**INNOVATIVE TECHNOLOGY**
*Summary Report*

DOE/EM-0550

# Remediation of DNAPLs in Low Permeability Soils

Subsurface Contaminants Focus Area

# Remediation of DNAPLs in Low Permeability Soils

OST/TMS ID 163

Subsurface Contaminants Area

*Demonstrated at*
U.S. Department of Energy
Portsmouth Gaseous Diffusion Plant
Piketon, Ohio

# *Purpose of this document*

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether 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.

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# SECTION 1
# SUMMARY

## Technology Summary

### Problem

Dense, non-aqueous phase liquid (DNAPL) compounds like trichloroethene (TCE) and perchloroethene (PCE) are prevalent at U. S. Department of Energy (DOE), other government, and industrial sites. Their widespread presence in low permeability media (LPM) poses severe challenges for assessment of their behavior and implementation of effective remediation technologies. Most remedial methods that involve fluid flow perform poorly in LPM.

### How It Works

Hydraulic fracturing can improve the performance of remediation methods such as vapor extraction, free-product recovery, soil flushing, steam stripping, bioremediation, bioventing, and air sparging in LPM by enhancing formation permeability through the creation of fractures filled with high-permeability materials, such as sand. Hydraulic fracturing can improve the performance of other remediation methods such as oxidation, reductive dechlorination, and bioaugmentation by enhancing delivery of reactive agents to the subsurface.

Hydraulic fractures are typically created using a 2-in. steel casing and a drive point pushed into the subsurface by a pneumatic hammer (Figure 1).

Hydraulic fracturing has been widely used for more than 50 years to stimulate the yield of wells recovering oil from rock at great depth and has recently been shown to stimulate the yield of wells recovering contaminated liquids and vapors from LPM at shallow depths. Hydraulic fracturing is an enabling technology for improving the performance of some remedial methods and is a key element in the implementation of other methods.
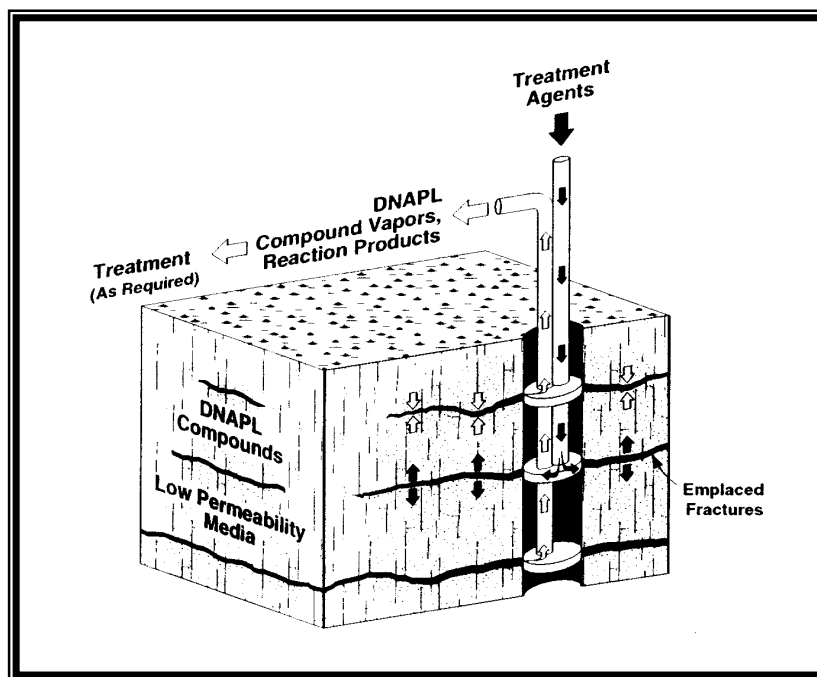


**Figure 1. Schematic of hydraulic fracturing process.**

### Potential Markets

DOE, other government, and industrial sites containing contaminants in LPM, such as clays and shales, are the most appropriate for hydraulic fracturing. Hydraulic fractures can be used to better access the subsurface for any contaminants. In particular, remediation of fractured rock sites containing vertical fractures can be significantly improved by emplacing horizontal fractures.

**Advantages Over Baseline**

The baseline against which hydraulic fracturing plus an in situ remediation technology in LPM can be compared is excavation and ex-situ treatment. The advantages hydraulic fracturing has over baseline approaches include:

- improved accessibility to contaminants and delivery of reagents (steam, oxidant, etc.) by increasing subsurface permeability (e.g., improved mass transfer rates);

- limited site disruption minimizing adverse effects on surface features (e.g., parking areas, buildings, etc.) as fewer wells can be installed.

## Demonstration Summary

A comparative field demonstration of hydraulic fracturing to enhance mass recovery or emplace reactive barriers was conducted during the fall of 1996 through the spring of 1998 at the Portsmouth Gaseous Diffusion Plant (PORTS) X-231A land treatment site. The demonstration treated chlorinated solvents (specifically TCE) in both the vadose and saturated zones within low permeability silt and clay deposits of the Minford (Figure 2).



Four test cells were established to investigate steam and hot air enhanced soil vapor extraction through fractures and reactive barriers of reductant (iron metal) and oxidant (potassium permanganate) emplaced in fractures. Test cells A and B were actively operated with hot-fluid flushing for ~60 days in fall 1996 and for ~45 days in summer 1997. Test cells C and D were passively operated as reactive barriers during the two-year period.

**Figure 2. The demonstration site at PORTS.**

**Key Results**

- Hydraulic fracturing was successfully used at the X-231A site to efficiently create over 25 fractures at depths ranging from 4- to 18-ft bgs and at spacings of as little as 2 to 3 ft.

- The iron proppant remained reactive (~30 to 40% degradation of TCE within 24 to 48 hours) for up to 27 months after emplacement, but with little effect to surrounding soil matrix.

- Fractures containing potassium permanganate remained highly reactive (>99% degradation of TCE within 2 hours) within the fractures and created zones of reactive soil (diffusion of the oxidant in the soil matrix) that continued to grow away from the fracture (~30-cm thick after 3 months to nearly 90-cm thick after 15 months to continuous reactive zones between the fractures at 27 months).

- Mass recovery can recover volatile organic compounds (VOCs) with vapor pressure > 10 mm Hg; iron barriers can reduce many oxidized compounds, including TCE, $NO_3$ and some metals; permanganate barriers can treat unsaturated halocarbons, aromatics, phenols, and may precipitate some metals.

The demonstration at PORTS was conducted by Oak Ridge National Laboratory and sponsored by the DOE, Office of Science and Technology (OST), and the DOE Portsmouth Site Office. This demonstration was conducted as part of a larger ongoing project with contributions from: Becthel Jacobs Company LLC (formerly Lockheed Martin Energy Systems), Colorado School of Mines, FRx, Inc., and Carus Chemical Company.

The primary regulatory consideration for hydraulic fracturing is the requirement for an underground injection control permit.

Hydraulic fracturing is commercially available from FRx, Inc. and several other companies.

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**Other**

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under "Publications." The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST/TMS ID for Remediation of DNAPLs in Low Permeability Soils is 163.

# SECTION 2
# TECHNOLOGY DESCRIPTION

## Overall Process Definition

Hydraulic fracturing is a method to enhance the permeability of LPM by creating a series of horizontal propped fractures in the subsurface. Hydraulic fracturing:

- is applicable to both the vadose and saturated zones at sites composed of consolidated and overconsolidated materials;

- creates new or enlarges existing fractures to improve delivery of treatment agents and/or recovery of contaminants (Figure 3).
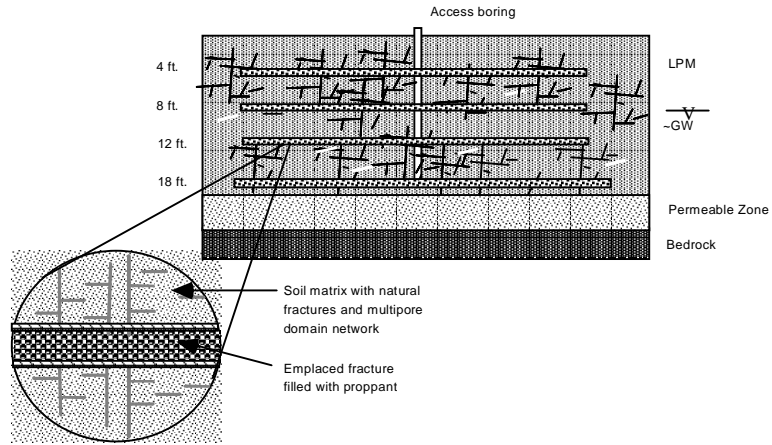


**Figure 3. Illustration of stacked hydraulic fractures.**

Coupling hydraulic fracturing with (1) hot fluid (steam or air) movement and soil vapor extraction or (2) reactive solids delivery (e.g., iron, permanganate) to create a reactive horizontal barrier offers remediation options that have the potential to enhance VOC removal or destruction.

Treatment processes demonstrated at the X-231A site within four side-by-side test cells are shown below (Figure 4, Table 1).



**Figure 4.**

**Schematic of the treatment processes demonstrated using hydraulic fracturing.**

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**Table 1. Demonstration site features**
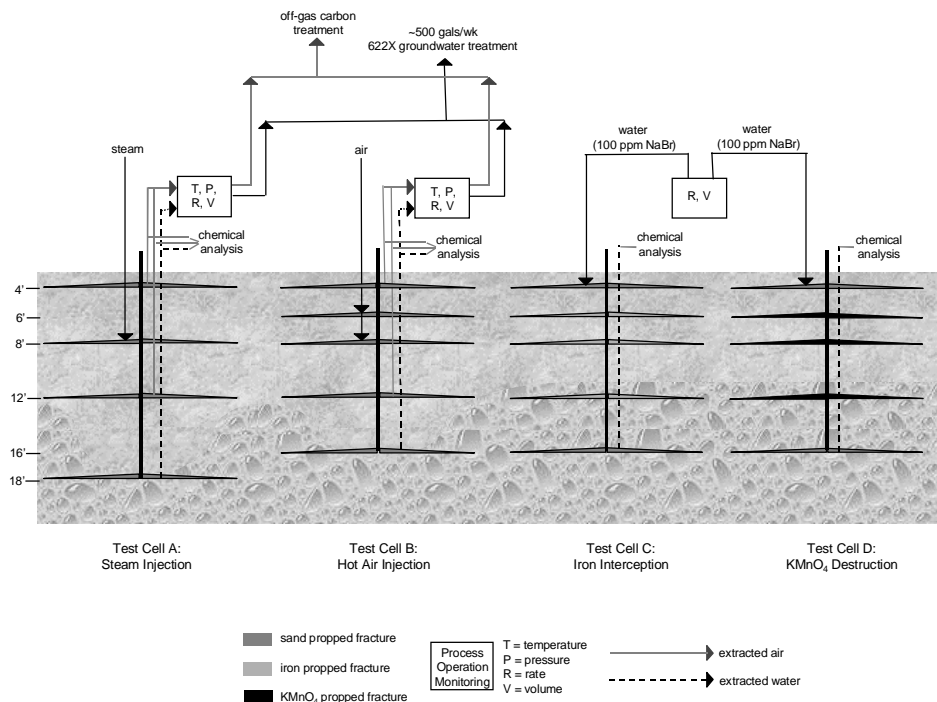
| Test cell characteristic | Steam injection for mass removal | Hot air injection for mass removal | Iron metal fracture for dechlorination | Permanganate fracture for oxidation |
|---|---|---|---|---|
| **Test cell label** | **A** | **B** | **C** | **D** |
| Fracture locations (ft bgs) - proppant | 4 - sand<br>8 - sand<br>12 - sand<br>18 - sand | 4 - sand<br>6 - sand<br>8 - sand<br>12 - sand<br>16.5 - sand | 4 - sand<br>6 - iron<br>8 - iron<br>12 - iron<br>16.5 - sand | 4 - sand<br>7 - $KMnO_4$<br>9 - $KMnO_4$<br>12 - $KMnO_4$<br>16.5 - sand |
| Volume of proppant<br>  4 ft fracture<br>  6 ft fracture<br>  8 ft fracture<br>  12 ft fracture<br>  16.5 ft fracture<br>  18 ft fracture | $8 ft^3$<br>-<br>$10 ft^3$<br>$13 ft^3$<br>-<br>$20 ft^3$ | $5 ft^3$<br>$8 ft^3$<br>$12 ft^3$<br>$15 ft^3$<br>$20 ft^3$<br>- | $5 ft^3$<br>$9 ft^3$<br>$12 ft^3$<br>$24 ft^3$<br>$20 ft^3$<br>- | $5 ft^3$<br>880 lb.<br>1320 lb.<br>1320 lb.<br>$20 ft^3$<br>- |
| Test cell diameter | 20 ft | 18 ft | 20 ft | 20 ft |
| Fracture trend direction | NW | NE | SE | NW |
| Test cell depth | 18 ft | 16.5 ft | 16.5 ft | 16.5 ft |
| Test cell volume | $5650 ft^3$ | $4200 ft^3$ | $5180 ft^3$ | $5180 ft^3$ |
| **Treatment process:** | | | | |
|   4 ft fracture | vapor ext. | vapor ext. | none | none |
|   6 ft fracture | - | ambient air inj. | reduction | oxidation |
|   8 ft fracture | steam inj. | hot air inj. | reduction | oxidation |
|   12 ft fracture | vapor ext. | vapor ext. | reduction | oxidation |
|   16.5 ft fracture | - | dewatering | none | none |
|   18 ft fracture | dewatering | - | - | - |

The test site area was instrumented with various samplers and measurement devices to enable periodic monitoring of the subsurface including:

- sidewall piezometers for pressure/moisture content;
- sidewall Eh probes for redox potential;
- sidewall time-domain reflectometery (TDR) for soil moisture content;
- multi-level in situ thermistors for temperature;
- wiping thermocouple casings for temperature;
- neutron probe access casings for soil moisture content; and
- piezometers for ground water quality.

## System Operation

**Fracture Creation**

The hydraulic fractures were created by:

- pushing a 2-in. steel casing and PVC drive point into the subsurface (Figure 4a);
- dislodging the drive point downward an additional 1 to 4 inches, exposing an open hole in the subsurface (Figure 4b);

- cutting a horizontal notch into the soil using a high-pressure (2,500 psig) water jet; the notch served as the nucleation point for the fracture (Figure 4c);

- pressurizing the notch by injecting fluid (e.g., guar gum and sand, iron, permanganate) into the borehole at a constant rate that exceeds the critical pressure, and nucleating a fracture (Figure 4d);

- propagation of the fracture by continuing injection of the proppant (sand or reactive agent) and fluid as a slurry while the fracture grew away from the borehole (Figure 4e); and

- monitoring operational parameters (e.g., pressure) and fracture propagation (surface displacement) during operations.
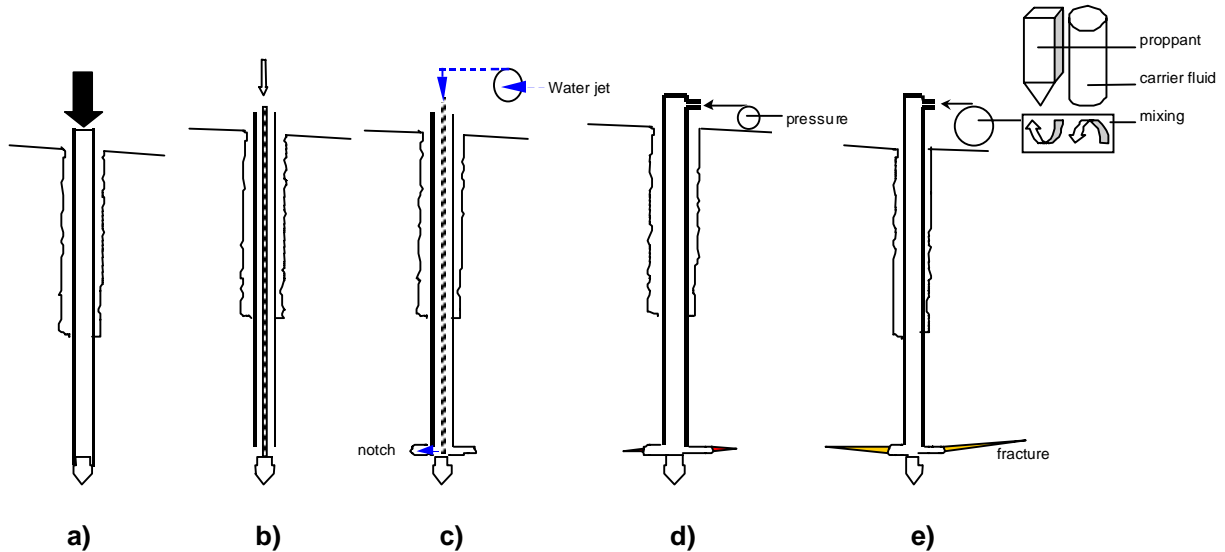


**Figure 4.  Illustration of hydraulic fracturing process.**

**Site Characterization**

Following installation of the fractures in the test cells and prior to operation of the treatment processes, extensive site characterization was conducted:

- 32 boreholes were drilled to ~17 ft bgs;

- soil samples were collected at 1 to 2-ft intervals and analyzed for VOCs, water content, pH, Eh, grain size, color, TOC, free iron oxides, cations, anions, and microbiological properties;

- 11 2-in PVC ground water piezometers (to a depth of 17 ft bgs) were installed; and

- three rounds of groundwater samples were collected from each piezometer prior to operations.

**Remediation**

Hot-fluid injection tests were conducted during fall 1996 and summer 1997 to demonstrate the effects of injecting thermal energy into contaminated LPM (i.e., the Minford).  Operational summaries for two tests are presented in Appendix D.

- At test cell A, steam was injected into the 8-ft bgs fracture; water and vapor were recovered from the 4-ft and 12-ft fractures.

- At test cell B, hot air was injected into the 8-ft fractures, ambient air was injected into the 6-ft fracture, and water and vapor were recovered from the 4-ft and 12-ft fractures.

- Deeper fractures in both test cells (18-ft in test cell A and 16-ft in test cell B) were used to recover water from each cell.

- Test cells A and B shared common vapor extraction and off-gas treatment systems (Fig. 3).

The sequence of process operations was similar for test cells A and B during both the fall 1996 and summer 1997 tests.

- The test cell was dewatered using down-hole pumps placed in the 16-18 ft fracture access casings.

- Suction was applied for up to 2 weeks to initiate vapor extraction and to accelerate dewatering.

- Following dewatering, hot fluids (steam and hot air) were injected.

- During the summer 1997 test, somewhat higher air pressures and a second air blower were used to enable higher air flow rates and to promote areal distribution of hot air; the temperature of the hot air was increased to 470 degrees C (Appendix D).

Test cells C and D were operated passively for approximately 10 months after fracture emplacement in the fall 1996. During summer 1997, tapwater was injected under low pressure (1.5 to 2.2 ft head) into the shallow sand-propped fracture and was allowed to percolate downward in each test cell for approximately 52 days (Appendix D). Test cells C and D were then again operated passively to the present.

Morphology and degradation efficiency of reactive fractures in test cells C and D were examined in December 1996, July 1997, December 1997, and again in December 1998 (approximately 3, 10, 15, and 27 months after reactive fracture emplacement).

**Post-test Characterization and Monitoring**

Monitoring of process function and performance included:

- operational parameters (vacuums, air flow rates, temperatures, energy use, dewatering rates);

- changes in subsurface conditions (temperature, soil moisture content, pH, Eh, microbial activity, alkalinity, total organic carbon, cations);

- changes in contaminant levels (off-gas monitoring and analyses, ground water sampling and analyses, and soil sampling and analysis);

- degradation experiments (degradation potential around the reactive fractures); and

- ancillary tests (e.g., helium tracer tests and sodium bromide tracer tests).

Post-test characterization was conducted in all test cells following the fall 1996 test (December 1996) and the summer 1997 test (September 1997).

**Manpower Skills, Secondary Waste and Operational Concerns**

- Hydraulic fracturing is a service provided by a commercial vendor requiring two experienced staff. Additional manpower and operational concerns are dependent on the treatment process deployed (e.g. one trained operator for active hot fluid flushing). Design expertise and a skilled contractor are needed.

- Minimal secondary waste is generated during hydraulic fracturing (soil spoils from access borehole and < 1 gallon water used during notching). Additional secondary waste is dependent on the treatment process deployed (e.g. potential off-gas during hot fluid flushing).

- Safety issues include chemical handling during installation of treatment barrier, and low pressures for creation of fractures.

# SECTION 3
# **PERFORMANCE**

## **Demonstration Plan**

The comparative demonstration was conducted at PORTS from 1996 through 1998 to evaluate soil fracturing with thermally enhanced mass recovery or reactive barrier destruction as a means of in situ remediation of DNAPL compounds in LPM. The principal objectives of this demonstration were to:

- determine and compare the operational features of hydraulic fractures as an enabling technology for the four selected treatment processes;

- determine the interaction of the delivered treatment agents with the LPM matrix adjacent to the fracture and within the fractured zone;

- assess the beneficial modifications to the transport and/or reaction properties of the LPM; and

- determine the remediation efficiency achieved by each of the treatment systems.

The demonstration involved treating a portion (4 treatment cells each ~45 ft by 45 ft by 16 ft) of the PORTS X-231A former biodegradation plot. The X-231A site consists of two unconsolidated units overlying bedrock, the Minford silt and clay and the Gallia sand and gravel, and is covered with a geomembrane liner. The Minford is approximately 20 ft thick in this area.  Additional site description is provided in Appendix C.

A set of four test cells was established in the southeastern portion of the X-231A land treatment unit. The test cells were unconfined (i.e., no sheet pile walls) to reduce costs and limit site disruption with hydraulic fractures emplaced at depths of ~ 4, 6, 8, 12, and 16 to 18 ft bgs in the vadose and saturated zones (Figure 3).  The fractures within each cell were roughly elliptical with a length of ~25 ft and a width of ~20 ft.

The demonstration was accomplished through a series of field activities divided into several phases including:

- Site Reconnaissance and Pre-Demonstration Testing

  — Site Reconnaissance
  — Equipment Testing and Shakedown
  — Reactive Fracture Proppant Formulation and Testing

- Phase 1 Demonstration Activities (Fall 1996)

  — Test Cell Setup and Operation
  — Monitoring and Measurement

- Phase 2 Demonstration Activities (Summer 1997)

  — Characterization of the Test Site
  — Subsurface Heating Achieved via Fractures in Test Cells A and B
  — Morphology and Degradation Efficiency of Reactive Fractures in Test Cells C and D
  — Injection/Percolation within Test Cells C and D

- Demonstration Close-out (Fall 1997)

- Final Sampling (Winter 1997)

- Morphology and Degradation Efficiency of Reactive Fractures in Test Cells C and D

# Results

**Fracture Emplacement**

Hydraulic fracturing was successfully used to create over 25 fractures at depths ranging from 4 to 18 ft bgs and at spacings of as little as 2 to 3 ft. Mapping of the fractures through surface lift measurements, and confirmed by observation of soil cores, revealed varied geometries. In general, the fractures were initially flat around the point of initiation and gradually climbed toward the surface at the fracture extremities. Fractures were emplaced in each of the four test cells. Relatively large volumes of reactive material were delivered to the subsurface by filling hydraulic fractures with:

- A specially formulated potassium permanganate grout, a low-cost oxidant with a high oxidation potential (it can oxidize a wide range of organic chemicals over a wide pH range);
- zero-valent iron with guar gum for degradation of halogenated compounds (the reactive zone is confined to the immediate vicinity of the iron metal).

**Site Characterization**

- Concentrations of TCE and related halocarbons in soil were highly variable, with concentrations up to 100 mg/kg.
- The water table in the silty clay soils was at ~11.5 ft bgs, and due to the fine-grained matrix, soil water contents were near saturation almost to the ground surface.
- Soil pH and Eh were in the range of 4 to 5 and 200 mV, respectively.
- Microbial densities per gram of soil included 100 anaerobic heterotrophs, 10000 to 100000 aerobic heterotrophs, and no detectable iron-oxidizers.

**Hot-Fluid Injection Results**

- Fracture flow rates averaged approximately 4 cfm in the shallow fractures at 4 ft bgs and ~1 cfm in the deeper fractures at 12 ft bgs.
- Off-gas total organic concentrations were in the 3000 to 5000 ppmv range in the shallow fractures and 20,000 to >100,000 ppmv in the deeper fractures.
- Analysis of the off-gas from the deep fractures indicated up to 17% $CH_4$ and >800 ppmv of TCE at test cell B.
- With continued active air flushing, rates of removal of volatile constituents gradually declined during ambient air flushing until hot-fluid injection began, after which time the rate of removal increased and was then followed by a gradual decline.

Injection of heat as either steam or hot air into shallow fractures increased the subsurface temperature in the vicinity of the well. However, with increasing heat injection over time, the fraction of injected heat lost also increased (Figure 5). [NOTE: filled circles are energy supplied to air heater or steam generator; open circles are heat energy in the ground estimated from change of in situ temperature.] Heat loss occurred primarily by conduction to the atmosphere as the ground surface warmed, by advection out of the ground surface, and by advection of water and air recovered by the overlying and underlying fractures. Thus, there is a maximum amount of heat that can be added to the shallow subsurface by the injection of hot fluids. Additional performance details are presented in Appendix D.
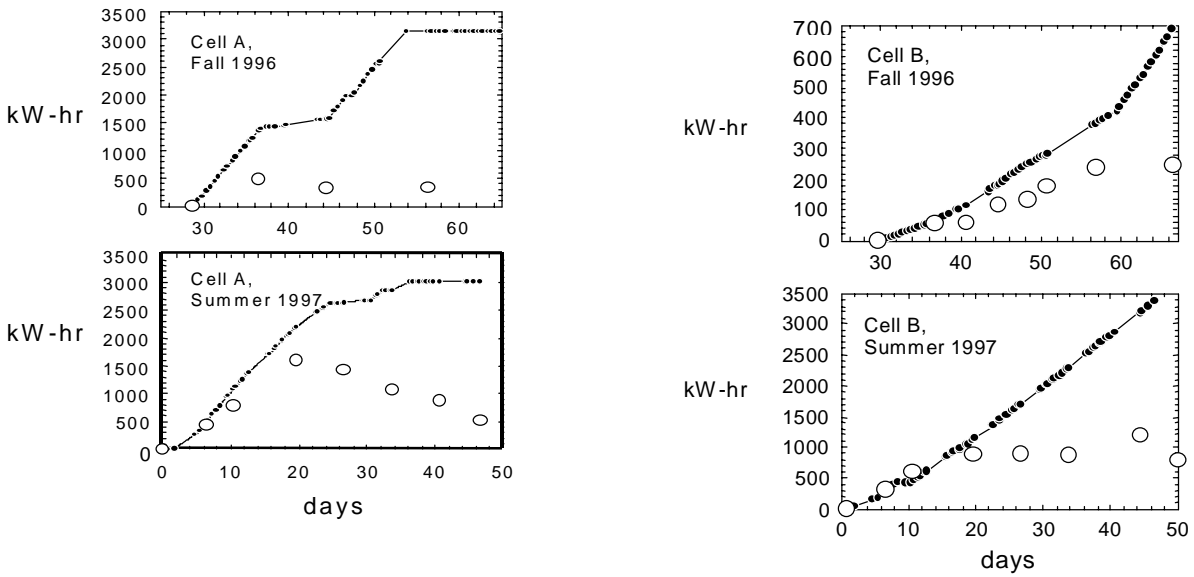
**Figure 5. Heat retention in steam flushing (cell A) and hot-air flushing (cell B) test cells (filled circles are energy supplied to air heater or steam generator; open circles are heat energy in the ground estimated from change of in situ temperature).**

Vapor-phase mass recovery processes coupled with hydraulic fracturing and thermal enhancements appear to be primarily focused on the region overlying fractures receiving hot-fluid injection. A highly heterogeneous distribution of contaminant mass, and low levels of contaminants in the vicinity of some test cells, particularly test cell A, preclude a thorough evaluation of the efficiency of contaminant recovery.

**Reactive Barrier Results**

Intact cores collected in December 1996, July 1997, December 1997, and December 1998 indicated that highly reactive barrier zones exist up to 27 months after emplacement.

- The iron metal fractures were highly reducing only within the fracture itself; degradation efficiencies were on the order of 35% after 48 hours of contact with TCE-contaminated groundwater.

- The permanganate filled fractures were highly oxidizing with a zone extending more than 30 cm above the fracture and 60 cm below it; TCE degradation potential was nearly 100% after minutes of contact with contaminated groundwater (Figure 6).
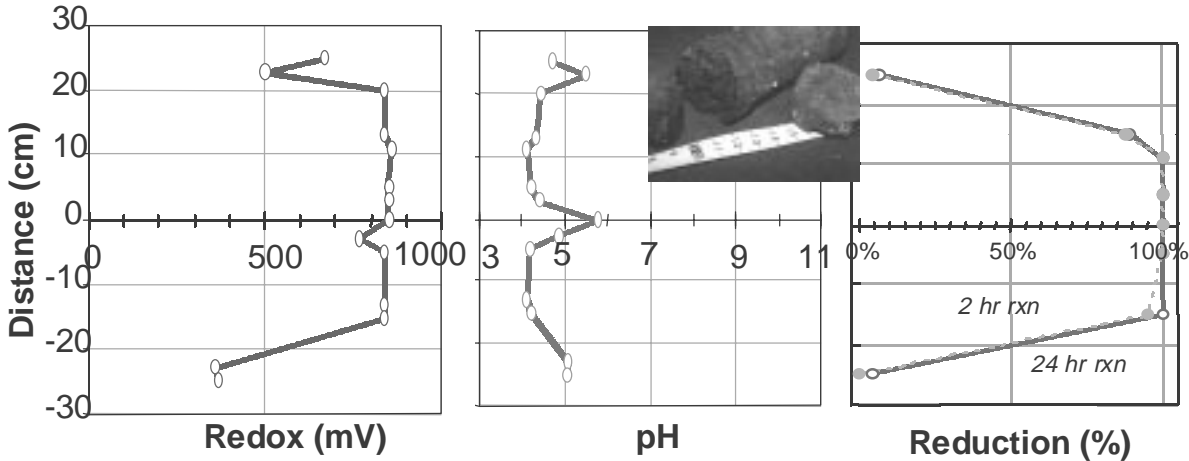


Figure 6. Permanganate-filled fracture characteristics 10 months after emplacement.

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# SECTION 4
# TECHNOLOGY APPLICABILITY AND ALTERNATIVES

## Competing Technologies

Ex situ technologies are commonly the preferred remediation technology because they have been proven in numerous field applications.  However, in situ technologies tend to reduce site disruption, are generally cheaper, require less handling, and limit potential exposure of workers or nearby residents to the chemical.

Alternatives to hydraulic fracturing for LPM remediation include other access technologies such as:

- pneumatic fracturing;
- trenches;
- vertical lances;
- deep soil mixing;
- vertical wells; and
- horizontal wells, if some permeability exists.

Several treatment processes are typically used to remove VOCs from the subsurface. These technologies, which require some permeability to effectively access the contaminated zone, include:

- soil vapor extraction (SVE);
- free-product recovery;
- soil flushing;
- steam stripping;
- air sparging; and
- "pump and treat" methods in saturated soils.

These technologies are most appropriate in permeable media.  In low permeability media, competing technology includes the baseline of excavation and ex-situ treatment or containment.

## Technology Applicability

Hydraulic fracturing is commercially available from FRx, Inc. and several other companies.  As enabling technology, it has been demonstrated for source removal and treatment of dissolved plumes at both DNAPL and BTEX contaminated sites.  Appendix B summarizes some of the sites where fracturing has been demonstrated or utilized to enhance soil or groundwater remediation.

Hydraulic fracturing combined with various treatment processes can be designed to treat a wide range of contaminants in both soil and groundwater.  Treatment processes that have been demonstrated with hydraulic fracturing include:

- steam or hot air flushing for mass transfer of VOCs (applicable for compounds with vapor pressures > 10 mm Hg, not suitable for recalcitrant non-volatile compounds);
- zero-valent iron for reductive dechlorination (may reduce $NO_3$ and some metals);
- permanganate for oxidation of alkenes, aromatics, PAH's, phenols, pesticides, organic acids;
- enhanced soil vapor extraction of VOCs;
- LNAPL recovery;

- bioaugmentation by placement of porous granular material inoculated with selected microorganisms; and
- horizontal Lasagna®.

The key parameters affecting deployment of hydraulic fracturing are summarized in Table 2.

**Table 2. Summary of key parameters affecting deployment and performance of hydraulic fracturing**

| Key Parameter | Comment/Condition |
|---|---|
| Surface Topography and Land Use: | |
| Slope and potential runoff | Fractures tend to propagate in the downslope direction. Surface runoff around fracturing equipment, injection locations, and any possible vent location should be contained if injecting reactive material. |
| Surface obstructions | Subsurface must be accessible by direct-push or drilling (hand-held lance drivers available for restricted spaces). Can fracture under structures. Overlying structures should accommodate surface tilting of 1:300. Large rigid structures (reinforced concrete slab) appear to be unaffected. |
| Subsurface interferences | Location of utility lines or open boreholes may limit applicability. Fractures that encounter backfilled soil will tend to propagate along the wall of the excavation and fracture slurry will vent to the ground surface. |
| Formation Properties: | |
| General soil properties | Well suited in bedded material. Not suitable in areas of fill. Drilling alternatives available if direct-push meets refusal. |
| Soil state of stress | Best if soils are overconsolidated. |
| Grain size distribution | Best suited to fine-grained materials. No data for massive, sandy soils. |
| Contaminant Properties: | |
| Depth (ft bgs) | > 5 ft (1.5m). |
| Areal extent | Must identify hot spots prior to fracturing to strategically locate fractures. |
| Presence of co-contaminants | Hydraulic fracturing may stimulate microbial activity. Treatment process may alter subsurface biogeochemistry. |

Benefits of hydraulic fracturing include:

- easily combined with a variety of active and passive treatment processes for unsaturated and saturated zone contaminants, including LNAPL, DNAPL, chlorinated solvents, hydrocarbons, VOC's, and heavy metals;
- easily applied and controlled.

## Patents/Commercialization/Sponsor

FRx. Inc. conducted the hydraulic fracturing for the demonstration at X-231A.

The principals of FRx, Inc. developed hydraulic fracturing for environmental application's as part of US EPA funded research projects during the 1980's and early 1990's. FRx, Inc. has license to practice the technology invented by its principals and is pursuing patent protection for recent inventions. The principals of FRx, Inc. and of Foremost Solutions, Inc., have sought a provisional patent for methods to create reactive sheets for remediation of ground water. FRx, Inc. and Foremost Solutions, Inc., have executed a patent agreement by which Foremost Solutions, Inc. bears the cost of filing and maintaining the patent and receives assignment of it while both companies have a cost-free license to practice the technology. The concept of horizontal fracturing in soils now rests in the public domain.

A patent application for the specially formulated permanganate grout submitted by project investigators from ORNL and FRx has been granted.

# SECTION 5
# **COST**

## Methodology

The cost information presented here is based on the demonstration conducted at PORTS in 1996 - 1998. The demonstration cost was jointly funded by the OST Subsurface Contaminants Focus Area and the PORTS DOE Site Office with a total cost of approximately $1,258.7K. The majority of the costs (~75%) were related to the technology operation and pre-demonstration characterization. Host site support costs (oversight, permits, waste management, health physics, and health and safety) are not included.

Demonstration activities were placed in one of several categories (Tables 3 and 4): project management, demonstration site selection, design, and equipment shakedown, pre-demonstration characterization, demonstration operation – phase 1, demonstration operation – phase 2, post-demonstration characterization, and reporting.

The typical costs of creating hydraulic fractures involve labor, materials, equipment usage, and mobilization expenses. The cost per fracture will decrease as the size of the job increases, largely because mobilization costs are distributed over several fractures and monitoring efforts can be shared.

The cost of the specific technique employed at each application needs to be considered (e. g. the cost of vacuum systems, vapor treatment equipment, and waste management) in addition to the cost for fracturing.

## Cost Analysis

**Table 3. Costs for the hydraulic fracturing demonstration**

| Demonstration Activity | Estimated Demonstration Cost |
|---|---|
| Project Management | $102,300 |
| Demonstration Site Selection, Design, and Equipment Shakedown | $80,700 |
| Pre-demonstration Characterization | $157,100 |
| Demonstration Operation – Phase 1 (60 days) | $715,900 |
| Demonstration Operation – Phase 2 (45 days) | $76,400 |
| Post-demonstration Characterization and Demobilization | $48,800 |
| Reporting | $77,500 |
| TOTAL | $1,258,700 |

Of the total demonstration costs:

- equipment shakedown at the clean test site accounted for approximately 4% ($51,000);

- materials (iron, permanganate, well materials, sampling supplies, etc.) accounted for approximately 9% (~$106,200);

- operations and monitoring (excluding the vendor subcontract) accounted for approximately 23% ($269,000); and

- the vendor subcontract accounted for approximately 27% (~$320,000).

**Table 4. Summary of X-231A demonstration costs (all costs estimated in $K)**

| | FY96 | FY97 | FY98 | Total |
|---|---|---|---|---|
| *Project Management* | *58* | *33.8* | *10.5* | *102.3* |
| *Demo Selection/Shakedown* | *71.2* | *0* | *0* | *71.2* |
|    Design | 7.6 | 0 | 0 | 7.6 |
|    Plans/Preparations | 12.6 | 0 | 0 | 12.6 |
|    Reconnaissance Sampling and Clean Test Site Shakedown | 51 | 0 | 0 | 51 |
| *Comparative Field Demonstration (60 d)* | *551.3* | *331.2* | *0* | *882.5* |
|    Plans/Preparations | 7.4 | 0 | 0 | 7.4 |
|    Design | 7.9 | 0 | 0 | 7.9 |
|    Setup/Baseline Characterization | 64 | 88.1 | 0 | 152.1 |
|    Field Test Operation, Monitoring, and Measurement | 101.2 | 167 | 0 | 268.2 |
|    FRx, Inc. Subcontract | 320 | 0 | 0 | 320 |
|    Terminal Sampling/Degradation Field Test/Closeout | 0 | 20.7 | 0 | 20.7 |
|    Materials/Supplies | 50.8 | 55.4 | 0 | 106.2 |
| *Comparative Demonstration - Phase 2 (45 d)* | *0* | *76.4* | *0* | *76.4* |
|    Plans/Preparation | 0 | 12 | 0 | 12 |
|    Field Work | 0 | 62 | 0 | 62 |
|    Materials/Supplies | 0 | 2.4 | 0 | 2.4 |
| *Site Closeout and Post Characterization Sampling* | *0* | *0* | *48.8* | *48.8* |
|    Plans/Preparations | 0 | 0 | 7.2 | 7.2 |
|    Field Work | 0 | 0 | 39.9 | 39.9 |
|    Materials/Supplies | 0 | 0 | 1.7 | 1.7 |
| *Reporting* | *0* | *34.8* | *42.7* | *77.5* |
|    Interim Demonstration Report | 0 | 23.4 | | 23.4 |
|    Final Demonstration Report | 0 | 11.4 | 42.7 | 54.1 |
| Total | 680.5 | 476.2 | 102.0 | 1258.7 |

## Cost Comparison

The following assumptions were used to complete the cost comparison.

- Cost estimates comparing thermally enhanced sand fractures to reactive barrier cells.

- The target site for remediation is ~950 ft by 225 ft (similar to the PORTS X-231A site).

- The region to be treated is from ~3 to 18 ft depth (15 ft thick).

- The total volume of soil to be treated is ~118,750 c.y.

- Fractures are emplaced at 5, 10 and 15 ft depths with a diameter of ~30 ft and ~10% overlap between adjacent cells (yields a total of ~325 cells).

- Installation of sand-propped fractures including labor and materials is ~$6000 per cell.

Given the above assumptions, the costs for sand fractures for thermally enhanced vapor extraction are estimated as follows:

- approximately $1.9 million or ~$16/c.y. of soil for installation of sand-propped fractures;

- approximately $2500 per day operational costs for resource consumption, routine operation and maintenance, and performance monitoring;

- up to ~$2,500 per day for off-gas treatment;

- for an operation period of 1 year, the total operational costs would be ~$1.8 million or ~$14/c.y.; and

- thus, an estimated cost per unit volume of soil remediated would be ~$30/c.y. If the treatment time were extended to 2 years, the cost per yard could increase up to $45/c.y.

Again given the above assumptions, the costs for reactive barrier cells are estimated as follows:

- approximately $2.8 million or ~$24/c.y. of soil for installation of iron-propped fractures (due to added cost of iron, ~$0.38/lb., compared to sand, ~$0.10/lb.);

- approximately $3.3 million or ~$28/c.y. of soil for installation of permanganate grout-propped fractures (due to added cost of permanganate, ~$1.60/lb., compared to sand, ~$0.10/lb.);

- approximately $275 per day operational costs for lower resource consumption (e.g., power), less sampling and analysis (e.g., no off-gas), reduced manpower requirements, and no off-gas treatment costs; and

- thus, for a comparable period of 1 year, the cost per c.y. of soil is ~$25 and $29 for the iron and permanganate systems, respectively. If the operational period exceeds one year, then the barrier systems become increasingly cost competitive.

More detailed cost analyses are currently being prepared.

## Cost Conclusions

The costs generally range from $850 to $1500 per fracture using current methods for sand-propped fractures. Based on the X-231A demonstration, the cost per fracture ranged from approximately $1750 to $2,300. The higher per-fracture cost is due to:

- working within a radiation zone; and

- the higher cost of the reactive agents used for the fracture:

  — ~$0.1/lb. of sand;
  — ~$0.3/lb. of iron.
  — ~$1.6/lb. of permanganate.

Cost estimates for sand fractures for thermally enhanced vapor extraction are ~$30 /45/c.y. for 1-2 years of operation. Cost estimates for reactive barrier cells are $25 and $29/c.y. for iron and permanganate systems, respectively.

# SECTION 6
# REGULATORY AND POLICY ISSUES

## Regulatory Considerations

Early and continuous discussions with the regulators will encourage more rapid permitting.

- An Underground Injection Control Permit will likely be required.

- Comprehensive Environmental Recovery, Compensation, and Liability Act or Resource Conservation and Recovery Act (CERCLA) permitting may be required.

- At federal facilities, a National Environmental Protection Act review is required.

- CERCLA did not apply to this demonstration; and a site-specific evaluation of the nine CERCLA criteria was not conducted.

## Safety, Risks, Benefits, and Community Reaction

### Worker Safety

Elevated pressures (70 psi) during hydraulic fracturing are sustained for brief periods (<1 second) during fracture initiation. All equipment contains safety features such as pressure relief valves and hose restraints and must be regularly checked.

Potential worker safety risks include those associated with standard construction operations as well as those associated with work at a contaminated site and with potentially hazardous chemicals. The primary risk to workers occurs during handling of the reactive agents (e.g., steam, permanganate solids). Permanganate is a strong oxidizer and is incompatible with combustibles. Care must be taken to avoid spills and to keep the material away from equipment that could generate sparks.

All field personnel must be 40-h Occupational Safety and Health Administration trained as required in 29 Code of Federal Regulations (CFR) 1910.120 for hazardous waste operations.

### Community Safety

Hydraulic fracturing does not produce routine release of contaminants. Materials injected (e.g., sand, iron, and permanganate) as fracture proppants pose no hazard to the community due to their innocuous nature and low concentration after dispersal into the soil or groundwater.

No unusual or significant safety concerns are associated with transport of equipment or other materials associated with this technology.

### Environmental Impact

Investigative-derived wastes are minimized with hydraulic fracturing. The fracture access borehole is installed using direct push techniques, which generate little, if any, excess soil cuttings.

### Socioeconomic Impacts and Community Reaction

Hydraulic fracturing has minimal economic or labor force impacts. The general public has limited familiarity with hydraulic fracturing; however, the technology can be explained to the public with ease, as it is similar to that of construction techniques or oil field recovery methodologies.

# SECTION 7
# LESSONS LEARNED

## Implementation Considerations

The primary factors involving the design of hydraulic fractures include:

- vertical and horizontal extent of the contaminated area;
- depth and number of fractures required.

Implementation of hydraulic fractures is dependent upon individual site conditions.

- Typically hydraulic fractures are installed at depths ranging from 5 to 60 ft (1.5 to 12 m) bgs.  At shallower depths fractures have a tendency to climb and vent to the surface.  However, hydraulic fractures can readily be created at greater depths.
- Typically hydraulic fractures propagate between 15 and 50 ft (5 to 10 m) outward (fracture radius).
- Between 500 to 2000 pounds of sand are typically injected into a fracture.  The average thickness of sand in a fracture ranges from 1/4 to 1/2 in. (5 to 10 mm).
- The fracture density has typically been limited to one or two fractures per location with intervals of 5 to 20 ft (1.5 to 6 m) between fractures, but as many as 6 to 10 fractures have been created from a single well. To avoid fracture co-mingling fractures should be emplaced at depths greater than 5 ft bgs and with intervals between stacked fractures of at least 5 ft.

Displacement of soil will accompany hydraulic fracturing and the effects of this displacement must be evaluated at each site; many structures can accommodate the displacement, whereas others cannot. Creating a shallow fracture (2 to 3 m depth, for example) in soil typically forms a broad dome roughly 1 in (2 cm) in amplitude and 15 and 50 ft (5 to 10 m) across.  At the ground surface, vertical fractures in soil or pavement are commonly dilated during the doming.

Implementation of this technology does not require permanent infrastructure such as a permanent power source (temporary power is required), permanent water and chemical tanks, etc.  Temporary power may be required depending on the selected treatment process.

Additional design parameters are related to each specific treatment process.

- If hot-fluid recirculation is planned, power consumption, off-gas containment and treatment, and subsurface dewatering (water generated by steam injection or to lower the water table for SVE) must be considered.
- If chemical oxidation is planned, then the mass of oxidant to be delivered based on the estimated contaminant mass present and the behavior of the oxidant within the matrix must be considered.
- Effects of hot fluids may increase biological activity for which a bio-venting component must be considered.  If reductive dechlorination were ongoing, the airflow could induce oxidizing conditions and negate it.
- Vapor-phase processes need dewatering; barrier techniques do not.

Features and relative merits of the individual treatments demonstrated at PORTS are summarized in Table 1, Appendix E.

## Technology Limitations and Needs for Future Development

- Hydraulic fracturing is not suitable for disturbed soils or fill material.
- Fractures created to improve fluid delivery or recovery (e.g. hot air injection or SVE applications) are most effective in low permeability material.

- Fractures may not be suitable at sites with large, numerous, or delicate surface obstructions or subsurface interferences (utility lines, etc).

- Fracture aperture decreases with depth; greater quantities of proppant may be required to obtain fractures of desired thickness at increased depths.

- Fracture form, especially orientation, varies with depth; vertical fractures are favored at greater depths.

Potential limitations of individual treatment processes must also be considered. Of the processes tested during the demonstration, limitations include:

- dewatering is required for hot fluid flushing;

- reliance upon mobilization of the contaminants to the fracture for the reaction with iron to occur; and

- the presence of organic matter, chloride ions and lower temperatures tend to slow the reaction kinetics of the oxidation of TCE with permanganate; however, the presence of such interfering chemical and physical conditions still allows for greater than 99% degradation of TCE within 60 minutes.

Further development opportunities with regard to full-scale deployment include:

- optimization of fracture emplacement methods for deep placement of fractures and of reactive media to create treatment barriers;

- development of design and implementation protocols for depth and interval emplacement, and reactivity and capacity over time;

- evaluation of the behavior of horizontal reactive barrier systems under conditions of forced advection to understand the benefits/costs of recirculation approaches; and

- completion of modeling evaluations to further the understanding of risk reduction as a function of treatment efficiency achieved; this information is critical to establishment of reasonable and achievable cleanup goals.

## Technology Selection Considerations

The primary factors contributing to the decision to select hydraulic fracturing include (see Table 3):

- formation properties (general soil properties, grain size distribution, porosity, permeability, and conductivity);

- surface topography and land use (surface slope, obstructions, and interferences); and

- contaminant properties (depth, thickness, areal extent, type and concentration, potential co-contaminants).

Other considerations when selecting treatment processes for LPM include the following.

- Heterogeneities limit mass transfer rates for contaminant recovery and reagent delivery.

- High water contents reduce the media porosity, which inhibits the mass transfer rate for contaminant recovery.

- Poor accessibility to the contaminants and the difficulty in delivery of treatment reagents have rendered many conventional processes ineffective.

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# APPENDIX B
# FRACTURING DEPLOYMENT LOCATIONS

**Table B.1. Example locations where fracturing has been utilized**

| Site | Remedial Process |
|---|---|
| Laidlaw Disposal Site, Sarnia, Canada | Fractures created for hydrological control within a controlled release test cell. |
| DOE Portsmouth Plant, Piketon, Ohio | Sand filled and reactive fractures for comparative evaluation of fracture enabled treatment processes (described herein). |
| Linemaster Superfund Site, Woodstock, Connecticut | Fractures for dual phase recovery (dewater and SVE) of chlorinated solvents. |
| CSX Morris Avenue Rail Yard, Birmingham, Alabama | Recovery of LNAPL (diesel fuel) |
| Colorado DOT Material Testing Lab, Denver, CO | Fractures for control/reduction of chlorinated solvent plume |
| New Mexico DOT Service Yard, Continental Divide, NM | Fractures filled with porous solids inoculated with selected microorganisms for control and in situ biodegradation of gasoline plume |
| U-Pump-It Station, Lakewood, Colorado | Fractures filled with porous solids inoculated with selected microorganisms for interception and destruction of gasoline plume. |
| Mustang Gas Site, Grand Lake, Colorado | Fractures filled with porous solids inoculated with selected microorganisms for interception and destruction of gasoline plume. |
| Offutt Air Force Base, Omaha, Nebraska | Fractures for demonstration of horizontal Lasagna®, in situ remediation by electro-osmotic migration of groundwater and contaminants into reactive zones. |
| Denver Federal Center, Denver, Colorado | Fractures filled with porous solids inoculated with selected microorganisms for remediation of soil contaminated with cutting and machining oils (BTEX and TPH). |
| Chemical Manufacturing Plant, Macedonia, Ohio | Fractures for dewatering and contaminant recovery by SVE to control a solvent plume. |
| Lima Gas Station, Lima, Ohio | SVE recovery of gasoline compounds. |
| University Gas Station, University Heights, Ohio | SVE recovery of gasoline compounds. |

# APPENDIX C
# DEMONSTRATION SITE CHARACTERISTICS

## Site History/Background

PORTS is approximately 80 miles south of Columbus, 20 miles north of Portsmouth, and 1 mile east of U.S. Route 23, near Piketon in south-central Ohio (Fig. C.1). The industrialized portion of PORTS is approximately 1,000 acres of a 3,714-acre DOE reservation. PORTS was constructed between 1952 and 1956 and has operated since January 1955 enriching uranium for electrical power generation. Until 1991, PORTS also provided highly enriched uranium to the U.S. Navy.

PORTS occupies an upland area of southern Ohio with an average land surface elevation of 670 ft above mean sea level. The plant site sits in a mile-wide abandoned river valley situated 130 ft above the level of the nearby Scioto River to the west.

In much of the industrialized area of PORTS, the original topography was modified for construction of buildings and other facility components. The surfacial material over much of the industrialized area of PORTS is fill removed from the higher elevations of the plant site.

The X-231A unit is located in the southeastern portion of the PORTS site and consists of an old waste oil biodegradation site. The unit, approximately 950-ft by 225-ft in area, was reportedly used for the treatment and disposal of waste oils and degreasing solvents, some containing uranium ($^{235}$U) and technetium ($^{99}$Tc). A similar land treatment site, the X-231B unit, is located nearby.
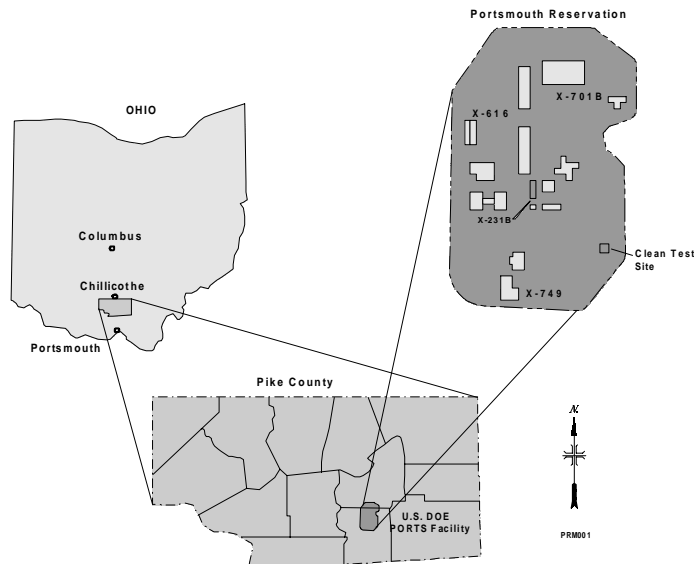


**Figure C.1. Location of the Portsmouth Gaseous Diffusion Plant.**

## Contaminant Locations and Hydrogeologic Profiles

The stratigraphy at the X-231A site consists of two unconsolidated units overlying bedrock. The stratigraphy from the surface downward consists of:

- the Minford silt and clay, with a thickness of 20 to 25 ft;

- the Gallia sand and gravel, which has a thickness varying from 3 to 7 ft;

- the Sunbury shale, the first bedrock layer, consisting of 10 to 15-ft of moderately hard shale that often exhibits an upper weathered zone of gray, higher plastic clay; and

- the Berea sandstone and shale.

In the X-231A demonstration area, the Minford is ~20 ft thick and the ground water table is ~10 to 14 ft bgs. Ground water flow occurs vertically downward through the Minford Member into the Gallia Member where flow is predominantly horizontal to the south toward the X-230K pond.

Soil samples collected prior to the demonstration indicated total VOCs (primarily TCE and 1,1,1-trichloroethane [TCA]) ranging from less than 1 to 282 mg/kg at the southeast corner of the site (ASI 1989). Low concentrations of metals (primarily Ba, Cr, Pb, and Ni) were detected throughout the unit. Low total beta activities and total U were also detected ranging from 11 to 64 nCi/kg and 1 to 11 mg/kg, respectively throughout the unit ranging. No PCBs were detected.

Numerous soil and ground water samples were collected and analyzed prior to, during, and after the demonstration within and surrounding the area. Based on this information, an area with DNAPL was delineated south and west of test cells A and B and the distribution of DNAPL compounds, such as TCE, within the Minford was estimated. A variety of equilibrium and fugacity-based approaches are commonly used to assess how DNAPL compounds are distributed under a given set of conditions. A fugacity-based model (Dawson 1997) was used to assess the TCE distribution within the Minford. Based on literature data for key properties of TCE and using representative measured values of porosity (40% v/v) (Siegrist et al. 1995, West et al. 1995, and Gierke et al. 1995), volume fraction of water (36% v/v), and mass fraction of organic carbon (500 mg/kg) for the Minford, a bulk concentration of 300 mg TCE per kg of soil can result in 15% of the mass of TCE being present in a nonaqueous phase with 69% in the soil water, 14% on the soil solids, and 2% in the soil air.

# TECHNOLOGY DESCRIPTION / PERFORMANCE DETAIL
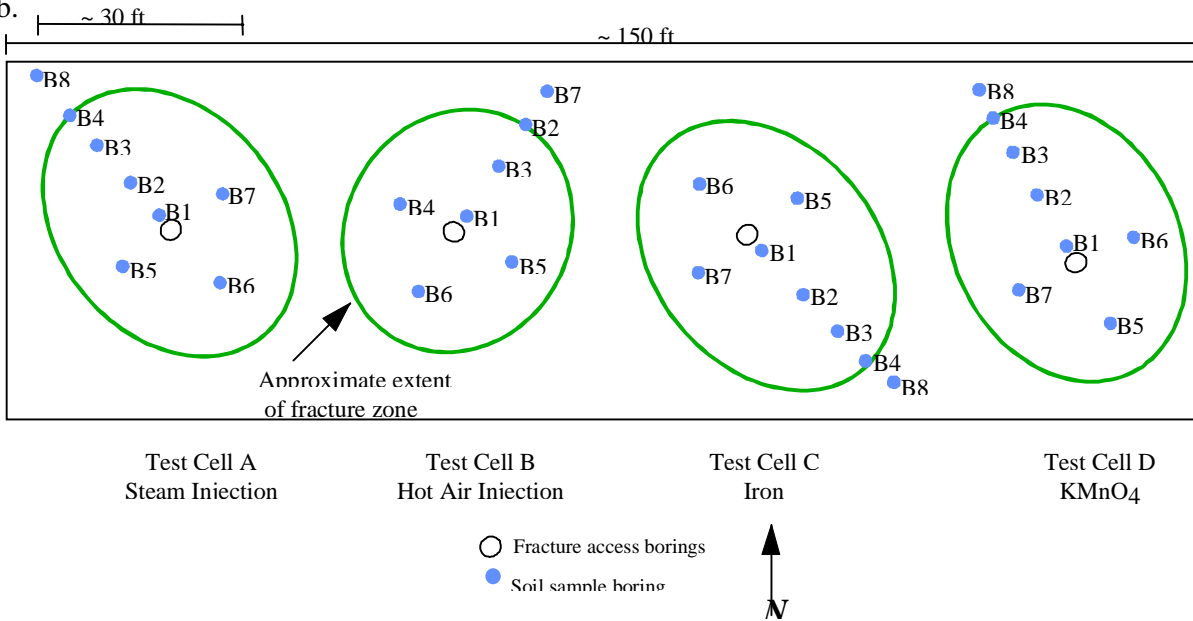
## Demonstration Plan

a.
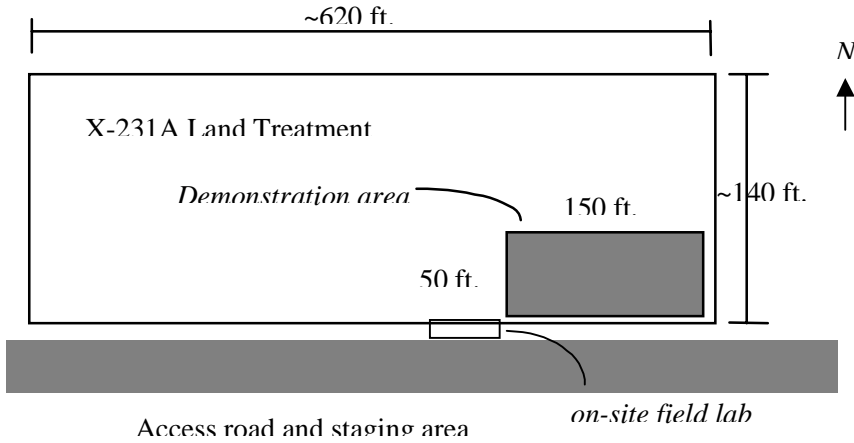


b.



**Figure D.1. Location of (a) the demonstration site within the X-231A
Site at PORTS, and (b) the test cells within the demonstration site.**

## Operating Conditions

**Table D.1.  Summary of operations at the X-231A site during fall of 1996**

| Parameters | (A) Steam injection recovery | (B) Hot air injection recovery | (C) Iron metal barrier | (D) Permanganate barrier |
|---|---|---|---|---|
| Treatment process<br>  4 ft fracture<br>  6 ft fracture<br>  8 ft fracture<br>  12 ft fracture<br>  16.5 ft fracture<br>  18 ft fracture | vapor extraction<br>-<br>steam injection<br>vapor extraction<br>-<br>dewatering | vapor extraction<br>ambient air injection<br>hot air injection<br>vapor extraction<br>dewatering<br>- | passive<br>reduction<br>reduction<br>reduction<br>passive<br>- | passive<br>oxidation<br>oxidation<br>oxidation<br>passive<br>- |
| Cell operation | active | active | passive | passive |
| Treatment start date | 10/19/96 ambient air flushing;<br>11/4/96 steam injection | 10/19/96 ambient air flushing;<br>11/4/96 hot air injection | 8/27/96 | 9/18/97 |
| Treatment end date | 12/3/96 | 12/12/96 | 12/10/96 | 12/10/96 |
| Treatment duration | 10 days (ambient air)<br>10 days (steam, maximum continuous operation) | 10 days (ambient air)<br>52 days (hot air) | ~108 days (passive) | ~86 days (passive) |
| Injected fluid | potable water as steam (~130 °C) | ambient air into 6 ft fracture; heated ambient (~160 °C) into 8 ft fracture | None | None |
| Hot fluid injection rate | ~23 gal/day | 3-9.1 cfm (~5 ave) into 6 ft fracture;<br>2.1-11.6 (~5.9 ave) into 8 ft fracture | NA | NA |
| Injection pressure | 8 psi | 0.8 - 2 psig (~1 ave) into 8 ft fracture | NA | NA |
| Vacuum pump | 0.5 psig | 0.5 psig | NA | NA |
| Extraction rate<br>  4 ft fracture<br>  12 ft fracture | 0.5 - 7.1 cfm<br><0.1 - 4 cfm | 1.3 - 13.1 cfm<br><0.1 - 3 cfm | NA | NA |
| Total injection volume | 1400 gal | ~134,000 cf into 6 ft fracture;<br>~225,000 cf into 8 ft fracture | 500 - 2000 kg (reactant mass per fracture) | ~530 kg (reactant mass per fracture) |
| Total energy use | 3200 kW-hr (2.75 kW-hr/gal ave) | 700 kW-hr | none | none |

**Table D.2  Summary of operations at the X-231A site during summer 1997**

| Parameters | (A) Steam injection recovery | (B) Hot air injection recovery | (C) Iron metal barrier | (D) Permanganate barrier |
|---|---|---|---|---|
| Treatment process<br>  4 ft fracture<br>  6 ft fracture<br><br>  8 ft fracture<br>  12 ft fracture<br>  16.5 ft fracture<br>  18 ft fracture | vapor extraction<br>-<br><br>steam injection<br>vapor extraction<br>-<br>dewatering | vapor extraction<br>ambient air injection<br><br>hot air injection<br>vapor extraction<br>dewatering<br>- | passive<br>reduction<br><br>reduction<br>reduction<br>passive<br>- | passive<br>oxidation<br><br>oxidation<br>oxidation<br>passive<br>- |
| Cell operation | active | active | passive | passive |
| Injection start date | 7/20/97 | 7/21/97 | 7/24/97 | 7/24/97 |
| Injection end date | 8/25/97 | 9/06/97 | 9/05/97 | 9/05/97 |
| Injection duration | 37 days | 49 days | 45 days | 45 days |
| Injected fluid | potable water as steam (~130 ºC) | ambient air into 6 ft fracture; heated ambient air heated (~230 ºC) into 8 ft fracture | potable water with 100 ppm NaBr tracer | potable water with 100 ppm NaBr tracer |
| Injection rate | ~ 30 gal/day | 10.5 to 13 scfm (~12 ave) at 6 ft fracture; 13 to 14.75 scfm (~14 ave) at 8 ft fracture | ~7.5 gal/day | ~4.5 gal/day |
| Injection pressure | 8 psi | ~1.2 psig into 6 ft fracture; ~0.95 psig into 8 ft fracture | NA, gravity feed | NA, gravity feed |
| Vacuum pump | 0.5 psig | 0.5 psig | NA | NA |
| Extraction rate<br>  4 ft fracture<br>  12 ft fracture | <0.1 - 2.5 cfm<br><0.1 - 2.5 cfm | 1.7 - 4 cfm<br>4 - 48 cfh | NA | NA |
| Total injection volume | 1170 gal potable water | ~847,000 cf into 6 ft fracture; ~988,000 cf into 8 ft fracture | 350 gal | 201 gal |
| Total energy use | 3000 kW-hr (2.7 kW-hr/gal ave.) | 3400 kW-hr | none | none |

## Treatment Performance

**Hot Fluid Flushing (test cells A and B)**

- Approximately 3200 kW-hr and 1400 gal of water (injected as steam) were used during the steam injection demonstration at X-231A.

- Two hot-air injection tests were conducted during the demonstration.

- During the first 60-day test (fall 1996) the cumulative thermal energy input was 720 kW-hrs at 260$^o$C.

- During the second 45-day test (summer 1997) the cumulative thermal energy input was 3500 kW-hrs at 430$^o$C.

- During the fall 1996 test, air was injected at approximately 720 cfh and was recovered at a combined rate (4-ft and 12-ft fractures) of approximately 550 cfh.

- Approximately 25% of the injected air was not recovered by the fractures and presumably flowed to the ground surface.

- During the summer of 1997, up to 85% of the injected air was not recovered; this was attributed to fractures or gaps around the well casings that presumably were opened by desiccation resulting from the injection of hot-air.

- During steam injection, approximately 70% of the injected heat accumulated in the soil and 30% was lost.

- During hot-air injection, approximately 75% of the injected heat accumulated in the soil and 25% was lost.

- Approximately 60 to 90 gallons of water were dewatered from the steam injection test cell per day of operation, while approximately 10 to 75 gallons of water were dewatered from the hot-air injection test cell per day.

**Reactive Barriers (test cells C and D)**

Test cells C and D were operated passively for approximately 10 months after fracture emplacement in the fall of 1996. During summer 1997, tapwater was injected under low pressure (1.5 to 2.2 ft head) into the shallow sand-propped fracture in each test cell for approximately 52 days. The delivery rate (or acceptance rate) was controlled by the amount of water that could flow into the sand-filled fracture from the fracture access tube and then be infiltrated and percolated away into the surrounding natural soil.

A 500 gal tank filled with potable water supplemented by a 100 mg/L NaBr tracer solution was used for injection into either test cell C or D. The discharge from the tank was controlled by a set of high and low-level float switches installed in the shallow fracture access casing. The float switches provided a constant head of 1 to 3 ft in the shallow sand-filled fracture. The tank fed both test cells C and D via two independent high-and low-level switches in the fractures and the associated control boxes and flow meters located at the feed basin.

In test cell C, the initial acceptance rate was ~2.1 gph compared to test cell D which was slower, at only ~0.1 gph. For comparison purposes, an acceptance rate of 0.2 gph into a 10-ft diameter sand fracture is equivalent to a flux density of only 0.25 cm/d or ~3 x $10^{-6}$ cm/s. This flux density is within the range of the bulk saturated hydraulic conductivity for the Minford deposit.

During gravity-feed injection of water with sodium bromide into the reactive fracture test cells, no bromide was detected in soil or groundwater samples suggesting that either:

- the injected water had not traveled through the test cell to the underlying ground water;

- the $Br^{-}$ concentrations may have been lower than the field method detection limit; or

- the infiltrating water may have traveled vertically downward, but the monitoring locations and/or observations made were not conducive to its detection.
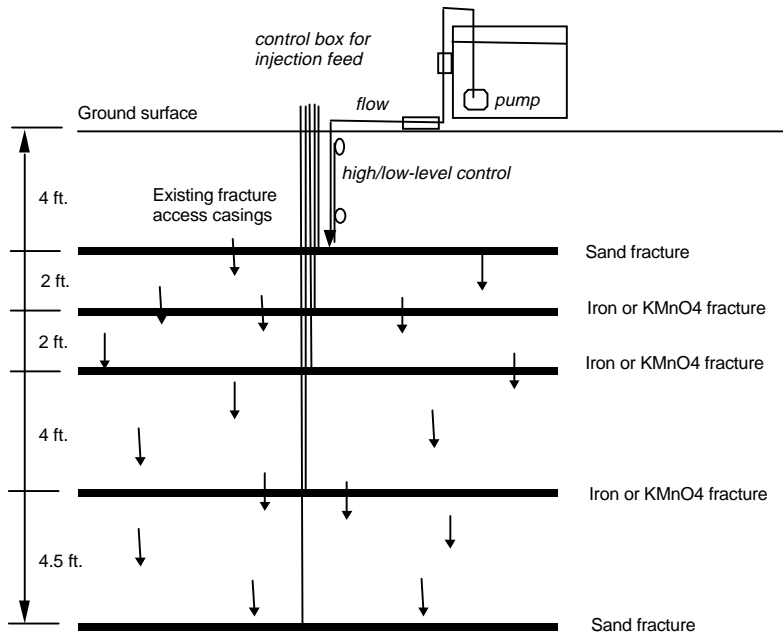
**Figure D.2. Illustration of the water infiltration/percolation system used for test cells C and D during summer of 1997.**

# APPENDIX E
# **IMPLEMENTATION DETAILS**

**Table E.1.  Features and relative merits of individual technologies tested at the X-231A site**

| Feature | Steam mass recovery | Hot air mass recovery | Iron barrier degradation | Permanganate barrier degradation |
|---|---|---|---|---|
| Method of installation | Standard fracturing | Standard fracturing | Standard fracturing with iron proppant | Standard fracturing with permanganate proppant |
| Time of installation per fracture | ~2 hr | ~2 hr | ~2 to 3 hr | ~2 to 3 hr |
| Predictability of fracture propagation | Good | Good | Good | Good |
| Applicability to saturated zones | Only with dewatering | Only with dewatering | Yes | Yes |
| Basis of TCE reduction | Mass transfer and vapor phase transport | Mass transfer and vapor phase transport | Interception and reductive dechlorination | Interception and oxidative degradation |
| Applicability for non-VOCs | Potentially SVOCs | Potentially SVOCs | Potentially for metals, nitrates | Potentially for metals, most organics |
| Requirement for off-gas treatment | Yes | Yes | No | No |
| Potential for ground water impact by technology itself | None | None | Possibly Fe(II) | Possibly Mn (II) |
| Potential daughter products not removed | None | None | Vinyl chloride | Organic acids |
| Operation facets | Operation of vacuum and off-gas system, dewatering | Operation of vacuum and off-gas system, dewatering | None, passive unless forced injection | None, passive unless forced injection |
| Resources consumed during operation | Power, water | Power | None, unless forced injection | None, unless forced injection |
| Performance monitoring | Off-gas, GW | Off-gas, GW | GW | GW |
| Installation waste generated | Borehole spoil, excess fracture proppant, decon water, trash | Borehole spoil, excess fracture proppant, decon water, trash | Borehole spoil, excess fracture proppant, decon water, trash | Borehole spoil, excess fracture proppant, decon water, trash |
| Process waste generated | Off-gas, dewatering | Off-gas, dewatering | None | None |
| Safety risks | Hot surfaces, gases | Hot surfaces, gases | Material handling | Material handling |
| Cost per c.y. | $30 to $60 | $30 to $60 | $30 | $30 |