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In Situ Remediation Technology Status Report:

Hydraulic and Pneumatic Fracturing

**U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office
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For more information about this project, contact:

Rich Steimle
U.S. Environmental Protection Agency (5102W)
Technology Innovation Office
401 M Street, SW
Washington, DC 20460
703-308-8846

Notice

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Foreword

The purpose of this document is to describe recent field demonstrations, commercial applications, and research on technologies that either treat soil and ground water in place or increase the solubility and mobility of contaminants to improve their removal by pump-and-treat remediation. It is hoped that this information will allow more regular consideration of new, less costly, and more effective technologies to address the problems associated with hazardous waste sites and petroleum contamination.

This document is one in a series of reports on demonstrations and applications of in situ treatment technologies. To order other documents in the series, contact the National Center for Environmental Publications and Information at (513) 489-8190 or fax your request to NCEPI at (513) 489-8695. Refer to the document numbers below when ordering.

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Walter W. Kovalick, Jr., Ph.D.
Director, Technology Innovation Office

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Abbreviations

BTEX	= Benzene, Toluene, Ethylbenzene, Xylene
CERCLA	= Comprehensive Environmental Response, Compensation, and Liability Act
DNAPL	= Dense Non-Aqueous Phase Liquid
DOE	= Department of Energy
PAH	= Poly-Aromatic Hydrocarbon
PCE	= Tetrachloroethylene (Perchloroethylene)
RCRA	= Resource Conservation and Recovery Act
SITE	= Superfund Innovative Technology Evaluation Program
SVE	= Soil Vapor Extraction
SVOC	= Semi-Volatile Organic Compound
TCA	= 1,1,1-Trichloroethane
TCE	= Trichloroethylene
TPH	= Total Petroleum Hydrocarbon
VOC	= Volatile Organic Compound

Introduction

Purpose and Process

The purpose of this document is to describe the research and development of hydraulic and pneumatic fracturing technologies to remove contaminants from soil and ground water at waste disposal and spill sites. The research and development activities include research, demonstrations, and field application of these technologies.

Information in this report was found in computerized databases such as the Environmental Protection Agency's (EPA) Vendor Information System for Innovative Treatment Technologies (VISITT) and Alternative Treatment Technologies Information Center (ATTIC) and the Dialog Information Services; and in publications such as the Hazardous Substance Research Center Annual Reports, the Superfund Innovative Technology Evaluation Technology Profiles and the Department of Energy Office of Technology Development Program Summary. The review also included conference summaries, proceedings and compendiums. It was supplemented with personal interviews and discussions with representatives of other federal agencies, academic research centers, and hazardous waste remediation consulting firms.

Technology Needs

Numerous hazardous waste sites have significant concentrations of organic contaminants in saturated and unsaturated soils. In a permeable matrix, soil vapor extraction in the unsaturated zone and air sparging in the saturated zone appear to be successful in removing some of the volatile phase of the contaminant. However, the low permeability of clays, organic soils, and other tight subsurface formations is a limiting factor to the success of these two techniques. With this limitation, substantial removal of contaminants by soil vacuum extraction may be long and costly. Hydraulic and pneumatic fracturing are enhancement technologies designed primarily to increase the efficiency of soil vapor extraction and other technologies in soil conditions that would otherwise be difficult to treat. With hydraulic fracturing, pressurized water is injected and with pneumatic fracturing, pressurized air is injected through wells to develop cracks in low permeability and over-consolidated sediments. The new passageways increase the effectiveness of many in situ processes and enhance extraction efficiencies by increasing contact between contaminants adsorbed onto soil particles and the extraction medium.

Technology Descriptions

The pneumatic fracturing process involves injection of highly pressurized air into consolidated sediments that are contaminated to extend existing fractures and create a secondary network of fissures and channels. This enhanced fracture network increases the permeability of the soil to liquids and vapors and accelerates the removal of contaminants, particularly by vapor extraction, biodegradation, and thermal treatment.

Hydraulic fracturing creates distinct sand-filled fractures in low permeability and over-consolidated clays or sediments. High pressure water is first injected into the bottom of a borehole to cut a disk shaped notch that serves as the starting point for the fracture. A slurry of water, sand, and a thick gel is pumped at high pressure into the borehole to propagate the fracture. The residual gel biodegrades and the resultant fracture is a highly permeable sand-filled lens that may be as large as 60 feet in diameter. The fractures serve as avenues for bioremediation, steam or hot air injection or contaminant recovery and can also improve pumping efficiency and the delivery for other in situ processes. Precise measurement of ground elevation before and after fracturing allows for a determination of the fracture thickness and lateral location. Other granular materials such as graphite can be used instead of sand to create fractures with different properties.

Technology Demonstrations

Industrial Site, Hillsborough, New Jersey Pneumatic Fracturing Extraction (PFE) Accutech Remedial Systems

Description of Demonstration: Fracture wells were drilled in the contaminated vadose zone of a siltstone formation and left as open boreholes. The pneumatic fracturing process was applied to isolated two foot intervals of the formation. Short bursts (less than 20 seconds) of air were injected into the formation at successive depth intervals of the fracture well to create an intensely fractured unsaturated zone. Each injection extended and enlarged existing fissures in the formation and created new fissures, primarily in the horizontal direction. Following fracturing, contaminated vapors were extracted from the fracture well utilizing a vacuum.

Wastes Treated: VOCs and SVOCs including TCE, PCE, and benzene

Status: A demonstration was conducted under the SITE Demonstration Program in the summer of 1992.

Demonstration Results: The PFE process was observed to increase extracted air flow by more than 600% relative to that achieved in the site formation prior to the application of pneumatic fracturing. Even higher air flow rate increases (19,000%) were observed when one or more of the monitoring wells were opened to serve as a passive air inlet to enter the formation. The effective radius of influence was observed to increase from 380 square feet to at least 1254 square feet, an increase of over threefold. Pressure data, collected at perimeter monitoring wells, and surface heave measurements indicate that fracture propagation extended well past the farthest monitoring wells (at 20 feet) to at least 35 feet.

While TCE concentrations in the air stream remained approximately constant at roughly 50 parts per million, the increased air flow rate resulted in an increase in TCE mass removal of 675%. When wells were opened to passive air inlet, the increase in TCE mass removal was 2300% following the application of pneumatic fracturing. Additional, chemical analysis of the extracted air during post-fracture testing showed high concentrations of organic compounds that had only been detected in trace amounts prior to application of pneumatic fracturing. This confirmed that the pneumatic fracturing process had effectively accessed pockets of previously trapped VOCs. The cost for full-scale remediation was estimated at \$307/kg (\$140/lb) of TCE removed based on the demonstration and information provided by the developer.

Contacts:

John Liskowitz
Accutech Remedial Systems, Inc.
Cass Street and Highway 35
Keyport, NJ 07735
908-739-6444
Fax: 908-739-0451

John Schuring, Ph.D.
Hazardous Substance Management Research Center
New Jersey Institute of Technology
138 Warren Street
Newark, NJ 07102
201-596-5849

Uwe Frank
National Risk Management Research Laboratory
2890 Woodbridge Avenue
Edison, NJ 08837
908-321-6626
Fax: 908-906-6990

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Schuring, John R. et al. "Pneumatic Fracturing of Low Permeability Formations." EPA Region II Technology Conference, 1993.

Technology Evaluation Report: Site Program Demonstration Test. Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase 1. U.S. Environmental Protection Agency. EPA/540/R-93/509

**Closed UST, Military Facility, Oklahoma City, Oklahoma
Pneumatic Fracturing Extraction (PFE)
Accutech Remedial Systems**

Description of Demonstration: Pneumatic Fracturing was used to enhance the rate of #2 fuel oil recovery in a sandstone/shale formation. The free product was trapped in porous layers beneath fine textured confining zones and beneath a decommissioned tank. Several recovery wells had been installed in the vicinity of the closed tank, but the recovery rates were very low. A single pneumatic injection was applied adjacent to the tank at a depth between 26 and 28 feet to increase the yield of the free product from the formation.

Wastes Treated: #2 fuel oil existing as free product

Status: The project was conducted under DOE & DOD grant in conjunction with the Hazardous Substance Management Research Center. Further application of the technology occurred at the site in 1995.

Demonstration Results: Pneumatic fracturing provided direct access to the trapped oil, as was observed during static conditions. Prior to fracturing, oil in a recovery well eight feet from the fracture well would reach static conditions after approximately 300 hours with 1.5 feet of free product floating on the water table. Following application of pneumatic fracturing, equilibrium was attained in only 80 hours when the well contained 20.2 feet of free product.

Pump system operations, including additional recovery wells on site, further showed the increased rate of product recovery. During the 17 months prior to pneumatic fracturing, the system averaged 155 gallons of free product recovered per month. Following application of pneumatic fracturing this rate increased to 435 gallons per month. The total amount of free product recovered in seven months following pneumatic fracturing application surpassed the total recovered over the life of the system in the previous 17 months.

Pneumatic fracturing also was demonstrated to increase the ratio of oil to water recovered from the formation. During pre-fracture pumping, the product represented only an average of 12 percent of the total fluid recovered. Following pneumatic fracturing application oil was 74 percent of the total fluids recovered. This reduced water treatment costs tremendously.

Contacts:

John Liskowitz and Conan Fitzgerald
Accutech Remedial Systems, Inc.
Cass Street and Highway 35
Keyport, NJ 07735
908-739-6444
Fax: 908-739-0451

**Industrial Facility, Santa Clara, California
Pneumatic Fracturing Extraction (PFE)
Accutech Remedial Systems**

Description of Demonstration: A pneumatic fracturing well was installed in the vadose zone contaminated by TCE. The site geology featured a semi-permeable layer of sandy silts and sandy clays overlaying a "fat" silty clay with very little permeability. During standard vapor extraction operations, the majority of the soil vapor extracted was from the high permeability zones, leaving the lower permeability clay unaffected. Pneumatic fracturing was applied in successive two foot intervals particularly to create permeability uniformity across the various zones of the formation.

Wastes Treated: VOCs, primarily TCE

Status: The project was conducted as a pilot test in July 1993.

Demonstration Results: The rate of air flow increased 3.5 times during extraction tests utilizing the entire fracture well. More dramatic was the increase in permeability in the clay zones, where the permeability rose up to 510 times.

The rate of TCE mass removal increased six times during extraction tests from the fracture well. The greatest increases in TCE mass removal were observed in the clay zones, where the contaminants were removed at a rate of up to 46,000 times greater than the natural unfractured condition.

Pneumatic fracturing was effective for making the permeability of the formation more uniform, thereby allowing extraction air to flow through and remediate the formerly low permeability clay zones of the formation.

Contacts:

John Liskowitz or Conan Fitzgerald
Accutech Remedial Systems, Inc.
Cass Street and Highway 35
Keyport, NJ 07735
908-739-6444
Fax: 908-739-0451

**Former Manufacturing Facility, Highland Park, New Jersey
Pneumatic Fracturing Extraction (PFE)
Accutech Remedial Systems**

Description of Demonstration: Pneumatic fracturing was used to increase formation transmissivity and vadose zone permeability in a fractured shale formation contaminated with trichloroethylene. Previous attempts to remediate the site utilizing standard Dual Vapor Extraction (DVE) combined with air injection had been ineffective due to low air flow rates, small and sporadic vacuum influence, and an inability to effectively control the ground water. Two foot pneumatic injections were applied at successive intervals to a depth of 25 feet in two 4" open rock wells. Following application of pneumatic fracturing, the ground water in the test area was effectively controlled via pumping, and each of the fracture wells was placed under a vacuum.

Wastes Treated: VOCs, primarily TCE

Status: This project was conducted as first step to final Remedial Action in July of 1994. Full remediation system featuring Pneumatic Fracturing is being constructed in the Spring/Summer of 1995 under the EPA SITE Demonstration Program.

Preliminary Results: Pneumatic Fracturing was demonstrated to effectively improve the hydraulic connection between the wells in the test area. Prior to application of pneumatic fracturing, only minimal (less than 0.2') ground water drawdown influence was observed at wells on site. Following pneumatic fracturing, the formation was effectively dewatered to expose the vadose zone to effective vacuum influence.

Extraction of TCE vapors following pneumatic fracturing also showed a much higher rate of mass removal. The average rate of mass removal after pneumatic fracturing was over three times the peak rate of mass removal during the DVE pilot test before pneumatic fracturing. The greater rate of TCE mass removal reduced the design for the full-scale remediation system duration from ten years to two years.

The vacuum radius of influence increased from 11 feet prior to application of pneumatic fracturing to between 15 and 40 feet (influence varied between strike and dip). Vacuum influence became a predictable function of strike and dip rather than an unpredictable product of formation heterogeneities. The much greater radius of influence substantially reduced the number of wells required and tremendously reduced remediation system installation costs.

Contacts:

John Liskowitz or Conan Fitzgerald
Accutech Remedial Systems, Inc.
Cass Street and Highway 35
Keyport, NJ 07735
908-739-6444
Fax: 908-739-0451

**Manufacturing Facility in New York; Service Station in Louisiana
Injection Vac Pneumatic Fracturing
Terra Vac, Inc.**

Description of Demonstration: Pneumatic fracturing is used to supplement soil vapor extraction in low permeability formations where diffusive flow of soil vapor is poor. Air at high pressure is injected into the zone of low permeability via fracturing probes. The high pressure air fractures low permeability soils, enhancing advective flow by creating microfractures which act as new flow paths through the soil matrix. The additional flow paths enhance the advective mass transfer of volatile contaminants to increase contaminant extraction rates and shorten cleanup time. Injection Vac™ is Terra Vac's term for the combination of pneumatic fracturing with soil vapor extraction in low permeability soils.

Wastes Treated: TCE, PCE, BTEX, and other VOCs

Status: The technology was demonstrated and commercialized beginning in 1990.

Demonstration Results: At the New York manufacturing site in July 1990, pneumatic fracturing was used to enhance recovery of TCE and other VOCs from low permeability clays. Dual vacuum extraction (simultaneous recovery of soil vapors and ground water) had proven only slightly effective in removing VOCs from the site. During the initial application of pneumatic fracturing, the concentration of VOCs in the extracted air stream increased one order of magnitude from 20mg/L to 200mg/L. Extracted air flows did not increase appreciably. Pneumatic fracturing is thought to have redistributed subsurface flow. The Injection Vac™ phase of operations doubled the recovery of VOCs compared to dual vacuum extraction without pneumatic fracturing over similar operating times. This operation was

a pilot test to demonstrate the in situ remediation process. The system removed 340 kg (750 lb) of VOCs in 200 days.

At the Louisiana service station in November 1991, pneumatic fracturing was used to enhance recovery of gasoline-range VOCs from firm, plastic clays. Permeability testing of the soil indicated hydraulic conductivities of 10^{-8} cm/sec. The clay layer was 23-26 feet thick. Initial air flow rates from a dual vacuum extraction system were 10-15 standard cubic feet per minute (scfm). Injection VacTM operations yielded 16-23 scfm. VOC extraction rates more than doubled following pneumatic fracturing. The pilot operations removed over 650 kg (1400 lb) of VOCs over 6 days. Full scale operations remediated the site in just over a year.

Capital and operating costs of Injection VacTM are slightly higher than vacuum extraction without enhancement. The added costs of a suitably sized air compressor and, possibly, a high vacuum pump with additional energy and maintenance costs for soil vapor recovery must be factored into the overall cost. The major benefits are shorter remediation time and more effective subsurface remediation than standard, unenhanced extraction with low flow.

Contacts:

James Malot
Terra Vac, Inc.
356 Fortaleza Street
PO Box 1592
San Juan, PR 00902-1592
809-723-9171

Ed Malmanis
Terra Vac, Inc.
806 Sylvia Street
West Trenton, NJ 08628-3239
609-530-0003

**Gasoline Refinery in Marcus Hook, PA
Pneumatic Fracturing/Bioremediation
New Jersey Institute of Technology**

Description of Demonstration: The technology uses pneumatic fracturing to enhance microbial processes. Aerobic processes dominate at the fracture interfaces and, to a limited distance, into the soil away from the fracture. Depletion of oxygen during aerobic biodegradation allows methanogenic and denitrifying populations to form at greater distances from the fractures. Contaminants diffuse toward the fracture, serving as a substrate for various microbial populations. This enhances the growth of aerobic microbial populations by reducing substrate concentrations in the denitrifying and methanogenic zones.

The site was pneumatically fractured and periodic injections were performed over a period of 12 months. Subsurface injections introduced nitrate and ammonium salt in the form of

calcium ammonium nitrate to facilitate the development of aerobic, denitrifying, and methanogenic biodegradation zones. Off-gases from the monitoring wells were analyzed for benzene, toluene, and xylenes (BTX), oxygen, methane, and carbon dioxide to evaluate process effectiveness. Additional soil borings were carried out and samples analyzed to measure the change in extent of site contamination as a result of the process. Carbon mass balances considering contaminant reduction, carbon dioxide evolution, methane evolution, and contaminant recovery through vapor extraction were used to evaluate process performance.

Wastes Treated: BTEX

Status: Field scale pilot testing was completed in March 1995 under the SITE Emerging Technology Program.

Demonstration Results: Initial site characterization indicated low subsurface permeability and the presence of BTX at concentrations of up to 1500 ppm in the soil phase. Results show that fracturing increased subsurface permeability by up to 40 times within an effective radius of approximately 20 feet.

After one year of sampling and monitoring, soil samples at the end of the demonstration show a 79% reduction in soil-phase BTX concentrations. Results from the analysis of soil samples obtained from three distinct depths of the soil bed in the pre-demonstration stage were compared with those in the post-demonstration stage. From these results, the total mass of BTX removed was computed to be 22 kg. Based on periodic soil-gas sampling, the mass of BTX removed through vapor extraction was computed to be 3.1 kg or 11%. Vapor extraction was the predominant abiotic mode of BTX removal. The other abiotic pathways—BTX losses through fracture and amendment injections, perched water removal, and passive volatilization—accounted for a total of 0.8 kg or 4% based on mean BTX concentrations. The mass of BTX removed by biodegradation was calculated to be over 82%.

Contacts:

John Schuring and Peter Lederman
Hazardous Substance Management Research Center
New Jersey Institute of Technology
138 Warren Street
Newark, NJ 07102
201-596-5849

Uwe Frank
National Risk Management Research Laboratory
2890 Woodbridge Avenue
Edison, NJ 08837-3679
908-321-6626
Fax: 908-906-6990

**LUST site near Dayton, Ohio
Hydraulic Fracturing
National Risk Management Research Laboratory
University of Cincinnati**

Description of Demonstration: The fracturing is created when fluid is pumped down a borehole until a critical pressure is reached to fracture the soil. Sand-laden slurry is then pumped into the fracture to create a highly permeable pathway that enhances delivery of the bioremediation organisms. At this site, there were two wells. One well was fractured at 4, 6, 8, and 10 feet below the ground surface. Hydrogen peroxide and nutrients were added to both wells.

Wastes Treated: BTEX and TPH

Status: The demonstration was completed in September 1992.

Demonstration Results: Fluid flow rates into the fractured well were 25 to 40 times greater than into the unfractured well. After one month, soil moisture content 5 feet from the fractured well was 1.4 to 4 times greater than the unfractured well. Moisture content generally was greater near the fracture, with the largest increase near the uppermost fracture. The same trends in moisture content were also observed at 10 and 15 feet from the wells. Effectiveness of the bioremediation was measured by reduction in BTEX and TPH concentrations in soil samples. Bioremediation at 5 feet from the fractured well after 1 month was 97% for ethylbenzene and 77% for total petroleum hydrocarbons compared with 8% and 0% respectively near the unfractured well. After six months, benzene, ethylbenzene, and TPH continued to have a higher degradation percentage near the fractured well than the unfractured well. However, considerable variation among the degradation data is evident and may be due to local variations in contaminant concentration that was unresolved by sampling.

Contacts:

Larry Murdoch
Center for Geo-Environmental Science
& Technology
University of Cincinnati
Engineering Research Division, ML 0384
1275 Section Rd.
Cincinnati, OH 45237-2615
513-556-2472
Fax: 513-556-2522

Bill Slack
FRX, Inc.
PO Box 37945
Cincinnati, OH 45222
513-556-2526

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U.S. Environmental Protection Agency. *Hydraulic Fracturing Technology: Technology Demonstration Summary*, EPA/540/SR-93/505, 1993.

Site in Bristol, Tennessee Hydraulic Fracturing Remediation Technologies, Inc.

Description of Demonstration: Naturally propped fractures were created at depths of 100 to 200 feet in rock to enhance the recovery of free-phase TCE and other DNAPLs. The fractures were created by injecting water into sections of the well isolated by straddle packers. Three wells were drilled to approximately 200 feet. Pumping tests and vapor extraction tests were conducted to evaluate the effects of the fractures.

Wastes Treated: TCE

Status: The process was demonstrated with vapor extraction in July 1991.

Demonstration Results: The specific discharge of the three wells increased by factors ranging from 2.8 to 6.2. Pumping test results indicate that hydraulic conductivity increased by factors of 20 or more. Vapor extraction appeared to be a feasible remedial technique after fractures were induced. Vapor discharges were on the order of 285 to 700 L/min and suction could be detected 33 feet from the recovery well after fracturing. Both discharge and suction had been negligible prior to fracturing. During a two-day test of vapor extraction, DNAPLs were recovered at a rate of approximately 82 kg/day.

Contact:

Don Lundy
Remediation Technologies, Inc.
23 Old Town Square, Suite 250
Fort Collins, CO 80524
303-493-3700

Reference:

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Site in Oak Brook, Illinois

Hydraulic Fracturing University of Cincinnati

Description of Demonstration: The site contains solvents that were spilled during the filling of a storage tank. The site is underlain by silty clay till contaminated with TCE, TCA, DCA, PCE, and other solvents to depths of 20 feet. Since the low conductivity of the site hindered vapor extraction, hydraulic fractures were created at depths of 6, 10, and 15 feet below-ground at two locations. Multi-level recovery wells were installed to connect each fracture individually to a two-phase vapor extraction system. The vapor flow rates and contaminant concentration were measured using variable area flow meters and gas chromatography.

Wastes Treated: TCE, TCA, DCA, PCE

Status: The demonstration took place over 21 weeks beginning in July 1992.

Demonstration Results: The average discharge rates from the fractured wells were 15 to 20 times greater than the unfractured well. Discharge from the fractured wells tended to fluctuate, possibly due to changes in the ground-water recharge caused by rainfall. Total recoveries for ten compounds were computed for each well from concentration and discharge rates. Recovery performances from the fractured wells were approximately one order of magnitude greater than that from the unfractured well. Recovery rates from all wells decreased through time.

Contact:

Larry Murdoch
Center for Geo-Environmental Science
& Technology
University of Cincinnati
Engineering Research Division, ML 0384
1275 Section Rd.
Cincinnati, OH 45237-2615
513-556-2472
Fax: 513-556-2522

Bill Slack
FRX, Inc.
PO Box 37945
Cincinnati, OH 45222
513-556-2526

EPA Center Hill Testing Facility, Cincinnati, Ohio Hydraulic Fracturing University of Cincinnati

Description of Demonstration: The EPA Center Hill Facility is an uncontaminated testing facility in Cincinnati underlain by silty clay with soil and gravel. Five wells were installed to compare the differences in performance of fractured and unfractured wells.

Three wells were hydraulically fractured and the performance of these wells was compared to two unfractured wells. The wells were connected to a vacuum blower. Pneumatic piezometers were installed around the wells to measure suction head in the soil.

Wastes Treated: None

Status: The demonstration took place in January 1992.

Demonstration Results: Well discharge, as both vapor and liquid, was an order of magnitude greater for the fractured wells than the unfractured wells. For the fractured wells, the rate corresponded strongly with precipitation. The vented fracture was more responsive to rainfall than the unvented fractures. The conventional wells were unaffected by rain. Suction head was detectable at a greater distance from the wells with fractures than from the wells without fractures. Around the conventional wells, suction was 1.18 inches of water at a distance of 3.3 feet. The same suction head could be observed 25 feet from the fractured wells.

Contacts:

Larry Murdoch
Center for Geo-Environmental Science
& Technology
University of Cincinnati
Engineering Research Division, ML 0384
1275 Section Rd.
Cincinnati, OH 45237-2615
513-556-2472
Fax: 513-556-2522

Bill Slack
FRX, Inc.
PO Box 37945
Cincinnati, OH 45222
513-556-2526

Reference:

Wolf, A. and Murdoch, L. "Field Test of the Effect of Sand-Filled Hydraulic Fractures on Air Flow in Silty Clay Till." *Proceedings of the 7th National Outdoor Action Conference, May 1993.*

**Storage Tank Site in Beaumont, Texas
Hydraulic Fracturing
University of Cincinnati**

Description of Demonstration: Sand-filled hydraulic fractures were created in swelling clay to enhance the recovery of free-phase LNAPLs. The area contained gasoline and cyclohexane approximately 5 to 10 feet from the surface spill. The pilot test compared the performance of two designs of fractured wells to a control well. One of the fractured wells consisted of two casings that access fractures at different depths, one in the LNAPL

and the other in the water bearing zone below. The other well contained one fracture near the bottom of the NAPL zone. The test was designed to recover NAPL from the upper fracture and water from the lower one.

Wastes Treated: Gasoline and cyclohexane

Status: Fractures were created in July 1993 and a pilot test was conducted in February 1994.

Demonstration Results: Both wells containing fractures produced LNAPL at rates an order of magnitude or greater than the conventional well.

Contacts:

Larry Murdoch
Center for Geo-Environmental Science
& Technology
University of Cincinnati
Engineering Research Division, ML 0384
1275 Section Rd.
Cincinnati, OH 45237-2615
513-556-2472
Fax: 513-556-2522

Bill Slack
FRX, Inc.
PO Box 37945
Cincinnati, OH 45222
513-556-2526

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