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A MULTIPLE-FRACTURING TECHNIQUE FOR ENHANCED GAS RECOVERY

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SUMMARY

The use of progressively burning propellants is a promising new technique for producing multiple fractures in a wellbore. Three series of multiple fracturing experiments have been conducted under realistic in situ conditions and directly observed by mineback in a tunnel complex at the Nevada Test Site. The first two series (1-3) showed that multiple fracturing by propellant deflagration is feasible and depends most critically on the initial pressure loading rate produced by the propellant burn. The most recent series verified scaling criteria developed by semi-empirical and analytical modeling. It showed that results from small scale tests can be adequately scaled and that they can provide an effective method for investigating and optimizing multiple fracture generation and extension, for developing optimum propellants for multiple fracturing, and testing technologies such as forcing proppant into fractures.

INTRODUCTION

The multiple fracturing technique involves use of progressively burning propellant to tailor pressure rates in a wellbore to produce multiple fractures and utilizes the combustion gases to extend them. Such multiple radial fractures may be very desirable in wells in naturally fractured reservoirs such as Devonian shale. Figure 1 is a schematic of a wellbore in a naturally fractured reservoir. Three conditions are shown (a) no fracture treatment, (b) a hydraulically fractured well, and (c) a multiply fractured wellbore. The production from an unstimulated well depends strongly on the number of natural fractures which it intersects. Hydraulic fracturing typically

produces a single large fracture normal to the minimum in situ principal stress. If it runs parallel to the existing fractures, as appears likely, little enhancement will result. Multiple fractures may not extend as far as hydraulic fractures but should cut across natural fractures and connect more of them to the wellbore. On the other hand, the use of explosives has been shown to result in the creation of a stress cage surrounding the wellbore and an actual decrease in transmissivity to the well (4,5).

Sandia National Laboratories, under joint Gas Research Institute-Department of Energy funding, is developing a high energy gas fracturing technique for producing multiple fractures about a wellbore. The objective of the program is to optimize the High Energy Gas Frac (HEGF) technique for use in gas well stimulation. Three activities are included in the program: (1) in situ experiments, (2) analytic and modeling efforts, and (3) design and development of hardware for use in a full scale experiment in a Devonian shale gas field.

The in situ experiments are conducted in a tunnel complex at the Nevada Test Site (NTS). Typically, pressure-time measurements are made in boreholes which contain propellant canisters. Stress and acceleration measurements are made simultaneously in adjacent boreholes. Post-test mineback through fractured zones permits correlation of created fracture systems with borehole pressure and stress and acceleration time histories and modeling predictions. Transmissivity tests before and after fracturing provide quantitative data on the degree of fracturing resulting from the propellant burn.

To date three series of in situ experiments have been completed at NTS. The first two series were done in 0.15 m and 0.20 m diameter boreholes with an emplacement depth of 12 m from the tunnel face. This location was at a depth of 427 meters and had in situ stresses of 5.4, 8.6, and 10.3 MPa. The first series GF 1, 2, and 3 was a comparison of three High Energy Gas Frac (HEGF) experiments at slow, intermediate and fast burn rates, respectively. The second series was a comparison of the "intermediate" rate HEGF experiment with two commercially available techniques--Dynafrac (6) and Kinefrac (7)--in different fielding modes. Table 1 is a summary of the results of these two series of experiments, grouped according to the type of fracture observed during mineback.

Hydraulic fracture behavior normally consists of only a single fracture normal to the direction of minimum in situ stress. Explosive fracture inplies a crushed borehole with a stress cage formed about the wellbore with few if any raidal fractures. Multiple fracture behavior implies a total of 4-8 major fractures radiating from the wellbore.

Table 1

A Summary of the Results of Tailored Pulse Experiments

Experiment	Wellbore Diameter	Peak Pressure MPa	Pressure Rate MPa/sec	Fracture Type
Sandia GF 1	0.20	47	$6x10^2$	Hydraulic
Dynafrac GF 8	0.15	30	$7x10^3$	Hydraulic
Sandia GF 2	0.20	95	$1.4x10^5$	Multiple
Sandia GF 4	0.15	250	$4.3x10^5$	Multiple
Kinefrac GF 5, 6	0.15	38	$1.4x10^5$	Multiple
Dynafrac GF 7	0.15	7.82	$7.72x10^5$	Explosive
Sandia GF 3	0.20	~200	$>10^7$	Explosive

The third series of experiments was conducted in 0.025, 0.05, and 0.075 m diameter boreholes. The 0.075 m diameter was defined by the propellant canister which was centered in a 0.15 m diameter borehole packed with 20-40 mesh bauxite proppant. This series had several objectives.

(1) To test scaling predictions for pressure rates required to produce multiple fractures for different borehole diameters. Semi-empirical and analytical modeling predicted that smaller boreholes require faster propellants.

(2) To examine the feasibility and limitations of using such small scale experiments to study fracture initiation and extension, propellant optimization, and technology development--i.e., use of proppants. Such small experiments could greatly reduce installation and mineback costs during testing to expedite the development of the concept.

(3) To compare the effectiveness of a new sand tamp scheme with conventional grouting for experiment containment. This would allow a potential five-week decrease in length of time required to do an experiment resulting in significant cost reduction, and would be a technique applicable in actual wellbore use.

(4) To test a new pressure grouted stress gage--accelerometer installation to permit measurement of tensile as well as radial stress and acceleration. This would permit improved data for modeling and tests of predictions for pressure rate requirements in gas well applications.

The results of this most recent experiment series and their application to these objectives form the focus of this paper.

EXPERIMENT DESIGN

Figure 2 is a schematic of the small scale experiments emplaced in the end of a tunnel drift in ashfall tuff at NTS. The dashed circles denote predicted fracture radii. Table 2 gives the specifications for each of the experiments. The borehole total depths were all nominally 3 m. Boreholes A, B, C, and D contained propellant canisters and pressure transducers. Borehole E contained stress and acceleration sensors.

Table 2

Small Scale Feasibility Experiment Specifications

Borehole	Diameter (m)	Canister Length (m)	Canister Diameter (m)	E/L Joule/M	Propellant**
A	0.032	0.7	0.025	1	M5(155)
B	0.032	0.7	0.025	1	M5(90)
C*	0.150	1	0.076	9	M5(155)
D	0.048	1	0.041	4	25%M5(90)
				-	75%M5(155)

*C was surrounded with 20-40 mesh bauxite proppant.
**The number in parenthesis is the grain size or proportional to size; the larger numbers denote larger grains. The smaller the grain, the faster the burn rate and hence the shorter pressure rise time.

Figure 3 is a schematic of the propellant canister's design used in the small scale feasibility experiment. In experiments A and B the canisters were of paper phenolic and aluminum, respectively, instead of PVC. In all cases the propellant canister was fastened to a housing containing a fluid coupled plate pressure transducer.

Figure 4 is a schematic of the instrument assembly before it was potted in epoxy in a 0.01 m diameter cylinder. It contained two bipolar stress gage-accelerometer pairs oriented perpendicular to each other. By installing the gage oriented at 45° to the vertical four gages were thus sufficient to record both radial and tangential components for all four successive experiments.

Experiment A was grouted with a high strength grout. The instrument package was grouted under pressure and maintained under pressure during cure to establish a pre stress on the package so as to enable measurement of tensile as well as radial components.

Experiments B, C, and D were stemmed with a new sand tamp technique. After experiment emplacement, wet Overton Nevada sand was tamped into the boreholes. A short plug (0.3 m) of a fast-setting, sulfur-based cement near the pressure gage housing and at the collar served to exclude sand and water from the propellant canister region and prevented drying and collapse of the sand plug near the collar.

RESULTS AND DISCUSSION

The four experiments were fired in the sequence A, B, D, C. Both the instrument pressure grouting and the sand tamps worked well. All the sand tamps were intact after the experiments were completed. However, borehole A, which was grouted, vented during its shot resulting in lower than predicted pressure buildup. Table 3 summarizes the results.

The proppant in borehole C was injected more than 1 m into fractures. In one case, for a vertical fracture below the borehole, the fracture was propped open to a width of about 0.006 m at the borehole.

Table 4 summarizes the results of pre-test and post-test transmissivity measurements for boreholes A, B, and D. Because the initial coring resulted in an irregular borehole for C, it was not possible to set a packer in it for the transmissivity test. The technique used for measuring transmissivity has been previously described (2).

Table 3

Borehole Pressure and Fracture Summary

Borehole	Peak Pressure (MPa)	T_{max} (sec)	Pressure Rate (MPa/sec)	Fracture Type
A	20	6.5×10^{-3}	3.1×10^{3}	Hydraulic
B	310	5×10^{-5}	6.2×10^{6}	Multiple
C	76	1.1×10^{-4}	6.9×10^{5}	Multiple
D	77	4×10^{-3}	1.9×10^{4}	Hydraulic

Table 4

A comparison of Pre-Test and Post-Test Transmissivity

Borehole	Pre-Test (md)	Post-Test (md)	Factor Increase
A	2.6×10^{-1}	2.6	10
B	2.9×10^{-2}	3×10^{-1}	10
D	1.5×10^{-2}	3.23	215

The design of the small scale experiment involved two main design and scaling considerations. These were (1) scaling of a pressure pulse from a large borehole size to a small one so as to ensure equivalent fracturing and (2) determination of fracture radius as a function of borehole size and propellant change. The term "equivalent fracturing" is best explained in terms of pressure and pressure rate ralationships which define the boundaries of hydraulic-multiple and multiple-explosive fracturing as a function of borehole size.

Using an idealized pressure pulse of the form $P = P_o te^{-\alpha t}$, an analytical elastic model was constructed which predicts the dynamic stress, acceleration, velocity, and displacement in the formation in response to the pulse (8,9). In the idealized pulse equation, P is the borehole pressure, Po is the pressure rate, t is the time, and α is $1/t_m$, where t_m is the time at which the peak presure P_m occurs. In general the idealized pulse is a good approximation to that which is measured experimentally.

Figure 5 is a plot of tensile stress pulse risetime vs pressure pulse risetime as a function of borehole size. Starting from the right, it is noted that there is a linear region which descends further to the left for smaller boreholes than large ones before becoming non-linear.

The locations of HEGF experiments which were done in the first two series are plotted on Figure 5. GF 1 and GF 8 exhibited hydraulic fracture, GF 4, 5, and 6 were multiply fractured. GF 7 exhibited explosive fracture. Because of extensive circumferential fractures about the GF 4 borehole it was believed to be near the upper limit of pressure rate for multiple fracture for a 0.15 m diameter borehole. Likewise, GF 1 and GF 8 appeared to be near the hydraulic-multiple fracture boundary. Thus, the linear region between GF 1 and GF 4 roughly defines the multiple fracture region for 0.15 meter diameter boreholes. For smaller boreholes the range extends to faster risetimes.

The pressure and stress risetimes are related to their respective rates and maxima as follows:

$$t_m(p) \cong \frac{P_m}{\dot{P}} \quad \text{and} \quad t_m(\sigma_t) \cong \frac{\sigma_m}{\dot{\sigma}} \qquad (1)$$

For the linear region, $t_m(P) = t_m(\sigma_t)$ and $\sigma_m \cong P_m$ (1a)

Empirically, it was found that the $t_m(\sigma)$ vs $t_m(P)$ curves became non linear at approximately

$$\frac{\pi D}{\nu_c} = t_m(P) = t_m(\sigma_t), \qquad (2)$$

where D is the borehole diameter, and ν_c is the compressive wave velocity. Combining equations 1 and 2, one obtains

$$\frac{D\dot{P}}{P_{max}} = \frac{D\dot{\sigma}}{\sigma_{max}} = \text{Constant}, \qquad (3)$$

which constitute scaling criteria for going from one size borehole to another, at least for ash-fall tuff. Thus equivalent fracturing ought to occur if one adjusts pressures and pressure rates or stresses and stress rates so that

$$\frac{D_1\dot{P}_1}{P_{max_1}} = \frac{D_2\dot{P}_2}{P_{max_2}} \quad \text{or} \quad \frac{D_1\dot{\sigma}_1}{\sigma_{max_1}} = \frac{D_2\dot{\sigma}_2}{\sigma_{max_2}} \tag{4}$$

The results of the small scale experiment are consistent with these pre-test modeling predictions which indicated that faster pressure risetimes are required for smaller boreholes for an equivalent degree of fracturing. If pressure risetimes measured for experiments B and C had been imposed on a 0.15 m diameter borehole, deformation of the borehole would have occurred. The experiment in borehole A was within the hydraulic fracture regime of a 0.15 m diameter borehole. The experiment in D, however, was a classic hydraulic fracture occurring within the region where multiple fracturing would occur for a 0.15 m diameter experiment. Thus the boundary for hydraulic-multiple fracture also appears to occur at faster risetimes for smaller boreholes. The results of the small scale experiment are also shown in Figure 5 to emphasize the shift to faster required pressure risetimes for comparable fracturing. The stress and acceleration data have not yet been fully analyzed and are in the process of being correlated with the analytical model predictions. In experiments where multiple fracture occurs, both in the small scale experiments and previous full scale tests, fractures appear to occur approximately along principal planes of stress--both tensile and shear. In particular, the most prominent fracture occurs, in each case, perpendicular to the minimum in situ stress--the direction of hydraulic fracture.

CONCLUSIONS

The objectives of the small scale experiment were achieved. The basic results were:

(1) semi-empirical and analytic model scaling predictions were verified,

(2) the feasibility of scaling small experiment results to larger boreholes was demonstrated,

(3) the successful injection of proppant into fractures during a HEGF was demonstrated,

(4) factors of 10-215 increase in transmissivity were measured as a result of the small scale HEGF experiments,

(5) a new sand tamp stemming scheme was tested and found completely adequate, and

(6) pressure grouting and cure of an instrument package containing stress and accelerometer transducers resulted in exceptional quality tensile stress and accelerometer data.

The success of this experiment establishes a new data base for expediting the development of the multiple fracturing technique toward a full scale experiment in a gas field environment.

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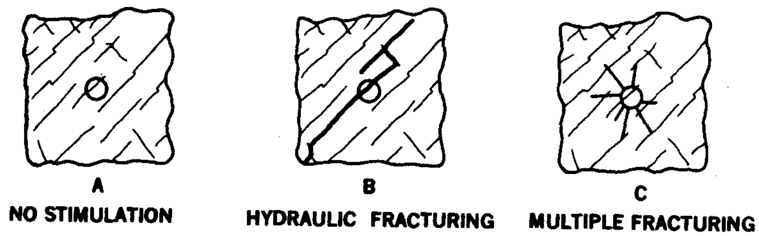

Figure 1. Stimulation of naturally fractured reservoir.

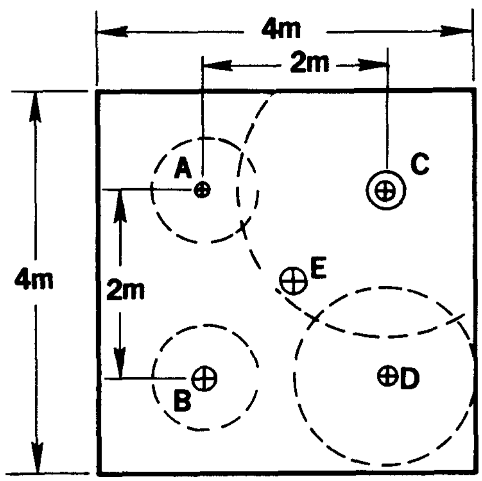

Figure 2. Schematic, small scale feasibility experiment.

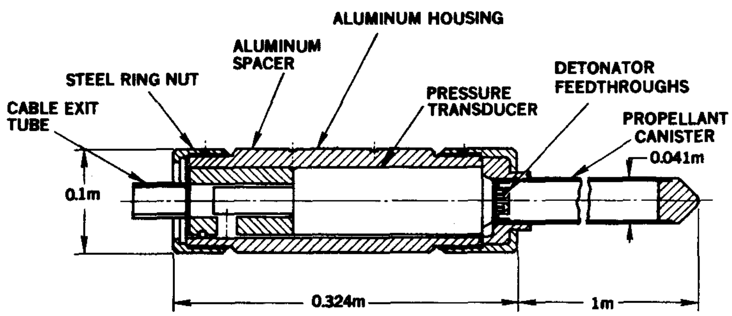

Figure 3. Propellant canister schematic.

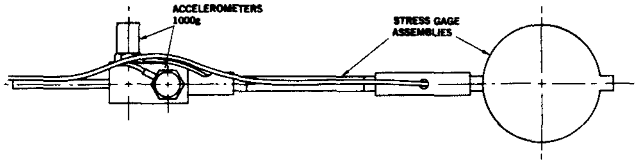

Figure 4. Stress gage and accelerometer configuration.

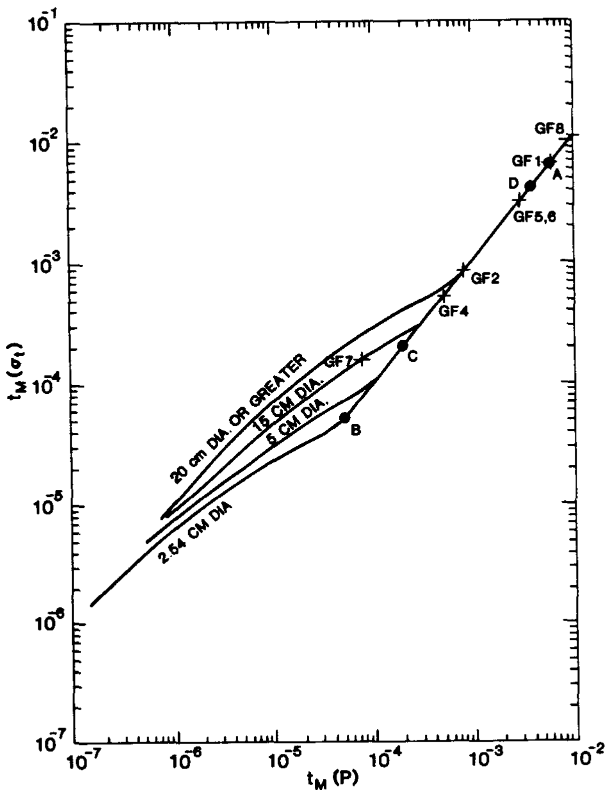

Figure 5. Stress pulse risetime vs pressure pulse risetime.