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# GEOTHERMAL WELL STIMULATED USING HIGH ENERGY GAS FRACTURING

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## ABSTRACT

This paper reports the result of an experimental study of the High Energy Gas Fracturing (HEGF) technique for geothermal well stimulation. These experiments demonstrated that multiple fractures could be created to link a water-filled borehole with other fractures. The resulting fracture network and fracture interconnections were characterized by flow tests as well as mine back. Commercial oil field fracturing tools were used successfully in these experiments.

## INTRODUCTION

Drilling is often a substantial fraction of the overall cost of a geothermal well. It may, therefore, be more economical to stimulate an under-productive well instead of redrilling a new well. Sandia National Laboratories, with funding from the U. S. Department of Energy has conducted studies on the use of High Energy Gas Fracturing (HEGF) techniques for geothermal well stimulation. By HEGF, we refer to any of the experimental and commercial techniques for inducing multiple, radial fractures in a wellbore using rapid pressure loading with propellants or explosives. A HEGF tool was originally developed at Sandia as a well stimulation technique for gas wells [2,3]. The geothermal applications represent an extension of this technology from gas filled to water filled boreholes.

Most HEGF techniques use propellants to pressurize a wellbore. With the right pressurization rate, they can produce multiple radial fractures emanating from a wellbore with typical fracture length up to 10 meters. Radial fractures in the non-hydraulic-fracture directions are most desirable for geothermal well stimulation since they are most likely to intersect the existing production fractures which typically run parallel to the hydraulic-fracture direction. While no detailed mappings are available to determine fracture spacings in a production field, field data show that typically production fracture spacings should be in the range of one to tens of meters. At the Geysers, production wells are known to be drilled as close as 3 meters from non-productive wells. HEGF will certainly be useful for fields where fracture spacing falls in the 1-10 meter range. Additionally, in our own study, [5], computer modeling of HEGF shows that HEGF is superior to hydraulic fracturing in correcting near wellbore damage.

The present study is a joint project between Sandia National Laboratories and Servo-Dyanmics, Inc. We are interested in evaluating the performance of commercial oil field fracturing tools for geothermal well stimulation. These tests were conducted in G-Tunnel, Rainier mesa, at DOE's Nevada Test Site (NTS). G tunnel is a tunnel system that is driven more than a mile into volcanic tuffs at a depth of about 425 m (1400 ft). It is ideal for fracturing experiments because it provides an in situ medium with appropriate boundary conditions (an isotropic stress field, no free surfaces) yet still allows detailed examination of the created fractures through mine back.

In a previous series of experiments in horizontal boreholes, we demonstrated the feasibility of producing multiple fractures in water filled boreholes [1,4]. However, because the tools used were relatively short, there were large end effects and multiple fractures were only observed in a portion of the test zone. Therefore, the present series of experiments were carried out in vertical boreholes using longer tools.

## EXPERIMENTAL DESIGN AND PROCEDURE

The current series of tests were conducted in peralkaline ash fall tuffs of Tunnel Bed 5 of the Indian Trail Formation, which is approximately 30 m (100 ft) thick at the test location. Properties of these peralkaline tuffs are shown in Table I.

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They are usually soft, low modulus, low permeability and high porosity rocks and, as such, are well suited for mineback experiments since they allow for easy excavation with a continuous mining machine. The in situ stresses have been measured in the vicinity of these tests yielding an overburden stress of about 7 MPa (1000 psi) and horizontal stresses of about 3.4 MPa (500 psi) and 5.5 MPa (800 psi). The maximum horizontal stress (hydraulic-fracture) direction is S30°W.

Five vertical holes were cored into the the test drift. They are number 1 through 5. The layout of the hole pattern is shown in Figure 1. Because we were interested in observing fracture intersections and bore-hole to borehole interconnections, the borehole patterns were designed to facilitate the formation of fracture intersections.

Two holes (2 and 5) were placed along the hydraulic-fracture direction 4.5 meters (15 ft.) apart. Two more were located between 2 and 5, on either side of the line connecting the two, 2.4 meters (8 ft.) apart. A practice hole, hole 1, was located 3.0 meters (10 ft) down from hole 2, in the main drift direction (N42°W). The practice hole (1) was 17.4 meters (57 ft.) TD; the four test holes were 12.3 meters (42 ft) TD. The vertical displacement lessens the possible influence of practice shot in hole 1 on the rest of the tests. All holes, except hole 2 were open holes 9.60 cm (3.78 in.) in diameter. Hole 2 was cased with N80 casing and perforated, with 1.5 cm (0.6 in.) diameter perforation, 8 perf/ft with 90° phasing. Two sets of perforations were in line with the hydraulic-fracture direction, the other two perpendicular to it. Thus, hole 2 was designed to create fractures along the line connecting holes 2 and 5 and fractures perpendicular to this line. With this arrangement, we enhanced the probability of fractures from holes 3 and 4 intersecting the fractures from hole 2.

The experimental assembly consists of the propellant tool, the pressure transducer assembly, a rubber wiper above it and a cable tube. All the propellant tools used were 3.7 meters (12 ft.) in length. The Servo-Dynamics tools, trademark StressFrac tools, were used in holes 1-4; these are one piece solid propellants with a thin aluminum skin. There were three liner ignitors parallel to the axis of the tool. The reason for using three ignitors instead of one as in oil field tools was to insure ignition and to provide a way to control initial burning rates. Two sizes of StressFrac tools, one 6.4 cm. (2.5 in.) diameter with 16.6 Kgs (36.6 lbs) of propellant and one 7.6 cm (3.0 in.) diameter with 26.2 kgs (55.7 lbs) of propellant, were used. The Sandia tool was used in hole 5. This tool uses a 3 in. PVC tubing (8.26 cm, 3.25 in. I.D.; 8.89 cm, 3.50 in. O.D.) filled with a 50/50 mixture of M30A and M30B artillery propellant pellets; a RIP ignitor runs down the axis of the tool. The top of each tool is connected to the pressure transducer assembly with a 138 MPa (20k psi) pressure transducer to record the pressure/time history during the test and a crush gauge to record maximum pressure.

The tools were installed 0.3 meters (1 ft) above the bottom of the borehole. Upon installation of the tool, a sand tamp was formed above the wiper to within 15 cm of the collar to contain the gas pressure during the experiment. The test zone defined by the bottom of the sand tamp and the hole bottom was typically 4.4 meters (14.5 ft). Fifteen centimeters of a 50/50 mix of sand and sulfate-based cement at the collar insured containment of the stemming.

Core samples obtained during drilling were examined for existing fractures before the experiments. Some healed fractures were found, but there were no open fractures observed. Before each test, a TV log and a constant pressure permeability test were performed. During the test, pressure history and peak pressure were measured. Observations were also made of borehole-fracture interaction through video camera recordings. Before each shot, all the holes were filled with water. If interconnections were made during the shot between the test hole and any particular hole, water would be ejected from that particular hole, see for example Figure 2. Following each test, a TV log was used to examine the fracture patterns, Figure 3, and a constant flow test was performed to obtain the effective permeability of the borehole. Dyed water of different colors was used in the flow test to mark the fractures. In cases where borehole ejection occurred, permeabilities of holes other than the test hole were also measured after a shot to determine the effect of the shot on neighboring holes.

At the conclusion of all the shots, the test bed was mined back to examine the fractures in detail. To prevent the near wellbore fracture patterns from being damaged during mining, the patterns were potted in place by filling the borehole with grout. The grout was sufficiently fluid to also fill the near wellbore fractures. Mine back was accomplished by excavating a drift 38 feet below the test drift in the N11°E direction; centerline of the drift passed 0.76 meters to the right of hole 5 and 0.76 meters to the left of hole 2, Figure 1. The mineback drift was 3.7 meters (12 ft) by 3.7 meters (12 ft).

Each successive face corresponds to a vertical cross-section of the test bed, exposing the last 31 meters (10 ft) of the test zone and 0.6 meters (2 ft) beyond the bottom of the boreholes. Since the miner cuts typically a horizontal trough 0.5 meters high by 3.7 meters long by 0.5 meters deep, at each cut a strip of the "horizontal" section is also revealed.

RESULTS

The present test series is designated as GTSF86 and each test is identified by the hole number following the GTSF86 designation. The results of each shot are discussed in the sequence that the shots were made because the fracture patterns are significantly influenced by the fractures already existing at the time of the shot. Detailed fracture mapping is still under way at the present time. A composite schematic of the fracture network in the test zone is shown in Figure 4. TV logs show that in all the tests, fractures actually start to appear at about 2 meters above the test zone first in the hydraulic-fracture direction only. In cases where multiple fractures exist, the first occurrences were usually very near the top of the test zone; fracture width at the wellbore continues to increase downhole until the middle of the test zone.

EXPERIMENT GTSF-1

This was a practice test to help define the type of tool and pressurization rate that would be needed for the other holes. A StressFrac slow burning 6.4 cm diameter tool was used. The maximum pressure as recorded by the pressure transducer was 34.3 MPa (4970 psi); the value given by the maximum pressure crush gauge was 35.2 MPa (5100 psi). This close agreement is typical for all the shots; therefore, for subsequent shots only the valve obtained by the pressure transducer will be reported. The average pressurization rate, defined as the ratio of the maximum pressure to the pressure rise time (the time required to reach the peak pressure), was 9KPa/µs (1.3 psi/µs).

Hole 1 is outside of the mine back zone; no information on the fracture pattern is available. The TV log shows that the main fracture to be in the hydraulic-fracture direction with intermittent sections showing fracture initiation in the non-hydraulic direction. The fracture width at the wellbore was as wide as 4 centimeters.

EXPERIMENT GTSF-2

The second shot of the series was in hole 2, the cased/perforated hole, with an identical tool to the one used in hole 1. A peak pressure of 104 MPa (15,000 psi), was reached at an average pressurization rate of 110 Kpa/µs (16 psi/µs).

As designed, the shot produced fractures in the two principal stress directions, see Figure 4. The hydraulic fractures are the most prominent. The southern branch is fully exposed with a length at least 7 meters long. The northern branch should be of comparable length. In the direction perpendicular to the hydraulic fracture to the west, there is a short fracture of about 0.5 meters. The casing was found to be split on the east side along the perforation around 11 meters from the collar (the hole is 12.8 m TD) for about 0.5 meters. The split is as wide as 5 centimeters. Correspondingly, near the casing split the fracture going east of hole 2 is also quite wide, with a fracture aperture of about 0.6 centimeters wide as far as 0.5 meters away from the hole. The east-going fracture has not been mined back fully, but it appears to be turning south, possibly toward the hydraulic-fracture direction. The edge of this fracture can be traced at least as far as 3 meters along the east rib (sidewall) of the mine back drift.

On a more local scale, there appear to be two sets of fractures out of each perforation, one vertical and one horizontal. The horizontal fractures usually do not extend more than 0.3 meters beyond the borehole; the vertical one is distinct for each perforation. Due to a slight misalignment in the perforation shot, every other perforation is displaced from the neighboring one. Up to about one foot away, the edge of the fracture has the appearance of a sine wave with trough and valley corresponding to the perforation locations. These individual fractures eventually merge into a single fracture away from the hole.

EXPERIMENT GTSF-4

Hole 4 was shot with a 7.6 cm diameter StressFrac tool. A peak pressure of 10 MPa (10,150 psi), was reached at an average pressurization rate of 350 KPa/µs (51 psi/µs). During the test, water ejection was observed out of holes 2 and 5.

As many as six major fractures grow out of the borehole, Figure 4. A TV log shows that the fractures are about 5 to 7 centimeters wide near the borehole. Near the middle of the test zone, the circular borehole geometry is replaced by a star pattern (similar to Figure 3). The enlargement is not due to plastic deformation corresponding to borehole crushing rather, it appears to be caused by rock pieces detaching from the borehole as a result of fine fracturing near the borehole. This star pattern at the borehole is also typical of other holes with multiple fractures. Of the six fractures, two are in the hydraulic-fracture direction, two toward the west, and two toward the east. One of the east running fractures intersects the hydraulic-fracture from hole 2. In this case, the advance of the fracture has been arrested at the intersection, Figure 5. This fracture intersection is the cause of water ejection at hole 2. There does not appear to be any direct link between holes 4 and 5 in the mine back zone. A TV log of hole 5 after the shot in hole 4 indicated a small localized fracture at about 9 meters corresponding to a healed fracture observed in the core samples of hole 5. Apparently, this fracture was reopened and caused the ejection out of hole 5.

EXPERIMENT GTSF-5

Following hole 4, hole 5 was shot with the Sandia tool. The peak pressure was 69.6 MPa (10,100 psi), 65.5 MPa (9500 psi) crush gauge; the pressurization rate was 33 KPa/μs (4.8 psi/μs). Water ejection occurred at holes 2 and 4.

Again there are as many as six fractures extending out of the borehole, Figure 4. The non-hydraulic fractures do not extend as far as those out of hole 4. Two of the fractures going east intersect the hydraulic fracture from hole 2. The northern branch of the hydraulic fracture from hole 5 runs very close to the southern branch of the hydraulic fracture from 2; at some depths (not throughout the entire depth of the test zone) they are probably merged. The southern branch of the hydraulic fracture runs into the left rib. Where it enters the rib, the wall simply slabs off revealing the fracture surface for a one meter length over the height of the drift. The multi-colored surface of the fracture is a vivid example of the hole to hole interconnection through a fracture network. During mine back, pieces of PVC from the propellant canister were found trapped in the fractures as far as 5 meters from the borehole. Since the PVC tube wall has an original thickness of 3 mm, the fracture aperture during the formation of the fracture is at least that wide.

EXPERIMENT GTSF-3

The last shot was done in hole 3 using a fast burning, 6.4 cm StressFrac tool, resulting in a peak pressure of 79.3 MPa (11,500 psi), 65.5 MPa (9500 psi) by crush gauge. The pressurization rate was 172 KPa/μs (25 psi/μs). Water ejection was observed at hole 2.

The shot results in multiple fractures, Figures 4 and Figure 5. The fractures in the non-hydraulic-fracture direction extend 1 meter or less from the borehole except the one perpendicular to the hydraulic-fracture direction going east. That particular fracture has not been fully excavated, but it appears to be turning south toward the hydraulic-fracture direction. The edge of the fracture is visible along the right rib of the drift for about 2 meters. The southern branch of the hydraulic fracture extends at least 3.7 meters. The northern branch intersected the non-hydraulic fracture going east from hole 2. In this case, the hydraulic fracture did not stop at the intersection, it went through the existing fracture out of hole 2. This hole 3 to hole 2 interconnection was the most productive fracture interconnection of the entire series (more in the next section).

FLOW TESTS

The pre-shot permeability of each borehole was measured using a constant pressure injection. The post-shot permeability was measured using a constant flow rate test. In both cases, the shut-in data were found to give the most consistent results. The results of the permeability tests are summarized in Table II. Generally, the primary effect of a shot is to increase the permeability of the test hole. While typical pre-shot permeabilities are in the range of 0.4-0.7 md, post-shot effective permeability ranges between 80 to 170 md. The shots also have secondary effects, i.e. effects on neighboring holes. For example after the shot in hole 4, the effective permeability of hole 5 increased to 2.0 md due to the interconnection between hole 4 and 5. Secondary effects are not always positive; effective permeability of holes 2 and 4 both show a decrease as a result of shots in neighboring holes, Table II.

The fracture network grew with each shot. Production was observed out of neighboring holes during permeability flow tests for later shots. Fracture aperture was estimated using production data from flow test of hole 3. During the last ten minutes of the test the average driving pressure was 1.3 MPa (190 psi); a steady production rate of 4.2ℓ/min (1.1 gpm) was observed out of hole 2. Using a fracture length of 3.5 meters consistent with the mineback result and a fracture height of 4.6 meters (essentially the entire test zone), the permeability aperture width product was calculated to be 0.04 darcy-meter. Assuming the fracture to be a parallel plate channel, the average fracture aperture for the hole 3 to hole 2 interconnection was then estimated to be approximately 0.1 mm (4 mils). This is considerably smaller than the estimated aperture width of greater than 3 mm at the formation of the fracture. Ash fall tuff is relative soft and may have poor self-propping properties. The actual fracture width observed during mine back varied from several centimeters to submillimeters.

## CONCLUDING REMARKS

The present series of tests demonstrated conclusively that it is possible to create multiple fractures in water filled boreholes. It is useful to note that multiple fractures were obtained with average pressurization rates ranging from 33 KPa/μs to 350 KPa/μs. The fact that the operating range spans one order of magnitude in the pressurization rate means that the method is practical for field applications. The experiments also demonstrated that fracture interconnections can be made.

These tests have been conducted in ash fall tuffs which are not the typical geothermal reservoir rock, but proper application of rock mechanics principles allows these results to be extrapolated to other rock types. For example, energy considerations lead to the deduction that the fracture length is proportional to the square root of Young's modulus [4]. Greater lengths are expected in higher modulus formations because the crack is narrower and the gas volume can create more length. Thus, granites or basalts should have greater fracture lengths. On the other hand, length is obviously inversely proportional to the in situ stress level since any pressure below the minimum stress cannot do any useful work. A considerable amount of energy may be needed in pressurizing up to the in situ stress level.

Multiple fracture initiation also depends on the rock type and stress levels. We should expect that the pressure loading rate required for multiple fracturing will be

$$\frac{dp}{dt} \alpha \frac{\sigma_{Hmax} - \sigma_{Hmin}}{D} V_p ,$$

where $\sigma_{Hmax}$ and $\sigma_{Hmin}$ are the maximum and minimum principal in situ stresses perpendicular to the axis of the hole, $V_p$ is the compressional wave velocity of the rock and D is the borehole diameter. High velocity rocks, such as granite, will require faster load rates, as will formations with large horizontal stress differences. Such design calculations as these should always be considered when a new rock type is to be fractured.

Because the fracture aperture was found to be as wide as 3 mm during the shot, it will be useful, in the future, to test shots loaded with proppants. If the fractures can be propped near the borehole, it might then be useful to use multiple shots to achieve fracture extension. Finally, for actual applications, it will be necessary to develop high temperature tools. While the propellant in the StressFrac tools might be stable up to 650°F, high temperature ignition systems need to be developed.

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TABLE I

Peralkaline ash-fall tuff properties

| | |
|---|---|
| Bulk Density | 1.8± 0.1 gm/cc |
| Porosity | 40 ± 5 % |
| Water Saturation | 90 ± 5 % |
| Young's Modulus | 2-3 GPa; 0.3-0.4x10$^6$psi |
| Poisson's Ratio | 0.15 |
| Compressive Strength (unconfined) | 14 MPa; 2x10$^3$psi |
| Tensile Strength (unconfined) | 0.7 MPa; 100 psi |
| Permeability | 0.1 - 2 md |
| Compressional Wave Velocity | 1500-2500 m/sec |
| Shear Wave Velocity | 900-1500 m/sec |

**EFFECTIVE BOREHOLE PERMEABILITY, md**

| TEST SEQUENCE | Hole 1 | Hole 2 | Hole 3 | Hole 4 | Hole 5 |
|---|---|---|---|---|---|
| PRE-TEST | 0.4 | 2.0 | 0.4 | 0.7 | 0.5 |
| 1 | 78 | | | | |
| 2 | | 172 | | | |
| 4 | | | | 161 | 2.0 |
| 5 | | | | 69 | 79 |
| 3 | | 142 | 149 | | |

Table II

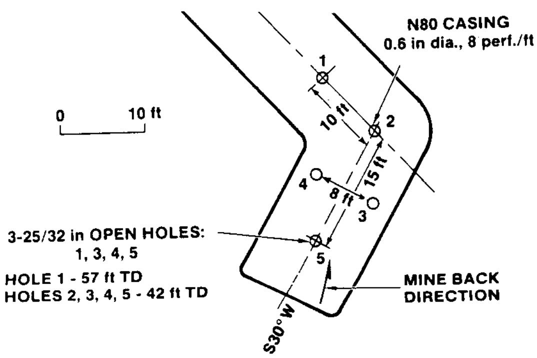


Figure 1. Test Layout

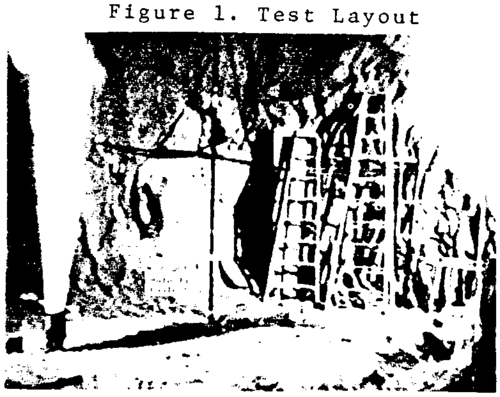

Figure 2. Water Ejection out of Hole 2 due to shot in Hole 3

Figure 3. Multiple Fracture Pattern of Hole 3

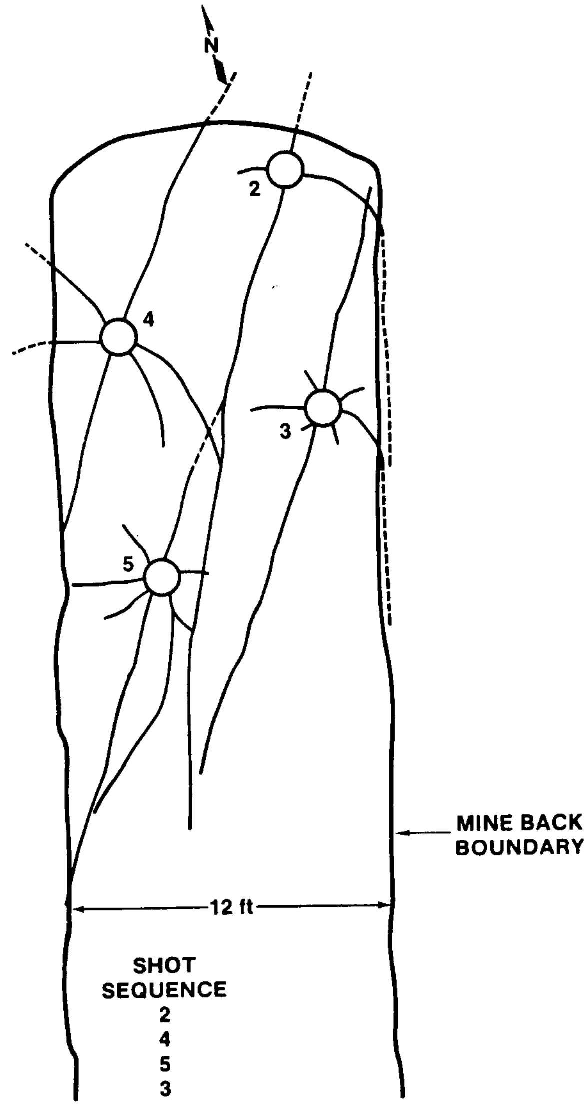


Figure 4. Schematic of Fracture Network

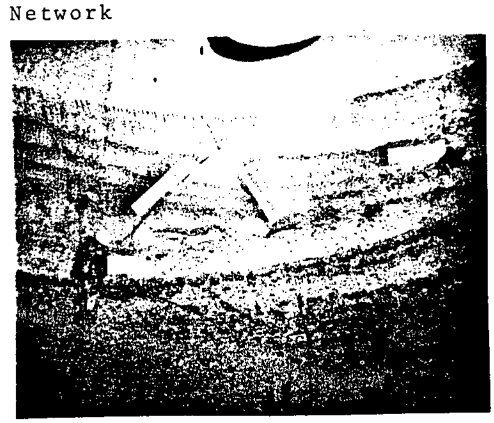

Figure 5. Fractures from Holes 2, 3, 4