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SANDIA REPORT

SAND85—2809 • Unlimited Release • UC—92A

Printed July 1986

High Energy Gas Fracture Experiments in Fluid-Filled Boreholes—Potential Geothermal Application

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A05
Microfiche copy: A01

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Unlimited ReleaseHIGH ENERGY GAS FRACTURE EXPERIMENTS IN LIQUID-FILLED BOREHOLES--
POTENTIAL GEOTHERMAL APPLICATION*

by

J. F. Cuderman, T. Y. Chu, J. Jung, R. D. Jacobson
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ABSTRACT

High Energy Gas Fracturing is a tailored pulse fracturing technique which uses propellants to obtain controlled fracture initiation and extension. Borehole pressurization rates can be tailored, by suitable choice of propellants, to produce four or eight fractures radiating from the wellbore. High Energy Gas Fracture (HEGF) research is conducted at DOE's Nevada Test Site (NTS) in a tunnel complex where experiments can be done under realistic in situ stress conditions (1400 psi (9.7 MPa) overburden stress). Pressure measurements are made in the test borehole during all fracturing experiments. Experiments are mined back to provide direct observation of fracturing obtained.

The initial objective of HEGF research was to develop multiple fracturing technology for application in gas well stimulation. HEGF research at NTS and in Devonian shale demonstration tests has resulted in a completed technology for multiple fracturing in uncased, liquid-free wellbores. Current research is directed toward extending the technique to liquid-filled boreholes for application in geothermal in addition to gas and oil wells. For liquid-free boreholes, multiple fracturing is specified in terms of pressure risetime required for a given borehole diameter. Propellants are mixed to achieve the desired risetime using a semiempirical mixing equation. The same techniques were successfully applied to fracturing in liquid-filled wellbores. However, the addition of liquid in the borehole results in a significantly more complicated fracturing behavior. Hydrodynamic effects are significant. Multiple fractures are initiated but only some propagated. Multiple- and hydraulic-type fracturing and wellbore crushing have been observed in the same experiment. The potential of using HEGF for geothermal well stimulation has been demonstrated through the present experiments.

*This work supported by the U. S. Department of Energy under Contract DE-AC04-76DP00789.

ACKNOWLEDGMENTS

Useful discussions with Dave Northrop, Jim Dunn, and Dave Glowka are gratefully acknowledged. The efforts of an additional number of individuals in organizations at Sandia National Laboratories and from REECO and EG&G contributed significantly to the experiment fielding effort. These include John Patrick, John Talbutt, and Dave Amsler, project engineering and coordination; Don Werner, Larry Skenandore, and Harold Roberts, AF&F; Bob Williams and Erv Henshaw, transmissivity; Ken Melloy and Carl Crowe, data acquisition; Mike O'Brien, geological support; Cris Salinas, photography; and Carl Davis, borehole tv logging.

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HIGH ENERGY GAS FRACTURE EXPERIMENTS IN LIQUID-FILLED BOREHOLES-- POTENTIAL GEOTHERMAL APPLICATION

by

J. F. Cuderman, T. Y. Chu, J. Jung, and R. D. Jacobson

I. Introduction

High Energy Gas Fracturing (HEGF) is a propellant-based technology initially developed for enhancing production in natural gas wells.¹⁻⁴ The basic concept involved is that propellants can be chosen to produce pressurization rates which result in multiple radial fractures emanating from the wellbore. For very fast propellants or high order explosives (≤ 0.1 ms pressure risetimes), a crushed zone is produced about the wellbore which can result in decreased communication with the surrounding formation. For very slow pressurizations (> 1 ms pressure risetime), only hydraulic-type fractures occur. For intermediate burn rates (in the range of 0.1 to 1 ms risetimes), four or eight major fractures emanate from the wellbore, oriented along principal in situ stress directions. While hydraulic fractures are usually parallel to existing major natural fractures and do not connect additional fractures to the wellbore, the HEGF multiple fractures serve as conduits into the well from fractures that do not normally communicate with it. For this reason, HEGF is particularly applicable to stimulating naturally fractured reservoirs. Because permeability in geothermal reservoirs is typically fracture dominated rather than matrix dominated, HEGF appears to be a logical candidate technology for stimulating those reservoirs.

Geothermal reservoirs can be classified into two main types: vapor dominated (dry steam) and liquid dominated (hot water). The Geysers of California and the Larderello field of Italy are examples of vapor dominated systems. Liquid-dominated reservoirs include Wairakei in New Zealand, Bulalo in the Philippines, Coso in California, and Baca in New Mexico. Production zones in geothermal wells are typically at depths of 5000-10,000 ft (1500-3000 m). Because reliable methods for fracture mapping at these depths do not exist, fracture characteristics can only be inferred from field observations. For example, wells drilled in the Geysers as close as 100 ft (30 m) from commercial producers failed to encounter sufficient fractures for economic production. Alternatively, productive fractures have been encountered as little as 10 ft (3 m) from a previously drilled dry hole.⁵ Interference tests at Coso indicated immediate response between two wells 30 ft (10 m) apart, but no communication at all

with a well 130 ft (40 m) away. Extensive drilling experience in New Zealand indicates that productive fractures are 300 ft (100 m) or more apart. Thus, productive fractures in geothermal reservoirs appear to be in the range of 30-300 ft (10-100 m) apart. Further, the major fractures are thought to be parallel, since attempts to stimulate near-commercial wells using hydraulic fracture techniques have generally been unsuccessful.

Because HEGF has been shown to produce multiple radial fractures 30 ft (10 m) or more into a formation at angles to the hydraulic fracture direction, it is potentially useful for geothermal stimulation. Potential geothermal candidates for stimulation using HEGF include both hot water and dry steam reservoirs, wells having near-wellbore damage incurred during drilling, and wells with insufficient near-wellbore permeability in matrix-dominated fields. Computer modeling of HEGF at Sandia⁶ shows that HEGF's ability to create multiple fractures is better in overcoming wellbore damage than conventional hydraulic fracturing.

The initial research and development for HEGF was conducted in G Tunnel at the Nevada Test Site (NTS) where mineback could be conducted to examine the fracturing obtained. The pressure pulse and fracturing achieved were studied as a function of the propellant mixture, in situ stress, and borehole diameter. These tests, together with modeling, produced a methodology for specifying propellants to achieve a desired pressure pulse and fracturing behavior. The experiments in Devonian shale in Rowan County, KY and Meigs County, OH,^{7,8} verified that the criteria developed at NTS to specify pressure risetimes and propellants for multiple fracture are also applicable to other rock types.

Most of the experiments for natural gas applications in ash fall tuff and Devonian shale were done in liquid-free boreholes. Development of the HEGF technique for possible applications in liquid-dominated geothermal wells requires a knowledge of how the pressure pulse and fracturing behavior are affected by the presence of liquid in the borehole and surrounding formation. Multiple fracturing in a water-filled borehole was demonstrated in a previous test series using a commercially available, proprietary propellant.² The pressure risetime and peak pressure in that experiment were 1 ms and 15,000 psi (105 MPa), respectively. This was consistent with requirements for multiple fracturing in liquid-free boreholes. Mineback showed multiple fractures. No

data were obtained for the performance of the proprietary propellant in a liquid-free borehole. A subsequent small-scale experiment in a water-filled borehole^{4,8} indicated that results might be much different for the same propellant package in liquid-free and liquid-filled boreholes. In the water-filled borehole, the pressure pulse risetime was much shorter and the pulse amplitude only half that of a comparable liquid-free borehole, even accounting for the decreased free volume. This result suggested that the propellants for producing multiple fractures in liquid-filled wellbores might need to be significantly slower than for liquid-free wells to obtain the same pressure pulse.

For this study, a total of four experiments were conducted in the G Tunnel complex at NTS in order to evaluate the potential role of HEGF for hot water geothermal application. The objectives of the experiments were to: (1) test applicability of the liquid-free risetime criteria to liquid-filled boreholes, (2) establish the effect of liquid on pressure risetime and amplitude, (3) compare fractures produced in liquid-filled and dry boreholes, and (4) produce a designed multiple fracture in a liquid-filled borehole. Experiments were designed near the hydraulic-multiple and the multiple-crushing boundaries. Fracturing achieved in each case was verified by mineback. Preliminary experiments conducted at Sandia's explosive test facilities in heavy-walled, schedule 160 pipe (both water filled and liquid free), served to provide an estimate of pressure risetimes expected with different propellants. At NTS, experiments were installed in the boreholes, the test zone backfilled with water, and the interval between the propellant canister and the collar stemmed with sand. A pressure transducer was an integral part of each propellant canister assembly. In two of the experiments, stress gages and accelerometers recorded radial and tangential components induced in the formation.

This report summarizes (1) the design techniques developed for liquid-filled boreholes as developed from the liquid-free case, (2) pipe test results (Appendix A), (3) NTS experiment description and results including pressure, stress, and acceleration data, pre- and post-test transmissivities, and mineback results, and (4) numerical modeling conducted in support of the experiments.

II. Experimental

A. Experiment Design

The design of multiple fracturing involves specifying a pressure risetime and propellants that achieve the desired risetime for a given borehole/propellant canister geometry. The geometry of the multiple fractures produced, as well as the peak pressures obtained, are influenced by in situ stresses in the formation to be fractured. This section summarizes (a) pressure risetime specification, (b) propellant specification, (c) fracture geometry considerations, and (d) expected peak pressures.

(1) Pressure-Risetime Specification

Fig. 1 is a typical pressure pulse observed during multiple fracturing. Normally, an initial pressure rise is observed, after which the pressure drops and then again increases until the propellant burn is complete or the signal is lost. The pressure drop after the initial rise is interpreted to be due to the increase in free volume accompanying fracture initiation. Subsequent increase in fracture volume is more gradual, permitting the pressure to rebuild.

Figure 1. Typical Pressure Pulse Obtained During Multiple Fracturing

Examination of data from the NTS experiments revealed that the most important parameter affecting fracture behavior is the pressure risetime. Through a combination of modeling efforts^{9,10} and experimental verification,¹⁻⁴ it was shown that the multiple-fracture regime is defined in terms of pressure risetime, t_m , by

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

where C_R is the Raleigh surface wave velocity¹¹ and D is the borehole diameter. The term at the left is a derived result⁸ and represents the multiple-explosive boundary. The term at the right is an empirical fit of the same functional dependence to the observed hydraulic-multiple boundary.

Fig. 2 is a plot showing the multiple-fracture regime for ash fall tuff. In more than 20 experiments, no exceptions have been found to the risetime band for multiple fracturing defined by Eq. (1) and shown in Fig. 2. Note that a faster-burning propellant is required for equivalent fracturing in a smaller diameter borehole.

Figure 2. Risettime-Specification Plot for Ash Fall Tuff.

For a different rock type, Fig. 2 must be adjusted by using the correct C_R . Fig. 3 defines the relationship between C_R and the more commonly characterized properties,

Figure 3. Surface Wave Velocity (C_R) as a Function of Compressive Wave Velocity (C_P) and Poisson's Ratio (ν).

compressive wave velocity, C_P , and Poisson's ratio, ν . The compressive wave velocity in ash fall tuff is typically 6900 ft/s (2100 m/s). Poisson's ratio is in the range of 0.2-0.3. It is noted that for $\nu = 0.3$, $C_P = 2C_R$.

(2) Propellant Specification

Several different propellants have been used in HEGF experiments. Their specifications appear in Table I. For the propellants used, standard ballistics calculations to define pressure using ballistic calculations response proved inadequate in several respects. First, the predicted risetime to a given pressure was systematically longer than observed experimentally. Second, the predicted difference in risetimes of the M5A and M5B propellants used in liquid-free experiments was smaller than measured. A similar difference might be expected for any other pair of propellants. Fig. 4 shows the experimentally determined risetime behavior as a function of borehole diameter. The data for M5A and M5B propellants in ash fall tuff for liquid-free boreholes are represented by the curves labeled M5A propellant and M5B propellant, respectively.

Table I.
Characteristics of Propellants Used in HEGF Experiments

VARIABLE	M5A	M5B	M30A	M30B
Grain Length (mm)	6.73	11.0	16.8	23.75
Grain Diameter (mm)	1.40	5.00	7.11	11.87
Perforation Diameter (mm)	0.33	0.50	0.70	1.07
Number of Perfs	1	7	7	7
Density (kg/m ³)	1660		1660	
Isochronic Flame Temperature (K)	3245		3040	
Gas Production Constant in ³ /lb (m ³ /kg)	24416 (0.88)		26727 (0.96)	
Burn Rate Constant*A	0.000761		0.00576	
Burn Rate Constant*n	0.895		0.652	

* Burn Rate $R(\text{in/sec}) = A[P(\text{psi})]^n$

Figure 4. Propellant-Specification Chart. The curves labeled M5A and M5B are experimental data from liquid free experiments in ash full tuff. The M30A and M30B points are from water-filled pipe tests.

A horizontal line in Fig. 4 corresponds to emplacement of a canister of the indicated size in the same size borehole (zero annulus). The indicated risetimes t_A and t_B , at the intersection of the horizontal line with the propellant curves, result from filling this canister with M5A and M5B propellants, respectively. For a given diameter, a desired risetime, t_m , is chosen from Fig. 2. In general, this will fall between t_A and t_B in Fig. 4. The fraction f_A of M5A, by weight, required to produce t_m is determined^{7,8,12} by

$$f_A = \frac{\log(t_B/t_m)}{\log(t_B/t_m) + 2 \log(t_m/t_A)} \quad (2)$$

where the factor 2 is an empirical constant for the propellants used.

The free volume in the borehole consists of void space between propellant grains, the propellant grain perforation volume, and the annulus between the canister and the wellbore. If the borehole is larger than the propellant canister diameter, t_A and t_B must be adjusted^{7,12} by

$$t'/t = V'/V, \quad (3)$$

where the primed symbols represent the larger free volume and corresponding risetime, and the unprimed symbols represent the zero annulus case shown in Fig. 4. The corrected values t'_A and t'_B are then inserted into Eq. (2), along with the desired risetime, t_m , to calculate f_A .

As noted, shorter risetimes were observed in water-filled boreholes than for corresponding liquid-free geometries.^{4,8} Thus, the M5A and M5B curves in Fig. 4 are not appropriate inputs for designing experiments in liquid-filled boreholes. A series of experiments were conducted in 4-in (0.10 m) ID heavy wall pipes to attempt to define appropriate propellants for use in liquid-filled, 4-in (0.1 m) diameter boreholes at NTS. Candidate propellant canisters of 1.4-in (0.034 m) ID and 3.2-in (0.08 m) ID were tested in water-filled and in water-free, schedule 160 XHD pipes instrumented with pressure transducers. The canisters were then buried to contain fragmentation when the pipes burst. Propellants tested were M5 and M30 candidates from Table I. The 3.2-in (0.08 m) canisters used a 0.840-in (0.02 m) diameter RIP ignitor; the 1.4-in (0.034 m) canisters used a 0.540-in (0.014 m) diameter RIP ignitor. This is an important point

since the pressure response is a function of the RIP ignitor as well as the propellant used. Because the pressure in the pipe tests does not simulate borehole fracture initiation behavior, the critical risetime was chosen to be that at which the pressure attained 20 kpsi (138 MPa). This corresponds to an average expected peak pressure, since previous experiments had shown that the rock fractures at between 5000 and 30,000 psi (34.5 and 206 MPa). Points labeled M30A and M30B in Fig. 4 represent only those results from water-filled pipe tests used in designing experiments for NTS. These are discussed in detail in Table A1, Appendix A. M30 propellants were used in two water-filled experiments at NTS. One test used M5A in a 1.5-in (1.75-in OD) canister; the other a mixture of M30A and M30B in a 3-in (3.2-in OD) canister. The risetime for the mixture was designed using Eq. (3) for the individual risetimes shown in Fig. 4 and Table A1.

(3) Fracture Geometry

Fig. 5 is a mapping of a multiple-fracture pattern radiating from a borehole oriented along a principal in situ stress direction. The maximum principal stress in the plane normal to the borehole is designated σ_1 , the minimum σ_2 . The vertical and horizontal fractures in Fig. 5 are thus in the two principal stress planes. It is suggested that the fractures at roughly 45° are along planes of maximum in situ shear stress.

The geometry shown in Fig. 5 is that obtained for risetimes near the multiple-explosive boundary in Fig. 2 for a liquid-free borehole. In the hydraulic fracture regime of Fig. 2, only two fractures, such as those along σ_1 in Fig. 5, are observed. For risetimes in the multiple-fracture region but near the multiple-hydraulic boundary, fractures also occur parallel to σ_2 . For pressure pulses with shorter risetimes, the four fractures (two horizontal and two vertical) become wider and more open. For risetimes shorter than those in the middle of the multiple fracture regime, a major fracture also occurs in each of the four quadrants formed by the fractures in the principal stress planes. These fractures first appear at about 30° to σ_1 and shift toward 45° as t_m approaches the multiple-explosive boundary. The first case corresponds to brittle-fracture behavior, the latter to near-ductile failure. Thus, depending on risetime, two, four, or eight fractures result. The principal stress parallel to the

Figure 5. Typical Multiple Fracturing Geometry and its Relationship to Principal In Situ Stress.

borehole does not appear to influence fracturing behavior. The fracture phenomenology and dependence on in situ stress reported here have also been recreated by finite-element modeling.¹³

The average fracture length (r) in ash fall tuff was found¹⁰ to be approximately

$$r = 10^{-3} \sqrt{E_p} \quad (4)$$

where E_p is the energy contained in the propellant per unit length of canister (J/m).

Energy considerations provide a qualitative insight into the variation of fracture length with rock properties. The energy, E_p , necessary to open a fracture is given¹⁴ by

$$E_p = \frac{\pi (1 - \nu^2) P^2 r^2 h}{E} \quad (5)$$

where ν = Poisson's ratio, P = pressure in the fracture, r = fracture length, h = fracture height, and E = Young's modulus.

Solving for r , one obtains

$$r = \frac{1}{P} \sqrt{\frac{E_F E}{\pi h (1 - \nu^2)}} \quad (6)$$

Noting that E_F/h must be proportional to the energy available per unit length and that ν plays a minor role,

$$r \propto \frac{1}{P} \sqrt{E_P E} \quad (7)$$

It is noted that for ash fall tuff a fracture length of about 25 ft (7.6 m) was observed for a 6-in (0.15-m) diameter, fluid-free borehole with $E_P = 36$ MJ/m. Since Young's modulus (E) for ash fall tuff is lower than that of most reservoir rocks, Eq. (7) would predict longer fractures in other rock types. While the length of the radial fractures could not be observed in Devonian shale experiments, where the modulus was about twice that of ash fall tuff, the borehole tv log showed that the fractures extended vertically about 20 ft (6.1 m) above the propellant canister, compared to 10 ft (3.0 m) in ash fall tuff.⁷

(4) Peak Pressure

As indicated, a prediction of peak pressure is not needed to specify propellants for multiple fracturing; only the pressure risetime is required. In general, a prediction of peak pressure is much less accurate than that of the risetime for a given propellant mixture. However, if the principal in situ stresses normal to the borehole are known, an estimate can be made.

Fig. 6 shows the observed peak pressure as a function of pressure risetime for in situ experiments in liquid-free boreholes done in the tunnel complex at NTS. The in situ stress was essentially constant in these experiments. For propellant mixtures

Figure 6. Peak Pressure as a Function of Pressure Risetime under Constant In Situ Stress

that produce pressure risetimes longer than about 1.0 ms, a peak pressure in the range of 4,000–7,000 psi (28–48 MPa) is obtained. For shorter risetimes, the peak pressure rises rapidly to the 30,000 psi (200 MPa) range, or higher. Hydraulic fracture occurs in the longer risetime, constant-peak-pressure regime. Multiple fracturing is obtained for the region having risetimes shorter than about 1 ms.

Fig. 7 shows the peak pressure obtained in multiple-fracturing experiments plotted as a function of in situ stress. Peak pressure appears to increase linearly with in situ stress. The data points are from both tunnel and vertical borehole experiments at NTS. It is thus seen that the peak pressure rises sharply with shortened risetime and increases linearly with increased stress.

B. Experiment Description and Results

A total of four experiments (GT1–GT4) were performed in water-filled boreholes in the present experiment series. Fig. 8 is a typical experiment installation in liquid-filled boreholes as conducted in G Tunnel. The present experiments were all done in 4-in

Figure 7. Peak Pressure as a Function of In Situ Stress

Figure 8. Experiment Installation

(0.1 m) diameter boreholes. The experiment assembly consists of the propellant canister, pressure transducer, packer, and cable tube. The firing cables, pressure transducer cables, and line for pressurizing the packer are routed out the cable tube. The packer confines water to the experiment zone and is fabricated of lightweight elastomer; an internal pressure of 15-25 psi (0.1-0.17 MPa) is sufficient to confine the water to the test zone. Upon installation of the experiment package, the borehole is backfilled with water and the packer pressurized with air or water. The water outside the test zone is then blown out with compressed air and the borehole stemmed with damp Overton, Nevada sand. About a foot of 50/50 mix of sand and sulfate-based cement at the collar ensures containment of the stemming.

Table II is a summary of propellant canisters and propellant mixtures used in the present experiment series. All references in the text to specific canisters are in terms of the inside diameter. Two different propellant canister designs were used in the current experiments. The first, used in previous liquid-free, 1.4-in (0.034 m) diameter experiments and in GT1, was initiated using three exploding bridge wire (EBW) detonators, each surrounded by about 6 gm of black powder. This design proved unsatisfactory for use in water-filled boreholes because of quenching. The second design shown in Fig. 9 was used for the 3.2-in (0.08 m) experiments and subsequent 1.755-in (0.044 m) ID small canister tests as well. This design consists of a section of 3.2-in (0.08 m) ID PVC tubing and a centered RIP ignitor with the annulus filled with propellant. One end of the assembly is closed off with an endcap, the other by the pressure transducer assembly. The RIP ignitor is initiated by an EBW initiator; it ignites the entire length of the propellant essentially simultaneously since the burn rate of the RIP ignitor is 7000 m/sec. For the 3.2-in (0.080m) canister, the RIP ignitor was 0.840-in (0.02 m) OD; that for the smaller canisters was 0.540-in (0.014 m) OD. In each case the RIP had a center core of lead-sheathed mild detonating fuse (MDF) surrounded by B/KNO₃ pyrotechnic. The ends of the MDF were terminated with aluminum endcaps containing a small pressing of RDX explosive. A short length of MDF ribbon was sandwiched between two EBW initiators and the RIP endcap. This design provided firing redundancy. The pressure transducers used were four-arm, bridge-type, commercially available gages rated at 30,000 psi (207 MPa).

Table II. Propellant Canister Specifications for GT1-4

Test	PVC Size in	ID in	(m)	OD in	(m)	Length ft	(m)	Propellant	Ignitor*
GT1	1.25	1.36	(0.034)	1.66	(0.042)	8	(2.44)	1.25 kg M5B	PD
GT2	3	3.23	(0.080)	3.50	(0.089)	8	(2.44)	11.2 kg M5B	L RIP
GT3	1.5	1.75	(0.044)	1.90	0.048)	4	(1.22)	1.36 kg M30A	S RIP
GT4	3	3.23	(0.080)	3.50	(0.089)	4	(1.22)	2.59 kg M30A 2.68 kg M30B	L RIP

*PD:EBW point detonators. L RIP: 0.84 in (0.02 m) diameter.
S RIP: 0.54 in (0.014 m) diameter.

Figure 9. Schematic RIP Ignitor Design Propellant Canister Assembly

Fig. 10 is a schematic of the G Tunnel test bed used in experiments GT1 and GT2 showing the emplacement face of the drift and an elevation view of the boreholes. An array of five boreholes was emplaced as shown. The two boreholes at the left were used for other experiments. A stress gage/accelerometer package containing two stress gage accelerometer pairs was installed in the center borehole. The 2-ft (0.3 m) long instrument package was emplaced with its center at 36 ft (11 m) in the borehole. The instrument package was then grouted in place with expansive, rock-matching grout. This was to put a "set" on the gages so that tangential, as well as radial components could be measured. The gage orientation was such that for each borehole in the test bed, one stress gage/accelerometer pair measured primarily the radial components; the other the tangential.

The test bed for GT3 and GT4 was identical to that for GT1 and GT2 except that the borehole total depth was 25 ft (7.6 m) instead of 40 ft (12.2 m) and no instrumentation was emplaced at the center of the array.

Fig. 11 compares the lithologies for the two experiment zones. As is seen, all intervals are shifted upward about 5 ft (1.52 m) for GT3-4 relative to GT1-2. Two types of ash fall tuff are indicated--red ash fall and peralkaline. Table III compares their physical properties. The red ash fall has a higher modulus and Poisson's ratio and a lower porosity. Because these values are closer to those of reservoir rocks, it is the preferred of the two test media. Fig. 12 shows core from the test zones of experiments GT1-4.

The results of the individual experiments, GT1-4, are described in the following sections.

EMPLACEMENT VIEW

ELEVATION VIEW

Figure 10. G. Tunnel Test Bed Schematic for GT1 and GT2.

EXPT GT-1, GT-2

EXPT GT-3, GT-4

Figure 11. Lithologies for Experiment GT 1-4.

Table III. Comparison of Physical Properties of Tuffs

<u>Property</u>	<u>Red Ash Fall</u>	<u>Peralkaline</u>
Density g/cm ³ (kg/m ³)	2.00 (2000)	1.85 (1850)
Young's Modulus 10 ⁶ psi (GPa)	1.2 (8.2)	0.46 (3.2)
Shear Modulus 10 ⁶ psi (GPa)	0.49 (3.4)	0.19 (1.3)
Bulk Modulus 10 ⁶ psi (GPa)	0.90 (6.2)	0.23 (1.6)
Poisson's Ratio	0.27	0.19
Compressive Wave Velocity		
ft/s (m/s)	8500 (2590)	8200 (2500)
Shear Wave Velocity ft/s (m/s)	5500 (1670)	4900 (1500)
Compressive Strength psi (MPa)	3200 (22)	1450 (10)
(Unconfined)		
Compressive Strength psi (MPa)	5650 (39)	3200 (22)
(1000 psi (6.9 MPa) confining pressure)		
Tensile Strength psi (MPa)	238 (1.58)	50 (0.34)
Plasticity Parameters a ₀	3.66x10 ⁶	7.8x10 ⁵
(Ref. 16) a ₁	0	0
a ₂	0	0

CORE FROM TEST INTERVALS EXPT GT1-4

GT 1

GT 2

GT 3

GT 4

Figure 12. Core from Test Intervals Experiment GT 1-4

(1) Experiment GT1

Four attempts were made to initiate and burn an 8-ft (2.44 m) long, 1.4-in (0.034 m) diameter propellant canister containing 1.25 kg M5B propellant in a 4-in (0.1 m) water-filled borehole. As noted, the initiation system for igniting the propellant consisted of three EBW initiators emplaced in the propellant and surrounded by about 6 gm of black powder. In all but the last attempt, the EBW ignitors initiated and the black powder burned but quenched before significant propellant burn occurred. In the fourth attempt, the propellant was successfully initiated and a pressure pulse obtained.

These pressure data are shown in Fig. 13. The risetime to the apparent fracture pressure of 8000 psi (55 MPa) was 0.2 ms. On the basis of a previous test of a 1.4-in (0.034 m) canister in a 1.89-in (0.05-m) borehole, a pressure risetime of 1 ms with a 5000 psi (35 MPa) peak pressure was predicted. The subsequent very slow pressure

Figure 13. GT1 Pressure Record.

decay was similar to that observed in the previous 1.89-in (0.048 m) test.⁴ In comparison with behavior in liquid-free boreholes, the 0.2 ms risetime was about a factor of 5 shorter. No meaningful stress or acceleration data were obtained because of the 25-ft (7.6 m) experiment emplacement (the bottom 15 ft (4.6 m) of the borehole was backfilled with sand to eliminate a rough section of the wellbore). Post-test examination of the borehole contents showed that only about a third (by weight) of the propellant burned before quenching occurred. Examination of the propellant grains showed that they had burned uniformly before being quenched. Only a single, radial fracture was observed along the hydraulic direction, as indicated in the mineback sketch shown in Fig. 14. This fracture had a radial length of about 3 in (0.08 m) and was observed only between 20.7 ft and 23.4 ft (6.3 and 7.13 m) in the test zone which extended between 17 and 25 ft (5.2 and 7.6 m). Because no fracture extension occurred, the pressure was essentially contained in the borehole. The single small fracture indicates that the energy release was barely at the threshold for fracturing. The transmissivity (apparent permeability) increased slightly from 0.2 md before the test to 0.8 md after the test.

Figure 14. Mineback Results--GT1.

(2) Experiment GT2

Experiment GT2 used a 3.2-in (0.08 m) diameter, 8-ft (2.4 m) long propellant canister filled with 11.2 kg of M5B propellant. It was emplaced at the bottom of the 40-ft (12.2 m) total depth, 4-in (0.1 m) wellbore, backfilled with water, stemmed, and shot. Fig. 15 shows the pressure pulse obtained. Using the design curves presented in Section II-A, a 0.7 ms risetime was predicted assuming that the effect of water is only to eliminate the free volume in the annulus. The corresponding liquid-free borehole would produce a 1.2 ms risetime. As is seen, the observed risetime was 0.3 ms, which is still within the multiple fracture regime.

Figure 15. GT2 Pressure Record.

Fig. 16 shows views of the drift face at three locations during mineback. A large, hydraulic-type fracture was observed which apparently started near the gage end of the test zone, then propagated both toward the collar of the borehole and over the test zone, for a total length of about 23 ft (7 m). The mineback sequence, Fig. 16 A-C, and the three-dimensional fracture drawing of Fig. 17 show this behavior. In addition, a

Figure 16. GT2 Mineback Sections.

Figure 17. GT2 Mineback Three-Dimensional View.

horizontal fracture was observed between 25 ft and 31 ft (8.8 and 9.14 m) (Fig. 16B, Fig. 17). In the region containing the horizontal fracture, the fracturing is characterized as multiple. It is noted that this occurred just before the test zone. The horizontal fracture corresponds to the maximum principal stress plane; the vertical to the minimum principal stress plane. In the test zone itself, the fracturing is characterized by the behavior depicted in Fig. 16C. Multiple fractures were initiated; however, crushing apparently occurred before they had a chance to propagate. Thus, while the same charge in a liquid-free borehole would have produced a clearly defined multiple fracture pattern emanating from the test zone with secondary hydraulic fractures out the ends of the region, what is seen here is a more complicated combination of hydraulic, multiple, and explosive fracturing. From the pressure record, one would not predict the degree of crushing observed--the pressure risetime required is considerably faster than that measured at the end of the borehole. It is probable that the large hydraulic fracture originating in the vicinity of the pressure gage significantly perturbed the measurement.

Post-test transmissivity, attributed primarily to the hydraulic-type fracture, was 8 md compared to 0.02 md pre-test.

Fig. 18 shows the stress and acceleration data obtained for experiment GT2 as measured in the center instrumentation borehole. While direct comparable stress and acceleration measurements are not available for liquid-free boreholes, the sustained high levels of stress seen here were not observed previously. For liquid-free boreholes, the stress decays to ambient in a few milliseconds.⁴

(3) Experiment GT3

Experiment GT3 used a 1.75-in (0.044 m) diameter, 4-ft (1.22 m) long, propellant canister with a small diameter RIP ignitor. Three lbs (1.36 kg) of M30A propellant were used. A pressure risetime of 1.2 ms was predicted from pipe test data (Fig. 4, Table A1). Fig. 19 shows the measured pressure pulse. Following an initial delay of about 0.75 ms after firing, maxima occurred having characteristic risetimes of about 0.03, 0.25, and 1.9 ms. Fig. 2, for these risetimes in a 4-in borehole, would predict borehole crushing, multiple, and multiple-hydraulic fracturing, respectively. Crushing appears unlikely for a peak pressure of only 1700 psi (11.7 MPa) and a 0.1 ms or less peak width;

Figure 18. GT2 Radial and Tangential Stress and Acceleration.

Figure 19. GT3 Pressure Record.

however, the initiation of multiple-hydraulic fracturing is indicated. It is noted that the 1.9 ms risetime is consistent with pipe test results (Appendix A). The earlier peaks may be due to pressure wave generation in the water surrounding the propellant canister.

Fig. 20 is a composite of photographs taken at different sections of the mineback, starting at the emplacement face of the drift. The maximum and minimum stress directions normal to the borehole are indicated in the first section. In liquid-free boreholes, the predominant radial fractures were those in the principal planes of stress. Fractures in the quadrants between the principal stress directions, corresponding to principal shear planes, were secondary; here they appear to be primary. Even though horizontal and vertical fractures were clearly initiated, as shown in Fig. 20, they did

Figure 20. GT3 Mineback Photos.

not propagate. Little, if any, wellbore crushing was observed. The fracture behavior is thus seen to be consistent with the pressure record.

Fig. 21 is a three-dimensional drawing which summarizes the mineback results for GT3. It shows the predominant fractures observed--at 55° and at 215°. In addition, a small fracture nearly parallel to the 55° orientation broke out of the borehole near the center of the test zone. The length of the two major fractures was about 5 ft (1.52 m).

The pre- and post-test transmissivities were 0.2 md and 0.9 md, respectively.

Figure 21. Three-Dimensional Representation of GT3 Mineback, (the Test Zone Is from 20 to 25 ft).

(4) Experiment GT4

Experiment GT4 used a 3.2-in (0.08 m) diameter, 4-ft (1.22 m) long, propellant canister with an 0.84-in (0.02 m) diameter RIP ignitor. 5.27 kg of a 50/50 mixture of M30A/M30B propellants was used. A pressure risetime of 0.5 ms was predicted from Fig. 4 and Eq. (2) based on the pipe test results. Fig. 22 is a plot of the pressure pulse obtained in Experiment GT4. The peak pressure for the overall pulse occurred at 7.4 ms. As is seen in Fig. 22 and in expanded scale in Fig. 23, three sharp pressure spikes are observed in the first millisecond of pressure buildup, with risetimes ranging from 0.07 ms to 0.2 ms. These risetimes are such that any one of them could initiate crushing. However, the impulse contained under the first two spikes is probably insufficient to produce significant crushing even though the compressive strength of the peralkaline tuff is less than 2000 psi (13.8 MPa). The third spike is probably both

Figure 22. GT4 Pressure Record.

Figure 23. GT4 Pressure Record (Expanded Scale).

sufficiently fast and large to result in significant crushing. Alternatively, if the pulse governing fracture behavior consists of either the first three pulses, or the second and third acting collectively, resulting in effective risetimes of 1 ms and 0.3 ms respectively, multiple fractures should result. An additional feature appearing in Fig. 23 is that of evenly spaced pressure oscillations commencing with the third pressure spike. Since the resonance frequency of the gage is much higher (~ 785 kHz), these appear due to pressure waves oscillating in a short column of water near the end of the test zone at the pressure transducer.

Fig. 24 is a composite of experiment GT4 mineback section photographs commencing 19.5 ft (5.9 m) from the experiment emplacement face. The experiment zone extended approximately between 20 and 25 ft (6 and 7.6 m). Significant borehole crushing occurred throughout the test zone. A multiple fracture pattern was again initiated, as in experiments GT2 and GT3, at the borehole, but only one to three of these fractures propagated more than a few inches (cm) into the formation at any given section. A vertical fracture above the borehole, corresponding to the hydraulic fracture direction, was present in most of the mineback. The other major fractures are mainly in principal shear plane directions.

Fig. 25 is a three-dimensional drawing of the GT4 mineback. Four main fracture sets, labeled 1-4, were mapped. These fractures and their inclinations are also shown as cross section views in the figure.

Fractures 1 and 1A are vertical fractures extending upward from the borehole (Sec. A-A and Sec. C-C). Fracture 1 extended radially about 5-6 ft (3 m) between 15 and 22 ft (3 and 6.7 m) along the borehole. Fracture 1A appeared in the same plane between 24 ft and 26 ft (7.3 and 7.9 m) and extended out about 2 ft (0.6 m) from the borehole.

Fracture 2 was encountered at 23.7 ft (7.2 m). It propagated radially for about 3 ft (1 m) at 110° , then abruptly turned in a 45° direction (Sec B-B). The 45° fracture was probably a natural fracture which opened up when encountered by the 110° wing of fracture 2.

MINEBACK (fluid filled expt)

Figure 24. GT 4 Mineback Sections.

Figure 25. Mineback Summary.

Fracture 3 broke out of the borehole at about 24 ft (7.2 m) with a lower extension commencing at 25 ft (7.6 m). The fracture extended upward for about 5 ft (1.5 m), at 130°-150° (Sec. B-B and Sec C-C), and propagated over the borehole from 21-25.9 ft (6.4 to 7.9 m). Beyond 25 ft (7.6 m), the fracture turned vertically above and below the borehole (Sec DD). The fracture continued into the invert and into the drift face beyond the mineback.

Fracture 4 originated at the end of the borehole and proceeded vertically into the formation and invert beyond the mineback region (Sec D-D).

Fig. 25 shows that essentially all of the fracturing in the test zone occurred above the wellbore. This was also true in GT2. Both experiments used a 3.2-in (0.08 m) OD canister in a 4-in (0.1 m) borehole. This suggests that the gas bubble formed by the burning propellant rose to the top of the borehole and that the water at the bottom served to block fracture propagation. Fracture 1 was along the hydraulic fracture plane, and fractures 2 and 3 were along shear fracture planes. All three fractures were of approximately the same length indicating no directional preference.

The mineback results are consistent with the interpretation that the several risetimes observed in the pressure record all contribute to the resulting fracturing.

The pre-test transmissivity was 1 md. The post-test value was approximately 7 md.

III. Modeling and Analysis

A. Introduction

In parallel with the experimental work, a series of finite element analyses of the experiments were conducted. Analyses of the GT2, GT3, and GT4 experiments were performed, and the predicted pressure histories and resulting crack patterns were compared with the experimental results. In these analyses the borehole pressure histories were calculated via a propellant burn model,¹⁵ and rock cracking and crushing was represented with a material constitutive model.¹⁶ In addition, the experimentally measured borehole pressure histories were used as inputs in a separate series of analyses so that the effects of different pressure histories could be examined.

The objectives for these analyses included evaluating the adequacy of the propellant burn model and the predictive capabilities of the cracking and crushing models in water-filled boreholes, and, of course, to gain more insight into the problem.

B. Analysis Plan

Four analyses of each experiment were conducted. For each experiment, the burn model was used for analyses using red ash fall tuff and peralkaline tuff material properties. Also, the experimental pressure history was used as input for analyses using the two material property sets. This combination of analyses was chosen to provide an evaluation of the burn and the material models for water-filled boreholes. The experiments were conducted in an area where both red ash fall tuff and peralkaline tuff were present. By performing analyses using both sets of material properties, it was hoped that the two material representations would bound the actual physical situation.

The propellant parameters for the burn model are given in Table I. Note that GT2 used M5B propellant, while GT3 and GT4 used M30. For these analyses, the water was modeled simply as an incompressible solid that occupied all of the initial volume between the canister and borehole. Possible thermodynamic effects associated with water in the borehole are not part of the burn model.

The elastic-plastic cracking material model¹⁶ was used for the analyses. The material properties^{2,17} are used for the red ash fall and peralkaline tuff, respectively, and are summarized in Table III.

The in situ stress field used was -1490 psi (10.3 MPa) along the axis of the borehole, -1250 psi (8.6 MPa) in the vertical direction, and -780 psi (5.4 MPa) in the horizontal direction.²

C. Results

Comparisons for the experimental and numerically predicted borehole histories are shown in Figs. 26 to 28, and a tabulation of the initial pressure rates and pressure peaks is given in Table IV. The curves in these figures have all been adjusted so that the zero

Figure 26. Comparison Between Experimental and Calculated Pressure Histories for GT2.

Figure 27. Comparison Between Experimental and Calculated Pressure Histories for GT3

Figure 28. Comparison Between Experimental and Calculated Pressure Histories for GT4

time corresponds to the beginning of the pressure rise and not to the ignition time since a short, variable delay occurs before the pressure begins to increase.

Table IV. Comparison of Predicted and Experimental Pressure Rates and Peak Pressures

<u>Experiment</u>	<u>Initial Pressure Rate</u> <u>psi/sec (MPa/sec)</u>		<u>Peak Pressure psi (MPa)</u>		
	<u>Computed</u>	<u>Experimental</u>	<u>Computed</u>		<u>Experimental</u>
			<u>Red Ash</u>		
			<u>Fall</u>	<u>Peralkaline</u>	
GT2	2.6x10 ⁷ (179x10 ³)	6.28x10 ⁷ (4.33x10 ³)	10670 (73.6)	9250 (63.8)	21160 (146)
GT3	3.44x10 ⁷ (237x10 ³)	9.60x10 ⁶ (66.2x10 ³)	6146 (43.4)	5153 (35.5)	5100 (35.1)
GT4	9.68x10 ⁶ (66.7x10 ³)	1.75x10 ⁷ (121x10 ³)	3573 (24.6)	3309 (22.8)	5454 (37.6)

The average calculated peak pressures (average of the red ash fall and peralkaline results) for GT2 and GT4 underpredicted the experimentally measured peaks by approximately 50 and 37 percent, respectively. The average calculated peak pressure for GT3 is ten percent over the experimentally measured values. These numbers are typical of past results¹⁵ using the burn model for air-filled boreholes in which the computed results are within a factor of two or three of the measured values.

In all cases, in the present analysis, the predicted peak pressure for a borehole in red ash fall is higher than that for peralkaline. This is primarily due to the fact that the volumes of the boreholes in peralkaline increased at a faster rate than those in red ash fall tuff. The larger borehole volumes mean that the gases from the propellants had more room to expand into, and hence, the pressure peaks were not as high.

Although GT2 and GT4 used different propellants, their predicted initial pressure rates were within 60 percent of their respective actual values. The computed GT3 pressure rate is 360 percent of its experimental value. These comparisons can be considered good given the simple way that the water in the borehole was modeled.

The final computed fracture patterns for GT2 are different, depending on whether the burn model or the experimental pressure history was used as input (Figs. 29 and 30). Except for the analysis using the experimental pressure record for red ash fall, each analysis yielded two major cracks extending between 120 to 140 in (3.0 - 3.6 m) from the center of the borehole. The fact that two lines of cracks were predicted in most of the analyses is in qualitative agreement with the experimental data (Fig. 16). For the cases in which the experimentally measured pressure was specified as input to the analyses, the calculations showed significant cracking adjacent to the borehole and the radius of the borehole increased to approximately 4.5 in (0.11 m) (Figs. 31 and 32). These results are consistent with the mineback data (Fig. 16) and the experimental observation that the borehole radius increased from 2 in (0.05 m) to approximately 3 in (0.08 m) in the test zone. Given that there is significant damage to the borehole wall, it is not surprising that the number of major cracks predicted is variable (Fig. 29). It would be expected that the final crack pattern would be highly dependent on the particular damage field adjacent to the borehole, which depends on the particular loading parameters and material properties.

Each of the analyses for GT3 predicted a major vertical fracture and some short fractures adjacent to the borehole wall (Figs. 33-36). These results are not consistent with the experimental results that showed major fractures at 55° and 215° relative to the horizontal axis (Fig. 20).

The analyses for GT4, using the burn model, predicted one major vertical crack with the crack being longer in the analysis using red ash fall material properties (Figs. 37 and 38). For each material, the length of the vertical crack is approximately the same regardless of whether the burn model or the experimental pressure history was used for the analysis. When the experimental pressure history was used, a vertical crack was again predicted, but short cracks adjacent to the borehole also formed (Figs. 39 and 40). These predicted fractures are approximately the length of some of the observed ones (Fig. 24). It is interesting that the multiple fractures appeared only in the analyses using the experimental pressure record and that these cracks initiated after the second pressure peak in these analyses.

Figure 29. GT2 Final Predicted Fracture Using Red Ash Fall Tuff Properties

Figure 30. GT2 Final Predicted Fracture Using Peralkaline Tuff Properties.

Figure 31. GT2 Close-up of Borehole Showing Final Predicted Fracture Patterns Using Red Ash Fall Tuff Properties.

Figure 32. GT2 Close-up of Borehole Showing Predicted Fracture Patterns Using Peralkaline Tuff Properties.

Figure 33. GT3 Final Predicted Fracture Patterns Using Red Ash Fall Tuff Properties.

Figure 34. GT3 Final Predicted Fracture Patterns Using Peralkaline Tuff Properties.

Figure 35. GT3 Close-up of Borehole Showing Final Predicted Fracture Patterns Using Red Ash Fall Tuff Properties.

Figure 36. GT3 Close-up of Borehole Showing Final Predicted Fracture Patterns Using Peralkaline Tuff Properties.

Figure 37. GT4 Final Predicted Fracture Patterns Using Red Ash Fall Tuff Properties.

Figure 38. GT4 Final Predicted Fracture Patterns Using Peralkaline Tuff Properties

Figure 39. GT4 Close-up of Borehole Showing Final Predicted Fracture Patterns Using Red Ash Fall Tuff Properties.

Figure 40. GT4 Close-up of Borehole Showing Final Predicted Fracture Patterns Using Peralkaline Tuff Properties.

D. Discussion of Analysis Results

The pressure rates predicted by the burn model were within 60 percent of the experimental values for GT2 and GT4, and 360 percent for GT3. The reason for the better predictions for GT2 and GT4 is the fact that although the borehole diameter was the same for all of the tests, the canisters were larger for GT2 and GT4 (3.5-in OD); and there was less water in these tests, hence, any thermodynamic and hydrodynamic effects due to the water were probably minimized. For the cases in which there is relatively little water, the water can be represented, in the first order, as an incompressible material occupying volume.

Although the burn model underpredicted the peak pressures severely in GT2 and GT4, this did not affect the predicted final fracture patterns significantly. Higher peak pressures do, in general, produce longer fractures. In other words, according to the analyses, the pressure rate is the primary variable that determines the number of cracks that will form and the pressure peak governs the fracture lengths. The fracture lengths are not strong functions of the peak pressure, though. These analyses showed that doubling the peak pressures may produce only a small increase in fracture length.

The predicted fracture patterns were in qualitative agreement with the experimental results for GT2 and GT4, but did not predict the GT3 results well. Even the analyses using the experimental pressure history did not predict the major fracture that were at angles to the vertical direction in GT3. There is no good explanation in the framework of the present model for the observed lack of agreement.

The analyses using red ash fall and peralkaline material properties produced different, but not significantly different, results in that the fracture patterns for each material were similar. It was experimentally observed that the peralkaline material crushed significantly compared to the red ash fall tuff, although the analyses using peralkaline properties did not show significant crushing in GT3 and GT4. This suggested that the material properties used in the analyses may not be representative of the actual rock properties. This notion points to the possible large variability of peralkaline properties because the material properties used in the analyses were based on rock samples taken at GT2.

The elastic-plastic cracking material model, used for the analysis, appeared to do a good job in representing material crushing (in GT2) and in the overall fracture behavior. This is true in spite of possible shortcomings with possible finite element mesh dependencies.^{16.}

In general, the analyses yielded better results for water-filled borehole fracturing problems in which the propellant canister is relatively large compared to the borehole diameter. In this situation, the thermodynamic and hydrodynamic effects in the water are probably minimized and the propellant burn model can make reasonable pressure history predictions.

The model showed the sensitivity of fracture behavior to detailed structure of the pressure-time history. It did not predict fractures along apparent shear planes as observed experimentally (GT3). The only way the present model would produce fractures in the apparent shear plane directions is to impose a rotation on the in situ stress direction.

IV. Summary and Discussion

Experiments GT1-4 showed that fracturing behavior is considerably more complex in liquid-filled boreholes than in the liquid-free case. Specifically, in liquid-free boreholes, fracturing can be characterized simply in terms of a single pressure risetime and borehole diameter. Only one type of fracture behavior is seen in the test zone of the experiment borehole. For liquid-filled boreholes, all three types of fracture behavior can be seen in the same borehole--hydraulic, multiple, and explosive. This suggests the presence of much more severe pressure gradients along the borehole axis. The peak pressure measured is typically half or less of that obtained in liquid-free tests. End effects are much more pronounced for liquid-filled boreholes with extensive hydraulic fractures extending up to ten meters beyond the test zone. The character of fracturing in liquid-filled boreholes also differs in that major fractures occur at least as readily along principal shear planes as along hydraulic fracture planes. This has favorable implications for geothermal stimulation. In liquid-free boreholes, fractures occur preferentially along principal stress planes (parallel to the borehole): first, normal to the minimum principal stress, then normal to the maximum principal stress. Another effect of liquid is that it can exclude fracturing from parts of the borehole. For example, fracturing in GT4 was effectively excluded from the bottom half of the horizontal borehole. This would presumably not occur in vertical boreholes.

Despite the complexity of the test results, considerable insight was acquired on multiple fracturing in liquid-filled boreholes, the primary objective of the experiment program. Typically, multiple fracture initiation occurs when the pressure record shows the appropriate risetimes. However, the initiated fractures do not necessarily propagate. Elements of multiple fracture behavior were seen in all but the GT1 experiment where the energy release was apparently insufficient to produce either fracture initiation or extension. Yet, no complete multiple fracture pattern, such as shown in Fig. 5, occurred in any liquid-filled experiment. No major fractures occurred in directions perpendicular to the maximum principal stress (normal to the borehole) even though the fractures were initiated. The predominant multiple fractures were in principal shear planes and in the hydraulic fracture direction (normal to the minimum principal stress). Both fracture sets were of comparable length, indicating that both were equally favorable for fracture propagation.

Table V summarizes the predicted and measured pressure pulse behavior for experiments GT1-4. As is seen, the predicted behavior based on pipe test results did not reliably extrapolate to predict results in ash fall tuff. It is proposed that the reasons for this are (1) the extensive fractures at the ends of the boreholes in experiments GT2 and GT4, (2) the production of pressure waves in the water, and (3) early crushing of the boreholes in the experiments GT2 and GT4. The end effect fractures and the crushing would result in a decreased peak pressure. The pressure oscillations produce amplified, shorter risetime pressure spikes which appear to significantly affect fracture behavior; the amplitude and duration appear to determine the amount of contribution of a given spike.

Table V. Predicted and Measured Pressure Risetimes

<u>Experiment</u>	<u>Predicted Risetime (ms)</u>	<u>Measured Risetime (ms)</u>
GT1	1	0.2
GT2	0.7	0.3
GT3	1.2	0.03, 0.25, 1.9
GT4	0.5	0.07, 0.02, 1

In liquid-free boreholes, only a single component of the pressure pulse--the risetime to apparent fracture--was sufficient to characterize and predict fracture behavior. In liquid-filled boreholes, correlation with fracture behavior appears to be

better if one considers all features of the pressure record, including risetimes of both individual pressure spikes and the overall pressure pulse, and the amount of impulse contained in a given pulse element. This approach helps identify which elements of the pulse caused observed hydraulic, multiple, and explosive fracturing. The peak pressures observed were typically lower by up to a factor of two or three than would be expected for liquid-free boreholes. This implies that considerable energy is lost early in the borehole fracturing that is not lost in the liquid-free case. Possible loss mechanisms include energy used to produce the end fractures, energy dissipated in wellbore crushing (accompanied with a pressure decrease due to the attendant volume expansion), and energy converted into accelerating water out of the borehole into fractures. Energy loss due to heating water of generating steam does not appear to be significant. For the 3000K temperature of the combustion gases, the primary heat transfer mode is radiation. Simple calculations show that the amount of energy transfer in millisecond timeframes is only a few percent. A more detailed analysis of the pressure behavior and energy losses in liquid-filled borehole is given elsewhere.¹⁸

Pre- and post-test transmissivity measurements were used to evaluate the extent of fracture systems produced. Transmissivity increases by factors of 4 to 400 were observed for the four experiments. However, quantitative comparisons aren't warranted due to the complex fracture behavior observed, particularly the end effects seen outside of the test zone.

The more complicated behavior of HEGF in liquid-filled, open boreholes limits current application in geothermal and other liquid-filled well stimulations. More research is clearly required, particularly for full borehole sized propellant charges where the objective is to obtain multiple fracturing and to maximize fracture length. Optimal multiple fracturing was not achieved in either GT2 or GT4, probably because of borehole crushing and the unexpectedly large end fractures. The end effects might be minimized by using 20- to 30-ft (6 - 9 m) long charges instead of the 4- to 8-ft (1.2 - 2.4 m) long canisters used to date. The borehole crushing may be initiated by pressure waves generated in the liquid, although the low modulus of the peralkaline tuff in GT2 and GT4 is believed to have been a factor. Pressure wave effects might be minimized by the addition of dispersive material to the liquid. Since no fractures occurred below the wellbore in GT4, experiments are desirable in vertical boreholes, preferably with mineback. Finally, none of the experiments in liquid-filled boreholes were done in a naturally or prefractured test bed. Such tests need to be done to evaluate the effect of

natural fractures on fracturing in liquid-filled boreholes. Experiment GT3, which used a small diameter charge, performed much closer to predictions of the semiempirical model than the experiments using essentially full wellbore charges. Multiple fractures produced were comparable in length to those in GT4 without the presence of wellbore crushing. Thus, GT3 indicates feasibility for applications where wellbore cleanup is the primary objective to stimulating production.

The HEGF technique, as developed for liquid-free boreholes, should be directly applicable in dry steam geothermal reservoirs. However, for any geothermal application, the wellbore environment requires development of high temperature propellants and canister hardware or wellbore temperature control during stimulation.

Results of the present study which impact specifically on geothermal applications are:

- (1) Multiple fractures along hydraulic fracture directions and principal shear planes were created in water-filled boreholes.
- (2) Fractures along principal shear planes, such as those observed, would typically intersect natural fractures, thus increasing communication and flow to the wellbore.
- (3) Additional experiments are needed to develop better understanding and control of fracturing in liquid-filled boreholes--to optimize number of fractures and fracture length, and to study fracturing in a fractured formation.
- (4) The use of HEGF as small diameter charges in hot water wells for wellbore cleanup appears feasible from present experiments; its use as a primary fracturing technique needs further development.
- (5) The liquid-free wellbore HEGF technology should be directly applicable in dry steam wells.
- (6) Any application in geothermal wells requires development of high temperature propellants, initiators, and canister hardware or temperature control of wells during stimulation.

V. References

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APPENDIX A

Pipe Tests

APPENDIX A

Pipe Tests

A number of propellant burn tests in steel pipes were performed in parallel with the NTS GT test series. In these tests, PVC propellant canisters were initiated in steel pipes; the space between the canister and the pipe was filled with either air or water. The experiments were used to qualify canister designs for use in water-filled boreholes. The experiments tested various propellants and propellant mixtures both in air and in water. The objective was to design propellant canisters to achieve desired pressure risetimes for HEGF experiments at NTS.

A. Experiment Design

A typical schematic of the pipe test is shown in Figure A1. PVC propellant canisters 48-in (1.22 m) long with inside diameters ranging from 1.5 in to 3.2 in (0.04 m to 0.08 m) were used. The propellant canister consists of an outer PVC tube with co-axial RIP ignitor. Propellant filled the annular space between the PVC pipe wall and the RIP ignitor. An exploding bridge wire (EBW) next to one end of the RIP ignitor was used to initiate the RIP ignitor. Two different size RIP ignitors were used: 0.54-in (0.014 m) and 0.84-in (0.02 m) diameter.

The propellant canister was centered in an outer steel pipe. The ends of the pipe were closed with screw-on end caps. For most tests, 72-in (1.83 m) long, extra heavy-duty (XHD), schedule 160, 4-in (0.1 m) pipe was used, although three experiments used 60-in (1.52 m) long, schedule 80, 4-in (0.1 m) pipes. Typically the leads for the EBW initiator came through one end cap and the pressure transducer was installed in the opposite end cap. In some experiments, an additional pressure transducer was installed either at the initiator lead end or at mid-length of the pipe. Shown in Figure A2 is a 1-1/2-in (0.038 m) PVC propellant canister next to the XHD steel pipe. Note the small pipe stand flange at the end of the canister used to attach the propellant canister to the end cap. This arrangement permitted the canister to rotate with the end cap during assembly, thus preventing damage to the initiator lead wires.

Figure A1. Pipe Test Schematic.

Figure A2. 1-1/2-in canister next to XHD 4-in pipe.

B. Results

A summary of all the pipe tests is given in Table A1. Test conditions as well as pressure risetimes are listed. The standard position, A, for the pressure transducer was at the end opposite to the initiator leads. Risetimes corresponding to other positions are denoted by a letter following the values given. Letter B corresponds to the end cap with the initiator leads and C corresponds to transducers installed through the pipe wall at mid-length. Column P indicates the pressure at which the risetime is calculated. The annulus column indicates whether the space between the pipe and the canister is occupied by air or water. The additional designation "air/water" denotes cases when there is an air cushion outside the canisters. The air cushion is formed by the use of an intermediate, larger diameter, PVC pipe outside the propellant canister.

The results of the tests are discussed in terms of the pressure risetime observed. An examination of the risetimes presented in Table A1 and of the pressure records indicates that within one experiment, risetimes measured at different locations can be quite different. While some of the discrepancies could be assigned to peculiarities in an experiment (such as debris blocking or restricting access to a transducer), there are real differences.

As a result of the compressibility of the water, changes of pressure do not take place instantaneously throughout the pipe but are propagated by pressure waves.^{1A} Pressure wave effects for air-filled, long cylindrical vessels have been documented in the ballistics literature.^{2A} Typically, the time scale involved is of the order of ℓ/c where ℓ is a characteristic length of the system and c the velocity of sound. Using a value of $\ell = 0.20$ m as a typical dimension and $c = 1500$ m/s, the characteristic time is calculated to be 0.13 ms. This time scale is of the same order of magnitude as the risetime of some of the pressure pulses.

Such pressure wave effects are believed to account for differences in pressure histories observed at different locations as well as shot-to-shot differences for similar configurations. How the pipe deforms and fractures (Fig. A3) is an additional factor affecting pressure behavior. The results of these experiments show that there is considerable variation in failure pressure and degree of

Table A1. Summary of Pipe Tests

TEST	CANISTER SIZE (in)	PROPELLANT	MASS (g)	RIP SIZE (in)	ANNULUS	P(psi)	RISETIME (ms) MEASURED AT *		
							A	B	C
P1, 1-18/1	1-1/4	M5B	1231	EBW	AIR ¹	12000	11.40		
P2, 1-18/2	1-1/2	M5B	1231	0.84	AIR ¹	12000	5.40		
P3, 1-13/1	3	M5B	6200	0.84	AIR	20000	0.75		
P4, 1-13/2	3	M5B	6200	0.84	WATER	20000	0.14		
P5, 2-13/1	1-1/2	M5B	1231	0.84	WATER	20000	0.22		
P6, 2-13/2	1-1/2	M5B	1231	0.84	WATER/AIR ²	16000	0.40		
P7, 2-14/1	3	M30B	5860	0.84	WATER	20000	1.10		
P8, 2-21/1	3	M30A	5860	0.84	WATER	20000	0.23		
P9, 2-21/2	1-1/2	M5B	1231	0.54	AIR ¹	12000	5.70		
P10, 3-6/1	3	44M30A/56M30B	2578/3282	0.84	WATER	20000	0.42		
P11, 3-6/2	1-1/2	M30A	1231	0.84	WATER/AIR ³	20000	3.00		3.90
P12, 3-13/1	1-1/2	M30A	1430	0.54	WATER	17500	1.25	2.30	
P13, 3-13/2	1-1/2	12.6M5B/87.4M30B	246/1704	0.54	WATER	17500	2.10	2.40	
P14, 3-21/1	2-1/2	12.6M5B/87.4M30B	369/2556	0.54	WATER	17500	2.10	2.20	

(1) Schedule 80 4-in pipe, 60 in long; all other tests used XHD 4-in pipe, 72 in long.

(2) 3-in PVC pipe air cushion around 1-1/2-in canister; defective XHD, 4-in pipe.

(3) 2-1/2-in PVC pipe air cushion around 1-1/2-in canister.

*(A) transducer opposite the ignitor lead end

(B) transducer at the ignitor lead end

(C) transducer at mid-length of the pipe

	ID(in)	OD(in)
PVC pipe sizes:		
1-1/4 in	1.53	1.66
1-1/2 in	1.75	1.90
2-1/2 in	2.88	2.45
3 in	3.23	3.50
Steel pipe Sizes:		
Schedule 80, 4 in	3.83	4.50
Schedule 160, XHD, 4 in	4.06	5.56

Figure A3. XHD 4-in pipe after test. Note deformation near the ends.

deformation and fracturing. To eliminate these variables as much as possible, the risetime to 20,000 psi (140 MPa) before pipe failure was taken, where possible, as the reference for comparing experiments. This pressure level is also in the range at which brittle, nondeforming fracture occurs in wellbores at NTS. When the peak pressure for some experiments in a set is less than 20,000 psi, a common maximum pressure for the set of experiments is used to facilitate comparisons.

Because of the aforementioned reasons, the use of single risetimes to characterize a pressure-time history, while convenient, does not fully describe the pipe tests. While there is no ambiguity in applying the risetime concept to a simple pressure history, the use of a single risetime only affords an approximate description of the more complicated pressure histories observed.

The results of the experiments are presented in terms of the issues addressed.

(1) The Effect of Initiation Method on Risetime

This set of experiments consisted of tests P1, P2, and P9. All tests used 1231 g of M5B propellant. The canister for test P1 was 1-1/4-in (0.03 m) PVC. The canisters for test P2 and P9 were of 1-1/2-in (0.04 m) PVC tubing. The outer steel pipe was 60-in long (1.52 m) schedule 80, 4-in (0.1 m) pipe. The annulus between the canister and the pipe was air filled for all three experiments. The initiation system for test P1 consisted of three EBW initiators emplaced in the propellant and each surrounded by approximately 6 g of black powder. Test P2 used a 0.84-in (0.02 m) RIP ignitor and Test P9 a 0.54-in (0.014 m) RIP ignitor. The pressure time histories of the tests are shown in Figs. A4 and A5. The pressure rise curves of the two RIP ignitor initiated tests are essentially the same, and the risetimes to 12,000 psi (83 MPa) just before failure were nearly identical. The black powder-initiated burn showed a much longer risetime--11.4 ms. However, it is interesting to note that the major difference between P1 and set [P2, P9] is mainly in the initial part of the burn (Fig. A4).

(2) Comparison of Risetime for Air-Filled and Water-Filled Pipes

Two sets of experiments were performed. Each set included two experiments using identical canisters, one air filled and one water filled.

Figure A4. Test P1 (EBW) and Test P2 (Large Rip, Air)

Figure A5. Test P9 (Small Rip)

The first set consisted of tests P3 and P4. Both used a 3-in (0.08 m) PVC canister filled with 6200 g of M5B propellant. The outer pipe was a 72-in (1.83 m) long XHD schedule 160, 4-in (0.1 m) pipe. Test P3 was air filled and test P4 was water filled. For the second set, P2 and P5, the propellant canister was made of 1-1/2-in (0.04 m) PVC filled with 1231 g of M5B propellant. The outer pipe was again XHD 4-in (0.1 m) pipe. Test P2 was air filled and P5 was water filled. The 0.84-in (0.02 m) ignitor was used for both sets of experiments.

The increase in pressure in a pipe (or borehole) is the result of gas generation in a confined volume. Since water is much less compressible than air, a major effect of filling a pipe with water is to reduce the free (air) volume available for the gas generated during the burning of the propellant. Therefore, one would expect that a water-filled borehole would result in a faster risetime. This is shown to be qualitatively correct by comparing Tests P3 with P4 (Figures A6, A7) and Tests P2 and P5 (Figures A4 and A8).

If the free volumes are assumed not to be functions of time, it can be shown that the risetimes t_1 and t_2 corresponding to two boreholes (pipes) with free volumes respectively of V_1 and V_2 are related through the approximate relation.^{3A}

$$\frac{t_1}{t_2} = \frac{V_1}{V_2} \quad (\text{A.1})$$

The assumption of constant free volume is not strictly true. Compressibility of water nearly doubles the free volume in the 1-1/2-in (0.04 m) canister. Deformation of the pipe can also increase the free volume in some experiments.

The predicted risetime is the risetime calculated for water-filled pipe based on the risetime measured in air (t_1 or reference) using Eq. (A.1). The results are shown in Table A2. For the 3-in (0.08 m) canister, the agreement is quite good and for the 1-1/2-in (0.04 m) canister, the prediction (0.4 ms) is within the range of the measured risetimes (0.16, 0.5 ms).

Figure A6. Test P3 (3-in Canister, Air)

Figure A7. Test P4 (3-in Canister, Water)

Figure A8. Test P5 (1-1/2 in, Canister, Water)

Table A2. Comparison of Risetimes in Air-Filled and Water-Filled Pipes

Test	Canister Size (in)	Free Volume (in ³) (m ³)	Risetime (ms) at	Predicted Risetime (ms)
P3, Air	3	651 (.0167)	0.75 A	Reference
P4, Water	3	132 (.0022)	0.14 A	0.15
P2, Air	1-1/2	580 (.0095)	5.4 A	Reference
P5, Water	1-1/2	44 (.0007)	0.16 A	0.4
			0.5 C	

(3) The Use of an Air Cushion to Modify Pressure Risetime

The approach here was to provide additional air space (cushion) around a canister to achieve a pressure risetime in between that of the water-filled and air-filled cases. The air cushion was formed by enclosing the propellant canister in a PVC pipe of larger diameter. The annular space between the two pipes formed

the air cushion. This concept was evaluated using two sets of experiments: [P2, P5, P6] with M5B propellant, and [P12, P11] with M30A propellant. Experiments P2 and P5 are described in previous sections, P6 is identical to P5 except the canister was enclosed in a 3-in (0.08 m) PVC pipe; the air cushion was an annulus between a 3.2-in (0.082 m) ID outer pipe and a 1.9-in (0.05 m) OD canister. P12 used a 1-1/2-in (0.04 m) PVC propellant canister with 1470 g of M30A propellant and a 0.54-in (0.014 m) diameter RIP ignitor. P12 was water filled. P11 was of identical design, but the canister was enclosed in a 2-1/2-in (0.06 m) PVC pipe. Both sets of experiments were in XHD 4-in (0.1 m) pipes. Pressure histories for tests P6, P11, P12 are shown in Figures A9-A11, respectively. Test results are summarized in Table A3:

Table A3. Effect of an Air Cushion on Risetime

Test	Propellant	Free Volume (in ³) (m ³)	Risetime (ms) at	Predicted Risetime (ms)
P2 Air	M5B	5008 (.0082)	5.4 A	Reference
P5 Water	M5B	447 (.0007)	0.22 A	0.4
			0.5 C	
P6 Air/Water	M5B	294 (.0048)	0.4 A	2.7
P12 Water	M30A	52 (.0009)	1.25 A	Reference
			2.3 B	Reference
P11 Air/Water	M30A	128 (.0021)	3.0 A	3.1
			3.9 C	5.7*

*Calculation based on measurement at (B) (2.3 ms)

There is reasonable agreement between experiments P12 and P11 through the volume ratio relation. But the set [P2, P5, P6] shows no consistency. Part of the reason might be due to the fact that the steel pipe for P6 was defective, resulting in premature failure. Instead of the usual end cap thread failure, the pipe for P6 fractured lengthwise. Despite the lack of consistency in set [P2, P5, P6], the two sets of experiments do demonstrate the usefulness of air cushion to reduce risetime.

(4) Propellant Mixing Law for M30A and M30B Mixtures

The M5B propellant appears to give risetimes that were too short to achieve risetimes corresponding to the multiple fracture regime both in water-filled pipes and at NTS in water-filled boreholes. A slower burning propellant, M30, was thus introduced. Two sizes of M30 were obtained--M30A and M30B--described in

Figure A9. Test P6 (1-1/2-in canister, with 3-in outer pipe to form air cushion).

Figure A10. Test P11 (1-1/2-in canister with 2-1/2-in outer pipe to form air cushion).

Figure A11. Test P12 (1-1/2 in canister, water)

Table 1 of main text. M30A is faster burning. A set of three water-filled experiments [P7, P8, P10] were conducted using the new propellant. Identical 3-in (0.08 m) PVC canisters with 0.84-in (0.021 m) RIP ignitor in XHD schedule 160, 4-in (0.10 m) steel pipes were used. M30B was used in P7, M30A in P8 and a 44% M30A/56% M30B mixture (by weight) in P10. The pressure histories for P7, P8 and P10 are shown in Figures A12, A13, and A14, respectively. The risetimes are summarized in Table A4:

Table A4. Risetimes for M30 Propellants and Mixtures

<u>Test</u>	<u>Canister (in)</u>	<u>Propellant</u>	<u>Risetime (ms) at</u>	
P7, Water	3	M30B	1.1	A
P8, Water	3	M30A	0.23	A
P10, Water	3	44M30A/56M30B	0.42	A

The mixing law for the propellants is given in Eq. (2) of the main text. For M5 propellant, the constant C was found to be 2.0. Using data obtained in the present set of experiments, C was also found to be 2.0 for M30 propellants. Since the mixing laws are the same, it also becomes possible to mix M30 and M5 propellants with predictable results.

(5) Effect of Canister Size on Risetime for Identical Propellant Mixtures

Two canisters, both with 12.6% M5B and 87.4% M30B (by weight), were tested in water-filled pipes. Test P13 used a 1-1/2-in (0.04 m) canister with a total of 1950 g of propellant; test P14 used a 2-1/2-in (0.06 m) canister with 2925 g of propellant. The steel pipes were 4-in (0.1 m) XHD schedule 160. The ignitors were 0.54-in (0.014 m) diameter. The pressure histories of P13 and P14 are shown in Figures A15 and A16, respectively. The resulting risetimes were nearly identical as shown in Table A5.

Table A5. Effect of Canister Size
(12.6% M5B and 87.4% M30B)

<u>Test</u>	<u>Canister Size (in)</u>	<u>Risetime (ms) at</u>	
P13, water	1-1/2	2.2	A
		2.3	B
P14, water	2-1/2	2.1	A
		2.2	B

Figure A12. Test P7 (M30B)

Figure A13. Test P8 (M30A)

Figure A14. Test P10 (44% M30A/56% M30B)

Figure A15. Test P13 (1-1/2 in canister)

Figure A16. Test P14 (2-1/2-in canister)

A comparison of the two sets of pressure histories is shown in Figure A17. This similarity is somewhat unexpected, since previous experiments indicate that there should be a canister size effect (see Figure 4, main text). However, the sizes of the canisters are probably not sufficiently different to show the effect.

C. Summary

The present series of tests resulted in pressure risetimes in the 0.1 ms to 4 ms range in water-filled pipes. This range of risetime spans the values required for HEGF applications in most geologic media of interest.

The pressure histories observed in water are more complicated than those observed in air (in previous and present experiments) due to pressure transient effects. To fully understand the pipe test, a much more detailed analysis coupling the burning of the propellant with hydrodynamic effects and deformation of the pipe is required. A much larger number of tests would also be needed. However, it appears that the main effect of water is to deplete the free volume and to increase the rate of pressure rise. Extrapolation of data using the free volume concept does give results in the correct range, and the pipe test results provide an empirical basis for design of experiments in water-filled boreholes.

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Figure A17. Comparison of Tests P13 and P14

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