POTENTIAL OF PNEUMATIC FRACTURING TO ENHANCE IN SITU REMEDIATION TECHNOLOGIES

Lewis L. Goodroad and John R. Schuring
Rust Remedial Services, Inc.
Clemson Technical Center and New Jersey Institute of Technology

ABSTRACT

Pneumatic fracturing is an in-situ process which enhances the removal and treatment of hazardous organic contaminants from the vadose zone. Its purpose is to reduce treatment time of contaminated formations, and extend available technologies to more difficult geologic conditions.

The pneumatic fracturing process consists of injecting air or other gases into contaminated geologic formations at controlled flow rates and pressures. The process enhances apertures in the formation in a predominately horizonal direction from the point of injection. This minimizes the potential for vertical transport within the formation. The potential benefits of pneumatic fracturing depend on the type of soil or rock being treated. In fine-grained soils, such as silts and clays, pneumatic fracturing increases the permeability of the formation. In coarse-grained soils, the process provides a means for rapidly aerating the formation. In sedimentary rock formations, pneumatic fracturing can widen the aperture of existing discontinuities and clear away soil in the aperture. Pneumatic fracturing can be integrated with a number of in-situ technologies including vapor extraction, bioremediation, soil flushing, and thermal treatment. Since any in-situ remedial technology is limited by the pore gas exchange of the soil or rock being treated, the potential uses of pneumatic fracturing are significant.

Present estimates of the pressure gradient required to initiate pneumatic fractures range from 60 to 120 kPa per meter (3 to 5 psi/ft) of depth, depending on the geologic medium. In fractured flow studies, analysis of field data has indicated that pneumatically fractured formations conform with the cubic law, i.e. the flow rate through the fractures is proportional to the cube of the fracture aperture. This result emphasizes the high flow potential for even small fractures.

Field testing has confirmed the feasibility of pneumatic fracturing to enhance remediation of the vadose zone. Measurement of residual ground surface heave and increased flow rates after injection confirm the existence of new conductive channels. Field studies also show that pneumatic fractures remain viable for extended periods.

Research is continuing to expand the application of pneumatic fracturing. It is anticipated that the pneumatic fracturing process is capable of injecting both low and high permeability formations with micro-organisms, nutrients, and large volumes of selected gases to encourage microbial growth.

INTRODUCTION

Pneumatic fracturing is a process under development by the Hazardous Substance Management Research Center (HSMRC). The process uses a proprietary HQ injector to inject large volumes of air into a geological formation. The air is injected at pressures high enough to overcome in situ stresses, and volumes exceeding the permeability of the formation. This results in the enhancement of existing channels and interconnection of existing discontinuities in the formation. Pneumatic fracturing has been demonstrated in both soils and sedimentary rock. Due to the nature of the principal geostatic stresses, the fractures are primarily horizontal.

The process increases the permeability of the formation. Existing technologies including in situ bioremediation, vapor stripping, and liquid extraction which are dependent on the permeability of the formation would be enhanced by the application of pneumatic fracturing. Contamination of a site is expected to occur initially in discontinuities within a formation; diffusion into the bulk formation would follow at a slower rate. Since pneumatic fracturing is propagated along existing discontinuities, remediation should be directed at the areas of greatest contamination within a formation.

THEORETICAL CONSIDERATIONS

Pneumatic fracturing is a patented process (1) which is similar in concept to the hydraulic fracturing process used in civil engineering and the petroleum industry. In hydraulic fracturing the fractures are created by injecting water or other liquids into the formation. In pneumatic fracturing, the fractures are created by injecting air or other gases into the formation.

The theoretical considerations of pneumatic fracturing are discussed by Schuring et al (2). A fracture network is created by injecting gas at pressures exceeding the in situ stresses in the formation and at flows rates which exceed the permeability of the formation. When the medium fails, a fracture network is created. The pressure required to initiate fracture, P_i is given by the following expression:

$$P_i = C_1 Y z + C_2 c' \cot(\text{phi}) + B C_3 \qquad (1)$$

where

Y	is the bulk density of the medium
z	is the overburden depth
c'	is the cohesion of the formation
phi	is the angle of internal friction
B	is the factor for fluid compressibility and inertia
C_1, C_2, and C_3	are coefficients

The equation is based on the Coulomb-Mohr failure criterion and assumes that the formation is unsaturated and overconsolidated.

The generally accepted theory of Hubbert and Willis (3) predicts that hydraulic fractures will form perpendicular to the direction of the least principal stress. In an overconsolidated formation, the predominant fracture direction should be horizontal. The natural weaknesses along the bedding planes in stratified formations tend to accentuate the horizontal propagation of the fractures. Fig. 1 depicts the horizontal propagation concept of pneumatic fracturing.

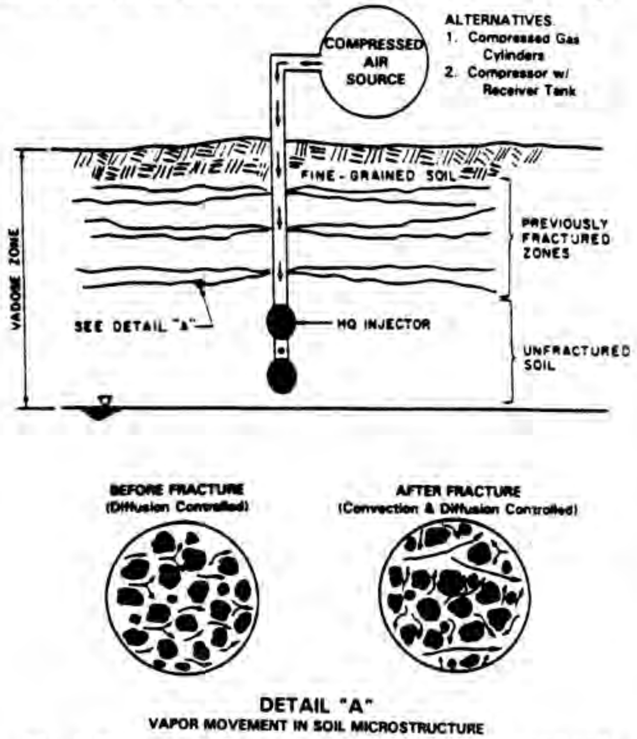

Fig. 1. Pneumatic fracturing concept fine-grained soils.

Another theoretical consideration of pneumatic fracturing is the enhancement of flow rates. Since the flow rate of fractures has been shown to be proportional to the cube of the fracture aperture, the potential increase in flow rate would be significant even for small fractures. The resultant increased flow rate should expand the volume of soil affected by convective flow (see Fig. 1 Detail "A"). Any of the in situ remedial technologies are affected by pore gas exchange. Improvement of the flow rate to reduce the dependence of the remediation technology on diffusion controlled vapor movement should reduce the time required for remediation and improve the effectiveness of the treatment. Vapor extraction, bioremediation, thermal flushing, and soil flushing are examples of in situ remediation technologies expected to be significantly enhanced by pneumatic fracturing.

THE PNEUMATIC FRACTURING PROCESS

Initial site preparation consists of drilling a series of wells in a pattern similar to Fig. 2. The center well is the fracturing well which is 8.9 cm in diameter. The fracturing well is constructed to accommodate the proprietary HQ injector fracturing device which consists of two inflatable packers, a rigid pipe for compressed gas delivery, and a device to evenly distribute the compressed gas over the fracturing interval. The fracturing interval is usually 60 cm. The fracturing device is moved within the well to achieve the desired fracture thickness within a formation by repeated fracturing. For example, to fracture a region 300 cm thick would require positioning the HQ injector at five adjacent locations within the fracture well.

The HQ injector is connected to a compressed gas supply capable of supplying adequate pressure and volume to fracture the formation. The pressure needed to initiate fracturing is dependent on the medium being fractured, but pressures on the order of 60 to 120 kPa per meter (3 to 5 psi per foot) of depth have been used in field studies conducted to date. Pneumatic fracturing is effective at depths in the range from 3 to 20 m.

To initiate fracturing, it is necessary to inject compressed gas volumes greater than the permeability of the formation. The required volume of compressed gas depends on the formation; volumes of up to 50 m^3/min. may be required. The duration of the fracture injection is usually from 10 to 20 seconds. After the injection, the HQ injector is moved to the next fracture interval which may take several minutes for injections in the same fracture well or longer if the injector is moved to another well. Banks of compressed gas cylinders have been used to supply adequate volumes of gas. If compressed air is used, the cylinders can be recharged on the site with an air compressor.

Observations of the direction of fracture propagation from the fracture well have confirmed the predominately horizontal orientation predicted by theoretical consideration. Horizontal fractures are favored in overconsolidated formations since the direction of the least principal stress is vertical. In addition, geological stratification tends to be horizontal. Further evidence for the horizontal orientation of the fractures is provided by electronic tiltmeters. The electronic tiltmeters show surface heave in circular patterns 8 or more meters from the fracture well (Fig. 2b) which is consistent with surface deformation patterns observed for horizontal fractures with hydraulic fracturing. Some dilation of existing vertical fractures is expected, but fracturing of perpendicular planes in a formation is unlikely. The continued presence of perched water tables in some zones after fracturing also indicates that vertical fractures do not form.

Verification and evaluation of fracturing is done using: air communication between the fracturing well and surrounding wells, change in air flow rate in the formation, change in contaminant concentration, ground surface heave, and video camera observations of the fracture well (2). The pattern of wells shown in Fig. 2 is used to determine when fracturing occurs. Pressure measurements are made at the wells surrounding the fracturing well during the fracture injection. When the fracture occurs, pressure surges are observed at the surrounding wells. Measurements of air flow between the fracture well and the surrounding wells are made before and after pneumatic fracturing. Air flow measurements can be made with the surrounding wells closed or open to determine the pattern of fracturing in the formation. Because increased permeability shortens diffusion pathways in the media, the concentrations of volatile contaminants are increased following fracturing. Surface heave is measured by electronic tiltmeters and surface heave rods. The vertical rise of the surface indicates the minimum fracture aperture and the radius of the fracture. Residual surface heave has been observed providing evidence that the fractures remain open after fracturing. Video cameras are used to view the walls of the fracture well before and after fracturing to evaluate the uniformity and extent of fracturing over the fracture interval.

FIELD APPLICATIONS OF PNEUMATIC FRACTURING

The results of a pilot demonstration of pneumatic fracturing at the AT&T Richmond Works established the potential of pneumatic fracturing for enhancement of volatile organic carbon (VOC) extraction from a coastal plain

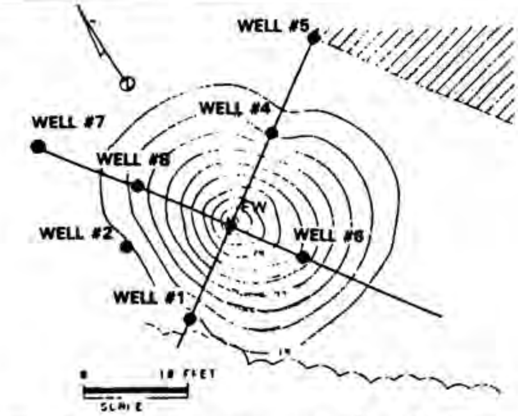

Fig. 2a. Prefracture vacuum radius of influence.

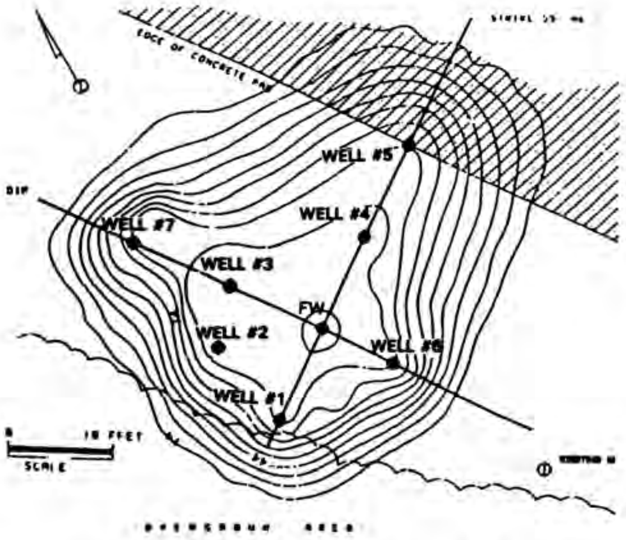

Fig. 2b. Postfracture vacuum radius of influence.

formation consisting of stratified clay, silt, sand, and gravel.(2) Compressed air was injected at 3000 kPa (150 psi) and 20 m^3/min for intervals of less than a minute. VOC concentrations in the vapor extraction stream increased significantly after fracturing compared to pre-fracture conditions. After an initial concentration surge, sustained concentrations of methylene chloride and 1,1,1-trichloroethane(TCA) rose to 432 and 21 ppm, respectively. Measurements of flow within the formation after fracturing indicate more than a thousand-fold increase over pre-fracture conditions. Surface heave measurements estimated the radius of fracture to be more than 4 meters from the fracture well. Residual surface heave was from 10 to 25 percent of the 2.5 cm surface heave observed during fracture injections.

A recent report (4) demonstrated the application of pneumatic fracturing to the process of Pneumatic Fracturing Extraction $(PFE)^{SM}$ in a low permeability formation of clay and shale. Air flow rates were increased over 600 percent by pneumatic fracturing. The radius of fracturing as measured by air communication between the fracturing well and surrounding well was at least 7 meters. Vapor extraction of VOC increased by approximately 675 percent.

The range of formations in which pneumatic fracturing has been successfully tested include: sedimentary rock, stratified coastal plain soils, unconsolidated fill, and low permeability clay and shale. Observed fracture radii range from 3 to 10 meters, the observed fracture propagation is predominantly horizontal, and measured flow rates increased up to 10^3.

APPLICATIONS

Pneumatic fracturing has been demonstrated in a variety of geological formations. The resulting increase in permeability could be used to enhance in situ remediation technologies. Examples of these technologies include: vapor and liquid extraction, sparging, and bioremediation. Research is continuing to broaden the application of pneumatic fracturing.

REFERENCES

1. SCHURING, J. R. et al, U. S. Patent 5,032,042, "Method and Apparatus for Eliminating Non-naturally Occurring Subsurface Liquid Toxic Contaminants from Soil." July 16, 1991.

2. SCHURING, J. R., Valdis Jurka, and P. C. Chan. Pneumatic Fracturing to Remove VOCs. Remediation. 1992.

3. HUBBERT, M. K. AND D. G. WILLIS. Mechanics of Hydraulic Fracturing. Tran. AIME 210:153-166. 1957.

4. Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase I. EPA/540/AR-93/509. 1993