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EGR Stimulation Research Project -
Direct Observation of Hydraulic and Dynamic Fracturing*

by

D. A. Northrop, N. R. Warpinski, and R. A. Schmidt
Sandia Laboratories
Albuquerque, NM 87185

ABSTRACT

The project objective is to contribute to the understanding of various stimulation processes for enhanced gas recovery. A primary activity has been to conduct hydraulic and dynamic fracturing experiments adjacent to an existing tunnel complex at DOE's Nevada Test Site which are then directly observed by subsequent mineback through the experimental area. Rock mechanics and fluid dynamics investigations complement these field experiments and significant insight into hydraulic fracturing is being obtained. Activities during the past year focused on two main areas: hydraulic fracture containment and multiple fracturing from a wellbore.

Experiments and calculations have been performed to study the factors which influence the containment, and hence the overall geometry, of hydraulic fractures at a formation interface. Evaluation of full-scale fracturing tests at an interface between geologic formations with significantly different properties, most notably an order of magnitude difference in elastic modulus, showed that the interface did not contain the fracture. Smaller-scale experiments are being conducted at this same interface to examine the effect of fluid pumping rate on containment. Numerical modeling techniques are being used to calculate the fluid pressure distribution and the fracture mechanics of the crack approaching a smeared interface - one where the interface has been modeled as being well-bonded and having a continuous change in properties over a short distance. Laboratory experiments in "smeared" materials support this field and analytical work.

Multiple fracturing from a wellbore has been demonstrated for a High-Energy Gas Frac concept. In this concept, the gas pressure pulse due to the deflagration of a propellant is designed to give pressure loading rates sufficient to initiate multiple fractures, peak pressures below the flow stress of the formation to avoid rock compaction, and a duration of burn sufficient to allow gas penetration and extension of the fractures. Three experiments with different burning rates yielded phenomenologically different results. Mineback of the intermediate test (pressure loading rate of 20 psi/μsec, peak pressures of 13,800 psi, and burn time of 9.0 msec) indicated 12 separate fractures from 0.5 to 8 ft long for the 20 lb propellant charge. Tests with a faster and slower propellant yielded only single fractures and associated features normally associated with explosive and hydraulic fracturing, respectively. An expanded test series has been defined to examine several techniques for multiple fracturing based on this concept.

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INTRODUCTION

The objective of the Stimulation Research Project is to understand, and thus improve, stimulation processes for the recovery of natural gas from low permeability formations. The project participates in both the Eastern Gas Shales Project and Western Gas Sands Project which are major parts of the Department of Energy's (DOE) Unconventional Gas Recovery Program. This project provides a broad, supporting research and development capability. Activities are planned, conducted, and reported with the aim of contributing to both the Eastern and Western Projects and to the overall development of enhanced gas recovery technology.

A primary activity has been to conduct fracturing experiments adjacent to an existing tunnel which are then observed by subsequent mineback through the experimental area. A detailed physical description can be obtained directly and can be correlated with measured geologic material properties, in situ stress distributions, fluid behavior, and the operational parameters of the test. Supportive rock and fluid mechanics laboratory and modeling work will be performed to aid in this interpretation. The mineback also allows for the calibration of instrumentation techniques. This program provides a unique opportunity to quantify and understand fracture behavior. Industry interest in the project has been high. Industry inputs into experiment planning and analyses have been valuable and the results from this project are influencing the technology.

The Stimulation Research Project was initiated in FY 77. However, the program has built upon fracturing and mineback activities which have been conducted since 1974 in G tunnel, at the Nevada Test Site, as part of a nuclear containment program sponsored by the Division of Military Applications under DOE. The commonality of objectives between the containment and enhanced gas recovery activities is striking. Previously reported experiments include: (a) initial hydraulic fracturing experiments[1], (b) a staged proppant distribution fracture experiment,[2-5] (c) investigation of fracturing and residual stresses around a contained explosive detonation,[3-5] and (d) small volume hydraulic fracturing as a diagnostic tool.[3]

This paper summarizes the activities and results obtained in the period June 1, 1978, to June 1, 1979, for two main areas: hydraulic fracture containment and multiple fracturing from a wellbore. Details for these activities and additional work conducted under this project can be found in the references.

MINEBACK EXPERIMENT FACILITIES

A major activity of this project is the direct observation and mapping of fracture behavior and the qualitative and quantitative analysis of these results. The program utilizes the G Tunnel complex and existing support facilities at DOE's Nevada Test Site as a geophysical laboratory for basic and applied fracture research. Besides the direct evidence obtained from mineback, this facility provides for exploratory coring to locate fractures and determine their extent, in situ stress measurements in regions of interest, material property samples at various locations, detailed "reservoir" geology and the capability of monitoring the dynamics of hydraulic fracturing.

Essentially all of G tunnel was driven into bedded ash fall volcanic tuffs, but a thin (<150 ft) welded ash flow tuff unit overlays the tunnel complex. Although the volcanic tuffs at Ranier Mesa are not geologically similar to sandstones and shales, the knowledge gained from these conditions can be applied directly or extrapolated to the conditions existing in gas reservoirs. In particular, considerable information can be obtained about the effects that faults, fractures, bedding planes, geologic interfaces, material properties and in situ stresses have on fracture growth. The tunnel has an overburden of 1200-1500 ft.

Large-scale experiments are conducted in holes drilled from the top of the mesa, but small tests are also carried out in horizontal holes drilled from the tunnel. A rotating drum, Alpine mining machine is generally used for mineback. It provides an exceptionally clean face which allows for detailed evaluation. Conventional blast and muck techniques are employed in special situations where the Alpine miner cannot be utilized. Fracture and geologic descriptions are obtained via photography and geologic notes and maps.

HYDRAULIC FRACTURE CONTAINMENT

The behavior of hydraulic fractures at geologic formation interfaces is not well understood and this effect is of prime interest to industry. A hydraulic fracture is usually designed to be contained within the pay zone where it was initiated. Failure to do this results in an effective loss of the expensive fluid and proppant used to fracture the unproductive strata and some of the resource may even be lost if the fracture provides a leak path for the gas or oil to escape the pay zone. Other deleterious effects can also occur should the fracture penetrate a water-bearing zone. Due to the complexity of the problem, present design calculations assume, a priori, that the hydraulic fracture is contained and that a vertical fracture of constant height is created. Recent efforts, however, have demonstrated that fracture geometry and containment (or lack of it) may be affected by parameters such as interface strength, in situ stress, stress gradients, fluid pressure distribution, and material properties such as Young's modulus and fracture toughness. While these parameters may be recognized as important, little has been done to test these effects and to develop quantitative criteria useful for design calculations.

A formation interface fracture experiment (Hole #6) has been conducted.[6,7] In this experiment, hydraulic fractures were created above and below an interface existing in G tunnel. As shown in Figure 1, the formations have significant differences in their properties and the interface region between them consists of approximately 10 ft of several layers with differing properties. Standard fracture calculations[8,9] were used to design two rectangular, vertical fractures of 50 ft height and 600 ft total length; 256 and 117 bbls of colored cement were injected at 6 bbls/min into the ash fall tuff and welded tuff zones, respectively, at depths of 1355 ft and 1328 ft.

One wing of the fracture was located by coring from the adjacent tunnel and mineback followed the entire length of the fracture, including the wellbore, at the elevation of the interface. A 6 by 6 ft rise was blasted up along the wellbore through the upper fracture interval. Thus, mineback allowed direct observation of the fractures in both formations and the transition region. Additional coring is now underway to define the overall extent and widths of the fractures. Figure 2 presents the results of the mineback and the results of the coring to date.

Findings of the experiment to date include:

(1) The fracture that was initiated in the lower, ash fall tuff was not contained and was found to propagate up through the transition zone and well into the welded tuff above it despite the significantly different properties of the overlying formation.

(2) Overall fracture length at the elevation of the interface was ~150 ft. The overall fracture geometry is clearly not a 50 x 600 rectangle. The fracture was apparently little influenced by the interface.

(3) The observed fracture widths were consistent with those predicted by design and properties: 5-10 mm and 2-5 mm for the ash fall and welded tuffs, respectively.

(4) Limited information on the fracture that was initiated in the welded tuff indicates that the behavior was strongly influenced by pre-existing fractures in that formation and broke alongside the hydraulic fracture created from the lower interval.

Presently, a series of small scale, in situ experiments is being conducted to evaluate the importance of pump rate effects on the behavior of a fracture near a material property interface. Four to six zones in three separete horizontal holes that were drilled somewhat below the welded tuff/ash-fall tuff interface will be treated with small volumes (50-150 gal) of dyed water at different flow rates ranging from 8 gpm to 0.5 gpm. All of these zones will subsequently be mined back to examine the fracture behavior at the interface.

The first hole of this series is a preliminary test that was conducted to evaluate the technique, reconfirm the results of the large scale formation interface fracture experiment (Hole #6) and determine the in situ stresses in this region. Six zones in this hole were fraced with 150 gal of fluid at 8 gpm and pressure and flow rate were recorded. Tiltmeters were installed in the adjacent tunnel to monitor the progress of the fractures and calibrate the tiltmeter data. All six zones were then mined back, photographed and mapped.

The results of the mineback showed that all six fractures broke through the interface without any obvious change in orientation or behavior. However, none of the fractures propagated lower than approximately 3 ft below the hole, which suggests that the state of stress near the interface played a major role in fracture propagation. Fractures will be initiated at lower flow rates in at least four zones of each of the remaining two holes to provide a comparison of the fracture behavior under varying rate conditions.

Field experiments such as these in tuff formations are able to provide direct information and insight as to the important parameters that govern hydraulic fracture behavior. However, these physical simulations must be accompanied with adequate modeling to provide a dependable predictive capability for the design of hydraulic fractures in actual reservoirs.

Existing analytical models for the growth of a crack near a material interface[7,10] are not consistent with observed behavior in these field experiments. It is hoped that the unrealistic aspects of the present models can be avoided by simulating the interface with a gradual change of properties. This "smeared interface" model is being addressed by numerical and analytical calculations, material property measurements, and physical simulations by laboratory experiments. Numerical calculations are being performed on a layered model with gradual property changes using a finite element code called APES[11] that incorporates enriched crack tip elements. Analytical modeling is focusing on a microcrack model[12] that predicts the size and shape of the crack tip process zone which is at least partially responsible for the smearing effect that averages material properties ahead of the crack tip. Material properties such as Young°s modulus, tensile strength, and fracture toughness are being measured for the various layers near the Hole #6 experiment. Laboratory experiments are focusing on layered fracture specimens made of various concrete mixes that simulate the situation of a hydraulic fracture propagating in a material of varying properties.

An activity to assemble a realistic model of the fluid mechanics of fracturing has been initiated. The purpose of this modeling effort is to obtain a better understanding of the interplaying mechanisms that control the process; to aid in the interpretation of previous mineback experiments; to provide a basis for the analysis and interpretation of the upcoming experiments where dynamic fracture widths and pressures will be measured; and to provide realistic conditions (e.g., pressure loading in the crack) upon which to apply rock mechanics considerations for the study of the effect of interfaces, in situ stresses, etc. on fracture propagation.

The proposed model employs a complete width equation (i.e., the width distribution can be determined for any pressure distribution in the fracture), and one dimensional continuity and momentum equations that include the transient and convective terms. The increasing crack length is handled by a transformation that will account for the moving boundary and the system of equations is solved by a finite difference procedure using an iterative technique. This model should provide realistic values of the width, pressure and length and their time dependence for idealized systems (2-dimensional or penny-shaped cracks).

MULTIPLE FRACTURING FROM A WELLBORE

A High Energy Gas Frac field test has shown that multiple fractures can be created from an interval along a wellbore.[13] The High Energy Gas Frac is a dynamic wellbore fracturing technique designed to increase the permeability of a formation near the wellbore. By imparting a controlled high intensity and short term pressure load to the wellbore, multiple fractures are created and extended in a pay zone to overcome wellbore damage, to connect the wellbore with natural fracture systems, or to provide an effectively enlarged wellbore. As a stimulation tool, this technique can be applied to the Eastern Devonian shales and tight gas sands and has applications in other in situ technologies.

The concept of High Energy Gas Frac is to tailor the pressure-time behavior of the deflagration of a suitable propellant to create multiple fractures and avoid limitations inherent in both hydraulic fracturing and explosive fracturing. Hydraulic fractures, which are propagated at pressures that are slightly higher than the minimum in situ stress and for pumping times that are on the order of hundreds of seconds, typically produce only a single fracture whose orientation is aligned with the in situ stresses. Detonations, which usually have peak pressures that are orders of magnitude above the in situ stresses and occur in microseconds, often cause considerable crushing and compaction of the rock and leave a residual compressive stress zone around the wellbore. This results in wellbore damage and may seal of any cracks that are formed.

The High Energy Gas Frac on the other hand, imparts a controlled pressure load about one order of magnitude above the in situ stress level but below the flow stress of the rock. This pressure load is applied over an interval on the order of milliseconds to create and extend multiple fractures radially from the wellbore. The initial loading rate must be large enough to initiate multiple fractures. The number of fractures appears to be pressure-rate dependent and is probably influenced by properties of the rock, the size of the borehole, and the number of available flaw sites for crack nucleation. In order to achieve substantial fracture growth, the propellant must continue to burn for a period of time so that the hot, high pressure gases will enter the initiated fractures and extend them. The pressure must be considerably above the in situ stresses to that the near-wellbore stress field is dominated by the effect of the pressure in the cracks and wellbore. However, if the pressure is too large and results in crushing, small particles may enter the cracks and seal them off.

Three different propellants were tested in the ash fall tuff in G tunnel. In each test, canisters containing 20 lb of propellant, ignitors and a fluid-coupled-plate pressure transducer were stemmed into an 8 in diameter horizontal borehole, 20 ft deep, with a high strength grout. The propellants utilized were JPN, a relatively slow burning rocket propellant, M26, a large bore gun propellant having an intermediate burn rate, and M5, a small arms propellant with a fast burn rate.

The results of three tests showed phenomenologically different behavior. JPN, the slow propellant (burn time = 0.9 sec), had a pressure loading rate of 0.09 psi/μsec and a peak pressure of 6250 psi. The loading rate was too small to induce multiple fracturing and the peak pressure was lower than the crush strength of the rock. This test resulted in a single fracture that was similar in appearance to hydraulic fracture typically observed in tuff. M26, the intermediate propellant (burn time = 9.4 msec) had a loading rate of about 20 psi/μsec and a peak pressure of 13,800 psi. This was sufficient to initate and extend 12 separate fractures in different radial directions. Lengths of these fractures varied from 6 in to 8 ft. There was no apparent crushing of the rock near the wellbore. The fast propellant (burn time ≈ 1 msec) had a pressure loading rate greater than 1500 psi/μsec and a peak presure greater than 20,000 psi. These values were so large that considerable crushing of the rock near the wellbore was observed and only one fracture was extended a significant distance from the wellbore. Several incipient cracks (< 4 in) that barely extended out of the crushed zone were also observed. The crushed cativy region was similar in appearance to typical high explosive shots conducted in tuff.

Analysis of the intermediate propellant test shows that a lower bound crack length of 1.6 ft is calculated by assuming a loaded borehole with no gas entering the fractures. On the other hand, if it is assumed that gas enters the fracture and the crack propagates at its maximum velocity for as long as the pressure is higher than the fracturing pressure in this medium, an upper bound crack length of 30 ft is obtained. Generally, the observed crack lengths in general fall between these two bounds. Realistic calculations for these final crack lengths will require knowledge of the complex gas dynamics in the cracks.

Another in situ test series similar to the High Energy Gas Frac tests is being conducted as part of the Eastern Gas Shales Project. This series, known as the Multi-Frac Test Series, is designed to evaluate various commercially-available well shooting devices that rely on the concept of tailored-pulse loading which avoids borehole compaction and enhances multiple fracturing. The concepts to be evaluated involve various combinations of propellants and de-coupled explosives, with and without water pads.

This test series is similar to the hydraulic fracture test program in that the field tests must be supported with adequate modeling to evaluate properly the test results and to provide design parameters and some assurance that behavior in actual reservoirs can be adequately predicted. Hence, the Multi-Frac Test Series is designed also to evaluate several numerical models presently available and to indicate specific parameters that need to be included in these models to make them applicable to tailored-pulse loading of wellbores. As a result, this test series will be heavily instrumented (pressure transducers, stress gages, and accelerometers) and will include extensive post-shot evaluation (permeability enhancement, borehole televiewer, caliper log, as well as direct observation by mineback).

SUMMARY

1. Conducting controlled fracture experiments which are subsequently available for direct observation has been shown to be feasible and is producing significant new observations. Such testing in this geophysical laboratory provides a unique opportunity for basic and applied fracture research.

2. Hydraulic fractures have been shown to be relatively unaffected by interfaces between formations with different properties. Specifically, the upwards growth of a fracture was not contained by an overlying formation with significantly higher modulus and rectangular, bounded fracture geometries should not be assumed.

3. The High Energy Gas Frac has been shown to be a viable technique for creating multiple, randomly oriented fractures in a borehole. This field test has demonstrated that a propellant can be suitably designed to provide (1) a large enough loading rate to initiate multiple fractures, (2) high enough pressures to extend fractures radially, but not so high as to exceed the flow stress of the rock, and (3) sufficient gas generation to allow most of the fractures to be pressurized and propagated further. A test series will be conducted during 1979 which will examine several similar concepts for multiple fracturing.

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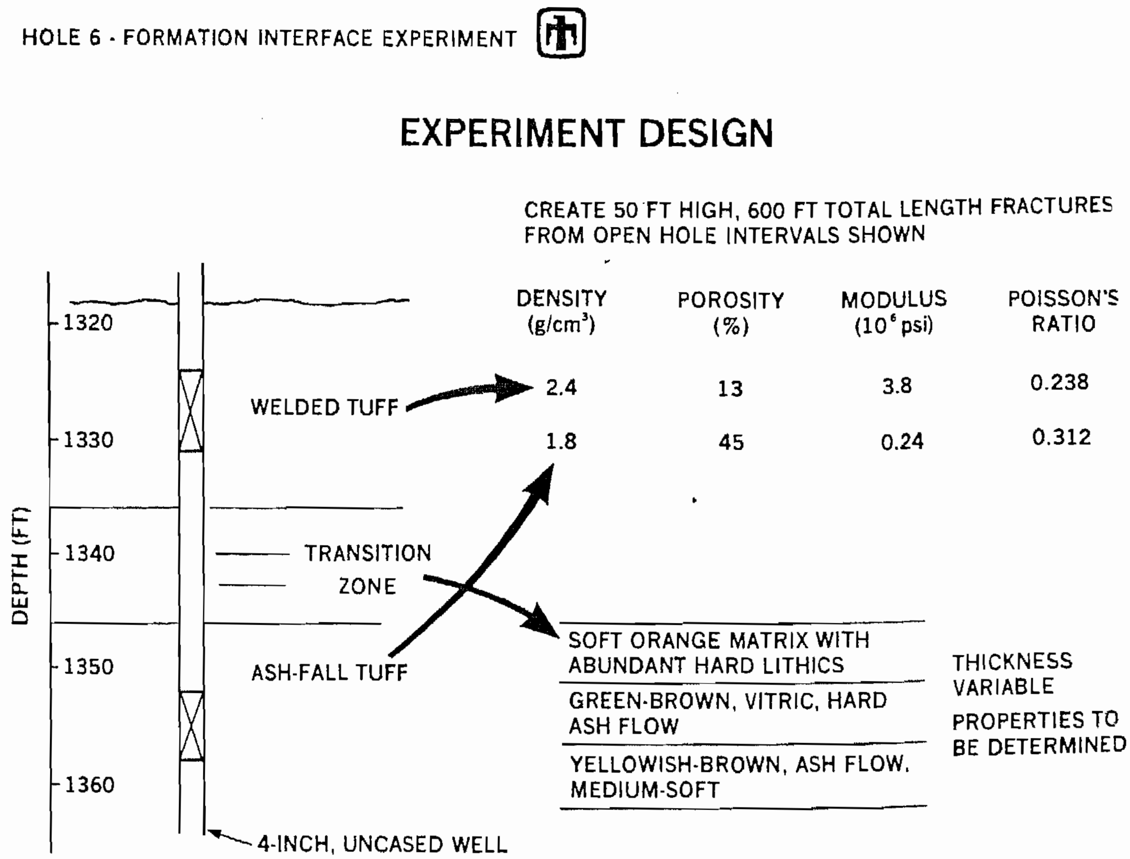

Figure 1. Material properties and experiment design for the Hole #6 formation interface experiment.

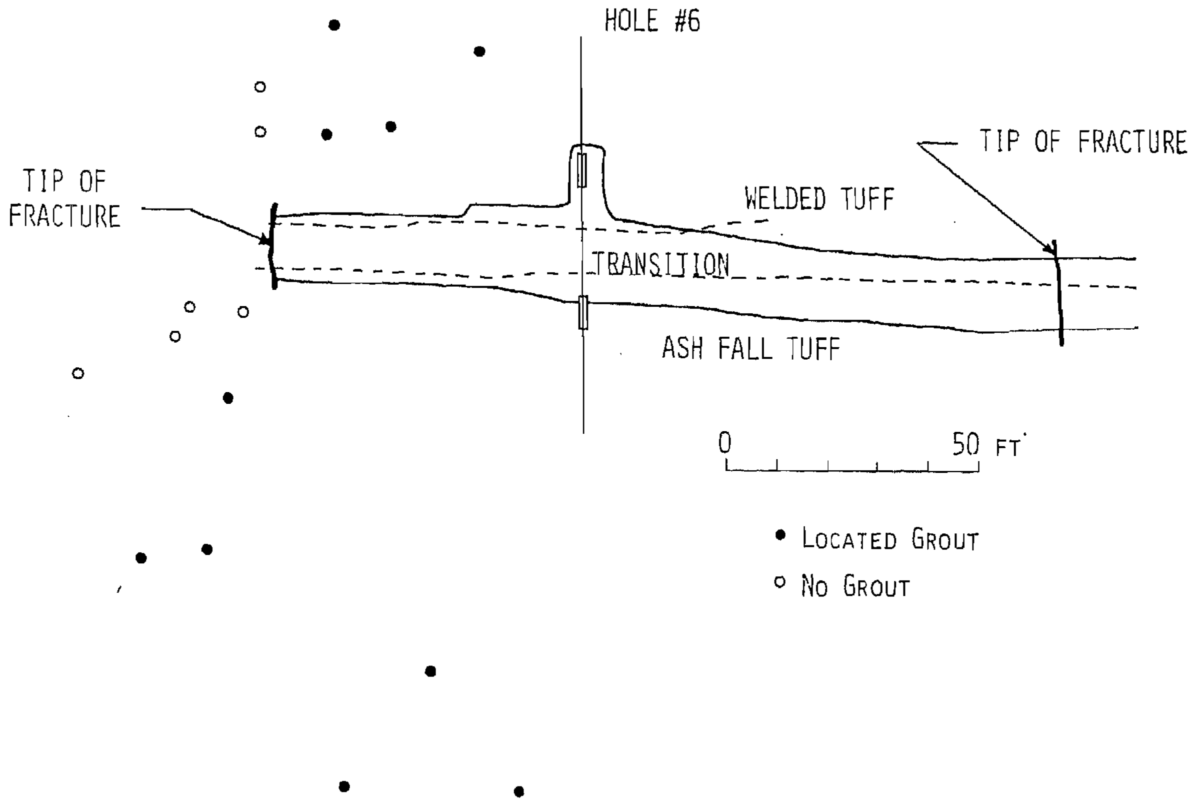

Figure 2. Results of the mineback and exploratory coring to date on the Hole #6 experiment. The lower fracture broke upwards into the welded tuff at all locations and can be seen in the back of the tunnel between the two tips of the fracture.