Case Study Abstract

Hydraulic and Pneumatic Fracturing, U.S. Department of Energy (Portsmouth Gaseous Diffusion Plant, Ohio), Department of Defense, and Commercial Sites

Site Name:
1. U.S. Department of Energy (DOE), Portsmouth Gaseous Diffusion Plant (PGDP)
2. DoD (e.g., Tinker AFB) and Commercial sites (various)

Location:
Piketon, Ohio (for PGDP)

Contaminants:
- Demonstrations conducted at sites contaminated with Volatile Organic Contaminants (VOCs) (including Trichloroethene (TCE)), Dense Nonaqueous Phase Liquids (DNAPLs), and at uncontaminated sites

Period of Operation:
July 1991 - August 1996 (multiple demos during this time period)

Cleanup Type:
Field demonstration

Technical Information:
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SIC Code:
9711 (National Security)
Others - information not provided

Technology:
Hydraulic and Pneumatic Fracturing
- Hydraulic fracturing equipment includes lance, notch tool, slurry mixer, and pump
- Gel-laden proppant is pumped into notch under 60 psig to create a fracture
- Pneumatic fracturing equipment includes high-pressure air source, pressure regulator, and receiver tank with inline flow meter and pressure gauge
- Air is injected at 72.5-290 psi for <30 seconds using a proprietary nozzle
- Design considerations include formation permeability, type, and structure; sand proppant; state of stress; site conditions; and depth
- Fracturing used in conjunction with other in situ technologies such as SVE, bioremediation, and pump and treat

Cleanup Authority:
Information not provided

Points of Contact:
Skip Chamberlain, DOE, (301) 903-7248
James Wright, DOE, (803) 725-5608

Waste Source:
Tinker - Underground Storage Tank
Others - Information not provided

Purpose/Significance of Application:
Demonstrations of technology used to increase hydraulic conductivity, contaminant mass recovery, and radius of influence (for example, in a SVE application)

Type/Quantity of Media Treated:
Soil and Ground Water
- Generally applicable in low permeability formations
- At PGDP, was used at uncontaminated site underlain by low permeability clays and silts to a depth of approximately 15-22 ft

Regulatory Requirements/Cleanup Goals:
- No special permits were required for use in the demonstrations
- Some states may be concerned about injection of fluids and other materials that may alter the pH of the subsurface

Hydraulic and Pneumatic Fracturing, U.S. Department of Energy (Portsmouth Gaseous Diffusion Plant, Ohio), Department of Defense, and Commercial Sites (Continued)

Results:
- Hydraulic fracturing demonstrations showed mass recovery increased from 2.8-50 times, and radius of influence from 25-30 times
- Pneumatic fracturing at Tinker Air Force Base increased product thickness in recovery well from 1.5 to 20.2 ft
- Pneumatic fracturing at PGDP doubled hydraulic conductivity, and increased radius of influence by 33% after one day of pumping

Cost Factors:
- Capital and annual costs not provided for demonstrations
- Hydraulic fracturing projected to cost $5,400 for one-time costs, and $5,700 for daily costs (corresponding to $950-1,425 per fracture, for 4-6 fractures)
- Pneumatic fracturing projected to be similar to those for hydraulic fracturing ($400-1,425 per fracture)
- Pneumatic fracturing at a SITE demonstration estimated at $140/lb of TCE removed; other estimates predict pneumatic fracturing cost of $8-17/yd^3 soil treated

Description:

Hydraulic and pneumatic fracturing are technologies that can enhance access to the subsurface for remediation of contaminants above and below the water table. Enhanced access is provided by creating new or enlarging existing fractures in the subsurface. These fractures enhance the performance of in situ remediation technologies such as SVE, bioremediation, and pump and treat by increasing the soil permeability; increasing the effective radius of recovery or injection wells; increasing potential contact area with contaminated soils; and intersecting natural features. Fracturing can also be used to improve delivery of materials to the subsurface (e.g., nutrients).

A number of demonstrations of hydraulic and pneumatic fracturing have been conducted to show technology applicability and performance in a variety of settings. Hydraulic fracturing demonstrations have showed mass recovery increases from 2.8-50 times, and radius of influence increases from 25-30 times. Pneumatic fracturing demonstrations have been conducted at Tinker Air Force Base and PGDP, with results provided in terms of increased product thickness in recovery wells and increases in hydraulic conductivity and radius of influence. Hydraulic fracturing is commercially available from several companies, while pneumatic fracturing has been patented by the New Jersey Institute of Technology (NJIT). The NJIT has licensed pneumatic fracturing to Accutech Remedial Services (ARS). While hydraulic fracturing produces larger apertures and can be performed at greater depths than pneumatic fracturing, the addition of water in hydraulic fracturing may create a larger volume of contaminated media possibly requiring remediation. Prior to proposing fracturing, sites should be analyzed for permeability. Sites with extensively fractured strata will have permeabilities that are high enough that fracturing may not be required.

SECTION 1

SUMMARY

Technology Description

Hydraulic and Pneumatic Fracturing are two technologies that can enhance access to the subsurface for remediation of contaminants both above and below the water table.

- Enhanced access is provided by creating new or enlarging existing fractures in the subsurface to improve fluid flow to encourage removal or treatment of contaminants.
- The innovation adapts a petroleum recovery technique to the environmental field. Fracturing can then be combined with other innovative technologies to provide an effective remediation system at difficult sites.

Induced fractures enhance the performance of in situ remediation technologies in low-permeability strata by

- increasing the permeability of the soil,
- increasing the effective radius of recovery or injection wells,
- increasing potential contact area with contaminated soils,
- intersecting natural fractures.

Better extraction of contaminants from or delivery of materials (gases, liquids, or solids) to the subsurface can produce a more effective in situ remediation. Examples of innovative materials that can be introduced through fractures include:

◊ Nutrients or slowly dissolving oxygen sources to improve bioremediation processes;
◊ Electrically conductive compounds (e.g., graphite) to improve electrokinetic processes;
◊ Reactant materials such as zero-valent iron or permanganate.

These technologies are particularly useful at contaminated sites with low-permeability soil and geologic media, such as clays, shales, and tight sandstones. However fracturing technology is not limited to low-permeability sites.

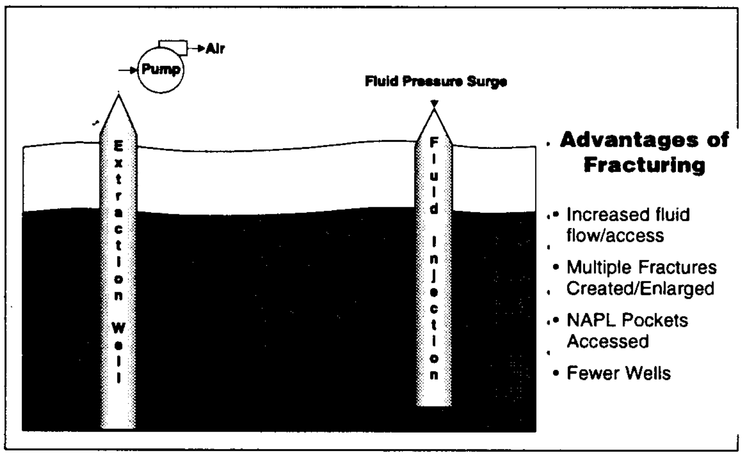

Figure 1. Fracturing of Low-Permeability Formation. Extraction/treatment can be accomplished either in the fluid injection borehole or in adjacent boreholes.

- Fractures are typically created in a horizontal or subhorizontal plane at specific horizons (<2 feet) by injecting a fluid (either liquid or gaseous) into a sealed borehole until the pressure exceeds a critical value, thus nucleating a fracture. After injection is complete, fractures are held open naturally or with an introduced proppant, a material injected to "prop" open the fractures. If a liquid (e.g. guar gum gel) is used to create the fracture, a granular proppant can be introduced to assist with maintenance of fracture openings.

- The direction of fracture propagation is controlled by the state of stress in the subsurface. Sites with horizontal stress greater than vertical stress will produce horizontal or subhorizontal fractures. These sites typically consist of overconsolidated fine-grained deposits (silts and clays). For Pneumatic Fracturing a directional nozzle can be used to control the direction of fracture propagation.

- Creation of fractures does not add significant up-front costs (up to a few percent) to an overall remediation system and it may provide significant reduction in the life-cycle costs to remediate a site because fewer wells may be required and cleanup may be accomplished more rapidly.

Technology Status

- Hydraulic Fracturing has been extensively researched and used in the petroleum industry for over 50 years. It has required modification for use in the environmental field. Since the early 1990's, research has been conducted on the viability of both Pneumatic and Hydraulic Fracturing for environmental applications.

- A number of demonstrations of Hydraulic and Pneumatic Fracturing have been conducted to show their applicability to the environmental field. Both technologies were demonstrated under the EPA SITE program jn the early 1990's. Technology Evaluation and Applications Analysis Reports are available for both technologies (see references).

- Bench-scale tests, followed by pilot- and field-scale tests on both clean and contaminated sites, have been conducted by NJIT and ARS using Pneumatic Fracturing. Terra Vac, Malcolm Pirnie, and others have also participated in Pneumatic Fracturing projects. The U.S. Department of Energy (DOE) has supported several demonstrations of Pneumatic Fracturing, including one at Tinker Air Force Base and one at the DOE Portsmouth Gaseous Diffusion Plant. New Jersey Institute of Technology (NJIT) patented Pneumatic Fracturing for environmental applications. In 1992 they licensed the technology to Accutech Remedial Systems (ARS).

- FRX in cooperation with the University of Cincinnati has conducted pilot and field scale tests of hydraulic fracturing on both clean and contaminated sites in 9 states and Canada (TX, OH, ID, IL, CT, ME, MI, NJ, CO). Golder Associates has conducted bench, pilot and field scale tests concentrating on hydraulic fracturing. A hydraulic fracturing demonstration has been completed at the DOE Portsmouth Gaseous Diffusion Plant. Future development will include coupling of in situ mass transfer and destruction processes. Advanced applications such as injection of graphite, iron filings, oxidants and activated carbon were tested.

- ***Key Results***
  - Hydraulic and Pneumatic Fracturing at geologically appropriate sites have significantly improved recovery of contaminated fluids (~10 to >1000 times). These technologies typically have generated fractures that significantly increase the radius of influence for vertical recovery wells at the sites (10-fold).
    - ◊ Hydraulically developed fractures were demonstrated to be effective for a period of more than one year. Vapor flow rates were increased by 15 to 30 times that of unfractured wells. Water flow rates were increased by 25 to 40 times that of unfractured wells.

  - Hydraulic and Pneumatic Fracturjng have been used in conjunction with soil vapor extraction, pump and treat, bioremediation, free product recovery, and in situ vitification at contaminated sites. Demonstrations of other applications, such as passive chemical barriers or electrokinetics, are underway.

  - Hydraulic Fracturing is commercially available from several companies: FRX, Inc., Golder Associates Ltd., Hayward Baker Environmental, Inc., and perhaps others. Larger scale, more costly applications are performed by several companies for oilfield applications. Pneumatic Fracturing is commercially available from ARS. ARS has used Pneumatic Fracturing at over 30 sites in North America. ARS has recently signed an agreement with DOWA Mining Company LTD of Japan to market Pneumatic Fracturing in Japan.

CONTACTS

Technical/

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(Information in this report is based on technologies as implemented by ARS and FRX.)

TECHNOLOGY DESCRIPTION

Process Schematic

Hydraulic Fracturing

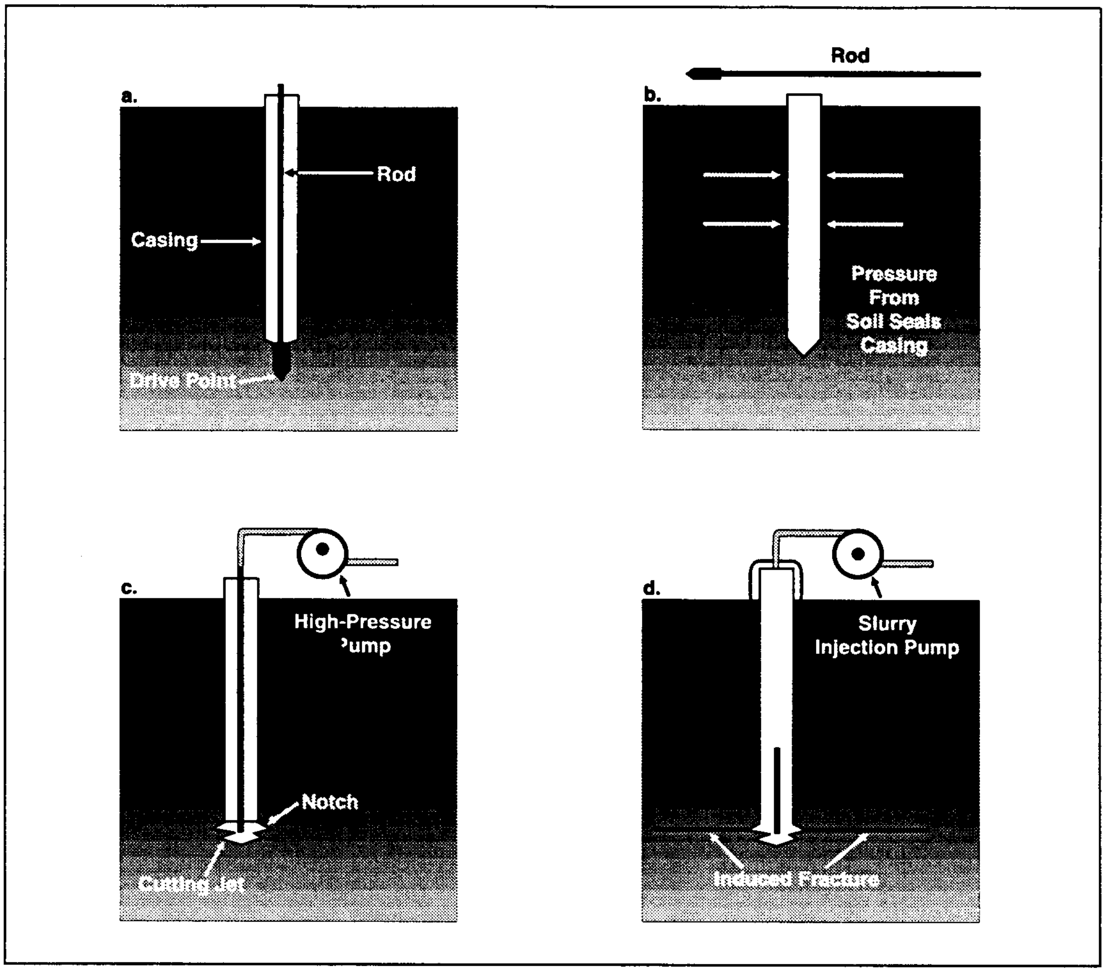

Figure 3. Hydraulic Fracturing Schematic (from U.S. EPA, 1994)

Equipment

- The fracturing equipment consists of a lance, a tool to create an initial notch, a continuous slurry mixer, a positive displacement pump mounted on a trailer, and the fracture mixture (fluid and proppant).

Process

- A well is drilled and cased down to the depth where fractures are desired in lithified sediments (in unlithified sediments a straddle-packer system is used). A rod with a cone-shaped end, the lance, is introduced into the bottom of the borehole and is driven to the depth at which the fracture is desired. The lance tip remains in the soil whereas the lance is later removed from the borehole.

- A water jet (steel tubing with a narrow orifice at one end) is inserted into the cone-shaped rod, water is pumped through the tubing to create a high-pressure water jet (pressure 3500 psi). The jet is rotated within the borehole to create a disc-shaped horizontal notch extending 4 to 6 inches from the borehole.

- The gel-laden proppant is then pumped into the notch under relatively low pressures (60 psig) to create a fracture. Lateral pressure from the soil on the outer wall of the casing effectively seals the casing and prevents leakage of the slurry. The fracture nucleates at the notch and grows radially up to about 20 feet from the borehole wall. The gel to sand ratio is adjusted from fracture to fracture, depending on depth and site-specific soil conditions.

Pneumatic Fracturing

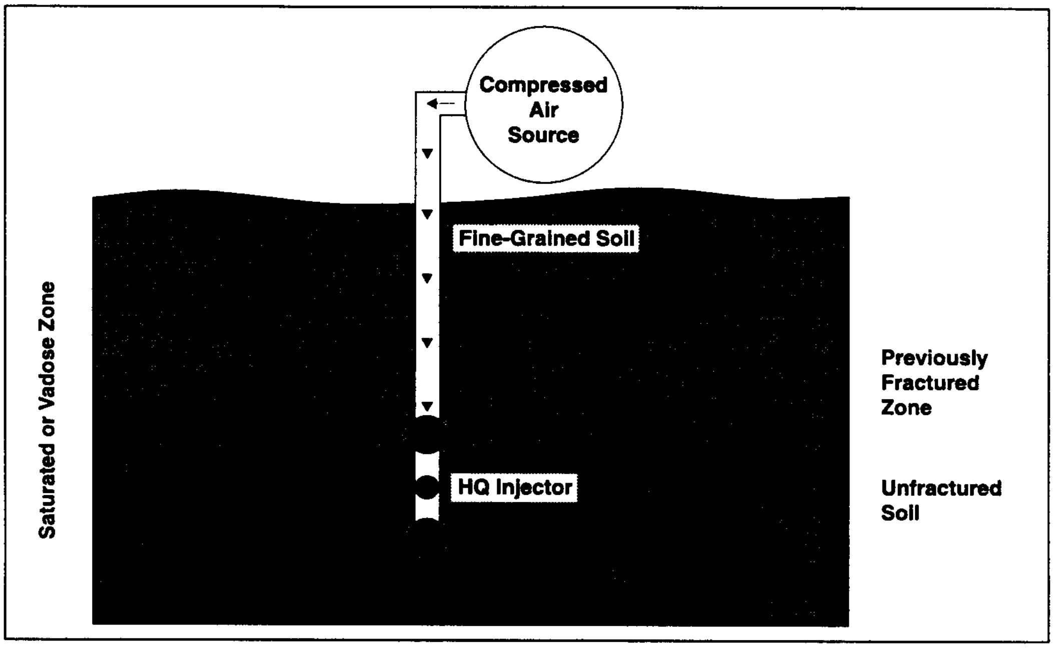

Figure 4. Schematic of Pneumatic Fracturing Process

Equipment

- The fracturing equipment consists of a high-pressure air source (e.g., compressed gas cylinders) with pressure regulator, and a receiver tank attached to a pipe with an inline flow meter and pressure gauge.

Process

- An uncased or cased well is drilled. A small vertical section of the well (up to two feet) is isolated, then high-pressure air is injected for short periods of time (< 30 seconds) using a proprietary nozzle. Air is injected at rates of 25 to 50 cubic meters (883 to 1,766 cubic feet) per minute at pressures of 0.5 to 2MPa (72.5 to 290 psi).

- The isolation and injection are repeated at the desired vertical intervals.

General Considerations

- The direction of fracture propagation will be perpendicular to the minimum principal stress in the subsurface at a particular site. Recent field data indicate that soil fabric or lithology may have a greater influence on fracture orientation than the in situ state of stress in the soil mass in some soil deposits.

- Injection pressure required to initiate a fracture generally increases with increasing depth, injection rate, and fluid viscosity.

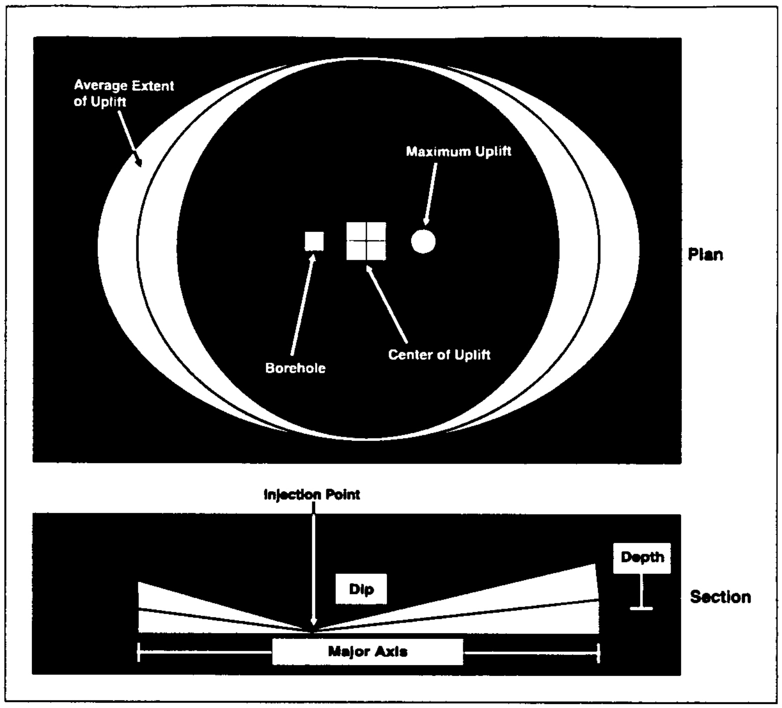

Figure 2. Plan and section of a typical hydraulic fracture created in overconsolidated silty clay. (modified from U.S. EPA, 1994).

Injection Fluids

- Guar gum gel is commonly used in hydraulic fracturing. The gel carries sand into the subsurface to prop the fractures open.
  - ◊ Guar gum is a food additive and when mixed with water forms a short-chain polymer with the consistency of molasses.
  - ◊ A crosslinker is added to lengthen the polymer chains and create a thick gel capable of suspending high concentrations of sand.
  - ◊ An enzyme is added to the gel that breaks down the polymer chains in a few hours to allow recovery of the thinned liquid.

- Pneumatic Fracturing (i.e., injection of air) typically uses no propping agents and is thus best applied at sites where the geology is conducive to maintaining open any dilated existing fractures or newly created fractures.

Leakoff

- Leakoff occurs when some of the injected fluid flows out through the walls of the fracture. The rate of fracture propagation decreases as the rate of leakoff increases, and propagation ceases entirely when the leakoff rate equals the rate of injection.

- Leakoff generally controls the size of the fractures. Leakoff is minimized by controlling amount and rate of injection.

Monitoring Fracture Location

- The most widely used method of monitoring fracture location is measuring the displacement of the ground surface, using either surveying of field staffs before and after or tiltmeters during fracture propagation. Pressure influence in surrounding monitoring wells can also be measured to determine fracture locations.

Design Considerations

The table below summarizes the factors that should be considered when deciding if a site is appropriate for fracturing and if so how to best design the project (modified from US EPA, 1994).

Factor	Favorable	Unfavorable
Formation permeability	Moderate to low(k $<10^{-6}$ cm^2)	Unnecessary in high permeability formations
Formation type	Rock or fine-grained sediment	Coarse-grained sediment
Formation structure	Horizontal bedding planes	Vertical structures
Sand proppant	Unlithified, saturated sediments	May be unnecessary in consolidated units
State of stress	Horizontal stress > vertical stress (overconsolidated)	Horizontal stress < vertical stress (normally consolidated)
Site conditions	Open ground over fracture/ no buried utilities	Structures sensitive to displacement over fracture/ buried utilities
Depth	One to eight meters	Surface or > eight meters

SECTION 3

PERFORMANCE

Demonstration Plan

Major elements of the demonstrations included:

- Initial flow rates and contaminant extraction levels from extraction and monitoring wells (monitoring wells sampled to determine whether fractures have established connections between the fracture well and the monitoring wells.)
- Final flow rates and contaminant extraction levels from extraction and monitoring wells;
- Pressures at both monitoring wells and extraction wells.

Specific examples of demonstrations for each of the technologies, with focus on those supported by DOE, are presented in this section.

Demonstration Summary

Hydraulic Fracturing

- Hydraulic fracturing was demonstrated under the EPA SITE program in July of 1991 at sites in Oak Brook Illinois and Dayton Ohio. Both sites contained low-permeability soils ($<10^{-7}$ cm/sec) that were contaminated with volatile organic compounds (VOCs). Fracturing was accomplished to a depth of 15 feet below ground surface.
  - ◊ In Illinois, contaminants removed by soil vapor extraction were increased by 7 to 14 times and the area of influence was 30 times greater after fracturing.
  - ◊ In Ohio flow of water into the fractured well was increased 25 to 40 times and bioremediation rate was increased by approximately 75%.

- Demonstrations have also been conducted at the DOE Portsmouth Gaseous Diffusion Plant (August 1996), the Laidlaw site near Sarnia, Ontario, Canada (cofunded by DOE), the Bristol Tennessee site, the Beaumont Texas site, and the Linemaster Switch Superfund Site in Woodstock Connecticut. At the DOE site, fractures were propped with sand, oxidants, and reductants; the site was then treated with hot air/steam enhanced air flushing and in situ chemical degradation.

Pneumatic Fracturing

- An EPA SITE demonstration was conducted at a site in Hillsborough, New Jersey in 1992. Fractures created during the demonstration significantly increased the effective radius of influence and increased the rate of mass removal about 675% over the rates measured before fracturing. By installing wells to be used as passive inlets/outlets, improvements in mass removal rates were as high as 2300%.

- DOE supported demonstration at the Tinker Air Force Base in Oklahoma and the Portsmouth Gaseous Diffusion Plant in Ohio.

Treatment Performance

Hydraulic Fracturing:

Site 1 - Laidlaw Site, Sarnia, Ontario

- The sheet-pile test cell was a clean site located adjacent to a major hazardous waste landfill. A synthetic gasoline blend with a tracer of trichloroethylene (TCE) was released into the cell in 1992. Soil vapor extraction was then initiated. Surface materials at this location are composed of clay-rich glacial till.

- In August of 1994, hydraulic fracturing was conducted. Fifteen fractures were emplaced at 9 locations outside of the sheet-pile cell at depths of 1.2 and 5.6 meters.
  - ◊ Minimum surface uplift from the fracturing was observed as 1 to 4.65 centimeters.
  - ◊ More symmetric fractures were created at shallow depths, while asymmetric fractures were created at depths greater than 2.5 meters. In addition, the dip of the fractures increased with the depth of the fracture, if greater than 2.5 meters.

Other Sites

- Performance of wells that have been hydraulically fractured generally increases by a factor of 1.5 to 10 but the range varies up to 100 or more.
- Several examples of demonstration performance are listed below.

Site Name	Contaminant/Geology	Mass Recovery Change	Radius of Influence Improvement
Oak Brook IL	VOCs in Silty Clay	7 to 14	30 times
Dayton OH	VOCs in Silty Clay	25 to 40	
Bristol TN	DNAPL/Fract. Bedrk.	2.8 to 6.2	30 times
Regina Saskatchewan	VOCs in Silty Clay		25
Calgary Alberta	VOCs in Silty Clay	10	
Linemaster, CT	Solvents in Till	4 to 6	
Beaumont TX	DNAPL in Silty Clay	50	~25

Pneumatic Fracturing:

Site 1- Fuel Oil In Sedimentary Strata : Tinker Air Force Base, Oklahoma

- Fuel oil had leaked from an underground storage tank into interbedded sedimentary strata. A pump and treat system was installed and recovered 155 gallons per month for 17 months.

- Four wells were installed at the site and pneumatically fractured.

- Key results were:
  - ◊ After installation of the first fractured well, fuel oil (as floating product) thickness in the nearby recovery well increased from 1.5 feet to 20.2 feet (see figure below) and oil recovery increased to approximately 435 gallons per month.
  - ◊ Other fracture wells improved performance from other recovery wells from 224 to 434%.
  - ◊ Oil production was increased in wells as far as 59 feet from the injection point.
  - ◊ Oil recovered as a percentage of total fluid pumped increased from 12 to 90%.

- Fracture wells were also installed at an adjacent site to enhance bioremediation in a clayey silt and sand formation. Air flows from vapor extraction increased 500 to 1700%.

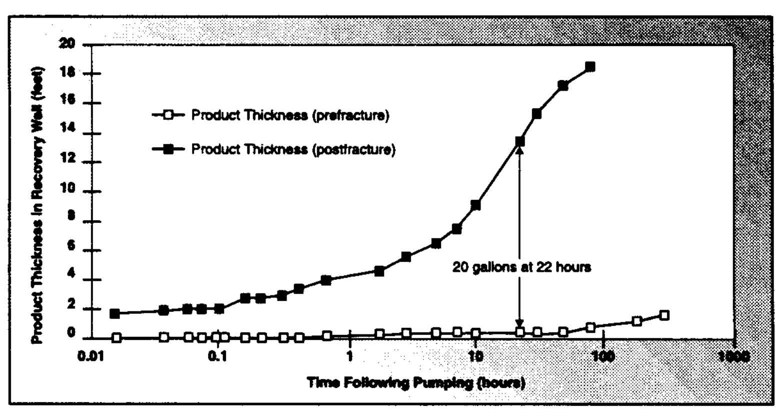

Figure 5. Floating Product (fuel oil) Thickness Data for Recovery Well 4

Site 2- VOCs and DNAPLs in silts and clays: DOE Portsmouth Gaseous Diffusion Plant, Ohio

- The Clean Test Site (CTS) is underlain by low-permeability clays and silts to a depth of approximately 15 to 22 feet. During the summer of 1994, two fracture wells were created. Post-fracture hydraulic conductivity was determined to be 1.0 feet/day, a two-fold increase with a radius of influence increasing by 33% from 200 to 300 feet after one day of pumping.

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- Fracturing enhances current remediation technologies by increasing permeabilities and improving flow, recovery and destruction rates for:
  - ◊ vapor extraction,
  - ◊ ground water extraction,
  - ◊ bioremediation,
  - ◊ free product recovery (LNAPLs and DNAPLs),
  - ◊ possibly electrokinetics and other innovative in situ technologies, such as permeable barriers with chemical oxidants or reductants.

- Hydraulic and Pneumatic Fracturing for fluid recovery enhancement have been successfully demonstrated on the field scale in both the vadose and saturated zones.

- Hydraulic and Pneumatic Fracturing are well suited for sites with an assortment of underlying strata, especially such as low-permeability sandstones, clays, siltstones, and shales.

Competing Technologies

The baseline against which fracturing can be compared is remediation, such as soil vapor extraction, without fracturing. Improvements in recovery of contaminants after fracturing can then be used to compare to the baseline.

Hydraulic and Pneumatic Fracturing are competing technologies. A site being considered for fracturing must be evaluated to determine which technology would perform as required and be the most cost effective. A table comparing the two technologies is presented in Appendix B (from Keffer et al., 1996).

Another technology designed to enhance access to the subsurface is that of directionally drilled horizontal wells. Fracturing of geologic media and soils at low-permeability sites contaminated with VOCs also competes with soil heating technologies, designed to enhance contaminant removal by soil vapor extraction (see Six Phase Soil Heating ITSR report, DOE, 1995, as an example.) In situ enhanced soil mixing has been used to treat VOC-contaminated sites with low-permeability soils and geologic media (see ITSR In Situ Enhanced Soil Mixing, DOE, 1996). Other remediation technologies such as surfactant flushing and bioremediation do not compete directly as they do not enhance access to the subsurface.

Technology Maturity

Hydraulic Fracturing

- Hydraulic Fracturing has been used extensively for over fifty years in the petroleum industry. It has been demonstrated at a number of sites in North America for fluid recovery enhancement but not yet fully implemented for a site cleanup. Advanced applications of fracturing technology represent an earlier stage of development.

Pneumatic Fracturing

- Pneumatic Fracturing has been demonstrated at over thirty sites in North America and has been utilized for full implementation of site cleanup at six or more sites.

SECTION 5

COST

Hydraulic Fracturing

The EPA has reported the cost per single fracture ranging from $950-$1425, however the cost is highly dependent upon the number of fractures to be placed in each borehole. EPA also reported a daily cost of $5700 to create 4 to 6 fractures. Golder Associates Ltd. reports costs of $400-500 per fracture or $2000 to $6000 per well.

Type of Cost	Daily Cost ($)
Site Preparation	1,000
Permitting and Regulatory	5,000
Capital Equipment Rental	1,000
Startup	0
Labor	2,000
Supply and Consumables	1,000
Utilities	0
Effluent Treatment and Disposal	0
Residual and Waste Shipping and Handling	0
Analytical and Monitoring	700
Maintenance and Modifications	0
Demobilization	400
Total One-Time Costs	5,400
Total Daily Costs	5,700
Estimated Cost per Fracture	950-1425

Source: U.S. EPA 1993a.

Pneumatic Fracturing

Pneumatic Fracturing costs can be estimated to be similar to those of Hydraulic Fracturing reported above, $400-1425 per fracture. However, an alternative cost estimating method, based upon dollars per pound of contaminant removed, was completed by EPA. Costs calculated for the EPA SITE demonstration in New Jersey were estimated at $140/lb of TCE removed for a hypothetical remediation, assuming constant removal rate:

- site = 100 feet by 150 feet
- effective radius of influence 25 feet
- 15 wells required to get a 15-20% overlap
- one-year operating cycle with capital cost amortization.

Costs were extrapolated from a 4-hour postfracture test:

- labor 29%
- capital equipment 22%
- offgas treatment 19%
- site preparation 11%
- residuals disposal 10%

Other estimates predict Pneumatic Fracturing to cost $8 to $17 per cubic yard of soil treated. Fracturing can be completed using a weekly rate of $15,000 to $20,000.

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- To date, no special permits are required for the use of Pneumatic or Hydraulic Fracturing. Fracturing activities are considered under the requirements for the remediation of a particular site.
  - ◊ Gels used in Hydraulic Fracturing (usually guar gum) are biodegradable and non-toxic. Other additives, such as the proppants (usually sand of various grain sizes) and water, are naturally occurring and not a regulatory concern.
  - ◊ However, some state agencies are concerned about injection of fluids and materials that may alter the pH of the subsurface.

- A possible concern is the lack of control of fracture generation.
  - ◊ Behavior of a strata prior to fracture, such as the quantity, size and direction of the generated fractures, is not well-defined. Information on site geology/hydrology can be used to model the placement of fractures.
  - ◊ In a highly fractured system, further fracturing may drive contamination away from the pressure front, thus increasing the area of contamination.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Health and safety issues for fracturing technologies do not present significant hazards over conventional field remediation operations.
- Pressures used are high enough to require extreme caution. All equipment is checked regularly and contains safety features such as pressure relief valves. All workers are trained regularly in safe equipment operation and are required to take OSHA 40-hour training. An addendum to the Health and Safety Plan addressing pressure issues would typically be required.

Community Safety

- Fracturing technologies do not produce any routine release of contaminants.
- No unusual safety concerns are associated with the transport of equipment to and from the site.
- Careful monitoring of field operations assures safety to the workers and the public.

Environmental Impacts

- No additional impacts will be produced over that already underway as a result of the site remediation efforts. Equipment is transported to the site and then removed after the fractures are created.

Socioeconomic Impacts and Community Perception

- Fracturing has a minimal economic or labor force impact.
- The general public has limited familiarity with this technology.

SECTION 7

LESSONS LEARNED

Implementation Considerations

- The precise geometry (direction, length and size) of fractures cannot be determined prior to generation, but likely characteristics can be generalized by experienced practitioners based on site conditions and experience.
- Sites should be analyzed for permeability before fracturing is proposed. Extensively fractured strata will have permeabilities high enough such that they will not require fracturing and fracturing will not be optimal as the pressure required to fracture the strata further may be much larger than the operating range of the injection equipment (i.e too much leakoff occurs).
- Perched water may hamper measurement of the extent of fracturing or interfere with the remediation system performance for vadose-zone soil vapor extraction systems.

Technology Limitations and Need for Future Development

- Fracturing for ambient temperature fluid recovery has been demonstrated at many sites; existing and future development includes coupling of in situ mass transfer and destruction processes.
- The degree of post-emplacement healing of fractures (especially with unpropped fractures) and the degree of pore continuity disruption furing operation are not well documented at this time.
- Fracturing near foundations or utilities should include a risk analysis before the fracturing is initiated, as strata upheaval may weaken supports and crack foundations and utilities. The utilities or foundations may also act as preferential pathways, thus limiting fracture generation. However, many sites in the vicinity of utilities and foundations have been fractured without significant problems.

APPENDIX A

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APPENDIX B

Comparison of Pneumatic Fracturing and Hydraulic Fracturing

(Modified from Keffer et al., 1996)

PNEUMATIC FRACTURING	HYDRAULIC FRACTURING
Fracture apertures are small (usually measured after settling) on the order of 500 - 1,000 microns. The smaller openings create a lower cumulative heave, which could reduce or eliminate the long-term impact to structures.	Fracture apertures are large, usually on the order of 1 - 2 centimeters. The use of proppants in these fractures translates to a significant amount of cumulative heave, which can have a direct impact on nearby structures, but which also can further increase permeability.
The flow through these fractures is conductive and the lack of a proppant allows flow to be governed by the "cubic law," which states that the flow rate is proportional to the cube of the aperture opening allowing high flow rates through smaller openings.	The flow through the fractures is Darcian in nature. Thus a larger aperture opening is required to achieve equivalent flow rates.
The fluid used to fracture is air. This creates a cleaner operation where the volume of contaminated media is not increased, allows better control of fracture propagation and reduces the possibility of a hazardous waste spill due to back pressure venting through the fracture well. Air is also less expensive to produce.	The fluid used is usually water which can contact the waste product and dissolves into the water creating a larger volume of contaminated media. When the operation is complete, back pressures can eject hazardous waste to the surface making a dirty operation and possibly a reportable spill. Water introduced to a vadose zone needs to be removed.
The orientation of pneumatic fractures in soil formations is more consistently horizontal. Some upward migration occurs at the outer edges of shallow fractures.	Fracture orientation has been demonstrated to have a vertical component which often creates an angular fracture that intersects the surface.
Pneumatic fractures propagate between 20 and 50 feet outward. The farthest has been 70 feet.	Hydraulic fractures propagate between 15 and 50 feet outward.
Pneumatic fractures are best emplaced less than 75 feet. Below 75 feet the weight of the overburden decreases the effect of self-propping. Engineering adjustments also need to take place below this depth.	The depths at which hydraulic fractures can be emplaced are significantly higher than the depths Pneumatic Fractures can be emplaced.
Fracture density occurs as both a dense network of micro-fractures that impact a smaller area around the fracture point and a few major fractures which migrate outward into the formation. This density occurs in each interval of 2 – 3 feet.	Fracture density is typically limited to one or two major fractures per injection interval. The injection interval is larger varying between 5 and 20 feet.
Pneumatic Fracturing is faster. Injections typically last 20 seconds.	Hydraulic fracturing typically takes 5 to 10 minutes per fracture.