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IN SITU EVALUATION OF SEVERAL TAILORED-PULSE WELL-SHOOTING CONCEPTS

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ABSTRACT

Dynamic stimulation techniques that produce multiple fracturing in a wellbore are being investigated for enhanced gas recovery. Multiple fracturing appears to be especially promising for stimulating naturally-fractured reservoirs, such as the Devonian shales, since this may be the most effective technique for connecting a wellbore to a pre-existing fracture network. Previous studies have demonstrated that detrimental effects can occur with high-strength explosive techniques and that these effects can be avoided through the use of propellants.[1,2] The use of propellants and other so-called tailored-pulse techniques depend on a controlled pressure-time behavior to minimize wellbore damage and maximize fracture growth by gas penetration.

This paper describes a series of five full-scale tests performed to evaluate various multi-frac concepts. The tests were conducted at the Nevada Test Site in cased, horizontal boreholes drilled in ash-fall tuff from a tunnel under 430 m of overburden. This site provides both realistic in situ conditions for the tests and access to the stimulated regions by mineback which permits direct observation of results. The five tailored-pulse concepts tested involve:

Case A - a decoupled explosive,[3]
Case B - a decoupled explosive with propellant booster,[3]
Case C - a small-diameter propellant charge with pressurized water pad,[4]
Case D - three successive shots of Case C, and
Case E - a full-diameter charge of a progressively-burning propellant.[2]

While direct observation by mineback is highly beneficial, evaluation and analysis of these test results also depended heavily on other diagnostics. Thirty-six stressmeters and accelerometers were fielded in the surrounding rock to record the dynamic disturbances, and each borehole contained transducers to measure the actual cavity pressures. Pre-test and post-test evaluations include TV log, caliper log, and permeability measurements. Permeability, which evaluates the effectiveness of the created fracture network to transmit fluids, was determined by analysis of constant-pressure, water-injection tests and the subsequent pressure decline after shut-in.

Results show a large increase in formation permeability for Case E, modest increases for Cases B, C, and D and a decrease for Case A that appears due to the formation of a stress cage. A comparison of Case E results with previous tests suggests a multiple fracture criterion based on pressure rate with little effect of peak pressures.

INTRODUCTION

Oil and gas wells have been stimulated with high-energy explosives since the late 1800's. It appears, however, that the term "well shooting" originated many years before this in days when a water well was sometimes rejuvenated by shooting a rifle down the well. Well shooting as discussed herein refers to any rapid release of energy from a chemical reaction in a wellbore for the purpose of stimulating production, presumably by fracturing the reservoir rock. This includes explosives (solid, liquid, and gas) and propellants that deflagrate rather than explode. In a broad sense, well shooting has been applied in several geotechnical fields; e.g., preparation of oil shale beds for true in situ processing, preparation of underground mineral deposits for solution mining, etc.

Problems of wellbore damage, safety hazards, and upredictable results have

References and illustrations at end of paper.

reduced the relative number of wells stimulated by high-strength explosives. In recent years hydraulic fracturing has been favored, and sophisticated techniques, equipment, fracturing fluids, and proppant have been developed to optimize the hydraulic fracturing process.

Unfortunately, similar efforts toward general understanding and process optimization have been lacking for well shooting. However, recent findings (summarized in Ref. 1) have shed new light on the process of dynamic wellbore fracturing. These findings indicate that vast improvements may be possible using "tailored-pulse" loading techniques.

Tailored-pulse loading involves using propellants, decoupled explosives, or explosive gases to produce a controlled, but rapid, release of energy. This concept is more fully described in a later section, but first the general behavior and limitations of conventional well shooting with high-strength explosives need to be described to understand better the benefits derived from tailored-pulse loading.

GENERAL BEHAVIOR OF A DEEPLY-BURIED CHARGE

One important aspect common to most well shooting configurations is the fact that there is no free surface near enough to the charge to affect the behavior. The phenomena associated with deeply-buried charges, as they are called, differ significantly from those of blasts that occur near a free surface as in excavations, quarries, and road cuts.

Briefly, the high pressures of a detonation in a wellbore are known to be sufficient to cause the nearby rock to yield and compact (plastic flow). When the stress wave passes, the rock unloads elastically leaving an increased borehole diameter and a residual stress field which is compressive near the wellbore. Figure 1 depicts these general steps that take place during such an event.

The creation of this residual stress field is closely analogous to the process of autofrettage or the "gun barrel problem" in which pressure vessels are often overpressurized sufficiently to yield the inside wall and develop residual compressive stresses that help prevent crack growth during service. The zone of highly compacted rock with its associated residual compressive stresses is sometimes referred to as a stress cage, and the phenomena is sometimes called the bladder effect. Fracturing caused by high pressure gas may also be inhibited in this situation since fines are created during the compaction process that can plug newly formed cracks and prevent gas penetration. Some or all of these effects may actually cause decreased permeability near the wellbore and are probably responsible for many well-shooting failures.

The existence of residual stress regions around boreholes that have been subjected to explosive detonations is a well documented phenomenon. Most of these observations have been made with regard to field experiments at the Nevada Test Site[1,5] as well as laboratory experiments[6] and computer code calculations[1,5,7] for the purpose of understanding containment of underground nuclear blasts. This general behavior of a deeply-buried charge, however, is rather universal since it has been demonstrated to occur for detonations ranging from a one pound charge of TNT to a nuclear detonation of several kilotons. Further description of these general phenomena and details of the supporting evidence can be found in Ref. 1.

TAILORED-PULSE LOADING

ADVANTAGES

With the basic knowledge that the bladder effect impedes fracture growth near an explosively loaded cavity, one might wonder how conventional well shooting would ever enhance production. Experience has shown, however, that improved production is sometimes realized. There are several reasons for such results, including the possibility that explosive stimulation may at times be capable of removing skin damage, and that leakage paths may be formed that connect the cavity to the region outside the stress cage. Situations can also occur in which the stress cage will break up and slough into the wellbore. These possibilities are not necessarily predictable or applicable in all formations. It would, of course, be desirable if reliable procedures could be developed to replace conventional well shooting.

Several viable alternatives to explosive well shooting have been considered and tested in recent years that show promise of substantial improvement.[2-4] An approach that has received considerable attention is to tailor the pressure-time behavior of the explosive or a suitable propellant so as to keep the maximum pressure and the loading rate below a level that would cause the rock to crush and undergo plastic flow. The intent here is to avoid entirely the formation of a stress cage while still loading at a sufficiently high rate to produce multiple fractures from the wellbore. Unfortunately, the proper combination of loading parameters that will produce optimal multiple fracturing and avoid the formation of a stress cage are not, as yet, well known.

Tailored-pulse loading of a wellbore has several advantages over hydraulic fracturing that make this technique attractive in certain situations. For example, hydraulic fractures, which are propagated at pressures that are slightly higher than the minimum in situ stress and pumping times that are on the order of hundreds of seconds, typically produce only a single fracture whose orientation is perpendicular to the minimum principal stress.[8,9] Higher wellbore pressures, such as are achieved in tailored-pulse loading, are needed to drive cracks in less favorable directions with respect to the in situ stresses in order to produce multiple fractures.

Multiple fractures may be highly desirable in naturally fractured reservoirs such as Devonian shale for reasons depicted in Figure 2. The production from an unstimulated well, Figure 2a, depends strongly on the number of fractures intersected. Hydraulic fracturing typically produces a single fracture that is likely to run parallel to most of the existing fractures, Figure 2b, since its orientation is governed by in situ stresses that probably also govern the pattern of the natural fractures. Multiple fractures may not extend as far as a hydraulic fracture but may link the well to more, natural fractures, Figure 2c.

In addition, tailored-pulse loading with propellants are likely to produce little formation damage due to the interaction of fluids with the rock. Very little water is produced by these materials, and the products have very little time to react with the rock. Some hydraulic fracturing fluids, on the other hand, are known to cause swelling in shale and other deleterious effects.

Cost is also a factor that may make tailored-pulse techniques very attractive, particularly in marginal wells that probably are not promising enough for expensive hydraulic fracturing treatments. Igniting an explosive or a propellant charge in a well requires very little equipment or time when compared to even a small hydraulic fracture job.

CONCEPTS

Several tailored-pulse concepts rely on the use of propellants which deflagrate rather than detonate. Unlike explosives, the burn front in these materials travels slower than the sound speed, and the burning rate can be varied over a wide range. Pressure-time behavior of propellants differ from explosives in that peak pressures are lower, and burn times are longer. Total energy available, however, is similar in both materials (typically 4kJ/g).

One of the first tailored-pulse concepts investigated was a decoupled explosive such as that used for Case A.[3] A conventional explosive is used, but the charge diameter is some eight times less than the wellbore diameter. The charge is surrounded by water, and the peak pressure reaching the rock after detonation is thus mitigated, presumably to a value below the yield stress. The total explosive energy, however, is limited by the small diameter of the charge.

The concept employed in Case B uses the same decoupled explosive in conjunction with a small propellant charge.[3] The decoupled explosive is designed to initiate multiple cracks and the propellant is then burned to drive water into these cracks to extend them. The propellant is essentially a rocket motor that burns for several seconds. Some field testing has been performed using this device but results are inconclusive.

Case C is a small diameter (4cm) pressure-insensitive propellant charge that is designed both to initiate and propagate multiple cracks.[4] A typical rise time is 3 ms with a burn time of 0.5 s. This device is also designed to push water into the cracks ahead of the gas generated by the propellant reaction products. It has been used in the field as a cleaning tool and as a fracture initiating device to reduce the breakdown pressure for hydraulic fracturing. The number and size of the fractures created by this tool are largely unknown. Case D was three successive shots using the same configuration as Case C.

Case E consists of a gas-producing, progressively-burning propellant with a suitable rise time to initiate and propagate multiple fractures while avoiding the damage of a stress cage.[2,10] This concept differs from the others in three main areas: 1) A full-diameter charge is used that fills the wellbore to maximize the energy released. 2) Lightweight gas products from the propellant itself, rather than water, are pushed into the created fractures. This maximizes the speed in which fractures are penetrated and pressure loaded. 3) The propellant is of the progressively-burning type in that the burning rate increases as material is consumed. This allows energy to be saved and not released until it is most needed, later in time, when fractures are long and system volume is large.

MULTI-FRAC TEST SERIES

FEASIBILITY STUDY

Experiments to investigate tailored-pulse concepts have been conducted in a tunnel complex at the Nevada Test Site. The tunnel facility provides a means of performing realistic tests of deeply-buried charges in rock formations at depth and yet allows for direct observation of resulting fracture behavior by mining back to uncover the test bed itself. The purpose of this test series is two-fold: (1) evaluate and compare several tailored-pulse concepts in a controlled test bed to determine the ability of each to produce multiple fractures and to enhance formation permeability and (2) provide data for testing and verification of various modeling schemes presently being used to describe the complex behavior of tailored-pulse loading.

The feasibility of performing such experiments was demonstrated previously in a test series conducted on Gas Frac.[2] Three canisters, each containing propellant with markedly different burning rates, were ignited in grouted horizontal holes drilled in a water-saturated ash-fall tuff formation. The results of the three tests showed phenomenologically different behavior as depicted in Figure 3. The slowest-burning propellant created a single fracture similar to a hydraulic fracture, the intermediate-rate propellant produced extensive multiple fractures, and the fast-burning propellant produced explosive-type behavior as evidenced by an enlarged borehole and minimal fracturing.

TEST SETUP

The previous Gas Frac tests were not instrumented except for a pressure transducer to measure dynamic cavity pressures. The five tests described below make up the so-called Multi-Frac Test Series and involved thirty-six stressmeters and accelerometers to measure rock formation response as well as pressure transducers to record dynamic cavity pressures. Along with direct observation by mineback, post-test evaluation included a reentry into each test zone for borehole television log, caliper log, and permeability measurements. The caliper log is intended to detect the degree of borehole enlargement (indicating plastic flow) and the permeability test is designed to measure the effectiveness of each test to increase the formation's ability to transmit fluids (i.e., conductivity of fracture network). The rock formation is a water-saturated ash-fall tuff having material properties as listed in Table 1.

The experiments were all conducted in 15 cm diameter, nearly horizontal holes drilled 12.2 m deep from a tunnel drift as depicted in Figure 4. The holes were spaced 6.1 m apart. Experiments A and B were conducted with 3.05 m of open hole and 9.15 m of casing while Experiments C, D, and E had 6.1 m of open hole and 6.1 m of casing. The mineback (not completed as of this writing) is planned so that half of each test zone will be mined out and examined thoroughly, leaving any fracture patterns occurring at the midpoint displayed on the right rib of the tunnel (Figure 4). All test setups were similar and a cross-section of the Case B configuration is seen in Figure 5.

Rock mass instrumentation consisted of an array of stressmeters and accelerometers as depicted in Figure 6. This array of gages was fielded only for Experiments B, D, and E. The stressmeters were special, strain-gaged, borehole-inclusion stressmeters.[11] Two of these transducers were set and preloaded in each instrumentation hole to measure diameteral deformations in the radial and transverse directions. Calibration of these gages was accomplished by static loading of a block of ash-fall tuff that contained a gage mounted in a hole drilled in the sample. Commercially available accelerometers were also set and preloaded in a similar fashion to measure radial and transverse accelerations. (Note that transverse accelerations would not be expected in a symmetric displacement field but could result from motions due to the dynamic propagation of a nearby crack.)

SPECIFIC TEST CONFIGURATIONS

The device fielded in Experiment A was simply a 2 cm diameter by 3 m long PVC tube filled with 2.3 kg of Comp C4 explosive. This was centralized in the hole and the cavity filled with water under atmospheric pressure. The water contained a blue dye to stain the created fractures and to ease identification and mapping during mineback. Dynamic cavity pressure was measured in this experiment using both Kulite* sensors and specially designed ytterbium paddle gages[12] located near the end of the casing section (Figure 5). The Kulite gage model HKM-375, is a piezoresistive integrated sensor. This gage has a 200 MPa pressure range and consists of a miniature silicon member on which a temperature compensated wheatstone bridge is atomically bonded. The miniaturization results in a natural frequency of 400 kHz.

Experiment B involved the same Comp C4 explosive setup but also contained a 2.7 kg charge of propellant. This relatively slow-burning propellant charge consisted of a single, internal-star rocket grain ignited with a black-powder-filled spit tube and housed in a sealed aluminuim canister. The canister was located in the casing section against the bulkhead and was designed to act as a dynamic plunger to push the dyed water down the casing and into fractures initiated by the explosive charge. The fire set was designed to ignite the propellant charge first and then to detonate the explosive 70 msec later by which time the propellant would have reached sufficient pressure. Transducers fielded in this experiment to measure the dynamic cavity pressure event included Kulite and ytterbium gages at the end of the casing section and a fluid-coupled-plate gage[13] located at the bulkhead near the propellant canister. The sensing element used in the fluid-coupled-plate transducer is the same Kulite gage mentioned previously.

The device used for Experiments C and D consisted of a 2 cm diameter by 6.1 m long soft aluminum tube filled with 2.3 kg of propellant which was ignited at one end. The device was centralized in the test hole and the cavity filled with dyed water. The water was pressurized statically to 3.4 MPa using a hydraulic pump just prior to these shots in order to simulate the containment from a 300 m column of water. Dynamic cavity pressure was measured in each of these shots by means of Kulite gages located near the end of the casing section.

The device fielded in Experiment E included a number of design improvements over the previous configuration.[2] The device (Figure 7) consisted of six canisters, each 12.7 cm diameter by 1 m long that screwed together. The canisters were made of perforated plastic tubes with a heat-shrinkable vinyl covering to make the unit watertight. Each canister contained 9.1 kg of M5 multi-perf propellant grains with a 1 mm web thickness. This propellant was ignited by means of a 3.2 cm diameter perforated-steel primer tube that runs through the center of each canister and becomes a continuous igniter when the units are screwed together. The

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*Kulite Semiconductor Products, Inc., Ridgefield, NJ.

primer tube contained an explosive and igniter which provided ignition along the entire 6 meter length in less than 1 msec. The primer tube itself was initiated with an exploding bridge wire device as were all other experiments.

Since the propellant burns cleanly, several bags containing carbon black were taped to the outside of the canisters (Figure 7) to act as crack markers so that the created fractures would be more visible during mineback. Also, a number of 1.3 cm diameter ceramic spheres and 0.6 cm diameter cylinders were taped to this device in hopes that they would be propelled into the fractures and thereby act as dynamic crack width indicators when located during mineback. (These spheres and cylinders were used in the other experiments as well.) The assembly was placed in the dry 6.1 meter test section and sealed with a grout plug. The opposite end of the test zone contained a fluid-coupled plate transducer to measure dynamic cavity pressure.

Estimates of the grout-to-casing and grout-to-rock shear strength indicated that sufficient load-carrying capacity was available to contain these shots (refer to Figure 5). However, a strong-back brace was added as a backup measure (Figure 8). The brace was designed to transmit the load from the casing and bulkhead to the opposite tunnel rib if complete containment was not achieved. All shots were fired remotely and were monitored by close-circuit television.

All shots were fired using a capacitive discharge unit which dumps to an exploding bridge wire. Data was recorded in a separate instrumentation trailer using a 50 kHz analog system with voltage-controlled-oscillator and multiplexer. The analog data was recorded on magnetic tape and later digitized, reduced, and plotted.

RESULTS AND DISCUSSION

Note: Reduction and analysis of the test data and mineback evaluation were not complete at the deadline of this paper. Thus, the results and conclusions presented here are preliminary.

All shots were fired successfully except Experiment B. On that test, the propellant charge was ignited as planned. After a 70 msec delay, a signal was sent to the explosive charge, but detonation did not occur. Post-shot evaluation disclosed that the exploding bridge wire was intact, but that the detonation cables had been severed in two places by the propellant charge, preventing the bridge from receiving the impulse required.

Pressure-time and stress-time records from Experiment D are displayed in Figure 9. The stress-time behavior is for radial and transverse stress at a location 1 m from the test section. Note that the presure-time record shows a second pressure peak that occurs 9 msec after the first. This corresponds to the transit time of the stress pulse propagating from the gage to the steel bulkhead and back. This second pulse is also observed in the stress records.

Peak borehole pressure is seen to be 46 MPa. If this pressure were assumed constant and confined to the borehole, a 0.32 MPa stress would be expected at the 1 m stressmeters (with radial stress being compressive and tangential being tension). Peak stresses, however, were much higher: 1.06 MPa tangential tension and 2.16 MPa radial compression. Wave-code analysis indicates that little dynamic effect is present in this rate regime. Note that the tangential and radial stress become nearly equal in magnitude at late times as expected from quasi-static analysis. The discrepancy is likely due, instead, to pressure escaping from the borehole and loading the created fractures, thereby strongly affecting the loading configuration.

Preliminary results of stressmeter data from Experiment E indicate that stresses were more than 10 times larger than calculated from assumptions of a static borehole pressure. This discrepancy must be a result of substantial gas penetration into fractures and is consistent with observations of extensive fracturing detected in this experiment as discussed later.

A pre-test and post-test evaluation of in situ permeability was made for each test to indicate the capability of each device to increase the formation's ability to transmit fluids. Since this water-saturated ash-fall tuff formation has no "reservoir" pressure, *per se*, measurements were made by pressurizing each zone with water at a constant pressure of 2.8 MPa and recording the decay of flow with time. The flow rate data could then be fit to give the appropriate parameters which characterize the porous media and boundary conditions. However, since flowing time was always greater than a few minutes, the analysis was greatly simplified by an approximate logarithmic equation. The inverse of the flow rate (1/q) is plotted against the logarithm of time, and the permeability is determined from the slope of this line by

$$K = \frac{(185.7)\mu}{H(P_o - P_\infty)m}$$

where

K is permeability in md
μ is viscosity in kPa·s
H is zone length in m,
$P_o - P_\infty$ is injection over-pressure in kPa, and
m is slope in $(cm^3/sec)^{-1}$/cycle

An example of this measurement scheme is displayed in Figure 10. The pressure decay after shut-in was also analyzed in a manner similar to that for a standard pressure buildup record in a gas well.

Results of the pre-test and post-test permeability measurements are presented in Table 2. Each value of permeability is the average of the flow test and the shut-in. A large permeability enhancement is seen for Experiment E which is a clear indication of extensive fracturing. Experiments B, C, and D display a moderate increase in permeability. Experiment A, however, produced a decrease in formation permeability. This is apparently due to the creation of a stress cage (the bladder effect) even though the explosive was "decoupled" from the formation by an 8 to 1 ratio of hole diameter to charge diameter.

These observations are consistent with post-test TV logs. Several, wide radial fractures were seen in the log of Experiment E, and a few narrow fractures were seen in C and D. While no fractures were seen in the log of Experiment B, a single hydraulic-type fracture is expected here due to the very low pressure-loading rate of the propellant used. The presumption of a stress cage in Experiment A was confirmed in the TV log by the observation of an enlarged, distorted borehole with no apparent fractures.

Closed circuit television of Experiment E also showed indications of extensive fracturing. Shortly after ignition, a gas-driven fracture apparently reached an instrumentation hole located 2 m from the test section, which then pressurized the hole and propelled a 3 m long grout plug across the tunnel. Shortly after this another fracture apparently reached the test section of Experiment C (see Figure 4) 6.1 m away and propelled water and debris out of that hole. These observations were confirmed upon reentry in the tunnel when significant levels of combustion gas (carbon monoxide) were monitored coming out of these holes.

An enlightening comparison can also be made among the three previous Gas Frac shots[2] and Experiment E. Pressure-time characteristics and observed fracture behavior are compared in Table 3. Note that a good correlation between pressure rate and resulting behavior exists while no such correlation occurs with peak pressure. This indicates that pressure rate may be the governing parameter in determining whether resulting behavior is hydraulic fracturing, multiple fracturing, or explosive compaction. A preliminary closed-form analysis was performed that indicates the pressure rates in GF2 and Experiment E were low enough such that tangential stress at the borehole wall begins and remains tensile. On the other hand, the pressure rate of GF3 was sufficiently high to cause tangential compression initially. These initial compressions probably delay the tensile failure until after the compaction process has begun causing the bladder effect. This suggests a multiple fracture criterion that is based on a pressure rate being less than a value that would produce tangential compressive stress at the borehole wall. This criterion was previously suggested by Bligh as a means to avoid explosive compaction.[14]

CONCLUSIONS

These experiments have shown that multiple fractures can be created from a borehole while avoiding the formation of a stress cage by using an appropriately designed tailored-pulse technique. In particular, results of TV logs, permeability tests and other indirect data showed that the Case E technique produced a highly stimulated zone around the wellbore; Case B, C, and D resulted in a modest stimulation; and Case A, which apparently induced a stress cage to be formed in this rock even though it was a decoupled charge, actually decreased the formation permeability.

The results of these tests and previous experiments suggest that a multiple fracture criterion be based on borehole pressure-loading rate. Peak pressure conditions may not be important if loading-rate requirements are adequate.

Finally, these tests show the value of carefully designed in situ experiments for evaluating stimulation techniques. Instrumentation such as stressmeters, accelerometers, and pressure transducers can be fielded in critical locations, evaluation techniques such as TV and caliper logs and permeability tests can be conveniently employed, and ultimately, mineback can provide a complete diagnosis of the resultant fracture patterns.

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TABLE 1

ASH-FALL TUFF MATERIAL PROPERTIES

DENSITY	1.8 gm/cm^3
POROSITY (WATER FILLED)	40%
PERMEABILITY	SEE TABLE 2
ELASTIC MODULUS	5 GPa
COMPRESSIONAL WAVE VELOCITY	2.1 mm/μs
SHEAR WAVE VELOCITY	1.2 mm/μs
TENSILE STRENGTH	700 kPa
COMPRESSIVE STRENGTH (UNCONFINED)	30 MPa
FRACTURE TOUGHNESS	400 kPa $\sqrt{m}$

TABLE 2

PERMEABILITY ENHANCEMENT

CASE	TAILORED-PULSE CONCEPT	PRE-TEST PERMEABILITY (md)	POST-TEST PERMEABILITY (md)	FACTOR OF INCREASE	OBSERVATIONS FROM TV LOG
A	DECOUPLED EXPLOSIVE WITH WATER PAD	0.20	0.05	0.25	ENLARGED, DISTORTED BOREHOLE
B	DECOUPLED EXPLOSIVE* WITH PROPELLANT PUSHER (WATER PAD)	0.83	5.6	7	NO FRACTURES APPARENT
C	SMALL DIAMETER PROPELLANT WITH PRESSURIZED WATER PAD	0.0015	0.008**	5**	MULTIPLE FRACTURES (VERY NARROW)
D	THREE SHOTS OF CASE C WITH PRESSURIZED WATER PAD	0.007	0.034	5	MULTIPLE FRACTURES (NARROW)
E	FULL BORE, PROGRESSIVELY-BURNING PROPELLANT WITH AIR PAD	0.014	25.0	1800	MULTIPLE FRACTURES (WIDE)

*EXPLOSIVE DID NOT DETONATE

**SOME PERMEABILITY INCREASE MAY BE DUE TO FRACTURE CAUSED BY EXPERIMENT E

TABLE 3

PRESSURE LOADING CHARACTERISTICS VS. OBSERVED BEHAVIOR

EXPERIMENT	PEAK PRESSURE (MPa)	PRESSURE RATE (kPa/μs)	RESULTING BEHAVIOR
PREVIOUS GAS FRAC TEST SERIES[2]	43	0.6	HYDRAULIC FRACTURE
	95	140	MULTIPLE FRACTURES
	~200	>10,000	EXPLOSIVE STRESS CAGE
EXPERIMENT E	250	430	MULTIPLE FRACTURES

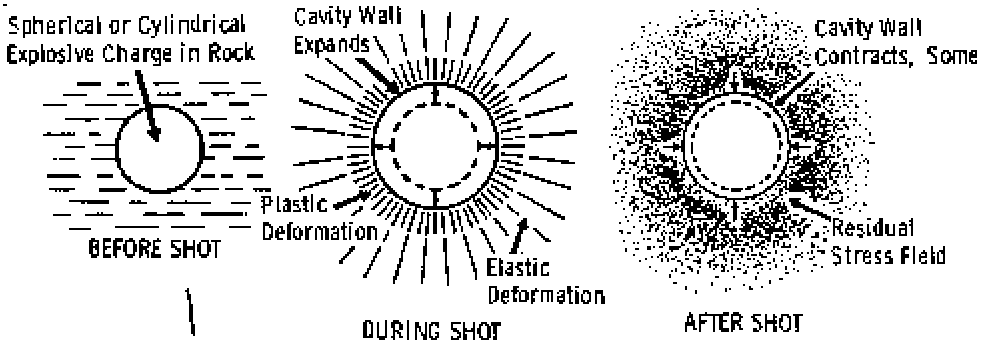
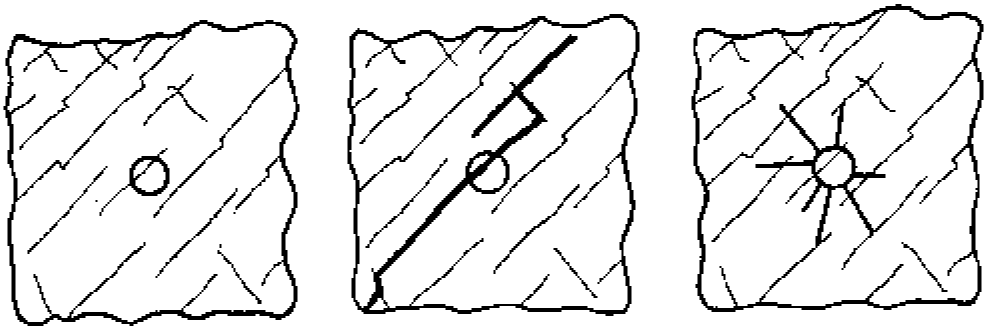


Fig. 1 - General behavior of deeply-buried charge.



A

NO STIMULATION

B

HYDRAULIC FRACTURING

C

MULTIPLE FRACTURING

Fig. 2 - Stimulation of naturally fractured reservoir.

	GF1 "SLOW"	GF2 "INTERMEDIATE"	GF3 "FAST"
LOADING RATE (kPa/µs)	0.6	140	>10,000
PEAK PRESSURE (MPa)	43	95	>~200
PULSE DURATION (msec)	900	9	~1

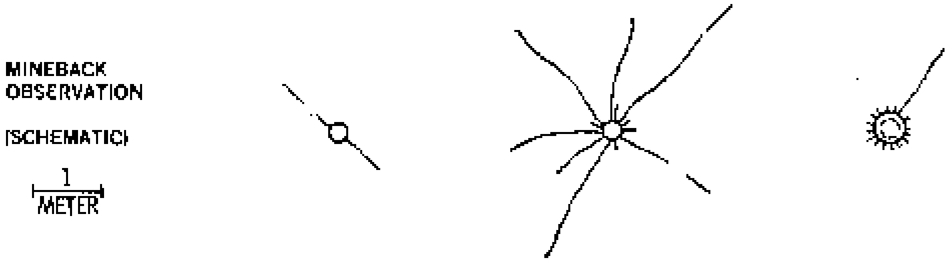


Fig. 3 - Results of gas frac experiments[2]

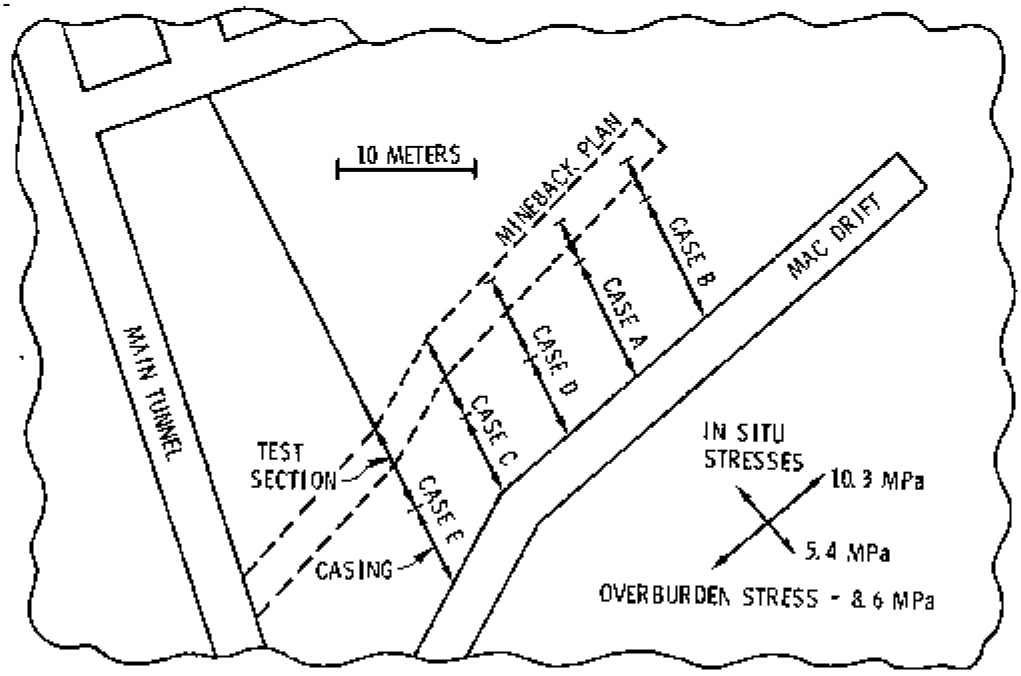


Fig. 4 - Tunnel plan for multi-frac test series

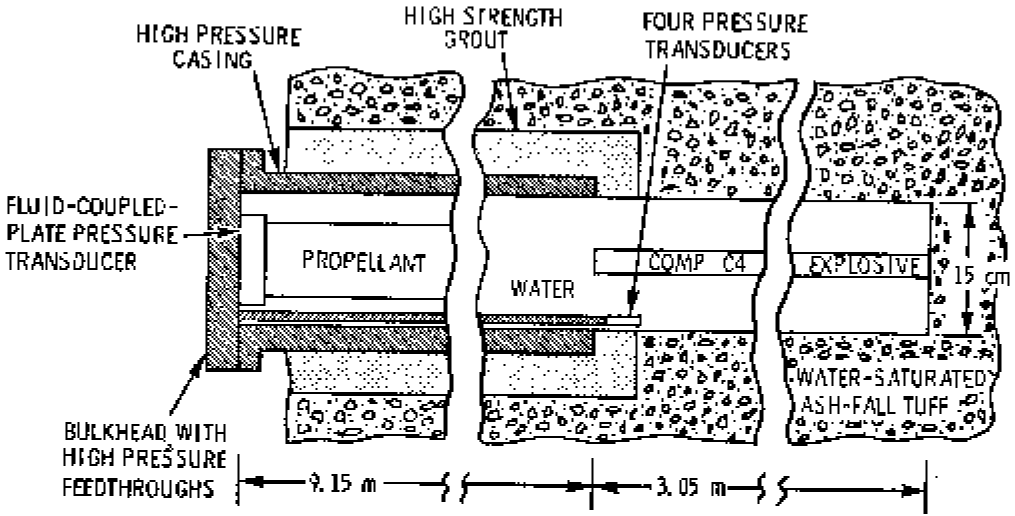


Fig. 5 - Cross section of test setup for experiment B.

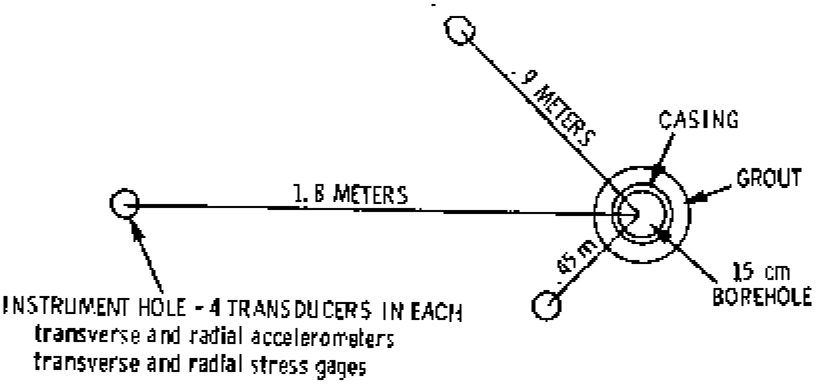


Fig. 6 - Layout of instrumentation holes.

Fig. 7 - Loading of propellant device for experiment E.

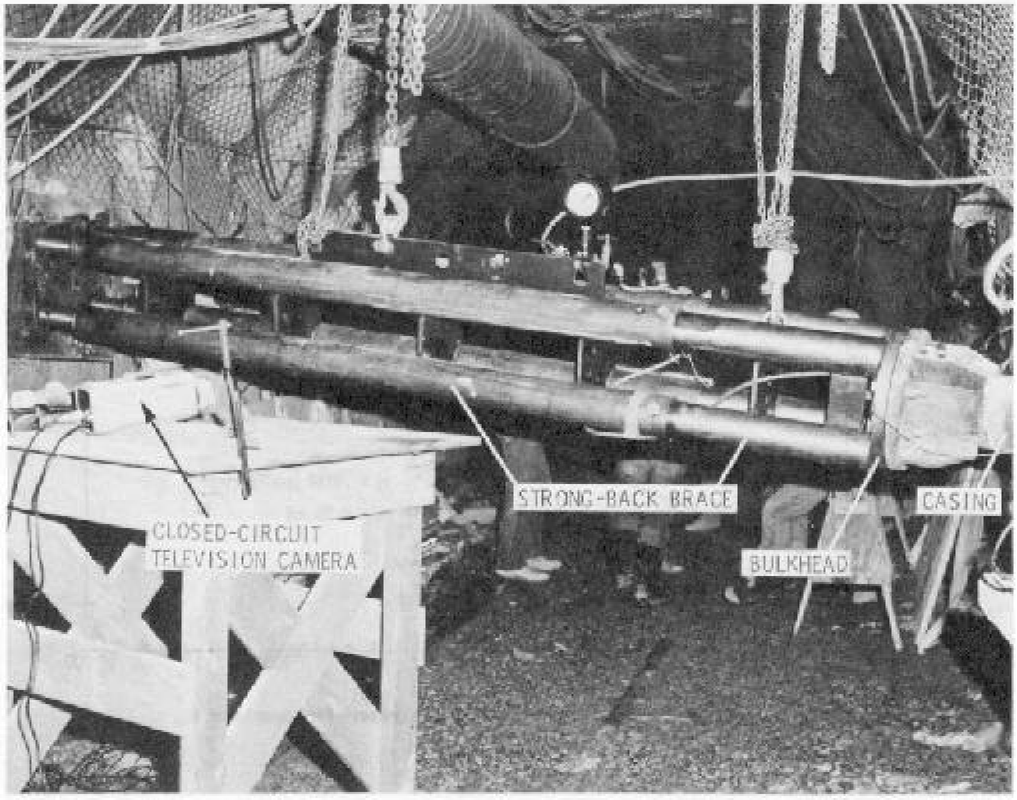


Fig. 8 - Typical view of experiment ready for arming and firing.

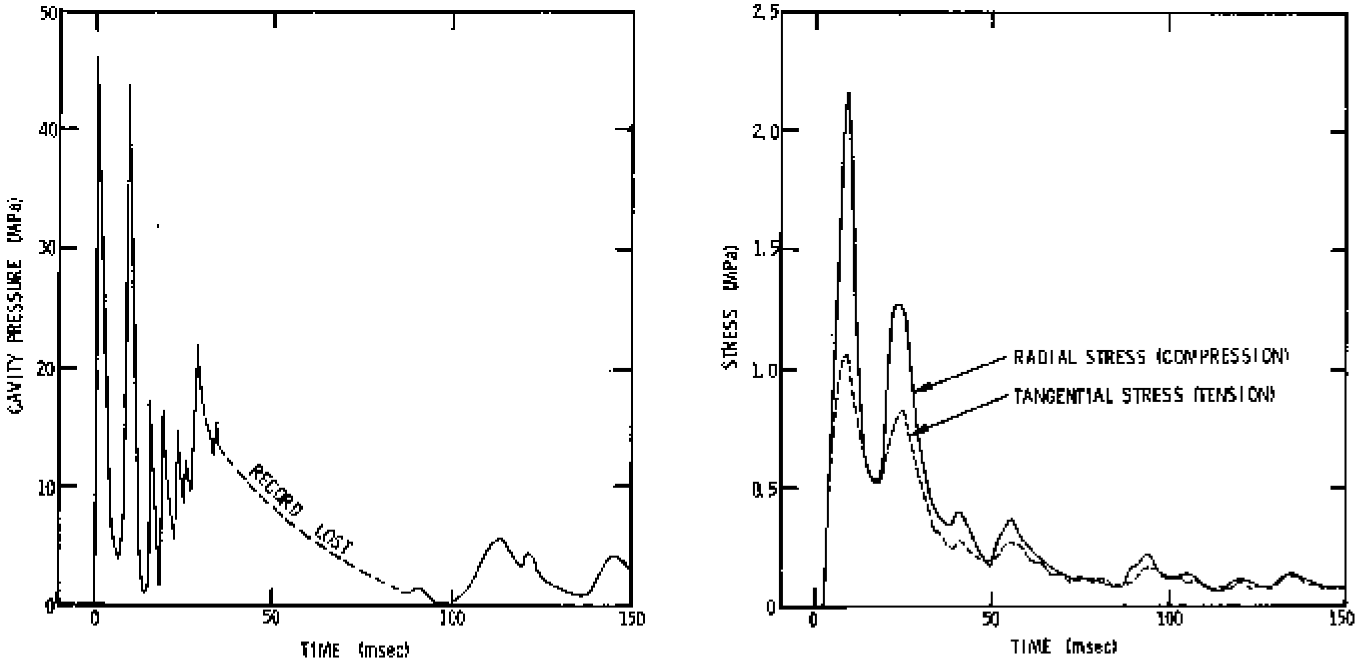


Fig. 9 – Record of cavity pressure and stress at 1 m for experiment D.

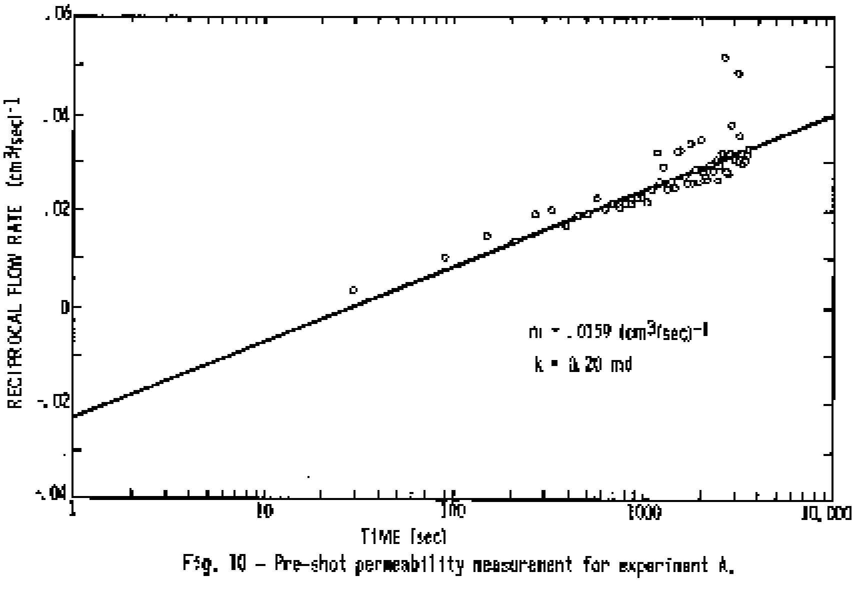


Fig. 10 – Pre-shot permeability measurement for experiment A.