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HIGH ENERGY GAS FRACTURING DEVELOPMENT

ANNUAL REPORT
(April 1981 - March 1982)

Prepared by
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Sandia National Laboratories
Box 5800
Albuquerque, New Mexico 87185

GRI-80/0144
SAND82-0866

for

GAS RESEARCH INSTITUTE
Contract No. 5080-321-0434

GRI Project Manager
John C. Sharer

April 1982

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This annual report is an interim report, and as such the data, conclusions, and calculations herein are preliminary and should not be construed as final.

RESEARCH SUMMARY

Title	High Energy Gas Fracturing Development Accession Code: GRI-80/0144
Contractor	Sandia Corporation GRI Contract Number: 5080-321-0434
Principal Investigator	J. F. Cuderman
Report Period	April 1981-April 1982 Annual Report
Objective	To develop and optimize the High Energy Gas Fracturing technique for producing multiple fractures about a wellbore and thereby stimulate natural gas production.
Technical Perspective	Most gas wells in Devonian shales require stimulation to obtain commercially economic production. Traditionally this has been done with high explosives and more recently with hydraulic and foam fracturing. However, high explosives can produce a crushed, compacted region in the immediate vicinity of the wellbore that would can effectively seal off production. Recent experiments have shown that, through the use of propellants (which burn rather than detonate), it is possible to tailor the pressure loading of a borehole to avoid crushing and to produce multiple radial fractures.
Results	A propellant based technology has been developed which permits control of pressure loading to obtain multiple fracturing in a borehole. The High Energy Gas Fracturing technique uses a full borehole charge of propellant tailored to produce multiple fractures radiating from the wellbore. The multiple fracture regime has been defined as a function of borehole size, pressure risetime, and surface wave velocity. The pressure risetime and peak pressure obtained in a borehole have been measured for different propellants and borehole diameters. These data make possible propellant specifications for a given peak pressure and pressure risetime. Semiempirical models using results from earlier experiments successfully predict stress and acceleration levels and fracture radii in surrounding rock. A finite element model has been developed which predicts fracture type, and direction of fractures as a function of pressure loading, in situ stress, and material properties.

Technical The High Energy Gas Fracturing program consists of three parts:
Approach (1) In situ experiments at DOE's Nevada Test Site (NTS), (2)
 modeling activities, and (3) a full scale experiment in a Devon-
 ian shale gas well. The in situ experiments serve to determine
 peak pressures and pressure risetimes as a function of propellant
 type and borehole size. They also serve to verify model predic-
 tions and to test full scale hardware being developed for the
 Devonian shale experiment. The semiempirical modeling is
 used to predict stress and acceleration for instrument settings.
 The finite element model serves to analyze experimental results
 and predict fracture behavior. Both the modeling effort and
 the in situ experiments are directed toward the design of the
 Devonian shale experiment planned for September 1982.

All in situ experiments to date have been conducted in a tunnel complex at NTS. The experiments are emplaced in horizontal boreholes in beds of ash fall tuff. A sand tamp with a short cement plug at the collar serves to contain the experiments. Post-experiment mineback permits direct observation of fracturing obtained. Vertical tests in abandoned boreholes at NTS are planned to test tamping designs and fracture behavior in a different rock type, and to "proof test" the Devonian shale experiment design.

Project This project is currently planned to conclude in the winter of
Implications 1982-1983 with a single test series, to be implemented in the
 eastern United States in a Devonian shale gas reservoir. If
 these investigations are successful, additional testing will be
 performed to overcome any operational problems encountered,
 and to quantify Devonian shale fracture regimes with additional
 eastern field work.

GRI Project Manager
John C. Sharer
Director, Natural Gas Supply Research

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High Energy Gas Fracture Annual Report

April 1981-March 1982

I. Introduction

The overall objective of the High Energy Gas Fracture (HEGF) Program is to develop and optimize the technique for gas well stimulation. The specific objectives for the current year included (1) in situ experiments to develop the capability for specifying a propellant mixture to obtain a specified peak pressure and pressure risetime, (2) modeling activity to develop ability to predict fracture behavior in the in situ experiments and to extend the predictions to other rock types (i.e., Devonian shale), and (3) development of the design for a full scale Devonian Shale Experiment planned for September 1982.

Tables 1-3 summarize work planned and completed during the report period, in each of the three major program areas: (1) in situ experiments, (2) modeling, and (3) the full scale Devonian Shale Experiment. Each of these respective areas will be briefly described in terms of program history, and reasons for doing certain of the tests.

Table 4 summarizes all HEGF experiments performed to date; Table 5 presents the program schedule during the report period and beyond, to October 1982. In situ experiments prior to April 1981, under DOE sponsorship, include the GasFrac¹ and MultiFrac^{2,3} series which were done in 0.200 m and 0.150 m (8- and 6-in) diameter boreholes, respectively. The Gas Frac series consisted of three shots, GF1-3, which used slow, medium, and fast propellants, respectively. The respective fracture types produced were hydraulic, multiple, and explosive. The MultiFrac series was to evaluate the HEGF concept relative to two commercially available techniques.

Table 1
In Situ Experiment Summary

Item	Planned	Objective	Status
(1)	Small Scale Feasibility Experiment	To test feasibility of doing small, less expensive experiments and scaling of results	Completed
(2)	Small Scale Experiments.	(a) Compare propellant behavior in different size boreholes	Completed
		(b) Determine shot-to-shot variation in same and in different boreholes	Completed
		(c) Proppant test	Completed
(3)	Pipe Tests	(a) Low cost "propellant behavior" tests	Completed
		(b) Sand tamp development	Completed
(4)	Gun Tests	(a) Sand tamp minimization tests	Completed
		(b) Prototype full scale propellant canister test	Completed
		(c) Pressure variation along full scale canister length	Completed

Table 2
Modeling Summary

Item	Planned	Objective	Status
(1)	Semiempirical, Analytical	Determine experiment design	Completed
(2)	Numerical, Finite Element Modeling	(a) Fracture initiation and growth	Completed
		(b) Fracture length and orientation	Partially Completed
		(c) Effect of pressure varia- tion in fractures (gas dynamics)	Partially Completed
		(d) Effect of in situ stress	Completed

Table 3
Full Scale Experiment

Item	Planned	Status
(1)	Design of full scale propellant canister system consisting of a 30.4 m (100 ft) long propellant canister, downhole pressure transducer and arming and firing system with a detachable cable system extending to the surface	Complete except for tamp design

Table 4. Summary of HEGF Experiments Performed to Date

Experiment Series	Expt.	Date Done	Experiment Description	Fracture Type
Gas Frac	GF1	8-78	Multiple fracture feasibility experiments comparing results of slow, medium, and fast propellants--0.200 m (8 in) dia. borehole--0.61 m (2 ft) long canister. Proved feasibility.	Hydraulic
	GF2	8-78		Multiple
	GF3	8-78		Explosive
Multi-Frac	GF4	9-80	Comparison of Sandia's multiple fracture GF4 (medium rate propellant) with 2 versions of Kinefrac GF5, 6, and two versions of Dynafrac GF7, 8. GF4 proved superior. 0.150 m (6 in) diameter boreholes, 6.1 m (20 ft) long experiments.	Multiple
	GF5	9-80		Multiple
	GF6	9-80		Multiple
	GF7	9-80		Mult.-Hydr.
	GF8	9-80		Explosive
GFSE1	A	1-81	GFSE1 & 2 were small-scale feasibility experiments which demonstrated that results from such small experiments could be extended to predict results for full-scale experiments. 1 m (3 ft) long experiment canisters, 0.0254 m (1.25 in) diameter and 0.048 (1.89 in) diameter boreholes. Used combinations of medium and fast propellants.	Hydraulic, vented
GFSE2	B	5-81		Multiple
	C	5-81		Multiple
	D	5-81		Hydraulic
GFSE3	A1	5-81	Same as GFSE2 except multiple shots in same borehole and comparison of same propellant in different boreholes. Established shot-to-shot variation, effect of borehole damage. D4 was backfilled with water after installation.	Multiple
	B1	5-81		Multiple
	B2	5-81		N.V.*
	C1	5-81		Hydraulic
	D1	5-81		Hydraulic
	D2	5-81		Hydraulic
	D3	5-81		Hydraulic
	D4	5-81		N.V.*
GFSE5	-	5-81	First truly tailored pulse experiment--yielded predicted pulse. 0.25 M5(A)/0.75 M5(B) propellant--0.102 m (4 in) diameter borehole 2.44 (8 ft) long propellant canister.	Multiple

*N.V., not verified by tv or mineback.

Table 5. Program Schedule

Experiments done between April and October 1981 were under joint GRI-DOE funding and included two series of small scale experiments, GFSE1 and GFSE2. These experiments were small scale feasibility experiments designed to test whether or not experiments could be done more economically in smaller boreholes and the results scaled to larger boreholes. These experiments demonstrated that practical scale experiments can be done in 0.048 m (0.189 in) boreholes but that a faster propellant is required for equivalent fracturing. The tamp developed for these experiments consisted of 2.44 m (8 ft) of tamped, damp Overton Nevada sand followed by a 0.15 m (0.5 ft) long plug of sulfa set cement ($2 \text{ CaSO}_4 \cdot \text{H}_2\text{O}$) at the collar.

Experiments subsequent to October 1981 have been funded entirely by GRI. These consisted of a third small scale series (GFSE3), and GFSE5 (a single experiment in a 0.10 m (4 in) diameter borehole).⁷

Pipe and gun experiments are included in Table 1 with the in situ experiments since they were in support of the NTS experiments. These experiments were done at Sandia's explosive test facility. The pipe tests were done to obtain propellant burn rates and to develop a sand tamp alternative to grout. However, the peak pressures attained when the pipes burst were only 40 to 80 MPa (6000-12,000 psi). Thus, several military surplus cannons were obtained for additional tests. Attempts were made to limit peak pressure in the cannon by using very short lengths of sand tamp. These tests were dropped when it was found that a 0.15 m (6 in) long sand tamp held to 345 MPa (50,000 psi) in a smooth, rifled gun barrel.

A test of a prototype full scale canister design was successfully conducted in a 90 mm cannon. The pressure record was used as a guide for an in situ experiment design (GFSE5).

In a subsequent experiment, two full scale canister segments were initiated in an instrumented 155 mm cannon. All previous pressure measurements were made at the end of a propellant canister. This was the first measurement of pressure distribution along the length of the canister during propellant burn and also demonstrated ignition transfer from one segment to another. Preliminary analysis indicates agreement between end and longitudinal pressure data.

Very little "in-house" modeling was done prior to the past year. An approximately one man-year effort devoted to semiempirical, and analytical modeling successfully extended the results from the "Gas Frac" and MultiFrac" series to predict the results for small experiments in ash fall tuff. The finite element model was developed to extend results to other materials and to predict fracture behavior not only in terms of loading rate but also as a function of in situ stress and fracture pressure. The finite element model developed during the current year should be adequate to specify the pressure pulse required for multiply fracturing Devonian shale, but needs additional development for dependable, detailed predictions of fracture extent and geometry.

The hardware design for the full scale Devonian shale experiment is essentially complete except for tamp emplacement. Two emplacement modes are currently slated for test in abandoned, existing boreholes at NTS.

Subsequent sections of this report will (1) briefly describe experiment design, (2) present the pertinent experimental results which contribute to our present understanding of multiple fracturing, (3) discuss the finite element model and present examples of its application to in situ experiments, and (4) present an overview of the Devonian Shale Experiment.

II. In Situ Experiment Design⁵

The initial large (0.200 (8 in) and 0.150 m (6 in) diameter) experiments^{1,2,3} emplaced at 12 m (40 ft) depths demonstrated the feasibility of producing multiple fractures using "intermediate" burn rate propellants. Equally important, they established a data base from which modeling and analysis could proceed. By combining the data with analytical modeling,⁴ which predicted tangential stress about a dynamically pressurized borehole, a scaling criterion was developed which has since been verified experimentally. Stress, acceleration, and fracture length measured in the large experiments permitted formulation of semi-empirical equations for practical predictions in subsequent experiments.

Using the combination of semi-empirical and analytic modeling, the pressure risetime regime for multiple fracturing was defined as

$$\frac{\pi D}{2C_R} < t_m < \frac{8\pi D}{C_R} \quad (1)$$

where t_m = pressure risetime to peak pressure

D = borehole diameter

C_R = surface wave velocity

Dividing through by the diameter yields

$$\frac{\pi}{2C_R} < \frac{t_m}{D} < \frac{8\pi}{C_R} \quad (2)$$

Equation 2 suggests a scaling relationship of

$$\frac{t_{m1}}{D_1} = \frac{t_{m2}}{D_2} \quad (3)$$

for equivalent fracturing in two different sized boreholes. This implies that a faster pressure risetime is required in a smaller borehole.

Since all of the in situ experiments featured measurements of stress and acceleration, it was necessary to estimate expected stress in order to set signal levels properly. The measured peak radial stress levels are much greater than if the borehole were statically pressurized to the value of the peak pressure .

A good approximation for radial stress in the ash fall tuff formation normalized to results from the MultiFrac experiments was found to be

$$\sigma_r \cong 100 P_m \frac{r_o^2}{r^2} \quad (4)$$

where P_m = peak pressure

r_o = borehole radius

r = distance in the formation. Thus, the measured peak radial stress appears to be 100 times that for a borehole pressurized to the same pressure.

Similarly, the displacement, U , predicted by the static theory of elasticity is

$$U = \frac{P}{E} (1 + \nu) \frac{a^2}{r} \quad (5)$$

where

P = borehole pressure

a = borehole radius

r = radius to an arbitrary point in the formation

E = modulus of elasticity

ν = Poisson's ratio .

An estimate of the maximum radial acceleration can be derived from the static displacement, dimensional considerations, and comparison with experimental results. Calculating the displacement for P_m and dividing by t_m^2 should yield a rough estimate of the maximum acceleration, at least for relatively slow risetimes when dynamic effects are minimal. Thus

$$a_r(\text{quasistatic}) \propto \frac{P_m}{E} \frac{(1 + \nu)}{t_m^2} \frac{a^2}{r} \quad (6)$$

However, the measured radial accelerations for GF4 in the MultiFrac Series were systematically about a factor of 20 higher than predicted by Eq. (6). Thus the semiempirical radial acceleration estimate was

$$a_r = 20 \frac{P_m}{E} \frac{(1 + \nu)}{t_m^2} \frac{a^2}{r} \quad (7)$$

Experiment spacing was based on the observation that the volume of fractured rock was roughly proportional to the energy contained in the borehole. The fracture radius thus obtained is

$$R = 5 \times 10^{-4} \sqrt{\frac{E}{L}} \text{ meters} \quad (8)$$

where E = total energy in the borehole (Joules)

L = total borehole length (meters).

Since the typical emplacement area for small scale experiments measured 4 m by 4 m (12 ft by 12 ft), four non-interacting 0.05 m (2 in) diameter experiments could be emplaced 2 m (6 ft) apart.

It is emphasized that while the functional form of the semiempirical Eqs. (4), (7), and (8) used for estimating stress, acceleration, and fracture length, respectively, should be the same for other rocks as well, the empirical "multiplier" is likely to be different in each case.

III. In Situ Experiments

A. Experiment Description

In situ experiments to test concepts and develop hardware are conducted in a tunnel complex at NTS.^{2,3,6,7} The experiments are done in this tunnel complex and location for several reasons. First, mineback can be done to observe fracturing results; second, the homogeneity of the beds and presence of realistic in situ stress fields results in a nearly ideal test bed to evaluate modeling and fracture behavior, and, third, although the ash fall material properties differ considerably from those of Devonian shales, modeling efforts indicate that only relatively small adjustments in pressure rates should be required for experiments in Devonian shale.

Experiments of 0.100 m (4 in) diameter or larger are emplaced from an existing drift at a 12 m (40 ft) depth and stemmed with damp sand. A mineback drift is subsequently extended to expose the fractured zones. Smaller "Scale Experiments" are emplaced in the end face of a drift and stemmed with sand. These experiments are typically at 3 meter (10 ft) total depths. Figure 1 is a schematic of the borehole configuration used in the small scale experiments. For each individual test, a 0.10 m (4 in) or 0.15 m (6 in) diameter (D_0) borehole is drilled almost horizontally to a depth L_0 . Then a smaller borehole, usually of 0.048 m (1.89 in) diameter D is drilled concentrically to a depth L_1 , usually 1 m (3 ft). Boreholes A, B, C, and D contain propellant canister-pressure transducer assemblies. Borehole E contains stress and acceleration instrumentation. The end of the scale experiment drift contains nearly homogeneous layers of two different kinds of tuff. The upper half of the drift face, in which the A and C experiment boreholes are drilled, is a porous, yellow, peralkaline tuff, with permeability typically in the 10^{-1} md range.

Figure 1. Typical Small Scale Experiment Configuration

the lower half is a competent, red tuff of about 10^{-2} md permeability.

However, the mechanical properties, listed in Table 4, are similar for both.

The canister assembly developed for the smaller in situ experiments,⁶ consists of a PVC propellant canister attached to a pressure transducer assembly. Two exploding bridge wire initiators are installed 0.3 m (1 ft) from each end. The initiator cables and pressure transducer cables are brought out of the borehole through a pipe attached to the back of the pressure transducer units.

The experiment canister for GFSE5 used the same pressure transducer assembly. It was also of PVC construction, but employed a centralized Rapid Ignition Propagation (RIP) ignitor. This ignitor, when initiated at one end with an exploding bridge wire, ignites the entire length of the canister nearly simultaneously.

Two military surplus, M5 large gun propellants, designated M5(A) and M5(B), were used which bracket burn rates necessary for multiple fracture in most rock types of interest. Their descriptions appear in Table 5. The smaller grain propellant, M5(A), produces pulses whose risetimes are less than 1 msec in small boreholes. The use of the larger grains M5(B) produces pressure risetimes of several msec in 0.048 m (1.89 in) diameter boreholes.⁶ Prior to experiment installation, the borehole transmissivities were measured using both constant pressure injection and shut-in tests.

After experiment insertion, damp Overton, Nevada sand was mechanically tamped to fill the borehole. A short plug of a fast setting, sulfur-based cement mixed with sand and water, was ordinarily set in the collar. This served to contain the propellant burn and retain the experiment and sand in the borehole.

Table 6.

ASHFALL TUFF MATERIAL PROPERTIES

Density	1.9 gm/cm ³ (112 lb/ft ³)
Porosity (Water filled)	40%
Elastic Modulus	5.5 GPa (8x10 ⁵ psi)
Compressional Wave Velocity	2700 m/sec (6900 ft/sec)
Shear Wave Velocity	1200 m/sec (3900 ft/sec)
Tensile Strength	700 kPa (100 psi)
Compressive Strength (Unconfined)	14 MPa (2000 psi)
Fracture Toughness	400 kPa m (105 psi ft)

Table 7.

PROPELLANT DESCRIPTION

Item	M5(A)	M5(B)
Grain Diameter	1.397 mm (0.055 in)	5 mm (0.197 in)
Grain Length	6.731 mm (0.265 in)	11 mm (0.433 in)
Perf. Diameter	0.330 mm (0.13 in)	0.50 mm (0.019 in)
# Perfs	1	7
Density	1.66 gm/cm ³ (0.06 lb/in ³)	1.66 gm/cm ³ (0.06 lb/in ³)

A number of experiments were done in test series GFSE3 to compare data scatter as a function of propellant and borehole condition. Referring again to Figure 1, a single experiment was done in Borehole A, while two successive identical experiments were conducted in B. The propellant used in the Borehole A and B shots was M5(A). Similarly, only one experiment was done in Borehole C and four in Borehole D with M5(B) propellant. For the fourth experiment in D, the free volume around the canister was eliminated by filling with water. The single shot data from A and C not only permit a comparison between single and multiple shot results, but result in an evaluation of the effect of material change, since the tuff in the top half of the drift face is more porous than that below it. The identical experiments in different boreholes were designed to establish shot-to-shot variability, those of successive shots in the same borehole were to determine the effect of damage caused in previous shots and variation of free volume on the resulting pressure pulse.

The canister used in the GFSE5 experiment was first tested in a 90 mm army surplus cannon using M5(B) propellant. A 0.3 m (1 ft) long wet sand tamp at each end of the canister contained the burn to 345 MPa (50,000 psi). It achieved 250 MPa (36,000 psi) pressure, in 1.25 msec. Since there was essentially no annular free volume around the canister in the 90 mm cannon, this risetime is faster than would occur in a 0.10 m diameter borehole. A 2 msec risetime is estimated for straight M5(B) propellant in a 0.10 (4 in) diameter borehole. On the basis of previous tests, a 25 percent M5(A)/75 percent M5(B) mixture, by weight, was specified for a 0.5 msec risetime.

B. Data and Results

Figures 2-6 are mineback photographs which characterize fracturing obtained as a function of propellant and borehole size. Figures 2, 3, and 4 show hydraulic and multiple fractures obtained in GFSE2-B, C, and D, respectively (see Figure 1). Borehole B was of 0.0254 m (1 in) diameter and contained a canister of M5(A) propellant. The fractures were barely multiple and nowhere along the borehole did more than four fractures appear, usually vertical and horizontal. Borehole C contained a 0.762 m (3 in) diameter canister surrounded by a 0.038 m (1.5 in) wide annulus filled with 20-40 mesh bauxite proppant. This experiment used a 25 percent M5(A)/75 percent M5(B) propellant mixture; the fracture type was multiple. Experiment D used M5(B) propellant in a 0.048 m (1.89 in) diameter borehole. A hydraulic fracture was produced. Figure 5 is a mineback photograph of GF4 of the MultiFrac series. Figure 6 is a photograph of an explosively crushed borehole such as was produced by GF3 experiment. These two experiments used M5(A) and M5(B) propellants, respectively. The respective borehole diameters were 0.150 m (6 in) and 0.200 m (8 in).

Thus propellant M5(B) which produced the large multiple fractures seen in a 0.150 m (6 in) diameter (GF4) only produced hydraulic fracture in a 0.048 m (1.89 in) diameter borehole. Propellant M5(A) which produced explosive fracture (crushing) in a 0.200 m (8 in) diameter borehole (GF3) results in barely multiple fracture in a 0.025 m (1 in) diameter borehole. Thus, the prediction was verified that a faster propellant is required to produce fracturing in smaller boreholes.

Figure 7 is a composite mapping of the fractures obtained in experiment GF4. It is noted that the predominant fractures are horizontal and vertical with an additional major fracture in each quadrant, roughly at 45 degrees.

Figure 2. GFSE2-B Mineback Photo Showing Weak Multiple Fracture

Figure 3. GFSE2-B Mineback Multiple Fracture Pattern

Figure 4. GFSE2 D1 Mineback Hydraulic Fracture Pattern

Figure 5. GF4 Multiple Fracture

Figure 6. GF3 Explosive Fracture Example

Figure 7. GF4 Multiple Fracture Composite Mapping

The in situ principal stresses are an overburden stress of 8.6 MPa (1250 psi), with horizontal principal stresses of 10.3 MPa (1500 psi), and 5.4 MPa (783 psi). In GF4, the 5.4 MPa stress was parallel to the borehole. In the small-scale experiments the 10.3 MPa stress was aligned with the borehole. It appears that the fracture pattern is determined by the principal stresses normal to the borehole. In GF4, the minimum stress normal to the borehole was the 8.6 MPa overburden stress. In the small scale experiments it was the 5.4 MPa stress. In each case, the longest fracture was normal to the minimum stress direction; horizontal for GF4, vertical for the small scale experiments. In all cases of multiple fracture, major fractures occur along the principal planes of stress, perpendicular to the principal stress directions. The directions of the additional major fractures which usually occur in each quadrant are less well defined. In some instances they occur at 45 degrees, along planes of maximum shear stress. However, modeling results indicate sensitivity to the combination of in situ stress values and effective fracture pressure.

Figure 8 presents the pressure waveforms obtained for the slower of the two propellants, M5(B) for several borehole conditions. These experiments were done in Boreholes C and D, Figure 1. (The number after the borehole designation denotes the shot number; for example GFSE3 D2 refers to the second shot in Borehole D in experiment GFSE3.) In each case, there is an initial pressure rise followed by a decrease of several msec duration. The pressure then continues to rise to a maximum and subsequently decays. A borehole tv scan after each test revealed hydraulic type fracture. It appears likely that the break in the pressure rise coincides with fracture formation. The origin of the high frequency noise imposed on the pulse is unknown. It may be due to pressure wave phenomena in the borehole or to excitation of a resonance in the gage, although tests show the gage response is linear into the microsecond regime.

a

d

b

e

c

f

Figure 8. Pressure Records for Identical M5(B) Propellant Shots in Different (a,b,c), the Same (a,d,e) and WATER Filled (f) Boreholes

It is seen that there is a factor of three difference in peak pressure between identical first shots in three different boreholes. However, for successive shots in the same borehole, the amplitudes are essentially identical except for shot 4, where the hole was backfilled with water to reduce free volume. The presence of water in the borehole resulted in a decrease in pressure risetime to 2 msec from the 5 to 8.5 seen in the preceding shots. It also attenuated the peak pressure attained by about a factor of two.

Figure 9 presents the pressure records from the 0.048 m (1.89 in) diameter Boreholes A and B of GFSE3. The faster M5(A) propellant was used in these tests. Typical risetimes are a few tenths of a msec to the "apparent" peak pressure. Expanded records show that the pulses have superimposed upon them a ringing frequency of 0.1 to 0.15 msec periodicity as did those of Experiments C and D. However, here it is more serious, since it cuts off the pressure rise in a few tenths of a msec or less and prevents identification of the true risetime and peak pressure. In A1 and B2, the signal goes negative at 0.1 and 0.2 msec, respectively, after ignition. A pressure drop of 110 MPa in 0.1 msec is unlikely, since fractures sufficient to relieve that much pressure in such a short time are improbable. Therefore the "apparent" peak pressures should be regarded as lower bounds. This is also true of B1 even though it did not go negative, but suffered a pressure drop from 158 MPa (23,000 psi) to 100 MPa (14,000 psi) in less than 0.1 msec at 0.2 msec into the pulse.

Because of the high frequency oscillations, it is not clear whether the observed large difference in peak amplitudes for shots A1 and B1 is real. It is noted that the pressure decay, starting 3 msec after the start of the initial pressure rise, is only slightly less for A1 than for B1. The difference

(a)

(b)

(c)

Figure 9. Pressure Records for Identical M5(A) Shots in Different (a,b) and the Same Borehole (b,c)

between B1 and B2, however, appears significant. A tv log of the borehole after shot B1 revealed a highly multiple fractured borehole condition. This conclusion was further supported by a transmissivity increase from 5×10^{-2} md before the test to 1.93 md post-test. Measurement of transmissivity after shot B2, however, showed a decrease to 0.96 md (see Appendix B). Both the decrease in transmissivity and the 0.04 msec apparent risetime suggest that shot B2 produced a crushed borehole. The GFSE5 experiment, designed to produce a 250 MPa (36,000 psi) peak pressure with a 0.5 msec risetime yielded a 258 MPa (37,500 psi) peak pressure at a 0.56 msec risetime. A borehole tv scan verified that multiple fracturing was achieved.

Table 8 summarizes both the data obtained in the present experiments and those which are appropriate from previous series for comparison with results of the present experiments.

It is noted that stress and acceleration records are much more reproducible from shot-to-shot than are the pressure data. Traces either from several shots in the same borehole, or from different boreholes, for a given propellant, when overlaid are virtually indistinguishable. This may indicate that the pressure along the borehole is more reproducible than is measured at the end of the borehole. Because the stress and acceleration do not bear directly on the conclusions reached on the basis of in situ experiments they are included in Appendix A for completeness. They will be discussed further in the section on finite element modeling where they play a critical role in evaluating effective fracture pressurization.

C. Interpretation of Data

Figure 10 is a plot of the boundaries of multiple, hydraulic, and explosive fracture as defined by Equation (1) in terms of borehole diameter, D , and

Table 8. SUMMARY OF DATA USED IN EXPERIMENT ANALYSIS

EXPERIMENT		BOREHOLE DIA. m(in)	PROPELLANT TYPE	P _m [MPa(KPsi)]	t _m (msec)	FRACTURE TYPE
GFSE 2 (REF. 5,6)	C1	0.0889 (3.5)	0.25 M5(A) 0.75 M5(B)	86 (12.5)	0.7	MULTIPLE
	D1	0.048 (1.89)	M5(B)	36 (5.2)	6.5	HYDRAULIC
GFSE 3	A1	0.048 (1.89)	M5(A)	110 (16)**	0.1**	MULTIPLE
	B1	0.048 (1.89)	M5(A)	162 (23.5)**	0.2**	MULTIPLE
	B2	0.048 (1.89)	M5(A)	110 (16)**	0.04**	EXPLOSIVE
	C1	0.048 (1.89)	M5(B)	100 (14.5)	6.8	HYDRAULIC
	D1	0.048 (1.89)	M5(B)	52 (7.5)	5.2	HYDRAULIC
	D2	0.048 (1.89)	M5(B)	48 (7)	5.0	HYDRAULIC
	D3	0.048 (1.89)	M5(B)	48(7)	8.5	HYDRAULIC
	D4	0.048 (1.89)	M5(B)	28 (4)	2.0	HYDRAULIC
GFSE 5	1	0.102 (4.00)	0.25 M5(A)/ 0.75 M5(B)	258 (37.5)	0.56	MULTIPLE
MULTI-FRAC (REF. 5,6)						
	GF4	0.150 (6.00)	M5(B)	250 (36.3)	0.5	MULTIPLE
	GF5,6	0.150 (6.00)		38 (5.5)	1.0	MULTIPLE
	GF8	0.150 (6.00)		30 (4.35)	13	HYDRAULIC
GAS FRAC (REF. 1)						
	1	0.200 (8.00)	M5 (VERY LARGE GRAIN)	47 (6.8)	8	HYDRAULIC
	2	0.200 (8.00)	M5(B)	95 (14.0)	0.7	MULTIPLE
	3	0.200 (8.00)	M5(A)	200 (29)	0.02	EXPLOSIVE

** SHOULD BE REGARDED ONLY AS A LOWER BOUND.

Figure 10. Hydraulic, Multiple, and Explosive Fracture Regimes Predicted by Semiempirical Modeling.

pressure risetime t_m . Essentially all the experimental data points to date appear on Figure 10. Those indicated only as A1, B2, C1...on this and succeeding figures are all from GFSE3. Thus, for some 21 fracture experiments to date there appear no exceptions to the fracture type obtained and that predicted by the semi-empirical model in terms of borehole diameter and pressure risetime.

Figure 11 is a log-log plot of peak pressure vs pressure risetime. The data points on Figure 11, as can be checked in Table 8, are plotted without regard to borehole size. The data spread for the dry hydraulic fracture type experiments extends from 30-100 MPa and from 5-8.5 msec in risetime, and is even greater when one includes D4. The reasons for this large scatter may include small differences in free volume, rock properties, material inhomogeneities, propellant packing density, and small natural fractures. In any event, such small perturbations or combinations of them is expected to result in a greater data spread for small boreholes than for large ones. Thus, the nearly horizontal part of the curve in Figure 11 was drawn with a bias toward the data of GF 1, 5, 6, and 8 and is still consistent with the small borehole results. The implication of the design curve drawn in Figure 11 is that the peak pressure is independent of borehole radius but not the pressure risetime, which is determined by the rock response to a given propellant.

Figure 12 is a plot of borehole size vs pressure risetime on which are plotted available data points for the M5(A) and M5(B) propellants. Since the risetime for GF3 was determined to be "less than 0.02 msec," the curve for M5(A) was arbitrarily drawn through 0.01 msec for a 0.200 m diameter to make it parallel to that of M5(B). Figure 12 graphically illustrates the difficulty of specifying a propellant for a desired risetime. A factor of 10 difference in

Figure 11. Peak Pressure vs Pressure Risetime

Figure 12. Pressure Risetime as a Function of Propellant and Borehole Size

risetime appears to occur for the same propellant for boreholes ranging in size between 0.05 m and 0.15 m.

A method is proposed, using the GFSE5 data and Figure 12 for specifying a propellant mixture for a given pressure risetime and borehole size. It is noted that for a constant borehole diameter in Figure 12, the risetime varies logarithmically from one propellant to the other. It is therefore suggested that the logarithm of the desired risetime t_m , obtained from a mixture of two propellants of risetime t_A and t_B can be expressed as a linear combination of their logarithms weighted by their mass fractions:

$$\log t_m = K f_A \log t_A + (1 - K f_A) \log t_B \quad (2)$$

where t_m = the desired pressure risetimes

f_A = mass fraction of propellant M5(A)

t_A = risetime if borehole filled with M5(A)

t_B = risetime if borehole filled with M5(B)

K = calibration fraction (obtained by substituting GFSE5 experimental data)

Solving for f_A and normalizing to the GFSE5 data, one obtains:

$$f_A = \frac{\log \frac{t_m}{t_B}}{1.8 \log \frac{t_A}{t_B}} \quad (3)$$

D. Summary of In Situ Experimental Results

The experiments described in this paper focused on the problems of shot-to-shot variability and the selection of propellants for multiply fracturing a wellbore. Factors of 1.7 and 3 were shown to occur as shot-to-shot variations in pressure risetime and peak pressure, respectively, for M5(B) propellant. The results for M5(A) propellant were inconclusive because of high frequency oscillations in the pressure record. The multiple fracturing data, to date, displayed in Figures 10, 11, and 12, indicate that the critical parameters are the logarithms of t_m and P_m and not their absolute values. Thus, factors of 2 or 3, or more, in shot-to-shot variability of P_m and t_m do not seriously affect the ability to design a multiple fracture experiment.

Data from previous experiments,^{2,3,6} established the specification of pressure pulse characteristics (t_m , P_m) required for multiple fracturing (Figures 10 and 11). The present data permit a specification of propellants for obtaining the required pulse (Figures 11 and 12). More specifically, Figure 10, or its equivalent for another rock type, allows selection of a risetime t_m for optimal multiple fracturing as a function of borehole size. Given the risetime, Figure 11 gives the expected peak pressure. The loading rate required for the more detailed finite element modeling, is approximated by P_m/t_m . Figure 12, for a given borehole size, yields the risetimes expected for each of the two available propellants if used alone. If the required risetime is intermediate between them, a mixture of the two is needed. In that case, Eq. (3) should give the fraction of M5(A), by weight, needed to produce the required risetime t_m .

IV. FINITE ELEMENT MODELING

A. Introduction

As indicated in Sec. II, Eq. (1), a semiempirical model was developed which successfully predicts the fracture regimes for tests completed to date in ash fall tuff. It should also be applicable to other rock types having similar in situ stress conditions when the appropriate value of C_R is used. It does not, however, predict fracture orientation, dependence on stress or pressure in fractures.

To address these questions, a modeling effort was initiated using the finite element method. In the analysis, no assumptions are made as to crack orientation. Instead, a pressure history representing propellant burn is applied to the borehole. Fractures form when stress exceeds a specified tensile strength. Gas pressure is then applied to the crack face. The calculation then proceeds with old fractures extending and new ones forming whenever the tensile strength criterion is met.

B. Model Description

Modeling and analysis for the HEGF in situ experiments was performed using the HONDO⁸ finite element code. This code can solve the large deformation response of axisymmetric solids and is very efficient for performing dynamic calculations. Figure 13 shows a typical finite element mesh representing the borehole. Plane strain assumptions were used and in situ stresses were included in the calculations. To minimize boundary effects, the outer radius of the problem was defined at 25.4 m (1000 in) and damping was included in the solutions.

Figure 13. Finite Element Mesh

A material model was used in which fractures form when the maximum tensile stress exceeds a specified tensile failure stress. Cracks can form at each integration point in each element (these are locations where stresses are calculated). At each time step in the solution, the magnitude and direction of the maximum tensile stress are calculated. If the fracture criterion is exceeded, a crack is assumed to form at the integration point in the direction normal to the maximum tensile stress (see Fig. 14). In subsequent time steps, the strain normal to each fracture is calculated to determine if the cracks are open or closed. If open, the global stresses at that point are rotated to the crack orientation. The shear stress is set to zero and the normal stress is set to a fraction of the borehole pressure. These modified stresses are then rotated back to the global coordinates. The material was assumed to behave elastically if a fracture was closed.

It is noted that use of a stress criterion for crack growth does not involve the fracture mechanics of crack growth. A fracture mechanics criterion based on the energy required for crack extension might appear preferable but is extremely cumbersome to implement for the multiple fracture case. In addition, it can be shown that the energy required to propagate the crack is a small fraction of the energy required to open the crack and also a small fraction of the available propellant burn energy. This reduces the sensitivity of the solution to some particular crack growth criterion. As a result, use of a stress criterion does not introduce large errors. A second feature of the model is that, because of the finite element formulation, cracks preferentially extend parallel to the element mesh lines. This does not preclude the possibility of cracks turning and running diagonally across the mesh, as is seen in some of the analyzed cases, but the geometry of the finite element mesh does have some effect on the crack

Figure 14. Schematic-Fracture Initiation.

formation. However, experiments show that the cracks tend to be radial and with the radially symmetric meshes used in this work, the mesh geometry effect is not significant.

In the analysis, the propellant burn pressure is defined as a function of time on the surface of the borehole. In addition, after a crack forms and if it is open, a pressure is applied to the crack face. The actual gas flow into the crack is a complex function of fracture geometry and gas parameters. For these studies, the fracture pressure was specified as a fraction of the borehole pressure. This corresponds to instantaneous flow into the crack with a pressure reduction. The effect of the assumed pressure in the cracks is examined and discussed.

C. Experiment Modeling

The analysis of two small scale experiments--GFSE2 C1 and GFSE2 D1--is presented to demonstrate the current modeling capability. The experimentally measured pressure pulse was used in each case but smoothed to eliminate large fluctuations. When calculations were performed with pressure in the fractures assumed to be equal to the pressure in the borehole, the predicted stress was too large and predicted fracture length too long compared with experimental results. In addition, fracture patterns were not correctly reproduced. Therefore, calculations were performed in which the fracture pressure, P_C , was assumed to be 0.25 and 0.50 of the borehole pressure, P_B . Figure 15 compares predicted and measured stresses for GFSE2 C1. For this case, the measured and predicted stress levels compare favorably when the crack pressure $P_C = 0.25 P_B$. Figure 16 is a comparison of predicted and observed fractures for GFSE2 C1. Again good correlation is obtained when $P_C = 0.25 P_B$.

Figure 17 is a comparison of measured and predicted stresses for GFSE2 D1. Again the best correlation occurs for $P_C = 0.25 P_B$. A better fit would be

Figure 15. A Comparison of Measured and Predicted Stress for Experiment GFSE2 C1.

EXPERIMENTAL

PREDICTED

Figure 16. Comparison of Measured and Predicted Fracture Lengths: #GFSE2 C1.

Figure 17. A Comparison of Measured and Predicted Stresses for GFSE2 D1

obtained for some fracture pressure larger than $0.25 P_B$ but smaller than $0.50 P_B$. Whereas, GFSE2 C1 was a multiple fracture case, GFSE2 D1 was a hydraulic type fracture. Since the pressure pulse was much longer, more time was available for gas flow into the fracture and the effective fracture pressure was a larger fraction of the borehole pressure. The predicted fracture pattern (Fig. 18) matches that which is observed, but the fracture length is too short. That would also increase with a higher assumed crack pressure.

As part of the pretest design calculations, a parametric study of both the loading rate and peak pressure was made for the GFSE3 experiment series. Figure 19 shows the predicted fracture regimes. The fracture orientation and predicted geometry is shown pictorially. The experimental data points for GFSE3 are indicated in Figure 19. Good agreement is seen with pretest predictions.

D. Modeling Summary

Two applications of the HONDO finite element model were presented. The first was a multiple fracture experiment, the second a hydraulic type fracture result. The pressure assumed in the fractures was shown to be critical to reproduce experimental results. When the proper effective fracture pressure is applied in the model, the experimentally observed fracture pattern, fracture lengths and stress level are correctly reproduced. The pre-test calculations correctly predicted the general fracture behavior for the GFSE3 experiments.

The dominant parameters governing fracture growth were found to be borehole loading rate, gas pressurization of the fractures, and in situ stresses. The loading rate determines the fracture type and number. Pressurization of newly formed fractures extends them and inhibits formation of additional ones by putting adjacent material in compression. In situ stresses govern the orientation of the major fractures.

EXPERIMENTAL

PREDICTED

Figure 18. A Comparison of Measured and Predicted Fractures for GFSE2 D1

Figure 19. Hydraulic-Multiple-Explosive Fracture Regimes as Predicted by Finite Element Modeling. Experimental Data Points are Indicated.

The current models correctly predict the type of fracture obtained when given the peak pressure and pressure risetime measured for a given propellant and have been valuable in studying sensitivity to changes in key variables. However, they need to be extended to include propellant-rock response and gas dynamic effects. This would result in direct predictions of peak pressure, pressure risetime, and fracture geometry.

A complete report of all finite element modeling done is in preparation.⁹

V. Devonian Shale Experiment

A. Experiment Design

Figure 20 is a schematic of a conceptual design for a full scale experiment in a Devonian shale gas well. It includes (1) a propellant canister, (2) a pressure transducer, (3) a downhole fire set, (4) a sand tamp, and (5) a cable system. If the experiment is not done at the bottom of a borehole, the interval below it will be blocked off with a sand tamp resting on a bridge plug.

The propellant canister consists of 12 segments of 2.44 m (8 ft) length which are connected as they are emplaced into the borehole. Figure 21 is a schematic of such a canister segment. Each segment consists of a section of 5 inch PVC tubing (5.563 in O.D.), machined, mating endcaps, and a centered RIP ignitor enclosed in a section of 0.0127 m (1/2 in) PVC tubing. The propellant fills the annulus between the 1/2 inch and 5 inch PVC tubing. The canister design is such that the endcaps shield the ends of the RIP ignitor. This will permit standing the canisters on end for easier loading, protect them from damage, and enhance safety. The choice of PVC for the canister material is based on the fact that it shatters on sudden pressurization, it is readily available, and it is economical. Further, 0.127 m (5 in) PVC tubing has sufficient strength to support several hundred feet of propellant canister. A detent groove in the top endcap of each canister segment will enable the clamping of successive downhole, assembled canisters, as the next segment is attached in place. The first segment is lowered with a plug in the bottom end. The last segment mates to a canister which contains two exploding bridge wire (EBW) initiators, and a fire set. A cable tube which extends through the sand tamp fastens to the top of the canister.

Figure 20. Conceptual Design Full Scale Devonian Shale Experiment.

Figure 21. Canister Segment Conceptual Design.

The two initiators mount flush against the top end of the last RIP ignitor. The initiators and in turn the RIP ignitor, are ignited by the high voltage output of the fire set. Each RIP ignitor initiates the one below it even if gaps should occur between the ends of successive ignitors. Tests are planned to determine the maximum allowed gap. A pressure transducer protected against thermal and impact damage mounts directly above the initiators.

A downhole fireset will be used to eliminate the need to convey high voltage (~ 5000V) to the initiators from the surface. This is desirable both to minimize noise pickup on the signal cable, and to simplify the arming and firing logistics. A commercial design has been adapted for this application.

The sand tamp will consist of a column of Overton Nevada sand. The length of the tamp will be determined in forthcoming vertical borehole experiments at NTS. About 0.3 m (1 ft) of Sulfa Set cement may be placed at the top of the sand column to ensure bridging upon propellant ignition and survival of the instrument package and cable system. To ensure recording of the pressure data and survival and retrievability of the cable, it is vital that the sand tamp and measurement package not move during the propellant burn. In tests at NTS, in 3 m (10 ft) deep, horizontal boreholes tamped with wet Overton sand, a 0.15 m (6 in) long Sulfa Set plug at the collar proved both necessary and sufficient to contain the instrumentation, sand tamp, and Sulfa Set plug. Eliminating the Sulfa Set plug at the collar resulted in ejection of both sand and instrumentation.

The design and implacement of a vertical borehole sand tamp has been the major technical problem encountered during the year. This is because the instrument cable greatly complicates the installation. Without the cable, one could use pea gravel as is often done in current practice. The use of pea gravel in

this installation could result in a severed cable. It is not clear whether dry sand dropped from the surface would present bridging problems or how much would arrive at the bottom of the borehole. Finally, there is the problem of putting Sulfa Set, or equivalent, plug at the top of the sand column. Experiments are scheduled to test a tamping scheme where sand is dropped from the surface into a 300 foot deep well at NTS and also a tamping scheme where sand, Sulfa Set and water are carried to the bottom with the experiment package and released at the bottom.

The cable system will consist of a cable tube through the sand tamp, a remotely detachable cable head and primary cable to the surface. The cable in the tube will be shielded and potted but not armored. Just above the Sulfa Set plug, the primary cable will connect to the cable tube with the remotely detachable cable head. The remote detachment feature will permit primary cable removal if the instrument and fire set package remains bridged in place and can't be removed with the primary cable. In that event, the cable release mechanism would be activated and the primary cable removed. The instrument and fire set package would then be removed by drilling. For this eventuality, the instrument canister, cable tube, and as much of the fire set and pressure transducer housing as feasible, will be fabricated of aluminum or other readily drillable material.

The primary cable will be a multi-pair shielded type.

B. Hardware Tests

The development program leading to a full scale stimulation in a Devonian shale gas well includes experiments in other rock types (in the course of tamp and proof tests), gun barrel tests recently done to examine possible pressure

variation along the propellant canister, and a full scale proof test in an abandoned 6-1/2 inch diameter wellbore at NTS.

The "second rock type" experiment will be done in an existing 4 inch diameter wellbore in Eleana Argellite at NTS. The rock properties of this material are more similar to those of Devonian shale than are those of ash fall tuff. It will also be a test of a prototype canister having a RIP ignitor. An identical experiment will be done in a horizontal borehole in ash fall tuff. The experiment will thus test both the capability of models to specify a pressure pulse that yields multiple fracturing for different materials and the ability to specify a propellant that achieves multiple fractures for a rock type similar to Devonian shale. The comparison with the test in ash fall tuff will determine whether the pulse shape, risetime, and peak pressure are significantly affected by rock type.

In all experiments to date, the pressure sensor has been located at the end of the propellant canister. It has been assumed that this measurement is representative of the entire borehole cavity. This assumption was tested by firing a full scale canister segment in an instrumented 155 mm naval gun barrel. The breech end of the gun had a sand and Sulfa Set tamp. The muzzle was sand tamped. Preliminary analysis of the data indicates that the end pressure measurement is representative.

Finally, a full scale 100 foot long canister will be emplaced in a 385 foot, 6-1/2 inch diameter borehole in limestone at NTS as a proof test of the entire system. Caliper and TV logs will be run to determine borehole condition prior to designating emplacement depth. The borehole contains intervals of ash fall tuff, limestone and argellite.

An important aspect of all of these experiments will be the exercise of safe handling procedures. The safe handling procedures for a propellant

canister filled with propellant and containing a RIP ignitor are the normal Class B procedures for propellants. Drop tests will be conducted to determine sensitivity, if any, of the ignitors and canister assembly to shock.

C. Devonian Shale Gas Well Requirements

This experiment has as its primary goal the production of multiple fractures about a wellbore in Devonian shale. If, in doing so, gas production is significantly enhanced, the applicability of HEGF to Devonian shale gas well stimulation will have been demonstrated. If gas production does not result from multiple fracturing, additional tests in other wells will be required to fairly evaluate the technique as a stimulation tool. Thus, to maximize the probability that gas production is achieved in the first test, it is vital that the borehole be located in a region where previous efforts proved highly successful, and that the well be drilled in a manner to minimize wellbore damage. It is thus desirable that the well have measurable pre-test production. This would enable meaningful pre- and post-experiment well tests.

From the literature, it would appear that air drilling produces the least damage, and that any operation requiring the use of fluids (water) should be avoided. It is assumed that the wellbore will be dry. Since the proof test will be done in a 6-1/2 inch diameter borehole, a 6-1/2 inch diameter borehole is desirable for the Devonian shale as well. This will permit the use of the same canister in the same wellbore geometry. From an operational viewpoint, the well should be as shallow as possible, yet consistent with a high production probability. To minimize the chances of "hanging up" the package during installation, the drilling method chosen should be that which produces the straightest hole.

Core from the interval to be fractured would be extremely desirable. It would serve to provide information on natural fractures, permit use of actual material properties for specifying an optimum pulse, and provide an estimate of gas content. However, these elements need to be balanced against possible increased borehole damage during coring. Alternatively, preserved core samples from a nearby well in the same formation might meet the core requirements.

A normal suite of logs is required to identify promising regions for stimulation. These include gamma, caliper, density, neutron, induction, and lithologic logs. Any logs requiring fluid should be avoided before simulation, if at all possible. In addition, minimal "fracture logs" are required before stimulation to document natural fractures present. These might include a TV scan, downhole photograph, or impression packers. Several of these techniques are being evaluated in situ experiments at NTS. Post-test fracture logs may include one or more of the above and possibly a new radiography fracture diagnostic to be tested during in situ experiments at NTS. These fracture logs are particularly essential if gas production does not result from the experiment and analysis of the pressure pulse indicates that multiple fracturing should have occurred. If gas production is achieved, such a verification would be desirable but not mandatory, since presumably multiple fracturing would also be indicated with the pressure record.

Well testing before and after the high energy gas fracturing should consist of both drawdown and buildup tests on the 100 foot long experiment interval. This would effectively establish the amount of production stimulated by the experiment. The buildup tests would provide formation permeability, wellbore damage (skin), and the reservoir pressure. In this sense, the well

testing constitutes an important fracture diagnostic. Because pre-test production is likely to be low, well tests should be started several months before the experiment is conducted.

VI. Conclusion

Major achievements during the current year include:

- (1) The development of finite element modeling which correctly describes the fracturing behavior in ash fall tuff and should do so in other materials as well,
- (2) The development and verification of semiempirical models which define pressure risetimes as a function of borehole size, and provide estimates of stress, acceleration and fracture length in the rock,
- (3) The experimental determination of peak pressure obtained as a function of pressure risetime,
- (4) The experimental determination of pressure risetime obtained with the two propellants which will be used in the Devonian shale experiment as a function of borehole size, and
- (5) Design and development of practical propellant canisters for both small and full scale experiments.

Items 1 and 2, above permit specification of a pressure pulse for multiple fracturing, items 3 and 4 permit specification of a propellant to achieve the desired pulse.

Less major, but nevertheless important achievements include the development of the sand Sulfa Set plug tamping scheme, and the gun test of a prototype full scale canister with RIP ignitor system. The tamp experiments were interesting in that so little material ensures closure. They were important because they resulted in significant savings in both the time and cost of conducting experiments as compared with using grout. The gun tests were noteworthy because the pressure pulse, which reached 50,000 psi, was used to successfully specify propellant to obtain a faster, tailored pulse in a similar experiment in ash fall tuff, and the pressure measurement being used in boreholes was validated.

A substantial number of experiments and tests were conducted to achieve the results listed above. They include 17 in situ small scale experiments at NTS, 5 sand tamp experiments in schedule 80 pipe, 2 sand tamp experiments in a 90 mm cannon, 1 proof test (in a 90 mm cannon) of a full scale canister prototype, and 1 pressure profile test in a 155 mm cannon.

The present level of understanding permits specification of pressure pulses and propellants to reliably produce multiple, hydraulic, or explosive fracturing in ash fall tuff. Whether the technique used for specifying propellant mixtures holds for other materials as well or needs modification will be tested during the vertical tamp development and full scale proof tests. The conclusion of these tests will complete preparation for a Devonian shale gas well experiment.

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Appendix A

Stress and Acceleration Data

Although the stress and acceleration data proved vital in "calibrating" the finite element model for predicting fracture behavior, they are secondary in the sense that they do not impact on specification of pressure risetime or peak pressure required. They are therefore presented in appendix form. Table A1 summarizes the observed peak values of radial stress, σ_r , tangential stress, σ_t , radial acceleration, a_r , and tangential acceleration, a_t . The borehole notation is the same as used in the main text. For example GFSE2-C1 translates to experiment series GFSE2, shot number 1 in Borehole C (see Figure 1 text).

The stress and accelerometer instrumentation consisted of 2 bipolar stress gage-accelerometer pairs oriented perpendicularly to each other. The entire assembly was potted in epoxy. By installing the gage package so that the gage axes were at 45° to the vertical (see Figure 1), four gages were sufficient to record both radial and tangential components for all four successive experiments. The instrument package was grouted under pressure and maintained under pressure during cure to establish a pre-stress on the package to enable measurement of tensile as well as radial components.

In each case, Boreholes A and C were in porous, peralkaline tuff; Boreholes B and D were in the more competent red tuff. Experiment GFSE5 was also in the red tuff. Propellant M5(A) was always used in boreholes A and B, M5(B) in Boreholes C and D except for GFSE2 C1.

Pertinent observations regarding the data in Table A1 include:

- (1) Repeated identical shots in the same borehole, GFSE3-1,2,3, for M5 (B) propellant, give more repeatable results than identical shots in different boreholes GFSE2-D1, GFSE3-C1, D1.
- (2) Multiple shots in the same borehole using M5(A) propellant do not yield repeatable stresses and accelerations. The faster propellant apparently changes the borehole boundary conditions significantly.
- (3) GFSE3-D4 was a water filled borehole -- the effect was to decrease stress but increase acceleration.
- (4) Stress levels in the softer peralkaline tuff were lower but the accelerations appear somewhat higher.
- (5) The relatively smaller values seen for GFSE5 are due to a larger experiment-instrument canister spacing (4.57m).

Figures A1 and A2 present typical stress and accelerometer data for M5(A), and M5(B) propellant shots, respectively.

Table A1

Summary of Small Scale Experiment Stress and Acceleration Measurements

Experiment	σ_r [MPa(Psi)]	σ_r [MPa(Psi)]	α_r (g's)	α_t (g's)
GFSE2 C1	5.4 (780)	0.48 (70)	160	100
GFSE2 D1	2.1 (300)	0.80 (115)	10	10
GFSE3 A1	0.48 (70)	0.34 (50)	200	150
GFSE3 B1	2.06 (300)	0.48 (70)	140	75
GFSE3 B2	0.59 (85)	0.28 (40)	175	100
GFSE3 C1	1.45 (210)	0.59 (85)	20	20
GFSE3 D1	2.75 (400)	0.52 (75)	10	14
GFSE3 D2	2.96 (430)	0.45 (65)	5	5
GFSE3 D3	2.75 (400)	0.48 (70)	5	5
GFSE3 D4	2.20 (320)	0.24 (35)	10	10
GFSE5	0.23 (33)	0.20 (29)	40	20

Figure A1. Typical Stress and Acceleration Records Obtained with M5(A) Propellant in a 0.048 m (1.89 in) Diameter Borehole.

Figure A2. Typical Stress and Acceleration Records Obtained with M5(B) Propellant in a 0.048 m (1.89 in) Diameter Borehole in Ash Fall Tuff.

Appendix B

Summary of Pre and Post Test Transmissivity Measurements for Small Scale Experiments

A standard fracture diagnostic measurement used in all the fracturing experiments to date has been the measurement of apparent pre- and post-test transmissivity.³ It is a relative measurement of the apparent increase in effective borehole surface area. The measurements are generally repeatable to within a factor of two. Table B1 summarizes the transmissivity results for the small scale experiments.

Table B1

Summary of Pre- and Post-Test Transmissivity Measurements for Small Scale Experiments

<u>Experiment</u>	<u>Pre-test (md)</u>	<u>Post-test (md)</u>
GFSE3 A1	0.2	10
GFSE3 B1	0.05	2
GFSE3 B2	2	1
GFSE3 C1	0.5	4
GFSE3 D1	0.13	1.3
GFSE3 D2	1.3	1.5
GFSE3 D3	1.5	1.6
GFSE3 D4	1.6	1
GFSE5	0.3	10