SELECTION OF CANDIDATE GEOTHERMAL WELLS FOR DEFLAGRATION

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ABSTRACT

Deflagration uses the energy created by the expanding gas generated from the slow burning of propellant to enhance the near wellbore permeability of an inherently tight or skin-damaged well through the creation and propagation of fractures. Deflagration is an established stimulation method for oil and gas wells but the application of deflagration on geothermal wells is limited. One of the difficulties of the application of the deflagration technology to a geothermal well is the lack of definitive criteria for determining what makes a good candidate well for deflagration.

A matrix for selecting candidate wells for deflagration was developed based on published geothermal case studies and consultation with subject matter experts on deflagration. The matrix included resource potential and well suitability for deflagration as main factors. The resource potential considered both reservoir and well characteristics. Reservoir properties, *e.g.* well location, number of offset producing wells, and average power output or injection capacity were used for determining the potential of the well to produce steam or accept brine injectate. Well characteristics, *e.g.* shut-in temperature, permeability, skin, injectivity ratio and potential gain in output were included for estimating well potential. The suitability of a well for deflagration was determined based on its primary feedzone characteristics and structural geology.

The matrix was used to evaluate each deflagration target depth based on rock properties, geological and drilling indicators, presence of geological structure and permeability, and capacity of the feedzone. The evaluation method, however, was limited by the absence of a geomechanical model hence book values for rock properties and regional stress regime were used for the assessment.

1. INTRODUCTION

The Energy Development Corporation (EDC) is evaluating the application of deflagration technology for enhancing the permeability of its non-commercial wells and commercial yet marginal wells.

The candidate wells were selected from a pool of non-commercial production and reinjection wells (≤ 10 kg/s) and some marginally producing (≤ 3 MWe) wells. The non-commercial wells are those that were never utilized and cut-in to system due to numerous factors, but primarily because of low permeability.

This part of the study discusses the process of selecting the best candidate well for deflagration.

1.1 Background

The first stimulation technology using explosives could be traced back into the 1860's when liquid explosive nitroglycerine was introduced to an oil and gas well to stimulate it. The popular use of explosives for well stimulation however, came late in the 1970's as result of a worldwide shortage in oil supply.

In the 1980's, the breakthrough on the use of propellants which detonate at subsonic velocities rather than at supersonic velocities allowed the process of controlled burning, in effect producing a high pressure event that could last a few hundred milliseconds and produce a network of multiple fractures. This advancement led to the routine use of this technique in the former Soviet Union where ~1,500 to 3,000 treatments were performed between 1980 and 1990 (Al-Hashlm *et al.*, 1993). The technique has been applied to more than 3,000 6-km deep cased holes with a success rate of 98% and stimulation efficiency of 70 to 85% (Li and Xue, 2000).

The present propellant stimulation technology are designed to withstand temperatures of up to 204°C which allows the propellants to be conveyed to the target depth without concern for premature detonation thus making it viable for geothermal application.

1.2 Description of deflagration technology

Deflagration is an original oil and gas stimulation technique that uses the energy or pressure wave generated from the combustion of a propellant to create and extend multiple fractures into the near wellbore formation. It is also widely known in the industry as gas fracturing, controlled pulse fracturing, tailored pulse fracturing, high-energy gas fracturing, dynamic gas pulse loading, and propellant fracturing among others.

The propellant sticks are housed inside a gun carrier which is conveyed to the targeted zones via wireline, coiled tubing, or drill pipe depending on the required carrying capacity. The propellant sticks are then ignited at depth triggering the propellant to rapidly deflagrate in a controlled burn. The resulting gas contained by the liquid column in the wellbore is pushed into the existing fracture network, and props them open as the gas expands.

1.2 Comparison of different fracturing techniques

Stimulation is required for wells which have limited permeability or have suffered from near-wellbore formation damage, either during well drilling, well cementing, well completion, and/or during the production process.

Conventional stimulation may be conducted via chemical treatment, where an acid mix is pumped into the formation to dissolve the obstruction whether mud, cement, or mineral deposits. Conventional stimulation may also be conducted by mechanical methods where blockages or impediments are intentionally fractured to create permeability. Mechanical methods may also be employed for enhancing inherently tight reservoirs and improving permeability to a limited extent.

Hydraulic fracturing

A typical fracturing method is through hydraulic fracturing, where voluminous liquid is pumped using high pressure pumps delivering an injection rate of least 50bpm. This method has been proven for increasing production rates in low permeability formations. Hydraulic stimulation is dependent on the stress orientation of the field and thus, there is limited control over the direction of fracture. The disadvantages of this technology include high cost of operation, thus limiting its application for high rate wells, large space requirements, and logistics for mobilization and demobilization.

Explosive fracturing

Explosive fracturing is a mechanical method which uses the energy generated by blasting for creating fractures. The high pressure generated by the explosives can cause severe damage to the wellbore. The residual stress from the almost instantaneous stress wave creates a 'stress cage' that could clog the created fractures. Operationally, it is generally limited to open-hole completion and is a high risk for stuck situation due to the collapse of the formation upon ignition.

Propellant-based fracturing

An innovation from the explosive fracturing is the pulse fracturing or propellant-based fracturing. Though it is not as effective as hydraulic fracturing in terms of the fracture length generated, it may be useful for the treatment of near wellbore damage or for connecting to a nearby potential fracture network. With the lessons learned from explosives fracturing, the design for deflagration could be improved to control the pressure rising time and produce enough energy to create multiple fractures but still remain within the rock yield stress to prevent 'stress cage'. It could be applied to cased holes without any damage to the casings.

A comparison of the different fracturing techniques is summarized in Table 1.

1.3 Deflagration mechanism

Propellants are explosive materials which deploy high quantity of gaseous products mainly composed of H_20, H_2, HCL, CO_2, CO, and N_2 (Ohren *et al.*, 2011). The high energy potential is later converted to mechanical energy with the expansion of the gas bubble.

The different phases of gas fracturing are described by Lie and Xue (2000) in Figure 1.

Table 1: Performance comparison of different fracturing techniques modified after Krilove *et al.* (2008).

Parameter	Hydraulic Fracturing	Explosives Fracturing	Deflagration
Period of Pressure Increase (s)	10 to 100	10^{-7} to 10^{-6}	10^{-4} to 10^{-3}
Impact Pressure Period (s)	10^3 to 10^4	10^{-6} to 10^{-5}	10^{-2} to 1
Peak pressure (MPa)	10	10^4 to 10^5	10 to 100
Number of fracture generated	1 or more	High	3-10
Fracture length (m)	10 to 300	<1	10 to 30
Shape and distribution of fractures	Bi-wing or Multiple, fractures	Irregular	Multiple, radial
Applicability	Open or cased hole	Open hole only	Open or cased hole
Remarks	Fracture orientation dictated by direction of minimal formation stress	Possibility of mechanical damage of casing and well bore wells	

(a) *Wellbore pressurization.* A substantial increase in pressure is observed upon ignition. The pressure continues to increase until it reaches the pressure needed to initiate the fracture. Fracturing of the rock will be started when the wellbore compressive forces exceed the tensile strength of the rock.

(b) *Fracture Initiation.* The fracture initiation phase or the rupture of the formation begins upon reaching the fracture pressure. The reduction in pressure signifies the creation of a pathway for the gas thus allowing the pressure to drop gradually. Multiple radial fractures are created during this phase.

(c) *Fracture extension.* After the pathway has been created, the continuous burning of the propellant would supply gas into the formation until the whole volume of propellant is completely combusted. The expansion of the gas bubble with the reduction in temperature would prop the fractures open.

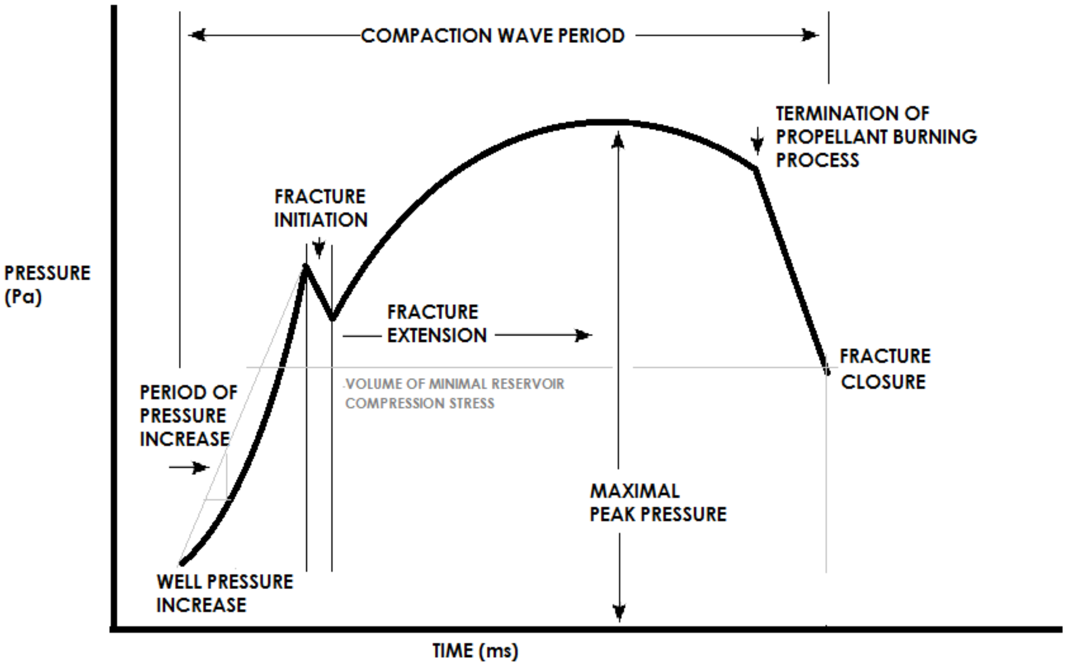

Figure 1 Pressure-Time Diagram for a Propellant Based Fracturing

(d) *Fracture Closure.* After the propellant is completely combusted, the fractures that were propped open with the gas expansion will stabilize and try to go back to their initial state, thus fracture closing happens to a certain extent after the stimulation. However, due to its mechanism, deflagration has a high chance of producing self-supporting fractures as the shattered grains, or difference in geometry act as a natural proppant. Final fracture aperture will be governed by the rock properties and the intensity of erosion created by the gas bubble.

For (c) above, the fracture length or propagation depends mainly on three (3) factors:

(1) *Stress orientation of the field.* The fractures will tend to propagate in the direction that is of least stress, or parallel to the maximum field stress orientation.

(2) *Volume of the propellant.* The distance by which the fractures would travel will be dictated by the amount of gas generated; the higher the volume of the gas, the farther it could reach into the formation.

(3) *Rate of combustion.* The rate of combustion is dictated by the number of slits, the lower the number of slits, the slower the propellant will burn. A longer burning process will augment the possibility of propagation of the gas farther into the formation. As this is a tradeoff with the intensity of the energy generated, it would be critical to design the combustion such that it allows fracture initiation at the start but allows fracture extension after.

2. CASE STUDIES

Soda Lake, Nevada, USA

Though deflagration technology has been used in oil and gas since the 1980’s, its application in geothermal industry began only in 2009. The first documented deflagration job was in Soda Lake, Nevada, USA with Magma Energy Corporation where three wells, *i.e.*45A-33,41B-33 and 25A-33 were tested (Ohren *et al.,* 2011).

For wells 41B-33and 25A-33, the deflagration targets depths were defined based on inflection points seen on the temperature profiles. For well 45A-33, the deflagration target depths were based on known permeable zones since this well is an old producer.

The completion test in well 45A-33 and 41B-33 was conducted after casing perforation has been performed on the well together with deflagration. Hence it is difficult to determine the improvement in permeability attributable to deflagration. The use of large-diameter propellant sticks (4.5" OD) resulted to a modest increase in injection from 0.4 to 1.9 L/s (7 to 30 gpm). Extended pumping for at least 5 days is recommended based on the results from well 25A-33 where the injection capacity has significantly improved to an average of 37.8 L/s (maximum of 44.1 L/s) (Ohren *et. al*., 2011).

Reykjanes, Iceland

The deflagration jobs performed on wells RN-29, RN-30, RN-22, and RN-33 in Reykjanes, Iceland with HS Orka showed mixed results. The deflagration target depths were identified using temperature profile and known permeable zones. For well 33, borehole imaging was also used to identify the fracture targets. Based on the result from well 33, the correct identification of the feed zones allowed the high pressure gas to be focused more precisely on these deflagration target depths (Sigurdsson, 2015).

The results from the deflagration jobs on these two fields are summarized in Table 2.

Table 2: Summary of deflagration results after Ohren *et al.* (2011) and Sigurdsson (2015)

Well Name (Year)	Total no. of zones/ total no. of shots	Basis for Zone Selection	Results
45A-33 (2009)	1/ 2	Old producer	Inconclusive[a]
41B-33 (2010)	2/ 4	Temperature profile	Inconclusive[a]
25A-33 (2010)	3/ 3	Temperature profile	Increased from 7 to 30 gpm
RN-29 (2010)	7/ 9	Temperature profile	Injectivity index increased from 3.3 to 4.3 L-s/bar
RN-30 (2011)	5/6	Temperature profile	No improvement
RN-22 (2013)	4/4	Old producer	No improvement
RN-33 (2013)	4/ 4	Temperature profile; sonic televiewer	Injectivity index increased from 0.7 to 2 L/s-bar

[a] *Result of completion tests was inconclusive since it is conducted right after two activities*

2. CRITERIA MATRIX FOR CANDIDATE WELL SELECTION

Deflagration aims to improve permeability through the enhancement of the fracture network tapped by the wells for improving their communication with the reservoir. The case studies on the application of deflagration on geothermal wells do not include a discussion or a detailed process or criteria for what makes a good candidate well for deflagration. The authors devised a matrix for candidate selection for this study for addressing this gap.

Fox *et al.* (2013) made a brief discussion on what makes a rock 'frackable' and this was described in terms of brittleness. Brittleness increases with increasing Young's modulus and decreasing Poisson's ratio; nonetheless brittleness values are mostly empirical (Altindag and Guney, 2010). Although a detailed discussion was not presented on the type lithology considered for 'fracking,' the principles are applied here for determining which rocks may be suitable for deflagration based on the premise that both hydrofracturing and deflagration have the same objectives of fracture initiation and propagation.

The diverse characteristics of geothermal reservoirs provided some challenge in well selection. With no established guidelines, all pertinent well and reservoir parameters are considered and evaluated with regards to their potential impact on a successful deflagration project. Two major subcategories were determined: (1) Resource potential; and (2) Suitability of well for deflagration.

2.1 Resource potential

The resource potential determines the viability of a candidate well to produce commercially based on the reservoir and well characteristics.

The location of the well with respect to resource, injectivity index, output of the offset wells, and properties of intersected structures are used as measures in the characterization of the reservoir. From the resistivity maps, the wells are either located within, at the periphery or outside the resource boundary. Higher mark is given to those that are close to the upflow.

2.1.1 Reservoir properties

Reservoir properties, particularly related to the location of a well in the geothermal field, were factored in as they would aid in determining the potential of the well to produce steam (for production wells) or accept injectates (for injection wells). These include the following:

- Location of the well in the geothermal system (upflow, outflow, or boundary)
- Number of producing offset wells in the sector
- Average well output in the sector (in MWe or kg/s)

2.1.2 Characteristics of individual wells

Individual well characteristics were also studied for a more deterministic analysis of the well's potential well. These include the following parameters:

- Maximum temperature measured
- Permeability measurements (including skin)
- Injectivity
- Potential gain in output

A candidate production well should have a minimum downhole temperature of 220°C at the production casing shoe for it to flow and sustain discharge. The temperature of the candidate wells ranged from 150°C to 300°C. Wells with higher temperatures at the deflagration target feed zones were given higher scores while the wells affected by cold water inflow were given low scores and put on low priority.

The enhancement in permeability achieved using deflagration is estimated through permeability indicators such as injectivity index and permeability thickness product or kh. It is aimed that deflagration could enhance near well permeability through the creation of near wellbore fractures and connect to the productive reservoir tapped by the offset wells.

An average injectivity index value is established for each sectoral area in the reservoir based on values given by good producer or injector offset wells. Many of the candidate wells of EDC have values lower than this, indicating permeability damage. Each candidate well is graded based on its injectivity index vis-a-vis sectoral injectivity index representing good producer or acceptor offset wells.

Drilling mud and continuous well utilization lead to the formation of filter cakes and scales, causing damage to permeability. Deflagration mainly affects permeability at the near wellbore which can be measured through skin factor. The improvement in well output or injection capacity is higher from a well with skin damage compared to a well with stimulated skin.

The performance of offset wells shows whether a candidate well is displaying outlier behaviour or is drilled in an area where the productive resource cannot be accessed. The number of producing wells and average capacity are used as additional parameters for scoring each well. Offset wells are selected on the basis of common intersected fault structures that are known to be contributing to production.

The evaluation of the reservoir and well properties is deemed useful for estimating potential gain in production or injection capacity and for deciding whether a well would be elected for conversion from a production well into an injection well or vice versa.

2.2 Suitability for deflagration

The suitability of a well for deflagration was based primarily on deflagration target feed zone characteristics and the structural geology of individual wells. The feed zones are mostly structure-related and are dependent on the stress regime and the characteristics of the fault or structural targets.

Differential stress, as reflected by the presence of structures, is seen to aid in the propagation of fractures induced through deflagration, thus enhancing connectivity to the reservoir and improving permeability.

Each target feed zone per well was evaluated based on the rock properties, *e.g.* lithology, compressive strength, porosity, coherence, ductility and brittleness, geological and drilling indicators, and capacity (acceptance) of the feed zone.

2.2.1 Types of lithologic units

Lithology is a crucial factor for deciding whether a feed zone is deemed a good target for deflagration. The lithologic units encountered by geothermal wells are highly variable, even within a well. For many cases, the reservoir rocks may be composed of various lithologies which range from volcanic units, intrusive rocks, contact metamorphic rocks, to sedimentary formations. The inconsistency and variation of the lithology in a well have to be considered when selecting target depths for deflagration. Hence, the type of lithology for every feed zone as well as the inconsistency of the lithology within the well are evaluated to determine holistically whether the well could benefit from a deflagration job.

Consultation with the deflagration service provider established that coherent or homogeneous rocks favour fracture propagation. Cosgrove and Engelder (2004) features the study by Brenner and Gudmundsson (2004) where fracture propagation in rocks are shown to be most efficient in ‘stiffer’ and coherent formations, thus fracture density is noted to be higher in stiffer formations such as lavas and intrusive rocks.

It is expected that in softer and less coherent formations, the energy from deflagration is more readily absorbed by the ductile formation and is impeded by numerous fragment contacts which limits fracture propagation. For this reason, the lithologies are ranked in terms of coherence; hence the more homogeneous lithologies are expected to become more fractured after deflagration. High-ranking lithologies would include crystalline rocks such as lavas, intrusives, contact metamorphic rocks or hornfels, siliceous or silicified rocks. On the other hand, ultramafic rocks are expected to have negligible response to deflagration due to their ductile nature and their tendency to seal rapidly when fractured due to serpentinisation (Farough *et al.*, 2014). The ranking of lithologies based on rock coherence range from high (*e.g.* lavas) to low (ultramafic).

2.2.2 Rock compressive strength

The compressive strength of the rocks is also another factor considered in the deflagration job. At some point a rock will experience stress beyond its limit, resulting to failure and creating a fracture (Fox *et al.*, 2013). The compressive strength values of the rocks would provide an indication of how much energy is required to break them. Typically, the values for rock compressive strength are empirical due to variations in mineralogy, crystallinity, and coherence. However, book values were assumed due to the lack of petrophysical data obtained from cuttings and core samples.

It is also noted that many of the lithologies have been hydrothermally altered which most likely lowered their compressive strength unless the rocks are silicified or altered to quartz. It is generally considered that fractures are easier to generate in weaker rocks, notwithstanding brittleness and ductility which are also empirical values. Brittleness and ductility are important considerations for suitability for deflagration but with the absence of petrophysical data, making the assumptions is difficult due to the variability of values. For example, sandstones, mudstones and shales can both be brittle and ductile.

The generalised ranking of lithologies was made according to the uniaxial compressive strength based on the rankings given by Hoek and Brown (1997), Altindag and Guney (2010), and Kahraman *et al.* (2012).

2.2.3 Interconnectivity of fractures

Cosgrove and Engelder (2004) emphasized the importance of the interconnectivity of fractures particularly along the vertical direction which was mentioned to be more influential than the lateral interconnectivity of horizontal units and the non-fracture porosity of the rock matrix. In a geothermal system the structural intercepts, which are mainly vertical to sub-vertical faults and their associated fracture systems, have been primary targets for permeability. Therefore, it follows that the number of faults intersected by the wells, as well as their orientations, are considered for the deflagration criteria. The more faults intersected, the more favourable it is in terms of having more potential targets.

2.2.4 Principal stress regimes

It is not sufficient to have numerous fault targets because it is also critical to consider the fault orientation with respect to the principal stress directions since this will determine which structures are expected to be most permeable.

Fracture dilation is expected in structures that are oriented perpendicular to the least primary horizontal stress and parallel to the maximum horizontal stress. Fracture initiation and propagation is also influenced by the orientation of the principal stresses. This is best demonstrated in wells with borehole imaging, wherein tensional drilling-induced fractures are developed along the maximum horizontal stress direction. However, no borehole image logs have been acquired from the wells considered. In the absence of borehole images, knowledge of the local stress regime of the geothermal field may aid to a certain extent in approximating which faults are favourably oriented along the principal stress directions.

A thorough geomechanical study of the geothermal sites would have been highly beneficial in the evaluation of fault targets in terms of their response to the in-situ stress but in the absence of pertinent data, a rudimentary approximation is herein employed. Thus, fault orientations are arbitrarily categorized into parallel (0-30 deg), sub-parallel (30-60 deg), and perpendicular (60-90 deg) with respect to the maximum horizontal stress direction as defined by the convergence vector in each geothermal site. Parallel-oriented structures were ranked first and perpendicular structures were ranked last.

2.2.5 Precision targeting

Fault intercepts derived from geologic and drilling data

For optimising the benefits of the deflagration job, it is important to have accurate depth values of potential target zones which are often interpreted to be the fracture occurrences associated with the intercept of faults.

In the absence of borehole images, approximation of the fault intercepts can be interpreted by noting various parameters derived from geological and drilling data and correlating them with completion tests results. Geological indicators of permeability associated with structures can be noted from drill cuttings and core samples, if available. Circulation losses encountered during drilling and permeable zones detected from completion tests are often associated with the occurrence of these indicators.

Fault intercepts derived from drilling parameters

Fractured formation due to fault intercept may also be reflected by drilling parameters, which may include occurrences of losses in circulation during drilling (TLCs and PLCs), surface pump pressure drop (accompanying massive circulation losses), drilling breaks, gas kick, temperature spike, ‘bit-walking’, and recurring tight spots or bridges. These indicators, when correlated with permeable zones detected from completion tests results, which can be targeted for the deflagration job.

Circulation losses are deemed to be the direct manifestation of permeability at a particular interval as the drilling fluids invade the formation through the available openings usually associated with the interconnected fracture network of a faulted section. Drilling breaks may indicate either a formation change from hard rock to soft formation or encroachment from a solid rock mass to a highly fractured interval. The other indicators listed may not be sufficient indicators when observed separately but adds confidence to the presence of a fractured or faulted interval when noted occurring together especially with the higher ranking indicators.

Targets for deflagration were chosen based on the interpreted permeable zones. For each well, every target depth is evaluated and ranked among other targets for prioritization. To optimize the result, the most productive zone is prioritized. This is measured by well test parameters and correlated with the occurrences of drilling and geologic indicators.

The geologic and drilling indicators of fractures and/or faults are ranked based on circulation loss (high) to other minor indicators such as gas kicks, *etc* (low).

3. SUMMARY

The applicability of deflagration for improving the permeability of its non-commercial and marginal geothermal wells was investigated by EDC.

A criteria matrix was developed to provide basis for the selection of the candidate wells. Resource potential and suitability were included as the main parameters to be considered. The resource potential which includes both reservoir and well properties was used for evaluating the capacity of the well to produce steam or accept brine injectate. The suitability of a well for deflagration was determined based on its primary feedzone characteristics and structural geology. The deflagration target depths were determined based on rock properties, geological and drilling indicators, presence of geological structure and permeability, and capacity of the feedzone.

The aptness of the matrix will be revisited and recalibrated once the results are out for the target wells for deflagration. Detailed documentation of the well enhancement shall be conducted to assess the effect and success of this technology on geothermal wells. This will also aid in determining the critical parameters that should be considered in selecting wells for deflagration in the future.

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