Title

ROCK MECHANICS ISSUES AND RESEARCH NEEDS IN THE DISPOSAL OF WASTES IN HYDRAULIC FRACTURES

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T.W. Doe and W.C. McClain

July 1984

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ROCK MECHANICS
ISSUES AND RESEARCH NEEDS IN THE DISPOSAL OF WASTES IN HYDRAULIC FRACTURES

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SUMMARY

ROCK MECHANICS ISSUES

The proposed rock mechanics studies outlined in this document are designed to answer the basic questions concerning hydraulic fracturing for waste disposal. These questions are: (1) how can containment be assured for Oak Ridge or other sites; and (2) what is the capacity of a site. To answer these questions, we have identified several issues which address the questions.

State of Stress: The state of stress is the single most important factor in determining whether a hydraulic fracture will be horizontal (and remain confined to the shale bed) or vertical (and pass out of the shale bed to a more permeable strata). Conditions will be favorable for horizontal fracture propagation if the minimum principal stress is vertical.

Effect of Ground Surface on Fracture Orientation: The virgin in situ stress field is the main factor controlling the fracture orientation when the fracture size is small relative to its depth. However, as the fracture diameter approaches a value equal to its depth, the ground surface exerts an influence which can cause the fracture to propagate upwards. The fracture may then propagate out of the shale into overlying strata. The factors controlling this upward propagation of the fracture must be well understood if this breech of containment is to be avoided.

Effect of Material Anisotropy on Fracture Orientation: The bedding and foliation planes impart anisotropic strength and deformational properties to rocks. At Oak Ridge, the bedding of the shales is probably oriented nearly normal to the minimum in situ stress; thus, the stress and the bedding both encourage horizontal fracture growth. Its not clear, however, that the bedding planes would control fracture growth if the minimum stress were horizontal. Such could be the case at other potential disposal sites or at greater depths at Oak Ridge.

Effect of Multiple Injections: In the hydraulic fracturing waste disposal operation, several injections are made into a single slot and several slots may be made in a given well. Each injection deforms the surrounding strata and affects the local stress field, thus, altering the in situ conditions for subsequent injections. The optimal size and number of injections, their spacing in the well, and their sequence, are not yet known. These factors critically influence the disposal capability of a site.

Pore Pressure Effects: Pressures as great as 1.0 MPa (145 psi) have been observed in monitoring wells during the injections at Oak Ridge. These data suggest that the pore fluids are being stressed as the rock accommodates the volume of the grout sheet. Therefore, the mechanics of the rock deformation may not be simply elastic, but also may involve poro-elastic factors and transient phenomena related to fluid diffusion. Furthermore, pore pressure build-up may induce additional fracturing or slip on preexisting fractures in the vicinity of the grout sheet.

Effect of Discontinuities and Heterogeneities on Fracture Growth: The shale strata may contain heterogeneities (such as lenses of carbonates or other rock types) and discontinuities (faults or joints) which influence the propagation of the fracture. When a fracture intersects such a feature, its propagation may be arrested, it may be diverted to another bedding plane in the shale, or it may change orientation. The effects, which the several types of discontinuities and heterogeneities have on the propagation of a fracture, must be understood.

Effects of Fluid Properties of Grouts: The surface uplift and the potential for upward fracture propagation depend on the pressure distribution in the fracture. This pressure distribution is controlled in part by the fluid properties of the grout, which may be complex due to non-Newtonian behavior.

PROPOSED RESEARCH

The suggested rock mechanics program consists of four major tasks: (1) numerical modeling, (2) laboratory testing, (3) field testing, and (4) monitoring. These tasks are described below.

Numerical Modeling: The ultimate goal of numerical modeling for hydraulic fracturing waste disposal is development of a fully verified and validated model which completely and accurately simulates all aspects of the process. However, the development of such an inclusive, fully-coupled model from the present state of the art would not be cost effective and would not provide timely analysis for the further development of the technique. Instead, the proposed program is to pursue as many as three separate model approaches in order to assess the relative significance of certain issues. The three types of models considered appropriate are: (1) deformation mechanics; (2) fracture mechanics; and (3) coupled fluid flow and deformation.

The first step is to develop these existing models to make them more specifically applicable to the waste disposal process. The required modifications include enlarging to three dimensions, provision for multiple fractures and anisotropic material properties, inclusion of pore pressure effects, pore compaction and other nonelastic deformations, and the addition of a capability for handling arbitrary discrete discontinuities and inhomogeneities.

As these code developments progress, the codes should be verified (by comparison with analytical solutions, performing benchmark calculations, etc.) and parametric calculations should be undertaken to assess the individual aspects such as the effect of the free surface, the effect of bedding plane anisotropy, and the operating optima for number, size, and sequence of injections.

Later, as data from laboratory simulations, field tests, and monitoring activities become available, the models should be validated and any necessary refinements made. Finally, an evaluation of the numerical modeling effort should be made, including recommendations for the most effective way to proceed with the development of a complete simulation model.

<u>Laboratory Experiments</u>: There are two purposes in performing laboratory experiments. First, measurements of material properties must be made to provide data for the numerical modeling. Second, laboratory-scale simulations of hydraulic fracturing should be performed to validate calculations made by numerical models.

Among the material properties that must be determined for the shales at Oak Ridge are fracture toughness, porosity, permeability, and deformational properties (including drained and undrained moduli). Where possible, the variation of material property values should be determined as a function of orientation relative to bedding. Shale may rapidly degrade due to moisture loss so cores must be sealed immediately upon their removal from boreholes. The samples tested must be in as little disturbed a state as possible.

Laboratory testing is also a useful means of validating the performance of numerical models. Hydraulic fracturing simulations may be a particularly useful means of studying the influence of bedding plane orientation relative to the in situ stress directions on the propagation of the hydraulic fractures. Laboratory tests may also be used to investigate pore pressure effects around hydraulic fractures and the influence of free surfaces on fracture propagation.

<u>Field Experiments</u>: Field experiments are performed to explore and elucidate the basic rock deformational phenomena and to provide data to validate the

numerical calculations. They have advantages over laboratory tests in that they provide data at scales more appropriate than laboratory tests. Field tests are, however, considerably more expensive, and it is more difficult to isolate the effects of specific phenomena or material properties on the overall behavior of the injection. Thus, while field tests are the best simulation experiments, they must be very carefully designed if they are to yield unambiguous results.

We therefore propose a modest effort for designing field tests during the early stages of the program, with a provision for implementing tests at a later time, if appropriate. Results from the modeling program will be incorporated into the field testing plans. Among the considerations to be dealt with in the test planning are (1) the role of smaller scale tests focused on specific issues (e.g., anisotropy and heterogeneity effects) versus tests which completely simulate a disposal injection; (2) the smallest scale and least depth at which a field experiment can be said to simulate a disposal injection; and (3) identification of potential sites and their relative advantage.

Monitoring: Much can be learned about fracture behavior using data which has been and will be gathered during the monitoring of injections at Oak Ridge. The monitoring data is of two types; that which has been gathered on previous injections, and that which should be gathered during injections performed in the future.

First, there is existing data from the current series of disposals and from previous experimental disposal sites. These data consist mainly of the following: gamma logs of observation wells, pressure measurements in the rock cover wells, and surface leveling data. More recently, feasibility experiments have been performed using tiltmeters and microseismic monitoring arrays. An important task will be to review and compile all existing data, both published and unpublished, and make it accessible for use in the computational program.

Monitoring activities should be expanded for future injections at Oak Ridge. The seismic array should be expanded to allow precise location of events. Packer systems with pressure transducers should be placed at the bottom of the casing of the observation wells to provide rapid response piezometers. If possible, monitoring wells should be drilled and instrumented to provide a profile of pore pressure change with distance from the hydraulic fracture. The feasibility of using other forms of geophysical monitoring (such as electrical methods) should be investigated. A permanent tiltmeter system should be installed and surface leveling should continue.

1 INTRODUCTION

Hydraulic fracturing has proven to be an effective and economical method of disposing of radioactive wastes at the Oak Ridge National Laboratory. After the initial experiments of the late 1950's and early 1960's demonstrated the feasibility of the concept, development of the engineering and rock mechanics were undertaken. Work by McClain [1968], Sun [1969], and others drew on available analytical methods and experimental data to conclude that the rock mechanics of the disposal were both feasible and favorable.

During the decade that has passed since the original rock mechanics investigations were undertaken, hydraulic fracturing has become a standard procedure at the Oak Ridge site, and a considerable body of experience and expertise has been developed in the operation of disposal facilities. At the same time, major advances have been made in the science of rock mechanics in understanding the basic processes of hydraulic fracturing, in situ stress measurement, and rock deformation. The rapid development of numerical methods has resulted in powerful new tools for simulating hydraulic fracturing and other rock mechanics problems.

Currently, the hydraulic fracturing operation at Oak Ridge is the only permanent geologic disposal operation for radioactive wastes in the United States. The successful experience gained thus far in the operation has encouraged consideration of expanding its use to disposal of radioactive wastes at other sites, as well as to disposal of nonradioactive toxic materials at Oak Ridge and elsewhere. Given the current interest in the technique and the prospect of its application for solving other waste disposal problems at other sites, the time appeared appropriate to undertake a review of the progress in the field of rock mechanics over the last decade and how recent development could be applied to improving our understanding of the basic processes of hydrofracture disposal.

This review was accomplished by first compiling a summary of the relevant research in the form of a draft report on the important rock mechanics issues in the disposal of wastes by hydraulic fracturing. Then, a workshop of 19 earth scientists and engineers was held on November 21-22, 1983, at the Lawrence Berkeley Laboratory (LBL) to both examine the completeness and validity of the draft issues document and to identify appropriate research programs for resolving those issues. The literature review and draft issues document was prepared by Thomas Doe of LBL and the workshop participants were:

Christopher Barton	U.S.G.S., Denver, CO
Michael Cleary	Dept. of Mech. Engr., MIT, Cambridge, MA
Neville Cook	Dept. Mining Engr., University of California, Berkeley, CA
Thomas Dey	Los Alamos National Laboratory, Los Alamos, NM
Steven Haase	Oak Ridge National Laboratory, Oak Ridge, TN
Bezalel Haimson	Dept. Met. and Min. Engr., University of Wisconsin, Madison, WI
Francois Heuze	Lawrence Livermore National Laboratory, Livermore, CA
Gary Holtzhausen	Applied Geomechanics, Santa Cruz, CA
Tony Ingraffea	Lawrence Livermore National Laboratory, Livermore, CA (on sabbatical leave from Cornell University)
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This report is the combined result of the draft issue document, the workshop review of it, and a distillation of the research activities proposed and discussed at the workshop. In addition, many of the workshop participants submitted written contributions on specific topics which were freely drawn upon in the preparation of this summary.

This report contains two major sections. The first, Section 2 - Issues and Research Needs, was developed largely from the draft issue document augmented to incorporate the review and comments at the workshop. In this section, each of seven issues and their research needs are discussed separately under the subheadings of:

- 2.1 State of Stress
- 2.2 Effect of Ground Surface on Fracture Orientation
- 2.3 Effect of Material Anisotropy on Fracture Orientation
- 2.4 Effect of Multiple Injections
- 2.5 Pore Pressure Effects
- 2.6 Effect of Discontinuities and Heterogeneities on Fracture Growth
- 2.7 Effects of Fluid Properties.

The second main section is an outline of a research program for resolving the issues. This research program is based on the workshop discussions and the subsequent written contributions of the participants and is presented under the subheadings of:

- a. Modeling Calculations
- b. Laboratory Studies
- c. Field Tests
- d. Monitoring Activities at the Oak Ridge Site.

2 ISSUES AND RESEARCH NEEDS

2.1 STATE OF STRESS

The state of stress is the single most important factor affecting the orientation of hydraulic fractures. In homogeneous isotropic rocks, the fracture orientation should always be perpendicular to the least principal stress direction. Other sections of this report discuss the effects of anisotropy (Section 2.3) and heterogeneity (Section 2.6); however, in situ stress may strongly affect fracture orientation even where these conditions exist. Therefore, the best assurance of a horizontal hydraulic fracture is gained by selecting sites and depths where the minimum principal stress is the vertical stress.

2.1.1 Stress Measurements in the Oak Ridge Vicinity

Overcoring stress measurements at a depth of 282 m have been reported by Aggson and Hooker [1980] at the Immel Mine near Knoxville, Tennessee. The measurements indicated a maximum horizontal stress of about 24.1 MPa, a minimum horizontal stress of 7.1 MPa, and a vertical stress of about 6.4 MPa. The maximum horizontal stress orientation was northeast. The vertical minimum stress measured underground is consistent with the observations of Schaeffer [1979], who reported offsets in shallow coreholes in the Knoxville area which he interpreted as the reactivation of thrust faults. However, this interpretation has been questioned by Hatcher and Webb [1981] who attribute the offsets to surficial processes.

Hydraulic fracturing measurements in the southern Appalachians would suggest that the depth to which the vertical stress remains the minimum may not be great. Stress measurements have been made by hydraulic fracturing in West Virginia [Haimson, 1977] and South Carolina [Haimson, 1978]. In both cases the vertical stress was the minimum stress at shallow depths. For the West Virginia measurements, which were made in Devonian shale, the vertical stress remained the minimum stress to a depth of 600 m. In South Carolina, the minimum stress was vertical as deep as the tests were made (270 m). The impression packers showed clear traces of both vertical and horizontal fractures. In both sets of stress measurements, the direction of the maximum horizontal stress was northeast.

2.1.2 Stress Conditions in the U.S. and the Site Potential for Hydrofracture Disposal Facilities

As discussed above, the preferred stress conditions for a hydrofracture waste disposal facility would be those where the minimum compressive stress is vertical.

Focal mechanisms of earthquakes provide another indication of the relative magnitudes of the vertical and horizontal stresses. The pattern of the direction of first motions measured at the surface from earthquakes can be used to indicate the orientation of the fault and the sense of motion. These data are used to infer the relative magnitudes of the stresses at a site. Thrust faulting conditions, for example, would indicate a vertical minimum stress which is the optimal condition for hydraulic fracturing disposal.

Focal mechanism data for the U.S. compiled by Zoback and Zoback [1980] indicate that thrust faulting conditions exist in the Appalachian belt, the Columbia Plateau, and to a lesser extent, in the midcontinent region.

Compilations of in situ stress data for the Great Lakes region to 1,400-m depth indicate that the vertical stress and the minimum horizontal stress are nearly equal in value.

The most unfavorable conditions for creating horizontal fractures exist where the vertical stress is the maximum compressive principal stress, a situation which corresponds to normal faulting conditions. Such stress conditions exist in the Rocky Mountain and Basin and Range provinces, as well as in the Gulf Coast area. Favorable conditions for hydrofracturing disposal in these regions would exist only very close to the surface, if at all.

2.1.3 Procedures for Performing Stress Measurement

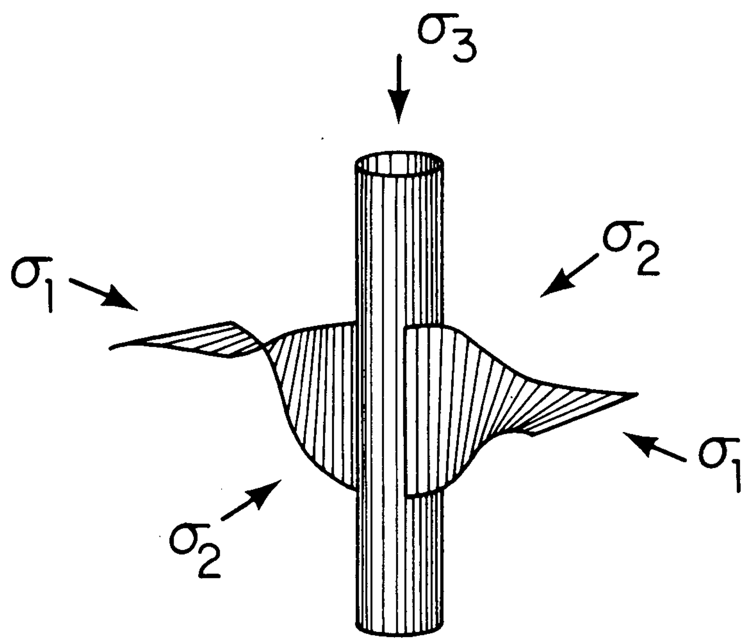
The most important information obtained from stress measurements is the state of stress at the disposal horizon. The selection of appropriate disposal horizons will require demonstrating that the vertical stress is the minimum stress to those depths or greater.

Although the hydraulic fracturing method of stress measurement has gained considerable acceptance over the last several years, questions still remain over a number of issues, particularly those affecting calculation of the maximum horizontal stress. But the maximum horizontal stress magnitude is not of major importance for waste disposal, as the horizontal fracture propagation is controlled by the ratio of the minimum horizontal stress to the vertical stress. The minimum horizontal stress can be calculated from the shut-in pressure of a vertical fracture alone, and the vertical stress can be determined by calculation of overburden weight or a shut-in pressure on a horizontal fracture.

The relationship of shut-in pressure to the minimum horizontal stress has been well established for holes where the horizontal stress is the minimum stress; however, where the vertical stress is the minimum stress, interpretation is not clear. Zoback and Pollard [1978] suggest that such stress conditions may be diagnosed from a series of reinjection test records. Specifically, the shut in pressure should have an initial value reflecting the minimum horizontal stress. It should decline as the fracture is propagated from the borehole and changes its orientation from vertical to horizontal. This change in orientation is shown schematically with the corresponding pressure-time records in Figure 1. The primary evidence that the late cycle shut-in pressure reflects the vertical stress acting on a fracture that has rotated horizontally is the correspondence of the value of the shut-in pressure with calculated overburden pressures. While this line of reasoning is appealing, its supporting evidence is largely circumstantial rather than based in theory or direct observation of fractures, which were known to change orientation as in a laboratory experiment. Given these uncertainties, it is desirable to have other, more direct evidence that the fracture has changed orientation. Either a surface tilt record or an acoustic tracking of the fracture's propagation could provide the necessary data.

2.1.4 Research Needs

Hydraulic fracturing as a stress measurement method should be performed at the Oak Ridge site over a range of depths above and below the disposal horizon. As discussed above, these tests need to be carried out with special attention paid to determination of the value of the minimum horizontal stress relative to that of the vertical stress. The proposed program is described in Section 3.



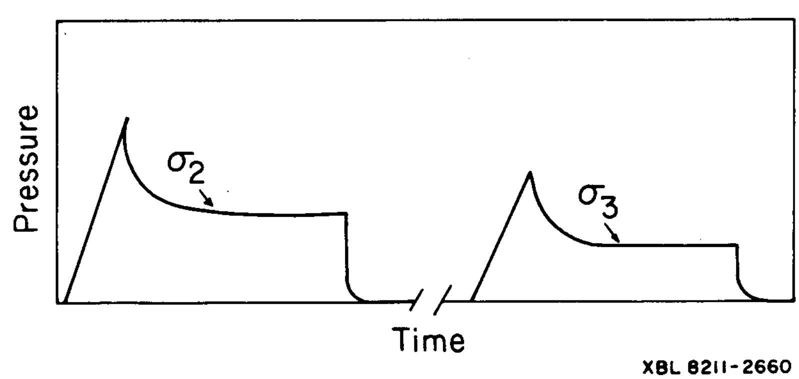


Figure 1. (a) Change in orientation of hydraulic fracture away from borehole when minimum stress in vertical.
(b) Corresponding pressure time record.

Knowledge of the state of stress is important not just because of its controlling influence on fracture orientation, but also as boundary and initial condition input into the several modeling programs.

2.2 EFFECT OF GROUND SURFACE ON FRACTURE ORIENTATION

The virgin in situ stress field is the factor controlling the orientation of the fracture when its length is small relative to its depth. However, as a horizontal fracture grows to a size where its diameter is approximately the same as its depth, the earth's surface begins to exert an influence tending to deflect the fracture upward.

The influence of the earth's surface on the stresses and deformations associated with hydraulic fractures has been studied by Sun [1969], Pollard and Holtzhausen [1979], and Davis [1983]. The Sun model, originally developed to interpret the surface deformations, is an analytical solution for the surface deformation associated with a circular, horizontal, penny-shaped crack. Pollard and Holtzhausen numerically modeled a two-dimensional fracture not only looking at the surface deformations, but also the mode I and mode II stress intensities in the vicinity of the crack tip. Davis used a dislocation model to obtain the surface deformation over hydraulic fractures of any inclination.

Despite being two-dimensional, the Pollard and Holtzhausen model is the most useful for studying the propagation of the fracture, as opposed to looking only at the surface deformation. Of particular significance is the observation that fractures will tend to propagate out of the horizonal plane after their size exceeds a critical value; hence, the model bears great significance to the question of how large a fracture can be emplaced at a site. The tendency of the crack to propagate out of its own plane is related to the shear stress intensity at the crack tip (K_{II}). Figure 2 shows how these stress intensity factors change as the fracture increases in its ratio of radius (or half length) to depth. The drastic change in values as the crack increases in size reflects the onset of the upwarping of the overlying strata. In terms of intrusive igneous structures, this is analogous to the transition from sill to laccolith.

One cannot accurately predict when the fracture will begin to turn upward without knowing fracture toughness values for the material (mode II fracture toughness values are quite controversial and difficult to obtain), but Figure 2

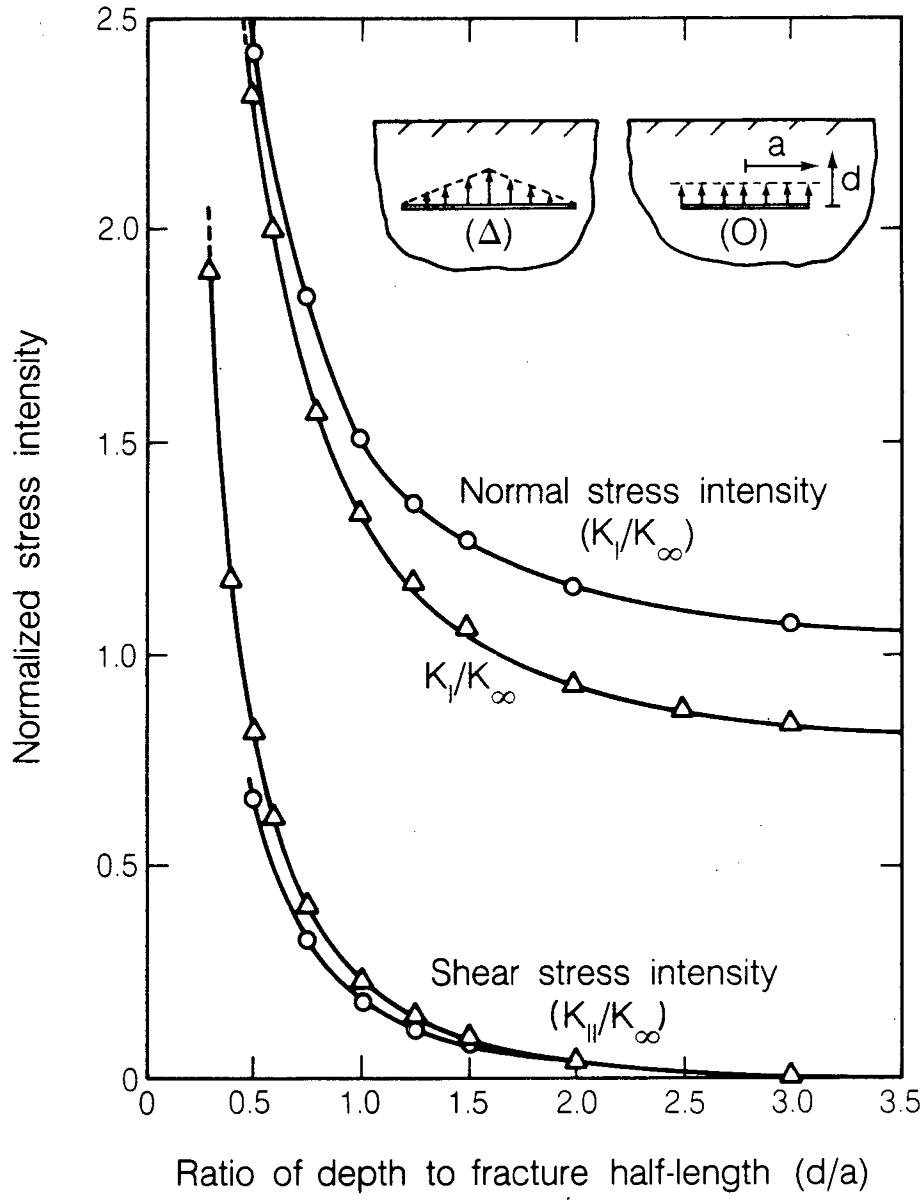


Figure 2. Change in mode 1 and mode 2 stress intensity at tip of fluid pressurized crack as a function of the ratio of depth to crack half length (d/a) (from Pollard and Holzhausen, 1979).

does indicate depth to length ratios where major problems might occur. If high shear stress intensity values promote upward fracture growth, such growth can be avoided by keeping the depth to half-length ratio above about 1.5. Thus, at 300 m, which is the current injection depth at Oak Ridge, the fracture half-length where vertical propagation would begin would be about 200 m.

Using this analysis, we can compare the parameters of the current disposal program with the critical values for upward propagation discussed above to obtain a rough safety factor. The half length of the current disposal fractures has been estimated as about 120 m based on the intersections with the observation wells. If the critical length is 200 m, then the disposal fractures reach about 3/4 of the initial value. A better measure of safety margin, however, is to consider the volume of waste currently injected into each fracture with the volume of the critical fracture. We can determine the volume of a fracture by combining a relationship for the volume of a fracture in an infinite medium [Davis, 1983].

$$\nu = \frac{8(1-\nu)Pa^3}{3\mu}$$

with the stress intensity necessary to propagate the fracture,

$$K_{IC} = \frac{2}{\pi} Pa^{1/2}$$

or

$$P = \frac{\pi}{2a^{1/2}} K_{IC}$$

to yield

$$V = \frac{4\pi(1-\nu)K_{IC}}{3\mu} a^{5/2}$$

where:

P = pressure

V = volume

ν = Poisson's ratio

a = crack radius

μ = shear modulus

K_{IC} = critical mode I stress intensity.

The volume of the fracture thus increases with the 5/2 power of crack radius. From this, one can readily show that although the ORNL fractures have radii which are 75 percent of the critical value, the storage capacity of the current fractures is only 28 percent of the storage capacity of the fracture with a critical radius value.

Accompanying the rise in stress intensity with crack length is a large increase in the opening of the fracture thickness as shown in Figure 3. Such an increase would be accompanied by a drop in pumping pressure or increase in flow rate depending on whether constant flow or constant pressure injection controls were used. This problem has been studied by Noorishad and Doe [1982]. As the pressure and flow records seem to indicate more or less steady conditions, the critical uplift apparently is not occurring in the disposal operations at the Oak Ridge site.

The complexity of the fracture propagation is increased where the hydraulic fracture is dipping rather than horizontal. For a fracture dipping 30°, Pollard [1983] has shown that crack extension force is greater at the fracture's up-dip edge (Figure 4), but that the shear stress intensity is greater at the down-dip edge (Figure 5). This result suggests that dipping fractures will propagate predominantly on the up-dip edge, but will tend to break more sharply toward the surface on the down-dip edge. This effect is consistent with the inferred geometry of the grout sheet from the first Oak Ridge tests of DeLaguna et al [1968] shown in Figure 6.

The vertical propagation of the fracture predicted by the Pollard and Holtzhausen model is a serious rock mechanics problem that should be considered in conjunction with the waste disposal operations. The main lesson to be learned is that disposal operations have a minimum depth for any given size of fracture or volume of waste disposed. Fortunately, the uplift failure should be easily detected from drastic changes in the pumping characteristics during a disposal operation. Thus, it is unlikely that such an event would go

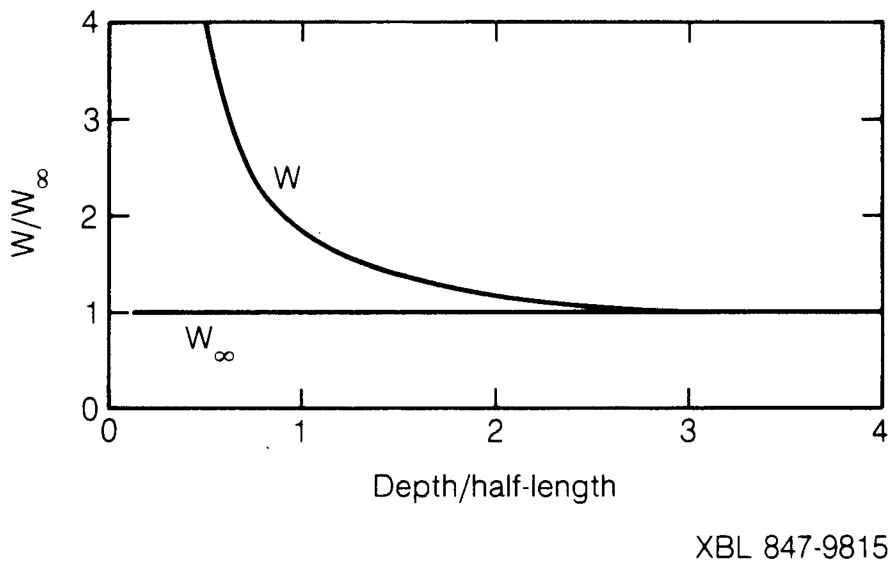


Figure 3. Opening, W, of fluid pressurized crack as a function of the ratio of depth to crack half length (Pollard and Holzhausen, 1979). W_∞ is the value obtained with no free space effect.

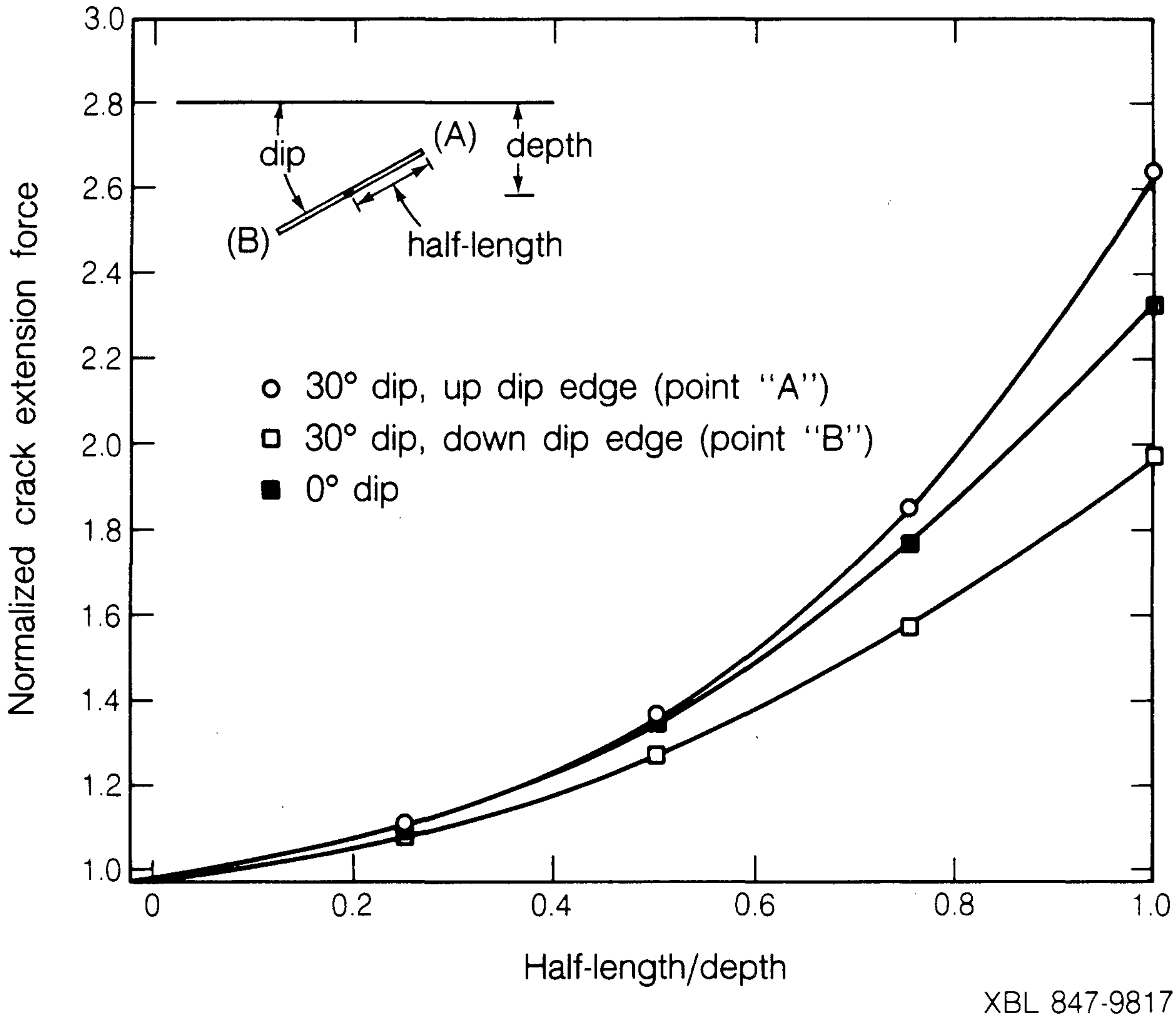


Figure 4. Crack extension force at up-dip and down-dip edges of a fluid pressurized crack dipping at 30°.

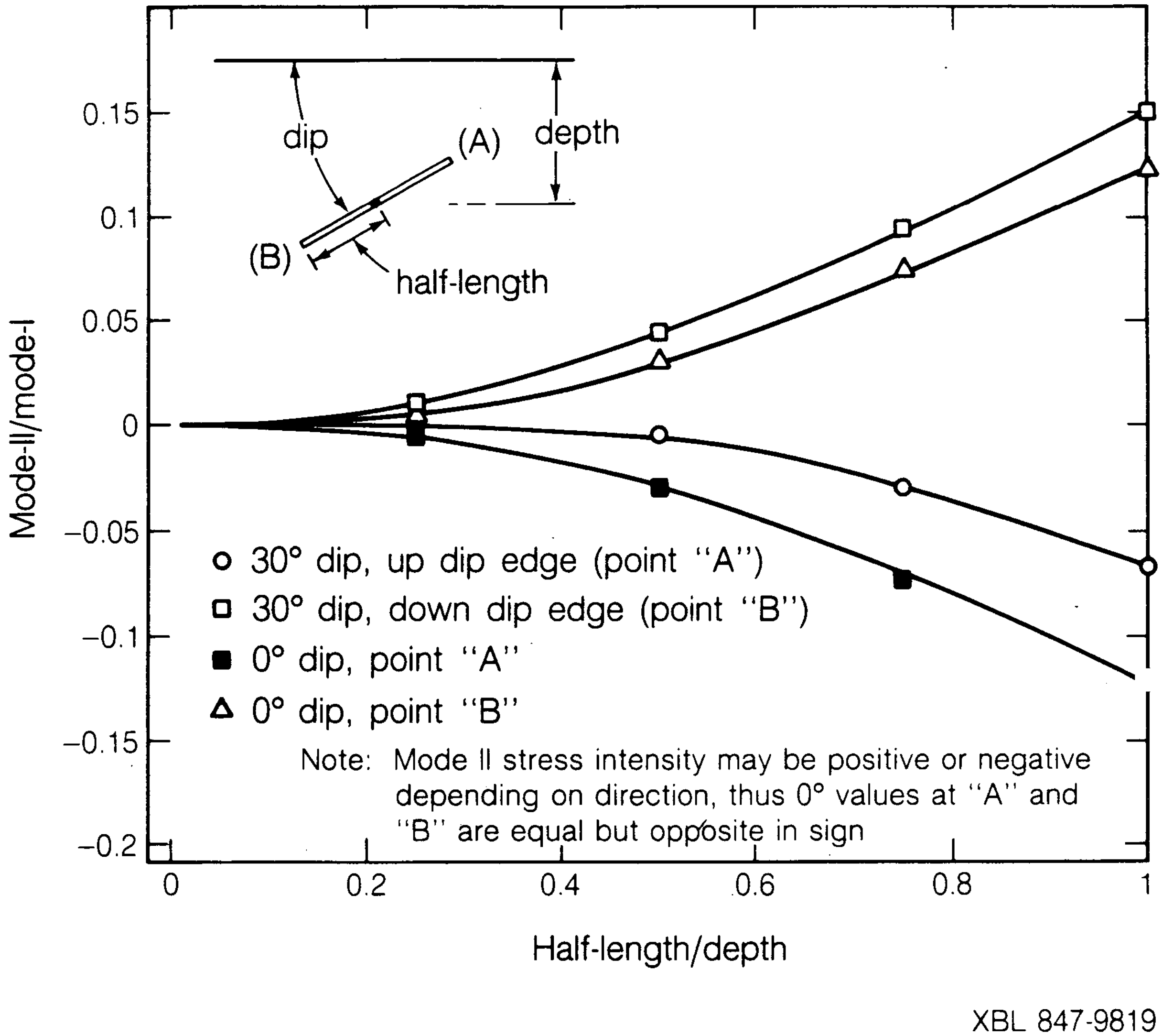


Figure 5. Shear stress intensity at up-dip and down-dip edges of a fluid pressurized crack dipping at 30°.

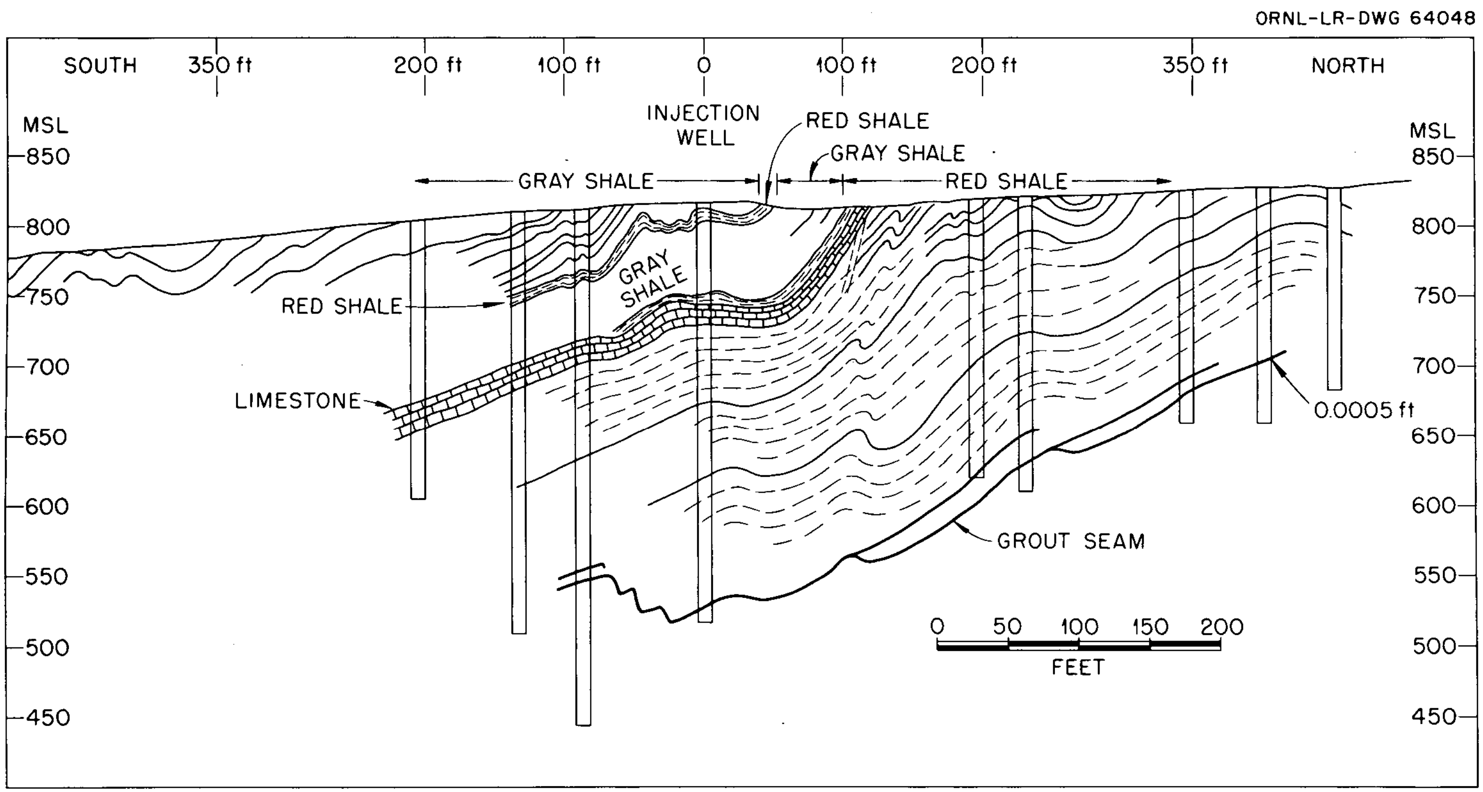


Figure 6. Inferred location of grout seam in first hydraulic fracturing experiment, 4-acre site, Oak Ridge (from De Laguna et al., 1968).

undetected or not be noticed until monitoring data had been analyzed long after the disposal.

2.2.1 Research Needs

The research needs for this issue involve calculational modeling, laboratory testing, and field testing. For the modeling, it would appear advantageous to examine the surface effects using two different models incorporating different and independently developed approaches; for example, the models of Pollard and Holzhausen [1979] and Cleary [1983]. With two different models, there is an opportunity to perform comparative (benchmark) analysis on the same problem, thereby providing greater confidence in the models. The fact that the models are based upon totally different approaches also provides a greater opportunity for gathering a greater insight and understanding of the entire hydraulic fracturing process. This is illustrated by some preliminary calculation of Narendran and Cleary [1983], which suggests that when horizontal fractures are deflected upward due to the surface effect, they may not necessarily continue in that direction but instead will turn horizontal again (Figure 7).

Both of these models will require some further development (to perform the calculations in axisymmetric three-dimensions rather than two-dimensions) to be suitable for analysis of the hydraulic fracture waste disposal problem.

Appropriate laboratory tests examining the effect of the surface are desirable as a means of validating the calculational models. A field test is highly desirable for validation of the calculational models of this surface effect. Such field tests may be difficult and expensive and should, therefore, await a better understanding of this phenomena.

2.3 EFFECT OF MATERIAL ANISOTROPY ON FRACTURE ORIENTATION

Well-bedded or strongly foliated rocks exhibit significant mechanical anisotropy, both in strength and deformational properties. By propagating the fracture along bedding planes, the grout sheet is confined to the host shale strata. If the bedding is nearly horizontal, it should assist in maintaining horizontal (or conformable) fracture propagation. Where the in situ stresses

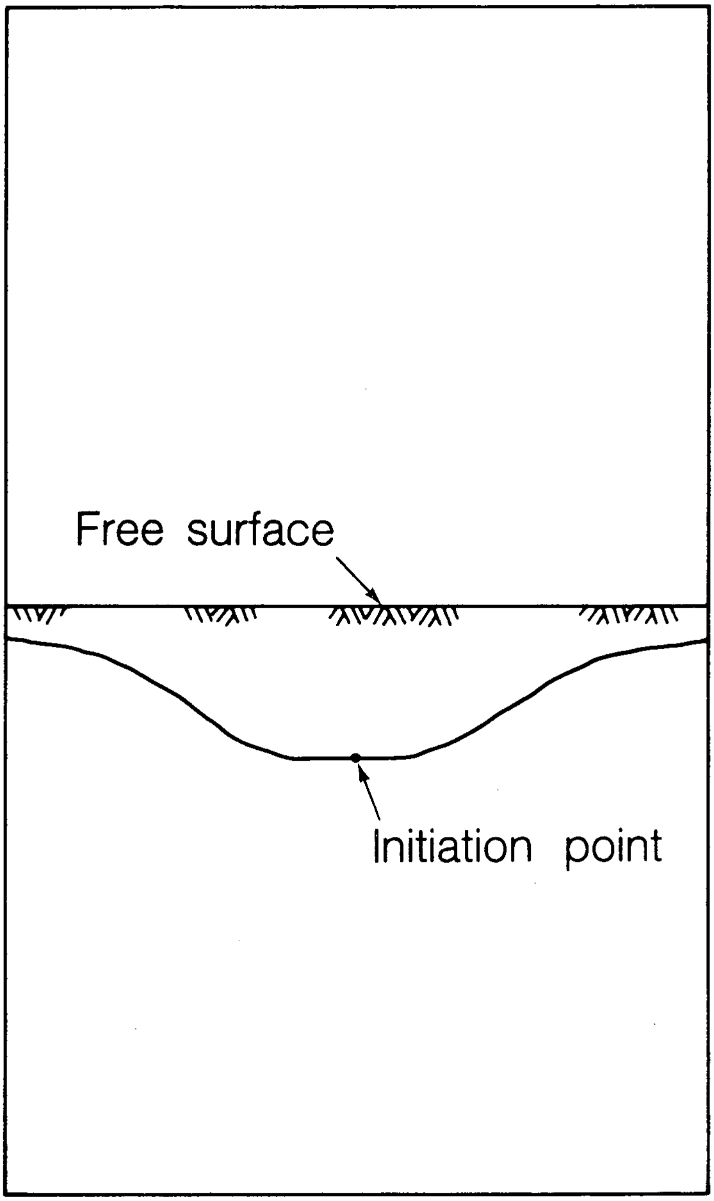


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Figure 7. Calculated propagation of hydraulic fracture towards surface using methods of Navendran and Cleary (1983). Note the turning of the fracture into the horizontal plane at a length of about three times the depth.

are hydrostatic or the minimum stress is oriented normal to the bedding, the confinement of the fracture to the bedding planes should be assured. However, it is not clear that the bedding will control fracture propagation when the stresses are not so favorably oriented.

Several laboratory studies of hydraulic fracture propagation in bedded or foliated rocks have been performed. Haimson and Avasthi [1973] simulated hydraulic fracturing stress measurements in slate. Some of the boreholes for the hydraulic fracturing were lined with plaster to test the influence of fluid penetration into the rock prior to fracturing. They found that the foliation controlled the fracture orientation when the foliation dip was within about 30° of the borehole, and the borehole was open. If the tests were run with a plaster borehole lining, the fracture propagation reflected only stress conditions regardless of the foliation orientation. Blaisdell and Kim [1979] studied the influence of the bedding planes in Antrim (Michigan) shale on the hydraulic fracture orientation. The tests were carried out on cylinders of rock with the bedding normal to the core axis. Variable confining stresses to about 2 MPa and a vertical stress of about 10 MPa were applied. Vertical fractures were produced only when the confining pressure was below about 0.7 MPa, and the remaining tests produced horizontal fractures along the bedding. These results imply that for this test configuration and material, the rock property anisotropy contributed the equivalent of a 9.3 MPa stress difference. Blanton [1981] performed hydraulic fracturing tests on blocks of Devonian shale from West Virginia using a polyaxial loading frame to simulate the in situ stresses. Four tests were run with a vertical stress of 20 MPa, maximum horizontal stresses of 10 to 20 MPa, and minimum horizontal stresses of 5 to 10 MPa. The fractures propagated vertically in three of the four tests. The remaining test was performed with the horizontal stress difference (2 MPa), and a horizontal fracture was opened along a bedding plane.

The influence of bedding anisotropy and moisture content on fracture toughness measurements in shale has been studied by Kenner et al [1982]. Their tests followed procedures developed by Ingraffea [1981] for obtaining mixed-mode propagation. They concluded that the critical stress intensity decreased with increased moisture content. Mode II results were found to be dependent on whether the loading was parallel or perpendicular to the bedding.

The laboratory studies suggest that hydraulic fractures can propagate along bedding planes when the vertical stress is not the minimum stress, provided the vertical stress and the minimum horizontal stress are sufficiently close in magnitude. The material anisotropy effect has not, however, been well quantified. It is not possible to predict at what stress levels and for what relative orientations of stress and bedding the anisotropy exerts a major influence. Conservative planning would not favor relying on material anisotropy for fracture containment under unfavorable stress conditions.

2.3.1 Research Needs

Numerical models for simulating hydraulic fracture propagation in anisotropic materials require development. Further laboratory testing of orientation effects is needed, particularly with regards to the role of fluid penetration along bedding or foliation planes. Field testing to investigate the relative influence of borehole direction, stress orientation, and material property anisotropy should be undertaken.

2.4 EFFECT OF MULTIPLE INJECTIONS

In the hydraulic fracturing waste disposal operation, several injections are made into a single slot, and several slots may be placed within a shale unit. Each of these injections results in a permanent change in the volume underground and, thus, produces a small but permanent change in the local stress field. It is this altered local stress field into which the next injection is made and which defines the "virgin" stress field for that next injection. At this time, the optimal size and number of injections, their spacing in the well, and the sequence, as well as the limits which this effect may place on the process and site, are not clear.

McClain [1968] developed a rationale for determining the capacity of the shale formation based on a "failure" condition where the minimum in situ stress after the injection would be horizontal rather than vertical. Should such a situation develop, the next fracture produced would be vertical rather than horizontal. McClain based his stress analysis on a solution for the stresses around a pressurized crack in an infinite isotropic elastic medium. The analysis identified a critical point above the injection at a height 0.55 times the radius of the injection where the increase in the vertical stress would be the greatest. The key to fracture design was proposed to be avoiding placing injections near this critical point. Among McClain's recommendations were: (1) to make as many injections into a single slot as possible; (2) to space the slots closely; (3) to use low viscosity grouts to obtain large horizontal dimensions and large capacity per grout sheet; and (4) to make no injection at a distance above the first injection of more than 0.3 times the grout sheet radius.

In the years since McClain developed his analysis, considerable advances have been made; both the computational abilities to simulate the fracturing, and in our understanding of the deformational processes. Among the deformational models which should be considered are: (1) the vertical propagation model of Pollard and Holtzhausen [1979]; (2) induced pore pressure effects; and (3) the anisotropy of the shale. The first of these factors, vertical propagation, suggests limits for the desirable horizontal extent of the fracture. The induced pore pressure effects might include pore pressure induced shear failure and permeability changes caused by excessive pore pressure build-up. Avoidance of pore pressure effects might dictate the rate of injection (and thus the rate of deformation) and the timing between injections to allow full dissipation of pore pressure.

2.4.1 Research Needs

It would appear that the only effort needed in this area is a series of parametric calculations using the much more complete and sophisticated models developed for the analyses of surface effect, anisotropy, and pore pressure. The parameters of interest are:

1. The size (volume) of a single injection.
2. The depth of the injection.
3. The variation in size (volume) from one injection to the next.
4. The average pumping rate for an injection.
5. The number of injections into a single slot.

6. The time delay between successive injections.

7. The spacing between successive slots.

8. The position of subsequent slots relative to previous slots (above or below).

9. The total volumetric capacity of a given thickness of shale formation.

10. Sensitivity of calculations to material properties of the rock including strength, deformational properties, porosity, and permeability.

The results of these parameter studies can be stated in terms of the optimum and limiting operating conditions.

Following the completion of the parameter studies, it may be worthwhile to consider confirming and validating some of the results with a limited series of laboratory tests. This may be especially valuable if new, different, or unexpected results are obtained.

2.5 PORE PRESSURE EFFECTS

The monitoring system at the Oak Ridge hydraulic fracturing site consists of cased "observation" wells and "rock cover" wells. The cased observation wells are drilled to a depth slightly below that of the disposal depth. The wells are logged with a gamma ray detector before and after each injection to locate the radioactive grout sheet. The rock cover wells are drilled to within about 120 m of the disposal zone and are cased except for an open interval of about 30 m at the bottom of the hole. Diagrams of typical completions are shown in Figure 8. The purpose of the rock cover wells is to monitor the integrity of the shale formation and to detect any vertical fractures that might propagate upwards from the disposal zone. Both the observation wells and the rock cover wells are capped during the injections and the pressures are monitored using Bourdon tube gauges. Despite the low permeabilities of the shale, the rock cover wells are generally flowing wells, that is the hydraulic head at the cased depth is higher than the ground surface. The high hydraulic heads are not surprising given the location of the facility near the floor of a valley.

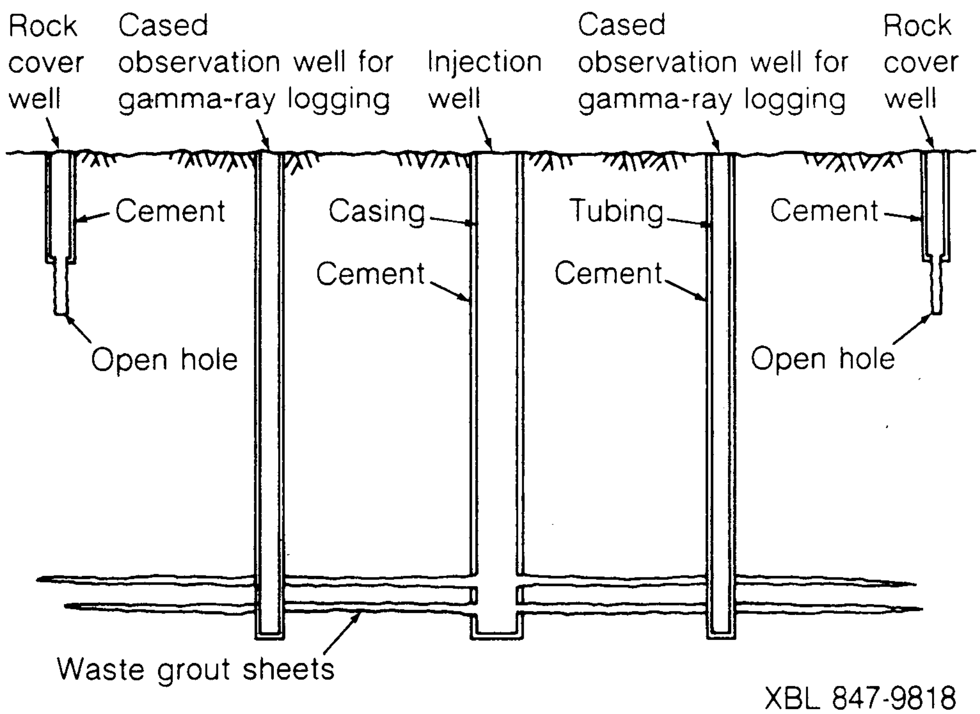

Figure 8. Typical well completions for rock cover and observation wells at Oak Ridge.

The pressures in the rock cover wells typically change during the injection. DeLaguna et al [1968] report that the pressures in the rock cover wells may decrease or increase depending on their position relative to the direction of fracture propagation; the largest increases appear to be in wells overlying the fracture. The increase in pressure measured at the surface may range from less than 70 kPa (10 psi) to over 700 kPa (100 psi). Pressure increases of over 7 MPa (1,000 psi) have also been observed in the observation wells, where the communication of the well with the formation or fracture has been attributed to leaks in the casing. Sample records of the pressure changes in the rock cover wells are shown in Figure 9.

The permeability of the rock cover wells may also be affected during the disposal operations. DeLaguna et al [1968] have also reported the results of injection tests performed during the waste disposal where the flow rate into the wells would vary with time during the injection.

The origin of the pore pressures induced by the disposal operations may be a key to understanding the deformational mechanisms by which the rock accommodates the injected volume. If the shales are compressible and porous, then a consolidation type of response (undrained compaction) can be considered in addition to elastic deformation of the rock overlying the hydraulic fracture. The consolidation response clearly would be time dependent; hence, the rate of pore pressure dissipation might be an important factor in setting the frequency of the injections. Furthermore, the material properties of the overlying shale may change with each additional injection as the shale "consolidates."

Excessive pore pressures may cause fracturing of the rock either by induced hydraulic fracturing or by contributing to shear failure. The induced hydraulic fracturing would occur if the rate of pore pressure build-up was sufficiently in excess of the rock's capacity to dissipate excess pore pressures that local fractures would be produced. The orientations of these fractures would conform to the altered stress field above the disposal zone. The formation of induced hydraulic fractures would not necessarily compromise the integrity of the site as the fractures would probably be too small to be significantly interconnected. High pore pressures can also lead to shear failure or shear displacement along bedding planes and discontinuities.

Knowledge of the distribution of pore pressure changes around the disposal zone would contribute greatly toward understanding the deformation of the rock mass. The increase or decrease of pore pressure should be directly related to

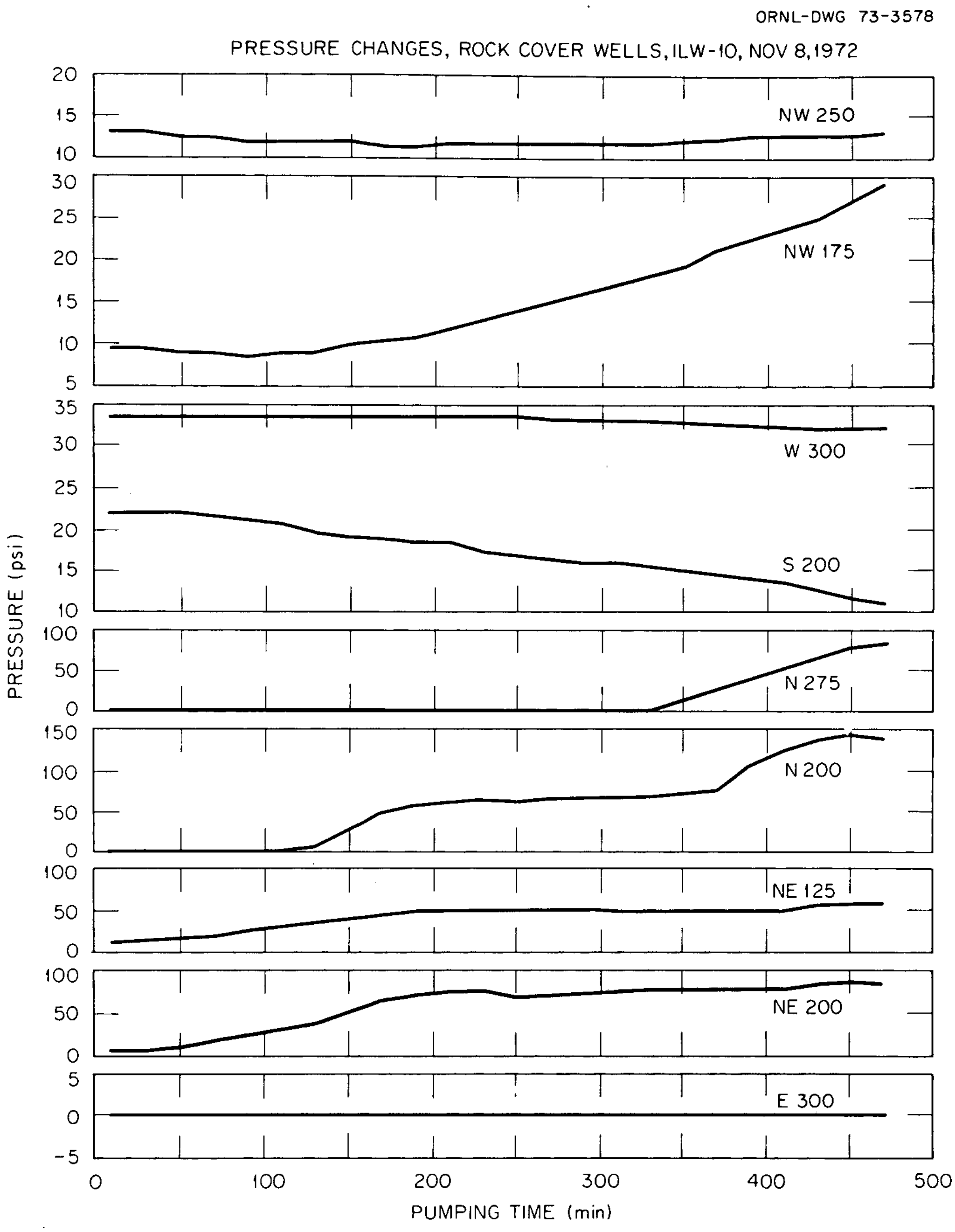

Figure 9. Pressure changes in rock cover wells during injection of Nov. 8, 1972.

the regions where compression and dilation are taking place. The pore pressure can also be used to determine to what extent consolidation takes place. If consolidation occurs, then interpretations of the fracture size based on elastic deformation could be in error. If there were a direct measurement of the hydrofracture aperture, discrepancies between its calculated surface deformation and the measured deformation could be attributable to nonelastic deformational mechanisms.

2.5.1 Research Needs

Calculations should be made to investigate sources of pressure build-up in observation wells during hydrofracturing. Possible mechanisms include fluid diffusion from the fracture zone and poro-elastic deformation of the rock. If poro-elastic processes are plausible, laboratory and field measurements of relevant material properties such as porosity, compressibility, and permeability should be made on shale cores. Care must be taken in core drilling and sampling to maintain samples in their undisturbed state, particularly with regards to moisture content. Records of observation well pressures should be reviewed to ascertain pressure trends during disposal operations. Pressures in observation wells should be continuously monitored, and additional wells should be drilled to monitor pressure as a function of depth. Permeability measurements should be made in the rock cover wells.

2.6 EFFECT OF DISCONTINUITIES AND HETEROGENEITIES ON FRACTURE GROWTH

The shale strata used for waste disposal may contain heterogeneities which influence the propagation of the grout sheet. Vertical discontinuities (fractures, joints, or faults) and local small scale folds within the shale are such features. When a hydraulic fracture intersects a discontinuity (1) it may be diverted to another bedding plane; (2) its propagation may be arrested; or (3) it may, in the case of a vertical fracture, pass out of the shale horizon into more permeable strata.

Diversion of the fracture from one bedding plane to another has been inferred from the tracking of the hydraulic fractures between the observation holes at Oak Ridge (Figure 6). The exact cause of these diversions is generally not known, but exposures of the shale reveal small scale structural irregularities (drag folds) which could readily be the cause. The arrest of the horizontally developing grout sheets by a vertical discontinuity has not been observed; however, a consistent asymmetry of the grout sheets about the injection well could be interpreted as the result of such an arrest. The diversion of the grout sheet out of the disposal horizon along a vertical fracture has not been observed at the Oak Ridge site.

The influence of rock heterogeneities on hydraulic fracture propagation has been extensively studied theoretically and experimentally to develop strategies for fracture containment in gas- or oil-bearing strata. Most of the work has been on vertical rather than horizontal fractures, yet the basic controls on containment are relevant to the problem of horizontal fracture propagation. Simonson et al [1978] identified modulus contrast and in situ stress as being the main controls on fracture containment in layered formations. Daneshy [1978] pointed out that the strength of an interface could also provide containment if the interface was sufficiently weak. Anderson [1981] showed experimentally that friction and normal stress contribute to the arrest of fractures at unbonded interfaces. Specifically, fractures could be propagated across unbonded interfaces when the normal stress or interface friction were high.

Warpinski et al [1982] performed an extensive program of field investigations of hydraulic fracture propagation in tuff which involved mining out the fractures and mapping their geometry. Their conclusions were that the variations in the in situ stresses had the greatest effect on fracture propagation. A complementary laboratory study [Warpinski et al, 1982a] concluded that stress contrasts of as little as 2 MPa were sufficient to restrict fracture growth. Another finding of this field work was that natural fractures could cause significant offsets in the hydraulic fractures while taking up substantial quantities of grout themselves.

2.6.1 Research Needs

The effort required on this issue is minimal, at least until enough additional understanding of the waste disposal hydraulic fracturing system is developed to identify specific concerns. The behavior of hydraulic fractures as they approach either discontinuities or heterogeneities can be modeled with existing analytical capability and that capability can be easily added to the calculational models required for other aspects. If a specific concern arises from some other part of the program (especially, for example, from geological and hydrological characterization studies currently being carried out at the Oak Ridge site), both additional calculations and appropriate laboratory studies can be undertaken. If a major investigation should be indicated, mine-back type tests are an effective (but expensive) method of obtaining relevant and exceeding useful information, provided that an appropriate underground test site can be identified.

2.7 EFFECTS OF FLUID PROPERTIES

The properties of the hydrofracturing fluid influence the uplift pressure on the overburden, the extension of the hydraulic fracture, and (under some circumstances) the direction of propagation. Properties of particular importance are viscosity and density.

The viscosity of the grout is a major factor in the flow of the fluid in the hydraulic fracture. The pressure losses along the wellbore and in the fracture are largely governed by the viscosity. Hence, the pressure profile along the fracture and the resulting uplift and stress concentration at the crack tip are affected by the fluid properties. The influence of pressure profile on crack tip stress concentration is shown in Figure 2.

The role of fluid viscosity is further complicated by the non-Newtonian nature of the Oak Ridge grouts. In such fluids, the viscosity increases with decreasing fluid velocity; hence, resistance to flow should increase as the grout spreads radially from the well.

For dipping hydraulic fractures, the density of the fluid will affect the stress intensities at the up-dip and down-dip edges of the fracture. Secor and Pollard [1975] have shown that when the fluid density is lower than the surrounding rock, stress intensities are higher at the up-dip edge. When the fluid density exceeds that of the rock, the down-dip edge has the higher stress intensity. To a limited extent, therefore, vertical propagation of the fracture may be controlled by the fluid density. However, the cost of preparing a grout whose density approaches lithostatic values would probably be prohibitive.

2.7.1 Research Needs

The main research need is a calculational program to determine the influence of non-Newtonian fluid properties on the behavior of the system. The task requires a model which couples the fluid flow, the rock deformation, and the fracture propagation. Examples of such models are those of Narasimhan and Palen [1981] and Cleary et al [1983].

Laboratory measurements of the viscosity of representative fluids are required to assure the quality of the numerical work.

The calculational program should address how varying the fluid properties can influence fracture geometry. For example, will higher viscosity grout mixes tend to produce shorter fractures with larger aperatures. Fluid density and viscosity should also be considered in designing experiments to evaluate the control of rock anisotropy on fracture growth and the intrusion of grout into natural fractures.

Due to the viscous nature of the fracturing fluid, the hydrofracture injection pressure should be monitored, if possible, at the bottom of the well in addition to monitoring at the well head. If such monitoring is impractical, pressure loss experiments should be performed in pipes using simulated grout mixtures to provide the data necessary to calculate bottom role injection pressures.

3 PROPOSED RESEARCH PROGRAM

3.1 INTRODUCTION

This section describes a research program for resolving the technical issues discussed in Section 2. The research program was developed by sifting, sorting, and shaping the ideas and suggestions discussed at the Berkeley workshop within the constraints. Those constraints did not permit the inclusion of all possible approaches but did allow for the development of a comprehensive program, which at least begins to address all of the rock mechanics issues related to hydraulic fracturing waste disposal. The program is organized around four broad categories of research work:

- Numerical modeling;
- Laboratory experiments;
- Field experiments; and
- Monitoring of the Oak Ridge hydraulic fractures.

The reason for this breakdown of activity is that we expect that most research tasks will provide insight into more than one of the technical issues. For example, a numerical model which can simulate the fracture growth and the deformation of the surrounding rock would be used for such issues as the surface uplift, fracture propagation across heterogeneities, and for fracture growth in anisotropic media. Similarly, laboratory or field experiments which are run in shale would provide information on issues relating to deformation around the fracture and anisotropic effects on fracture growth.

Each of the four tasks relies on the others for support. A description of each task and the interrelationships of the tasks to one another are contained in the following paragraphs.

Numerical modeling is considered here to be a broad category of all computational work, from "back of the envelope" calculations to sophisticated computer simulators. The ultimate, fully-coupled, numerical model would enable us to make accurate predictions of how a hydraulic fracture will behave underground. The model would be used to design each new injection at the Oak

Ridge site, and it would be essential to developing disposal strategies for new injection sites.

Developing such a model is a long and tedious process. First, one must understand the basic physical processes of hydraulic fracturing in shales. This understanding is gained by reviewing hydraulic fracturing case histories of all kinds and the experiences that have been gained at Oak Ridge in particular. Once a model has been prepared, it must be verified, which means one must confirm that the model is performing the calculations it claims to be making. Verification is usually done by comparing the model results with those of well known solutions. Once verified, the model must be validated. Validation for these purposes means that the model is an accurate simulator of field behavior. As the model is being developed, interim validation steps should include simulation of laboratory and field tests, as well as simulation of past injections at Oak Ridge. The ultimate validation must come from accurately predicting the behavior of an actual disposal operation or a large-scale field test.

Laboratory testing provides (1) material property data for use in calculations; (2) insight into the basic physical processes of hydraulic fracturing; and (3) validation of a numerical model through laboratory scale simulation tests. Laboratory testing for material property values and basic physical understanding should be undertaken early in the research program to provide guidance to the model development effort. Simulation studies may be planned while the model is being developed and undertaken after the model is operating.

Field experiments also provide insight into physical processes, and are used to validate the effectiveness of models and calculations. As simulations, field tests are performed at larger, more appropriate scales than laboratory tests. Field tests have disadvantages relative to laboratory tests. First, field tests are usually expensive. Second, the conditions of field tests (such as the material conditions, stresses, etc.), are not controlled and may not be well known; thus, it may be difficult to isolate the sources of variability in the experimental observations. Like the laboratory simulations, field experiments should be planned while models are being developed, to be undertaken once the models are running.

Monitoring activities consist of measurements and experiments which are performed as part of the disposal operations at ORNL. A considerable body of information has been gathered during the injections that have already taken place. Furthermore, opportunities exist to make measurements during future disposal operations. Data gathered from these injections may be obtained at lower cost than from corresponding field experiments. Monitoring cannot take the place of field experimentation, however, because many activities are not possible in an active disposal site, such as coring samples from the grout sheets.

3.2 NUMERICAL MODELING

If hydraulic fracturing is to become a widespread method of waste disposal, then a numerical model which completely simulates all aspects of the injection process should be prepared. The model should be truly three dimensional and must include the following:

- Elastic and nonelastic deformation of the rock (including poro-elasticity effects);
- Fluid flow (both Newtonian and non-Newtonian);
- Pore pressure effects;
- Fracture propagation;
- Effect of discrete discontinuities on fracture growth;
- Surface deformation and uplift;
- Material property anisotropy; and
- Ability to handle variable material properties.

We suggest that a model development program be undertaken which expands the capabilities of more than one of the existing modeling approaches toward developing a complete model. Among the possible approaches are surface integration techniques [Cleary, 1983], finite element methods [Ingraffea, 1983], integrated finite difference methods [Narasimhan and Palen, 1981], and interative superposition of analytical solutions [Pollard and Holzhausen, 1979]. Some of the models are now capable of limited coupling of the fluid flow and the rock deformation [Noorishad and Doe, 1982].

Although great strides have been made in the modeling of hydraulic fractures in recent years, the complete simulator described above does not exist, and it is not certain that a moderately funded, three year program would produce it. We therefore propose using numerical modeling to assess individual issues or problems involving combinations of the issues identified in Section 2. The complexity of simulating hydraulic fractures is great enough that one cannot confidently identify a single ideal numerical approach that will be successful. We therefore suggest pursuing independently as many as three separate model approaches--an uplift model, a detailed fracture propagation model, and a coupled fluid flow and deformation model.

First, a model of the surface uplift along lines similar to that of Pollard and Holzhausen [1979] should be expanded to include multiple fractures, pore pressure effects, nonuniform vertical stress (which result from irregular surface topography), and material anisotropy. This model employs analytical solutions which are superposed through an iterative scheme. Calculations should also be made to assess the significance of consolidation and pore pressure.

Second, a detailed model of the fracture propagation using interactive finite element models such as those developed by Ingraffea [1983] should be expanded to include material anisotropy and nonelastic deformation.

Third, existing coupled fluid flow and deformation models should be extended. Examples of such models include those of Cleary [1983] and Narasimhan and Palen [1981]. Of particular importance is obtaining a pressure profile in the fracture, which is required for uplift calculations in the surface uplift model described above. Also of great importance will be modeling pore pressure generation in the rock surrounding the hydraulic fracture.

We strongly recommend that modelers involved in the separate efforts communicate with one another frequently to compare results and conclusions. This should be accomplished through information meetings of the principal investigators with Oak Ridge's technical staff on a semi-annual, or perhaps even a quarterly basis.

3.3 LABORATORY TESTING

There are two principal purposes in performing laboratory experiments. First, measurements of material properties must be made to provide data for numerical modeling. Second, laboratory-scale simulations of hydraulic fracturing should be performed to validate calculations made by numerical models.

Among the material properties that must be determined for the shales at Oak Ridge are:

- Fracture toughness (both Mode I and Mode II);
- Porosity;
- Permeability; and
- Deformational properties (including drained and undrained moduli).

Where possible, the variation of the above material properties should be determined as a function of orientation relative to bedding. The samples tested must be as undisturbed as possible. As shale may rapidly degrade due to moisture loss, cores must be sealed immediately upon their removal from boreholes.

The physical properties of grout mixtures should be compiled and additional measurements should be made as necessary. Of particular importance are the density and viscosity of the grouts, along with the dependence of these properties on flow velocity.

Laboratory testing is also a useful means of identifying basic physical processes of fracture propagation and for validating the performance of numerical models. Laboratory tests may not always be appropriate in scale to be considered accurate simulations of field conditions. But, regardless of the scale, the results are useful for checking model calculations, which should at least be able to simulate the laboratory situation.

Particular experiments that should be undertaken include the following:

- Hydraulic fracture growth near free surfaces;
- Relative importance of in situ stress and bedding in controlling hydraulic fracture propagation;
- Hydraulic fracture growth near preexisting discontinuities; and
- Pore pressure changes in shales near hydraulic fractures.

Additional laboratory simulations may be identified as the validation needs of the numerical models become clearer.

We propose performing measurements of material properties in the initial year of the program as these data are required for the numerical modeling effort. Laboratory tests for simulating and validating models will be performed in the latter two years of the program, and detailed designs for these experiments will be prepared in response to the results of the initial modeling efforts.

3.4 FIELD TESTING

The purpose of field tests are (1) to provide site characterization data for the disposal site; and (2) to provide support for the model development and validation work.

Field testing for site characterization will include in situ stress measurements and measurements of hydraulic properties, specifically permeability. Rock stress measurements should be performed as soon as possible at the Oak Ridge site using hydraulic fracturing augmented by core strain relief methods (an elastic recovery or differential strain analysis), if these methods appear feasible. The most important stress information is to determine at what depth, if any, the vertical stress ceases to be the minimum stress, as this should be the depth beyond which a horizontal fracture cannot be assured. Although the fracture orientation can be inferred from the pressure records of the hydraulic fracturing, an independent means of demonstrating whether the fracture is vertical or horizontal should be used. A record of the surface tilts from the hydraulic fractures made for the stress measurements may suffice for this purpose.

Also important for site characterization are permeability measurements of the rock cover wells, and pore pressure measurements in the shales near the hydraulic fracturing disposal site. These measurements should be made from the surface to at least the depth of the fracturing zones.

Field experiments should also be performed to investigate basic rock behavior and to provide data to validate calculations. Some important field experiments include:

- Propagation of shallow hydraulic fractures toward the surface;
- Propagation of hydraulic fractures from boreholes drilled around underground openings in anisotropic and/or jointed rock where the fracture can later be mined out to verify its growth; and

- Pore pressure changes in rock surrounding a shallow hydraulic fracture.

Ideally, an experimental facility for testing hydraulic fracturing for a waste disposal should be developed before the method is applied to other sites or wastes. The primary use of the facility would be to perform experiments to resolve issues regarding controls on fracture growth. Such a facility would also be used to test monitoring technologies, such as multipoint piezometers, tiltmeters, and geophysical fracture detection methods.

A test facility may be either a test site where the fracturing is done from the surface or an underground facility in an existing mine. A underground test facility has the advantage of allowing direct observation of the hydraulic fractures by mining them out; however, such a facility may be expensive to maintain. Although not as satisfactory as mining back into fractures, the propagation of fractures made in a surface-based facility can be mapped by drilling the experimental grout sheets.

A full scale test facility may exceed the financial limits of this program; hence, more limited testing involving specific research issues should be considered. An experiment in the Mount Airy, North Carolina, granite quarry to test for upward propagation has been suggested. This quarry has used hydraulic fracturing (with air) as an excavation method and upward fracture growth has been observed [Pollard and Holtzhausen, 1979]. Experiments in the anisotropic schists of the Homestake Mine in South Dakota have also been proposed to examine the influence of material anisotropy on fracture growth.

The high cost of field testing necessitates that a test facility must be carefully planned to meet model development and validation needs. Tests carried out at other locations or in other rock types must also be carefully developed to assure their applicability to the Oak Ridge site. Given these considerations, we propose that the initial field testing work be limited to test plan development, with the actual testing to follow the development of numerical models and the analysis of their initial results.

3.5 MONITORING

A considerable body of data has been obtained from the hydraulic fracturing operations of the past at Oak Ridge. These data should be reviewed for insights into the performance of the disposal system. Monitoring data may also be used to aid in the validation for numerical models and calculations.

Existing data from the current series of disposal injections and from previous experimental disposal sites consist mainly of the following: gamma logs of observation wells, injection pressure records, pressure measurements in the rock cover wells, and surface leveling data. More recently, feasibility experiments have been performed using tiltmeters and microseismic monitoring arrays. All existing data, both published and unpublished, should be reviewed, compiled, and made accessible for use in the computational program.

Monitoring activities should be expanded for injections performed in the future. Future monitoring activities should include the following:

- Expansion of the pore pressure monitoring system and installation of a continuous-time monitoring system;
- Development of downhole systems for measuring fluid pressure and fracture aperture in the disposal well;
- Continued tilt monitoring;
- Investigation of transient changes in surface levels after injections; and
- Continued microseimic monitoring and investigation of use of other geophysical techniques (magnetic, resistivity, and controlled source audiomagnetotelluric).

The pore pressures in the rock surrounding the hydraulic fracture may be sensitive indicators of the deformation of the rock. Pore pressure changes may be related to the zones of compression and dilation around the fracture. The pore pressure monitoring array could be improved by the addition of measurements points at several new distances from the disposal well and at several depths. A continuous recording system for the pressure in these wells would also be desirable given the transient nature of the pore pressure dissipation.

Downhole systems for monitoring injection pressure and fracture aperture are desirable to assist in the interpretation of the deformation of rock surrounding the fracture. The data may be difficult to obtain in the hostile operating conditions of the disposal well. Nonetheless, some effort should be made to determine if such monitoring is feasible.

Efforts should be made to continue monitoring the surface tilts, and installation of a permanent array of tiltmeters should be considered. Continuous recording of the tilts should be made between injections to track the transient deformational behavior of the rock. This effort should be complemented by continued surface leveling.

Pending successful interpretation of the current experiments, the microseismic network should be expanded sufficiently to allow precise definition of the fracture propagation. The feasibility of using other geophysical methods (namely, the electrical and magnetic methods) should be investigated.

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