Hydraulic and Pneumatic Fracturing

OST Reference # 1917 (Hydraulic Fracturing)

OST Reference # 1916 (Pneumatic Fracturing)

Subsurface Contaminants Focus Area

Prepared for
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Demonstrated at
U.S. Department of Energy
Portsmouth Gaseous Diffusion Plant, Ohio and
Department of Defense and Commercial Sites

CONTENTS

DISCLAIMER

PURPOSE OF THIS DOCUMENT

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine if a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available online at http://em-50.em.doe.gov.

SECTION I

SUMMARY

Technology Summary

Hydraulic and pneumatic fracturing are two technologies that induce fractures in the subsurface to enhance the remediation of contaminants both above and below the water table. These technologies are particularly useful and cost-effective at contaminated sites with low-permeability soil and geologic media, such as clays, shales, and tight sandstones where remediation, without some sort of permeability enhancement, is difficult or impossible. However, the usefulness of fracturing technology is not limited to low-permeability sites.

Enhanced access is provided by creating new or enlarging existing fractures in the subsurface, which improves fluid flow to encourage removal or treatment of contaminants (see Figure 1). The innovation adapts a petroleum recovery technique, used for a number of years, to the environmental field. Fracturing can then be combined with other technologies to provide an effective remediation system at difficult sites.

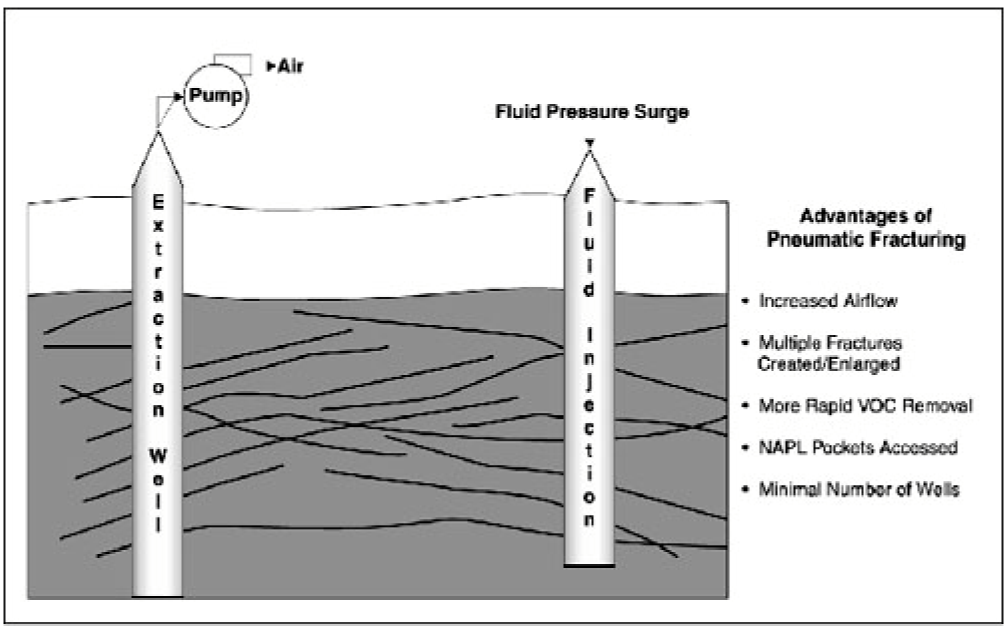

Figure 1. Fracturing of low-permeability formation. Extraction or treatment can be accomplished either in the fluid injection borehole or in adjacent boreholes.

Benefits

Fractures can enhance the performance of 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, and
- intersecting natural fractures, where contaminants may have localized.

Induced fractures promote better extraction of contaminants from or delivery of materials (gases, liquids, or solids) to the subsurface, producing 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, and
- reactant materials such as zero-valent iron or permanganate.
- 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.

How it works

- Fractures are typically created in a horizontal or subhorizontal plane at specific horizons (<2 ft) 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.

Demonstration Summary

This report covers demonstrations that took place between July 1991 and August 1996.

- 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 1990s, 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 U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) program in the early 1990s. Technology Evaluation and Applications Analysis Reports are available for both technologies (see references).

- These technologies have been demonstrated and deployed at U.S. Departments of Energy and Defense sites and commercial sites. Funding to support some of the technology demonstrations has been provided by the U.S. Department of Energy's (DOE) Office of Science and Technology under the Subsurface Contaminants Focus Area Program.

- In cooperation with the University of Cincinnati, FRX, Inc. has modified and developed hydraulic fracturing for environmental applications. Accutech Remedial Systems, Inc. (ARS) in cooperation with the New Jersey Institute of Technology (NJIT) has developed pneumatic fracturing for environmental applications.

- 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. DOE has supported several demonstrations of pneumatic fracturing, including one at Tinker Air Force Base and one at DOE's Portsmouth Gaseous Diffusion Plant. NJIT patented pneumatic fracturing for environmental applications. In 1992, the institute licensed the technology to ARS.

- In cooperation with the University of Cincinnati, FRX has conducted pilot- and field-scale tests of hydraulic fracturing on both clean and contaminated sites in nine states (Texas, Ohio, Idaho, Illinois, Connecticut, Maine, Michigan, New Jersey, and Colorado) and Canada. Golder Associates Ltd. has conducted bench-, pilot-, and field-scale tests concentrating on hydraulic fracturing. A hydraulic fracturing demonstration has been completed at DOE's 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 >1,000 times). These technologies typically have generated fractures that significantly increase (ten fold) the radius of influence for vertical recovery wells at the sites.

- 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 fracturing have been used in conjunction with soil vapor extraction, pump and treat, bioremediation, free product recovery, and in situ vitrification at contaminated sites. Demonstrations of other applications, such as passive chemical barriers or electrokinetics, are under way.

Commercial Availability

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

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

Other

All published Innovative Technology Summary Reports are available online at http://em-50.em.doe.gov. The Technology Management System, also available through the EM50 web site, provides information about OST programs, technologies, and problems. The OST Reference Numbers for hydraulic and pneumatic fracturing are 1917 and 1916, respectively.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

Hydraulic Fracturing

A schematic diagram of the hydraulic fracturing process is shown in Figure 2.

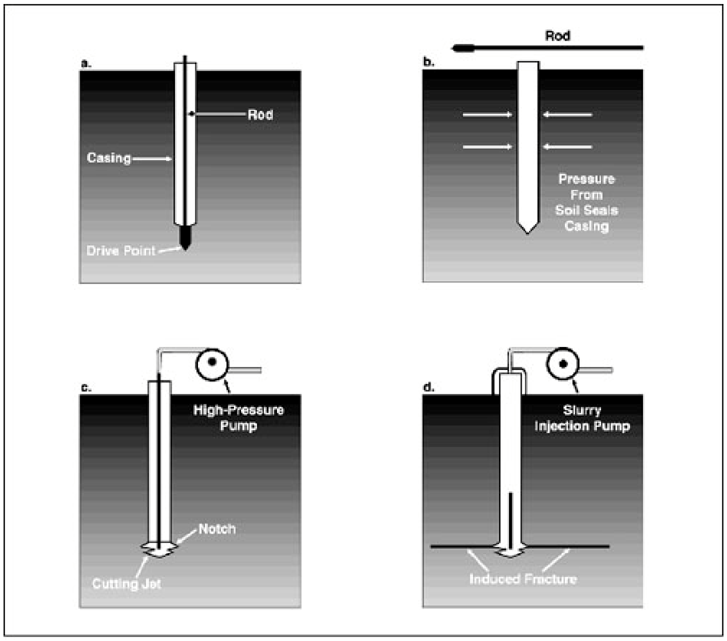

Figure 2. Hydraulic fracturing typically uses water to induce fractures.
Source:U.S. EPA, 1994.

Hydraulic Fracturing Equipment

The fracturing equipment consists of a rod, 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).

Hydraulic Fracturing 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. The lance, a rod with a cone-shaped end, 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, and water is pumped through the tubing to create a high-pressure(3,500 psi) water jet. The jet is rotated within the borehole to create a disc-shaped horizontal notch extending 4 to 6 in 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 begins at the notch and grows radially up to about 20 ft 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

The pneumatic fracturing process is shown in Figure 3.

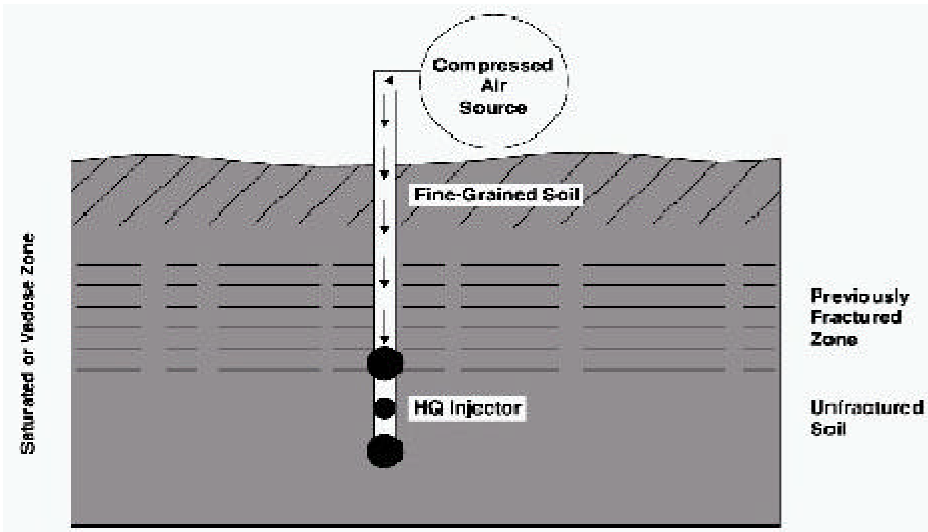

Figure 3. Pneumatic fracturing uses air to induce fractures.

Pneumatic Fracturing 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 in-line flow meter and pressure gauge.

Pneumatic Fracturing Process

- An uncased or cased well is drilled. A small (< 2-ft) vertical section of the well 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 m3 (883 to 1,766 ft^3) 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. Pneumatic fracturing uses air to cause fractures; hydraulic fracturing typically uses water. Appendix B contains a point-by-point comparison of the two technologies.

System Operation

- 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.

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 (Figure 4). Field staffs can survey before or after fracturing, or tiltmeters can be used during fracture propagation. Pressure influence in surrounding monitoring wells can also be measured to determine fracture locations.

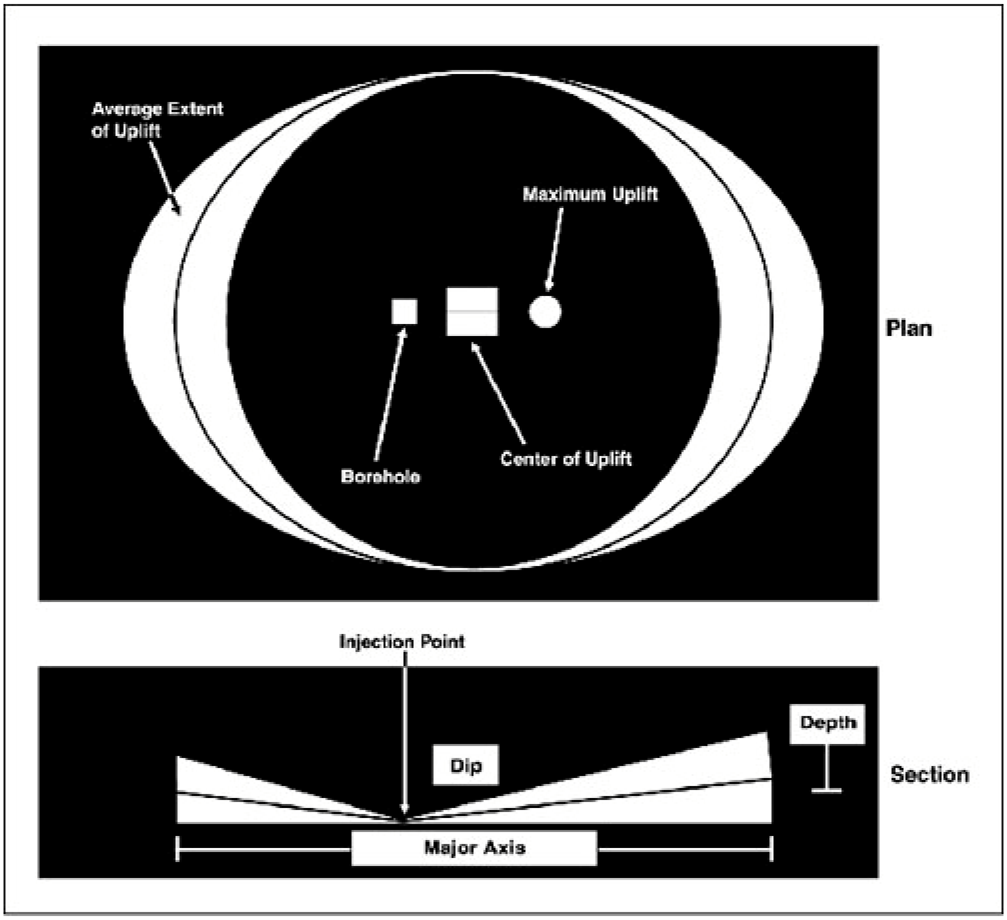

Figure 4. Plan and section of a typical hydraulic fracture created in overconsolidated silty clay. Source: U.S. EPA 1994.</CAPTION< Center>

SECTION 3
PERFORMANCE

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

Demonstration Plan

Major elements of the demonstrations included the following:

- Establish initial flow rates and contaminant extraction levels from extraction and monitoring wells. Sample monitoring wells to determine whether fractures connect fracture wells to monitoring wells.

- Establish final flow rates and contaminant extraction levels from extraction and monitoring wells.

- Determine pressures at both monitoring wells and extraction wells.

Demonstration Summary

Hydraulic Fracturing

- Hydraulic fracturing was demonstrated under EPA's Superfund Innovative Technology Evaluation (SITE) program in July 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 ft below ground surface.

    - In Illinois, contaminants removed by soil vapor extraction were increased by 7 to 14 times; 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; the bioremediation rate was increased by approximately 75 percent.

- Demonstrations have also been conducted at DOE's Portsmouth Gaseous Diffusion Plant in Ohio (August 1996); the Laidlaw site near Sarnia, Ontario, Canada (cofunded by DOE); a Bristol, Tennessee site; a Beaumont, Texas site; and the Linemaster Switch Superfund Site in Woodstock, Connecticut. At the Portsmouth Gaseous Diffusion Plant, 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 percent 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 2,300 percent.

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

Treatment Performance

Hydraulic Fracturing

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 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 1994, hydraulic fracturing was conducted. Fifteen fractures were emplaced at nine locations outside of the sheet-pile cell at depths of 1.2 and 5.6 m.

Key Results

- Minimum surface uplift from the fracturing was observed at 1 to 4.65 cm.
- More symmetric fractures were created at shallow depths, while asymmetric fractures were created at depths greater than 2.5 m. For fractures at depths greater than 2.5 m, the dip of the fractures increased with the depth of the fracture.

Key Results from Other Sites

Recovery 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 in Table 1.

Table 1. Data from a variety of sites demonstrate hydraulic fracturing's ability to improve remediation

Site Name	Contaminant/Geology	Mass Recovery Factor Increase	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	not reported (NR)
Bristol, TN	**DNAPLs/fractured bedrock	2.8 to 6.2	30 times
Regina,Saskatchewan	*VOCs in silty clay	NR	25 times
Calgary, Alberta	*VOCs in silty clay	10	NR
Linemaster, CT	Solvents in till	4 to 6	NR
Beaumont, TX	**DNAPLs in silty clay	50	~25 times

*** volatile organic compounds**
**** dense nonaqueous phase liquids**

Pneumatic Fracturing

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 gal per month for 17 months. Four wells were installed at the site and pneumatically fractured.

Key Results

- ✍ After installation of the first fractured well, fuel oil (as floating product) thickness in the nearby recovery well increased from 1.5 to 20.2 ft (Figure 5); oil recovery increased to approximately 435 gal per month.

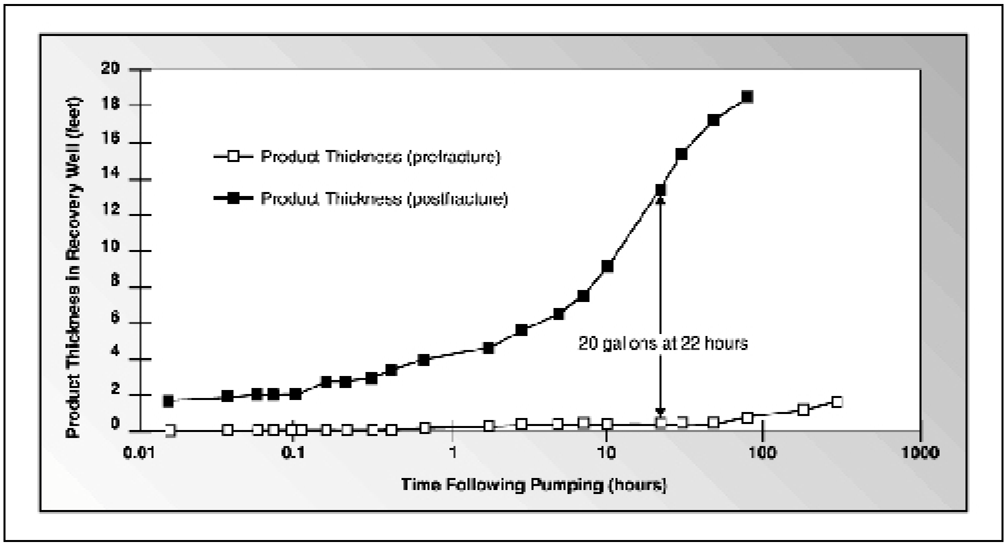

Figure 5. Floating product (fuel oil) thickness data for recovery well 4.
Source:U.S. EPA, 1993a.

- ✍ Other fracture wells improved performance from other recovery wells from 224 percent to 434 percent.
- ✍ Oil production was increased in wells as far as 59 ft from the injection point.
- ✍ Oil recovered as a percentage of total fluid pumped increased from 12 percent to 90 percent.

Fracture wells were also installed at an adjacent site to enhance bioremediation in a clayey silt and sand formation. **Key Result** - Air flows from vapor extraction increased 500 to 1,700 percent.

<u>DOE's Portsmouth Gaseous Diffusion Plant, Ohio</u>
The clean test site is underlain by low-permeability clays and silts to a depth of approximately 15 to 22 ft. During the summer of 1994, two fracture wells were created. **Key Result** Postfracture hydraulic conductivity was determined to be 1.0 ft/day, a two-fold increase with a radius of influence increasing by 33 percent from 200 to 300 ft after one day of pumping.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

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 comparison of 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 volatile organic compounds (VOCs) also competes with soil heating technologies, designed to enhance contaminant removal by soil vapor extraction (see Six-Phase Soil Heating, an Innovative Technology Summary Report [ITSR], DOE 1995, as an example.) In situ enhanced soil mixing has been used to treat VOC-conaminated sites with low-permeability soils and geologic media (see In Situ Enhanced Soil Mixing, ITSR, DOE 1996). Other remediation technologies such as surfactant flushing and bioremediation do not compete directly as they do not enhance access to the subsurface. Fracturing technologies could be used as an enhancement to these 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 for light nonaqueous phase liquids (LNAPLs) and dense nonaqueous phase liquids (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 for low-permeability sandstones, clays, siltstones, and shales.

Implementation Considerations

Table 2 summarizes the factors that should be considered when deciding whether a site is appropriate for fracturing and, if so, how best to design the project (modified from EPA 1994).

Table 2. Design factors for selection of fracturing technology at a site

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	Course-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	1 to 8 m	Surface or >8 m

Patents/Commercialization/Sponsor

Hydraulic Fracturing

- Hydraulic fracturing has been used extensively for over 50 years in the petroleum industry.
- FRX, Inc. in cooperation with the University of Cincinnati modified and developed hydraulic fracturing for environmental applications.
- It has been demonstrated at a number of sites in North America for fluid recovery enhancement but has not yet been fully implemented for a site cleanup.
- Hydraulic fracturing is commercially available from several companies: FRX, Inc. in Cincinnati, Ohio, Golder Associates Ltd. (20 offices in Canada), Hayward Baker Environmental, Inc. (11 offices in the United States and an office in Vancouver, British Columbia, Canada), and perhaps others.

Pneumatic Fracturing

- Pneumatic fracturing has been demonstrated at over 30 sites in North America and has been utilized for full implementation of site cleanup at six or more sites.
- New Jersey Institute of Technology (NJIT) in Newark patented pneumatic fracturing for environmental applications.
- In 1992, NJIT licensed the technology to Accutech Remedial Systems in Keyport, New Jersey.

SECTION 5
COST

Methodology

Hydraulic Fracturing

EPA has reported the cost per single fracture ranging from $950 to $1,425. However, the cost is highly dependent upon the number of fractures to be placed in each borehole. EPA also reported a daily cost of $5,700 to create 4 to 6 fractures. Golder Associates Ltd. reports costs of $400 to $500 per fracture or $2,000 to $6,000 per well.

Pneumatic Fracturing

Pneumatic fracturing costs can be estimated to be similar to those of hydraulic fracturing. However, an alternative cost estimating method, based upon dollars per pound of contaminant removed, was completed by EPA.

Cost Analysis

Hydraulic Fracturing

Cost data for hydraulic fracturing is presented in Table 3.

Table 3. Cost summary for hydraulic fracturing

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 to 1,425

Source: U.S. EPA 1993a.

Pneumatic Fracturing

Using the alternative cost estimating method devised by EPA for pneumatic fracturing, costs for the EPA SITE demonstration in New Jersey were estimated at $140/lb of trichloroethylene removed for a hypothetical remediation. The following assumptions were applicable:

- Site, 100 ft by 150 ft
- Effective radius of influence, 25 ft
- 15 wells required for a 15 percent to 20 percent overlap
- One-year operating cycle with capital cost amortization

Costs for pneumatic fracturing were extrapolated from a 4-hour postfracture test:

- Labor, 29 percent
- Capital equipment, 22 percent
- Off-gas treatment, 19 percent
- Site preparation, 11 percent
- Residuals disposal, 10 percent

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.

Cost Conclusions

Fracturing technology can be compared to a baseline where no fracturing is done. The costs identified above can then be considered in terms of the improvement in remediation performance (~ 150 percent to 2,300 percent, Section 3). Large increases in contaminant mass removal efficiency produce more rapid cleanup, thus significantly reducing maintenance and operating costs over the life cycle of the project.

SECTION 6
REGULATORY AND POLICY ISSUES

Regulatory Considerations

To date, no special permits are required for the use of pneumatic or hydraulic fracturing. Permitting expenses would typically be covered under existing requirements for the remedial action at the site. 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 nontoxic. 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.

- Another area of concern stems from lack of control over fracture generation.
  - Field staff may be uncertain about the effect of fracturing on a strata, such as the quan tity, size and direction of the generated fractures. 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 take 40-hour training required by the U.S. Occupational Safety and Health Administration. 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 under way 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 may have permeabilities high enough so that further fracturing is not required. Also, fracturing may not be optimal because 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/Needs 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 postemplacement healing of fractures (especially with unpropped fractures) and the degree of pore continuity disruption during operation are not well documented at this time.

- Fracturing near foundations or utilities should include a risk analysis before fracturing is initiated because strata upheaval may weaken supports and crack foundations and utilities. 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

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.

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 fluid used to fracture is air. This creates a cleaner operation because 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 orientation of Pneumatic Fractures in soil formations is more consistently horizontal. Some upward migration occurs at the outer edges of shallow fractures.

Pneumatic Fractures propagate between 20 50 ft outward. The farthest has been 70 ft.

Pneumatic Fractures are best emplaced less than 75 ft. Below 75 ft, the weight of the overburden decreases the effect of self-propping.Engineering adjustments also need to take place below this depth.

Fracture density occurs as both a dense network of microfractures that impact a smaller area around the fracture point and a few major fractures that migrate outward into the formation. This density occurs in each interval of 2-3 ft.

Pneumatic fracturing is faster. Injections typically last 20 seconds.

HYDRAULIC FRACTURING

Fracture apertures are large, usually on the order of 1-2 cm. 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 the fractures is Darcian in nature. Thus, a larger aperture opening is required to achieve equivalent flow rates.

The fluid used is usually water, which can contact the waste product and dissolve 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.

Fracture orientation has been demonstrated to have a vertical component, which often creates an angular fracture that intersects the surface.

Hydraulic Fractures propagate between 15-50 ft outward.
<BR< emplaced.

Fracture density is typically limited to one or two major fractures per injection interval. The injection interval is larger varying between 5-20 ft.

Hydraulic fracturing typically takes 5-10 min per fracture.
