PERMEABILITY ENHANCEMENT USING HIGH ENERGY GAS FRACTURING

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ABSTRACT
This paper reports the results of a preliminary study of using High Energy Gas Fracturing (HEGF) techniques for geothermal well stimulation. Experiments conducted in the G-tunnel complex at the Nevada Test Site (NTS) showed that multiple fractures could be created in water-filled boreholes using HEGF. Therefore, the method is potentially useful for geothermal well stimulation.

INTRODUCTION
Drilling is often a substantial fraction of the overall cost of a geothermal well. It may, therefore, be more economical to stimulate a nonproducing well instead of re-drilling a new well. Because permeability in geothermal reservoirs is typically fracture dominated any stimulation method must have the potential of connecting the wellbore to the existing productive fractures.

Attempts to stimulate sub-commercial wells using hydraulic fracturing have generally been unsuccessful because hydraulic fractures usually run parallel to natural fractures.

Sandia National Laboratories with funding from the U. S. Department of Energy carried out a series of experiments to evaluate the potential of the High Energy Gas Fracturing (HEGF) technique for stimulating geothermal wells. HEGF was developed at Sandia for stimulating gas wells [1,2]. The geothermal application represents an extension of this technology from gas filled to liquid filled boreholes.

The HEGF technique uses propellants to pressurize a wellbore. By proper design it can produce multiple radial fractures emanating from a wellbore with typical fracture length of 30 ft (10 m) or more [1,2]. This fracture length is comparable to typical distances between productive geothermal fractures. Therefore, HEGF produced radial fractures can be potential conduits connecting the wellbore to existing productive fractures.

Four experiments were conducted at the G-Tunnel complex at NTS in horizontal boreholes with mine back following the experiments to examine the fracture patterns. The fracture patterns were compared with the results from finite element analyses. Propellant burn tests in steel pipes were also performed to qualify canister designs, and to test propellants and propellant mixtures.

THE HIGH ENERGY GAS FRACTURING TECHNIQUE

The Pressure Risetime Criterion

The basic concept of HEGF is that fracture patterns achieved in pressurizing a borehole are dependent on the rate of pressurization or the pressure risetime. A typical pressure time profile in a gas filled borehole shows a monotonic initial pressure rise, followed by a slight drop in pressure at fracture initiation and then again a pressure increase until the propellant burn is complete. The pressure risetime is defined as the time span of the initial pressure rise; it is a convenient measure of the pressurization rate.

For explosives or very fast propellants (0.1 ms risetimes), a crushed zone is produced about the wellbore resulting in decreased permeability. For very slow pressurizations (1 ms risetime), only hydraulic type fracture occurs. For intermediate burn rates (0.1 to 1 ms risetimes), four or eight major fractures emanate from the wellbore, oriented along principal in situ stress directions. The number of fractures...
generally increases with shorter risetimes.

Experimentally, the multiple-fracture regime can be correlated in terms of pressure risetime \( t_m \) by

\[
\frac{\pi D}{2C_R} \leq t_m \leq \frac{8\pi D}{C_R}
\]  

(1)

where \( C_R \) is the Raleigh surface wave speed and \( D \) is the borehole diameter. The term at the left is derived by Cuderman [1,2] based on a surface standing wave concept; it represents the multiple-explosive crushing boundary. The term at the right is an empirical fit to the hydraulic-multiple boundary. The expression \( D/CR \) is a measure of the communication time between surface elements of the borehole. For the 4-in boreholes in ashfall tuff in the present experiments, equation (1) reduces to:

\[
0.15\text{ms} \leq t_m \leq 2.4\text{ ms} \]  

(1a)

Propellant Specification

M5A, M5B, M30A and M30B artillery propellants were used in HEFG experiments [3]. Pressurization rates calculated from ballistics data are inadequate for HEFG applications because ballistics data are for much higher pressures. The risetimes are, therefore, experimentally determined for each propellant for cases where the borehole is filled with the propellant [1,2]. When the propellant canister is smaller than the borehole, the free volume (volume not occupied by the propellant) is increased by the annular space between the canister and the borehole. There is a corresponding increase in risetime. The risetime variation is directly proportional to the free volume [1]:

\[
\frac{t'_m}{t_m} = \frac{V'}{V}
\]  

(2)

where the primed symbols correspond to the larger free volume and risetime.

When the desired risetime cannot be achieved by using a single propellant a mixture is formulated using a logarithmic mixing law [1].

Fracture Geometry

Figure 1 is a mapping of a multiple-fracture pattern radiating from a borehole. The maximum principal stress in the plane normal to the borehole is designated \( \sigma_{max} \), the minimum \( \sigma_{min} \). The vertical and horizontal fractures are thus in the two principal stress planes. The fracture in each quadrant corresponds to plane of maximum in situ shear stress. The average fracture length was found to be proportional to the square root of energy content per unit length of the propellant canister [1].

STEEL PIPE PROPELLANT BURN EXPERIMENTS

The design of the pipe experiment is shown in Figure 2. The propellant canister consisted of a 48 in. (1.22m) long RIP igniter co-axial with a PVC pipe; propellant grains filled the space between the pipe and the ignitor. The canister size varied from 0.04m to 0.08m. For most tests 72 in. (1.83m) long, extra heavy duty 4-in. pipes (4.1 in., 0.10m, I.D.; 5.6 in., 0.14m, O.D.) with screwed-on end caps were used. A total of fourteen experiments were conducted, with canister size, propellant and annular fill (water, air) as variables. Unlike gas filled experiments, the pressure histories of water filled experiments exhibit high frequency oscillations superimposed on the general trend of increasing pressure. The pressure histories were also spatially non-uniform, see Figure 3. The oscillations and non-uniformities are related to pressure transient effects in water.

The pipe experiments show that the main effect of water is to decrease the free volume thus decreasing the risetime. The risetime (can be scaled within a factor of about two by the free volume ratio, equation (2). Risetimes in the 0.1ms to 4ms range were obtained in water filled pipes spanning the values required for HEGF applications. The pipe experiments also showed that all of the propellants used obey the same mixing laws [2,3].

NTS BOREHOLE EXPERIMENTS

Four experiments (GT1-GT4) were performed in water-filled boreholes [3]. GT1 was used to test canister design and ignition schemes; only results of GT2-4 are reported here. The experiments were all done in 4-in. (0.1m) diameter boreholes.
drilled into the face of a horizontal drift. Four holes with a 3 1/2° dip to horizontal were drilled into each 12 ft x 14 ft (3.7m x 4.3m) face. Two out of the four holes were used for GT experiments. Lithologies of the experiment zones for GT 1-2 and GT 3-4 show two types of ashfall tuff - Red and Peralkaline, in bandlike intervals. Because the intervals are shifted upward down the drift, different rock types are encountered down the axis of the boreholes. Of the two rocks, the red is more competent [4].

The experiment assembly consists of the propellant canister, pressure transducer, packer, and cable tube, Figure 4. Upon installation of the experiment package, the borehole is backfilled with water and the packer pressurized with air or water. The borehole beyond the packer is stemmed with damp sand. A foot of 50/50 mix of sand and sulfate-based cement at the collar ensures containment of the stemming.

Experiment GT2

Experiment GT2 used a 3.2 in (0.08 m) ID, 8-ft (2.4m) long propellant canister filled with 11.2kg of M5B propellant, at the bottom of a 40-ft (12.2 m) borehole. The test zone was in a mixture of Peralkaline and Red Ash. A 0.7 ms risetime was predicted assuming the only effect of water was to reduce the free volume. The observed risetime was 0.3 ms, Figure 5. Both values are within the multiple fracture regime. The fracture pattern is shown in Figure 6. A large hydraulic type fracture started near the pressure transducer end of the test zone, then propagated both toward the collar of the borehole and over the test zone, total length 23 ft (7 m). Just before the test zone, a horizontal fracture was observed between 25 ft and 31 ft (8.8 and 9.4 m); in this region, the fracturing is characterized as multiple. In the test zone itself, multiple fractures were initiated but propagation was prevented. The same risetime in a liquid-free borehole would have produced a multiple fracture pattern. But here the pattern is a combination of hydraulic, multiple, and explosive fracturing. The fact that the test zone was partially in Peralkaline may be a contributing factor for crushing.

Experiment GT 3

Experiment GT3 used a 1.75-in (0.044 m) diameter 4-ft (1.22 m) propellant canister with 1.36 kg of M30A propellant. The borehole was 25 ft (7.62 m) deep. The test zone was mainly in Red Ash. A pressure risetime of 1.2 ms was predicted. Figure 7 shows the measured pressure history with two major pressure pulses having risetimes of 0.25 ms, and 1.9 ms, respectively. The 1.9 ms risetime is consistent with pipe results. These risetimes in a 4-in borehole, should result in multiple, and multiple-hydraulic fracturing, respectively.

The mineback results are summarized in Figure 8, showing major fractures at 55 degrees and at 215 degrees (measured from the direction of maximum principle stress) about 5 ft (1.52m) long. In addition, a small fracture nearly parallel to the 55° orientation broke out near the center of the test zone. In gas-filled boreholes, the predominant fractures are in the principal planes of stress; fractures in the quadrants between the principal stresses, corresponding to the principal shear planes, were secondary, but in liquid filled boreholes these appears to be no preference. Borehole televiewer observations indicated that horizontal and vertical fractures were clearly initiated but they did not propagate.

Experiment GT 4

Experiment GT 4 used a 3.2 in (0.08m) diameter 4-ft (1.22 m) propellant canister with 5.27 kg of 50/50 mixture of M30A/M30B propellants. The borehole was 25-ft (7.62 m) deep. The test zone was predominately in Peralkaline. A pressure risetime of 0.5 ms was predicted. Figure 9 is a plot of the pressure history. The peak pressure for the overall pulse occurred at 7.4 ms. But, three sharp pressure spikes are observed in the first millisecond of pressure buildup, with risetimes ranging from 0.07 ms to 0.2 ms. The 0.07 ms spike is expected to initiate crushing, the 0.2 ms multiple fracturing. The third spike is probably most important because of its larger impulse. If either the first three pulses or the second and third acted collectively resulting in effective risetimes of 1 ms and 0.3 ms respectively, multiple fractures should result.
Figure 10 is a 3-dimensional drawing of the GT-4 mineback. Four main fracture sets, labeled 1-4, were mapped. The borehole televiewer and mineback showed significant borehole crushing in the test zone. A vertical hydraulic fracture, see fracture 1 and 1A (Sec. A-A and C-C) Figure 10, above the borehole, was present in most of the mineback. The other major fractures were mainly in principal shear plane directions.

A multiple fracture pattern was again initiated at the borehole, but only one to three of these fractures propagated into the formation at any given section, see fracture 2 (Sec. B-B) and fracture 3 (Sec. DD) in Figure 10. Fracture 4 originated at the end of the borehole and proceeded well beyond the mineback region (Sec D-D).

The combination of fracture patterns observed in GT-3 and GT-4 both indicated that the fracture behaviors are best understood as the cumulative effects of individual pressure pulses.

**NUMERICAL ANALYSIS**

Two dimensional finite element analyses of the experiments were conducted for comparison with the experimental results. Since the observed fracture patterns are actually three dimensional, the comparison must be recognized as qualitative. The pressure histories were calculated via a propellant burn model, and rock cracking and crushing were represented with an elastic-plastic cracking material model and a tensile cracking criterion [4]. Water was modeled simply as an incompressible solid. Because of the aforementioned problems with ballistics data, the calculated pressure rates and peak pressures were only within a factor of two to three of the measured values. Therefore, the experimentally measured borehole pressure histories were used as inputs in a separate series of analyses.

**Results**

**GT2**

When the experimentally measured pressure was used, the calculations showed significant cracking adjacent to the borehole and the radius of the borehole increased to approximately 4.5 inches. These results are in qualitative agreement with the mineback data, Figure 6.

**GT3**

The analyses predicted a major vertical fracture, and some short fractures adjacent to the borehole. The result agrees qualitatively with the initiation of multiple fracture observed by the televiewer. However, the predicted fracture directions are not consistent with the experimental results.

**GT4**

The analyses using the burn model predicted one major vertical crack Figure 11a. However, when the experimental pressure history containing the pressure spikes was used, short cracks adjacent to the borehole of approximately the length of the observed ones also formed, Figure 11b. This result corroborates the observation that individual pressure spikes are important to the formation of the fractures.

**CONCLUDING REMARKS**

Multiple fractures along hydraulic fracture directions and principal shear planes such as those observed in GT 3 and GT 4 were created in water-filled boreholes, using the HEGF technique, thus demonstrating the potential of HEGF for Geothermal Stimulation.

The fracturing behavior is considerably more complex in liquid-filled boreholes than the liquid-free case. More research is needed with longer test zones, where the influences of end effects and pressure transients are expected to be less. Experiments should also be conducted in naturally fractured or prefractured test beds to simulate reservoir conditions. Finally, application in geothermal wells requires development and testing of high temperature propellant systems or temperature control of wells during stimulation.

**REFERENCES**


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Fig. 7 GT3 Experiment Pressure History

Fig. 8 GT3 Fracture Mapping

Fig. 9 GT4 Experiment Pressure History

Fig. 10 GT4 Fracture Mapping

Fig. 11 GT4 Calculated Fracture Pattern