Proceedings 20th NZ Geothermal Workshop 1998

POTENTIAL APPLICATION OF HYDRAULIC STIMULATION IN THE GEOTHERMAL INDUSTRY

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SUMMARY – Hydraulic fracturing has been employed to enhance the productivity of wellbores in both the petroleum and Hot Dry Rock (HDR) industries for a number of years. The geothermal industry is well positioned to benefit from the wealth of hydraulic fracture technologies. This will possibly reduce the number of wells required to exploit geothermal energy, and as a consequence, give this green energy a competitive edge over the fossil fuel energy.

1. INTRODUCTION

Hydraulic fracturing has been an indispensable tool employed by the petroleum industry for more than 50 years. Hydraulic fracture treatments increase petroleum reservoir penneabilities by creating large, highly conductivt, artificial fractures connecting the wellbore to hydrocarbon-bearing formations. These fractures are created by injecting large quantities of viscous fracturing fluid under high pressure into the formation. Propping material ('proppant') is usually mixed with the viscous fluid in order to keep the hydraulic fiactures open after injection has ceased. This practice is now routinely applied to oil, gas and coalbed methane wells. Hydraulic fracturing is even used in the North Sea to stimulate injection wells for disposal of cuttings during offshore drilling.

Hydraulic fracturing was first applied to Hot Dry Rock (HDR) stimulation at Fenton Hill, New Mexico, in the late 1970s (Tester et al., 1989). The major difference between HDR and conventional petroleum hydraulic fracture treatments, is that stimulation, in the case of HDR, creates three-dimensional networks of multiple, small *shear fiactures* rather than single large planar fractures as historically assumed. Subsequently, significant progress has been made in developing successful HDR stimulation technologies. Experience at various HDR sites has clearly demonstrated the fact that the permeability of crystalline rocks can be significantly enhanced by long term and low rate induced hydraulic fracture treatments.

In today's highly competitive, low oil price market, the recovery efficiency of the geothermal industry has to be increased drastically by implementing appropriate reservoir development and exploitation strategy. Such recovery efficiencies are currently improved by drilling an ever-increasing number of new wells. However, as an alternative to drilling new wells, the productivity of existing wells may be enhanced through the application of *hydraulic fracturing*.

The objective of this paper is to review, compare and contrast hydraulic fracturing as utilised by the petroleum and HDR industries, and to describe ways in which the geothermal industry may benefit from a transfer of techpology.

2. HYDRAULIC FRACTURING AS HISTROICALLY APPLIED TO TEE PETROLEUM INDUSTRY

The first experimental hydraulic fracture treatment of a petroleum reservoir was performed in the United States in 1947. Since then, at least one million fracture treatments have been performed and currently more that 40 percent of all petroleum wells are hydraulically fractured (NSI, 1992). After 50 years of practice, research and development, 'conventional' hydraulic fracturing is now regarded as a 'matured' technology. This section introduces some theoretical concepts upon which hydraulic fracture technology is based, and discusses practical field-implementation issues.

2.1 Hydraulic Fracturing: General Concepts

***Dimensionless Fracture Conductivity** (F_{cd})* A hydraulic fracture is usually assumed to be symmetrical with respect to the wellbore, with its size being represented by its half length (x_f).

Dimensionless Fracture Conductivity is a commonly employed means of defining hydraulic fracture characteristics (Cinco-Ley and Samaniego-V, 1981):

$$F_{cd} = \frac{k_{fw}}{kx_f}, \tag{1}$$

where k_{fw} is fracture hydraulic conductivity, and k is formation permeability.

Equivalent Wellbore Radius (r_w') A vertical wellbore of radius r_w connected to a vertical hydraulic fracture can be thought of as possessing an enlarged wellbore. This enlarged wellbore has the same inflow area as the hydraulic fracture dace. Based on this concept, Equivalent Wellbore Radius r_w' is defined as (NSI, 1992):

$$r_w' = 0.5x_f, \tag{2}$$

for an infinite conductivity fracture ($F_{cd} > 30$); and

$$r_w' \approx \frac{0.28k_{fw}}{k}, \tag{3}$$

when $F_{cd} < 0.5$.

FOI (*Folds-Of-Increase*) Utilising the Equivalent Wellbore Radius concept, 'Folds-Of-Increase' is defined as the ratio between the pre- and post-fracture production rates (NSI, 1992):

$$FOI = \frac{Q_f}{Q_{uf}} = \frac{\ln(\frac{r_e}{r_w})}{\ln(\frac{r_e}{r_w'})}, \tag{4}$$

where Q_{uf} and Q_f are the pre- and post-fracture production rates respectively; and r_e is the well's drainage radius. FOI provides a simple, yet powerful, concept for designing and assessing the effectiveness of hydraulic fracture treatments. FOI can range from less than 1 for poor treatments to above 10 for highly effective treatments.

2.2 Hydraulic Fracture Modelling

Most models describing hydraulic fi-actures are based on linear elastic fracture mechanics (Ben-Naceur, 1989). In addition, all such commercial models assume that hydraulic fractures develop exclusively under ***Mode-I*** (opening) crack growth (Figure 1). Only ***local crack tip criteria*** are considered for fracture propagation. According such criteria, fractures propagate when the crack tip ***stress intensity factors*** exceeds the ***critical stress intensityfactors*** (also called fracture toughness).

For hydraulic fracture treatment design, the elastic constants and fiacture toughness of the reservoir formation, and those above and below it, must be estimated. The single-most important parameter, however, is the ***minimum horizontal insitu stress.*** Insitu stress influences hydraulic fracture geometries, fracture propagation pressures and, together with the maximum horizontal insitu stress, formation breakdown pressures.

One challenge facing the designers of hydraulic hctures in the petroleum industry is to understand the influence of near-wellbore ***reservoir heterogeneities*** in the form of natural or induced fractures. It is generally considered that such pre-existing fractures are detrimental to hydraulic fracture treatments. Pre-existing fractures lead to increased fracture fluid leakoff, which results in low fluid efficiency and, in severe cases, proppant banking and premature screen-out. In addition, pre-existing fractures promote the formation of near-wellbore fracture complexities (commonly referred to as 'fiacture tortuosity'). Near wellbore tortuosity usually takes the form of ***multiple fracturing*** or ***fracture re-orientation*** (Cleary et al., 1993). The extreme difficulties encountered during hydraulic fracture treatments performed in coalbed methane reservoirs are testimony to the adverse role of pre-existing fractures. This, however, is in stark contrast to the beneficial effects of natural fractures in HDR reservoir stimulation to be discussed in Section 3.

2.3 Hydraulic Fracture Treatment Diagnostics

Analysis of bottomhole pressure during injection provides a valuable insight into hydraulic fracture growth and geometry characteristics, such as fiacture half-length and fracture conductivity. Bottomhole treating pressure is commonly analysed through use of 'Nolte-Smith plots', which are log-log plots of ***net*** fracturing pressure versus time (Nolte and Smith, 1981). Based on the slope of the log-log plot, one can diagnose hydraulic fracture growth behaviours, such as confined height growth and unrestricted extension, increased height growth and reduced fracture length extension, or screen-out. Field-measured bottomhole pressure records are routinely history-matched against similar pressure records simulated by commercial fracture modelling packages.

Post-fracture production tests are also employed by the petroleum industry to estimate hydraulic fiacture characteristics. This process involves flowing the hydraulically fractured well for a period of time after which it is shut-in. Throughout the flowing and shut-in periods, bottomhole pressures are continuously recorded. Distinct flow regimes (such as *fracture linear* and *bi-linearflows)* may be identified through analysis of the bottomhole pressure record, from which hydraulic fiacture characteristics may be identified (Cinco-Ley and Samaniego-V, 1981).

3. HYDRAULIC FRACTURING AS APPLICED TO HDR RESERVOIR STIMULATION

3.1 Brief history

HDR reservoir stimulation was initially conceived by the Los Alamos group as a straightforward application of conventional hydraulic fracturing technology. The first HDR reservoir stimulation was carried out at Fenton Hill, New Mexico in 1977 (Tester et al., 1989). During subsequent reservoir stimulation in the early 1980s, the hydraulic fracture treatments did not behave as expected. Analyses of microseismic events induced during the stimulation suggested that the stimulated zone was ***three dimensional*** rather than ***planar.*** Furthermore, it was evident that the micro-seismically active region represented the stimulation of multiple natural joints rather than the creation of a single vertical fracture, as predicted by conventional hydraulic fracture theory. More importantly, a ***shear-slippage*** mechanism was dominant in the microseismic signals, implying that the dominant stimulation mechanism was shear fracturing rather than tensile opening. The above findings have been confirmed by field experiments at other HDR sites such as Rosemanowes, Cornwall, England in the 1980s, and more recently at Hijiori, Japan and Soultz, France.

3.2 Theoretical Aspects of HDR Stimulation

HDR stimulation employs ***shear slippage*** (Mode-11) crack growth (Figure 1) along existing natural fractures (joints) due to the application of fluid pressure. Hydraulic fractures in the near-wellbore area may, however, due to high fluid pressure and thermal contraction, still be subject to Mode-I (opening) fiacture development. It is believed that the magnitude of the 'deviatoric stress' (the difference between the horizontal insitu stresses) is 'ne=-critical' or 'critical' state with respect to the strength of ' fractured crystalline in the upper crust (Evans et al., 1997). Small stress perturbations caused by fluid pressure can lead to friction slip and small-scale seismicity, as observed in all HDR sites.

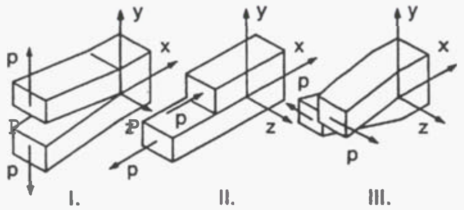

Figure 1. Fundamental modes of fractures

The principal mechanism for permeability enhancement associated with shearing is the dilation of joints (Figure 2). As joint wall surfaces are invariably rough, any offset between the two will lead to permanent separation (Figure 2). This permanent fracture wall separation (or 'offset') leads to a significant permeability enhancement. By experimentally offsetting two joint surfaces, Durham and Bonner (1994) observed a permeability increase of two orders of magnitude at zero confining pressure, and six orders of magnitude at 160 MPa confining pressure. Laboratory studies on coal samples by Durucan et al., (1993) displayed a three-order magnitude increase in permeability after failure of coal. Such permeability increases for fractured coal were retained even under high confining pressures. These experimental results suggest that once stimulated, natural fractures retain good flow properties even at great depths. This has been further confirmed by continental deep drilling. Another benefit associated with shear slippage is an increased connectivity of existing fracture networks, which leads to increased bulk rock permeability.

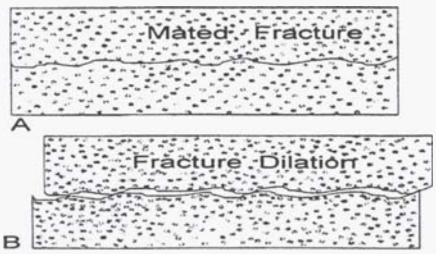

Figure 2. Fracture normal dilation due to shear displacement

Two critical factors, namely natural fracture network characteristics and deviatoric insitu stresses, determine the fate of HDR stimulation. Without a network of natural fractures, it would be impossible to create a large volume of reservoir of sufficient bulk permeability in crystalline granitic rocks at depths greater than four kilometers. Even if a large tensile fracture could be created with high injection fluid pressure, its low expected thermal efficiency would not make development of such a HDR reservoir economically viable. High deviatoric stresses are essential if shear fracturing is to occur.

Due to the interaction between natural fractures and insitu stresses, the geometry of HDR reservoirs is most likely to be ***three-dimensional,*** as opposed to single planar fractures assumed in conventional hydraulic fracturing. Figure 3 shows a HDR reservoir derived from stochastic modelling in a formation subject to a ***normal faulting stress regime*** (***$S_v > S_H > S_h$***) in three orthogonal directions. In plan view, the reservoir follows the direction of the maximum horizontal stress (S_H). In the NS cross section, the inclination of the reservoir reflects the dip of the dominant natural fiacture set. In a multi-well injection and production system, the optimal well spacing pattern is strongly affected by the dominant natural fiacture set azimuth.

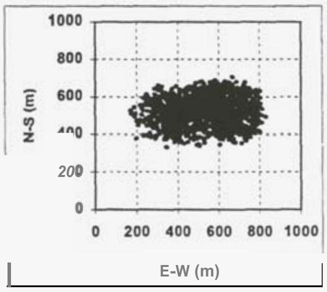

Fig. 3a. Plan view of microseismic images, as determined by the 3-D stochastic numerical model, for a reservoir subject to a normal faulting stress regime (S_v = 62 MPa, S_H = 60 MPa, S_h = 46.5 MPa, ϕ = 3°).

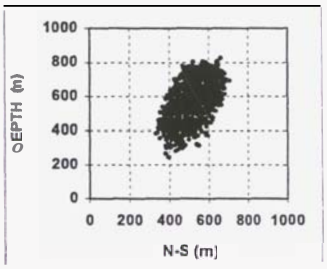

Fig. 3b. N-S side view of microseismic images, as determined by the 3-D stochastic numerical model, for a reservoir subject to a normal faulting stress regime (S_v = 62 MPa, S_H = 60 MPa, S_h = 46.5 MPa, ϕ = 3°).

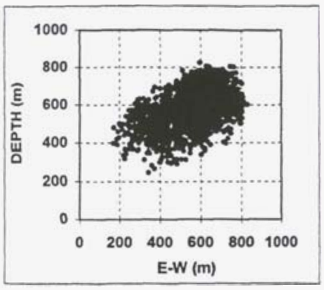

Fig. 3c. E-W side view of microseismic images, as determined by the 3-D stochastic numerical model, for a reservoir subject to a normal faulting stress regime (S_v = 62 MPa, S_H = 60 MPa, S_h = 465 MPa, ϕ = 3°).

It must be mentioned, however, that despite the significant progress made in understanding HDR stimulation technology, the formation and growth of Mode-II shear fractures in rocks and shear on joint offsets still requires extensive experimental studies.

3.3 Practical Issues Regarding HDR Stimulation

Unlike conventional hydraulic **fiacturing,** which is a well-established practice, many practical engineering issues in HDR stimulation are yet to be addressed.

In conventional hydraulic fiacture treatments, viscous fluids are injected for short periods at high flow rates to minimise fluid loss and maximise fiacture volume. In HDR stimulation a completely opposite approach is adopted, whereby fluids are injected over large time periods low rates in order to ***maximise fluid*** loss and ***minimise fiacture*** volume. This technique promotes shearing instead of tensile opening. As a consequence, a higher degree of self-propping, takes place.

Unfortunately, the injectivity of stimulated HDR wells, even after repeated stimulations, is not always high enough for commercially viable energy generation. At present, injection is limited to a few major joint intersections, permitting steady-state circulation (for example at **Soultz).** This problem may be solved through the use of multiple completions and stimulations, in contrast to single large open-hole sections.

It has been found that restriction to fluid injection occurs principally in the near-wellbore vicinity. It is envisaged that the application of propped conventional hydraulic fracturing in the late stages of HDR stimulation may be advantageous, from the point of view of creating propped, highly conductive tensile hydraulic fractures near the wellbore, thus removing flow impedance.

More advanced post-stimulation diagnostic methods and better terminology are desirable, as has been adopted by the conventional petroleum hydraulic fracturing industry. Currently, the term 'flow impedance' has been widely used to describe the capacity of stimulated HDR wells to accept or to produce fluid. Impedance is too general a term to describe the characteristics of hydraulic fractures.

4. HETEROGENEOUS NATURE OF GEOTHERMAL RESERVOIRS

Subsurface rocks in any geothermal system are highly heterogeneous on a field scale. This may be especially true for those systems located in regions dominated by volcanic rocks. Lithological changes in this case are more rapid than in a sedimentary environment. Importantly, the primary permeability of volcanic rocks is generally low. Natural fractures provide higher secondary permeability and are the dominant flow paths for steam production, as suggested by the relative permeability characteristics of reservoir rocks (Grant et al., 1982). In fact, dual porosity models developed specifically for fractured reservoirs in the petroleum industry, have been frequently used for geothermal reservoir simulation.

The inherent heterogeneous nature of geothermal reservoirs on a reservoir scale leads to non-uniform reservoir permeability. This heterogeneity holds two major implications: 1) Hot but dry holes are possible; 2) Existing well spacing is not fine enough to extract the stored heat with sufficient produced fluid temperatures and within an economical life span of the geothermal power plant. As such, some artificial stimulation techniques, similar to the so-called enhanced oil recovery techniques in the petroleum industry, may have to be developed in order to reduce drilling costs and to prolong producing life. Such enhanced recovery techniques may be performed by HDR-type stimulation.

5. WHICH GEOTHERMAL RESERVOIRS TO STIMULATE

Hydraulic fracturing is not new to geothermal systems. Nature has been carrying out hydraulic fracturing for millennia, as evidenced by the presence of hydraulic breccias in both active and fossil geothermal systems (Browne, 1982). Even man-controlled stimulations or other measures employed to increase well productivity are not new to the geothermal industry. Acidising has long been carried out in both the petroleum and geothermal industries. The application of large diameter holes ('big holes') has been applied in the Philippines. Hydraulic stimulation, however, will take well productivity enhancement in the geothermal industry to a new dimension.

Three situations where hydraulic stimulation may make profitable contributions to the geothermal industry are identified below:

1. Existing high temperature but low permeability wells in any geothermal field. This is particularly suitable to vapour-dominated systems such as the Kamojiang field, Indonesia.

2. Deep geothermal resources. As reservoir depths increase, penneability reduction is inevitable, as is the case in deep gas reservoirs, i.e. the Cooper Basin in Australia. Hydraulic stimulation is probably the only practical means through which these resources can be made economically viable. Hot Wet Rock (HWR), as proposed by Abe and Hayashi (1992) to describe conventional hydrothermal systems with low insitu permeabilities, belong to this category.

3. Vapour-dominated reservoirs with large pressure drawdowns. Using HDR stimulation and fluid injection to maintain pressure in steam fields, as suggested by Brown and Robinson (1990), is feasible. The Geysers field in the United States is a typical example of this type.

6. DISCUSSION AND SUMMARY

A brief summary has been given above of both conventional hydraulic fracturing (in the context of the petroleum industry) and HDR stimulation. Conventional hydraulic stimulation is a matured technology but its applicability to geothermal reservoirs might be limited due to the large differences in reservoir conditions between the two reservoir types. HDR stimulation, on the other hand, is more suited to geothermal well stimulation. However, a greater understanding of shear fiacture mechanics and associated permeability enhancement strategies is needed. The significant improvements in well injectivity produced by HDR stimulation warrants the trial of this technique in conventional geothermal reservoirs. It is hoped that the application of HDR stimulation technology will make geothermal energy a cheap, pollution-free reality in the not too distant future.

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