the desired fracture half length might be determined from the distance between the wellbore to the nearest existing natural fractures which is intersected by the other well (as it has been conducted in Baca, New Mexico, and Raft River, Idaho). In case of Hot Dry Rock stimulation, the desired fracture half length is simply the downhole distance between injection well and production well. The next step is designing the pumping schedule. An accurate pumping schedule is required to meet the desired fracture geometry. This pumping schedule design includes the pumping rate, the pumping stages, the slurry volume of each stage, the pumping time, the proppant mass and proppant concentration of each stage. In this study, the pumping schedule is generated by using PSG (Pumping Schedule Generator) available in the simulator. The PSG will generate the pumping schedule of the treatment based on the design of the fracture geometry and proppant concentration. Generating the pumping schedule by using PSG is faster and more efficient than adjusting the pump schedule and running the simulation over and over again until the desired fracture geometry is achieved (trial and error).

   The PSG provides three different types of treatment design capability, which are liquid only, non tip screen out, and tip screen out. In this study, as the simulation is conducted for both water fracturing and proppant fracturing, the pumping schedule will be generated based on treatment design capability of liquid only (for water fracturing), and non tip screen out (for proppant fracturing). The tip screen out design is not used since it is applied in designing a hydraulic fracturing treatment of which tip screen out was intentionally designed to occur. It is usually conducted in a hydraulic fracturing treatment of originally high permeability formation. The reason for this type of treatment is to by-pass near wellbore damage thus restoring/enhancing the well productivity (more to generate fracture conductivity than fracture length).16 The fracture created is short in fracture length but extends more on the fracture width. The fracture length is not necessarily long since the main target is to create a conductive conduit with penetration range just over the damaged zone (normally in few inches). Since this study is focused on how to increase the conductivity of tight reservoir or connecting the wellbore with the existing natural fractures, where a long hydraulic fracture half length is more preferable, then the suitable PSG treatment design is the non tip screen out (for proppant fracturing) and the liquid only (for water fracturing).

4) Fracture Geometry Model. Basically, several models that had been developed to simulate the propagation of fractures might be classified into below categories:

   a. Two dimensional models (2D)
   b. Radial models
   c. Pseudo three dimensional models (pseudo-3D)
   d. Three dimensional models (3D)

   Two dimensional model was developed under assumption that the fracture propagates in a plane strain condition (on horizontal or vertical plane). Included to this type of model are PKN (Perkins-Kern-Nordgren) and KGD (Kristianovich-Geertsma-De Klerck) model, both simulating fracture propagation with a constant-uniform height.

   The pseudo-3D models are used to simulate vertical and lateral propagation of a fracture by removing the assumption of constant-uniform height (the height depends on the position along the fracture and time) and applying assumption that the fracture length is greater than the height. The simulator used in this study allows the pseudo-3D modelling, but only for a condition of multi-lateral formations. Therefore, the synthetic model of single-thick layer formation of geothermal formation could not be run using pseudo-3D model.

   The 3D models were developed to simulate the general extension of the fracture considering the 3D stress distribution, fluid flow, fluid leak-off and heat transfer. However, the simulator used in this study does not provide this kind of model.

   The radial model was developed to simulate fracture that propagates radially with independent height growth (unlike the 2D models). This radial model may also be applied for thick formation (without barrier at top and bottom), so that the vertical growth of the fracture would extend radially.9 Regarding that the geothermal formation is commonly in great vertical extend (thickness ranges from tens of meters up to hundreds of meters), the simulation could be run based on the radial fracture geometry model.

In their study, Rachmat and Winarno (2010) developed a model of high temperature water dominated hydrothermal system using numerical simulator based on literature review concerning its reservoir property and well geometry. The hydraulic fracturing treatment introduced to the model is simulated in two distinctive methods of water fracturing and proppant fracturing. The conclusions are as the following:

1) The fracture created by means of water fracturing treatment simulation is kept open after the treatment has ceased although it does not involve any use of proppant. Nevertheless, the connection between the fracture body and the wellbore is not ensured, according to zero values of fracture conductivity.

2) Reservoir temperature, rock type, porosity, permeability, fracture gradient, fluid system, pumping rate, and proppant size affect the fracture geometry and the treatment efficiency of both water fracturing and proppant fracturing.

3) Fracture half length and treatment efficiency are decreasing with the increasing reservoir temperature. In the case of water fracturing treatment, the target 200 ft of fracture half length is not achieved at reservoir temperature higher than 400°F. As for proppant fracturing treatment, the 200 ft fracture half length is attained at reservoir temperature of 300°F and below.

4) Different rock type - and its coherency with Young's Modulus - imposes variation in fracture half length and treatment efficiency. In the case of water fracturing treatment, the achieved fracture half length is similar for all rock types. As for proppant fracturing treatment, the 200 ft target of fracture half length and highest treatment efficiency are attained only at lowest Young's modulus of siltstone.

5) High porosity reduces the fracture half length and treatment efficiency. In the case of water fracturing treatment, the 200 ft target of fracture half length is obtained at porosity of 10% and below. In the other hand, proppant fracturing treatment failed to meet the target at all range of porosity value due to proppant bridging.

6) High reservoir permeability lowers both fracture half length and treatment efficiency. In the case of water fracturing, the 200 ft target of fracture half length is achieved at reservoir permeability of 0.1 mD and above. As for proppant fracturing, all treatments have failed to meet the target due to proppant bridging. High treatment efficiency is obtained at low reservoir permeability.

7) High fracture gradient resulted in shorter fracture half length and lower treatment efficiency. In the case of water fracturing, the 200 ft target of fracture half length is achieved only at fracture gradient of 0.7 psi/ft and below. As for proppant fracturing treatment, all treatments ended up with proppant bridging. Similar trend is observed for both method where high treatment efficiency is in coherence with low fracture gradient. Higher fracture gradient also imposes higher surface treating pressure.

8) Different fluid system shows different performance and results in varying fracture half length and treatment efficiency. Fluid system added with fluid loss agent and other additives has better performance than pure water or 4% KCl brine due to lower fluid leak off coefficient.

9) Higher pumping rate is linearly proportional to longer fracture half length and higher treatment efficiency. In the case of water fracturing, both parameters keep increasing with higher pumping rate. As for proppant fracturing, applying 20 bpm pumping rate and above hindered the treatment from suffering near wellbore screen out and proppant bridging.

10) In the case of proppant fracturing treatment, utilizing smaller proppant size resulted in longer fracture half length. However, in term of treatment efficiency, larger proppant size has better efficiency since it propped wider fracture width.

11) Fracture gradient, among all parameters, imposes the most influential effect on fracture half length and treatment efficiency.in the case of water fracturing, the most influential parameters are fracture gradient, reservoir permeability, fluid system (fluid leak off coefficient), reservoir temperature, pumping rate, and porosity, respectively. In the case proppant fracturing, the most influential parameters are fracture gradient and reservoir temperature.

12) The cost of water fracturing treatment is less expensive than the cost of proppant fracturing treatment, mainly due to the exclusion of fracturing chemical cost and shorter time period required to complete the job. Water fracturing treatment costs only roughly 60% of the proppant fracturing cost.

13) Based on the result of the study, both water fracturing and proppant fracturing methods are applicable to high temperature water dominated hydrothermal system with each method has its own advantages and disadvantages.

14) Water fracturing has lower cost, and the main fluid system is easier to be found. Nevertheless, it is more severe to fluid loss, and the connection between fracture body and the wellbore is not ensured.

15) The connection between fracture body and the wellbore is ensured in proppant fracturing. Nonetheless, it is more expensive, and it is more severe to proppant bridging due to high reservoir temperature.

***Summary of Proposed Hydraulic Fracturing Scenarios in Indonesian Tight Sedimentary Formation (Saptadji and de Jong, 2015)***

Saptadji and de Jong (2015) conducted a study about hydraulic fracturing scenarios in Indonesian tight sedimentary formation with objectives of the following:

1) To study extensively sedimentary EGS cases taking the GeneSys and the Groß Schönebeck projects as main examples, from the viewpoint of geology, geomechanics, well design, stimulation scenarios and designs.

2) To simulate proposed scenarios to be applied in the under-producing Field-X located in Indonesia.

3) To propose list of considerations before performing a hydraulic stimulation in sedimentary formation taking into account all factors contributing to their success or failure.

By reviewing valuable lessons and insights from Groβ Schönebeck and GeneSys, which are both non-commercial researches of EGS in sedimentary formations, de Jong (2015) designs and proposes the most appropriate scenarios of hydraulic proppants fracturing in a low-permeable part of a sedimentary geothermal formation in Indonesia. Two wells in X field have been selected as fracturing candidates based on the relative orientations of their trajectories against the orientation of the formation's principal stresses. Two most optimum different scenarios have been designed for these wells which could give the biggest propped width and the longest fracture half-length using available resources of proppants type and fracturing fluids. Fold of Increase (FOI) of post-treatment production performance in both Well-1 and Well-2 are six (6) times that of pre-treatment. Compared to FOI in Groβ Schönebeck project which is predicted to be three (3) to five (5) times, this predicted FOI in Well-1 and Well-2 is relatively better. Important technical things to be considered before performing hydraulic fracturing, along with logs and tests which have to be done prior, during, and after such job, are also listed.

*Summary of Techno – Economic Study of Geothermal Well Hydraulic Fracturing in Indonesia (Rachmat and Prihatmaka, 2015)*

Rachmat and Prihatmaka (2015) techno – economic study on geothermal well hydraulic fracturing in Indonesia, with the objectives are to:

1) Develop a model based of geothermal reservoir for hydraulic fracturing treatment.
2) Develop hydraulic fracturing treatment design.
3) Develop design of experiment of geothermal reservoir parameter by using Plackett – Burman Method.
4) Develop simulation of hydraulic fracturing treatment for geothermal reservoir model.
5) Develop correlation of hydraulic fracturing treatment with calculation of geothermal well production and electricity power generation.

Simulations to apply hydraulic fracturing treatment design have been conducted into geothermal reservoir models. Hydraulic fracturing treatment design by using combination of parameters: pump rate, maximum proppant concentration, fracturing fluids and proppant selections. Geothermal reservoir model parameter is using height, poisson ratio, fracture gradient, young modulus, permeability, porosity, water saturation, heat capacity, thermal conductivity, spacing and specific gravity.

Simulations is successfully conducted by implementing design of experiment methods, Plackett – Burman. Simulation and analysis give results: Fracture length of 100 – 200 m, Efficiency increases with pump rate and maximum proppant concentration varied from 0.1 – 0.6 until 0.2 – 0.7. Average conductivity and FCD is affected by increasing pump rate and maximum proppant concentration, also affected by proppant selections. Significant value of average conductivity and FCD achieved for proppant 12/18 Carbo HSP2000.

#### 2.1.4 Review of Field Application on Hydraulic Fracturing Treatment Design and Evaluation

Successful hydraulic fracturing relies on good knowledge in multidisciplinary fields, i.e. rock mechanics to understand fracture geometry and propagation, fluid mechanics and reservoir engineering to understand fluid flow and proppants placement inside a fracture, and production engineering to understand operational constraints of a fracturing job (de Jong, 2015).

Areiyando Makmun (2015) suggested hydraulic fracturing stimulation concept as the following:

1) Injection above frac pressure.
2) Creates deep penetrating fractures
3) Two types:
   a. Acid Fracturing: Medium to High permeability Carbonate rock
   b. Proppant Fracturing: Low to high permeability Sandstone
4) Provide artificial conductivity to improve well productivity
5) Challenges/Limitation: Fracture Geometry optimization, weak barriers, high pore pressure formation, high degree of natural fractures/fissures

Moreover he suggested stimulation options for geothermal as the following:

- Matrix acidizing for high permeability or fractures/fissures
- Acid fracturing for low permeability and good solubility.

  Challenges: Placement, temperature and corrosion inhibitors, penetration, safety diversion and cost

- Proppant fracturing
- Challenges: Temperature and frac fluid stability, high degree of fractures/fissures height growth or other non ideal behavior.

According to Areiyando Makmun (2015), challenges in geothermal fracturing are:

1) Zonal isolation if well is completed OH or slotted liner.
2) Ability to intersect fracture network and keep them open.
3) Frac fluid stability. Unstable at very high temperature causing low capability to transport proppant.
4) Proppant may degrade at high temperature.
5) Excessive fluid leak-off leading to early screen out due to presence of fissures.

For field application, Areiyando Makmun (2015) provided rule of thumb for hydraulic fracturing job, some initial parameters which have to be confirmed before HF job execution and some important commonly observed results in HF job which can be used as benchmark. Rule of thumb for hydraulic fracturing job:

1) Proppants usage for reservoir with high permeability is 1,000-1,500 lb/ft
2) Proppants usage for reservoir with low permeability is 3,000 lb/ft
3) Folds of Increase (FoI) for reservoir with low permeability should be above 10 times
4) Folds of Increase (FoI) for reservoir with high permeability should be above 2 to 3 times

5) Fracture gradient (FG) can be approximated from overburden (OB) and reservoir pressure (Pres) as follow :

   FG = 1/3 * (OB + 2*Pres) or FG = 1.5*gradient of Pres

   Fracture gradient is typically in the range of 1.1 psi/ft

6) The most effective net pressure for HF job is between 500 psi to 1,500 psi. Any value below or above this range is deemed ineffective to create economical fracture.
7) Minimum height of layers neighboring our HF candidate layer(s) should be 25 ft
8) The critical values of near-wellbore friction are 500 to 700 psi. Above this range it would be in our advantage to re-perforate our zone of interest.
9) Size of perforation hole has to be 6 to 8 times bigger than the proppants size (diameter)
10) Maximum fracture width is usually in the range of 0.3 inch (or 7.6 mm)
11) Dimensionless fracture conductivity (CfD) should be above 1.26
12) Average proppants concentration should be in the range of 2 lb/ft2
13) Fracture conductivity value of 3,000 mD.ft should be aimed for

Some initial parameters which have to be confirmed before HF job execution:

1) Depth of HF candidate layer
2) Permeability of the zone of interest
3) Reservoir pressure
4) Closure pressure (fracture gradient is defined as closure pressure divided by depth)
5) Net pressure (Net pressure is defined as the difference between bottomhole pressure and closure pressure. Net pressure above zero means that fracture is created.)
6) Net pay of the zone of interest

Some important commonly observed results in HF job which can be used as benchmark:

1) Half-length of fracture in high-permeability reservoir is between 100 to 200 feet (or 30 to 60 meter)
2) Half-length of fracture in low-permeability reservoir is between 500 to 1,000 feet (or 150 to 300 meter)
3) Fracture height growth typically happens when net pressure (Pnet) is more than 80% of the stress contrast between neighboring layers
4) Proppants are typically injected in the range of 1 to 8 PPA (pound of proppants added per gallon of fluid).
5) In the case of calculation for pressure loss due to friction is too tedious to perform, value of 250 psi/ft as rough estimate for friction pressure can be used

6) Re-fracturing usually uses 1.5 times of proppants used in the original HF job
7) In the case of high fluid efficiency (FE), i.e. more than 0.3, we should inject less volume of pad fluid
8) In the case of low fluid efficiency (FE), i.e. less than 0.3, we should inject more volume of pad fluid
9) Since fracture width depends on the Young modulus (E) property of the rock, it is in our advantage to know this value. E value less than 3 million psi can be deemed as soft rock whilst E value above 10 million psi can be deemed as hard rock. It should be noted that all fracturing design commercial software in the current market average E values for all the layers. As such, assigning too accurate value of E in each layers of our model would not matter much.

## 2.2 CHEMICAL STIMULATION

Portier, (2007) has been attempted a study of the literature on acidification of geothermal reservoirs. The majority of the papers concern the cleaning out of geothermal wells. A summary are presented as following.

Matrix acidizing is used to remove near wellbore permeability damage with the objective of restoring the well to its natural undamaged inflow performance. This treatment involves injection of a reactive fluid, normally an acid, into the porous medium at a pressure below the fracturing pressure (Economides and Nolte, 1987). The acid works through a process of dissolution of (foreign) materials deposited within the porous formation, such as carbonates, metallic oxides, sulfates, sulfides or chlorides, amorphous silica, drilling mud and cement filtrates from invasion (Davies, 2003). A second type of acid stimulation and perhaps the most common one for geothermal environments, is the cleaning of (pre-existing) fractures. The intention is for the acid to dissolve (or mobilize sufficiently that they can be removed by later flow processes) either foreign or original fracture-blocking material. Treatment volumes, injection rates, acid placement techniques, acid system selection and evaluation of the results when stimulating geothermal wells all follow the same criteria as for oil wells. The important difference is the formation temperature. High temperatures reduce the efficiency of corrosion inhibitors (and increase their cost) as well as increasing the acid/rock reaction rate. The high acid rock reaction rate requires the use of a retarded acid system to ensure acid will not all be spent immediately next to the wellbore, but will penetrate deeper into the formation. Cooling the target formation by injecting a water preflush will reduce the temperature and the acid reaction rate.

Protecting the tubulars against corrosion is another serious challenge. This requires careful selection of acid fluids and inhibitors (Buijse et al, 2000), while cooling the well by injecting large volume water preflush may reduce the severity of the problem.

The cleaning out of geothermal wells to increase their productivity after scaling deposits constitutes the main application of the acid treatments. This technique has been used extensively in some geothermal fields in the Philippines (Buning et al, 1995; Buning et al, 1997; Malate et al., 1997; Yglopaz et al., 1998; Malate et al., 1999, Jaime-Maldonado and Sánchez-Velasco, 2003, Amistoso et al., 2005), in El Salvador (Barrios et al., 2002) and in USA (Morris et al., 1984; Entingh, 1999). It presents interesting results, such as the well injectivity increasing by 2 to 10-folds according to the studied reservoirs.

At the Larderello geothermal field (Italy), several stimulation methodologies have been used successfully by ENEL (Capetti, 2006). Among them, chemical stimulation operations were carried out by injection of acid mixtures. First, various laboratory tests were realized on reservoir rock samples to optimize the HCl/HF ratios and the effect on mineral dissolution. Field tests have shown impressive results on five deep wells for reservoir rocks composed of phyllites, hornfels and granites: the improvement of injectivity, respectively productivity ranged from a factor 4 to 10. In the field of EGS, few chemical treatments have been applied to stimulate fractured reservoirs. Since 1976, some experiments have been tried with more or less of success at Fenton Hill (USA) and Fjällbacka (Sweden). At Coso geothermal field however, 24 wells were successfully treated. A summary of the chemical stimulation experiments carried out on geothermal fields and EGS reservoirs are presented in Table 2.

Table 2: Results of HCl-HF treatments for scaling removal and connectivity development

| Geothermal Field | Number of treated wells | Variation of the injectivity index before and after acid treatment (kg/s/bar) | Improvement factor |
|---|---|---|---|
| Bacman (Philippines) | 2 | 0.68 → 3.01<br>0.99 → 1.4 | 4.4<br>1.4 |
| Leyte (Philippines) | 3 | 3.01 → 5.84<br>0.68 → 1.77<br>1.52 → 10.8 | 1.9<br>2.6<br>7.1 |
| Tiwi (Philippines) | 1 | 2.52 → 11.34 | 2.6 |
| Mindanao (Philippines) | 1 | | 2.8 |
| Salak (Indonesia) | 3 | 4.7 → 12.1 | 2.6 |

| | | | |
|---|---|---|---|
| | | 0.54 → 1.07<br>4.15 → 12.12 | 2.0<br>2.93 |
| Berlín (El Salvador) | 5 | 1.6 → 7.6<br>1.4 → 8.6<br>0.2 → 1.98<br>0.9 → 3.4<br>1.65 → 4.67 | 4.8<br>6.1<br>9.9<br>3.8<br>2.8 |
| Las Tres Virgenes (Mexico) | 2 | 0.8 → 2.0<br>1.2 → 3.7 | 2.5<br>3.1 |
| Los Azufres (Mexico) | 1 | 3.3 → 9.1 | 2.8 |
| Beowawe (USA) | 1 | - | 2.2 |
| Coso (USA) | 30 | 24 wells | successful |
| Larderello (Italy) | 5 | 11 → 54<br>4 → 25<br>1.5 → 18<br>-<br>11 → 54 | 4.9<br>6.3<br>12<br>4<br>4.9 |

**Salak geothermal field (Indonesia)**

An acid treatment was carried out to improve the production characteristics of a geothermal well in the Salak geothermal field following an accurate analysis of the possible causes for the initial poor performance of the well. Despite promising indications, the initial steam flow rate from the Awi 8-7 well, drilled during 2004, was below expectations (Pasikki and Gilmore, 2006). An acid stimulation treatment was designed and carried out to improve well performance. The treatment used a hydrofluoric acid system known as Sandstone Acid. The acid was placed to the target interval zone with a two-inch coiled tubing unit to maximize control over the treatment. Well test results before and after stimulation demonstrate that the acid stimulation has successfully produced improvements in overall well characteristics such as reduction of skin, increase of injectivity and permeability-thickness product, and production output. Based on the positive results obtained in this case, further application of this method is envisaged for other poor-performing wells with similar characteristics, Awi-10.3 and Awi 8.8 (Mahajan, et al. 2006).

**Las Tres Virgenes and Los Azufres geothermal fields (Mexico)**

In Las Tres Virgenes geothermal field, the steam is supplied by four wells located near the power plants, but LV-11 and LV-13 recorded low wellhead pressure and marginal steam production. LV-11 is a deviated well and was drilled in September 2000 to a total depth of 2081 m. LV-13 was drilled to a total depth of 2200 m. An acidizing job was performed in order to improve the production characteristics of these wells. Acid treatment included a pre, post and over flush using chloride acid (HCl) and a chloride acid-fluoride acid (10% HCl- 5% HF). The acid was injected using a coiled tubing unit. Matrix acid stimulation job for production well LV-11 and LV-13 was successfully conducted without major problems. Post-acid completion tests results indicated major improvements in the injectivity index where a considerable drop in wellbore pressures of the two wells (~30 bars) were recorded that indicated a reduction in the pressure resistance inside the wellbore. The post-acid pressure falloff data also confirmed the improvement in the well where a negative skin (-5.8) was obtained in LV-13 and similar for LV-11. The post-acidizing discharge tests also showed substantial improvement compared with the previous well production characteristics to the acid job. As a result, within less than a month the field steam production increased from 3.2 MWe to 7.3 MWe. The Los Azufres geothermal field is located in the northern portion of the transmexican volcanic belt, 250 km of Mexico city. Currently, 78 wells have been drilled at depths ranging between 700 and 3500 meters. Well Az-9AD is located in the northern zone of Los Azufres geothermal field and it was drilled from January 7 to April 22 on 2003, to a total depth of 1500 m. Early testing and survey analysis indicated that the low output of Az-9AD was caused by considerable drilling induced wellbore damage in its open hole section, where 1326 m3 of mud were lost. Skin factor of 16 was causing additional pressure drop equivalent to 41 bars, reducing its optimal flow rate. The success of earlier acid treatment jobs in Mexico and the analysis of the available information encouraged the company to apply the same technique for this well during 2005. Acid treatment of well Az-9AD introduced very significant improvement in the wellbore showing 174% increase in production capacity. The results of this job have been used for encouraging new stimulation programs, such as those in wells Az-56R and Az-9A located in the north zone of Los Azufres geothermal field.

**Beowawe geothermal field (Nevada, USA)**

The Beowawe geothermal field is composed of a production zone within a volcanic and sedimentary rocks sequence. The geothermal fluid contained in the formation is of NaHCO3 type with a very low salinity (1000-1200 ppm of total dissolved solids). A first acid stimulation was performed in November 1982 on the Batz well (Epperson, 1983). The acid amounts consisted of about 18.9 m3 of 15 % HCl acid for the preflush followed by a mainflush composed of 37.8 m3 of 12% HCl - 3% HF. Then, a Beowawe fluid injection of 35 m3 was performed to displace the acid farther in the formation. As a consequence, the acidification impact modified the acid displacement pressure from 27.5 bars to about 13.8 bars. In August 1983, a second acidification test was performed on another well, Rossi 21-19 (Morris et al., 1984). Firstly, 79.5 m3 of a 14.5% HCl solution was pumped at rates of 40-42 L.s-1 and was displaced deeper in the formation by injecting 389 m3 of water. A water injection test followed this first acidification but no significant change was noted in the injectivity of the well. Secondly, a new reservoir acidification was performed, using 156 m3 of a 12% HCl - 3% HF acid solution. A total of 480 m3 of water were injected to displace the acid solution in the formation. The following water injection test then showed a 2.2 fold increase of the injectivity.

**The Geysers geothermal field (California, USA)**

An acid stimulation was performed in January 1981 on the OS-22 well (Entingh, 1999). An amount of 75.7 m3 of 5 % HCl and 10% HF were pumped and 70 m3 of fresh water were injected to displace the acid mixture deeper into the formation. But, no effect on the well productivity was recorded.

**Coso geothermal field (California, USA)**

The Coso Geothermal Field, located in east central California, hosts a world-class power-generating project that has been in continuous operation for the past 15 years. A field experiment was designed for dissolving calcite in a wellbore at the Coso field. The most promising mineral dissolution agent to emerge from the laboratory studies was the chelating agent nitrilotriacetate (NTA) (Rose et al., 2007). The well that was selected was producer 32A-20, which had recently failed due to calcite deposition. A total of 57 m3 of a 10 wt% solution of NTA was injected into the well in a series of three injections. The solutions were each injected at 13.5-16 L.s-1. The total volume of fluid injected (57 m3 ) was calculated to be approximately the volume of the open-hole section of the well. Upon completion of the injection of the NTA solution, the well was shut in for approximately four hours, giving the chelating agent time to dissolve the calcite scale. Once the well was opened, at first the brine was clear, but soon turned to milky white, indicating the presence of the calcium-NTA complex. The concentration of the unreacted NTA dropped from about 34’000 ppm to approximately 2’000 ppm during the experiment. The final value of 2’000 ppm indicated that the milky white NTA solution being produced was nearly completely complexed with calcium. These experiments indicate that NTA can be an effective dissolution agent for the dissolution of wellbore calcite. The production of unreacted NTA early in the production cycle indicated that a longer shut-in period may have resulted in a more complete reaction of the NTA solution and more wellbore calcite dissolution. A total of 30 wells were treated with HCl and 24 gave successful results (Evanoff et al., 1995).

**Baca geothermal field (New Mexico, USA)**

For the development of the fracture network in the Baca Union Project, different methods of reservoir stimulation were compared. Acid stimulation had not been selected because of the filling of the natural fractures. Composed of authigenic material such as quartz, feldspar and pyrite (Pye and Allen, 1982). Therefore the acid stimulation should require substancial amounts of hydrochloric acid with uncertain results. A hydraulic fracturation was selected and performed on Baca-20 well in October 1981 utilizing cooling water followed by a high viscosity frac fluid (Morris and Bunyak, 1981). Different compounds were used to do this hydraulic stimulation as proppant (sintered bauxite), hydroxypropyl polymer gel (stable at high temperature) and calcium carbonate added to act as a fluid-loss additive. Nevertheless, all these treatments have not allowed a significant increase of the injectivity. It was also thought that the calcium carbonate has plugged the natural fractures and flow paths in the formation. As a consequence, an acid treatment was performed. A volume of 166 m3 of hydrochloric acid at a concentration of 11.9% was used but this acidizing treatment has not allowed the development of the well productivity (Entingh, 1999).

**Fenton Hill HDR project (New Mexico, USA)**

This HDR reservoir, located in north-central New Mexico, is composed at a depth of 3-4 km of a highly jointed Precambrian plutonic and metamorphic complex, basically of granitic composition. This HDR project was operated by Los Alamos National Laboratory. Many experiments, in the laboratory and on the field, were performed to study the impact of a chemical treatment on this rock. Different works were performed on cuttings and granite cores at the laboratory scale to study the impact of chemical treatments on permeability increases. Aqueous solutions of $Na_2CO_3$, NaOH and HCl were investigated on well-known crystalline rocks. Sarda (1977) reported the results (Table 3).

Table 3: Impact of three chemical treatments at 100 °C and 100 bars during 144 h

| Chemical Treatment | Weight Loss | Permeability increase |
|---|---|---|
| Na2CO3 | -0.3 % | 2-fold |
| HCl | - 6 % | Negligible |
| NaOH | - 6 % | 20-fold |

Those laboratory experiments have demonstrated that Na2CO3 dissolves SiO2 primarily by attacking the quartz component of the granite. Holley et al. (1977) showed that the amount of dissolved silica increased with increasing sodium carbonate concentration and with increasing time.

Field experiments were attempted in November 1976 to reduce the impedance of the deep enhanced reservoir by a chemical leaching treatment. Na2CO3 was used to dissolve quartz from the formation. A total of 190 m3 of 1 N Na2CO3 solution was injected. About 1000 kg of quartz were dissolved and removed from the reservoir but no impedance reduction resulted.

**Fjällbacka HDR project (Sweden)**

The experimental HDR reservoir of Fjällbacka is made of granite composed of two main facies, the predominant variety being a greyish-red, biotite monzogranite. This granite contains abundant fractures and minor fractures zones, which showed an evidence of being hydraulically conductive and which were filled with calcite, chlorite and clay minerals (Sundquist et al., 1988; Wallroth et al., 1999). Most of the stimulation experiments were hydraulic fracturing but an acid treatment was performed in 1988. An amount of 2 m3 of HCl-HF acid was injected in Fjb3 to leach fracture filling. The results have shown the efficiency of acid injection in returning rock particles.

**Experiments at EGS reservoir of Soultz-sous-Forêts (Alsace, France)**

The Soultz-sous-Forêts Enhanced Geothermal System (EGS), established in the Rhine Graben, North of Strasbourg (France), has been investigated since the mid 1980's. The final goal of this project is to extract energy for power production from a regional randomly permeable natural geothermal reservoir with the complementary resource coming from a forced fluid circulation between injection and production boreholes within a granitic basement. Recently chemical treatments were performed at Soultz-sous-Forêts (France).

This deep granitic reservoir contains fractures partially filled with a mixture of secondary carbonates (calcite and dolomite), various kinds of clay minerals (Illite, chlorite….) and silica. In order to dissolve these carbonates and to enhance productivity around the wells, each of the three 5-Km deep boreholes (GPK2, 3 and 4) were treated with different amounts of hydrochloric acid. If GPK3 has shown weak variations of its injectivity, GPK4 presented a real increase of its injectivity and productivity after the treatments and GPK2 presented also a very sensible improvement despite the fact that the treatment was only a very little test.

## 2.3 Thermal Stimulation

Thermal fracturing is a stimulation phenomenon that occurs when a fluid (e.g. produced water, seawater, aquifer water or surface water), considerably colder than the receiving hot formation, is injected. Injection of the cooler water leads to thermal contraction of the reservoir rock in the region near the injection well, reducing the stresses (Flores et al., 2005). The reservoir can be fractured at a significantly lower pressure than the original, in situ stress would indicate, when there is a large temperature contrast between injected water and the formation (Slevinsky, 2002). The occurrence of thermal fracturing during cold-water injection into porous and permeable classic formations is well documented. Suitable rock-mechanical process models have been developed for treatment control and optimization. The process is less well documented in geothermal production wells. Tulinius et al (2000) report thermal fracturing of such a geothermal well in Guadeloupe in France. A 253°C reservoir was stimulated using seawater mixed with an inhibitor to prevent anhydrite scaling. Production results showed an output increase of 50% compared with original production flow rate. The enhanced production rate made the well sufficiently economically successful that it was still flowing to an existing power plant one year after the treatment. Thermal fracturing will not always be a technically suitable solution – for example, if it is required to dissolve material that is blocking the flow of steam e.g. a scale. However, thermal fracturing is very attractive compared to the other options for cases when flow can be restored by the generation of a near wellbore fracture network that will reconnect to a main reservoir flow system. The fluids used during Thermal Fracturing are characterized by:

- Benign compared to aggressive acids
- Easy-to-prepare fluid with simple chemistry, especially when compared to a fully-formulated, high temperature, cross-linked fracturing fluid
- Requires mobilization of a minimum of equipment

- High pump pressures not normally required
- Treatment fluids present minimal Health, Safety & Environmental Issues
- Low Cost Fracture closure is frequently cited as a cause of concern when designing a thermal fracturing treatment, though the productive flow channel had clearly remained open in the case above.

Producing the treated well will increase the temperature of the cooled zone, with a consequent restoration of the previous rock stress. This would be expected to reduce the gain in flow capacity, since proppant is not present to keep the fracture open after the treatment. Although strain changes in the rock appear to be controlling the remaining increased permeability, there are no accepted models that describe the fundamentals of this process.

# 3 Workshop On Geothermal Stimulation

## 3.1 Objectives

The objective of this workshop is to improve the understanding of hydraulic fracturing and acidizing jobs to enhance productivity of geothermal wells in Indonesia.

## 3.2 AGENDA

Invited speakers of the workshop are from Netherlands and Indonesia. The speaker form industries in Indonesia are:

1) Riza Pasikki, Chevron Geothermal Indonesia Ltd, presented a lesson learn of hydraulic fracturing and acidizing from Awibengkok-Salak geothermal field.
2) Boyke Bratakusuma, Star Energy Geothermal (Wayang Windu) Ltd., presented a lesson learn of well intervention and stimulation from Wayang Windu geothermal field.
3) Areiyando, Schlumberger Ltd, presented the treatment design, operation and evaluation of hydraulic fracturing for geothermal application.

The detail of agenda of the workshop is follows:

**Engineering Workshop on "Geothermal Reservoir Stimulation: Hydraulic Fracturing and Acidizing"**
**Geothermal Graduate Program of ITB - Bandung, 29 – 30 October 2015**

| Thursday, 29 October 2015 | | | | |
|---|---|---|---|---|
| **Time** | **Topic** | **Institution/Name Of Company** | **Speaker** | **Duration (Minutes)** |
| 08.00 – 08.30 | Welcoming drink | | | 30' |
| 08.30 – 09.00 | Opening Speech | ITB and INAGA | Nenny Saptadji & Sanusi Satar | 30' |
| 09.00 – 09.50 | Hydraulic Fracturing: A lesson learned from Awibengkok-Salak Geothermal Field | Chevron Geothermal Indonesia Ltd. | Riza Pasikki | 50' |
| 09.50 – 10.40 | Well Stimulation for Geothermal Applications | IF Technology - Netherlands | Nick Buik | 50' |
| 10.40 – 11.30 | Well Intervention and Stimulation: A Lesson Learned From Wayang Windu Geothermal Field | Star Energy Geothermal (Wayang Windu) Ltd. | Boyke Bratakusuma | 50' |
| 11.30 – 12.30 | Question and Answer Session | | | 60' |
| 12.30 – 13.30 | Lunch (provided) | | | 60' |
| 13.30 – 14.20 | Temperature Effects During Injection in Fractured Reservoir: Numerical Modeling Approaches | TNO - Netherlands | Peter Fokker | 50' |
| 14.20 – 15.10 | Acidizing: A lesson learned from Awibengkok-Salak Geothermal Field | Chevron Geothermal Indonesia Ltd. | Riza Pasikki | 50' |
| 15.10 – 16.00 | Question and Answer Session | | | 50' |
| 16.00 – 16.15 | Description of Geocap Research on Hydraulic Fracturing and Acidizing | | Nenny Saptadji | 15' |
| 16.15 – 16.30 | Wrap Up | | | 15' |
| 16.30 – 17.00 | Networking (Tea/Coffee/Snack provided) | | | 30' |

| Friday, 30 October 2015 | | | | |
|---|---|---|---|---|
| Time | Topic | Institution/Name Of Company | Speaker | Duration (Minutes) |
| 08.00 – 08.30 | Welcoming drink | | | 30' |
| 08.30 – 09.20 | Geothermal Energy & Rock Mechanics/Fracturing | TU Delft | Auke Barnhoorn | 50' |
| 09.20 – 10.10 | Hydraulic Fracturing: Geometry Modeling in Geothermal | ITB | Sudjati Rachmat | 50' |
| 10.10 – 11.00 | Hydraulic Fracturing: Treatment Desain, Operation and Evaluation for Geothermal Application | Schlumberger Ltd. | Areiyando | 50' |
| 11.00 – 11.30 | Question and Answer Session | | | 30' |
| 11.30 – 11.40 | Wrap up | | | 10' |
| 12.00 – 14.00 | Lunch (provided) | | | 120' |

**LIST OF INVITATIONS:**

1. P.T Pertamina Geothermal Energy.
2. Chevron Geothermal Indonesia Ltd
3. Star Energy Geothermal (Wayang Windu) Ltd.
4. P.T Supreme Energy
5. P.T Geo Dipa Energi
6. Original Tata Power Ltd.
7. Sarulla Operation Ltd.
8. Schlumberger Ltd.
9. Halliburton Ltd.
10. Institut Teknologi Bandung (ITB)
11. Universitas Indonesia (UI)
12. Universitas Gajah Mada (UGM)
13. TNO – Netherlands
14. TU Delft – Netherlands
15. IF Technology

**Venue:** *Auditorium Campus Centre ITB*
**Commitee:** *Nenny Saptadji (nenny.saptadji@gmail.com), Sutopo (toppoitb@gmail.com), Nurita Putri H.(nurita_putri@yahoo.co.uk)*

## 3.3 PARTICIPANTS

The number of participants of this workshop is about 70 from 24 Institutions. The list of participants is as follows:

| No | Institution | # Participants |
|---|---|---|
| 1 | PT. Pertamina (Persero) | 2 |
| 2 | Star Energy Geothermal | 5 |
| 3 | Pertamina Geothermal Energy | 3 |
| 4 | Chevron Geothermal Indonesia | 2 |
| 5 | OTP Geothermal | 6 |
| 6 | Ormat Geothermal Indonesia | 4 |
| 7 | Schlumberger | 7 |
| 8 | PT. Geo Dipa Energy (Persero) | 3 |
| 9 | Hitay Energy Holdings | 1 |
| 10 | Supreme Energy | 5 |
| 11 | PT Gada Energi | 1 |
| 12 | PT Scomi Oil Tools | 1 |
| 13 | Halliburton Indonesia | 1 |
| 14 | PT. Sucofindo | 2 |
| 15 | PT. Wika Jabar | 1 |
| 16 | Ministry of Trade | 1 |
| 17 | Ministry of Energy | 2 |
| 18 | Akamigas Balongan | 2 |
| 19 | Geothermal ITB | 5 |
| 20 | ITB | 8 |
| 21 | Trisakti University | 4 |

| | | |
|---|---|---|
| 22 | Universitas Padjajaran | 1 |
| 23 | Researcher | 1 |
| 24 | Independent Consultant | 1 |

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