Technology
Status Report

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GWRTAC S SERIES

Technology Status Report Hydraulic, Pneumatic and Blast-Enhanced Fracturing

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Ground-Water Remediation Technologies Analysis Center (GWRTAC)

Technology Status Report: Hydraulic, Pneumatic, and Blast-Enhanced Fracturing for Environmental Application

March 29, 2000

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Ground-Water Remediation Technologies Analysis Center (GWRTAC)

Technology Status Report: Hydraulic, Pneumatic, and Blast-Enhanced Fracturing for Environmental Application

March 29, 2000

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FOREWORD

About GWRTAC

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) is a national environmental technology transfer center that provides information on the use of innovative technologies to clean up contaminated groundwater.

Established in 1995, GWRTAC is operated by Concurrent Technologies Corporation (*CTC*) in association with the University of Pittsburgh's Environmental Engineering Program through funding provided by the U.S. Environmental Protection Agency's (EPA) Technology Innovation Office (TIO), the U.S. Department of Defense (DoD) National Defense Center for Environmental Excellence (NDCEE), and the U.S. Department of Energy (DOE).

About "S" Series Reports

This report is one of the GWRTAC "S" Series of reports developed to provide a snapshot of the status of a given groundwater technology or topic, based on information compiled for GWRTAC's case study database. These reports are based on readily available information from literature or from personal communications with involved parties. These reports are not intended as in-depth technical analyses and are not peer-reviewed.

Acknowledgements

All charts in this report were created by Mr. Brian Bosilovich, *CTC*, from various database queries. His contribution to the completion of this report was invaluable. Mr. Vince Dick of Haley & Aldrich provided all blast-enhanced fracturing case studies as well as descriptive information. Dr. Frederick Pohland, University of Pittsburgh, provided important input to clarify the analyses provided herein.

ABSTRACT

This technology status report provides a snapshot of the status of the hydraulic, pneumatic, and blast-enhanced fracturing for environmental application technologies. The information provided herein is a reflection of the content of the Ground-Water Remediation Technologies Analysis Center's (GWRTAC's) case study database for innovative technologies. GWRTAC's case study database is not represented as being comprehensive, nor are the case studies included screened to verify their validity, quality, or "success" in remediation. Rather the case study database and resultant summaries are intended to provide members of the ground-water remediation community with basic information on activity in laboratory research, field demonstration, or full-scale application of innovative technologies in both the public and private sectors. The summaries are provided as a "snapshot" of the contents of GWRTAC's "living" case study database. Analysis of information present in GWRTAC's case study database and presented herein, is by GWRTAC.

Hydraulic, pneumatic, and blast-enhanced fracturing for environmental application are technologies by which less than optimal site geologic conditions may be improved to allow greater efficiency in a site remediation effort. Hydraulic and pneumatic fracturing may be performed in unconsolidated materials or in bedrock, while blast-enhanced fracturing is performed exclusively in bedrock. The three types of fracturing technologies are useful to assist in overcoming site-specific geologic constraints that limit application of a variety of *in situ* vapor, soil, and/or ground-water remediation technologies. A total of 86 cases of field applications of these technologies are documented in this report, with the distribution 43% pneumatic fracturing; 31% hydraulic fracturing, and 26% blast-enhanced fracturing. Integrated technologies vary greatly, though soil vapor extraction/dual phase extraction and pump and treat enhancements or hydraulic control assists predominate. Pump and treat and hydraulic control enhancements are the main applications of the blast-enhanced fracturing method. Other types of integrated technologies (as well as pump and treat) are used in combination with hydraulic or pneumatic fracturing, where fractures serve to increase permeability and/or decrease heterogeneity, or else the fracturing process may be used to inject treatment materials into the subsurface. Contaminants at the fracturing project sites reflect those targeted by the integrated technology(ies). Projects have been implemented within the U.S. and Canada, but are clustered near the locations of predominant vendors and research institutes. Fracturing has been conducted at varying depths in a wide variety of geologic materials needing permeability enhancement or improvement of interconnectedness of permeable lenses. Short-term testing of remediation efficiency changes or changes in hydraulic properties in pre- versus post-fracturing/blasting tests show marked improvements in these metrics. Revisiting some projects to document continued improvements may be an interesting and useful endeavor.

This document was prepared for distribution by the Ground-Water Remediation Technologies Analysis Center (GWRTAC). GWRTAC is operated by Concurrent Technologies Corporation (*CTC*) in association with the University of Pittsburgh's Environmental Engineering Program through funding provided by the U.S. Environmental Protection Agency's (EPA) Technology Innovation Office (TIO), the U.S. Department of Defense (DoD) National Defense Center for Environmental Excellence (NDCEE), and the U.S. Department of Energy (DOE).

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1.0 INTRODUCTION / PURPOSE OF STATUS REPORTS

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) continually compiles laboratory-, pilot- and full-scale case study information for a variety of innovative *in situ* technologies for ground-water and soil remediation. At this time, GWRTAC's case study database contains approximately 600 case studies. Periodically, GWRTAC provides "S" Series Status reports based on information contained in the GWRTAC case study database for a selected technology.

GWRTAC's case study database is not represented as being comprehensive, nor are the case studies included screened to verify their validity, quality, or "success" in remediation. Rather the case study database and resultant status reports are intended to provide members of the ground-water remediation community with basic information on activity in laboratory research, field demonstration, or full-scale application of innovative technologies in both the public and private sectors. The GWRTAC database was designed in a manner to allow analysis of the use of each innovative technology monitored by GWRTAC, which is accomplished by the preparation of various tables and charts to reveal trends in technology application. This analysis, presented in the "S" Series Status reports, is by GWRTAC, and is based solely on the information in the GWRTAC database. The status reports are provided as a "snapshot" of the contents of GWRTAC's "living" case study database. As such, status reports for a given technology will be repeated in the future to reflect additional case study information compiled, and/or updates/revisions/additions to the database.

Submission of innovative technology case study information to GWRTAC via our on-line data submittal form (http://www.gwrtac.org) will allow GWRTAC to continue updating the database. Such notifications are appreciated, and may be followed with a request for additional information when GWRTAC focuses on the technology prior to preparation of an "S" Series report.

In addition to this Section 1.0, Introduction / Purpose of Status Reports, the remainder of this report is organized as follows. Section 2.0, Hydraulic, Pneumatic, and Blast-Enhanced Fracturing (Fracturing) Summary, reviews and shows trends related to general information such as the scale and status of the fracturing projects in the database, project objectives, target media, and project locations. Section 3.0, Analysis of Hydraulic, Pneumatic, and Blast-Enhanced Fracturing Technology, provides GWRTAC's analysis of trends in type of fracturing, integrated technologies, contaminant classes addressed, site geology, geometry of induced fractures or blasted bedrock zone, and fracturing-related project results. Section 4.0, Summary, provides a final overview of the fracturing technologies, and Section 5.0 References, indicates those references used in preparation of the text of this report, as distinguished from references for individual project summaries, which are included in the Appendix.

The Appendix contains the detailed project summaries for each of the fracturing projects currently contained in the GWRTAC database, as well as GWRTAC's source(s) of information for the database, and also other external references, such as journal articles, pertaining to the project. It should be noted that the length and amount of detail in the project summaries greatly varies, depending upon whether published papers are available on the project, and/or the source material used by GWRTAC. For most enforcement sites, GWRTAC has not obtained copies of multiple documents submitted to regulatory agencies to gain a full and detailed picture of the project. For research sites where published papers or reports are readily available to summarize the fracturing project, executive summaries or project summaries were often electronically provided to GWRTAC for direct incorporation into the database. In still other cases, information found in the project summaries was provided by abstracts, or from vendors.

2.0 HYDRAULIC, PNEUMATIC, AND BLAST-ENHANCED FRACTURING SUMMARY

2.1 Definition / GWRTAC Report Availability

Hydraulic, pneumatic, and blast-enhanced fracturing for environmental application are technologies by which less than optimal site geologic conditions may be improved to allow greater efficiency in a site remediation effort. Hydraulic and pneumatic fracturing may be performed in unconsolidated materials or in bedrock, while blast-enhanced fracturing is performed exclusively in bedrock.

Figure 1 is a schematic which illustrates a generalized hydraulic/pneumatic fracturing process. Hydraulic and pneumatic fracturing use fluid (air or liquid) injection to dilate a wellbore and open cracks. After fluid pressure exceeds a critical value, a fracture propagates and grows until injection ceases, until a barrier is intersected (such as the ground surface), or until injected flulide leakoff occurs through the fracture walls. Fractures may be naturally propped, or proppant may be injected, to create a high permeability layer in the targeted formation. Induced fractures created through hydraulic or pneumatic fracturing can improve the performance of environmental wells, and thus the performance of any number of integrated *in situ* technologies, such as soil vapor extraction (SVE), dual vapor extraction, enhanced bioremediation, permeable reactive barriers, eleckrokinetics, and pump and treat or hydraulic containment efforts. Induced fractures have been seen to increase well discharge 10 to 50 times and increase the distance for detecting pressure effects ten times. Hydraulic and pneumatic fracturing may also be used to inject materials such as microbes, iron filings, nutrients, graphite, etc. to enhance *in situ* treatment efforts. Induced fractures are typically shaped like gently dipping disks, or may be bowl-shaped.

Figure 2 is a generalized schematic of the blast-enhanced fracturing process. Blasted bedrock trenches or blasted bedrock zones (BBZ) are primarily used to enhance permeability to aid in groundwater or product recovery or hydraulic control of contaminated groundwater. This method can be used in low permeability bedrock, and ground-water yield from a well in the BBZ typically increases by an average of 70 times compared to a conventional well in the same bedrock prior to blasting. BBZs enhance interconnectedness of native fractures in bedrock, and bulk hydraulic conductivity along the BBZ axis is also significantly increased. The extraction well is typically installed into the BBZ during or immediately following BBZ installation, with the screen section spanning the entire depth of the BBZ. The level of the extraction pump may then be changed to vary the drawdown levels within the BBZ and the fracture sets to which it is connected.

Additional information on blast-enhanced fracturing may be found in a GWRTAC Technology Overview “O”-Series Report by the title "Artificially-Induced or Blast-Enhanced Fracturing", (TO-96-01). In addition, one Technology Status “S”-Series Report (EPA 542-K-94-005 entitled “Hydraulic and Pneumatic Fracturing”) was prepared by the U.S. Environmental Protection Agency (EPA) on the subject, however, this information has been updated for this status report. All of these reports are available for downloading in *.PDF format from the GWRTAC website at http://www.gwrtac.org. Soon to be available from GWRTAC is an Evaluation "E"-Series report on fracturing, which is currently being prepared.

2.2 GWRTAC Database / Scale and Status of Projects

Currently, GWRTAC’s case study database contains a total of 86 hydraulic, pneumatic, and blast-enhanced fracturing (fracturing) projects. Table 1 provides a summary of pertinent information for the fracturing case studies which are currently part of the GWRTAC database. The case studies are listed in alphabetical order by project name, which often indicates project location and/or site owner. Also listed for each site is a unique identification number assigned by GWRTAC; for reasons involved in development of the database, the GWRTAC ID numbers are not in consecutive order, and there may be gaps in the sequence. It should be noted that where individual but unique pilot-scale demonstrations are planned or have occurred at the same location (e.g., Portsmouth Gaseous Diffusion Plant, Piketon, Ohio) these unique individual efforts may be counted as separate pilot-scale case studies. Table 1 lists not only the GWRTAC ID and project name and location, but also lists selected primary organization points of contact for the categories of: 1) Potentially Responsible Party (PRP)/Site Owner; 2) Funding Source/Sponsor; 3) Regulatory Agency; and 4) Technical Team Member. GWRTAC's actual database contains additional contacts as available in each category, including names, addresses and phone numbers for points of contact. This information is available upon request from GWRTAC. Table 1 also includes information on the project scale, contaminants addressed, target media, type of fracturing and integrated technologies, and the project status. It may be useful for the reader to refer to Table 1 while reviewing the remainder of this report.

In most cases, only the "most advanced" scale of the project is included in the GWRTAC case study database. That is, if both pilot- and full-scale demonstrations took place at a site, they are not listed as separate projects. As illustrated by the pie chart in Figure 3, of the 86 fracturing case studies, 0 are laboratory studies, 38 are pilot-scale studies, 41 are part or all of a full-scale site remediation, and the scale is uncertain based on available information for 7 projects. Figure 4 illustrates the status of the projects contained in the GWRTAC database. As indicated in the figure, the majority of the projects have been completed (73 projects) while an additional 13 projects are in-progress. Table 1 lists the scale and status information for each individual project summarized in Figures 3 and 4.

2.3 Project Objectives / Target Media

Figure 5 depicts the project objectives typically inferred from GWRTAC's sources of information. More than one project objective may be included per project. (In this and other figures where more than one chart option is applicable, the chart indicates the total number of selections, or "responses", and thus the number upon which the chart's percentage labels are based, as well as the number of case studies containing the information charted.) The full-scale/commercial projects are intended for site remediation. Several of the pilot/field demonstrations are undertaken as feasibility studies for collection of economic/design data, and may have either a research or a remediation aspect to them. Thus, approximately 73 projects (80% of 91), were identified as being conducted as part of full or partial site remediation efforts, and 11 projects (12% of 91) were identified as having research as an objective. Approximately 7 projects were inferred to have a feasibility aspect (collection of economic or design data).

Figure 6 displays, for case studies of all scales, the environmental media targeted by the projects, as identified from GWRTAC's sources of information. More than one target medium may be indicated for an individual project. In approximately 26 responses (27% of 96), both soil and groundwater are indicated as target media. There are about 23 responses where soil contamination only was targeted (where soil contamination is limited to the vadose zone). An additional 31 projects targeted groundwater only. A total of 11 responses (11% of 96) target either light nonaqueous phase liquid (LNAPL) or dense nonaqueous phase liquid (DNAPL), while the target medium was not specified in five cases.

Figure 7 shows the type of fracturing being applied for each of the fracturing case studies currently contained in the GWRTAC database. As shown, of the 86 projects, 37 of the projects utilize pneumatic fracturing, 27 utilize hydraulic fracturing, and 22 are blast-enhanced fracturing projects.

2.4 Project Location

Figure 8 depicts the distribution of the locations by EPA Region of the fracturing projects in the GWRTAC database which have advanced to pilot-scale or full-scale, as well as additional projects located outside the U. S.. EPA Region II by far contains the majority (over 30) of the fracturing projects, reflecting the regional influence of major vendors Haley & Aldrich, Inc. of New York, and ARS Technologies, Inc., and McLaren Hart, Inc., both of New Jersey, as well as the New Jersey Institute of Technology, which has performed research applications. EPA Regions containing from five to ten projects include Regions I, V, VI with a second strong activity in EPA Region V, the region including FRx, Inc., and the University of Cincinnati, which apply hydraulic fracturing techniques. Applications outside the U.S. also fall in the category of five to ten projects. Other EPA regions contain less than five projects. The map in Figure 9 graphically depicts the locations, per EPA Region in the U.S., of the pilot- or full-scale studies in the GWRTAC database, and also depicts the type of fracturing project. It can be seen that the Region II projects are nearly evenly split between pneumatic and blast-enhanced fracturing. The majority of the listed projects located outside the U.S. have been completed in Canada, and have been implemented by Frac-Rite Environmental, Ltd., a hydraulic fracturing vendor located in Alberta.

Table 2 lists the U.S. state, Canadian province or other country locations of each of the pilot-scale or field-scale studies in the database. Further detailing the major vendor and research centers identified above, the top states/provinces include New Jersey, New York, Ohio, Alberta, Canada, and Colorado. The diversity of the remaining locations suggests a wide variety of geologic conditions have been included in project applications.

3.0 ANALYSIS OF HYDRAULIC, PNEUMATIC, AND BLAST-ENHANCED FRACTURING TECHNOLOGY

3.1 Integrated Technologies and Contaminant Classes

The pie chart in Figure 10 depicts the primary integrated technology associated with each fracturing project in the GWRTAC database. For this figure, categories were made mutually exclusive to show some valid proportioning among the most common integrated technologies. Figure 10 indicates that fracturing is most commonly used to enhance soil vapor extraction (SVE) or dual phase extraction (DPE), as in 35 cases, and to enhance pump and treat or groundwater contaminant plume control, as in 16 projects. Other applications include enhancement or injection emplacement to augment *in situ* bioremediation (9 cases), installation of reactive media/permeable reactive barriers (3 cases), and product recovery enhancement (4 cases).

To provide a more comprehensive comparison to Figure 10, Figure 11 is a bar chart illustrating all of the technologies that have been integrated with the fracturing case studies. For this chart, if more than one integrated technology were specified in a project, both were counted. As indicated, the leading integrated technology where fracturing was used as an enhancement technique was SVE or DPE. In all these cases, either hydraulic or pneumatic fracturing was utilized for SVE/DPE enhancement. The second most common integrated technology was pump and treat, which is the primary technology targeted for efficiency improvement by blast-enhanced fracturing techniques. A third often-seen integrated technology is enhanced *in situ* bioremediation, where fracturing may be used to improve mass transfer capabilities, or to actually inoculate microorganisms or nutrients into the subsurface. Hydraulic and pneumatic fracturing have also been used to install reactive media to form permeable reactive barriers. Other technologies where fracturing has been used to enhance performance include air sparging, directional wells, NAPL remediation, electrokinetics, *in situ* chemical oxidation, *in situ* flushing, *in situ* vitrification, and thermal enhancements.

Figure 12 is a bar chart of all of the specific target contaminant classes for all of the fracturing projects. In the GWRTAC database, target contaminants are classified by choosing as many classes as applicable, using the most specific categorization possible based on the source information. From the 86 case studies included in this chart, the number of “responses” related to these projects is 123. It should be noted that in a few projects, clean sites were used to demonstrate fracturing; these were categorized as unknown contaminants. Fracturing is a technology type which, more so than many others, is relatively independent of contaminant type. The site geology will influence the choice to implement fracturing more than will the contaminant type. Still, based on Figure 12, halogenated VOCs, BTEX and other petroleum hydrocarbons are the prevalent contaminants at sites where fracturing has been implemented. This is likely due more to their ubiquitous nature as site contaminants rather than as any link to fracturing applicability, though the noted affinity for using fracturing as SVE/DPE enhancements also would explain the high proportion of the lighter VOCs.

3.2 Site Geology and Hydrogeology/Pre- and Post-Fracturing Hydraulic Properties and Radius of Influence/Fracturing and Blast Zone Depths and Geometries

For all fracturing types, Table 3 provides detailed information on the geologic materials present at each of the pilot/field to full-scale/commercial fracturing projects in the GWRTAC database. Also included in Table 3, where this information was discernable from available project summaries, are pre- versus post-fracturing hydraulic properties and pre- versus post-fracturing radii of influence. Fracturing, perhaps more than some other technologies, has a large variety of performance metrics used to evaluate its effectiveness. This variation does not easily lend itself to comparing one project to another, however, the detailed listings in Table 3 may assist in summarizing some of this pertinent information. Hydraulic properties measured or reported may include well yield information, permeability, suction head measurements, hydraulic conductivity, air permeability, and/or air flow rates. Radius of influence (ROI) given may be hydraulic, vapor, or both. Based on Table 3, significant increases to permeability, ROI, or well yield measures after fracturing are not uncommon.

Figure 13 shows the hydrogeologic setting of the target contaminants for pilot/field to full-scale/commercial projects; more than one setting may be indicated per project. As seen, approximately 50 projects target vadose zone contamination, 39 projects target an unconfined aquifer, 3 projects target a confined aquifer, and the information is not specified in an additional 35 cases. In many of the instances where the information is not specified, it is known that the saturated zone was targeted, but the project summary information supplied to GWRTAC did not clarify whether the targeted zone was confined or unconfined.

Figure 14 indicates the maximum depth of fracturing for all pilot/field to full-scale/commercial projects for all fracturing types. Approximately 68% of the projects (58 projects) are included in the combined categories: "less than 10 feet below ground surface (bgs)"; "10 to 25 feet bgs"; or "25 to 50 feet bgs" maximum depth ranges. Eight projects targeted contaminants at depths from "50 to 100 feet bgs". One project targeted a depth of greater than 100 feet bgs, while the information was not specified in 19 cases.

Figure 15 is a bar chart that further depicts the maximum depth of emplaced fractures or blasted bedrock zone by fracturing type. Based on this figure, blast-enhanced fracturing is, as expected, typically performed at a slightly deeper depth than is either hydraulic or pneumatic fracturing, because bedrock is targeted. Also, although the 10- to 25-foot bgs depth range is that most commonly targeted for both hydraulic and pneumatic fracturing, both fracturing types have otherwise been utilized at a variety of depths.

Table 4 lists, for each hydraulic and pneumatic fracturing project, the specific minimum and maximum depths, radius, and aperture of fractures, where this information was available. During implementation of hydraulic and pneumatic fracturing projects, a series of fractures at successive depths are typically installed at design intervals. Fracture properties, such as radius and aperture, may be directly measured (coring, tiltmeters to measure ground heave) or inferred (geophysical methods). Typical fracture radii range from 5 to 20 feet, and may reach 50 feet, based on Table 4; apertures are typically measured in fractions of inches or may be between one or two inches. For the projects summarized in Table 4, maximum depths below the ground surface at which fracturing has been conducted are 45 feet for pneumatic fracturing and 75 feet for hydraulic fracturing.

Table 5 lists the blasted bedrock zone (BBZ) dimensions (length, depth, and sidewall area) and the overburden depth for all of the blast-enhanced fracturing projects, as information availability allowed. These projects are typically conducted to enhance pump and treat or to assist in hydraulic control of the contaminant plume. As seen in Table 5, trench lengths have varied from 100 to 1,220 feet; this parameter can easily be expanded by designing the blasting project along the desired length to affect. The depth of the BBZ is the actual dimension of broken rock or rubble, and based on Table 5, has varied from 6 to 70 feet for the projects in the GWRTAC database. The overburden depth above the bedrock targeted for blasting has varied from 8 to 40 feet, based on Table 5. The maximum depth affected by blasting is the sum of the overburden depth and the depth dimension of the BBZ. For projects included in this report, a maximum depth of 100 feet below the ground surface was blast-enhanced fractured in FRAC0091, U.S. DOE, UMTRA, Tuba City, Arizona. At this site, a 70 foot deep BBZ was created beneath 30 feet of overburden.

3.3 Fracturing-Related Performance

Table 6 details results-oriented information available from project summaries, expressed in a variety of ways. Ratio of pre- to post-blast well yields was provided for the majority of the blast-enhanced fracturing projects. Pre- and post- or fractured versus unfractured well performance may also be included. Remediation efficiency improvements, such as rate of groundwater or contaminant recovery, is given in still other cases. Typically, substantial improvements in the results of these types of parameters are seen after a fracturing event. Less clear is the long-term outlook for maintaining these improvements. In some cases, multiple fracturing events were used to "supercharge" remediation efficiencies on a periodic basis. As would be expected, injection of proppants will assist in maintaining fracture integrity. Most of the readily available information on performance is that resulting from testing immediately after the fracturing event. Economic information available is also listed in Table 6, however, this information was not typically found in the project summaries.

4.0 SUMMARY

Hydraulic, pneumatic, and blast-enhanced fracturing for environmental application are useful technologies to assist in overcoming site-specific geologic constraints that limit application of a variety of *in situ* vapor, soil, and/or ground-water remediation technologies. A total of 86 cases of field applications of these technologies are documented in this report, with the distribution 43% pneumatic fracturing; 31% hydraulic fracturing, and 26% blast-enhanced fracturing. Integrated technologies vary greatly, though soil vapor extraction/dual phase extraction and pump and treat enhancements or hydraulic control assists predominate. Pump and treat and hydraulic control enhancements are the main applications of the blast-enhanced fracturing method. Other types of integrated technologies (as well as pump and treat) are used in combination with hydraulic or pneumatic fracturing, where fractures serve to increase permeability and/or decrease heterogeneity, or else the fracturing process may be used to inject treatment materials into the subsurface. Contaminants at the fracturing project sites reflect those targeted by the integrated technology(ies). Projects have been implemented within the U.S. and Canada, but are clustered near the locations of predominant vendors and research institutes.

Fracturing has been conducted at varying depths in a wide variety of geologic materials needing permeability enhancement or improvement of interconnectedness of permeable lenses. Short-term testing of remediation efficiency changes or changes in hydraulic properties in pre- versus post-fracturing/blasting tests show marked improvements in these metrics. Revisiting some projects to document continued improvements may be an interesting and useful endeavor.

5.0 REFERENCES

Haley & Aldrich, Inc. "Basic Technology Description of Bedrock Blast-Fracturing for Groundwater Remediation Projects", Prepared for GWRTAC, December 1999

Murdoch, L.C., D. Wilson, K. Savage, W. Slack, and J. Uber "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/003, 1995, available at www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html.

USEPA, Risk Reduction Laboratory and The University of Cincinnati "Hydraulic Fracturing Technology - Applications Analysis and Technology Evaluation Report" EPA/540/R-93/505, 1993, available at www.epa.gov/ORD/SITE/reports/051.htm.

Table 1. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Summary of Case Studies in the GWRTAC Database (Details for Each Project Included in Appendix)

Total Number of Case Studies = 86

GWRTAC ID	Project Name	City	State/ Prvnce	Primary PRP/Site Owner	Primary Funding Source/Sponsor	Primary Regulatory Agency	Primary Technical Team Member	Scale of Project	Contaminants	Target Media	Type of Fracturing/Integrated Technologies	Status of Project
FRAC0080	A.C. Roch. Corp., Rochester, NY	Rochester	NY	Delphi Automotive Systems	Delphi Automotive Systems	NY State Dept. of Environ. Conservation	Haley & Aldrich	Full-Scale/Commercial	Trichloroethylene, 1,1,1-trichloroethane, vinyl chloride, 1,2-dichloroethylene, 1,1-dichloroethylene, 1,1-dichloroethane, tetrachloroethylene, xylene, ethyl-benzene	Groundwater	Blast/Pump and Treat	Completed
FRAC0027	Abandoned Industrial Site, Flemington, NJ	Flemington	NJ	Private	U.S. Environmental Protection Agency	Not Specified	ARS Technologies, Inc	Pilot/Field Demonstration	Chlorinated Solvents (VOCs) including TCE, PCE and vinyl chloride	Vadose and Saturated Siltstone	Pneumatic/DPE,Bioremediation	Completed
FRAC0061	Aerospace Manufacturing Facility, Los Angeles, CA	Los Angeles	CA	Not Specified	Not Specified	Not Specified	TerraVac Corporation	Full-Scale/Commercial	Methyl ethyl ketone and trichloroethane	Soil, Groundwater	Pneumatic/SVE, Bioremediation	Completed
FRAC0044	AT&T Facility, Richmond, VA	Richmond	VA	AT&T	AT&T	Not Specified	New Jersey Institute of Technology	Scale Unknown	Chlorinated solvents	Vadose zone silty clay, clayey silt	Pneumatic/SVE	Completed
FRAC0032	Automobile Maintenance Facility, Lancaster, PA	Lancaster	PA	Private	Private	Not Specified	ARS Technologies, Inc.	Full-Scale/Commercial	VOCs, primarily TCE	Soil, Groundwater	Pneumatic/Bioremediation	In Progress
FRAC0031	Automotive Manufacturing Facility, Columbia City, IN	Columbia City	IN	Private	Private	Not Specified	ARS Technologies, Inc.	Full-Scale/Commercial	VOCs, primarily TCE, DCE, and vinyl chloride	Clay Formation	Pnumatic/SVE	Completed
FRAC0013	Black & Decker Plant, NY	Upstate NY	NY	Black & Decker	Black & Decker	Not Specified	Dunn Geoscience Corp.	Full-Scale/Commercial	VOCs	Groundwater	Blast/Pump and Treat	Completed
FRAC0033	Chemical Incineration Plant, Coffeyville, KS	Coffeyville	KS	Private	Private	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	VOCs, primarily TCE and Tetrachloroethene	Soil	Pneumatic/SVE	Completed
FRAC0002	Closed UST, Military Facility, Oklahoma City, OK	Oklahoma City	OK	U.S. Department of Defense	U.S. Department of Defense	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	#2 Fuel oil existing as free product	LNAPL recovery from sandstone/shale formation	Pneumatic/Bioremediation,LNAPL Recovery	Completed
FRAC0017	Corbett Creek, Former Gas Plant & Compressor Station, Alberta, Canada	Near Whitecourt	ALBERTA	Union Pacific Resources, Inc.	Norcen Energy	Alberta Environmental Protection	Komex International, LTD.	Full-Scale/Commercial	Liquid Hydrocarbons (Condensate) from Gas Plant Operations	Soil, Groundwater	Hydraulic/DPE,*In Situ* Flushing	In Progress
FRAC0040	Decommissioned Retail Service Station, Regina, SA	Regina	SASKATCHEWAN	Private	Private	Not Specified	FracRite Environmental, LTD.	Scale Unknown	Gasoline	Vadose zone soil	Hydraulic/SVE	Completed
FRAC0050	Denver Federal Center	Denver	CO	U.S. Gov't. General Services Administration	U.S. Environmental Protection Agency	U.S. Environmental Protection Agency	U.S. Environmental Protection Agency	Pilot/Field Demonstration	Total petroleum hydrocarbons	Soil, Perched Groundwater	Hydraulic/Bioremediation/PRBs	Completed
FRAC0089	Diaz Chemical Corporation, Holley, NY	Holley	NY	Diaz Chemical Corporation	Diaz Chemical Corporation	NY State Dept. of Environ. Conservation	Haley & Aldrich	Full-Scale/Commercial	Methylene chloride, ethylene dichloride, acetone, carbon disulfide, 1,2-dichloroethane, 1,2-dibromoethane, 1,1,2-trichloroethane, 1,1-dichloroethane, BETX, other halogenated aromatics and organics	Groundwater	Blast/Pump and Treat	Completed
FRAC0062	East Brunswick, NJ	East Brunswick	NJ	Not Specified	Not Specified	Not Specified	McLaren Hart, Inc.	Scale Unknown	Clean site	Clean site (water reinjection)	Pneumatic/Groundwater Reinjection	Completed
FRAC0048	East Orange, NJ	East Orange	NJ	Private	Not Specified	Not Specified	McLaren Hart, Inc.	Pilot/Field Demonstration	Petroleum hydrocarbons	Vadose zone - sand/sandy silt	Pneumatic/SVE	Completed
FRAC0082	Eastman Kodak, Industrial Landfill, Rochester, NY	Rochester	NY	Eastman Kodak Company	Eastman Kodak Company	NY State Dept. of Environ. Conservation	Haley & Aldrich	Full-Scale/Commercial	Methanol, 1,4-dioxane, isopropyl ether, trihalomethanes and chlorinated solvents, other organic compounds	Groundwater	Blast/Pump and Treat	Completed
FRAC0083	Eastman Kodak, Rochester, NY	Rochester	NY	Eastman Kodak Company	Eastman Kodak Company	NY State Dept. of Environ. Conservation	Haley & Aldrich	Full-Scale/Commercial	Acetone, methanol, methyl acetate, 1,4-dioxane, p-dioxane	Groundwater	Blast/Pump and Treat	Completed
FRAC0064	Egg Harbor, NJ	Egg Harbor	NJ	Private	Private	Not Specified	McLaren Hart, Inc.	Pilot/Field Demonstration	Manufactured gas plant (MGP) contaminants	Vadose zone silty sand	Pneumatic/*In Situ* Chemical Oxidation	In Progress
FRAC0011	EPA Center Hill Testing Facility, Cincinnati, OH	Cincinnati	OH	U.S. EPA	U.S. EPA RREL	Not Specified	University of Cincinnati	Pilot/Field Demonstration	None (Clean Demonstration Site)	Silty clay with lesser amounts of sand and gravel	Hydraulic/SVE	Completed
FRAC0025	Federal Government Facility	Oklahoma City	OK	U.S. Department of Defense	U.S. Department of Defense	Not Specified	ARS Technologies, Inc	Pilot/Field Demonstration	VOCs, mainly, BTEX and TCE, Petroleum Hydrocarbons	Vadose and Saturated Soil, Groundwater	Pneumatic/Bioremediation	Completed

Table 1. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Summary of Case Studies in the GWRTAC Database (Details for Each Project Included in Appendix)

Total Number of Case Studies = 86

GWRTAC ID	Project Name	City	State/ Prvnce	Primary PRP/Site Owner	Primary Funding Source/Sponsor	Primary Regulatory Agency	Primary Technical Team Member	Scale of Project	Contaminants	Target Media	Type of Fracturing/Integrated Technologies	Status of Project
FRAC0079	Fire Station 28, Denver, CO	Denver	CO	City and County of Denver	City and County of Denver	CO Dept. of Public Health and Environ.	Haley & Aldrich	Full-Scale/Commercial	BETX compounds, fuel oil #2	Petroleum products	Blast/LNAPL Recovery	Completed
FRAC0081	FMC Corporation, Middleport, NY	Middleport	NY	FMC Corporation	FMC Corporation	NY State Dept. of Environ. Conservation	Haley & Aldrich	Full-Scale/Commercial	Methylene chloride, arsenic, ammonia, other organic compounds including chlorinated compounds.	Groundwater	Blast/Pump and Treat	Completed
FRAC0094	Former Bayer Aspirin, NJ	Not Specified	NJ	Not Specified	Not Specified	Not Specified	ENSR	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0057	Former Dry Cleaning Facility, Northern Virginia	Not Specified	VA	Private	Private	Not Specified	ARS Technologies, Inc.	Full-Scale/Commercial	PCE and TCE	Soil and groundwater (Bedrock)	Pneumatic/DPE	In Progress
FRAC0035	Former Light Manufacturing Facility, Brookfield, WI	Brookfield	WI	Private	Private	Not Specified	ARS Technologies, Inc.	Full-Scale/Commercial	VOCs, primarily PCE and Gasoline Range Organics (GRO)	Soil, Groundwater	Pneumatic/DPE	Completed
FRAC0004	Former Manufacturing Facility, Highland Park, NJ	Highland Park	NJ	Private	Private	Not Specified	ARS Technologies, Inc.	Full-Scale/Commercial	VOCs, primarily TCE, Petroleum hydrocarbons	Vadose zone of fractured shale formation.	Pneumatic/DPE	Completed
FRAC0026	Former Manufacturing Facilty, Hillsborough, NJ	Hillsborough	NJ	Private	Private	Not Specified	ARS Technologies, Inc.	Full-Scale/Commercial	None (Fracturing done to improve effectiveness of groundwater re-injection system).	Siltstone Formation for Reinjection	Pneumatic/Groundwater Reinjection	Completed
FRAC0030	Former Processing Facility, Kansas City, KS	Kansas City	KS	Private	Private	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	VOCs, primarily TCE	Vadose and saturated soil and groundwater	Pneumatic/Air Sparging,PRBs	Completed
FRAC0029	Former Service Station, Newark, NJ	Newark	NJ	Private	Private	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	BTEX, TPH	Shale and sandstone	Pneumatic/SVE	Completed
FRAC0038	Former Sour Gas Plant Site	Not Specified	ALBERTA	Private	Private	Not Specified	FracRite Environmental, LTD.	Scale Unknown	Sour gas plant-derived	Not Specified	Hydraulic/SVE	Completed
FRAC0047	Former Sour Gas Plant Site, Wetaskiwin, Alberta, Canada	Wetaskiwin	ALBERTA	Private	Private	Not Specified	FracRite Environmental, LTD.	Pilot/Field Demonstration	Amine	Clay till soil	Hydraulic/Bioremediation,Directional Wells	Completed
FRAC0022	Fuel Terminal in Regina, Saskatchewan	Regina	SASKATCHEWAN	Private	Private	Not Specified	FracRite Environmental, LTD.	Full-Scale/Commercial	Gasoline Contamination, NAPL	Soil, Groundwater, NAPL	Hydraulic/DPE	Completed
FRAC0007	Gasoline Refinery in Marcus Hook, PA	Marcus Hook	PA	Not Specified	U.S. EPA NRMRL	Not Specified	Haz Subst Mgmt Res Cntr	Pilot/Field Demonstration	BTEX and TPH	Vadose zone of low permeability, dense silty clay and perched water.	Pneumatic/SVE,Bioremediation	Completed
FRAC0090	GM Delco Chassis, Bristol CT	Bristol	CT	General Motors Corporation	General Motors Corporation	CT Department of Environmental Protection	Haley & Aldrich	Full-Scale/Commercial	Hexavalent chromium	Groundwater	Blast/Pump and Treat	Completed
FRAC0104	Hallman Chevrolet, NY	Not Specified	ME	Hallman Chevrolet	Hallman Chevrolet	Not Specified	Day Engineering	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0055	Indian Village Site, Continental Divide, NM	Continental Divide	NM	NM Highway/Transportation Dept.	NM Highway/Transportation Dept.	New Mexico State Environmental Department	FRx, Inc.	Full-Scale/Commercial	BTEX, Naphthalene, Acetone, 2-Butanone (MEK), 1,2-Dibromoethane (EDB), 1,2-Dirchloroethane (EDC)	Soil, Groundwater	Hydraulic/Bioremediation	In Progress
FRAC0003	Industrial Facility, Santa Clara, CA	Santa Clara	CA	Private	Private	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	VOCs, primarily TCE	Vadose and saturated zones of sandy silts and sandy clays overlying a low permeability 'fat' silty clay.	Pneumatic/SVE	Completed
FRAC0065	Industrial Site, Elizabeth, NJ	Elizabeth	NJ	Private	Private	Not Specified	McLaren Hart, Inc.	Pilot/Field Demonstration	Trichloroethene (TCE)	Vadose and saturated zone clayey silt	Pneumatic/DPE	In Progress
FRAC0001	Industrial Site, Hillsborough, NJ	Hillsborough	NJ	Private	U.S. EPA NRMRL	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	VOCs and SVOCs including TCE, PCE and benzene	Vadose zone of siltstones and sandstones	Pneumatic/SVE	Completed
FRAC0028	Industrial Site, Roseland, NJ	Roseland	NJ	Private	New Jersey Institute of Technology	Not Specified	New Jersey Institute of Technology	Pilot/Field Demonstration	Chlorinated solvents (TCE, DCE)	Soil, Groundwater	Pneumatic/DPE	Completed

Table 1. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Summary of Case Studies in the GWRTAC Database (Details for Each Project Included in Appendix)

Total Number of Case Studies = 86

GWRTAC ID	Project Name	City	State/ Prvnce	Primary PRP/Site Owner	Primary Funding Source/Sponsor	Primary Regulatory Agency	Primary Technical Team Member	Scale of Project	Contaminants	Target Media	Type of Fracturing/Integrated Technologies	Status of Project
FRAC0088	Jurgason Gage & Valve Co. - Manufacturer, MA	Burlington	MA	Caswell, Eichler and Hill, Inc.	Caswell, Eichler and Hill, Inc.	MA Dept. of Environ. Protection	Haley & Aldrich	Full-Scale/Commercial	Trichloroethene , tetrachloroethene, 1,2-dichloroethene, 1,1,1-trichloroethane, vinyl chloride	Groundwater	Blast/Pump and Treat	Completed
FRAC0045	Laidlaw Site, Sarnia, Ontario, Canada	Sarnia	ONTARIO	Laidlaw	Not Specified	Not Specified	FRx, Inc.	Pilot/Field Demonstration	Synthetic gasoline with TCE tracer introduced into test cell.	Soil	Hydraulic/SVE	Completed
FRAC0053	LASAGNA, Cincinnati, OH	Cincinnati	OH	Not Specified	Not Specified	Not Specified	U.S. Environmental Protection Agency	Pilot/Field Demonstration	Not Specified	Not Specified	Hydraulic/Electrokinetics,PRBs	Completed
FRAC0052	LASAGNA, Offutt Air Force Base, NE	Offutt AFB	NE	U.S. Department of Defense	U.S. Department of Defense	Not Specified	U.S. Environmental Protection Agency	Pilot/Field Demonstration	Not Specified	Not Specified	Hydraulic/Electrokinetics,PRBs	Completed
FRAC0051	LASAGNA, Rickenbacker Air National Guard Base, OH	Rickenbacker ANGB	OH	U.S. Department of Defense	U.S. Department of Defense	Not Specified	U.S. Environmental Protection Agency	Pilot/Field Demonstration	TCE	Clay soil	Hydraulic/Electrokinetics,Bioremediation,PRBs	In Progress
FRAC0046	Linemaster Switch Superfund Site, Woodstock, CT	Woodstock	CT	Linemaster Switch Corporation	Linemaster Switch Corporation	U.S. EPA	FRx, Inc.	Full-Scale/Commercial	Trichloroethylene (TCE) and Other Solvents	Soil and Groundwater	Hydraulic/DPE	In Progress
FRAC0043	Loring Air Force Base, ME	Loring AFB	ME	U.S. Department of Defense	U.S. Department of Defense	Maine Dept. of Environmental Protection	U.S. Geological Survey	Full-Scale/Commercial	Jet fuel, waste oil, paint, solvents	Groundwater, LNAPL	Blast/Pump and Treat	Completed
FRAC0008	LUST Site near Dayton, OH	Dayton	OH	Not Specified	U.S. EPA, RREL	Not Specified	University of Cincinnati	Pilot/Field Demonstration	BTEX and TPH	Soil (sandy to silty clay, trace gravel)	Hydraulic/Bioremediation	Completed
FRAC0087	Manufacturer, ME	Not Specified	ME	Private	Private	Not Specified	Haley & Aldrich	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0005	Manufacturing Facility in NY		NY	Private	Private	Not Specified	Terra Vac, Inc.	Pilot/Field Demonstration	TCE, PCE, vinyl chloride, 1,1,1-trichloroethane	Unsaturated and saturated (via dewatering and vaccum extraction) glacial clay till	Pneumatic/SVE	Completed
FRAC0018	Manufacturing Facility, Huntsville, AL	Huntsville	AL	Private	Private	Not Specified	ARS Technologies, Inc.	Full-Scale/Commercial	TCE	Saturated sandy gravel	Pneumatic/Pump and Treat	Completed
FRAC0019	Manufacturing Facility, Shreveport, LA	Shreveport	LA	Private	Private	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	Chlorinated solvenets (TCE)	Vadose and saturated zones, DNAPL	Pneumatic/DPE,DNAPL Remediaiton,Pump and Treat	Completed
FRAC0039	Manufacturing Plant, Chicago, IL	Chicago	IL	Private	Private	Not Specified	FracRite Environmental, LTD.	Scale Unknown	Solvents	Soil, Groundwater	Hydraulic/DPE	Completed
FRAC0067	Maxwell Air Force Base, Montgomery, AL	Montgomery	AL	U.S. Department of Defense	U.S. Department of Defense	Not Specified	FOREMOST Solutions, Inc.	Pilot/Field Demonstration	TCE	Groundwater	Hydraulic/PRBs	Completed
FRAC0063	McGuire AFB, Wrightstown, NJ	Wrightstown	NJ	McGuire AFB, US DoD	McGuire AFB, US DoD	Not Specified	McLaren Hart, Inc.	Pilot/Field Demonstration	Fuel oil, jet fuel	Free product recovery	Pneumatic/DNAPL Remediation	Completed
FRAC0103	Mercury Aircraft Co., NY	Not Specified	NY	Mercury Aircraft	Mercury Aircraft	Not Specified	Malcolm-Pirnie	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0041	Metal Bellows Metal Finishing Plant, Sharon, MA	Sharon	MA	Metal Bellows	Metal Bellows	Not Specified	Thermo Consult Engrs/Normandeau Engineers	Full-Scale/Commercial	TCE	Groundwater	Blast/Pump and Treat	Completed
FRAC0021	Municipal Landfill, Edmonton, Alberta, Canada	Edmonton	ALBERTA	Waste Management, Inc.	Private	Alberta Environmental Protection	FracRite Environmental	Full-Scale/Commercial	Muncipal Landfill Leachate	Saturated Municipal Landfill Wastes	Hydraulic/Pump and Treat	In Progress
FRAC0068	Mustang-Shadow Mountain Gas Station, Grand Lake, CO	Grand Lake	CO	Hunt4 Solutions, LLC.	Hunt4 Solutions, LLC.	Colorado Dept. of Labor & Employment	Foremost Solutions, Inc.	Full-Scale/Commercial	BTEX	Soil, Groundwater	Hydraulic/Bioremediation,PRBs	In Progress
FRAC0014	New Jersey Environmental Cleanup Responsibility Act (ECRA) Site in South Plainfield, NJ	South Plainfield	NJ	Not Specified	U.S. EPA NRMRL	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	TCE, DNAPLs	TCE DNAPL in unsaturated zone	Pneumatic/SVE,Thermal,DNAPL Remediation	Completed
FRAC0106	New York Air Brake, NY	Not Specified	NY	New York Air Brake	New York Air Brake	Not Specified	EMCON	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed

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Total Number of Case Studies = 86

GWRTAC ID	Project Name	City	State/ Prvnce	Primary PRP/Site Owner	Primary Funding Source/Sponsor	Primary Regulatory Agency	Primary Technical Team Member	Scale of Project	Contaminants	Target Media	Type of Fracturing/Integrated Technologies	Status of Project
FRAC0105	New York Air Brake, NY	Not Specified	NY	New York Air Brake	New York Air Brake	Not Specified	EMCON	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0059	Newark, NJ	Newark	NJ	Not Specified	Not Specified	Not Specified	McLaren Hart, Inc.	Scale Unknown	VOCs - Petroleum	Vadose zone sandy silt	Pneumatic/SVE or DPE	Completed
FRAC0058	Newark, NJ	Newark	NJ	Not Specified	New Jersey Institute of Technology	Not Specified	McLaren Hart, Inc.	Pilot/Field Demonstration	Clean site demonstration	Vadose zone of sandstone	Pneumatic/SVE or DPE	Completed
FRAC0049	Northeast OH	Not Specified	OH	Not Specified	Not Specified	Not Specified	FRx, Inc.	Pilot/Field Demonstration	Mixture of industrial solvents	Soil, Groundwater	Hydraulic/SVE	Completed
FRAC0037	Petroleum Storage Terminal Site	Liege	BELGIUM	Private	Private	Not Specified	FracRite Environmental, LTD.	Scale Unknown	Petroleum-derived	Soil	Hydraulic/SVE	Completed
FRAC0056	Railyard in Birmingham, AL	Birmingham	AL	Not Specified	Not Specified	Not Specified	FRx, Inc.	Full-Scale/Commercial	LNAPL, Fuel Oil, Diesel	Groundwater, LNAPL	Hydraulic/LNAPL Recovery,Pump and Treat	Completed
FRAC0066	Raritan, NJ	Raritan	NJ	Private	Private	Not Specified	McLaren Hart, Inc.	Pilot/Field Demonstration	Chlorinated solvents	Perched water	Pneumatic/PRBs	In Progress
FRAC0054	Retail Gasoline Facility, Lakewood, CO	Lakewood	CO	Private	Private	Colorado Dept. of Labor & Employment	Foremost Solutions, Inc.	Full-Scale/Commercial	BTEX, TPH	Clay soil, Groundwater	Hydraulic/Bioremediation/PRBs	In Progress
FRAC0036	Rural Test Location, Frelinghuysen, NJ	Frelinghuysen	NJ	Not Specified	New Jersey Institute of Technology	Not Specified	New Jersey Institute of Technology	Pilot/Field Demonstration	Clean (uncontaminated) rural site	Vadose zone - clean soil	Pneumatic/SVE	Completed
FRAC0006	Service Station in Louisiana		LA	Private	Private	Louisiana Department of Environmental Quality	Terra Vac, Inc.	Full-Scale/Commercial	BTEX and Petroleum Hydrocarbons	Unsaturated and saturated (via dewatering and vaccum extraction) low permeability clay soil	Pneumatic/SVE	Completed
FRAC0060	Service Station, San Francisco, CA	San Francisco	CA	Private	Private	Not Specified	TerraVac Corporation	Full-Scale/Commercial	Unleaded gasoline	Free product-saturated strata	Pneumatic/DPE,Thermal,Free Product Extraction	Completed
FRAC0102	Sidney Landfill, NY	Not Specified	NY	Not Specified	Not Specified	Not Specified	Not Specified	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0009	Site in Bristol, TN	Bristol	TN	Not Specified	Not Specified	Not Specified	Remediation Technologies, Inc.	Pilot/Field Demonstration	Free-phase TCE, and other DNAPLs	Soil, Groundwater, DNAPL	Hydraulic/SVE,Pump and Treat	Completed
FRAC0095	Stearns & Foster Site, NJ	Not Specified	NJ	Stearns & Foster	Stearns & Foster	Not Specified	ENSR	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0034	Steel Manufacturing Facility, Western New York	Western New York	NY	Private	Private	Not Specified	ARS Technologies, Inc.	Pilot/Field Demonstration	High concentrations of benzene, many other contaminants (synthetic waste tar pit residues)	Soil, Groundwater, Waste Material	Pneumatic/SVE	In Progress
FRAC0012	Storage Tank Site in Beaumont, TX	Beaumont	TX	Not Specified	Not Specified	Not Specified	University of Cincinnati	Pilot/Field Demonstration	Gasoline and Cyclohexane	Saturated Silty Clay to Clayey Silt	Hydraulic/LNAPL Recovery	Completed
FRAC0016	Toronto, Ontario, Canada	Toronto	ONTARIO	Private	Private	Not Specified	McLaren Hart, Inc.	Full-Scale/Commercial	Volatile Organic Compounds - Petroleum	Vadose zone clayey silt	Pneumatic/SVE	Completed
FRAC0072	U.S. DoD Fort Hood, TX	Fort Hood	TX	U.S. DoD (Ft. Hood, TX)	U.S. DoD AATDF	Not Specified	Fluor Daniel GTI	Pilot/Field Demonstration	Jet Propellant 8 (JP-8)	Tight clay soil	Hydraulic/Thermal	Completed
FRAC0024	U.S. DOE Hanford, WA Facility	Hanford	WA	U.S. Department of Energy	U.S. Department of Energy	Not Specified	New Jersey Institute of Technology	Pilot/Field Demonstration	None. (Fracturing was done in clean (uncontaminated) portion of site.	Clean sand, gravel, cobbles (Hanford Fm)	Pneumatic/*In Situ* Vitrification	Completed
FRAC0020	U.S. DOE Portsmouth Gaseous Diffusion Plant, X231-A Land Trmt Site, Piketon, OH	Piketon	OH	U.S. Department of Energy	U.S. Department of Energy	Not Specified	Oak Ridge National Laboratory	Full-Scale/Commercial	TCE	Soil, Groundwater, DNAPL	Hydraulic/PRBs,*In Situ* Chemical Oxidation,Thermally Enhanced SVE	Completed
FRAC0023	U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, Ohio	Piketon	OH	U.S. Department of Energy	U.S. Department of Energy	Not Specified	New Jersey Institute of Technology	Pilot/Field Demonstration	None. (Fracturing was done in clean (uncontaminated) portion of site.	Saturated zone of clean formation consisting of two aquifers.	Pneumatic/ Pump and Treat	Completed
FRAC0091	U.S. DOE, UMTRA, Tuba City, AZ	Tuba City	AZ	U.S. DOE Sandia National Laboratories	U.S. DOE Sandia National Laboratories	U.S. EPA	Haley & Aldrich	Pilot/Field Demonstration	Uranium, nitrate, sulfate	Groundwater	Blast/Pump and Treat	Completed

Table 1. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Summary of Case Studies in the GWRTAC Database (Details for Each Project Included in Appendix)

Total Number of Case Studies = 86

GWRTAC ID	Project Name	City	State/ Prvnce	Primary PRP/Site Owner	Primary Funding Source/Sponsor	Primary Regulatory Agency	Primary Technical Team Member	Scale of Project	Contaminants	Target Media	Type of Fracturing/Integrated Technologies	Status of Project
FRAC0010	Xerox Corporation Site, Oak Brook, IL	Oak Brook	IL	Xerox Corporation	U.S. EPA, RREL	Not Specified	University of Cincinnati	Pilot/Field Demonstration	Trichlorothene (TCE), 1,1,1-Trichlroethane (TCA), 1,1-Dichloroethane (DCA), Tetrachloroethene (PCE), and other solvents	Soil	Hydraulic/SVE	Completed
FRAC0096	Xerox Corporation, Micheldean, England	Micheldean	ENGLAND	Xerox Corporation	Xerox Corporation	Not Specified	Haley & Aldrich	Full-Scale/Commercial	Not Specified	Groundwater	Blast/Pump and Treat	Completed
FRAC0015	Xerox Corporation, Webster, NY	Webster	NY	Xerox Corporation	Xerox Corporation	NY State Dept. of Environ. Conservation	Haley & Aldrich	Full-Scale/Commercial	Trichloroethene, 1,1,1-trichloroethane, tetrachloroethylene (and chlorinated breakdown products of these), mineral spirits, toluene (specific mixtures of compounds varies from one plume/trench to another).	Groundwater	Blast/Pump and Treat	Completed

Table 2. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing Distribution of Case Studies by U.S. State, Canadian Province or Country (Pilot/Field and Full Scale/Commercial Projects Only; This Table Excludes Laboratory/Bench-Scale Projects) Total Number of Case Studies = 86	
U.S. State, Canadian Province or Country	Number of Studies
New Jersey	18
New York	13
Ohio	7
Alberta	4
Colorado	4
Alabama	3
California	3
Maine	3
Connecticut	2
Illinois	2
Kansas	2
Louisiana	2
Massachusetts	2
Oklahoma	2
Ontario	2
Pennsylvania	2
Saskatchewan	2
Texas	2
Virginia	2
Arizona	1
Belgium	1
England	1
Indiana	1
Nebraska	1
New Mexico	1
Tennessee	1
Washington	1
Wisconsin	1

Table 3. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Geology of Targeted Treatment Zone/Pre- and Post-Fracturing Properties/Radius of Influence

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Geology of Zone Targeted for Fracturing	Site Geology Clarification	Pre-Fracturing Hydraulic Properties	Post-Fracturing Hydraulic Properties	Pre-Fracturing Radius of Influence	Post-Fracturing Radius of Influence
FRAC0080	A.C. Roch. Corp., Rochester, NY	Bedrock - Interbedded Sedimentary	Limestone/Shale	Pre-Blast Well Yield 1 gpm	Post-Blast Well Yield 100 gpm	Not Specified	Not Specified
FRAC0027	Abandoned Industrial Site, Flemington, NJ	Bedrock - Shale/Siltstone	Low Transmissivity Fractured Shale	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0061	Aerospace Manufacturing Facility, Los Angeles, CA	Unspecified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0044	AT&T Facility, Richmond, VA	Unconsol. Seds. - Predom. Clay/Silt	Silty clay/clayey silt	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0032	Automobile Maintenance Facility, Lancaster, PA	Unconsol. Seds. - Predom. Clay/Silt	Fine clay formation	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0031	Automotive Manufacturing Facility, Columbia City, IN	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Glacial till (sand, silt, and clay)	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0013	Black & Decker Plant, NY	Bedrock - Sandstone - Massive, Competent	Medina Sandstone Underlying Glacial Till	Pre-Blast Well Yield 3.5 gpm, 20 feet drawdown	Post-Blast Well Yield 18.5 gpm, 11.2 feet drawdown	Not Specified	Not Specified
FRAC0033	Chemical Incineration Plant, Coffeyville, KS	Unconsol. Seds. - Predom. Clay/Silt	Dense silty clay formation	Not Specified	Not Specified	0 ft	10 ft
FRAC0002	Closed UST, Military Facility, Oklahoma City, OK	Bedrock - Shale/Siltstone	Sandstone/shale formation	Permeability 0.017 darcy	Permeability 0.32 darcy	Not Specified	Not Specified
FRAC0017	Corbett Creek, Former Gas Plant & Compressor Station, Alberta, Canada	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Clayey Silts to Silty, Fine-Grained Sands	Not Specified	Not Specified	4.9-6.6 ft liquid, 13.1-16.4 ft vapor	23.0-32.8 ft liquid, 49.2-82.0 ft vapor
FRAC0040	Decommissioned Retail Service Station, Regina, SA	Unconsol. Seds. - Predom. Clay/Silt	Glacio-Lacustrine Clays	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0050	Denver Federal Center	Bedrock - Shale/Siltstone	Tightly-packed clay and shale	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0089	Diaz Chemical Corporation, Holley, NY	Bedrock - Shale/Siltstone	Shale	Pre-Blast Well Yield <0.5 gpm	Post-Blast Well Yield 5 gpm	Not Specified	Not Specified
FRAC0062	East Brunswick, NJ	Bedrock - Shale/Siltstone	Siltstone	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0048	East Orange, NJ	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Sand/Sandy silt	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0082	Eastman Kodak, Industrial Landfill, Rochester, NY	Bedrock - Sandstone - Massive, Competent	Sandstone	Pre-Blast Well Yield 0.5 gpm	Post-Blast Well Yield 12 gpm	Not Specified	Not Specified
FRAC0083	Eastman Kodak, Rochester, NY	Bedrock - Sandstone - Massive, Competent	Sandstone	Pre-Blast Well Yield Four Trenches: <0.1 gpm, 0.5 gpm, N/A, and N/A.	Post-Blast Well Yield Four Trenches: 5 gpm, 6 gpm, N/A, and N/A.	Not Specified	Not Specified
FRAC0064	Egg Harbor, NJ	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Silty sand	Not Specified	Not Specified	Not Specified	Not Specified

Table 3. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Geology of Targeted Treatment Zone/Pre- and Post-Fracturing Properties/Radius of Influence

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Geology of Zone Targeted for Fracturing	Site Geology Clarification	Pre-Fracturing Hydraulic Properties	Post-Fracturing Hydraulic Properties	Pre-Fracturing Radius of Influence	Post-Fracturing Radius of Influence
FRAC0011	EPA Center Hill Testing Facility, Cincinnati, OH	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Silty Clay with Lesser Amounts Sand and Gravel	Suction head 1.18 in water 3.3 ft from unfractured wells	Suction head 1.18 in water 25 ft from fractured wells	Not Specified	Not Specified
FRAC0025	Federal Government Facility	Bedrock - Interbedded Sedimentary	Sandy, silty shale, silty claystone, clayey silt, sandstone	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0079	Fire Station 28, Denver, CO	Bedrock - Shale/Siltstone	Claystone/Shale	Pre-Blast Well Yield <0.1 gpm	Post-Blast Well Yield 6 gpm	Not Specified	Not Specified
FRAC0081	FMC Corporation, Middleport, NY	Bedrock - Interbedded Sedimentary	Limestone and Sandstone	Pre-Blast Well Yield Eight Trenches: 0.1 gpm, <0.1 gpm, <0.1 gpm, <1 gpm, <1 gpm, 0.9 gpm, 0.9 gpm, and <0.1 gpm	Post-Blast Well Yield Eight Trenches: 8 gpm, 1.9 gpm, 0.41 gpm, 5.89 gpm, 4.6 gpm, 2.8 gpm, 2.8 gpm, and 7.5 gpm.	Not Specified	Not Specified
FRAC0094	Former Bayer Aspirin, NJ	Bedrock - Igneous/Metamorph. - Competent	Schist/Gneiss	Pre-Blast Well Yield 1.2 gpm	Post-Blast Well Yield <0.8 gpm	Not Specified	Not Specified
FRAC0057	Former Dry Cleaning Facility, Northern Virginia	Bedrock - Shale/Siltstone	Fractured Siltstone and Shale Formation	<0.2 ft drawdown	Formation dewatered to expose vadose zone	11 ft vacuum ROI	15-40 ft vacuum ROI, varying predictably w/ strike and dip
FRAC0035	Former Light Manufacturing Facility, Brookfield, WI	Unconsol. Seds. - Predom. Clay/Silt	Tight Clay Formation	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0004	Former Manufacturing Facility, Highland Park, NJ	Bedrock - Shale/Siltstone	Fractured Shale, Siltstone/Limestone with Carbonate	Not Specified	Not Specified	11 feet	15-40 feet
FRAC0026	Former Manufacturing Facilty, Hillsborough, NJ	Bedrock - Shale/Siltstone	Low Transmissivity Siltstone	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0030	Former Processing Facility, Kansas City, KS	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Fine to medium sand and silty sand	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0029	Former Service Station, Newark, NJ	Bedrock - Shale/Siltstone	Shale and sandstone formation	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0038	Former Sour Gas Plant Site	Unconsol. Seds. - Predom. Clay/Silt	Silt till soils	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0047	Former Sour Gas Plant Site, Wetaskiwin, Alberta, Canada	Unconsol. Seds. - Predom. Clay/Silt	Clay Till Soil	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0022	Fuel Terminal in Regina, Saskatchewan	Unconsol. Seds. - Predom. Clay/Silt	Low Permeability, Naturally Fractured, Glaciolacustrine Clays and Clayey Silts	Hydraulic Conductivity 4.3 x 10-6 to 8.0 x 10-6 cm/sec, Air Permeability 1.0 x 10-9 to 2.9 x 10-9 cm2	Hydraulic Conductivity 4.1 x 10-5 to 2.3 x 10-4 cm/s, Air Permeability 4.6 x 10-8 to 1.2 x 10-7 cm2	6.6 to 9.8 foot liquid ROI, 16.4 to 23.0 foot vapor ROI	52.5 foot liquid ROI, >52.5 foot vapor ROI

Table 3. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Geology of Targeted Treatment Zone/Pre- and Post-Fracturing Properties/Radius of Influence

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Geology of Zone Targeted for Fracturing	Site Geology Clarification	Pre-Fracturing Hydraulic Properties	Post-Fracturing Hydraulic Properties	Pre-Fracturing Radius of Influence	Post-Fracturing Radius of Influence
FRAC0007	Gasoline Refinery in Marcus Hook, PA	Unconsol. Seds. - Predom. Clay/Silt	Dense, low permeabilty silty clay formation	0.02 darcys	0.8 darcys	Not Specified	Not Specified
FRAC0090	GM Delco Chassis, Bristol CT	Bedrock - Igneous/Metamorph. - Competent	Schist/Gneiss	Pre-Blast Well Yield 0.2 gpm	Post-Blast Well Yield 10 gpm	Not Specified	Not Specified
FRAC0104	Hallman Chevrolet, NY	Bedrock - Carbonate - Massive/Non-Karst	Dolomite	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0055	Indian Village Site, Continental Divide, NM	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Layers of fine-grained alluvium (sand, silt, clayey sand, and sandy clay).	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0003	Industrial Facility, Santa Clara, CA	Unconsol. Seds. - Interbedded Sediments	Semi-permeable layer of sandy silts and sandy clays overlying a low permeability 'fat' silty clay	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0065	Industrial Site, Elizabeth, NJ	Unconsol. Seds. - Predom. Clay/Silt	Clayey silt	Not Specified	Not Specified	Immeasurable at wells 10 and 15 feet from DPE well	Measurable at wells 10 and 15 feet from DPE well
FRAC0001	Industrial Site, Hillsborough, NJ	Bedrock - Shale/Siltstone	Low permeability siltstones and sandstones	Not Specified	Not Specified	380 sq. feet area	1,254 sq. feet area
FRAC0028	Industrial Site, Roseland, NJ	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0088	Jurgason Gage & Valve Co. - Manufacturer, MA	Bedrock - Igneous/Metamorph. - Competent	Gabbro and Granite Underlying Glacial Till	Pre-Blast Well Yield 0.1 gpm	Post-Blast Well Yield 4 gpm	Not Specified	Not Specified
FRAC0045	Laidlaw Site, Sarnia, Ontario, Canada	Unconsol. Seds. - Predom. Clay/Silt	Clay-Rich Glacial Till	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0053	LASAGNA, Cincinnati, OH	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0052	LASAGNA, Offutt Air Force Base, NE	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0051	LASAGNA, Rickenbacker Air National Guard Base, OH	Unconsol. Seds. - Predom. Clay/Silt	Tight clay	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0046	Linemaster Switch Superfund Site, Woodstock, CT	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Fine-Grained Glacial Till (Unsorted Clay, Silt, Sand, Gravel, and Boulders) Overlying Schist Intruded by Granite	Not Specified	Not Specified	Suction field <5 ft from conventional well	Suction field 45 ft and 14 ft bgs around fractured well
FRAC0043	Loring Air Force Base, ME	Bedrock - Carbonate - Massive/Non-Karst	Limestone underlain by till	Not Specified	Post-Blast Well Yield 60 gpm	Not Specified	Not Specified

Table 3. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Geology of Targeted Treatment Zone/Pre- and Post-Fracturing Properties/Radius of Influence

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Geology of Zone Targeted for Fracturing	Site Geology Clarification	Pre-Fracturing Hydraulic Properties	Post-Fracturing Hydraulic Properties	Pre-Fracturing Radius of Influence	Post-Fracturing Radius of Influence
FRAC0008	LUST Site near Dayton, OH	Unconsol. Seds. - Predom. Clay/Silt	Stiff, Sandy to Silty Clay with Traces of Gravel	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0087	Manufacturer, ME	Bedrock - Igneous/Metamorph. - Competent	Schist	Pre-Blast Well Yield 0.25 gpm	Post-Blast Well Yield 8 gpm	Not Specified	Not Specified
FRAC0005	Manufacturing Facility in NY	Unconsol. Seds. - Predom. Clay/Silt	Glacial Till to 15 ft bgs, Consisting of Firm, Plastic Clay Underlain by Fractured Dolomite	10-7 cm/sec hydraulic conductivity	Not Specified	Not Specified	Not Specified
FRAC0018	Manufacturing Facility, Huntsville, AL	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Gravelly clay to sandy gravel	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0019	Manufacturing Facility, Shreveport, LA	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Sandy silt and silty clay	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0039	Manufacturing Plant, Chicago, IL	Unconsol. Seds. - Predom. Clay/Silt	Clay Till	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0067	Maxwell Air Force Base, Montgomery, AL	Unspecified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0063	McGuire AFB, Wrightstown, NJ	Unconsol. Seds. - Poorly Sorted Predom. Coarse Grained	Silty fine sand	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0103	Mercury Aircraft Co., NY	Bedrock - Shale/Siltstone	Shale	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0041	Metal Bellows Metal Finishing Plant, Sharon, MA	Bedrock - Igneous/Metamorph. - Weathered/Fractured	Fractured Granite Underlying 15 feet of Glacial Till	0.3 ft/day hydraulic conductvity	20 ft/day hydraulic conductivity	Not Specified	Not Specified
FRAC0021	Municipal Landfill, Edmonton, Alberta, Canada	Other	Saturated Municipal Landfill Wastes	4.0 x 10-4 cm/sec	2.1 x 10-3 cm/sec and 6.2 x 10-3 cm/sec	61.7 feet hydraulic ROI	82.0 feet hydraulic ROI and 153.5 feet hydraulic ROI
FRAC0068	Mustang-Shadow Mountain Gas Station, Grand Lake, CO	Unspecified	Not Specified	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0014	New Jersey Environmental Cleanup Responsibility Act (ECRA) Site in South Plainfield, NJ	Bedrock - Shale/Siltstone	Fractured Brunswick Shale aquifer	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0105	New York Air Brake, NY	Bedrock - Carbonate - Massive/Non-Karst	Limestone	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0106	New York Air Brake, NY	Bedrock - Carbonate - Massive/Non-Karst	Limestone	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0059	Newark, NJ	Unconsol. Seds. - Predom. Clay/Silt	Sandy silt	Not Specified	Not Specified	Not Specified	Not Specified

Table 3. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Geology of Targeted Treatment Zone/Pre- and Post-Fracturing Properties/Radius of Influence

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Geology of Zone Targeted for Fracturing	Site Geology Clarification	Pre-Fracturing Hydraulic Properties	Post-Fracturing Hydraulic Properties	Pre-Fracturing Radius of Influence	Post-Fracturing Radius of Influence
FRAC0058	Newark, NJ	Bedrock - Sandstone - Massive, Competent	Sandstone	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0049	Northeast OH	Unconsol. Seds. - Predom. Clay/Silt	Low permeability clay soils	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0037	Petroleum Storage Terminal Site	Unconsol. Seds. - Predom. Clay/Silt	Silt soils	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0056	Railyard in Birmingham, AL	Unconsol. Seds. - Predom. Clay/Silt	Silty clay overlain by fill (1/3 to 3 m thick), and underlain by fractured dolomite/limestone of the Conasauga Formation that is 4 to 8 m bgs.	1.9 x 10-6 cm/sec to 1.4 x 10-8 cm/sec Hydraulic Conductivity; 3 L/day Hydrocarbon Recovery (Well MW-1S)	14.7 L/day Hydrocarbon Recovery (Well MW-1S)	Not Specified	Not Specified
FRAC0066	Raritan, NJ	Bedrock - Shale/Siltstone	Fractured siltstone/shale	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0054	Retail Gasoline Facility, Lakewood, CO	Unconsol. Seds. - Predom. Clay/Silt	Clay Soils	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0036	Rural Test Location, Frelinghuysen, NJ	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Clayey and sandy silts	0.12 cfm air flow	10+ scfm with limited source vacuum	Not Specified	Not Specified
FRAC0006	Service Station in Louisiana	Unconsol. Seds. - Predom. Clay/Silt	Clay Soil Underlain by Sand Aquifer	Vapor flow rate 10-15 scfm	Vapor flow rate 16-23 scfm	Not Specified	Not Specified
FRAC0060	Service Station, San Francisco, CA	Unspecified	Low permeability strata	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0102	Sidney Landfill, NY	Other	Landfill	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0009	Site in Bristol, TN	Bedrock - Interbedded Sedimentary	Sandstone, Shale, and Limestone	Negligible Vapor Discharge, <3.1 ppd DNAPL Recovery	Vapor Discharge 285-700 L/min, 180 ppd DNAPL Recovery	Negligible Suction	Suction Detected 32.8 feet from Recovery Well
FRAC0095	Stearns & Foster Site, NJ	Bedrock - Shale/Siltstone	Shale	Pre-Blast Well Yield 1 gpm	Post-Blast Well Yield 5 gpm	Not Specified	Not Specified
FRAC0034	Steel Manufacturing Facility, Western New York	Other	Synthetic waste tar pit	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0012	Storage Tank Site in Beaumont, TX	Unconsol. Seds. - Predom. Clay/Silt	Silty Clay and Clayey Silt	Water recovery unfractured well 0.0079 gph, NAPL recovery unfractured well 0.06 gph	Water recovery range fractured wells 0.09 to 2.27 gph, NAPL recovery range fractured wells 0.02 to 1.16 gph	Not Specified	Not Specified
FRAC0016	Toronto, Ontario, Canada	Unconsol. Seds. - Poorly Sorted Predom. Fine-Grained	Clayey silt	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0072	U.S. DoD Fort Hood, TX	Unconsol. Seds. - Predom. Clay/Silt	Tight clay soils	Not Specified	Not Specified	Not Specified	Not Specified

Table 3. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Geology of Targeted Treatment Zone/Pre- and Post-Fracturing Properties/Radius of Influence

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Geology of Zone Targeted for Fracturing	Site Geology Clarification	Pre-Fracturing Hydraulic Properties	Post-Fracturing Hydraulic Properties	Pre-Fracturing Radius of Influence	Post-Fracturing Radius of Influence
FRAC0024	U.S. DOE Hanford, WA Facility	Unconsol. Seds. - Predom. Well Sorted Sand/Gravel	Sandy gravel (Sand, gravel cobbles - Hanford formation)	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0020	U.S. DOE Portsmouth Gaseous Diffusion Plant, X231-A Land Trmt Site, Piketon, OH	Unconsol. Seds. - Predom. Clay/Silt	Minford member low permeability clays and silts	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0023	U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, Ohio	Unconsol. Seds. - Interbedded Sediments	Uppermost aquifer targeted was a silt formation interbedded with clay and sand lenses, and the lower aquifer targeted consisted of sand and gravel.	Not Specified	Not Specified	Not Specified	Not Specified
FRAC0091	U.S. DOE, UMTRA, Tuba City, AZ	Bedrock - Sandstone - Massive, Competent	Sandstone	Pre-Blast Well Yield 0.5 gpm	Post-Blast Well Yield 1 gpm	Not Specified	Not Specified
FRAC0010	Xerox Corporation Site, Oak Brook, IL	Unconsol. Seds. - Predom. Clay/Silt	Silty Clay Till	Unfractured well average vapor discharge rate 8 gpm	Unfractured well average vapor discharge rate range 106-255 gpm	Not Specified	Not Specified
FRAC0096	Xerox Corporation, Micheldean, England	Bedrock - Shale/Siltstone	Sandstone/Shale	Pre-Blast Well Yield <0.1 gpm	Post-Blast Well Yield 6.6 gpm	Not Specified	Not Specified
FRAC0015	Xerox Corporation, Webster, NY	Bedrock - Shale/Siltstone	Flat-Lying Sandstone and Shale	Pre-Blast Well Yield Eight Trenches: 0.1 gpm, 0.1 gpm, <0.1 gpm, 1 gpm, <0.1 gpm, <0.5 gpm, 0.1 gpm, and <0.5 gpm. Trench at landfill: 0.1 gpm.	Post-Blast Well Yield Eight Trenches: 15 gpm, 40 gpm, 50 gpm, 30 gpm, 12 gpm, 20 gpm, 150 gpm, and 20 gpm. Trench at landfill: 100 gpm.	50 feet hydraulic ROI	Not Specified

Table 4. Hydraulic and Pneumatic Fracturing - Fracturing Depth/Fracture Radius and Aperture

Total Number of Case Studies = 64

GWRTAC ID	Project Name	Minimum Depth/Radius/Aperture of Induced Fractures	Maximum Depth/Radius/Aperture of Induced Fractures	Fracturing Type
FRAC0027	Abandoned Industrial Site, Flemington, NJ	14.5 ft depth	16.7 ft depth, 40 ft radius	Pneumatic
FRAC0061	Aerospace Manufacturing Facility, Los Angeles, CA	Not Specified	Not Specified	Pneumatic
FRAC0044	AT&T Facility, Richmond, VA	6.8 ft depth	10.7 ft depth, 9 ft radius	Pneumatic
FRAC0032	Automobile Maintenance Facility, Lancaster, PA	Not Specified	Not Specified	Pneumatic
FRAC0031	Automotive Manufacturing Facility, Columbia City, IN	4 ft depth	11.5 ft depth	Pneumatic
FRAC0033	Chemical Incineration Plant, Coffeyville, KS	7 ft depth	20 ft depth	Pneumatic
FRAC0002	Closed UST, Military Facility, Oklahoma City, OK	26 ft depth	28 ft depth	Pneumatic
FRAC0017	Corbett Creek, Former Gas Plant & Compressor Station, Alberta, Canada	23.0 ft depth, 0.5 in. average aperture, 9.8 ft radius	36.1 ft depth, 0.5 in. average aperture, 23.0 ft radius	Hydraulic
FRAC0040	Decommissioned Retail Service Station, Regina, SA	Not Specified	Not Specified	Hydraulic
FRAC0050	Denver Federal Center	8 ft depth	22 ft depth, over 20 ft radius	Hydraulic
FRAC0062	East Brunswick, NJ	Not Specified	Not Specified	Pneumatic
FRAC0048	East Orange, NJ	Not Specified	Not Specified	Pneumatic
FRAC0064	Egg Harbor, NJ	14 ft depth, 8 ft radius	27 ft depth, 10 ft radius	Pneumatic
FRAC0011	EPA Center Hill Testing Facility, Cincinnati, OH	5 ft depth	10 ft depth	Hydraulic
FRAC0025	Federal Government Facility	7 ft depth	28 ft depth, >50 ft radius	Pneumatic
FRAC0057	Former Dry Cleaning Facility, Northern Virginia	15 ft depth	30 ft depth	Pneumatic
FRAC0035	Former Light Manufacturing Facility, Brookfield, WI	4 ft depth	16.5 ft depth	Pneumatic
FRAC0004	Former Manufacturing Facility, Highland Park, NJ	9 ft depth	25 ft depth	Pneumatic
FRAC0026	Former Manufacturing Facilty, Hillsborough, NJ	9.1 ft depth	16.4 ft depth, >20 ft radius	Pneumatic
FRAC0030	Former Processing Facility, Kansas City, KS	25 ft depth	37 ft depth, 15 ft radius	Pneumatic
FRAC0029	Former Service Station, Newark, NJ	9 ft depth	13 ft depth	Pneumatic
FRAC0038	Former Sour Gas Plant Site	Not Specified	Not Specified	Hydraulic
FRAC0047	Former Sour Gas Plant Site, Wetaskiwin, Alberta, Canada	3.3 foot radius	Average aperture 0.6 inches, 16.4 foot radius	Hydraulic

Table 4. Hydraulic and Pneumatic Fracturing - Fracturing Depth/Fracture Radius and Aperture

Total Number of Case Studies = 64

GWRTAC ID	Project Name	Minimum Depth/Radius/Aperture of Induced Fractures	Maximum Depth/Radius/Aperture of Induced Fractures	Fracturing Type
FRAC0022	Fuel Terminal in Regina, Saskatchewan	Not Specified	Not Specified	Hydraulic
FRAC0007	Gasoline Refinery in Marcus Hook, PA	3 ft depth, 14 ft radius	8 ft depth, 40 x permeability increase observed within effective radius of approx. 20 feet	Pneumatic
FRAC0055	Indian Village Site, Continental Divide, NM	22 ft depth, 10 ft radius	54 ft depth, 15 ft radius	Hydraulic
FRAC0003	Industrial Facility, Santa Clara, CA	3.5 ft depth, 10 ft radius	13.5 ft depth, 15 ft radius	Pneumatic
FRAC0065	Industrial Site, Elizabeth, NJ	8 ft depth, 8 ft radius	16 ft depth, 15 ft radius	Pneumatic
FRAC0001	Industrial Site, Hillsborough, NJ	Not Specified	35 foot radius	Pneumatic
FRAC0028	Industrial Site, Roseland, NJ	4 ft depth	7 ft depth, 28 ft radius, 1.93 inch aperture during injection	Hydraulic
FRAC0045	Laidlaw Site, Sarnia, Ontario, Canada	3.9 ft depth, 1 cm surface uplift (aperture)	18.2 ft depth, 4.65 cm surface uplift (apeture)	Hydraulic
FRAC0053	LASAGNA, Cincinnati, OH	Not Specified	Not Specified	Hydraulic
FRAC0052	LASAGNA, Offutt Air Force Base	Not Specified	Not Specified	Hydraulic
FRAC0051	LASAGNA, Rickenbacker Air National Guard Base	Not Specified	13 ft depth	Hydraulic
FRAC0046	Linemaster Switch Superfund Site, Woodstock, CT	8 ft depth, 20 ft radius, 0.5 in aperture	45 ft depth, 25 ft radius, 0.5 in aperture	Hydraulic
FRAC0008	LUST Site near Dayton, OH	4 ft depth	10 ft depth	Hydraulic
FRAC0005	Manufacturing Facility in NY	Not Specified	Not Specified	Pneumatic
FRAC0018	Manufacturing Facility, Huntsville, AL	25 ft depth	37 ft depth, 49 ft radius of influence	Pneumatic
FRAC0019	Manufacturing Facility, Shreveport, LA	7 ft depth	22 ft depth, 1" aperture (evidenced by ground heave)	Pneumatic
FRAC0039	Manufacturing Plant, Chicago, IL	Not Specified	Not Specified	Hydraulic
FRAC0067	Maxwell Air Force Base, Montgomery, AL	55 ft depth, 5 ft radius	75 ft depth, 10 ft radius	Hydraulic
FRAC0063	McGuire AFB, Wrightstown, NJ	9 ft depth	13 ft depth, 4.5 ft radius, with average of 2-3 ft	Pneumatic
FRAC0021	Municipal Landfill, Edmonton, Alberta, Canada	Not Specified	Not Specified	Hydraulic
FRAC0068	Mustang-Shadow Mountain Gas Station, Grand Lake, CO	Not Specified	Not Specified	Hydraulic

Table 4. Hydraulic and Pneumatic Fracturing - Fracturing Depth/Fracture Radius and Aperture

Total Number of Case Studies = 64

GWRTAC ID	Project Name	Minimum Depth/Radius/Aperture of Induced Fractures	Maximum Depth/Radius/Aperture of Induced Fractures	Fracturing Type
FRAC0014	New Jersey Environmental Cleanup Responsibility Act (ECRA) Site in South Plainfield, NJ	Not Specified	Not Specified	Pneumatic
FRAC0059	Newark, NJ	5.3 ft depth	7.3 ft depth	Pneumatic
FRAC0058	Newark, NJ	9 ft depth	11 ft depth, > 10 ft radius	Pneumatic
FRAC0049	Northeast OH	15 ft radius, 2 cm aperture	20 ft radius, 3 cm aperture	Hydraulic
FRAC0037	Petroleum Storage Terminal Site	Not Specified	Not Specified	Hydraulic
FRAC0056	Railyard in Birmingham, AL	10.9 ft depth	18.9 ft depth	Hydraulic
FRAC0066	Raritan, NJ	25 ft depth, 10 ft radius	45 ft depth, 15 ft radius	Pneumatic
FRAC0054	Retail Gasoline Facility, Lakewood, CO	Not Specified	20 ft depth	Hydraulic
FRAC0036	Rural Test Location, Frelinghuysen, NJ	4 ft depth	8 ft depth	Pneumatic
FRAC0006	Service Station in Louisiana	Not Specified	Not Specified	Pneumatic
FRAC0060	Service Station, San Francisco, CA	Not Specified	Not Specified	Pneumatic
FRAC0009	Site in Bristol, TN	Not Specified	Not Specified	Hydraulic
FRAC0034	Steel Manufacturing Facility, Western New York	Not Specified	Not Specified	Pneumatic
FRAC0012	Storage Tank Site in Beaumont, TX	10 ft depth, 11.5 ft radius, 0.6 inch aperture	12 ft depth, 13 ft radius, 1 inch aperture	Hydraulic
FRAC0016	Toronto, Ontario, Canada	4 ft depth, 11 ft radius	12 ft depth, 16 ft radius	Pneumatic
FRAC0072	U.S. DoD Fort Hood, TX	12 ft depth, < 15 ft radius	21 ft depth, 15 ft radius	Hydraulic
FRAC0024	U.S. DOE Hanford, WA Facility	10 ft radius	14 ft depth, 14 ft radius	Pneumatic
FRAC0020	U.S. DOE Portsmouth Gaseous Diffusion Plant, X231-A Land Trmt Site, Piketon, OH	4 ft depth	16 ft depth	Hydraulic
FRAC0023	U.S. DOE Site, Ohio	8 ft depth	23 ft depth	Pneumatic
FRAC0010	Xerox Corporation Site in Oak Brook, IL	6 ft depth	1 inch aperture, 20 foot radius, 15 foot depth	Hydraulic

Table 5. Blast-Enhaced Fracturing - Blasted Bedrock Zone Dimensions/Overburden Thickness

Total Number of Case Studies = 22

GWRTAC ID	Project Name	Blast Zone Dimensions
FRAC0080	A.C. Roch. Corp., Rochester, NY	1,220 ft Length, 26 ft Depth, 22 ft Overburden, 31720 ft2 Sidewall Area
FRAC0013	Black & Decker Plant, NY	300 ft Length, 23 ft Depth, 15 ft Overburden, 6900 ft2 Sidewall Area
FRAC0089	Diaz Chemical Corporation, NY	265 ft Length, 6 ft Depth, 36 ft Overburden, 1590 ft2 Sidewall Area
FRAC0082	Eastman Kodak, Industrial Landfill, Rochester, NY	250 ft Length, 16 ft Depth, 30 ft Overburden, 4000 ft2 Sidewall Area
FRAC0083	Eastman Kodak, Rochester, NY	Four Trenches (Length x Depth, Sidewall Area): 150 x 15 ft, 2250 ft2, 200 x 15 ft, 3000 ft2, 100 x 13 ft, 1300 ft2, and 100 x 13 ft, 1300 ft2. Four Trenches (Overburden Depth): 20 ft, 30 ft, 10 ft, 10 ft
FRAC0079	Fire Station 28, Denver, CO	130 ft Length, 40 ft Depth, 5200 ft2 Sidewall Area
FRAC0081	FMC Corporation, Middleport, NY	Eight Trenches (Length x Depth, Sidewall Area): 300 x 16 ft, 4800 ft2, 300 x 28 ft, 8400 ft2, 150 x 13 ft, 1950 ft2, 800 x 10 ft, 8000 ft2, 450 x 10 ft, 4500 ft2, 200 x 13 ft, 2600 ft2, 50 x 17 ft, 850 ft2, and 300 x 14 ft, 4200 ft2. Eight Trenches (Overburden Depth): 13 ft, 13.5 ft, 15 ft, 12 ft, 10 ft, 8 ft, 11 ft, and 13 ft.
FRAC0094	Former Bayer Aspirin, NJ	100 ft Length, 66 ft Depth, 22 ft Overburden, 6600 ft2 Sidewall Area
FRAC0090	GM Delco Chassis, Bristol CT	355 ft Length, 42 ft Depth, 8 ft Overburden, 14910 ft2 Sidewall Area
FRAC0104	Hallman Chevrolet, NY	180 ft Length, 9 ft Depth, 11 ft Overburden, 1620 ft2 Sidewall Area
FRAC0088	Jurgason Gage & Valve Co. - Manufacturer, MA	650 ft Length, 30 ft Depth, 19500 ft2 Sidewall Area
FRAC0043	Loring Air Force Base, ME	150 ft Length, 50 ft Depth, 20 ft Overburden, 7500 ft2 Sidewall Area
FRAC0087	Manufacturer, ME	200 ft Length, 35 ft Depth, 7000 ft2 Sidewall Area
FRAC0103	Mercury Aircraft Company, NY	200 ft Length, 60 ft Depth, 5 ft Overburden, 12000 ft2 Sidewall Area
FRAC0041	Metal Bellows Metal Finishing Plant, Sharon, MA	250 ft Length, 15 ft Depth, 3750 ft2 Sidewall Area
FRAC0106	New York Air Brake, NY	700 ft Length, 15 ft Depth, 16 ft Overburden, 10500 ft2 Sidewall Area
FRAC0105	New York Air Brake, NY	1,500 ft Length, 12 ft Depth, 6 ft Overburden, 18000 ft2 Sidewall Area
FRAC0102	Sidney Landfill, NY	100 ft Length, 60 ft Depth, 20 ft Overburden, 6000 ft2 Sidewall Area
FRAC0095	Stearns & Foster Site, NJ	100 ft Length, 16 ft Depth, 9 ft Overburden, 1600 ft2 Sidewall Area
FRAC0091	U.S. DOE, UMTRA, Tuba City, AZ	50 ft Length, 70 ft Depth, 30 ft Overburden, 3500 ft2 Sidewall Area
FRAC0096	Xerox Corporation, Micheldean, England	120 ft Length, 50 ft Depth, 21 ft Overburden, 6000 ft2 Sidewall Area

Table 5. Blast-Enhaced Fracturing - Blasted Bedrock Zone Dimensions/Overburden Thickness

Total Number of Case Studies = 22

GWRTAC ID	Project Name	Blast Zone Dimensions
FRAC0015	Xerox Corporation, Webster, NY	Eight Trenches (Length x Depth, Sidewall Area): 700 x 25 ft, 17500 ft2; 675 x 25 ft, 16875 ft2; 800 x 20 ft, 16000 ft2; 600 x 25 ft, 15000 ft2; 330 x 25 ft, 8250 ft2; 500 x 24 ft.12000 ft2; 300 x 30 ft, 9000 ft2; and 450 x 47 ft, 21150 ft2. Trench at landfill: 850 x 26 ft, 22100 ft2. Eight Trenches (Overburden Depth): 6 ft, 12 ft, 25 ft, 9 ft, 6 ft, 11 ft, 12 ft, and 8 ft. Trench at landfill: 20 ft.

Table 6. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Fracturing Related Performance

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Application/Results	Economic Information	Scale of Project
FRAC0080	A.C. Roch. Corp., Rochester, NY	Ratio of Pre- to Post-Blast Well Yields was 100 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0027	Abandoned Industrial Site, Flemington, NJ	Aquifer transmissivities as measured during minimum 24 hour duration tests increased between 1.17 and 1.80 times. The average increase from all the monitor wells was 1.46 times. The effective area of influence also increased. Rising and falling head slug tests, conducted before and after Pneumatic Fracturing, showed that the hydraulic conductivity increased 3.54 times. The post fracture flow rate from the pumping well was 1 gallon per minute (gpm). When a vacuum was applied to the pumping well, the flow rate increased to 5 gpm. Pneumatic injection was also successful for the delivery of the microorganism to the subsurface. The fractures created from the initial field work enhanced the distribution of the microorganisms around the fracture well. Contaminant concentrations were reduced.	Not Specified	Pilot/Field Demonstration
FRAC0061	Aerospace Manufacturing Facility, Los Angeles, CA	Rapid remediation for property transfer accomplished.	Not Specified	Full-Scale/Commercial
FRAC0044	AT&T Facility, Richmond, VA	Mass removal of chlorinated solvents increased >200 times and airflows increased more than 1,000 times following fracturing.	Not Specified	Scale Unknown
FRAC0032	Automobile Maintenance Facility, Lancaster, PA	No movement of building structure was detected during pneumatic injection. Pressure influence was detected at surrounding monitoring wells, indicating subsurface fracture propagation.	Not Specified	Full-Scale/Commercial
FRAC0031	Automotive Manufacturing Facility, Columbia City, IN	The full-scale PF/SVE system recovered more that 1,330 lbs. of TCE from the subsurface in the first 9 months of operation, which is more than 20% beyond estimated design mass calculation believed to exist within the subsurface.	Not Specified	Full-Scale/Commercial
FRAC0013	Black & Decker Plant, NY	Ratio of Pre- to Post-Blast Well Yields is 5.3 (Unitless); drawdown in pumping well decreased from 20 feet at 3.5 gpm yield to 11.2 feet at 18.5 gpm yield, reflecting greater efficiency. Prior to blasting, observation wells showed little or no pumping response, and after blasting, pumping response in these wells was significant.	Not Specified	Full-Scale/Commercial
FRAC0033	Chemical Incineration Plant, Coffeyville, KS	Air permeability increased over five times and the vacuum radius of influence increased significantly. During the post fracture testing, vacuum influences of 14 and 10 inches of water were observed at respective 3 and 10 foot distances from the fracture well; pre-fracturing vacuum influence was negligible at several monitoring points.	Not Specified	Pilot/Field Demonstration
FRAC0002	Closed UST, Military Facility, Oklahoma City, OK	Free product recovery increase from 155 gal. per month pre-fracturing to 435 gal. per month post-fracturing. Increase of ratio of oil to water recovered from 12% of total fluid pre-fracturing to 74% of total fluid post-fracturing. Oil production per day from one recovery well increased from 1.2 gpd to 6.2 gpd. Static product thickness increased from 1.5 ft to 20.2 ft. Ave. monthly recovery rates increased from 155 gal. per month to 435 gal. per month. Product recovered increased from ave. of 12% to 74% of the total fluids recovered.	Not Specified	Pilot/Field Demonstration
FRAC0017	Corbett Creek, Former Gas Plant & Compressor Station, Alberta, Canada	Hydraulic conductivity increased by two orders of magnitude. Condensate liquid recovery rate increased 7.5 times. Condensate vapour recovery rate increased over 70 times. Condensate:Total fluids ratio increased from 0.18 to 0.77. Maximum radius of vapor and hydraulic influence both increased by 5 times. Effective plume capture in this area of the site has occurred.	The total capital cost savings to the client over five years of remediation using fractured wells vs. conventional remedial technologies is at $1.46 million dollars Canadian. The value of recovered liquid condensate that was reprocessed and sold by the client was approximately $63,000 Cdn. per year in 1996 and 1997.	Full-Scale/Commercial
FRAC0040	Decommissioned Retail Service Station, Regina, SA	Not Specified	Not Specified	Scale Unknown

Table 6. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Fracturing Related Performance

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Application/Results	Economic Information	Scale of Project
FRAC0050	Denver Federal Center	Fractures increased soil permeability significantly, causing trapped water in the clay to flow through the fractures and inoculated isolite, biologiclay degrading the cutting oil. The "biofractures" served as a permeable reactive treatment system for the ground water.	Not Specified	Pilot/Field Demonstration
FRAC0089	Diaz Chemical Corporation, Holley, NY	Ratio of Pre- to Post-Blast Well Yields was 10 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0062	East Brunswick, NJ	Not Specified	Not Specified	Scale Unknown
FRAC0048	East Orange, NJ	Not Specified	Not Specified	Pilot/Field Demonstration
FRAC0082	Eastman Kodak, Industrial Landfill, Rochester, NY	Ratio of Pre- to Post-Blast Well Yields was 24 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0083	Eastman Kodak, Rochester, NY	Ratio of Pre- to Post-Blast Well Yields ranged from 12 to 50 (Unitless). Individual values for two of the four trench locations were 50 and 12.	Not Specified	Full-Scale/Commercial
FRAC0064	Egg Harbor, NJ	Pneumatic fracturing was used to inject hydrogen peroxide and acetic acid into an area of MGP-impacted soil. Approximately 3,000 gallons of oxidizing liquid was injected into fine sandy soils. Individual injections were from 40 to 60 gallons.	Not Specified	Pilot/Field Demonstration
FRAC0011	EPA Center Hill Testing Facility, Cincinnati, OH	Well discharge, as both vapor and liquid flow rate, was an order of magnitude greater for the fractured wells than the unfractured wells, and varied with precipitation. Suction head was detectable at greater distance from the wells with fractures than from the unfractured wells, varying with precipitation. Around the conventional wells, suction was 1.18 in of water at a distance of 3.3 feet. The same suction head could be observed 25 feet from the fractured wells.	Not Specified	Pilot/Field Demonstration
FRAC0025	Federal Government Facility	Transmissivity increased five times in fracture well screened across target interval. Smaller transmissivity increases in wells screened across other, smaller, water bearing units. Aquifer made more isotropic in nature, allowing water to be pumped from the aquifer at a higher rate and allowing faster rate of dewatering. The aerial influence of the pneumatic injection was demonstrated to be greater than 50 feet from the injection well. Circulation of amendments to enhance bioremediation accomplished efficiently, with subsequent reductions in VOC concentrations. Post-fracture air flows during vapor extraction tests were 500-1700% higher than pre-fracture air flows.	Not Specified	Pilot/Field Demonstration
FRAC0079	Fire Station 28, Denver, CO	Ratio of Pre- to Post-Blast Well Yields was 60 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0081	FMC Corporation, Middleport, NY	Ratio of Pre- to Post-Blast Well Yields ranged from 3.1 to 80 (Unitless). Individual values for the eight trench locations were 80, 19, 4.1, 5.89, 4.6, 3.1, 3.1, and 75.	Not Specified	Full-Scale/Commercial
FRAC0094	Former Bayer Aspirin, NJ	Ratio of Pre- to Post-Blast Well Yields was 0.67 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0057	Former Dry Cleaning Facility, Northern Virginia	Hydraulic connection between the wells was improved. Prior to fracturing, less than 0.2' drawdown was observed at on-site wells. After pneumatic fracturing, the formation was effectively dewatered to expose the vadose zone to effective vacuum influence. The average rate of TCE mass removal in vapor increased over 3 times the peak rate prior to fracturing. The vacuum radius of influence increased from 11 feet to 15-40 feet (influence varied with strike and dip). The much greater radius of influence reduced the number of wells required and tremendously reduced installation costs.	The much greater radius of influence reduced the number of wells required and tremendously reduced installation costs and reduced design full scale remediation duration from ten years to two years.	Full-Scale/Commercial
FRAC0035	Former Light Manufacturing Facility, Brookfield, WI	Excellent pressure influence was observed during pneumatic injections, indication excellent fracture propagation. Vacuum influence data confirmed that a thorough fracture network was created throughout the remediation zone.	Not Specified	Full-Scale/Commercial
FRAC0004	Former Manufacturing Facility, Highland Park, NJ	Pneumatic fracturing improved hydraulic connection between wells in the test area and allowed dewatering of formation to expose vadose zone to effective vacuum influence. Mass removal of TCE vapors increased over three times post-fracturing. Design of full-scale duration decreased from ten to two years. Vacuum radius of influence increased from 11 to 15-40 feet post-fracturing.	Not Specified	Full-Scale/Commercial

Table 6. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Fracturing Related Performance

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Application/Results	Economic Information	Scale of Project
FRAC0026	Former Manufacturing Facilty, Hillsborough, NJ	Prior to application of Pneumatic Fracturing, an injection well could only receive 2 gallons per minute. Following Pneumatic Fracturing, the injection well was accepting 11 gallons per minute. Several other re-injection wells were fractured as part of the full-scale injection well system.	Not Specified	Full-Scale/Commercial
FRAC0030	Former Processing Facility, Kansas City, KS	Pneumatic Fracturing changed the soil structure to eliminate a low permeability lens. In another area pneumatic fracturing was used to inject 1,800 lbs. of iron filings. A 30-60% reduction in baseline TCE values was noted 60 days after installation.	Not Specified	Pilot/Field Demonstration
FRAC0029	Former Service Station, Newark, NJ	The effective vacuum influence was observed to increase as much as 2,900% , and hydrocarbon removal rates increased as much as 757% after Pneumatic Fracturing.	Not Specified	Pilot/Field Demonstration
FRAC0038	Former Sour Gas Plant Site	Not Specified	Not Specified	Scale Unknown
FRAC0047	Former Sour Gas Plant Site, Wetaskiwin, Alberta, Canada	Average fracture thickness was 0.6 in, and the fracture radii ranged from 3.3 to 16.4 ft depending on the extent of fracture fluid leak-off. Ffracture properties observed in the field (lateral extent, orientation, and thickness of excavated fractures) were in general agreement with those predicted by a model.	Not Specified	Pilot/Field Demonstration
FRAC0022	Fuel Terminal in Regina, Saskatchewan	Hydraulic conductivity and air permeabililty increased one to two orders of magnitude. Liquid radius of influence increased about five to eight times, and vapor radius of influence increased about two to three times. Unlike unfractured wells, hydrocarbon removal rates were sustainable at high operating vacuums in hydraulically fractured wells since the induced fractures were kept open by the frac sand proppant.	Not Specified	Full-Scale/Commercial
FRAC0007	Gasoline Refinery in Marcus Hook, PA	Permeability increased up to 40 times within effective radius of approx. 20 feet. Air extraction flow rate increased 24 to 105 times. Average permeability increased from 0.02 darcys pre-fracture, to 0.8 darcys, post-fracture. CO_2 levels were elevated after nutrient injection, indicating increased BTX degradation rates. PF greatly increased the mass of contaminants removed by biological degradation.	Not Specified	Pilot/Field Demonstration
FRAC0090	GM Delco Chassis, Bristol CT	Ratio of Pre- to Post-Blast Well Yields was 50 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0104	Hallman Chevrolet, NY	Not Specified	Not Specified	Full-Scale/Commercial
FRAC0055	Indian Village Site, Continental Divide, NM	Some ground water samples indicated an initial increase in the contaminant concentration following the injection of the IsoliteR, which was followed by a decrease to pre-inoculation levels or less. The injection of inoculated IsoliteR appeared to speed the remediation rate of some hydrocarbons with concentration below 100 ppb. The change in remediation rate with higher concentrations, especially in the 1000 to 10,000 ppb range, was not as evident. The amount of data and short length of time between inoculation and sampling may have been insufficient to measure the effectiveness with higher concentrations of hydrocarbons.	The system was designed and installed for $141,000.	Full-Scale/Commercial
FRAC0003	Industrial Facility, Santa Clara, CA	Air flow increased 3.5 times during extraction tests using the entire fracture well. Permeability increased in the clay zones by 510 times over the pre-fracture level. The rate of TCE mass removal increase six times during extraction tests from the fracture well. TCE mass removal increase in the clay zone was over 46,000 times greater than the natural, unfractured condition.	$60,000.	Pilot/Field Demonstration
FRAC0065	Industrial Site, Elizabeth, NJ	Injections were performed underneath an industrial building with no impact to the structure. Radial and directional fracturing were performed. Airflow permeability and mass removal were improved. Radius of influence of SVE was improved from 5 ft to 15 ft after the test.	$68,000.	Pilot/Field Demonstration

Table 6. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Fracturing Related Performance

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Application/Results	Economic Information	Scale of Project
FRAC0001	Industrial Site, Hillsborough, NJ	PFE increased air flow in the SVE system by more than 600%. When one or more monitoring wells was opened to serve as a passive air inlet, air flow rate increases of 19,000% were observed. The effective rate of influence increased from 380 sq. ft. to at least 1,254 sq. ft. The increased air flow rate resulted in an increase of TCE mass removal of 675%, and with adjacent monitoring wells opened, 2,300%. PFE also accessed pockets of previously trapped VOCs, evidenced by high concentrations of organic compounds in extracted air which prior to fracturing, had been present only in trace amounts.	Full-scale remediation costs were estimated at $307/kg ($140/lb) of TCE removed based on the pilot-scale demonstration and information provided by the developer.	Pilot/Field Demonstration
FRAC0028	Industrial Site, Roseland, NJ	Pneumatic fracturing was effective in enhancing the efficiency of the vapor extraction system installed at the Roseland site. The average (air) flow increased 5 to 70 times after fracturing. The maximum fracture radius was 28 feet. The maximum fracture aperture during injection was 1.83 inches. An 80% reduction in contaminants in target monitor wells was observed six months after application of the Pneumatic Fracturing technology.	Not Specified	Pilot/Field Demonstration
FRAC0088	Jurgason Gage & Valve Co. - Manufacturer, MA	Ratio of Pre- to Post-Blast Well Yields was 40 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0045	Laidlaw Site, Sarnia, Ontario, Canada	Minimum surface uplift from the fracturing was observed at 1 to 4.65 cm. More symmetric fractures were created at shallow depths, while symmetric fractures were created at depths greater then 2.5 m. For fractures at depths greater than 2.5 m, the dip of the fractures increased with the depth of the fracture.	Not Specified	Pilot/Field Demonstration
FRAC0053	LASAGNA, Cincinnati, OH	Not Specified	Not Specified	Pilot/Field Demonstration
FRAC0052	LASAGNA, Offutt Air Force Base, NE	Not Specified	Not Specified	Pilot/Field Demonstration
FRAC0051	LASAGNA, Rickenbacker Air National Guard Base, OH	TCE in the Biocell soil was reduced to a median of non-detect ppm. During the same time period, in the untreated but monitored natural attenuation area, increases in TCE concentrations were observed. Populations of methanotrophic bacteria were established and maintained in the treatment zone and may have moved into the contaminated soils, preferring the direction of the anode.	Not Specified	Pilot/Field Demonstration
FRAC0046	Linemaster Switch Superfund Site, Woodstock, CT	After fracturing, dewatering was much more efficient, allowing SVE to remove TCE vapors. Suction in the uppermost fractures influenced the suction field in the shallow till up to 45 ft from the well, as deep as 14 ft bgs. Suction applied to conventional wells was nondetectable >5 ft from the screen. TCE mass removal increased from 1 oz per day to 10 lb per day.	Not Specified	Full-Scale/Commercial
FRAC0043	Loring Air Force Base, ME	Post-blast effects on the hydrology of the are adjacent to the recovery trench include 1. A decline in static water levels; 2. Order-of-magnitude increases in upward flow in two wells; 3. Reversal of flow directions in two wells; 4. Order-of-magnitude increases in the estimated transmissivity of three wells; and, 5. An estimated increase in aquifer secondary porosity to two percent near the trench.	Not Specified	Full-Scale/Commercial
FRAC0008	LUST Site near Dayton, OH	Fluid flow rates into the fractured well were 25 to 40 times greater than into the unfractured well, and this difference clearly affected the moisture in the soil. Bioremediation 5 feet from the fractured well after 1 month was 97% for ethylbenzene and 77% for total petroleum hydrocarbons compared with 8% and 0% respectively near the unfractured well.	Not Specified	Pilot/Field Demonstration
FRAC0087	Manufacturer, ME	Ratio of Pre- to Post-Blast Well Yields was 32 (Unitless)	Not Specified	Full-Scale/Commercial

Table 6. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Fracturing Related Performance

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Application/Results	Economic Information	Scale of Project
FRAC0005	Manufacturing Facility in NY	VOC concentrations ranged from 10 to 20 ppm prior to the startup of the pneumatic soil fracturing, and were over 200 ppm during startup.	Capital and operating costs of Injection VacTM are slightly higher than vacuum extraction without enhancement. The added costs of a suitably sized air compressor and, possibly, a high vacuum pump with additional energy and maintenance costs for soil vapor recovery must be factored into the overall cost. The major benefits are shorter remediation time and more effective subsurface remediation than standard, unenhanced extraction with low flow.	Pilot/Field Demonstration
FRAC0018	Manufacturing Facility, Huntsville, AL	Based on pre- and post-fracture slug testing, the formation hydraulic conductivity increased up to 8.4 times in fractured wells, and up to 9.6 times in adjacent monitoring wells. Improved radius of influence of groundwater recovery wells to complete a capture zone for impacted groundwater.	Not Specified	Full-Scale/Commercial
FRAC0019	Manufacturing Facility, Shreveport, LA	Pneumatic fracturing was demonstrated to increase both the permeability of the formation, as was demonstrated by an increased flow rate, radius of influence, and the rate of TCE removal, observed in the extracted air stream. Pneumatic fracturing was also demonstrated to improve the hydraulic conductivity of the formation in an adjacent monitoring well 7.1 times. The results of this increase were also observed in the remediation system, which drew a much higher volume of ground water than typical for that time of year.	Not Specified	Pilot/Field Demonstration
FRAC0039	Manufacturing Plant, Chicago, IL	Not Specified	Not Specified	Scale Unknown
FRAC0067	Maxwell Air Force Base, Montgomery, AL	Three treatment wall panels installed in 14 days were 2 to 3 in. thick and extended radially 5 to over 10 ft from injection hole. Groundwater TCE concentrations reduced from 400-700 ppb to <40 ppb after 6 mos.	The project was designed and installed for $210,000 including the supplies and down-hole materials.	Pilot/Field Demonstration
FRAC0063	McGuire AFB, Wrightstown, NJ	The extended radius wells (ERWs) increased free product recovery by 225-325%. Conductive lenses (ave. thickness 1/8-1/4 inches) of media were created. Product recovery rate increased from 0.4 gpd to 1.3 to 1.7 gpd.	Projecting improved product recovery rates, treatment time would be expected to drop from 30 years to ten years, with an estimated $4 million savings compared to traditional free product recovery.	Pilot/Field Demonstration
FRAC0103	Mercury Aircraft Co., NY	Not Specified	Not Specified	Full-Scale/Commercial
FRAC0041	Metal Bellows Metal Finishing Plant, Sharon, MA	Aquifer testing indicates hydraulic conductivity was increased nearly 100 times. Uniform drawdowns along fractured zone length suggest continuous fracturing results.	Not Specified	Full-Scale/Commercial
FRAC0021	Municipal Landfill, Edmonton, Alberta, Canada	Hydraulic conductivity and flow rate increased by approximately an order of magnitude in a well enhanced by fracturing. The capture radius increased from 61.7 to 82.0 feet in the same well, and another fractured well had a capture radius of 153.5 feet.	By estimate, a reduction from 55 conventional recovery wells to 33 fractured recovery wells can be attained, which would result in a cost savings of $330,000 U.S. for the installation of fewer recovery wells. Additional savings would accrue because of fewer pumps and infrastructure required as well as significantly reduced operation and maintenance costs.	Full-Scale/Commercial
FRAC0068	Mustang-Shadow Mountain Gas Station, Grand Lake, CO	Hydraulic fracturing was used to install BioNets. After one year, BTEX concentrations have been reduced 66 percent and all 3 compliance wells met BTEX standards.	The design and installation cost $130,000.	Full-Scale/Commercial

Table 6. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Fracturing Related Performance

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Application/Results	Economic Information	Scale of Project
FRAC0014	New Jersey Environmental Cleanup Responsibility Act (ECRA) Site in South Plainfield, NJ	Preliminary results indicated that the PFE/HGI process significantly increased contaminant removal rates over conventional vapor extraction.	Not Specified	Pilot/Field Demonstration
FRAC0106	New York Air Brake, NY	Not Specified	Not Specified	Full-Scale/Commercial
FRAC0105	New York Air Brake, NY	Not Specified	Not Specified	Full-Scale/Commercial
FRAC0058	Newark, NJ	Not Specified	Not Specified	Pilot/Field Demonstration
FRAC0059	Newark, NJ	Not Specified	Not Specified	Scale Unknown
FRAC0049	Northeast OH	Suction applied to the uppermost fracture registered at the same elevation in six out of seven multilevel piezometers installed 5, 15, 30 and 45 feet from the nest of wells. Pilot test results justified additional deployment. Fractures were created at seven locations along a line that intercepted the contaminant plume, just above and just below the water table so contaminants could be recovered through both vapor and groundwater. After 2 years of operation, the site met standards for risk-based closure.	Not Specified	Pilot/Field Demonstration
FRAC0037	Petroleum Storage Terminal Site	Not Specified	Not Specified	Scale Unknown
FRAC0056	Railyard in Birmingham, AL	Recovery of free-phase hydrocarbon from low permeability soils can be enhanced and accelerated by sand-filled hydraulic fractures by providing low-resistance flow paths within the target soils. The greatest contrast between recovery rates of fracture-enhanced systems and conventional fluid recovery systems apparently can be realized if water and LNAPL are recovered from separate fractures, however the expense of treating the contaminated water recovered using the two-fracture system may out-weigh the efficiency of controlling water coning.	Not Specified	Full-Scale/Commercial
FRAC0066	Raritan, NJ	Pneumatic fracturing waas used to inject iron filings into fractured bedrock to build a permeable reactive wall. A total of 1700 lbs of iron was injected.	$60,000.	Pilot/Field Demonstration
FRAC0054	Retail Gasoline Facility, Lakewood, CO	A permeable reactive barrier system was installed in 12 days with hydraulic fracturing methods. Isolite innoculated with aerobic microbes was injected. After 14 months, BTEX concentrations have been reduced in groundwater from 11 ppm to less than 3 ppm. In some cases the concentrations in groundwater were reduced up to 94 percent.	The project was designed and installed for $160,000.	Full-Scale/Commercial
FRAC0036	Rural Test Location, Frelinghuysen, NJ	The natural (pre-fracture) extraction airflow was 0.12 cfm; the post-fracture extraction airflow was 10+ scfm with limited source vacuum. Fractures remained open seven years after application.	Not Specified	Pilot/Field Demonstration
FRAC0006	Service Station in Louisiana	Initial air flow rates from a dual vacuum extraction system were 10-15 standard cubic feet per minute (scfm). Injection VacTM operations yielded 16-23 scfm, a 50 to 100 percent increase. VOC extraction rates more than doubled following pneumatic fracturing. The pilot operations removed over 650 kg (1400 lb) of VOCs over 6 days. Full scale operation remediated the site in just over a year.	Capital and operating costs of Injection VacTM are slightly higher than vacuum extraction without enhancement. The added costs of a suitably sized air compressor and, possibly, a high vacuum pump with additional energy and maintenance costs for soil vapor recovery must be factored into the overall cost. The major benefits are shorter remediation time and more effective subsurface remediation than standard, unenhanced extraction with low flow.	Full-Scale/Commercial
FRAC0060	Service Station, San Francisco, CA	80,000 pounds of super unleaded gasoline have been recovered by the system. The site was recommended for closure in less than ten months. The hot air injection increased extraction rates by up to a factor of three over those without hot air injection.	Not Specified	Full-Scale/Commercial

Table 6. Hydraulic, Pneumatic, and Blast-Enhaced Fracturing - Fracturing Related Performance

Total Number of Case Studies = 86

GWRTAC ID	Project Name	Application/Results	Economic Information	Scale of Project
FRAC0102	Sidney Landfill, NY	Not Specified	Not Specified	Full-Scale/Commercial
FRAC0009	Site in Bristol, TN	The specific discharge of the 3 wells increased by 2.8 to 6.2 times. Hydraulic conductivity increased by factors of 20 or more. After fracturing, vapor discharges were 285 to 700 L/min and suction could be detected 10 meters (32.8 feet) from the recovery well, where both had been negligible prior to fracturing. During a two-day test of vapor extraction, DNAPL was recovered at a rate of approximately 82 kg/day (180 lbs per day). Concentrations diminished during this test, probably representing an upper limit of the recovery rate.	Reportedly, the cost to create the fractures used during this project was $1,500 per well.	Pilot/Field Demonstration
FRAC0095	Stearns & Foster Site, NJ	Ratio of Pre- to Post-Blast Well Yields was 5 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0034	Steel Manufacturing Facility, Western New York	Pneumatic fracturing increased air permeability and fluids recovery from the synthetic waste tar pit.	Not Specified	Pilot/Field Demonstration
FRAC0012	Storage Tank Site in Beaumont, TX	Fractured wells produced LNAPL at about an order of magnitude or greater than the conventional well. Head distribution is consistent with the relatively large NAPL recovery by wells intersecting sand-filled fractures. Bowl-shaped zones of relatively large drawdown occur in the vicinity of the fractures.	Not Specified	Pilot/Field Demonstration
FRAC0016	Toronto, Ontario, Canada	Radius of influence and airflow mobility were improved.	$50,000.	Full-Scale/Commercial
FRAC0072	U.S. DoD Fort Hood, TX	Steam injection and electro-heating combined with hydraulic fracturing enriched recovered vapor streams with heavier weight hydrocarbons as temperature increased.	Not Specified	Pilot/Field Demonstration
FRAC0024	U.S. DOE Hanford, WA Facility	The fracturing process allowed vitrification of a specific target zone which lowered energy requirements.	Not Specified	Pilot/Field Demonstration
FRAC0020	U.S. DOE Portsmouth Gaseous Diffusion Plant, X231-A Land Trmt Site, Piketon, OH	Controlled degradation tests showed iron in fractures (< 1 cm thick) degraded TCE at 36% efficiency after 24-48 hrs of contact, but effects in adjacent silty clay were negligible. Permanganate degraded TCE at 70 to >99% efficiency in diffusive reactive zone. Neither method showed marked effects on chemistry or groundwater contamination levels beneath test cells.	Not Specified	Full-Scale/Commercial
FRAC0023	U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, Ohio	The hydraulic conductivity of the upper silt formation doubled, and the hydraulic conductivity of the lower formation increased by 60%. Substantially increase the "dewatering" of the site, which can increase the unsaturated zone depth.	Not Specified	Pilot/Field Demonstration
FRAC0091	U.S. DOE, UMTRA, Tuba City, AZ	Ratio of Pre- to Post-Blast Well Yields was 2 (Unitless)	Not Specified	Pilot/Field Demonstration
FRAC0010	Xerox Corporation Site, Oak Brook, IL	Average vapor discharge rates from the fractured wells (which fluctuated) were 15 to 20 times greater than unfractured well. Mass recoveries from fractured wells were about one order of magnitude greater thatn the unfractured well, and decreased through time in all wells. Suction head decreased abruptly with distance from the unfractured well, and decreased gradually with distance from the fractured wells.	Not Specified	Pilot/Field Demonstration
FRAC0096	Xerox Corporation, Micheldean, England	Ratio of Pre- to Post-Blast Well Yields was 66 (Unitless)	Not Specified	Full-Scale/Commercial
FRAC0015	Xerox Corporation, Webster, NY	Ratio of Pre- to Post-Blast Well Yields ranged from 20 to 500 (Unitless). (Individual ratio values for the eight trench locations were 150, 400, 500, 30, 120, 40, 150, and 20. For a separate trench installed at a landfill, the ratio was 100). Since trench installation, over 120 million gallons of groundwater have been withdrawn, or about 10 times the known volume of contaminated groundwater. Dissolved phase contaminant concentration was reduced >90% and the areal extent of contamination was reduced >50%.	Not Specified	Full-Scale/Commercial

Figure 1. General Schematic of Hydraulic and Pneumatic Fracturing.

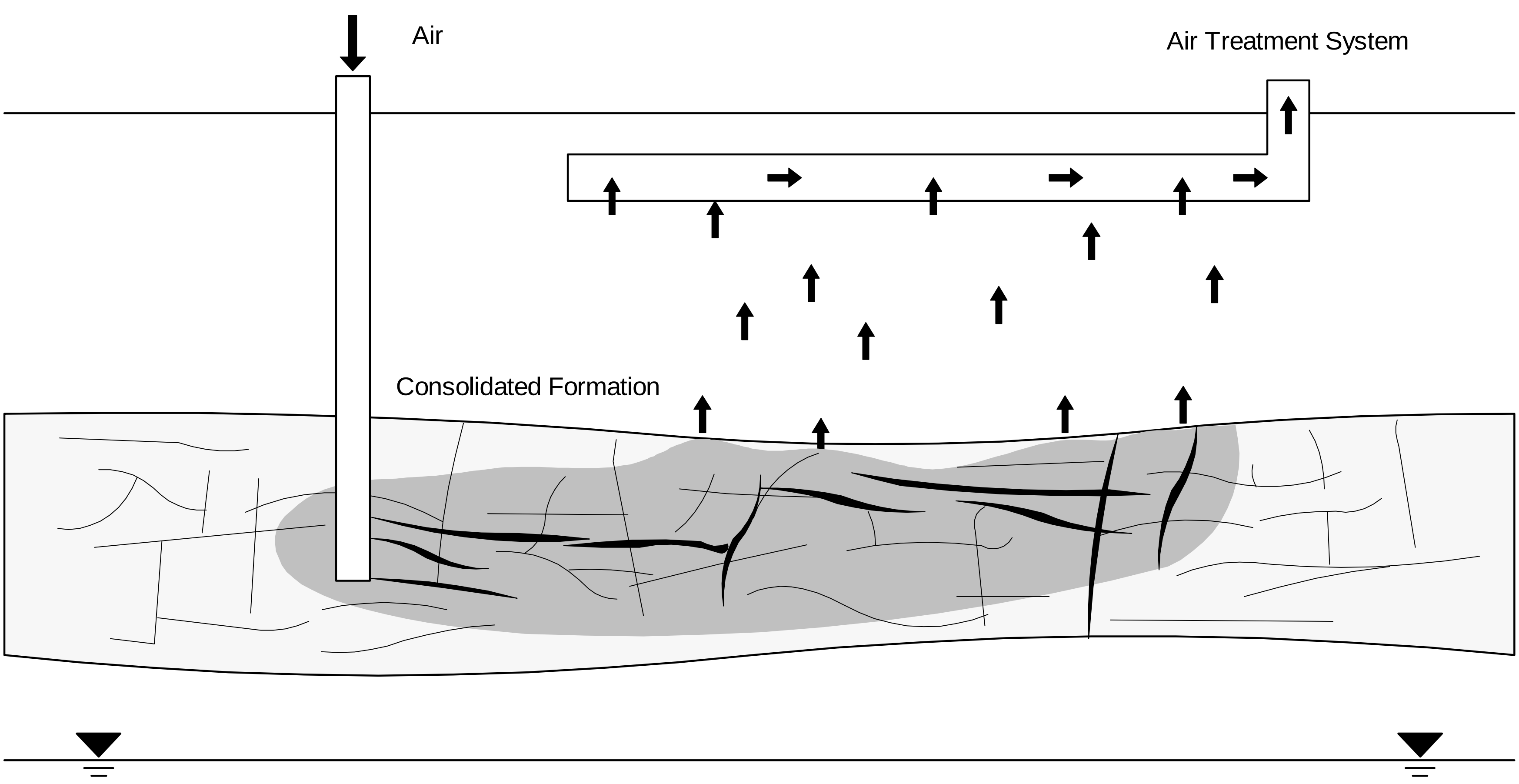


Figure 2. General Schematic of Blast-Enhanced Fracturing.

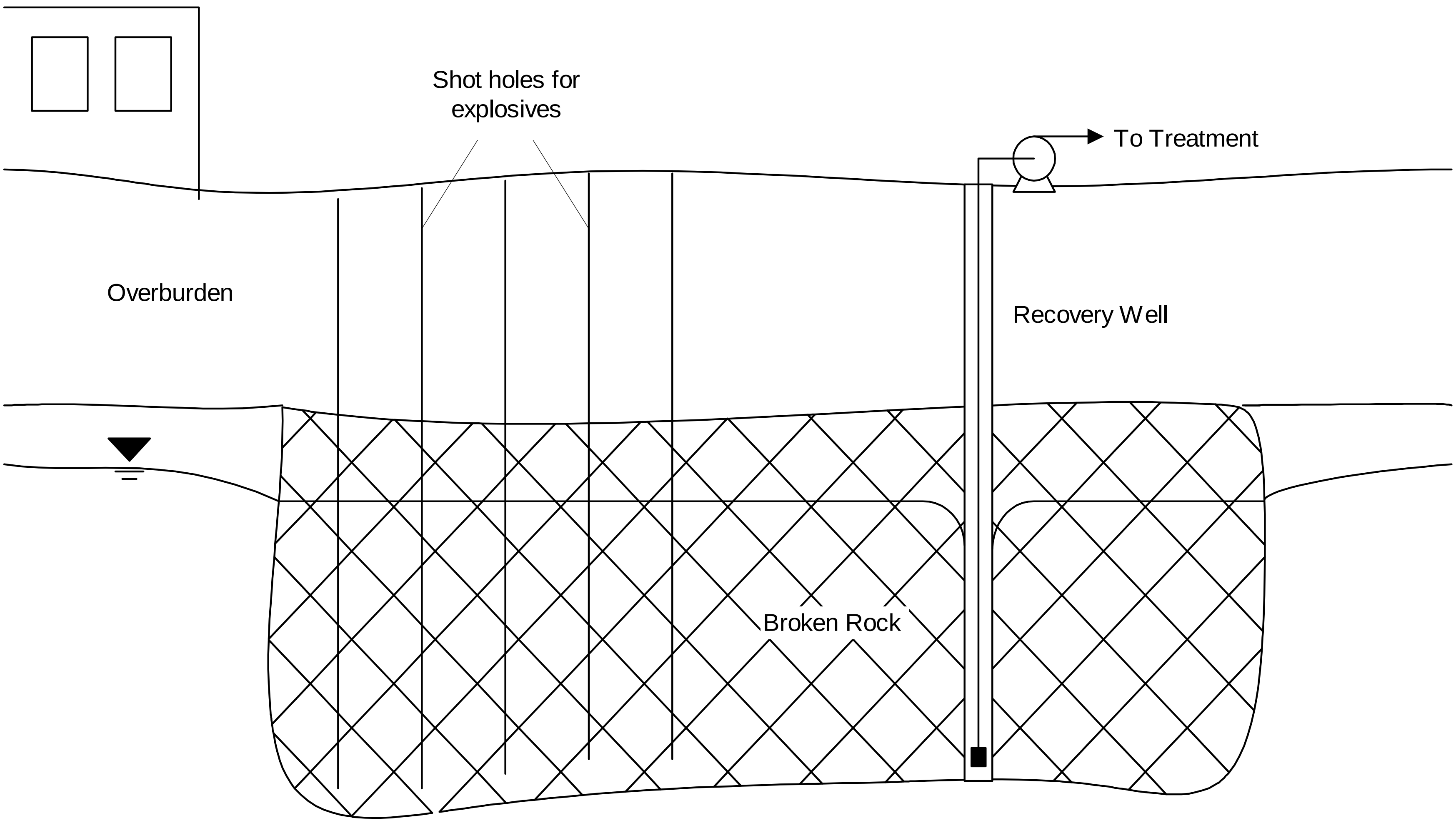
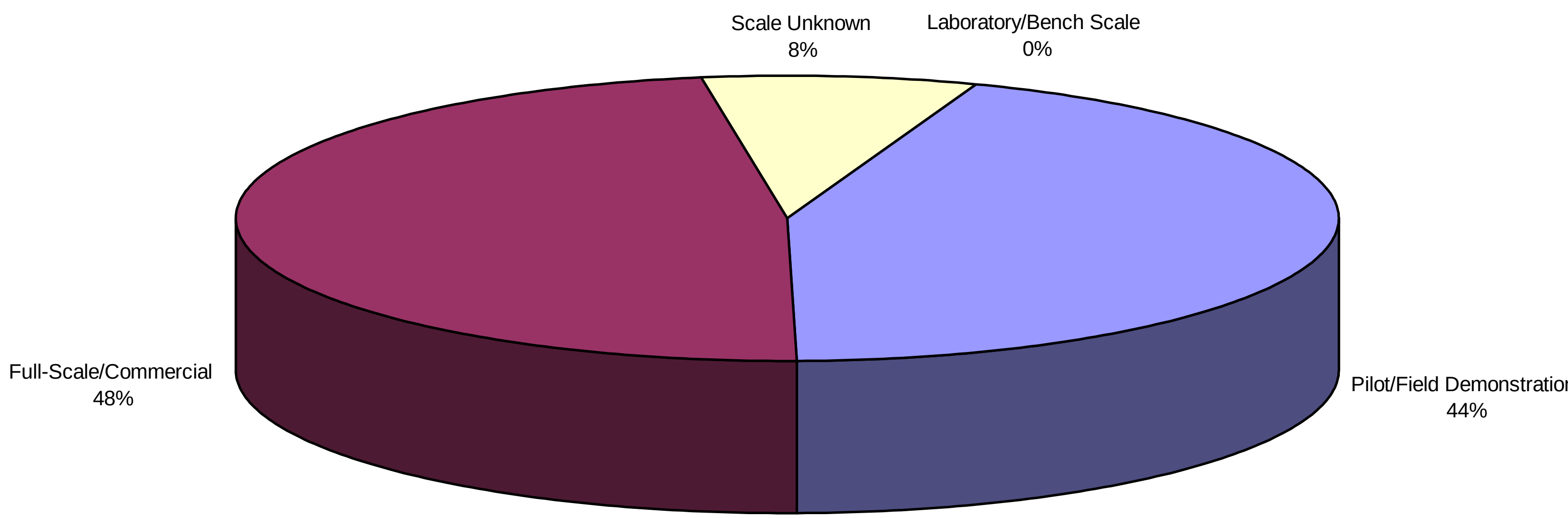
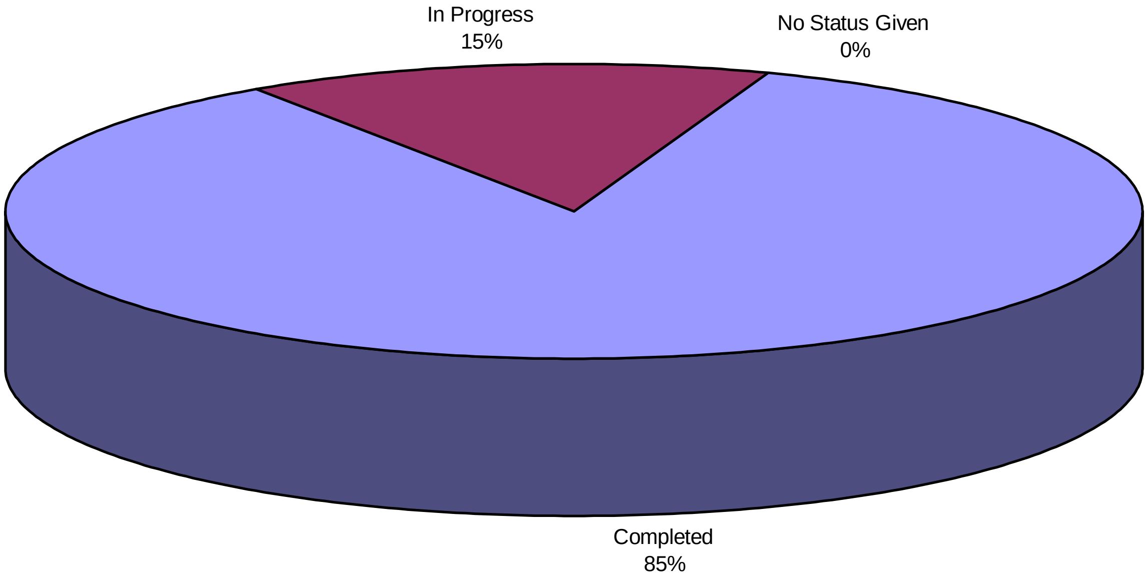


Figure 3. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Project Scale
(Only Includes "Most Advanced" Scale for Each Project)



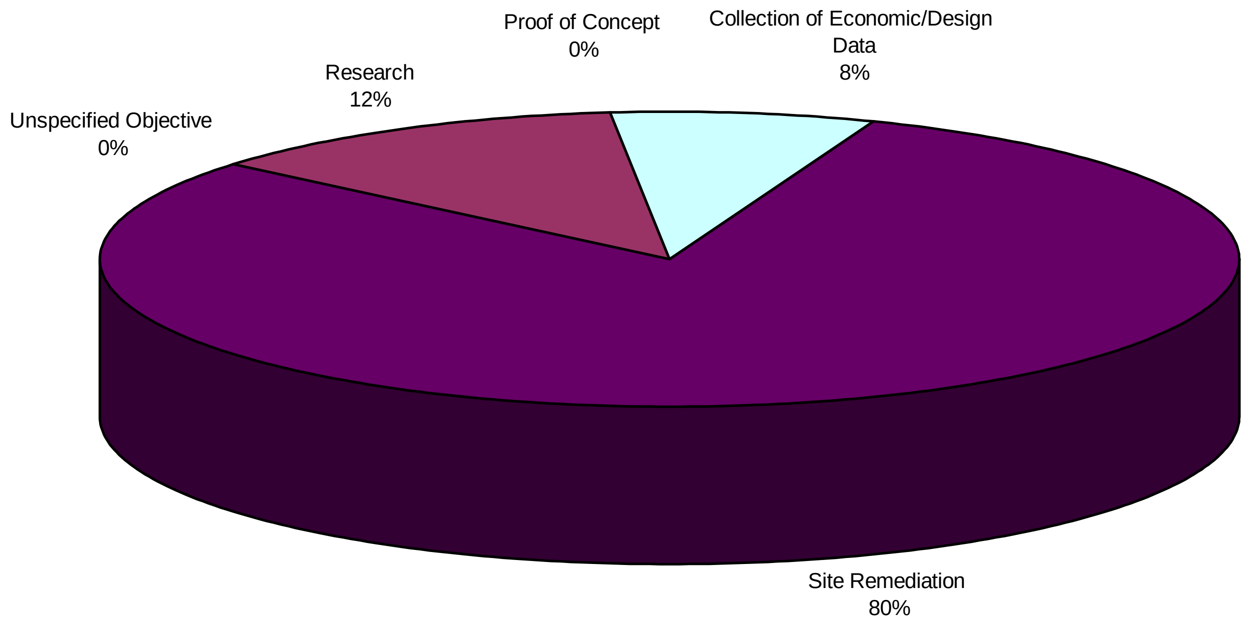
Total Number of Case Studies = 86

Figure 4. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Project Status



Total Number of Case Studies = 86

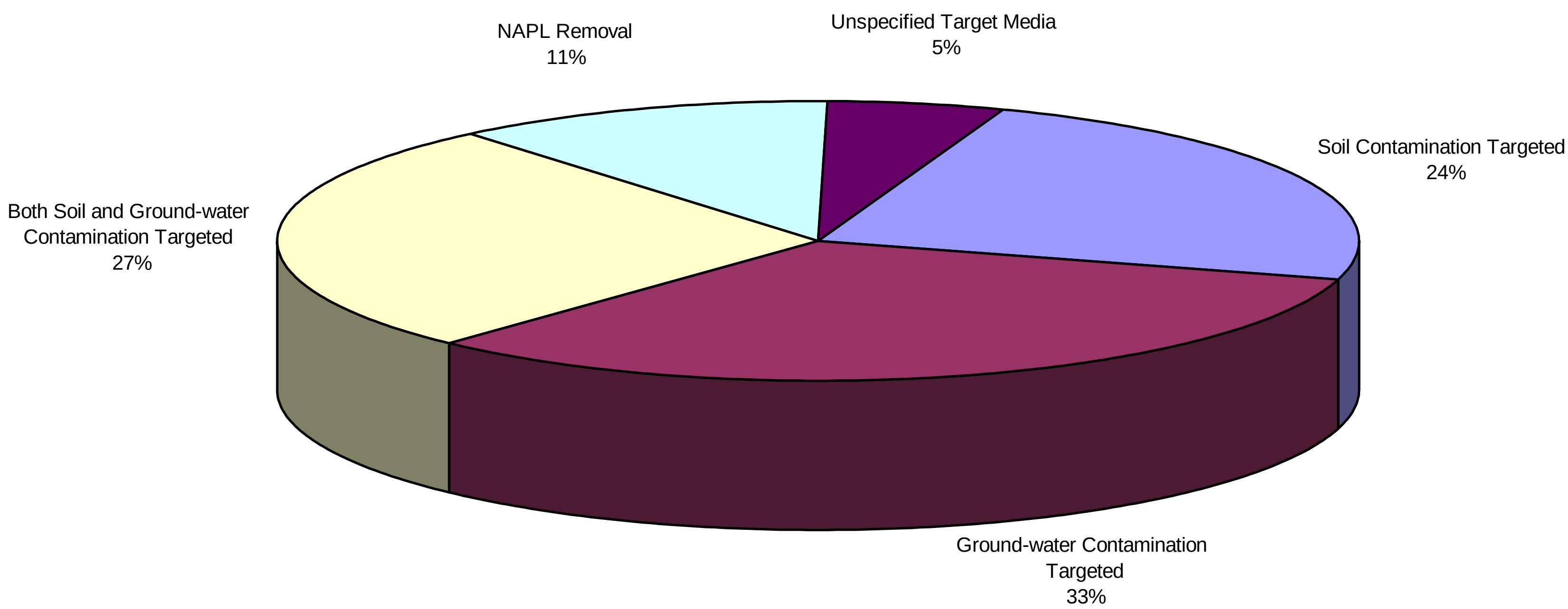
Figure 5. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Project Objectives
(May Include More than One Objective per Case Study)



Total Number of Case Studies = 86

Number of Responses on which Percentage Labels is Based = 91

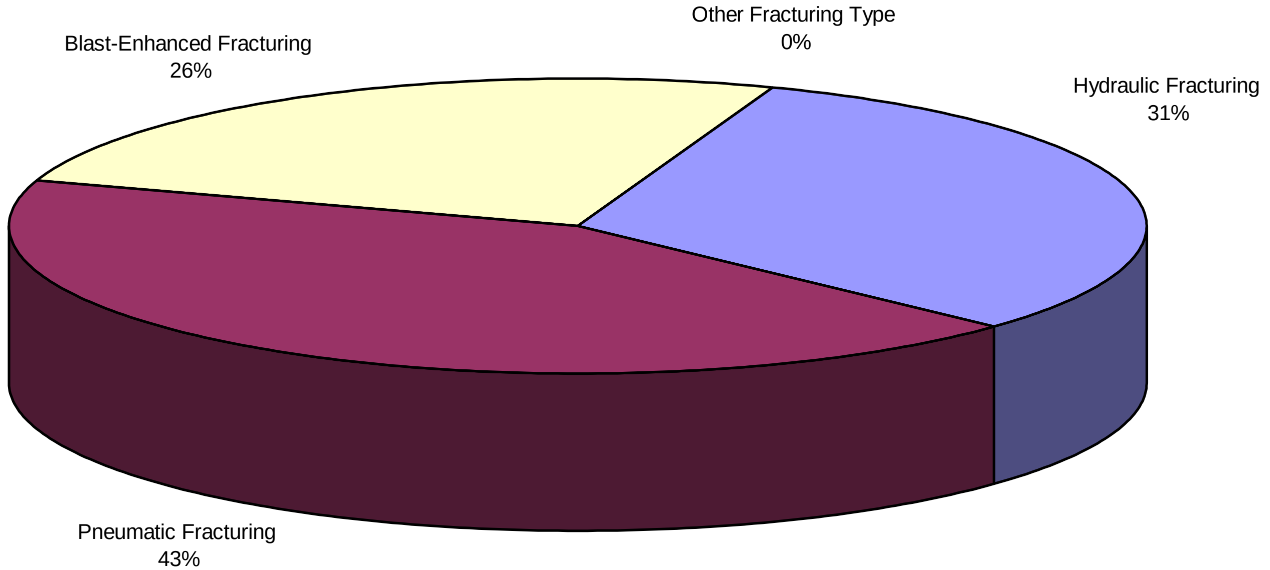
Figure 6. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Environmental Media Targeted
(May Include More than One Environmental Media Targeted per Case Study)



Total Number of Case Studies = 86

Number of Responses on which Percentage Labels is Based = 96

Figure 7. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Type of Fracturing



Total Number of Case Studies = 86

Figure 8. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing
Distribution of Case Studies by EPA Region
(EPA Region is given for Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only)

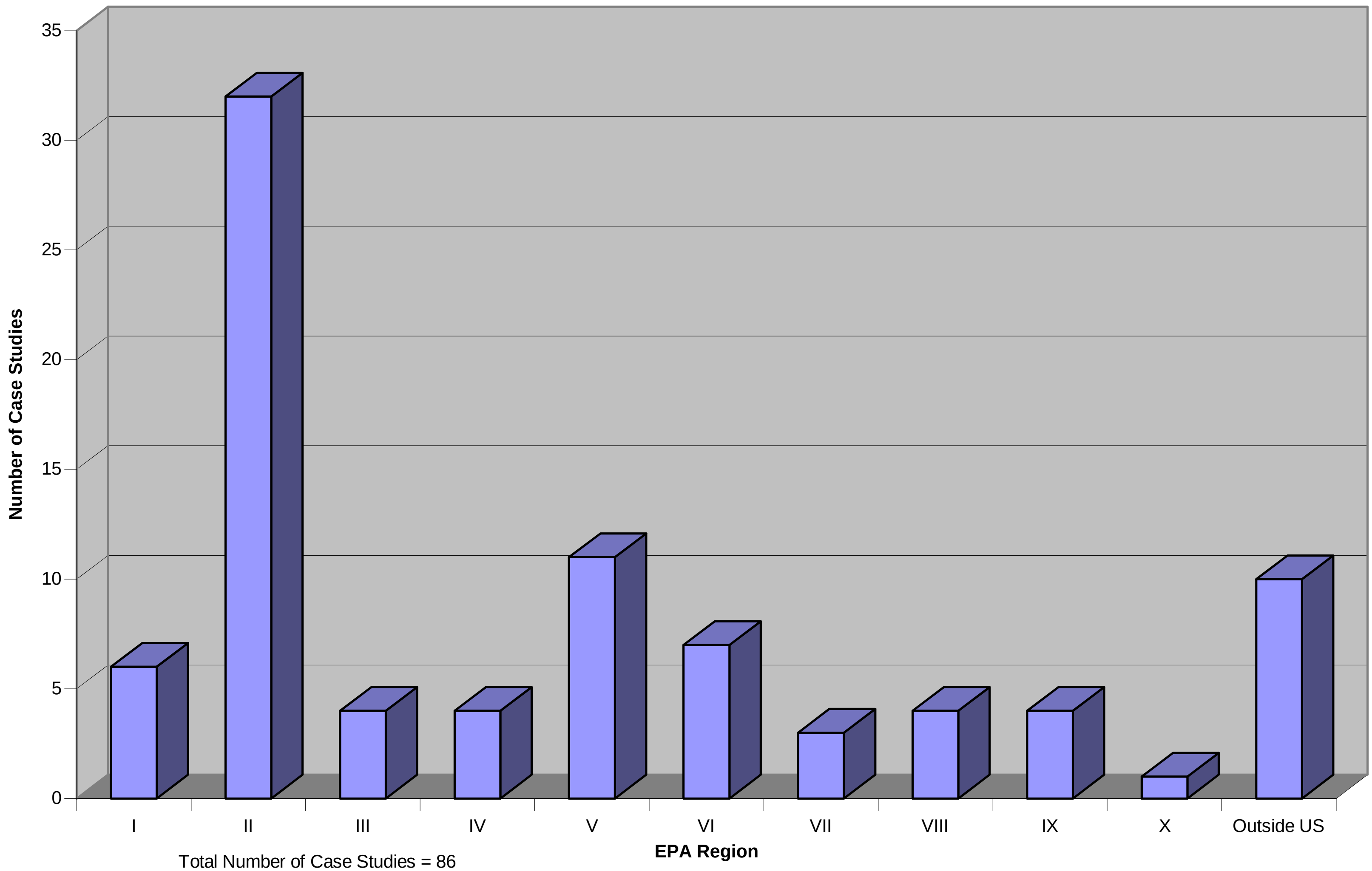


Figure 9. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing Distribution of Case Studies By EPA Region and Type of Fracturing
(EPA Region is given for Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only)

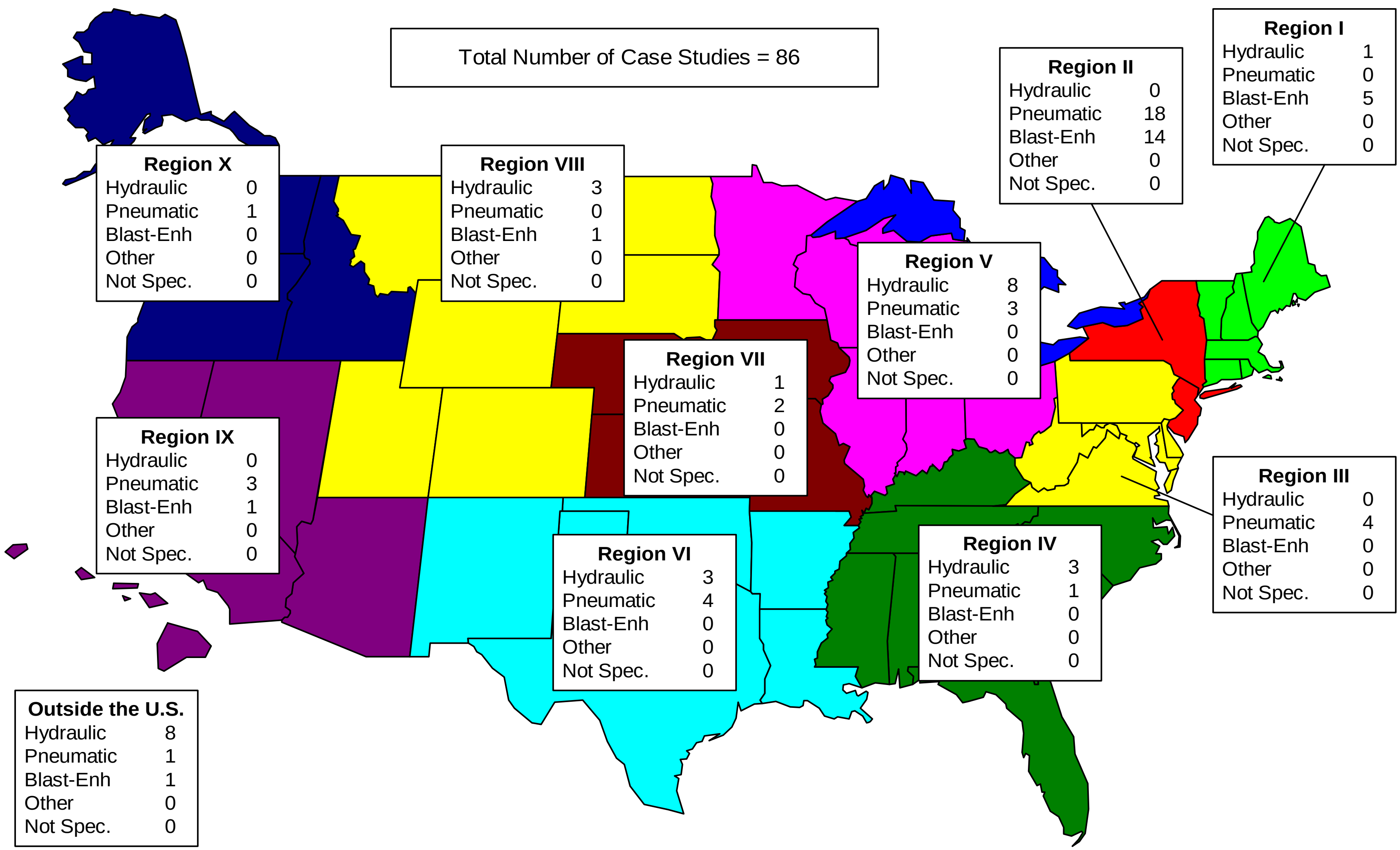
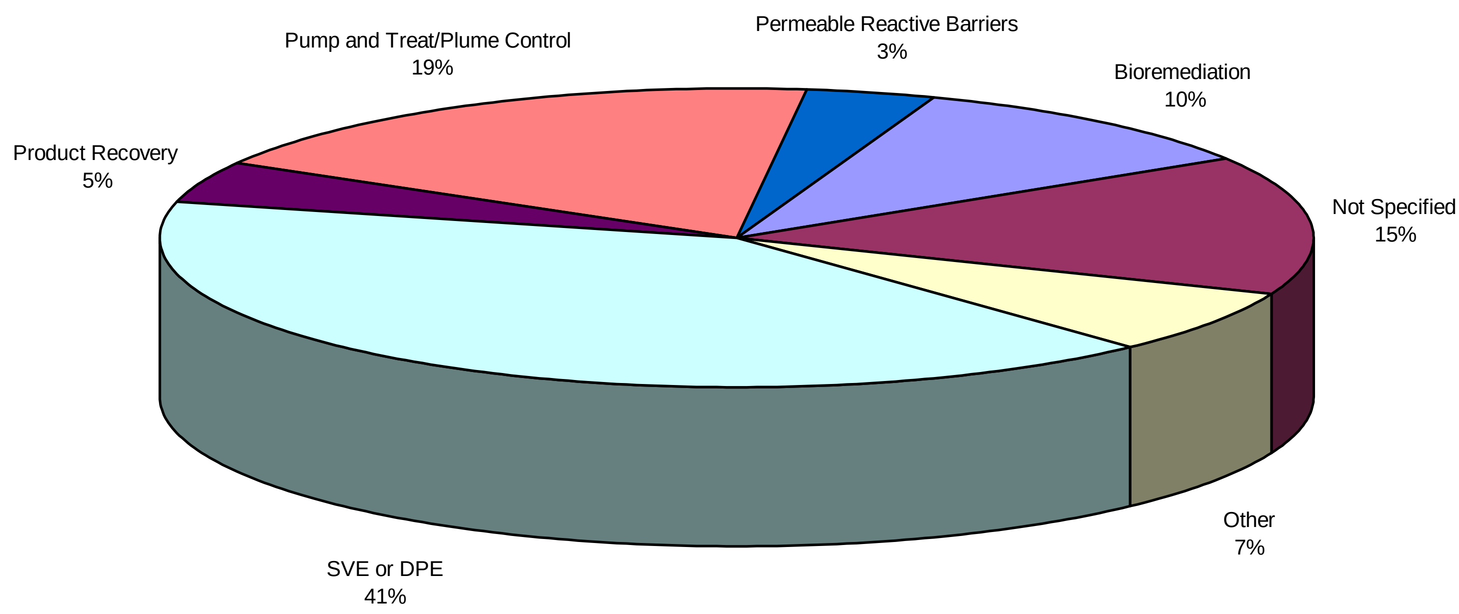
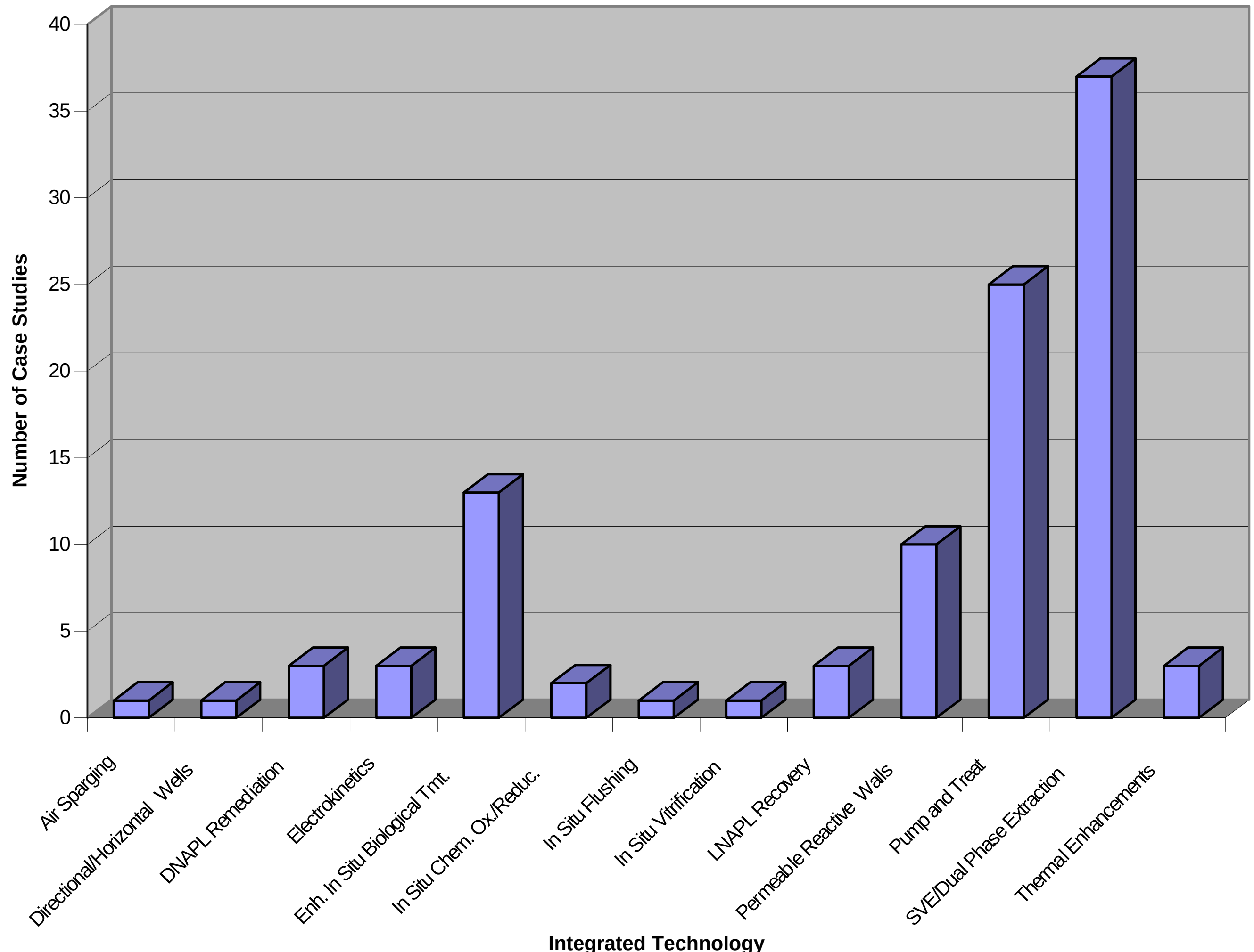


Figure 10. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Primary Integrated Technology Categories



Total Number of Case Studies = 86

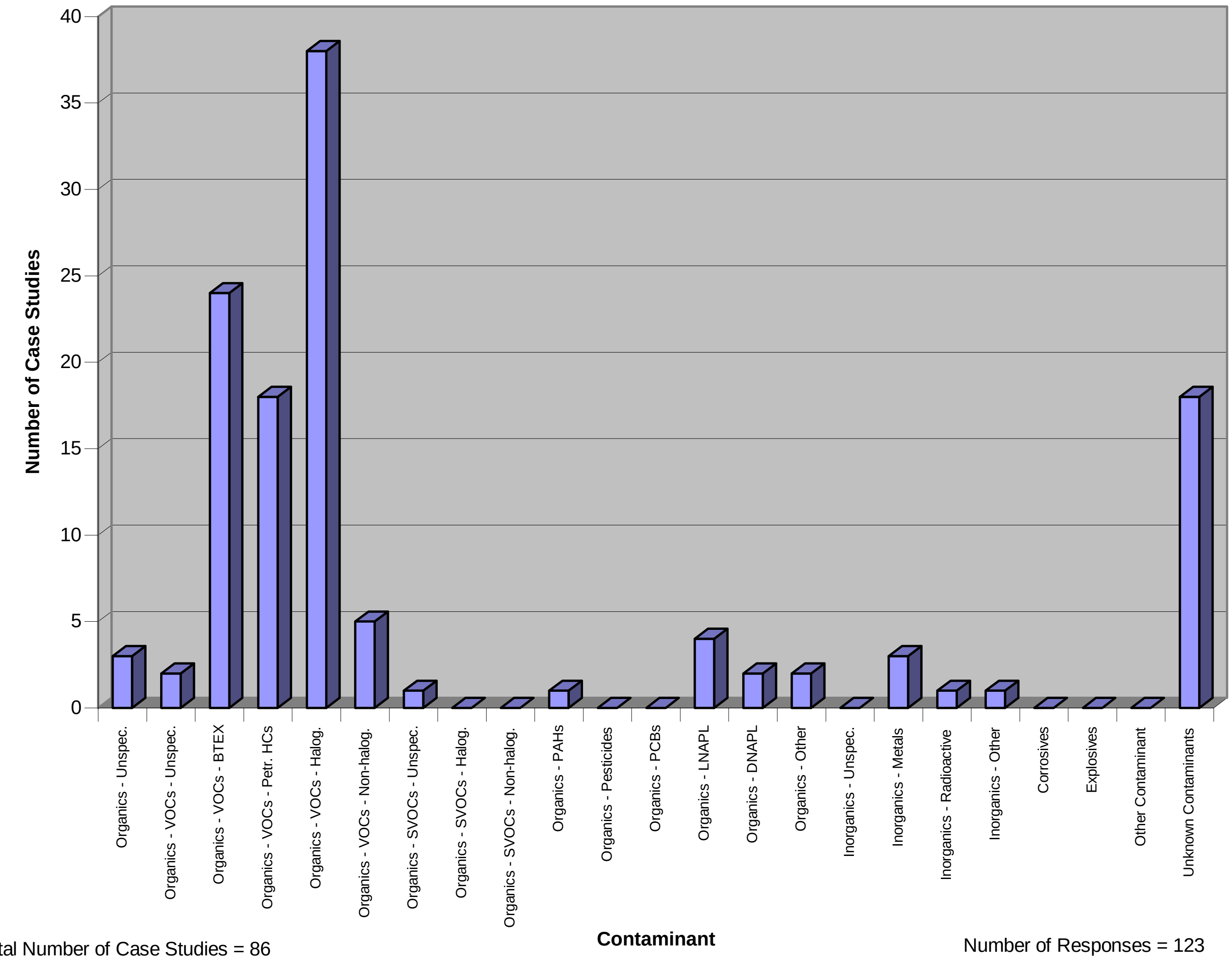
Figure 11. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Integrated Technology
(May Include More than One Integrated Technology per Case Study)



Total Number of Case Studies = 86

Total Number of Respones = 103

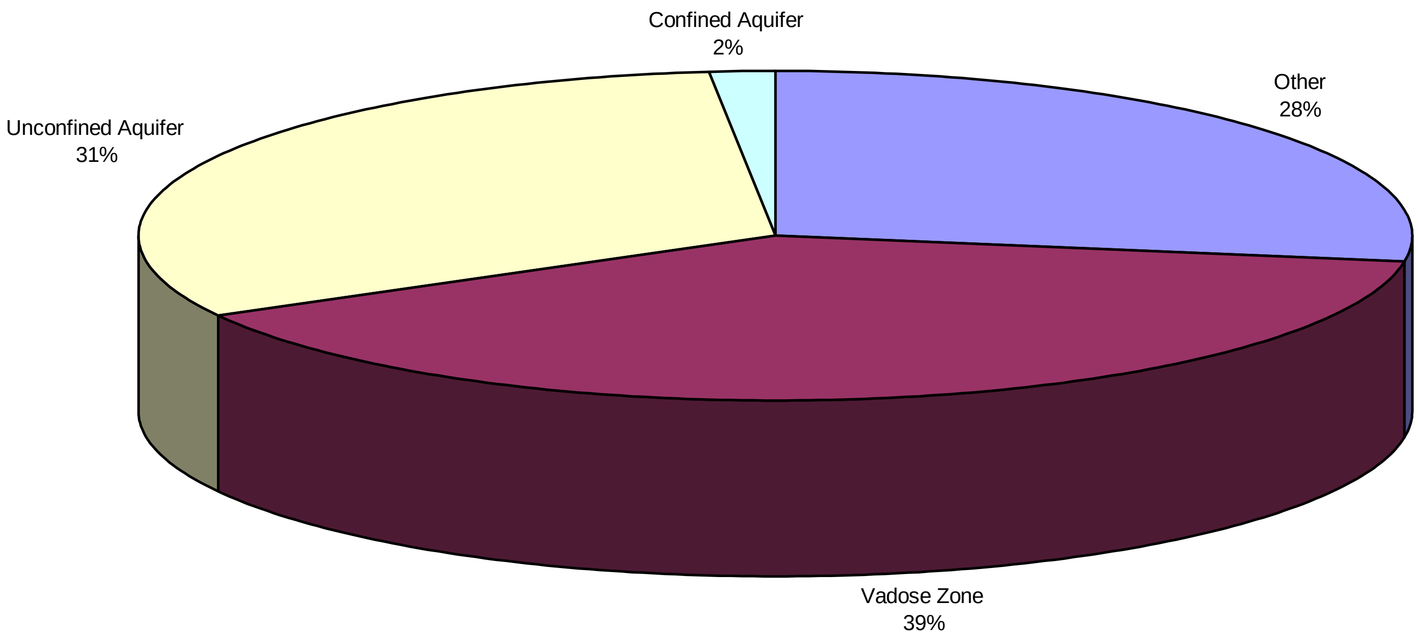
Figure 12. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Contaminant Class
(May Include More than One Contaminant Class per Case Study)



Total Number of Case Studies = 86

Number of Responses = 123

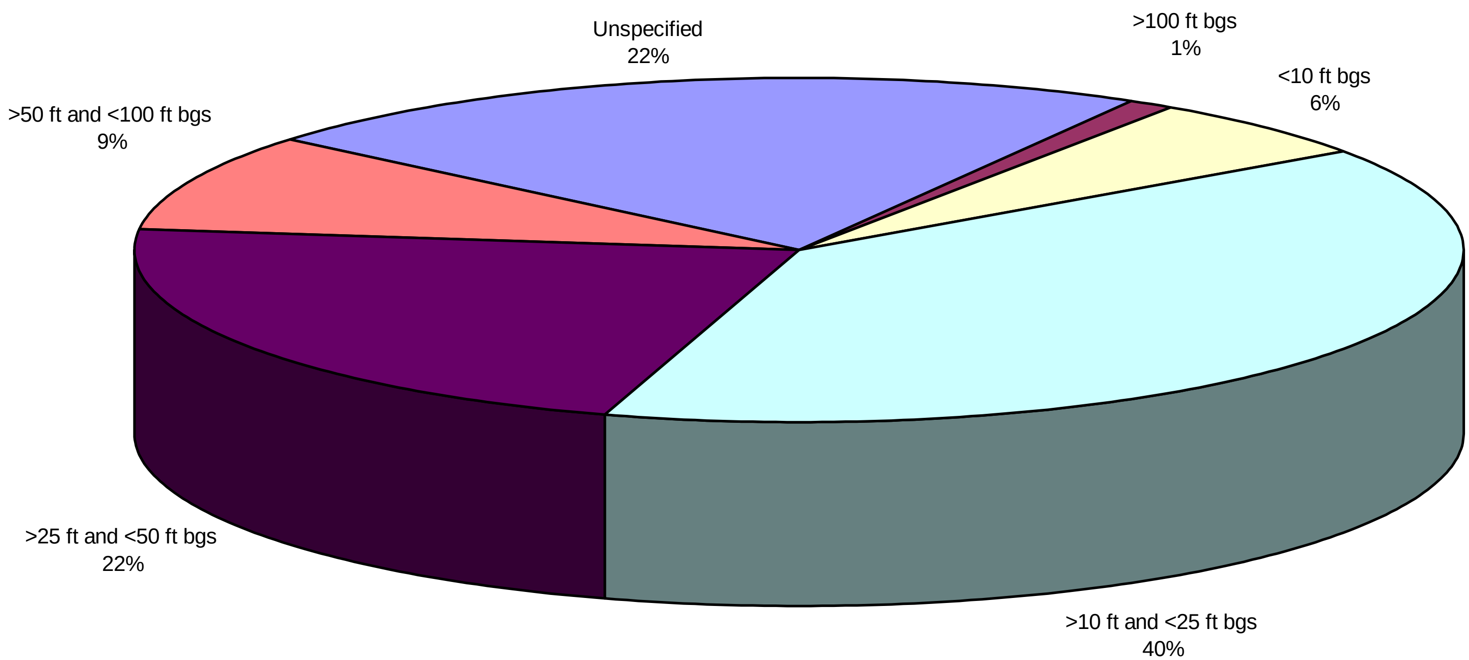
Figure 13. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Hydrogeologic Setting Zones Targeted for Fracturing
(Pilot/Field Demonstrations and Full-Scale/Commercial Projects;
Figure Excludes Laboratory/Bench-Scale Projects)
(May Include More than One Hydrogeologic Setting per Case Study)



Total Number of Case Studies = 86

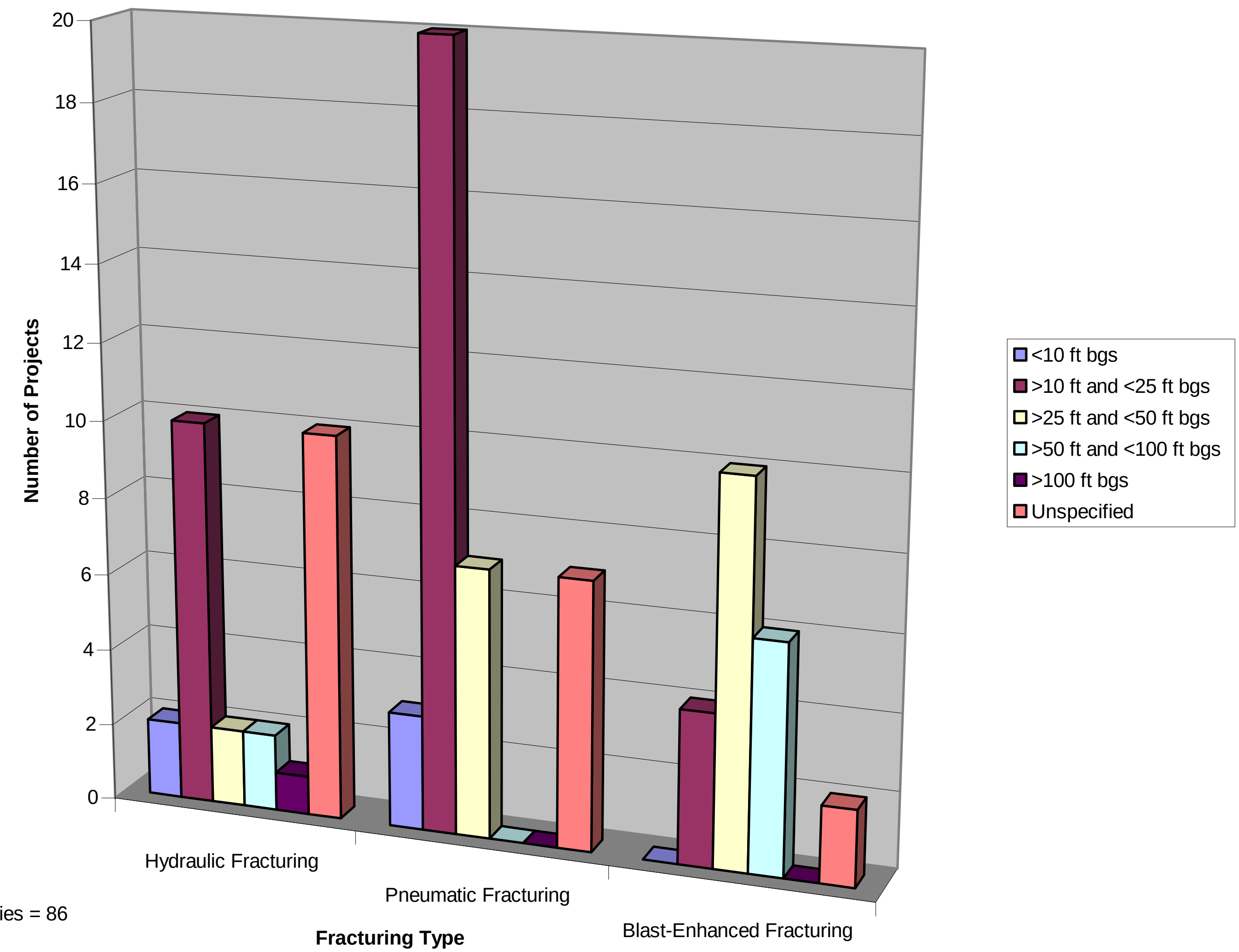
Number of Responses on which Percentage Labels is Based = 127

Figure 14. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Maximum Depth of Fracturing
(Pilot/Field Demonstrations and Full-Scale/Commercial Projects Only;
This Figure Excludes Laboratory/Bench Scale Projects)



Total Number of Case Studies = 86

Figure 15. Hydraulic, Pneumatic, and Blast-Enhanced Fracturing - Maximum Depth of Fracturing by Fracturing Type
(Pilot/Field and Full-Scale/Commercial Projects Only)



Total Number of Case Studies = 86

APPENDIX

GWRTAC INFORMATION SOURCES, PROJECT SUMMARIES, AND ADDITIONAL REFERENCES

Hydraulic, Pneumatic, and Blast-Enhanced Fracturing Project Summaries

GWRTAC ID: FRAC0080

Project Name: A.C. Roch. Corp., Rochester, NY

City: Rochester ***State/Province:*** NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Project Summary Information:

A migration control system was installed down-gradient of the facility to minimize the potential of off-site migration of a volatile organic compound plume. The contamination was a potentially a result of degreasing unit leakage and other unidentified site operations at the facility. The facility has been used for manufacturing from 1937 to present.

Bedrock at this location is Rochester Shale and Irondequoit Shale overlain by 22 feet of glacial till and lacustrine sediment overburden. Several utilities and past site filling related to in-fill of a former portion of the Erie Canal that crossed the northerly boundary of the site have added subsurface complexities. A blast-fracture trench of 1220 feet long and 26 feet depth below top of bedrock was installed on this site in 1992 by Haley & Aldrich, Inc. This corresponds to a sidewall area of 31,720 ft2. The alignment of the trench crosses a parking lot and roadway of the facility, as well as passing under a gas main and paralleling a municipal sewer tunnel that are present at the facility. Pumping from the trench is accomplished with one well that conveys water to peroxidation and air stripper treatment. Pre-blast well yields were 1.0 gpm, with post-blast well yields increasing to 100 gpm, for a ratio of pre/post-blast yields of 100.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0027

Project Name: Abandoned Industrial Site, Flemington, NJ

City: Flemington **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620.

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111.

Project Summary:

The following text was excerpted from company information attached, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com, and McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information:

Pneumatic fracturing wells were installed in a fractured shale formation that despite its fractured nature, had a very low transmissivity, at a private, abandoned industrial site with vadose and saturated zone siltstone contaminated by VOCs including TCE, PCE and vinyl chloride in Flemington, New Jersey. The pneumatic fracturing technology was applied over several two-foot intervals beneath the ground water table as a pilot test to enhance dual vapor extraction (DVE), in spring/summer 1995, and at a pilot-scale in 1995 to enhance n situ bioremediation in a project supported by the U.S. Environmental Protection Agency. Aquifer pumping tests and slug tests were performed prior to and upon completion of the pneumatic fracturing application performed to enhance DVE.

Aquifer transmissivities as measured during minimum 24 hour duration tests increased between 1.17 and 1.80 times. The average increase from all the monitor wells was 1.46 times. The effective area of influence also increased. Rising and falling head slug tests, conducted before and after Pneumatic Fracturing, showed that the hydraulic conductivity increased 3.54 times. The post fracture flow rate from the pumping well was I gallon per minute (gpm,). When a vacuum was applied to the pumping well, the flow rate increased to 5 gpm.

At this same site, pneumatic fracturing was used as an injection tool for the delivery of TCE degrading microorganisms and nutrientsto the subsurface to augment the bioremediation of VOCs including TCE, PCE and vinyl chloride. Fractures were injected at depths between 14.5 and 16.7 feet below the ground surface, and the estimated radius of influence of the fractures was 40 feet. The project field work was completed in April 1996 and documented as ‘Remediation of a Low Permeability TCE Contaminated Bedrock, Part One, Pneumatic Fracturing Technology For Permeability Enhancement’ by E. Keffer, J. Schuring, M. Ferries, and S. Abrams and submitted to the American Society of Civil Engineers in December of 1996.

Pneumatic fracturing was successful for the delivery of the microorganism to the subsurface. The fractures created from the initial field work enhanced the distribution of the microorganisms around the fracture well. Contaminant concentrations were reduced. Full-scale remediation is scheduled for 1997.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

Keffer, E., J. Schuring, M. Ferries, and S. Abrams, 1996, "Remediation of a Low Permeability TCE Contaminated Bedrock, Part One, Pneumatic Fracturing Technology For Permeability Enhancement", submitted to the American Society of Civil Engineers in December of 1996.

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information

GWRTAC ID: FRAC0061

Project Name: Aerospace Manufacturing Facility, Los Angeles, CA

City: Los Angeles ***State/Province:*** CA

Report(s)/Publication(s) (GWRTAC Source):

TerraVac Corporation, Pnumatic Soil Fracturing Case Studies, available at www.terravac.com.

Project Summary:

This information was excerpted from TerraVac Corporation, Pnumatic Soil Fracturing Case Studies, available at www.terravac.com:

Rapid remediation of methyl ethyl ketone in soil and groundwater beneath a manufacturing facility was necessary to expedite a property transfer. TerraVac Corporation utilized an integrated, pneumatic soil fracturing/vacuum extraction/bioremediation system. The system included 35 well casings and 210 pneumatic soil fracturing points, 4 separate piping manifold systems, and a 1,000 scfm thermal oxidizer.

Report(s)/Publication(s) (Additional Info Source):

TerraVac Corporation, Pnumatic Soil Fracturing Case Studies, available at www.terravac.com.

GWRTAC ID: FRAC0044

Project Name: AT&T Facility, Richmond, VA

City: Richmond **State/Province:** VA

Report(s)/Publication(s) (GWRTAC Source):

AT&T New Release, September 26, 1991, available at http://www.att.com/press/0991/7910926.cha.html.

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, Company Information, phone (908) 647-8111

Project Summary:

The following text was excerpted from AT&T New Release, September 26, 1991, available at http://www.att.com/press/0991/7910926.cha.html:

Pneumatic fracturing was tested in 1990 at an AT&T site in Richmond, Virginia where printed circuit boards are manufactured, to improve the soil vapor extraction system. At this site, vadose zone silty clay to clayey silt was impacted with chlorinated solvents. Fractures were injected at a 6.8 to 10.7 foot depth beneath the ground surface, and the estimated radius of influence of the fractures was 9 feet. Mass removal of chlorinated solvents increased >200 times following fracturing. Airflows increased more than a thousand-fold when compared to the pre-fracture airflow rates.

Report(s)/Publication(s) (Additional Info Source):

AT&T New Release, September 26, 1991, available at http://www.att.com/press/0991/7910926.cha.html.

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information.

Schuring, J.R., V. Jurka, and P.C. Chan, Winter 1991. "Pneumatic Fracturing to Remove VOCs", Remediation, pp. 51-68, 1991.

GWRTAC ID: FRAC0032

Project Name: Automobile Maintenance Facility, Lancaster, PA

City: Lancaster ***State/Province:*** PA

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

Pneumatic fracturing was applied in six fracture wells in a fine clay formation at an automobile maintenance facility contaminated with VOCs, primarily TCE, in Lancaster, Pennsylvania. Four fracture wells were installed inside of an active building and two fracture wells were installed just outside of the building. Ground surface heave was monitored during fracturing to observe any effects on the building structure. No movement of the building structure was detected during pneumatic injections. Pressure influence was detected at surrounding monitoring points, indicating fracture propagation in the subsurface. Pneumatic fracturing was part of full-scale remedial action at the site to enhance bio-stimulation. The pneumatic fracturing operations were completed in April 1996, and full-scale system was installed in late 1996.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

GWRTAC ID: FRAC0031

Project Name: Automotive Manufacturing Facility, Columbia City, IN

City: Columbia City **State/Province:** IN

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

Pneumatic fracturing was used in a clay formation to increase air permeability and vacuum radius of influence to enhance soil vapor extraction at an automotive manufacturing facility contaminated with VOCs, primarily TCE, DCE, and vinyl chloride, in Columbia City, Indiana.

Both a pilot test conducted in June 1996, and subsequent full-scale SVE system were installed under this project. The desired result of the PFE pilot test was to increase the surface air flow, mass removal rate of contaminants, vacuum radius of influence and demonstrate the overall ability of PF to enhance the SVE effort, given the geologic conditions at the site. At this site, eight SVE wells (part of a 200 cfm vapor extraction and treatment system) were installed, targeting the treatment depth of 4' to 13' bgs. There are two areas of PF/SVE treatment at the site; one is a 20' x 40' area outside the above ground storage area, and the second is a 50' x 90' area (inside building degreaser area).

The site geology consists of glacial till (sand, silt and clay). The depth zone of the residual phase (adsorbed) TCE is 0' to 10' bgs, and the depth zone of the PF intervals is 4' to 11.5' bgs. The concentration of TCE in groundwater downgradient of the source was as high as 17,000 ppb, with the concentration of TCE in soils from the source area as high as 25 ppm. The dates of the full-scale SVE operation are from April 1997 through the present (November 1998).

The effectiveness of PF was evaluated by comparing the results from pre and post fracture extraction tests in addition to data collected during the application of PF. Within the first year of operation, the full-scale PF/SVE system recovered more that 1,330 lbs. of TCE from the subsurface in the first nine months of operation at the site. This mass removal was more than 20% beyond estimated design mass calculation believed to exist within the subsurface. The site is currently under risk based closure proceedings.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

GWRTAC ID: FRAC0013

Project Name: Black & Decker Plant, NY

City: Upstate NY **State/Province:** NY

Report(s)/Publication(s) (GWRTAC Source):

Begor, K.F., M.A. Miller, and R.W. Sutch "Creation of an Artificially Produced Fracture Zone to Prevent Contaminated Ground-Water Migrataion", Groundwater, Vol. 27, No. 1, January-February 1989.

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 104

Project Summary:

The following was excerpted from U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 104, which cited Begor, K.F., Sutch, R.W., Dunn Geoscience Corporation, Albany, NY, Nothnagle, R.J., Nothnagle Enterprises, Scottsville, NY, "Capture of a Groundwater Contamination Plume in Fractured Bedrock by an Artificially Produced Fracture Zone Created through Controlled Blasting", in Proceedings: Fourteenth Conference on Explosives and Blasting Techniques, Anaheim, CA, Jan 31 - Feb 5, 1988, pp. 111-112, and Begor, K.F., M.A. Miller, and R.W. Sutch "Creation of an Artificially Produced Fracture Zone to Prevent Contaminated Ground-Water Migrataion", Groundwater, Vol. 27, No. 1, January-February 1989:

A manufacturing facility in Upstate New York operated a series of surface impoundments used to treat wastewater from plating operations and various other metal finishing processes. A comprehensive groundwater quality assessment program conducted at the facility identified contamination of the groundwater by VOCs within both the overburden and bedrock aquifers. Site investigations delineated the extent of a groundwater contamination plume migrating within a fractured bedrock aquifer (Medina sandstone) which underlies approximately 15 feet of glacial till. A 72-hour aquifer test involving one recovery well resulted in a low yield (3.5 gpm with 20 feet of drawdown). Data collected from adjacent observation wells indicated poor interconnection among the naturally occurring fractures. The response of some observation wells mirrored that of the recovery well, while others showed little or no response to pumping.

A corrective action program was implemented in 1987 upon completion of the groundwater assessment program. Using a carefully controlled single line pattern blasting technique, a 6-foot wide, 300-foot long fracture zone was created in the upper 25 feet of the bedrock aquifer perpendicular to the centerline of the plume, for a sidewall area of approximately 6,900 ft2. Following fracturing, a second 72-hour aquifer test was conducted at the same location and under conditions similar to the first test. The second test indicated that the single recovery well located in the newly created fracture zone should be fully capable of recovering contaminated groundwater and preventing further migration of the plume. The recovery well produced a substantially higher yield of 18.5 gpm with only 11.2 feet of drawdown, for a pre- to post-blast yield of 5.3. Furthermore, all of the nearby observation wells showed significant response to pumping. Success at this site is promising and the approach may prove useful at other sites involving contaminated bedrock aquifers.

Report(s)/Publication(s) (Additional Info Source):

Begor, K.F., Sutch, R.W., Dunn Geoscience Corporation, Albany, NY, Nothnagle, R.J., Nothnagle Enterprises, Scottsville, NY, "Capture of a Groundwater Contamination Plume in Fractured Bedrock by an Artificially Produced Fracture Zone Created through Controlled Blasting", in Proceedings: Fourteenth Conference on Explosives and Blasting Techniques, Anaheim, CA, Jan 31 - Feb 5, 1988, pp. 111-112

Begor, K.F., M.A. Miller, and R.W. Sutch "Creation of an Artificially Produced Fracture Zone to Prevent Contaminated Ground-Water Migrataion", Groundwater, Vol. 27, No. 1, January-February 1989.

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

U.S. Environmental Protection Agency (EPA), November 1996: Innovative Ground-Water Remediation Technologies: Publications and Conference Proceedings 1990-1996, U.S. EPA Technology Innovation Office (5102G) Washington, DC 20460, p. 104

GWRTAC ID: FRAC0033

Project Name: Chemical Incineration Plant, Coffeyville, KS

City: Coffeyville ***State/Province:*** KS

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

A Pneumatic fracturing extraction pilot test was performed in a single fracture well in a dense silty clay formation at a chemical incineration plant contaminated with VOCs, primarily TCE and tetrachloroethene, in Northern, Kansas. Pre- and Post-fracture extraction tests were performed to evaluate the effectiveness of the Pneumatic Fracturing technology. Pneumatic injections were applied from 7 to 20 below ground surface (bgs) in discrete 2.25' intervals. The pilot test was completed in October 1994.

As a result of Pneumatic Fracturing, air permeability was observed to increase over five times. The vacuum radius of influence increased significantly. At several monitor points vacuum radius of influence was not detected during the pre fracture extraction testing. During the post fracture testing, a vacuum influence of 14 inches of water was observed at a monitor point located three feet from the fracture well, while a vacuum influence of I0 inches of water was observed at a monitor point located I0 feet from the fracture well.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

GWTRAC ID: FRAC0002

Project Name: Closed UST, Military Facility, Oklahoma City, OK

City: Oklahoma City **State/Province:** OK

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620 or www.arstechnologies.com, Company Information;
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC, and
McLaren Hart, Inc., Warren, NJ Company Information:

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

The project was conducted under DOE & DOD grant in conjunction with the Hazardous Substance Management Research Center. Further application of the technology occurred at the site in 1995. Pneumatic fracturing provided direct access to the trapped oil, as was observed during static conditions. Prior to fracturing, oil in a recovery well eight feet from the fracture well would reach static conditions after approximately 300 hours with 1.5 feet of free product floating on the water table. Following application of pneumatic fracturing, equilibrium was attained in only 80 hours when the well contained 20.2 feet of free product. Pump system operations, including additional recovery wells on site, further showed the increased rate of product recovery. During the 17 months prior to pneumatic fracturing, the system averaged 155 gallons of free product recovered per month. Following application of pneumatic fracturing this rate increased to 435 gallons per month. The total amount of free product recovered in seven months following pneumatic fracturing application surpassed the total recovered over the life of the system in the previous 17 months. Pneumatic fracturing also was demonstrated to increase the ratio of oil to water recovered from the formation. During pre-fracture pumping, the product represented only an average of 12 percent of the total fluid recovered. Following pneumatic fracturing application oil was 74 percent of the total fluids recovered. This reduced water treatment costs tremendously.

Following this successful application, pneumatic fracturing was applied at three newly installed pneumatic fracturing wells. The objective for this project was to access the #2 fuel oil trapped in the sandstone/shale formation at other portions of the site where the free product had been detected but recovery operations had been ineffective. Two of these wells were located within 15 feet of an active parts cleaning and storage building. The project was completed in February of 1995.

During this second application, pneumatic fracturing was observed to increase the oil production in wells as far as 59 feet away from the closest injection point. The first order rate constant, which is a measurement of the rate at which oil enters the well, was found to increase 434% at one recovery well seven feet from an injection point, and 224% at another recovery well, '08 feet from the closest injection point. The production in oil per day from the first recovery well increased over five fold from 1.2 gallons per day to an average of 6.2, including a peak recovery rate of 8.4 gallons per day. Static product thickness increased from 1.5 to 20.2 ft following fracturing. Average monthly recovery rates increased from 155 gallons per month to 435 gallons per month following fracturing. During pre-fracture pumping, the produce represented an average of 12% of total fluid recovered. After fracturing, this increased to an average of 74% of the total fluid recovered.

During pneumatic fracturing applications, observations were made to determine whether the building was affected by the pneumatic fracturing process. Pneumatic fracturing was not observed to permanently affect the building structure, minor movement of structure below maximum criteria was observed, despite evidence of pneumatic connection at wells located II 5 feet away underneath the building.

At this same site, pneumatic fracturing was used to assist in the in-situ bioremediation process of treating BTEX and TPH compounds in a clayey silt and sand formation (FRAC0025). Pneumatic Fracture injections were made to determine the effect on the formation permeability and to determine if extraction of VOCs would improve significantly after fracturing.

Pneumatic fracturing increased air flows during vapor extraction tests 500% - 1700% higher than pre-fracture air flows. Permeability values increased from 0.017 darcy to 0.32 darcy after fracturing. A full-scale remediation system for this project was under construction in 1996.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Marketing Information

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID: FRAC0017

Project Name: Corbett Creek, Former Gas Plant & Compressor Station, Alberta, Canada

City: Near Whitecourt **State/Province:** ALBERTA

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from Company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2:

Soil and groundwater contamination was caused by a release of 460,000 litres (121,520 gallons) of liquid hydrocarbons (condensate) from a former flare pit over the course of 20 years of operation. Free phase liquid condensate is present up to a thickness of 4 m (13.1 feet) on the groundwater table both on site and beyond the property boundary. Potential receptors are groundwater supply wells, a recreational lake and gas pipeline located within 1.5 km (0.9 miles) of the site. The objective of the project was to halt the migration of condensate and recover the bulk of free-phase condensate to reduce the risk of impacting down-gradient receptors.

The contaminated soils consist of clayey silts to silty, fine grained sands. The depth of contamination and fracture initiation at the well locations ranges from 7 metres to 11 metres (23.0 to 36.1 feet) below ground surface. The groundwater table is located at 10 metres (32.8 feet) below ground surface. Fractures were initiated in both the vadose and saturated zones. A total of 8 fractured wells containing 6 fractures per well (48 fractures) were placed within the condensate plume in June, 1995. An additional 6 fractured wells containing 6 fractures per well (36 fractures) were placed within the leading edge of the plume in September, 1996 to contain the migration of the condensate plume. A surfactant was incorporated into the sand-laden fracture fluid to assist in the mobilization of liquid condensate to the wells by improving its relative permeability to water. The 14 fractured recovery wells were used for collecting liquid and vapour phase condensate using vacuum assisted, pneumatic pumps and also dual phase high vacuum extraction using liquid ring blowers.

Surface-mounted tiltmeters were used to individually map the size, geometry and thickness of fractures created in the subsurface during the fracturing process. Analysis of the tiltmeter data indicated that the average fracture thickness was 12.5 mm (0.5 inches), fracture radii ranged from 3 metres to 7 metres (9.8 to 23.0 feet), and fracture orientation varied from near horizontal to as great as 68 degrees from horizontal. There was an overall preference for fracture planes to align along a southeast to northwest axis. This preferred fracture growth is believed to be the result of strongly laminated, horizontal soil layering rather than by the local stress regime.

The performance of hydraulically fractured wells from June 1995 to June 1999 is summarized below:

PARAMETER	PRE-FRACTURING	POST-FRACTURING
Hydraulic conductivity	5 x 10-9 to 3 x 10-8 m/s 5 x 10-7 to 3 x 10-6 cm/s	7 x 10-7 to 4 x 10-6 m/s 7 x 10-5 to 4 x 10-4 cm/s
Condensate liquid recovery rate	48 litres/day (13 gal/day)	360 litres/day (95 gal/day)
Condensate vapour recovery rate	4 litres/day (1 gal/day)	285 litres/day (75 gal/day)
Condensate:Total Fluids ratio	0.18	0.77

Radius of Influence (liquids)	1.5 to 2.0 m (4.9 to 6.6 ft)	7 to 10 m (23.0 to 32.8 ft)
Radius of Influence (gas)	4 to 5 m (13.1 to 16.4 ft)	15 to 25 m (49.2 to 82.0 ft)

Effective plume capture in this area of the site has occurred. The total capital cost savings to the client over five years of remediation using fractured wells vs. conventional remedial technologies is at $1.46 million dollars Canadian. The value of recovered liquid condensate that was reprocessed and sold by the client was approximately $63,000 Cdn. per year in 1996 and 1997. Remediation is ongoing and is expected to be completed by the summer of the year 2000.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

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GWRTAC ID: FRAC0040

Project Name: Decommissioned Retail Service Station, Regina, SA

City: Regina ***State/Province:*** SASKATCHEW

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092:

Remediation of gasoline contaminated, glacio-lacustrine clays at a decommissioned retail service station site in Regina, Saskatchewan. Contamination was mitigated by the use of fracture-enhanced soil vapor extraction.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

GWRTAC ID: FRAC0050

Project Name: Denver Federal Center

City: Denver **State/Province:** CO

Report(s)/Publication(s) (GWRTAC Source):

Stavnes, Sandra, "Bioremediation Barrier Emplaced through Hydraulic Fracturing" in Groundwater Currents, March 1999, Issue No. 31, available at http://www.clu-in.org.

Project Summary:

The following text is excerpted from Stavnes, Sandra, "Bioremediation Barrier Emplaced through Hydraulic Fracturing" in Groundwater Currents, March 1999, Issue No. 31, available at http://www.clu-in.org:

The U.S. Environmental Protection Agency, General Services Administration, and the State of Colorado jointly sponsored a demonstration of an innovative bioremediation barrier to remediate both ground water and soil containing total petroleum hydrocarbons (TPH) at the Denver Federal Center in Denver, Colorado. This approach awas selected as an alternative to expensive excavation and disposal processes that otherwise would have been required in the tightly-packed clay and shale at the site. At the end of the 9-month demonstration, TPH concentations had fallen be an average of 91.5 percent.

Installation of a bioremediation barrier through hydraulic fracturing provides an excellent in situ environment for microbes to metabolize contaminants in ground water and soil. Hydraulic fractures are constructed and kept propped open by the simultaneous injection of small ceramic pellets made from diatomaceous earth (isolite). The pellets, which are 74 percent porous, are saturated with a liquid inoculum of selected indigenous microbes and nutrients that degrade the contaminants. The isolite pore spaces are small enough to protect the selected degrading microbes, but large enough to hold the nutrients, water, and oxygen required for bioremediation. Using this technology, isolite serves to transport microbes into soil and groundwater, maintain the opening and permeability of fractures, and create a permeable reactive treatment system that increases contact time with contaminants.

Diverse government operations have been conducted at the Denver Federal Center over the years. Contaminants targeted during the demonstration were derived from cutting oil that had been released during the 1940's when the Center served as a munitions plant. The average TPH concentration prior to the demonstration was 5,600 mg/kg.

The Denver Federal Center test area extended approximately 80 by 40 feet on the surface, and 22 feet deep. Fractures were created at the base of pre-drilled cased wells of varying depths. Using high pressure water jets, niches were cut at the bottom of each well to intiate horizontal fracturing. An aqueous guar gum slurry carrying the isolite was introduced into the boreholes and pumped under pressure to extend and fill the fractures. Over a period of two days, a total of six one-inch thick, pancake-shaped, horizontal fractures were created, each extending over 40 feet in diameter and stacked 8-22 feet below ground surface. The cased wells were vented passively through the top of the casing and recessed slightly below the surface in concrete well covers to allow easy access for future recharging, if necessary, and to allow unrestricted traffic flow.

The fractures were installed in the upper layers of the tightly-packed clay. However, perched ground water was present in the clay, resulting in treatment of both soil and ground water at the site. Data suggest that the fractures had increased the soil permeability significantly, thus causing trapped water in the clay to flow through the fractures. As the water passed through the inoculated isolite, the cutting oil was degraded biologically and the "biofractures" served as a permeable reactive treatment system for the ground water.

The success of the Denver Federal Center biofracturing demonstration proved to EPA Region 8 and the State of Colorado Oil Inspection Station that this is a promising technology for remediating tightly packed soils and ground water contaminated with TPH. Based on the demonstration results, which were released in 1996, emplacement of bioremediation barriers through the used of hydraulic fracturing has been undertaken recently at two commercial underground storage tank sites in Colorado. Preliminary data for one of these sites show an average reduction in benzene concentration in ground water of 80 percent and a total BTEX (benzene, toluene, ethylbenzene, and xylene) eduction of greater than 85 percent.

Field analytical results of the demonstration are available from Sandra Stavnes (EPA, Region 8) at 303-312-6117, email stavnes.sandra@epa.gov or Seth Hunt (FOREMOST Solutions, Inc.) at 303-271-9114, email foremost@earthlink.net.

Report(s)/Publication(s) (Additional Info Source):

Stavnes, Sandra, "Bioremediation Barrier Emplaced through Hydraulic Fracturing" in Groundwater Currents, March 1999, Issue No. 31, available at http://www.clu-in.org.

GWRTAC ID: FRAC0089

Project Name: Diaz Chemical Corporation, Holley, NY

City: Holley **State/Province:** NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, Rochester, NY, Project Summary Information:

A migration control blasted-bedrock trench was installed in 1995 by Haley & Aldrich, Inc. on the premises of this chemical manufacturing facility that opened in 1976. The source of the contamination release(s) is unknown. The facility manufactures chemical aromatic intermediates used in the pharmaceutical and agricultural industries. The function of blast fracturing at the site was to provide groundwater migration control, particularly to capture and allow treatment of groundwater at the site boundary.

Soil overburden at the site ranges from 33 to 36 feet thick and is underlain by Queenston Shale bedrock. The overburden is made up of glacial lacustrine silt, clay and sand. The blast-fractured trench is about 3 to 12 feet deep below top of bedrock and about 265 feet long. The top of rock topography undulates, and drainage along the top of rock and drainage interaction with natural fracture sets is fairly complex. Therefore pumping from the blasted trench is controlled by variable operation of 6 pumping wells and 5 drainage wells installed in the trench.

The blasted bedrock zone, created in shale bedrock beneath 36 feet of overburden, was 265 feet long and 6 feet in depth, corresponding to a sidewall area of 1,590 ft2. Pre-blast well yields were <0.5 gpm, with post-blast well yields increasing to 5 gpm, for a ratio of pre/post-blast yields of 10.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0062

Project Name: East Brunswick, NJ

City: East Brunswick **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

In 1992, a clean site in East Brunswick, New Jersey was the location of a pneumatic fracturing project to improve water reinjection volumes. At this site, fractures were injected into the underlying siltstone.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0048

Project Name: East Orange, NJ

City: East Orange **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

A pneumatic fracturing project was performed in 1993 at a private site in East Orange, New Jersey to enhance a soil vapor extraction system. Vadose zone sand and sandy silt impacted with petroleum hydrocarbons were targeted in this project. Fractures were injected at depths between 5 and 13 feet below the ground surface.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0082

Project Name: Eastman Kodak, Industrial Landfill, Rochester, NY

City: Rochester **State/Province:** NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, Rochester, NY, Project Summary Information:

The site is a formerly permitted industrial landfill in New York reported by NYSDEC to have received ash, glass grinding slurry, electroplating waste sludge, wastewater treatment sludge, and photographic developer. The landfill is equipped with a leachate collection system. A blast-fractured trench was installed in 1994 by Haley & Aldrich, Inc. as an Interim Remedial Measure to provide groundwater migration control along the northwesterly side of the landfill. The landfill was closed in 1998.

The soil on site consists of lacustrine sand and glacial till overlying bedrock. The overburden averages 9 feet thick and contains generally lacustrine sands and glacial till. The bedrock consists of sandstone and a thin layer of shale. The blasted bedrock zone, created in sandstone bedrock beneath 30 feet of overburden, was 250 feet long and 16 feet in depth, corresponding to a sidewall area of 4,000 ft2. Pre-blast well yields were 0.5 gpm, with post-blast well yields increasing to 12 gpm, for a ratio of pre/post-blast yields of 24.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0083

Project Name: Eastman Kodak, Rochester, NY

City: Rochester **State/Province:** NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, Rochester, NY, Project Summary Information:

A groundwater migration control system involving several trenches was installed on a portion of the property of Kodak Park, known as KPM. Compounds in groundwater result from releases from a reported spill to Bldg. 322 retention pond, and other unknown sources in KPM. The four trenches are intended to control groundwater migration on the KPM property and prevent migration to residential areas to the north. Installation was performed in 1995 and 1997 by Haley & Aldrich, Inc.

Overburden soils range from about 10 to 30 feet in thickness and are comprised of glacial till and lacustrine deposits. Bedrock is primarily sandstone, with interbedded siltstone and some shale. The trenches are 100 to 200 feet in length and blasted to a depth of 13 to 15 feet below the top of bedrock.

The dimensions of the blasted bedrock zones, and corresponding bedrock type and overburden depths were as follows:

Trench 1 (Length x Depth, Sidewall Area): 150 x 15 ft, 2250 ft2 in sandstone beneath 20 feet of overburden;
Trench 2 (Length x Depth, Sidewall Area): 200 x 15 ft, 3000 ft2 in sandstone beneath 30 feet of overburden;
Trench 3 (Length x Depth, Sidewall Area): 100 x 13 ft, 1300 ft2 in sandstone beneath 10 feet of overburden; and,
Trench 4 (Length x Depth, Sidewall Area): 100 x 13 ft, 1300 ft2 in sandstone beneath 10 feet of overburden.

Available pre-blast and post-blast well yields, and the ratio of the pre- and post-blast yields were:

Trench 1 (Pre-blast yield, Post-blast Yield, Ratio): <0.1 gpm, 5 gpm, 50; and,
Trench 2 (Pre-blast yield, Post-blast Yield, Ratio): 0.5 gpm, 6 gpm, 12.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0064

Project Name: Egg Harbor, NJ

City: Egg Harbor ***State/Province:*** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

In Egg Harbor, New Jersey, a pilot-scale pneumatic fracturing project was performed in 1999 at a private former manufactured gas plant (MGP) site to enhance in situ chemical oxidation. Typical MGP-related contaminants impacted the vadose zone of the silty sand underlying this site. Pneumatic fracturing was used to inject hydrogen peroxide and acetic acid into an area of MGP-impacted soil. Fractures were injected at depths between 14 and 27 feet below the ground surface, and the estimated radius of influence of the fractures was 8 to 10 feet. Approximately 3,000 gallons of oxidizing liquid was injected into fine sandy soils. Individual injections were from 40 to 60 gallons.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID:	FRAC0011		
Project Name:	EPA Center Hill Testing Facility, Cincinnati, OH		
City:	Cincinnati	***State/Province:***	OH

Report(s)/Publication(s) (GWRTAC Source):

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC.

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992,
Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994, and,
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

The site, an uncontaminated U.S. EPA testing facility in Cincinnati, Ohio, is underlain by a silty clay with lesser amounts of sand and gravel, and the characteristics of the soil are amenable to hydraulic fracturing. Five wells were installed to compare the differences of fractured and unfractured wells, to determine the effect on performance from venting of the fracture to the surface, and to assess the performance of wells with multiple fractures. Three wells with hydraulic fractures were installed. One well had hydraulic fractures at 1.5 and 3 m (5 and 10 feet) below the ground surface (bgs). A second well had a single fracture at a depth of 1.5 m (5 feet) that vented to the surface 7 m (23 feet) from the well. The third well had a single fracture at 1.5 m (5 feet) that remained below the surface. Two conventional wells were screened in unfractured ground. The wells were connected to a vacuum blower that was capable of 300 cm of water of suction. Pneumatic piezometers were installed around the wells to measure suction head in the soil. The demonstration took place in January 1992.

Well discharge, as both vapor and liquid flow rate, was an order of magnitude greater for the fractured wells than the unfractured wells. For the fractured wells, rate correlated strongly with precipitation; after heavy rainstorms yields of vapor would decrease, substantial water would be produced over the next few days, and the system would gradually recover. The vented fracture was more responsive to rainfall than the unvented fractures. The conventional wells were unaffected by rain.

Suction head was detectable at greater distance from the wells with fractures than from the unfractured wells. Around the conventional wells, suction was about 3 cm (1.18 in) of water at a distance of 1 m (3.3 feet). In contrast, the same suction head could be observed 8 m (25 feet) from the fractured wells. Also, suction around the fractured wells was influenced by rainfall events. Suction head would decrease gradually during drying of the soil and increase significantly after heavy precipitation.

Report(s)/Publication(s) (Additional Info Source):

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency, September 1993, Technology Evaluation and Applications Analysis Reports, University of Cincinnati/Risk Reduction Engineering Laboratory: Hydraulic Fracturing Technology. EPA/540/R-93/505.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC.

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

U.S. Environmental Protection Agency, 1995, "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/003, available at http://www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html.

GWRTAC ID: FRAC0025

Project Name: Federal Government Facility

City: Oklahoma City **State/Province:** OK

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information.

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com;, and, McLaren -Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information:

A pneumatic fracture well was installed in a semi-confined aquifer at a federal government facility contaminated with VOCs, mainly BTEX and TCE, in Central, Oklahoma, to enhance bioremediation. The site geology consisted of alternating layers of low permeable sandy silty shale and lower permeable silty claystone. The selected remedial strategy was enhanced bioremediation. However, concerns about the aquifer's permeability and anisotropy were raised as obstacles to the success of the project. Additional concerns were raised regarding downward propagation of pneumatic fractures since other areas of the site might contain DNAPLS. Pneumatic injections were performed across the thickness of the aquifer. Perimeter monitoring of the target zone and higher zones was performed to demonstrate the absence of downward migration of fractures. The pilot test was concluded in February of 1995.

The target aquifer's post-fracture transmissivity increased five times from the pre-fracture transmissivity. This increase was seen in the fracture well which was screened across the target interval. Transmissivity values obtained from other wells which had screen intervals across other smaller, water bearing units exhibited smaller increases. Evaluation of the data revealed that pneumatic fracturing made the aquifer more isotropic in nature. This allowed water to be pumped from the aquifer at a higher rate indicating that the formation would dewater quicker if dewatering becomes a strategy elsewhere on the site.

Injections in the target aquifer were not visible in any of the above aquifers indicating that fracture propagation was horizontal and none of the confining layers were breached. The exception was during one injection where pneumatic pressure migrated to the gravel pack of a nearby well, up the gravel pack and out into the formation through the other water bearing units. The aerial influence of the pneumatic injection was demonstrated to be greater than 50 feet from the injection well. Circulation of amendments to enhance bioremediation was accomplished in a more efficient and uniform manner with subsequent reductions in VOC concentrations.

In another area of the site, pneumatic fracturing was used to enhance free product recovery (FRAC0002). Static product thickness increeased from 1.5 ft to 20.2 ft following fracturing. Average monthly recovery rates increased from 155 gallons per month to 435 gallons per month following fracturing. During pre-fracture pumping, the product represented an average of 12% of the total fluid recovered. Following fracturing, this increased an average of 74% of the total fluid recovered.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information.

GWRTAC ID:	FRAC0079		
Project Name:	Fire Station 28, Denver, CO		
City:	Denver	***State/Province:***	CO

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, Rochester, NY, Project Summary Information:

Petroleum products were discovered leaking from an underground storage tank at a Denver fire station (Fire Station 28). Migration of petroleum compounds was found to extend from the front of the station, across a public street toward a residential area. The purpose of the blasted trench, installed by Haley & Aldrich, Inc., was to control migration and prevent it from affecting the residences. The trench was installed along the public street in front of the station in 1993.

Soil overburden at the site is about 10 feet thick comprised of clayey sand. The trench was blasted into a claystone/shale bedrock , and has dimensions of 130 feet length and 40 feet depth below top of bedrock, corresponding to a sidewall area of 5,200 ft2. Pre-blast well yields were <0.1 gpm, with post-blast well yields increasing to 6 gpm, for a ratio of pre/post-blast yields of 60.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0081

Project Name: FMC Corporation, Middleport, NY

City: Middleport **State/Province:** NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Project Summary Information:

Several migration-control trenches and recovery wells were installed between 1994 and 1998 on the property of this FMC Corporation chemical manufacturing facility in New York. Trenches were installed by Haley & Aldrich, Inc. in 1994, and by Conestoga Rovers Association in 1995 and 1998.
The trenches were placed within the contaminant plume to shrink it and prevent the plume from migrating off site. The specific source(s) of release at the site is unknown. Release investigations were initiated in 1973.

The average thickness of overburden is 10 feet, ranging from 8 to 15 feet at trench locations. The overburden overlies limestone and sandstone. NYSDEC reports the depth to groundwater at the site to be 3 to 5 feet below ground surface. The blasted trenches installed range from 50 to 800 feet in length and 10 to 28 feet deep below top of bedrock.

The dimensions of the blasted bedrock zones, and corresponding bedrock type and overburden depths were as follows:

Trench 1 (Length x Depth, Sidewall Area): 300 x 16 ft, 4800 ft2 in limestone/sandstone beneath 13 feet of overburden;
Trench A (Length x Depth, Sidewall Area): 300 x 28 ft, 8400 ft2 in limestone beneath 13.5 feet of overburden;
Trench B (Length x Depth, Sidewall Area): 150 x 13 ft, 1950 ft2 in limestone beneath 15 feet of overburden;
Trench C (Length x Depth, Sidewall Area): 800 x 10 ft, 8000 ft2 in sandstone beneath 12 feet of overburden;
Trench D (Length x Depth, Sidewall Area): 450 x 10 ft, 4500 ft2 in sandstone beneath 10 feet of overburden;
Trench E (Length x Depth, Sidewall Area): 200 x 13 ft, 2600 ft2 in limestone beneath 8 feet of overburden;
Trench E (Length x Depth, Sidewall Area): 50 x 17 ft, 850 ft2 in limestone beneath 11 feet of overburden; and,
Trench F (Length x Depth, Sidewall Area): 300 x 14 ft, 4200 ft2 in limestone beneath 13 feet of overburden.

The pre-blast and post-blast well yields in each trench, and the ratio of the pre- and post-blast yields were:

Trench 1 (Pre-blast yield, Post-blast Yield, Ratio): 0.1 gpm, 8 gpm, 80;
Trench A (Pre-blast yield, Post-blast Yield, Ratio): <0.1 gpm, 1.9 gpm,19;
Trench B (Pre-blast yield, Post-blast Yield, Ratio): <0.1 gpm, 0.41 gpm, 4.1;
Trench C (Pre-blast yield, Post-blast Yield, Ratio): <1 gpm, 5.89 gpm, 5.89;
Trench D (Pre-blast yield, Post-blast Yield, Ratio): <1 gpm, 4.6 gpm, 4.6;
Trench E (Pre-blast yield, Post-blast Yield, Ratio): 0.9 gpm, 2.8 gpm, 3.1;
Trench E (Pre-blast yield, Post-blast Yield, Ratio): 0.9 gpm, 2.8 gpm, 3.1;
Trench F (Pre-blast yield, Post-blast Yield, Ratio): <0.1gpm, 7.5 gpm, 75.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID:	FRAC0094
Project Name:	Former Bayer Aspirin, NJ
City:	
State/Province:	NJ

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Blast-fractured trenches were installed at this former manufacturing site owned by Bayer in New Jersey by ENSR in 1998. The blasted bedrock zone, created in schist/gneiss bedrock beneath 22 feet of overburden, was 100 feet long and 66 feet in depth, corresponding to a sidewall area of 6,600 ft2. Pre-blast well yields were 1.2 gpm, with post-blast well yields decreasing to <0.8 gpm, for a ratio of pre/post-blast yields of 0.67.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID:	FRAC0057
Project Name:	Former Dry Cleaning Facility, Northern Virginia
City:	
State/Province:	VA

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

Pneumatic Fracturing was used to enhance Dual Vapor Extraction operation as the remedial alternative at the site. Project conducted as first step to final Remedial Action in July of 1994. Startup of the remediation system is scheduled for October 1999. The contaminants in the area of concern were primarily PCE and TCE. Pneumatic Fracturing was used to increase formation transmissivity and vadose zone permeability in a fractured siltstone and shale formation impacted with Perchloroethylene. A Dual Phase Extraction (DPE) system was installed at the site to remediate existing contamination from bedrock in the subsurface. The use of pneumatic fracturing prior to DPE start-up enhanced air flow rates, vacuum influence, and an ability to increase total removal of the contaminant of concern. ARS applied three-foot pneumatic injections between 15 and 30 feet below surface grade in two 4" and 6" open rock wells.

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

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

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

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

GWRTAC ID: FRAC0035

Project Name: Former Light Manufacturing Facility, Brookfield, WI

City: Brookfield **State/Province:** WI

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

Pneumatic fracturing was used as part of a full-scale DVE remediation system at a former light manufacturing facility contaminated with VOCs, primarily PCE and gasoline range organics (GRO), in Milwaukee, Wisconsin. Previous site delineation and pilot testing characterized the tight clay formation as having a very low permeability, making the VOC contamination very hard to recover. Pneumatic fracturing was selected as a critical part of the full- scale remedial design in order to increase air permeability and hydraulic conductivity. The system installation and pneumatic fracturing operations completed January 1996, and the remediation system currently operative.

All six remediation well were successfully fractured from 4 feet to 16.5 feet below ground surface. Excellent pressure influence was observed during pneumatic injections, indication excellent fracture propagation. Vacuum influence data during the startup of the remediation system confirmed that a thorough fracture network was created throughout the remediation zone.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

GWRTAC ID:	FRAC0004
Project Name:	Former Manufacturing Facility, Highland Park, NJ
City:	Highland Park
State/Province:	NJ

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Marketing Information

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620 or www.arstechnologies.com, Company Information;
McLaren Hart, Inc., Warren, NJ Company Information, and
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

Pneumatic fracturing was used to increase formation transmissivity and vadose zone permeability in a fractured shale formation contaminated with trichloroethylene at a private, former manufacturing facility in Highland Park, New Jersey at pilot and full scale. Chlorinated solvents and petroleum hydrocarbons were impacting the vadose zone of the siltstone/carbonate limestone beneath this site. Previous attempts to remediate the site utilizing standard Dual Vapor Extraction (DVE) combined with air injection had been ineffective due to low air flow rates, small and sporadic vacuum influence, and an inability to effectively control the ground water. Two foot pneumatic injections were applied at successive intervals to a depth of 25 feet in two 4" open rock wells. Fractures were injected at depths between 9 and 24 feet below the ground surface, and the estimated radius of influence of the fractures was 35 feet. Following application of pneumatic fracturing, the groundwater in the test area was effectively controlled via pumping, and each of the fracture wells was placed under a vacuum.

This project was conducted as first step to final Remedial Action in July of 1994. A full remediation system treating approximately a 40,000 square foot area, and featuring pneumatic fracturing was constructed in the Spring/Summer of 1995 under the EPA SITE Demonstration Program, and is now operative. Since startup, of the remediation system in August 1995, over 300 pounds of TCE have been recovered from the subsurface as of July 1996.

Pilot Test Results:

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

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

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

Full-Scale Remediation System Results as of July 1996:

Since startup of the system in August 1995, to July 1996, the system has treated over 2,000,000 gallons of ground water. Over 300 lbs. of TCE has been recovered via the groundwater and vapor extraction systems. All source zone groundwater monitoring wells have been reduced by two orders of magnitude to below one ppm. Several operational start/stops have produced no significant "rebound", thus indicating source remediation. Site closure is anticipated for fall 1996.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID: FRAC0026

Project Name: Former Manufacturing Facilty, Hillsborough, NJ

City: Hillsborough ***State/Province:*** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620.

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111.

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com and McLaren -Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information:

Pneumatic fracturing was used to improve the effectiveness of a ground water re-injection system in a siltstone formation at a former manufacturing facility in Central, New Jersey. The client was required by permit to have ground water re-injected down gradient back into the formation following treatment to remove TCE. The transmissivity and storativity of the formation, however, were too low to allow the necessary flow rate of water to enter the formation. Pneumatic Fracturing was applied to increase the quantity of ground water which could be accepted by the formation. A full-scale remediation system is currently operating at facility.

Prior to application of Pneumatic Fracturing, an injection well could only receive 2 gallons per minute. Following Pneumatic Fracturing, the injection well was accepting 11 gallons per minute. Several other re-injection wells were fractured as part of the full-scale injection well system.

Report(s)/Publication(s) (Additional Info Source):

Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620.

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information

GWRTAC ID: FRAC0030

Project Name: Former Processing Facility, Kansas City, KS

City: Kansas City **State/Province:** KS

Report(s)/Publication(s) (GWRTAC Source):

Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620.

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111.

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com, and McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information:

Pneumatic Fracturing was used in a fine sand and silty sand formation to change the soil structure to increase effectiveness of air sparging at a private, former processing facility contaminated with VOCs, primarily TCE, in Kansas City, Kansas. Previous attempts to air sparge revealed thin lens of less permeable material in the formation. These less permeable lens caused sparged air to migrate laterally, reducing the effect of air sparging. Pneumatic Fracturing was utilized to eliminate these less permeable lenses. The pilot test was completed in July 1996. Full-scale remediation incorporating pneumatic fracturing occurred in 1996.

In a separate area of the site, pneumatic fracturing was used to create two reaction cells in unconsolidated material in 1997. Groundwater within the medium to fine sand beneath this site was contaminated with TCE in the saturated zone. Fractures were injected at depths between 25 and 37 feet below the ground surface, and the estimated radius of influence of the fractures was 15 feet.
Approximately 1,800 lbs. of iron filings were injected. Samples were collected prior to and following injection of the reactive media cell. Results of the sampling indicate a substantial reduction in TCE concentration in each well. A 30-60% reduction in baseline TCE values was noted 60 days after installation. These results confirm the effectiveness of the emplacement of the iron filings using pneumatic fracturing. Based on the results mentioned in the above paragraphs, the application of pneumatic fracturing and reactive media injection was a success in Eastern, KS. Distribution data will aid in calculating an upgrade of the reactive media cell, should this integration be applied full scale.

Report(s)/Publication(s) (Additional Info Source):

Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620.

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information

Schnell, D.L, 1997, "Integration of Pnematic Fracturing with Bioremediation and Reactive Media", MS Project, Dept. of Civil & Environmental Engineering, New Jersey Institute of Technology, Newark, NJ, 1997.

Schnell, D.L., T.M. Boland, J.R. Schuring, and C.B. Parks, 1998, "Pneumatic Injection of Iron to Treat Chlorinated Solvents", presented at the 4th International Symposium on Environmental Geotechnology and Global Sustainable Development (ASCE), Boston, MA, 1998.

GWRTAC ID:	FRAC0029		
Project Name:	Former Service Station, Newark, NJ		
City:	Newark	***State/Province:***	NJ

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

Pneumatic fracturing was used to increase soil permeability and enhance vapor extraction in a shale and sandstone formation at a former service station contaminated with BTEX and TPH, in Newark, New Jersey. A single pneumatic fracture well was installed and injections were applied from 9' - 13' below the surface. Changes in air flow, vacuum influence, and hydrocarbon removal rates were monitored before the application of the Pneumatic Fracturing technology. The pilot test was completed in September 1993.

The effective vacuum influence was observed to increase as much as 2,900% after the Pneumatic Fracturing. Hydrocarbon removal rates increased as much as 757% after Pneumatic Fracturing was applied.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

GWRTAC ID: FRAC0038

Project Name: Former Sour Gas Plant Site

City:

State/Province: ALBERTA

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092:

Hydraulic fracturing of silt till soils at a former sour gas plant site in Alberta. Project involved initiation and propagation of fractures; precise elevation survey of ground surface deformation; ground penetrating radar and electromagnetic surveys of fracture extent; excavation and visual confirmation of fracture geometry and thickness; and an assessment of fractured airflow performance relative to an unfractured extraction well.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

GWRTAC ID: FRAC0047

Project Name: Former Sour Gas Plant Site, Wetaskiwin, Alberta, Canada

City: Wetaskiwin **State/Province:** ALBERTA

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092:

Hydraulic fracturing research and development project conducted in 1997 to investigate the feasibility of fracture-enhanced bioventing of amine contaminated clay till soil. This project represented the first application in Canada of soil fracturing combined with horizontal directional drilling technology. A total of 12 fractures spaced at 2 metre (6.6 ft) horizontal intervals were initiated along 25 metres (82.0 ft) of a horizontal borehole. Depth of fracture placement was four metres (13.1 ft) (vadose zone). Fracture geometry, thickness, and orientation were remotely mapped during the fracturing process using surface mounted tiltmeters. Phosphate nutrients were injected during the fracturing process to assist in the biodegradation of amine contaminants.

Fractures initiated in the horizontal borehole were modeled as predominantly near-horizontal (ie. forming angles of 5 to 31 degrees from the horizontal). The average fracture thickness was 15 mm (0.6 in). The fracture radii ranged from 1 metre to 5 metres (3.3 to 16.4 ft) depending on the extent of fracture fluid leak-off through nearby testholes. A subsequent excavation of fractures was conducted to inspect their distribution and geometry. The fracture properties observed in the field (lateral extent, orientation, and thickness) were in general agreement with fracture properties predicted by the model.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

GWRTAC ID: FRAC0022

Project Name: Fuel Terminal in Regina, Saskatchewan

City: Regina **State/Province:** SASKATCHEW

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from Company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2:

Subsurface gasoline contamination originated from tanker truck fuel-loading racks. Gasoline contamination is present over an area of two hectares (4.94 acres) and is migrating off-site towards an adjacent industrial facility. The contamination is present in low permeability, naturally fractured, glaciolacustrine clays and clayey silts. The objective of the project was to assess the performance of fractured wells for enhancing the recovery of free-phase and residual hydrocarbons.

A total of 43 hydraulic fractures were induced at 7 fracture well locations within the contaminant plume identified at the site. Fractures were initiated within 1.5 metres (4.9 ft) above and below the saturated zone at four of the well locations, and in a four metre (13.1 ft) thick interval in the vadose zone at the remaining three well locations. Approximately 500 litres (132 gal) of sand-laden fracture fluids was used to induce each fracture. The performance of fractured wells was subsequently tested by connecting them to a high vacuum, Dual Phase Extraction (DPE) pump to pump both liquids and vapours. The DPE technology is often referred to as "bioslurping" in the literature.

The enhancements in fractured well performance are summarized below:

PARAMETER	UNFRACTURED BASELINE WELLS	FRACTURED WELLS
Hydraulic conductivity	4.3 x 10-8 to 8.0 x 10-8 m/s 4.3 x 10-6 to 8.0 x 10-6 cm/s	4.1 x 10-7 to 2.3 x 10-6 m/s 4.1 x 10-5 to 2.3 x 10-4 cm/s
Air permeability	1.0 x 10-9 to 2.9 x 10-9 cm2	4.6 x 10-8 to 1.2 x 10-7 cm2
Radius of influence (liquid)	2 to 3 m (6.6 to 9.8 ft)	16 m (52.5 ft)
Radius of influence (gas)	5 to 7 m (16.4 to 23.0 ft)	>16 m (>52.5 ft)

The results of testing both hydraulically fractured wells and unfractured baseline wells revealed that hydrocarbon removal rates were not sustainable in the unfractured wells because the high vacuum pressure induced closure of natural fractures at the well bore. This resulted in a "choking off" of the air flow which subsequently caused a pump failure. Conversely, hydrocarbon removal rates were sustainable at high operating vacuums in hydraulically fractured wells because the induced fractures were kept open by the frac sand proppant, thereby preventing these fractures from closing.

Dual Phase Extraction and Hydraulic Fracturing technologies are presently being considered by the client for application in contaminant plumes at their refinery complex.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax

(780) 287-7092, Company Information

GWRTAC ID: FRAC0007

Project Name: Gasoline Refinery in Marcus Hook, PA

City: Marcus Hook **State/Province:** PA

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620 or www.arstechnologies.com, Company Information;
U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992; and,
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

Pneumatic fracturing at pilot scale, in staggered spatial distribution for maximum effectiveness was used to enhance microbial processes in a dense silty clay formation at a petroleum refinery in Marcus Hook, Pennsylvania. The low permeability clay had been impacted by petroleum compounds (Benzene, Toluene, and Xylenes) in the vadose zone. In addition to enhancing formation permeability, pneumatic fracturing was utilized to inject a solution containing nutrients and pH buffering constituents to enhance microbial activity and biodegradation of the BTX. Aerobic processes dominate at the fracture interfaces and, to a limited distance, into the soil away from the fracture. Depletion of oxygen during aerobic biodegradation allows methanogenic and denitrifying populations to form at greater distances from the fractures. Contaminants diffuse toward the fracture, serving as a substrate for various microbial populations. This stacking arrangement enhances the growth of aerobic microbial populations by reducing substrate concentrations in the denitrifying and methanogenic zones. The site was pneumatically fractured and periodic injections were performed over a period of 12 months. Subsurface injections introduced nitrate and ammonium salt in the form of calcium ammonium nitrate to facilitate the development of aerobic, denitrifying, and methanogenic biodegradation zones. Off-gases from the monitoring wells were analyzed for benzene, toluene, and xylenes (BTX), oxygen, methane, and carbon dioxide to evaluate process effectiveness. Additional soil borings were carried out and samples analyzed to measure the change in extent of site contamination as a result of the process. Carbon mass balances considering contaminant reduction, carbon dioxide evolution, methane evolution, and contaminant recovery through vapor extraction were used to evaluate process performance.

This technology was accepted into the SITE program in July 1991, and field scale pilot testing was completed in March 1995 under the SITE Emerging Technology Program. The project was completed in conjunction with the Hazardous Substance Management Research Center.

Initial site characterization indicated low subsurface permeability and the presence of BTX at concentrations of up to 1500 ppm in the soil phase. The pneumatic fractures were installed at depths between 3 and 8 feet below the ground surface, and the estimated radius of influence of the fractures was 14 to 20 feet. Results show that fracturing increased subsurface permeability by up to 40 times within an effective radius of approximately 20 feet.

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

The pneumatic fracturing process consists of injecting high-pressure air or other gas into soil formations at controlled flow rates and pressures. In low permeability soils, the process creates conductive channels in the formation. These channels increase the permeability and exposed surface area of the soil, accelerating removal and treatment of the contaminants. In high permeability soils, the process provides a means for rapidly aerating the soil formation.

Pneumatic fracturing increased the formations air extraction flow rate 24 to 105 times. The average permeability increased from 0.02 darcys, pre-fracture, to 0.8 darcys, post-fracture. After increasing formation permeability, pneumatic fracturing was then utilized to inject the fluid solution containing nutrients and other soil amendments into the formation to encourage and stimulate microbial degradation of the BTX compounds. Soil gas data from the monitoring wells consistently showed elevated levels of CO_2 following nutrient injection, indicating increased rates of BTX degradation. Correspondingly, vapor phase BTX concentration levels in vapor monitoring wells were observed to decrease during the course of the demonstration. Soil samples were obtained from borings conducted at the conclusion of the demonstration to determine the actual decrease in BTX from the clay formation. These samples indicated a decrease of 79% reduction of total BTX mass in the formation. Given the low initial permeability of the clay soils at the site, the mass of contaminants removed by biological degradation greatly exceeded levels which would have been expected with traditional in situ bioremediation techniques or any other in situ remediation technology. It was concluded that the integration of pneumatic fracturing and bioremediation had a synergistic benefit to site remediation.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

Fizgerald, C.D., 1993. "Integration of Pneumatic Fracturing to Enhance In Situ Bioremediation", MS Thesis, Dept. of Civil & Environmental Engineering, New Jersey Institute of Technology, Newark, NJ

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID: FRAC0090

Project Name: GM Delco Chassis, Bristol CT

City: Bristol ***State/Province:*** CT

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, Rochester, NY, Project Sumary Information:

This facility is an automotive manufacturing facility in Connecticut. The apparent source of contaminant release was from a chromium plating manufacturing process. The contamination was discovered in 1989. A migration control blasted-bedrock trench was installed by Haley & Aldrich, Inc. on the site in 1996, to contain the migration of a hexavalent chromium plume.

The average thickness of soil overburden is about 8 feet and consists mainly of sand and silt. This overburden overlies Bristol Gneiss bedrock. The blast-fractured trench installed is 355 feet long and 42 feet deep below top of bedrock, corresponding to a sidewall area of 14,910 ft2. Pre-blast well yields were 0.2 gpm, with post-blast well yields increasing to 10 gpm, for a ratio of pre/post-blast yields of 50.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0104

Project Name: Hallman Chevrolet, NY

City:

State/Province: ME

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Blast-fractured trenches were installed at this manufacturing site owned by Hallman Chevrolet in New York by Day Engineering in 1997. The blasted bedrock zone, created in dolomite bedrock beneath 11 feet of overburden, was 180 feet long and 9 feet in depth, corresponding to a sidewall area of 1,620 ft2. Pre/post-blast yields were not available from source.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID: FRAC0055

Project Name: Indian Village Site, Continental Divide, NM

City: Continental Divide **State/Province:** NM

Report(s)/Publication(s) (GWRTAC Source):

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

Project Summary:

The following text was excerpted from information provided by FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, and
FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information:

The site is an abandoned service station known as the Indian Village Gift Shop. It is situated in the western part of New Mexico just north of Interstate 40 in Continental Divide, NM. The site is adjacent to and north of a service road that parallels Interstate 40 and south of a single east-west AT & SF rail line. Hydrocarbons were released into the subsurface from three leaking underground storage tanks (UST) that stored gasoline and possibly diesel fuel. The tanks were installed in 1964 and the service station was closed in 1992, with a new station built about 100 m west of the site. The tanks were removed in May, 1994 but subsequent investigation found one more UST at the site. Removal of the UST's eliminated the source of the contamination. Extensive contaminant plumes have been detected downgradient of the source, both in the groundwater and in the soils of the vadose zone.

Remedial action to remove the contaminants from the soil and ground water was performed by joint crews of FRx and Foremost Solutions between July 29 and August 6, 1998. Six Bio-Nets containing a total of thirty-one fractures were created downgradient of the source, generally to the north. All fractures used Isolite®, inoculated with a culture of hydrocarbon-digesting bacteria, at multiple elevations in the contaminant plume to enhance the biodegradation of the hydrocarbons. These closely spaced horizontal layers of porous solids that host degrading biomass are defined as Bio-Nets.

Ground water samples were collected and analyzed in November 1998 and February 1999 to determine any change in the contaminant concentration levels after the installation of the in situ Bio-Nets.

Although the continental divide, with an elevation of 2,213 m (7,260 ft) above sea level, is less than 100 m west of the location, the area has flat to gently rolling terrain that falls generally to the north in the immediate vicinity of the site. Bedrock was not encountered in boreholes that were advanced to 18 m (60 ft), although fragments of sandstone were found at depth. The first 9 m (30 ft) of overburden is fill consisting of very loose, fine grained silty sand, with the top portion well graded and the lower portion poorly graded. The next 9 m (30 ft) of overburden is composed of layers of fine-grained alluvium deposits consisting of sand, silt, clayey sand, sandy clay, and clayey sand. These deposits are of Quaternary age derived from Triassic sedimentary rocks exposed several miles north of the site.

The phreatic surface has been found at 10 to 16 m (32 to 54 ft) below ground surface in a perched, unconfined aquifer. Ground water mounding near the source of contamination may be the result of discharge from a local septic system and local runoff. The water table gradient is 0.011 ft/ft towards the north, following the general slope of the surface terrain. Local water supply wells are between 60 and 300 m (200 and 1000 ft) deep, screened in a confined aquifer. The estimated head in these wells is around 25 m (80 ft).

Hydrocarbons normally associated with leaking UST's containing automotive and truck fuel have been detected in the soil and ground water. Other hydrocarbon contaminants not directly associated with gasoline or diesel fuel, such as acetone and MEK (2-butanone or methyl ethyl ketone), have been detected. The source of this contamination is not known, but the closed service station building has been used for light manufacturing operations, such as jewelry production. Some of the contaminants, along with the maximum measured concentrations, are listed in Table 1.

Table 1

Chemical	Maximum Concentration (ppb)
Benzene	20,000
Toluene	32,000
Ethylbenzene	5,500
Xylene	21,000
Naphthalene	2,560
Acetone	10,000
2-Butanone(MEK)	5,700
1,2-Dibromoethane(EDB)	1,100
1,2-Dichloroethane(EDC)	4,100

The contaminant plume has moved downgradient underneath the railroad track and has been detected at least 140 m (450 ft) from the source. Contamination was also detected about 15 m (50 ft) upgradient of the source in 1994, but levels had dropped to 0 or "no detect" (ND) by 1998.

Fractures were created from 15-cm (6-inch) PVC schedule 40 casings. The casings were grouted into 20-cm (8-inch) boreholes. The integrity of the grout seal was assured by use of swelling grout. Fractures were created from slots cut through the PVC casings. The slots were created using a high-pressure water jet, which cut through the PVC casing and notched a kerf in the subsoil. Slots were placed at the designed elevation for each fracture.

A dual packer system was placed in the casing, straddling the targeted slot to direct the pressurized gel and Isolite® slurry, and isolating the other slots during the fracturing process. When the fracture was completed, the packer system was moved to the next slot and the process repeated. Generally the fractures were created from bottom to top, however, the exact order in which fractures were created was selected to optimize use of time and resources and to accommodate existing well conditions.

At this site the typical fracture was estimated to be horizontal and approximately 6 to 9 m (20 to 30 feet) in diameter. The surface uplift was minimal, with the average uplift being no greater than 1 to 2 mm. The uplift was observed over 6 m (20 ft) from the injection point in many of the fracture propagations. Fractures were injected with an average of 0.4 m3 (14 ft3) of Isolite®, which was approximately the designed volume. The conclusion is that most fractures were installed as designed, with the interstitial volume of the subsurface soils absorbing most of the uplift volume, translating only a fraction of the uplift to the surface. A few fractures may have merged.

Multi-level fractures were installed in a total of six wells, with depths ranging from as deep as 16.5 m (54 ft) bgs to the shallowest at 6.7 m (22 ft) bgs. Table 2 summarizes the depths of each fracture and the volume of Isolite® injected.

Table 2 Fracture Specifications

Frac ID	Depth (m)	Depth (ft)	Vol Isolite (m3)	Vol Isolite (ft3)
SC8-48	14.6	48	0.29	10.3
SC8-48	14.6	48	0.20	7.0
SC8-45	13.7	45	0.44	15.4
SC7-49	15.1	49.5	0.17	6.0
SC7-49	15.1	49.5	0.33	11.6
SC7-46	14.0	46	0.44	15.6
SC7-43	13.3	43.5	0.33	11.5
SC7-41	12.3	40.5	0.05	1.7
SC7-41	12.3	40.5	0.39	13.6
SC7-36	11.1	36.5	0.16	5.7
SC7-36	11.1	36.5	0.28	10.0
SC7-32	9.9	32.5	0.34	12.0
SC6-48	14.6	48	0.46	16.1
SC6-45	13.7	45	0.42	15.0
SC5-47	14.3	47	0.45	16.0
SC5-43	13.1	43	0.42	15.0
SC4-52	16.0	52.5	0.50	17.5
SC4-49	15.1	49.5	0.53	18.8
SC4-46	14.2	46.5	0.57	20.0
SC4-43	13.1	43	0.42	15.0
SC4-39	12.0	39.5	0.42	15.0
SC4-36	11.0	36	0.40	14.2
SC4-33	9.9	32.5	0.50	17.7
SC4-29	8.8	29	0.44	15.6
SC4-25	7.6	25	0.51	18.0
SC4-22	6.7	22	0.37	13.0
SC3-54	16.5	54	0.41	14.6
SC3-51	15.5	51	0.42	14.7
SC3-48	14.6	48	0.30	10.5
SC3-45	13.7	45	0.45	15.9
SC3-42	12.6	41.5	0.37	12.9
SC3-38	11.6	38	0.50	17.5
SC3-34	10.4	34	0.42	14.8
SC3-30	9.1	30	0.50	17.5
SC3-26	7.9	26	0.47	16.6

Ground water samples were collected and analyzed in November 1998 and February 1999 following the injection of inoculated Isolite® in July and August of 1998. Some of the samples indicated an initial increase in the contaminant concentration following the injection of the Isolite®, which was then followed by a decrease to pre-inoculation levels or less. This temporary increase may have been caused by a change in the flow paths when the fractures were created, resulting in a release of sorbed contaminants from the soil.

The injection of inoculated Isolite® appeared to speed the remediation rate of some hydrocarbons with concentrations below 100 ppb. The change in remediation rate with higher concentrations, especially in the 1000 to 10,000 ppb range, was not as evident. However, the amount of data and short length of time between inoculation and sampling may have been insufficient to measure the actual effectiveness with higher concentrations of hydrocarbons.

The downgradient monitoring wells (MW-10, 11, 12) furthest from the source (on the north side of the rail line) had either "no detect" (ND) levels prior to July of 1998 or decreasing amounts of benzene, xylene, EDC, and naphthalene. After the fracturing operation, two of the chemicals increased by a significant amount, then decreased. The latter two chemicals continued to decrease in concentration, with EDC becoming ND by February 1999. The levels were at or below 100 ppb at the time of inoculation.

The monitoring well close to the source of the contamination (MW-1) had a small but steady increase in levels until the end of 1997, when levels started dropping through the middle of June, 1998, two months before inoculation. Indications are that the source was producing a steady flux of contaminants into the system until the end of 1997, when natural remediation began to reduce the levels. Whether the reduced levels (range of 1000 to 21,000 ppb) resulted from a reduction of source contamination or natural microbial action is unknown. No data was collected after inoculation.

East of the center of the plume and downgradient from the source, the monitoring well (MW-8) showed a consistent decrease in levels up to the time of inoculation. Some contaminants that were low levels (100 ppb or less) just prior to injection of inoculated Isolite® were found to be at ND one month after inoculation. Others with larger levels actually increased from the time of inoculation through November of 1998, then all were found to be ND in February of 1999. This monitoring well is at the edge of the plume and indicates injection of inoculated Isolite® for low levels of contaminants (100 ppb or less) to be effective.

Closer to the center of the plume and downgradient of the source, the monitoring well (MW-2) showed a general decrease in levels before inoculation, but no major changes after. These levels were all above 100 to over 3000 ppb. There was again a small increase right after inoculation, but the concentrations then decreased or leveled out. The effectiveness of inoculation is difficult to measure, possibly due to the higher concentration levels.

Directly north of the source area, in the approximate direction of the downgradient, a monitoring well (MW-15) showed no appreciable change in contaminant levels over a 2-month period after inoculation. There was no data collected prior to August, 1998. Again, all of the levels were above 100 to almost 10,000 ppb.

West of the downgradient but still inside the plume, a monitoring well (MW-4) showed a general increase in levels through 1996, then a general decrease up to the time of inoculation. The concentration of the contaminants ranged from less than 100 ppb to 1500 ppb before inoculation. For the three months following inoculation, most levels of contaminants increased, then all levels dropped to ND by February, 1999, except for benzene, xylene, and EDB, which showed some minimal decrease in contamination levels after inoculation. Another monitoring well (MW-9) in the same direction but further from the source had a general decrease in concentration levels before inoculation. After inoculation, some increased while some continued to decrease. All of the contaminant levels were above 10 ppb and some were as high as 2,400 ppb.

Report(s)/Publication(s) (Additional Info Source):

Agra Earth & Environmental "Hydrogeological Investigation", 22 June 1998

Agra Earth & Environmental "Volatile Organic Compounds", 11 Feb 1999

FOREMOST Solutions, Inc. "Historic Summary of Analytical Testing Results", Nov. 1998

FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

FRx, Inc., "Hydraulic Fracturing Summary For Fractures Created at New Mexico Highway Department, Continental Divide, NM", December 1998

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

GWRTAC ID: FRAC0003

Project Name: Industrial Facility, Santa Clara, CA

City: Santa Clara **State/Province:** CA

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620 or www.arstechnologies.com, Company Information, McLaren Hart, Inc., Warren, NJ Company Information, and
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

A pneumatic fracturing well was installed in a vadose zone impacted by VOCs, primarily TCE, at a large private industrial facility in Santa Clara, California. The site geology featured a semi-permeable layer of sandy silts and sandy clays overlying a 'fat' silty clay with very little permeability. During application of standard Soil Vapor Extraction (SVE) technology, the majority of the soil vapor extracted was from the high permeability zones, leaving the lower permeability clay unaffected. Pneumatic Fracturing was applied in successive two-foot intervals to create permeability uniformity across the various zones of the formation. Fractures were injected at depths between 3.5 and 13.5 feet below the ground surface, and the estimated radius of influence of the fractures was 10 to 15 feet.

The project was conducted as a pilot test in July of 1993. A full-scale remedial system incorporating pneumatic fracturing extraction was installed as a result of pilot scale success..

During the pilot test, the rate of air flow increased 3.5 times during extraction tests utilizing the entire fracture well. More dramatic was the increase in permeability in the clay zones, where the permeability increased to 510 times its pre-fracture level. The rate of TCE mass removal increased six times during extraction tests from the fracture well. The greatest increases in TCE mass removal were observed in the clay zones, where the contaminants were removed at a rate of up to 46,000 times greater than the natural unfractured condition. In summary, Pneumatic Fracturing was effective for making the permeability of the formation more uniform, thereby allowing extraction air to flow through and remediate the formerly low permeability clay zones.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic

Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID:	FRAC0065
Project Name:	Industrial Site, Elizabeth, NJ
City:	Elizabeth
State/Province:	NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

At a private site in Elizabeth, NJ, several phases of a Remedial Investigation (RI) were conducted at the site between 1995 and 1999. The RI was undertaken pursuant to the requirements of New Jersey's Industrial Site Recovery Act (ISRA). The client announced closure of the Elizabeth facility in 1995 thereby triggering ISRA.

Results from the RI identified several areas of the site where constituents are present in soil and groundwater at concentrations that warrant remedial action in accordance with NJDEP's requirements. One area represents the source of the dissolved TCE concentrations previously identified in groundwater at the site. Costs were originally determined to remove the source by excavation. Due to the age of the building, demolition, bracing, excavation, and rebuilding of the facility, costs to perform this exceeded one million dollars. Dual phase extraction (DPE) is one of the remedial alternatives under consideration for addressing the TCE source area. As a result, McLaren/Hart conducted a DPE pilot study at the site during August 1999 to evaluate the viability of DPE for remediating the TCE source area. Pneumatic fracturing was applied to enhance the permeability of the formation and thus, increase the effectiveness of the DPE technology.

The subsurface conditions at the site include the following stratigraphic zones: 1) fill material; 2) native silt and clay; 3) sand; 4) silt; and 5) bedrock. The location of the source is in the silty clay with some perched water and an artesian water condition at approximately 16 feet below ground surface (bgs).

A baseline geotechnical evaluation was performed in advance of pneumatic fracturing as a precautionary step to ensure the safety of the building. The tasks associated with the evaluation included a review of as-built drawings, and a pre-fracture condition survey. The baseline geotechnical evaluation specified the allowable movement criteria of the building and provided recommendations for the pneumatic fracturing to minimize potential impacts to the building structures.

Fractures were injected at depths between 8 and 16 feet below the ground surface, and the estimated radius of influence of the fractures was 8 to 15 feet. The maximum heave observed at the columns during the 360 degree fracturing events was ¼ inch. The maximum heave observed during the directional fracturing was ? inch at the column and ¼ inch at the fracture well. Following all fracturing events, the only location indicating residual heave was the doorway near VW-1 at ? inch. No notable architectural damage (i.e., paint chipping or cracks) was observed following any fracturing event.

Relevant findings from the DPE pilot study are summarized as follows:

o Prior to pneumatic fracturing, measurable vacuum influences were apparent only at the nearest vapor monitoring well (PT-1), located a distance of five feet, while operating a vacuum of 15 inches Hg at the DPE well (VW-1). Vapor monitoring wells located at ten feet (PT-2) and 15 feet (PT-3) from VW-1 showed no measurable vacuum influence prior to pneumatic fracturing.

o Pneumatic fracturing was effective in increasing the radius of vacuum influence as indicated by measurable vacuum readings recorded at PT-2 and PT-3 during testing subsequent to fracturing. Directional fracturing appeared to exert the greatest influence to the formation in westerly direction. The decrease in vacuum influence at PT-1 after fracturing indicates an enhancement in permeability as a result of the fracturing. Although pneumatic fracturing was effective, some logistical problems were experienced as a result of the large screen slot size (0.125 inches) required for the fracturing. A significant rate of silt accumulation through the screen impeded efforts to accurately measure air flow rates during initial testing and presented a risk of possible subsidence in the area of VW-1. Consequently, VW-1 was promptly retrofitted with a smaller screen slot size following fracturing to address these issues.

o A vacuum of 15 inches Hg and a resulting air flow rate of 32 scfm provided the most effective operating parameters for DPE during the pilot study. After pneumatic fracturing, vacuums of 5 inches Hg and 10 inches Hg were insufficient to overcome the water column in VW-1. Vacuums higher than 15 inches Hg did not significantly increase the vacuum influences measured in the vapor monitoring wells.

o The collection of vapor samples during the 15 inches Hg constant rate DPE test permitted the calculation of mass removal rates as follows: 0.25 to 0.37 lb/hr for TCE; 0.08 to 0.13 lb/hr for cis-1,2-DCE; and, 0.016 to 0.025 lb/hr for vinyl chloride. The vapor sample analytical results indicated a steady increase in TCE concentrations during the constant rate test.

o Groundwater production during the DPE testing increased after pneumatic fracturing, but was typically low after the water column in VW-1 was evacuated and the formation began to dewater. Groundwater was generated at a rate of approximately 3 gallons per hour during the constant rate test. The collection and analysis of groundwater samples collected from VW-1 during the constant rate test indicated the following range in detected VOC concentrations: 1200 ug/L to 1400 ug/L of TCE; 710 ug/L to 990 ug/L of cis-1,2-DCE; 27 ug/L to 42 ug/L of vinyl chloride; and, 6 ug/L to 8 ug/L of trans-1,2-DCE.

Overall, DPE coupled with pneumatic fracturing enhancement is an effective remedial technology to address the TCE source area at the site. In summary,

o Pneumatic fracturing was effective in enhancing the permeability of the formation and extending the radius of influence.

o DPE was successful in enlarging the unsaturated zone through dewatering to allow the vapor extraction component to operate efficiently.

o DPE with pneumatic fracturing enhancement is a cost-effective approach for treatment of the TCE impacted area in comparison to other remedial technologies (i.e., excavation). Based on results obtained from the pilot study, DPE would generate water at a low rate, and therefore, minimal liquid phase treatment and disposal would be required.

o The treatment system needs to address both the liquid and vapor phase waste streams. The compounds of concern in each waste stream are TCE, cis-1,2-DCE, and vinyl chloride.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0001

Project Name: Industrial Site, Hillsborough, NJ

City: Hillsborough **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Marketing Information

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994, ARS Technologies, Inc., Keyport, NJ, McLaren Hart, Inc., Warren, NJ Company Information, and
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

Pneumatic fracturing is an innovative technology that enhances the in situ removal and treatment of volatile organic compounds (VOCs) in low permeabilty soil and rock formations. The process may be generally described as injecting air into a contaminated geologic formation at a pressure which exceeds the natural in situ stresses, and at a flow rate which exceeds the permeability of the formation. This causes failure of the medium and creates a fracture network radiating from the injection point. Once established, the fractures enhance the permeability of the formation, thereby increasing the flow rate of vapors and liquids through the formation for more efficient contaminant removal or treatment. For an EPA SITE demonstration, pneumatic fracturing was used to enhance a soil vapor extraction system installed in the low permeability siltstones and sandstones underlying an industrial site in Hillsborough, New Jersey. Technologies integrated with the pneumatic fracturing technique included soil vapor extraction, hot gas injection, and groundwater reinjection. The project was performed by the New Jersey Institute of Technology with support from the U.S. Environmental Protection Agency (EPA).

Pneumatic fracturing wells were drilled in the contaminated vadose zone (containing zones of perched water) of a siltstone formation and left as open boreholes. The pneumatic fracturing process was applied to isolated two foot intervals of the formation. Short bursts (less than 20 seconds) of air were injected into the formation at successively deeper intervals of the fracture well to create an intensely fractured unsaturated zone. Each injection extended and enlarged existing fissures in the formation and created new fissures, primarily in the horizontal direction. Fractures were injected at depths between 9.1 and 16.4 feet below the ground surface, and the estimated radius of influence of the fractures was >20 feet. Following fracturing, contaminated vapors were extracted from the fracture well utilizing a mobile vapor extraction system. The demonstration was conducted under the EPA SITE Demonstration Program in the summer of 1992.

The PFE process was observed to increase extracted air flow by more than 600% relative to that achieved in the site formation prior to the application of pneumatic fracturing. Even higher air flow rate increases

(19,000%) were observed when one or more of the monitoring wells were opened to serve as a passive air inlet to enter the formation. The effective radius of influence was observed to increase from 380 square feet to at least 1,254 square feet, an increase of over threefold. Pressure data, collected at perimeter monitoring wells, and surface heave measurements indicate that fracture propagation extended well past the farthest monitoring wells (at 20 feet) to at least 35 feet.

While TCE concentrations in the air stream remained approximately constant at roughly 50 parts per million, the increased air flow rate resulted in an increase in TCE mass removal of 675%. When adjacent monitoring wells were opened to allow a passive ambient air inlet to the formation, the increase in TCE mass removal was 2,300% following the application of pneumatic fracturing. In summary, permeability and TCE mass removal was increased eight times in sealed wells, and in open wells, permeability was increased 175 times and TCE mass removal 25 times. Total VOC mass removed increased from 0.78x10-5 lb-m/min for pre-fracture effluent to 113.6x10-5 lb-m/min.

Additionally, chemical analysis of the extracted air during post-fracture testing showed high concentrations of organic compounds that had only been detected in trace amounts prior to application of pneumatic fracturing. This confirmed that the pneumatic fracturing process had effectively accessed pockets of previously trapped VOCs. An extended vacuum radius of influence was also observed, which will result in a reduction of the number of extraction wells required to remediate the site. The application of PFE should decrease remediation time, and in the case of this site, eliminate the need to excavate or encapsulate the source area. The cost for full-scale remediation was estimated at $307/kg ($140/lb) of TCE removed based on the demonstration and information provided by the developer.

Work is continuing to expand the applications of pneumatic fracturing to other in situ technologies such as pump and treat, bioremediation, and thermal treatment. Experience is now available in both the vadose and saturated zones, and in several geologic formations including clay, silt, silty sand, cemented sand, sandstone, and siltstone.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Marketing Information

Frank, Uwe, "Pneumatic Fracturing Increased VOC Extraction Rate." Tech Trends. December 1993. EPA/542/N-93/010.

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Hasbach, A., Sr. Ed., 1993, "Pneumatic Fracturing Boosts Subsurface Cleanup" Pollution Engineering, April 15, 1993.

Liskowitz, John J.; Schuring, John; and Mack, James. "Application of Pneumatic Fracturing Extraction for the Effective Removal of Volatile Organic Compounds in Low Permeable Formations", National Ground Water Association Eastern Regional Ground Water Focus Conference Proceedings, September 1993.

Mack, J., 1992, "Breaking Up is Easy to Do", Soils, December, 1992.

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McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

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

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

U.S. Environmental Protection Agency, "Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase 1, Applications Analysis Report". U.S. Environmental Protection Agency, Superfund Innovative Technology Evaluation, Risk Reduction Engineering Laboratory, Office of Research and Development, Cincinatti, OH, EPA/540/AR-93/509, 1993.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID: FRAC0028

Project Name: Industrial Site, Roseland, NJ

City: Roseland **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111.

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com; and, McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information:

Pneumatic fracturing was used to enhance the efficiency of a combined vapor extraction system installed at an industrial site contaminated with TCE and DCE, in Roseland, New Jersey at a private industrial site by the New Jersey Institute of Technology. The geology consisted of clayey sand and silty sand. Pneumatic injections were applied at shallow depths (4 to 7 feet), and the estimated radius of influence of the installed fractures was 9 feet. The pilot test was completed in July 1991.

Pneumatic fracturing was effective in enhancing the efficiency of the vapor extraction system installed at the Roseland site. The average (air) flow increased 5 to 70 times after fracturing. The maximum fracture radius was 28 feet. The maximum fracture aperture during injection was 1.83 inches. An 80% reduction in contaminants in target monitor wells was observed six months after application of the Pneumatic Fracturing technology.

Report(s)/Publication(s) (Additional Info Source):

Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620.

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information

GWRTAC ID: FRAC0088

Project Name: Jurgason Gage & Valve Co. - Manufacturer, MA

City: Burlington **State/Province:** MA

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information, and from Gehl, R.W. "Hydraulic Enhancement and Control Strategies for Remediation of a Contaminated Fractured Bedrock Aquifer":

Release at this manufacturing facility in Burlington, Massachusetts was reportedly related to oil from machining process metal cuttings, placed in perforated trash dumpsters, would leak from the dumpsters. The practice reportedly occurred between 1956 to 1986. Site investigation revealed groundwater contamination by VOCs and an oil product floating on the water table. A blast-fractured trench was installed at this Massachusetts manufacturing site by Haley & Aldrich, Inc. in 1994. The blast-fractured trench was installed to recover contaminated groundwater.

Soil overburden on the site averages 13+/- feet thick and is composed of glacially deposited sands, silts, and gravels. The overburden overlays gabbro and granitic bedrock. Groundwater exists within the fractured bedrock with radial flow away from the site to the east, south, and west. The rock is moderately fractured within the top 10 to 15 feet of the bedrock surface in the eastern and western portions of the property, while the central portion of the property contains only poorly-fractured bedrock. Fracture density within the rock decreases sharply with depth. The bedrock surface drops off towards the west, east, and south, where till is overlain by stratified sand and gravel deposits. Based on permeability tests, a median hydraulic conductivity of 1.2 x 10-5 cm/second was calculated for wells installed in the upper bedrock, and 4.5 x 10-9 cm/second for wells installed in the deep bedrock. The total estimated flux of groundwater from the property is on the order of 2.5 gpm. In January 1990, the maximum levels of total VOCs were approximately 3.6 mg/L on site, and 0.9 mg/L off site. The primary contaminants are TCE and its breakdown products, the cis- and trans-isomers of 1,2-DCE and vinyl chloride. A layer of degraded cutting oil was found in monitoring wells east of the plant building.

After conducting three pumping tests in bedrock to illustrate the heterogeneity and anisotropy of the upper fractured bedrock zone, it was realized that it would be difficult to reover groundwater from unconnected zones, as drawdown patterns did not suggest a measurable orientation reflective of a fracture trend. Well yields from all pumping wells used in the test program were low; long-term sustained yields were estimated at 0.2 and 0.06 gpm for wells in the western and eastern plant area, and to the south of the plant building, sustained yields less than 0.03 gpm were estimated.

A controlled blasting method was employed to create a targeted zone of increased hydraulic conductivity in the bedrock. A line of shot holes space about four feet apart were drilled in the desired area of ground-water capture to the east and west of the main plant building, with each hole extending about 15 feet into bedrock. A continuous zone of highly-fractured rock was thus created to facilitate the interception of contaminated groundwater. A limited number of recovery wells were installed within the highly-fractured zone to serve as groundwater and oil product recovery points.

The trench installed was blasted to a depth of 30 feet below top of bedrock and is 650 feet long, corresponding to a sidewall area of 19,500 ft2. Pre-blast well yields were 0.1 gpm, with post-blast well yields increasing to 4 gpm, for a ratio of pre/post-blast yields of 40. The controlled blasting technique has been demonstrated to effectively control groundwater migration.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0045

Project Name: Laidlaw Site, Sarnia, Ontario, Canada

City: Sarnia ***State/Province:*** ONTARIO

Report(s)/Publication(s) (GWRTAC Source):

U.S. DOE, Subsurface Contaminants Focus Area, February 1998, "Hydraulic and Pneumatic Fracturing" OST Reference # 1917 (Hydraulic Fracturing), OST Reference # 1916 (Pneumatic Fracturing), available at http://em-50.em.doe.gov/ifd/scfa/itsrs/hydr/beginning.htm.

Project Summary:

The following text was excerpted from U.S. DOE, Subsurface Contaminants Focus Area, February 1998, "Hydraulic and Pneumatic Fracturing" OST Reference # 1917 (Hydraulic Fracturing), OST Reference # 1916 (Pneumatic Fracturing), available at http://em-50.em.doe.gov/ifd/scfa/itsrs/hydr/beginning.htm:

At the Laidlaw Site in Sarnia, Ontario, a sheet-pile test cell was constructed in a clean area 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.

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

Report(s)/Publication(s) (Additional Info Source):

U.S. DOE, Subsurface Contaminants Focus Area, February 1998, "Hydraulic and Pneumatic Fracturing" OST Reference # 1917 (Hydraulic Fracturing), OST Reference # 1916 (Pneumatic Fracturing), available at http://em-50.em.doe.gov/ifd/scfa/itsrs/hydr/beginning.htm.

GWRTAC ID: FRAC0053

Project Name: LASAGNA, Cincinnati, OH

City: Cincinnati **State/Province:** OH

Report(s)/Publication(s) (GWRTAC Source):

Davis-Hoover, W., Ph.D., "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206

Project Summary:

The following text was excerpted from "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", Wendy Davis-Hoover, Ph.D., U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206:

Using DOD and DOE sites, the United States Environmental Protection Agency with Monsanto, DuPont, and General Electric successfully developed and tested a layered process, Lasagna TM , to destroy trichloroethene (TCE) and its byproducts in soils. Removal of TCE from tight clay soils has been technically difficult and expensive. The advantage of this process is that it leads to complete destruction of TCE and its toxic byproducts with little personnel exposure and minimal above ground equipment while not using excavation. This allows for little disturbance of normal strategic operations. Use of this technology with bioremediation can lead to active scavenging of contaminants and perhaps residual treatment if recontamination occurs. The LasagnaTM technique uses hydraulic fracturing (pumping material into the contaminated soil to form a 1 inch pancake-like lense to use as electrodes or treatment zones) to allow electroosmosis movement (using a voltage gradient across the soil, the resulting movement of water causes movement of contaminates) of the TCE into treatment zones for biodegradation or dechlorination in place, lessening the costs of longer term treatment or monitoring and lessening the exposure to TCE.

Report(s)/Publication(s) (Additional Info Source):

Davis-Hoover, W., Ph.D., "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206

GWRTAC ID: FRAC0052

Project Name: LASAGNA, Offutt Air Force Base, NE

City: Offutt AFB **State/Province:** NE

Report(s)/Publication(s) (GWRTAC Source):

Davis-Hoover, W., Ph.D., "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206

Project Summary:

The following text was excerpted from "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", Wendy Davis-Hoover, Ph.D., U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206:

Using DOD and DOE sites, the United States Environmental Protection Agency with Monsanto, DuPont, and General Electric successfully developed and tested a layered process, Lasagna TM , to destroy trichloroethene (TCE) and its byproducts in soils. Removal of TCE from tight clay soils has been technically difficult and expensive. The advantage of this process is that it leads to complete destruction of TCE and its toxic byproducts with little personnel exposure and minimal above ground equipment while not using excavation. This allows for little disturbance of normal strategic operations. Use of this technology with bioremediation can lead to active scavenging of contaminants and perhaps residual treatment if recontamination occurs. The LasagnaTM technique uses hydraulic fracturing (pumping material into the contaminated soil to form a 1 inch pancake-like lense to use as electrodes or treatment zones) to allow electroosmosis movement (using a voltage gradient across the soil, the resulting movement of water causes movement of contaminates) of the TCE into treatment zones for biodegradation or dechlorination in place, lessening the costs of longer term treatment or monitoring and lessening the exposure to TCE.

Report(s)/Publication(s) (Additional Info Source):

Davis-Hoover, W., Ph.D., "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206

GWRTAC ID: FRAC0051

Project Name: LASAGNA, Rickenbacker Air National Guard Base, OH

City: Rickenbacker ANGB **State/Province:** OH

Report(s)/Publication(s) (GWRTAC Source):

Davis-Hoover, W., Ph.D., "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206

Project Summary:

The following text was excerpted from "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", Wendy Davis-Hoover, Ph.D., U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206:

Using DOD and DOE sites, the United States Environmental Protection Agency with Monsanto, DuPont, and General Electric successfully developed and tested a layered process, Lasagna TM , to destroy trichloroethene (TCE) and its byproducts in soils. Removal of TCE from tight clay soils has been technically difficult and expensive. The advantage of this process is that it leads to complete destruction of TCE and its toxic byproducts with little personnel exposure and minimal above ground equipment while not using excavation. This allows for little disturbance of normal strategic operations. Use of this technology with bioremediation can lead to active scavenging of contaminants and perhaps residual treatment if recontamination occurs. The LasagnaTM technique uses hydraulic fracturing (pumping material into the contaminated soil to form a 1 inch pancake-like lense to use as electrodes or treatment zones) to allow electroosmosis movement (using a voltage gradient across the soil, the resulting movement of water causes movement of contaminates) of the TCE into treatment zones for biodegradation or dechlorination in place, lessening the costs of longer term treatment or monitoring and lessening the exposure to TCE.

At the Rickenbacker Air National Guard Base (formerly the Rickenbacker Air Force Base) near Columbus, Ohio, electroosmosis was conducted between an anode of titanium mesh placed upon the ground surface and a cathode composed of a horizontal graphite-filled fracture created by hydraulic fracture at a depth of 4 m below the ground surface. In the unsaturated zone, liquids were also pumped out of the cathode and recirculated to the anode to maintain a downward hydraulic head gradient and liquid flow. Two types of remediation zones between the electrodes were created by horizontal fracturing methods, an iron wall (not discussed here), and a biologically active fracture.

For this bioremediation of the TCE, a single fracture consisting of granular activated carbon inoculated with a consortium of methanotrophic TCE degrading soil bacteria was created by hydraulic fracture between the electrodes within the contaminated clay material at 240 cm depth. These bacteria produce the enzyme soluble methane monooxygenase which is involved in methane utilization but can, fortuitously, dechlorinate TCE.

After 116 days of electroosmosis to transport TCE into the remediation zone, biodegradation within the zone was stimulated for 70 days by the continuous injection of 3 % methane in air into the treatment zone. Then both electroosmosis and methanotrophic biodegradation were practiced simultaneously. After 677 days (to Nov. 23, 1998), the concentration of TCE in the Biocell soil was reduced to a median of non-detect ppm. During the same time period, in the untreated but monitored natural attenuation area, increases in TCE concentrations were observed. Populations of methanotrophic bacteria were established and maintained in the treatment zone and may have moved into the contaminated soils, preferring the direction of the anode.

Report(s)/Publication(s) (Additional Info Source):

Davis-Hoover, W., Ph.D., "In Place Biological Destruction of TCE in Soils: Horizontal Lasagna", U.S. Environmental Protection Agency National Risk Management Research Laboratory, Cincinnati, OH, phone (513) 569-7206

GWRTAC ID: FRAC0046

Project Name: Linemaster Switch Superfund Site, Woodstock, CT

City: Woodstock **State/Province:** CT

Report(s)/Publication(s) (GWRTAC Source):

U.S. DOE, Subsurface Contaminants Focus Area, February 1998, "Hydraulic and Pneumatic Fracturing" OST Reference # 1917 (Hydraulic Fracturing), OST Reference # 1916 (Pneumatic Fracturing), available at http://em-50.em.doe.gov/ifd/scfa/itsrs/hydr/beginning.htm:

Project Summary:

The following has been excerpted from:

Fuss & O'Neill, Inc. and FRx, Inc., "Soil Fracturing Pilot Test Report, Linemaster Switch Corporation, Woodstock, Connecticut", submitted to US Environmental Protection Agency Region 1, February 1996.
Fuss & O'Neill, Inc. and FRx, Inc., "Phase 1A Area Fracturing Report, Linemaster Switch Corporation, Woodstock, Connecticut", submitted to US Environmental Protection Agency Region 1, November 1997.
Hart, Philip H., "Dewatering and Soil Vapor Extraction Using Hydraulic Fractures", Masters Thesis, Civil and Environmental Engineering, University of Cincinnati, Cincinnati, 1997.

From the late 1960's through the 1970's trichloroethylene (TCE) and other solvents were discharged into a shallow dry well in fine-grained glacial till at the Linemaster Switch Corporation facility in Woodstock, Connecticut.By the late 1980's, solvents had migrated into an underlying fractured bedrock aquifer and were detected in numerous drinking water wells on adjacent properties. The site was placed on the National Priorities List in 1990.

A bedrock aquifer interim removal and treatment system has been operated successfully since 1992. Since 1993, no water sample collected from drinking water wells on adjacent properties has tested positive for the presence of contaminants. However, the Record of Decision (ROD) for the site requires remediation of contaminated soils that continue to act as a source of contamination for the bedrock aquifer. The remedial approach identified within the ROD involves the application of dual phase vacuum extraction (DVE) to dewater the unconsolidated deposits immediately surrounding the source location and subsequent soil vapor extraction to remove volatile organic compounds, including TCE.

Previous investigations indicated that enhancement of conventional DVE fluid extraction methods is necessary due to the low permeability of the glacial till deposits underlying the target area. Consequently, hydraulic fractures were created.

Geology
Overburden consists of dense, compact, unconsolidated lodgment till composed of a poorly-sorted and non-stratified mixture of clay, silt, sand, gravel, and boulders. Color contrast permits definition of an upper and lower unit within the till. The upper till, which is brown, has a slightly larger grain size than the lower, gray till. The transition is distinct, occurring 15 ft to 18 ft bgs. Thickness of the overburden grades from 50 ft to 10 ft across the site, with an average thickness of 48 ft within the source area.

The Linemaster facility sits upon a bedrock high, which consists of ancient schist that has been intruded by granitic pegmatite. Cores show the schist to be moderately to slightly weathered whereas the granite-pegmatite is only slightly weathered.

Natural fractures occur in both the overburden and the bedrock. Oxidation patterns in one sample of the till delineated the 39° dip of a natural fracture. Additional fractures were not noticed, although a network of fractures is assumed to exist in the till. Fractures in core samples of the bedrock had greater aperture in the schist than in the granite - pegmatite. In any case, fractures serve as the principal flow paths.

Hydrology

The Linemaster facility sits upon a topographical as well as a hydrological high. In the vicinity of the contamination source, the general pattern of horizontal groundwater flow is towards the east and northeast. This pattern can be found in the till and bedrock, regardless of depth. Estimated flow velocities are shown in Table 1. The overburden, which is a glacial till, serves as the only source of recharge to the bedrock aquifer but also acts as a confining unit. Groundwater in the till typically rises to 6 to 10 ft bgs, with seasonal variation.

Table 1. Estimated Horizontal Groundwater Velocities in feet per day. The general direction of flow is to the E and NE.

Unit	Minimum	Maximum
Overburden	4 x 10-4	1 x 10-1
Shallow Bedrock	2 x 10-3	3 x 10-2
Deep Bedrock	4 x 10-2	8 x 10-1

The hydraulic conductivity, vertical and horizontal, of the shallow bedrock is greater than the deeper bedrock, and both are greater than the overlying glacial till. The upper and lower unit of the till have permeabilities that contrast by a half order of magnitude. The data shown in Table 2 were derived from slug tests and packer tests. Core measurements report permeabilities to be less by several orders of magnitude. The scale dependency of permeability at the site reflects the importance of naturally occurring fractures as transport pathways.

Table 2. Geometric Mean Hydraulic Conductivity in feet per day. These data were generated by slug and packer tests.

Unit	k
Upper Till	1.5 x 10-2
Lower Till	3 x 10-3
Shallow Bedrock	4.9 x 10-1
Deep Bedrock	3.4 x 10-1

Contaminants

TCE is the contaminant in greatest quantity, largest concentration, and most widespread distribution at the Linemaster site. It, therefore, serves as the benchmark for characterization and assessment. Clean-up goals for TCE content of soil have been set at 5 ug/kg, assuming that groundwater in contact with the soil will not dissolve more than 5 ug/l. Consequently groundwater data are often utilized to define zones of contaminated soil.

A plume of TCE can be charted from the location of the dry well, which was the source of contamination, vertically downward and hydrologically down gradient. Within the till, which is the target for the fracture enhanced extraction processes, the 5 ug/kg isopleth extends to or very close to the bedrock. In area, the plume approximates an ellipse of 310 x 150 ft.

As is commonly the case with contaminants that are denser than water, the concentrations reported in samples vary wildly in space and time. Below the dry well, which served as the source of contamination, groundwater samples recovered from 20 ft and 45 ft bgs (till - bedrock interface) contained 51,000 ug/l and 16,000 ug/l respectively. A few feet down gradient samples contained 220,000 ug/l. Recently, samples recovered from 12.5, 20, 27.5, 35, and 39 ft bgs from a location within 20 feet of the location of the dry well contained 79,000, 58,000, 86,000, 361,000, and 29,000 ug/l respectively.

Although samples containing more than 43,000 ug/l have been recovered from the deep bedrock, remediation methods enabled by hydraulic fracturing focus on the overlying glacial till. Substantial solvent mass remains in the till, and the till continues to acts as the source for bedrock contamination.

Fracture Placements
For the purpose of delineating treatment zones, the source area is defined by the limit of soil contaminated by TCE at concentrations exceeding 1000 ug/kg. Fractures were created in two episodes. In October 1995 sand-filled fractures were created at two adjacent locations on the down-gradient edge of the source area. Fractures were created at 5 foot intervals from 8 ft bgs to 43 ft bgs (bedrock) in one well, while a 10 foot interval was utilized in the other well. Dewatering and SVE operations were conducted with these fractures to demonstrate the applicability of the technology and to assess various operational practices. In November of 1996 and July of 1997, fractures were created at six more locations throughout the source area. These fractures were created at 7.5 ft spacing from wells located approximately 35 ft apart.

The procedures used to create the fractures closely followed the methods developed by US EPA development projects during the late 1980s and early 1990s. EPA publications (1993 and 1994) describe these in detail. In a major but not significant variation from these procedures, multiple fractures were created from a single well by cutting a slot in the well casing and isolating the slot with packers. The cost of drilling wells in the very dense till necessitated this approach. Also, a high-pressure hydraulic jet that directed fracture azimuth and influenced ultimate fracture form was used to mitigate possible interaction between fractures and surface structures.

The fractures created in 1995 contained 800 to 4200 lb of filter pack sand that was carried in guar gel based slurries containing 25% to 35% solids. Surface deformation and injection pressure characteristics suggested the fractures were horizontal or sub-horizontal with radii of 20 to 25 ft and apertures on the order of ½ inch. This assessment of fracture form was confirmed by soil samples collected during the placement of several multilevel piezometer nests around each well. In general, fractures created in the upper 15 to 20 feet of the glacial till were horizontal and symmetric while deeper fractures climbed steeply and were asymmetric with respect to the well. These variations from an idealized fracture form are due to local geological conditions that can not be assessed easily and thus justified pilot testing. Even though the pilot test fractures were not true to ideal form, they did appear to function adequately during testing of recovery processes.

Slightly smaller fractures, typically 1200 to 1500 lb, were created in 1996 and 1997. Approximately the same interval, ~10 to ~45 ft bgs, was targeted with fractures spaced 7.5 ft apart. As during the 1995 work, the fracture form was evaluated by a combination of surface deformation measurements, pressure signals, and exploration during subsequent sampling and installation of piezometers. In comparison to the 1995 fractures, the later fractures were commensurately smaller in extent but not substantially less in aperture. Otherwise, similar forms were created.

Methods for Verifying System Performance
A variety of methods have been and will be used to assess remedial process performance. Detection of requisite physical conditions, i.e. depression of the water table and vapor movement, has been paramount. Consequently, eleven multi-level piezometer nests were constructed around and among the fractures created in 1995. Each nest consisted of an 8-inch diameter borehole that contained as many as five 1-inch diameter x 6 inch long screens, each placed within 1 to 1.5 ft intervals of filter pack sand and isolated by bentonite and non-shrinking grout. These nests were located to complement existing monitoring wells in tracking the progression of the cone of depression in the water table. In addition these nests also permit assessment of head and pressure gradients - especially vertical gradients - that are induced around fractures.

Ongoing operations are evaluated by measurements made at 39 multi-level piezometers, which are configured to measure either water level or air pressure, and 36 time domain reflectometry probes to measure soil moisture changes, which have been installed in the wall of two borings between 12 ft bgs and the top of bedrock. In the end, effectiveness of the system will be assessed on the basis of mass removal. Contaminant removal will be monitored by in-line GC analysis of extracted vapor, periodic groundwater analysis, and datalogging of flow and pressure.

Operational Results

Pilot Tests

Operations performed with fractures created in 1995 showed that the soil column could be dewatered and that vapor flow could be induced in the newly exposed vadose soil. This pilot test utilized fractures at two locations about 70 ft apart. Several nests of multilevel piezometers were constructed around and among the fractures, and a of multilevel piezometer nest installed midway between the two locations also served as an experimental control that generated the comparable operating characteristics of a convention well at the site.

The pilot test was conducted in five sequential stages, as defined in Table 3.

Table 3. Pilot Test Operations and Results

Stage	Duration	Configuration
I	220	Dewater w/ 20+ ft drawdown
II	110	Vacuum enhanced dewater w/ 20+ ft drawdown + 200+ inch H_2O
III	33	Suction / air flow tests Location "B"
IV	46	Suction / air flow tests Location "A"
V	18	Suction / air flow tests conventional well

During Stage I, the aggregate discharge of water amounted to 0.1 and 0.2 gpm for the two locations. Upon application of vacuum during Stage II, discharge increased by 10% and 70%, respectively, for the two locations. In each case, discharge exceeded the performance of the previously tested control well by more than an order of magnitude.

The head distribution around both locations changed from a small downward gradient of 0.17 ft/ft prior to pumping to gradients of similar magnitude but orientation commensurate with flow into the fractures during the pilot tests. Consequently head measurements indicated downward and upward gradients, along with a horizontal gradients toward the extraction wells from which the fracture emanated.

Dewatering lowered the water table in an existing monitoring well offset 82 ft and 115 ft from Locations "A" and "B", respectively. The water table in monitoring wells approximately 45 ft up-gradient fell by nearly 3 ft. In contrast, a previous and longer term pumping test in a conventional well caused only 0.2 feet of drawdown in a monitoring well offset by 30 ft.

The suction and vapor flow tests conducted in Stages III and IV showed that only desaturated fractures conducted air at significant rates. Given the limited duration of dewatering, only the uppermost fracture at each location was completely exposed to air. Approximately 25 cfm vapor was discharged from each of these when suction of 200 inches water was applied. At least an order of magnitude less discharge was obtained from the deeper, saturated fractures as well as from the conventional well.

Table 4. Comparison of Vapor Discharge Capacity

Discharge Point	Rate: induced potential (m3/d/kPa2)
Upper Fracture, Location "A"	0.46
Lower Fractures, Location "A"	0.49
Upper Fracture, Location "B"	0.26
Lower Fractures, Location "B"	0.05
Control Well	0.0085

A consistent comparison of discharge capacity normalizes the magnitude of flow by induced potential. For vapor, which must be considered a compressible fluid, the rigorous definition of flow potential is the square of the applied suction. Table 4 shows that desaturated fractures have an order of magnitude better capacity than other configurations.

Suction in the uppermost fractures influenced the suction field in the shallow till up to 45 ft from the well and as deep as 14 ft below the surface near the well. In contrast, suction applied to the conventional well could not be detected more than 5 ft away from the screen.

Full Scale Operations

Operations in the entire source area, i.e. use of the six additional fracture locations, began in 1998, after construction of surface facilities. Dewatering from seven of the eight fracture locations began in April with the goal of draining water from the till down to the bedrock interface. By the end of summer, about 50% of the desired depression of the water table had been accomplished. Vacuum enhanced dewatering and vapor recovery began in December and continues. Contaminant recovery from the source area averages about 1 lb/day. This contrasts to the1 oz/day recovery from the interim bedrock groundwater removal and treatment system.

After DVE processes have reached steady-state, low pressure air will be injected into selected fractures. The inter-well and intra-well displacements resulting from these "push-pull" operations are expected to enhance recovery of contaminants.

Results are evaluated periodically. The first annual report of operating data will be issued in March 2000. The evaluations will be directed at determining the viability of remediation, expansion or contraction of the source area, and feasibility of additional enhancements. After five years of operation there will be an extensive soil sampling program that will serve as a compliance demonstration.

Report(s)/Publication(s) (Additional Info Source):

U.S. DOE, Subsurface Contaminants Focus Area, February 1998, "Hydraulic and Pneumatic Fracturing" OST Reference # 1917 (Hydraulic Fracturing), OST Reference # 1916 (Pneumatic Fracturing), available at http://em-50.em.doe.gov/ifd/scfa/itsrs/hydr/beginning.htm:

U.S. Environmental Protection Agency, September 1993, Technology Evaluation and Applications Analysis Reports, University of Cincinnati/Risk Reduction Engineering Laboratory: Hydraulic Fracturing Technology, EPA/540/R-93/505.

U.S. Environmental Protection Agency, 1995, "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/003, available at http://www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html.

Whiting, Timothy L., William W. Slack, and Lawrence C. Murdoch "Dual Phase Extraction with Hydraulic Fractures" First Chlorinated and Recalcitrant Compound Conference, Monterey, California, 1998. The slides and presentation text are available at http://www.frx-inc.com/linemaster.html.

GWRTAC ID: FRAC0043

Project Name: Loring Air Force Base, ME

City: Loring AFB **State/Province:** ME

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Lane Jr., J.W., F.P. Haeni, S. Soloyanis, G. Placzek, J.H. Williams, C.D. Johnson, M.L. Bursink, P.K. Joesten, and K.D. Knutson, "Geophysical Characterization of a Fractured-Bedrock Aquifer and Blast-Fractured Contaminant-Recovery Trench", in Proceedings on the Application of Geophysics to Engineering and Enviromental Problems, Compiled by R.S. Bell and M.H. Cramer, April 28-May 2, 1996, Keystone, CO, sponsored by Environmental and Engineering Geophysical Society

Project Summary:

The following text is excerpted from the Loring IRP Fact Sheet, The Loring Air Force Base Installation Restoration Program Vol. 2, No. 2; and,
Lane Jr., J.W., F.P. Haeni, S. Soloyanis, G. Placzek, J.H. Williams, C.D. Johnson, M.L. Bursink, P.K. Joesten, and K.D. Knutson, "Geophysical Characterization of a Fractured-Bedrock Aquifer and Blast-Fractured Contaminant-Recovery Trench", in Proceedings on the Application of Geophysics to Engineering and Enviromental Problems, Compiled by R.S. Bell and M.H. Cramer, April 28-May 2, 1996, Keystone, CO, sponsored by Environmental and Engineering Geophysical Society:

The Air Force Base Converstion Agency (AFBCA) is conducting a pilot study for remediation of fuel contamination in a fractured bedrock aquifer at a fire training area (FTA) at the former Loring Air Force Base (AFB), in Aroostook County, Maine. The FTA was used from 1952 to 1988, resulting in contamination of soil and groundwater by petroleum products and solvents, existing as LNAPL and in the dissolved phase. Blast fractuing was used to create an in situ recovery "trench" allowing water to flow more easily in the artificially fractured bedrock, in comparison to the naturally fractured bedrock. Wells were installed in the trench (actually a rubble zone in the bedrock) to remove the petroleum products. The AFBCA, U.S. EPA, and Maine Department of Environmental Protection worked over a year with AFCEE and the USGS to design and implement the pilot project.

The depth to groundwater at the site occurs in the bedrock about 20 feet bgs. The FTA is underlain by till and fractured bedrock. The till consists of 3 to 6 m of dense silty sand and sandy silt. The bedrock that underlies the FTA is likely the lower member of the Carys Mill Formation, composed of interbedded layers of dark to pale gray, laminated and non-laminated micritic limestone and light gray, massive, rusty-orange weathered calcareous slate and pelites with abundant calcite veins. The top of bedrock is about 6 m bgs, and the water table is within the bedrock. The hydraulic gradient in the upper bedrock is north-northeast at the site.

Groundwater flows through fractures and other bedrock openings. The blast-fractured recovery zone is 150 feet long, ten feet wide, and 70 feet deep, and was created in August of 1995. The trench was created by blasting three rows of explosive-filled boreholes along a 50-m "line". The rows were about 1.5 m apart, and boreholes within a row were about 1 m apart and 21 m deep. Wells installed in the blast-fractured trench will be pumped to recover LNAPLs.

The USGS confirmed through geophysical testing that the rubble zone created by the blast fracturing was contained within these design dimensions. Blast-induced porosity in the recovery trench was estimated from the borehole-radar data to be 13.5+/-5 percent at the midpoint of the trench, decreasing to 7.3 +/-6 percent at the northwestern end. Post-blast effects on the hydrology of the are adjacent to the recovery trench include 1. A decline in static water levels; 2. Order-of-magnitude increases in upward flow in two wells; 3. Reversal of flow directions in two wells; 4. Order-of-magnitude increases in the estimated transmissivity of three wells; and, 5. An estimated increase in aquifer secondary porosity to two percent near the trench. These effects, from geophysical characterization, are consistent with increased porosity and permeability in the blast-fractured recovery trench and with increased fracture transmissivity near the recovery trench. The increased fracture transmissivity resulted from an apparent hydraulic cleaning that occurred when water was ejected out of wells near the trench during the blast.

Three 70-foot deep recovery wells were installed in the trench, one at each end and one in the middle. Two pumps will be installed in each well; a submersible pump to recover groundwater, and a skimmer pump to recover LNAPL. Treated groundwater will be reinjected into bedrock upgradient of the LNAPL plume in an attempt to push LNAPL toward the recovery trench, and thus enhance recovery. System startup was scheduled for November 1995.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Lane Jr., J.W., F.P. Haeni, S. Soloyanis, G. Placzek, J.H. Williams, C.D. Johnson, M.L. Bursink, P.K. Joesten, and K.D. Knutson, "Geophysical Characterization of a Fractured-Bedrock Aquifer and Blast-Fractured Contaminant-Recovery Trench", in Proceedings on the Application of Geophysics to Engineering and Enviromental Problems, Compiled by R.S. Bell and M.H. Cramer, April 28-May 2, 1996, Keystone, CO, sponsored by Environmental and Engineering Geophysical Society

GWRTAC ID: FRAC0008

Project Name: LUST Site near Dayton, OH

City: Dayton ***State/Province:*** OH

Report(s)/Publication(s) (GWRTAC Source):

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992;
Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994; and,
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

The hydraulic fracturing techology entered the SITE Demonstration Program in July 1991 and the demonstration was completed in September 1992. Pilot-scale feasibility studies have been conducted in Dayton, Ohio, where the hydraulic fracturing process has been integrated with in situ bioremediation at a LUST site. The fracture is created when fluid is pumped down a borehole until a critical pressure is reached to fracture the soil. Sand-laden slurry is then pumped into the fracture to create a highly permeable pathway that enhances delivery of the bioremediation organisms

At the Dayton Site, six underground storage tanks were removed prior to fracturing work. Soil contaminants included BTEX and other petroleum hydrocarbons. The site is underlain by stiff sandy to silty clay with traces of gravel. Hydraulic fractures were placed at depths of 2.1, 2.4, 3, and 3.7 m (4, 6, 8, and 10 feet) bgs in one well. Water containing hydrogen peroxide and biological nutrients was introduced into the fractured well and an unfractured well.

Soil samples were collected at distances of 1.5, 3, and 4.6 m (5, 8 and 15 feet) from the wells using a split spoon sampler before and during remediation. The sample from each spoon was analyzed for moisture content, BTEX, total petroleum hydrocarbons (TPH), number of hydrocarbon degraders (colony forming units or CFUs), and microbial metabolic activity.

Fluid flow rates into the fractured well were 25 to 40 times greater than into the unfractured well, and this difference clearly affected the moisture in the soil. After one month, soil moisture content 1.5 m (5 feet) from the fractured well was 1.4 to 4 times greater than the unfractured well. Moisture content generally was greater near the fracture, with the largest increase near the uppermost fracture. The same trends in moisture content were also observed 3 and 4.6 m (10 and 15 feet) from the wells.

Percent Degradation at the Dayton Site

Percent Degradation After One Month

	Benzene	Ethylbenzene	Toluene	TPH
At 5' From Fractured Well	NI*	97	NI	77
At 5' From Unfractured Well	NI	8	NI	0
At 10' From Fractured Well	47	79	NI	58
At 10' From Unfractured Well	NI	72	NI	27
At 15' From Fractured Well	64	73	NI	51
At 15' From Unfractured Well	NI	NI	NI	NI

Percent Degradation After Six Months

	Benzene	Ethylbenzene	Toluene	TPH
At 5' From Fractured Well	80	60	NI	71
At 5' From Unfractured Well	NI	37	NI	55
At 10' From Fractured Well	12	NI	NI	54
At 10' From Unfractured Well	NI	90	NI	67
At 15' From Fractured Well	38	56	NI	68
At 15' From Unfractured Well	NI	NI	NI	25

* NI = No Impact

Effectiveness of the bioremediation was measured by reduction in BTEX and TPH concentrations in soil samples. Bioremediation at 5 feet from the fractured well after 1 month was 97% for ethylbenzene and 77% for total petroleum hydrocarbons compared with 8% and 0% respectively near the unfractured well. After six months, benzene, ethylbenzene, and TPH continued to have a higher degradation percentage near the fractured well than the unfractured well. However, considerable variation among the degradation data is evident and may be due to local variations in contaminant concentration that was unresolved by sampling.

Report(s)/Publication(s) (Additional Info Source):

Murdoch, L.C. "Hydraulic Fracturing of Soil During Laboratory Experiments. Part 1: Methods and Observations." Geotechnique, 43 (2), p 255-287.

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency. Technology Evaluation and Applications Analysis Reports: University of Cincinnati/Risk Reduction Engineering Laboratory: Hydraulic Fracturing Technology. EPA/540/R-93/505, September 1993.

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

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

U.S. Environmental Protection Agency, 1995, "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/003, available at http://www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html.

GWRTAC ID: FRAC0087

Project Name: Manufacturer, ME

City:

State/Province: ME

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information:

Blast-fractured trenches were installed at this Maine manufacturing site by Haley & Aldrich, Inc. in 1994. The blasted bedrock zone, created in schist bedrock, was 200 feet long and 35 feet in depth, corresponding to a sidewall area of 7,000 ft2. Pre-blast well yields were 0.25 gpm, with post-blast well yields increasing to 8 gpm, for a ratio of pre/post-blast yields of 32.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0005

Project Name: Manufacturing Facility in NY

City:

State/Province: NY

Report(s)/Publication(s) (GWRTAC Source):

Plaines, A.L., R.J. Piniewski, G.D. Yarbrough, Terra Vac Corporation, USA "Integrated Vacuum Extraction/Pneumatic Soil Fracturing System for Remediation of Low Permeability Soil", Copyright 1992, Hazardous Materials Control Resources Institute, Greenbelt, MD

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC and
Plaines, A.L., R.J. Piniewski, G.D. Yarbrough, Terra Vac Corporation, USA "Integrated Vacuum Extraction/Pneumatic Soil Fracturing System for Remediation of Low Permeability Soil", Copyright 1992, Hazardous Materials Control Resources Institute, Greenbelt, MD:

Pneumatic fracturing is used to supplement soil vapor extraction in low permeability formations where diffusive flow of soil vapor is poor. Air at high pressure is injected into the zone of low permeability via fracturing probes. The high pressure air fractures low permeability soils, enhancing advective flow by creating microfractures which act as new flow paths through the soil matrix. The additional flow paths enhance the advective mass transfer of volatile contaminants to increase contaminant extraction rates and shorten cleanup time. Injection VacTM is Terra Vac's term for the combination of pneumatic fracturing with soil vapor extraction in low permeability soils. The technology was demonstrated and commercialized beginning in 1990.

At the New York manufacturing site in July 1990, pneumatic fracturing was used to enhance recovery of TCE and other VOCs from low permeability clays. Dual vacuum extraction (simultaneous recovery of soil vapors and ground water) had proven only slightly effective in removing VOCs from the site. During the initial application of pneumatic fracturing, the concentration of VOCs in the extracted air stream increased one order of magnitude from 20mg/L to 200mg/L. Extracted air flows did not increase appreciably. Pneumatic fracturing is thought to have redistributed subsurface flow. The Injection VacTM phase of operations doubled the recovery of VOCs compared to dual vacuum extraction without pneumatic fracturing over similar operating times. This operation was a pilot test to demonstrate the in situ remediation process. The system removed 340 kg (750 lb) of VOCs in 200 days.

From extrapolation, the pneumatic soil fracturing allowed the extraction of approximately 400 pounds additional mass of VOCs during operation, primarily from an increase in VOC concentrations, rather than increased air flow. VOC concentrations ranged from 10 to 20 ppm prior to the startup of the pneumatic soil fracturing, and were over 200 ppm during startup.

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

Report(s)/Publication(s) (Additional Info Source):

Plaines, A.L., R.J. Piniewski, G.D. Yarbrough, Terra Vac Corporation, USA "Integrated Vacuum Extraction/Pneumatic Soil Fracturing System for Remediation of Low Permeability Soil", Copyright 1992, Hazardous Materials Control Resources Institute, Greenbelt, MD

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID: FRAC0018

Project Name: Manufacturing Facility, Huntsville, AL

City: Huntsville ***State/Province:*** AL

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Road at Route 35, Keyport, New Jersey, phone (908) 739-6444, Company Information

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text is excerpted from ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620 or www.arstechnologies.com, Company Information, and
McLaren Hart, Inc., Warren, NJ, Company Information:

In 1994, pneumatic fracturing was used at full scale to increase the hydraulic conductivity of a formation consisting of a gravelly clay at a a manufacturing facility where groundwater was impacted by TCE, at a private site in Huntsville, Alabama. The gravelly clay zones were saturated and locally interconnected. Overall, however, hydraulic connection throughout the various zones was very low. Pneumatic Fracturing was applied to increase connection throughout the aquifer, and thus reduce the number of recovery wells required for remediation. The ground water remediation system has been installed and is operating. Fractures were injected at depths between 25 and 37 feet below the ground surface, and the estimated radius of influence of the fractures was 49 feet.

Based upon pre fracture and post fracture slug testing, the hydraulic conductivity of the formation increased up to 8.4 times in wells which were pneumatically fractured, and up to 9.6 times in adjacent monitoring wells. Field observations, and post fracture water level data indicated that the Pneumatic Fracturing process was effective for uniformizing the conductivity between the remediation wells on site. This reduced the number of remediation wells required on site, resulting in substantial savings on installation costs. Improved radius of influence of groundwater recovery wells to complete a capture zone for impacted groundwater.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc., Warren, NJ 07059, phone (908) 647-8111, Company Information

GWRTAC ID: FRAC0019

Project Name: Manufacturing Facility, Shreveport, LA

City: Shreveport **State/Province:** LA

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc., Warren, NJ, phone (908) 647-8111, Company Information.

Project Summary:

The following text is excerpted from ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620 or www.arstechnologies.com; and,
McLaren Hart, Inc., Warren, NJ, phone (908) 647-8111, Company Information:

Pneumatic fracturing was utilized to improve the effectiveness of an existing extraction trench at a manufacturing facility where soil and groundwater was impacted with TCE, at a private site in Shreveport, Louisiana, as pilot scale. A 120 foot long by 20 foot deep extraction trench was being used to draw ground water and TCE vapors from a sandy silt and silty clay formation. Pneumatic Fracturing was applied at successive intervals on one side of the trench to increase both the extraction rate of VOCs and the hydraulic conductivity of the formation. Fractures were injected at depths between 7 and 22 feet below the ground surface. The project was completed in 1994, and the existing system is operative.

Pneumatic fracturing was demonstrated to increase both the permeability of the formation, as was demonstrated by an increased flow rate, radius of influence, and the rate of TCE removal, observed in the extracted air stream. Pneumatic fracturing was also demonstrated to improve the hydraulic conductivity of the formation in an adjacent monitoring well 7.1 times. The results of this increase were also observed in the remediation system, which drew a much higher volume of ground water than typical for that time of year. Application was conducted adjacent to an existing above ground tank. Although up to 1" of ground surface heave was observed at the tank, the structural integrity of the tank was not affected.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Keyport, New Jersey, phone (732) 296-6620, Company Information

McLaren Hart, Inc., Warren, NJ 07059, phone (908) 647-8111, Company Information

GWRTAC ID: FRAC0039

Project Name: Manufacturing Plant, Chicago, IL

City: Chicago **State/Province:** IL

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092:

Hydraulic fracturing and installation of wells in clay till for dual phase liquid/vapor extraction of solvents at a manufacturing plant near Chicago, Illinois.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

GWRTAC ID: FRAC0067

Project Name: Maxwell Air Force Base, Montgomery, AL

City: Montgomery **State/Province:** AL

Report(s)/Publication(s) (GWRTAC Source):

FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

Project Summary:

The following text was excerpted from FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information:

Permeable reactive treatment (PeRT) wall panels were installed 75 feet below ground surface (bgs) using a patented technique of jet assisted hydraulic fracturing to inject a reactive slurry containing zero-valent iron filings and other materials to treat TCE. The installation was completed in July 1988 as a pilot study at Maxwell Air Force Base in Montgomery, Alabama.

Boreholes were drilled with an 8 inch auger to depths ranging from 75 to 80 feet below ground surface (bgs). Poly-vinyl chloride (PVC) casings were cemented into each borehole. A high-pressure jet -cutting tool was used to cut slots through the PVC casing. The slots were aligned to produce either V- or Y- shaped panels. The jetting tool was inserted into the bottom of the casing and lifted out with hydraulic jacks as the casing and soils were cut with the high-pressure water jets between 55 and 75 feet bgs. A slurry of zero-valent iron filings, humates, enzymes, guar gum, and water was pumped underneath a packer into the slots cut by the water jets. The emzyme breaks the guar gum-water polymer leaving the iron filings in place to hold open the slots or fractures and to treat the groundwater as it passes through the wall.

A radio-wave imaging method (RIM) was used to monitor the location and thickness of the wall panels. A radio-wave signal depression provided a measure of the extent and thickness of the slurry panels. The RIM monitoring of three of the panels indicated that these panels were about 2 to 3 inches thick and extended radially from 5 to over 10 feet from the injection hole.

The project was designed and installed for $210,000 including the supplies and down-hole materials. The field installation was completed in 14 days. Concentrations up-gradient of the PeRT system varied from 400 to 700 parts per billion (ppb) TCE. As the groundwater flowed through the PeRT system, the concentration was reduced to less than 40 ppb after the PeRT system had been in operation for about 6 months. There were no adverse signs of deterioration or reduced groundwater flow.

Report(s)/Publication(s) (Additional Info Source):

FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

GWRTAC ID: FRAC0063

Project Name: McGuire AFB, Wrightstown, NJ

City: Wrightstown **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

The Bulk Fuel Storage Area (BFSA) is located in the central portion of McGuire Air Force Base (AFB). The total area occupied by the tank farm is approximately 10 acres. The tanks originally were used for the storage of AVGAS, JP-4 jet fuel, and fuel oil. At present, the BFSA contains eight aboveground storage tanks used for storing JP?8 and heating oil, which are surrounded by asphalt-covered earthen dikes.

The BFSA has been in operation since 1963, and several spills have occurred during its operation. In 1967, a 500,000-gallon discrepancy was discovered in fuel inventory sheets, and it is believed this discrepancy was the result of minor releases over a period of time. A JP-4 spill occurred in 1984 as a result of a leak in a pressurized underground line, and a heating oil spill occurred in 1988. This site was identified as an Installation Restoration Program (IRP) site in the 1982 Records Search and was given an IRP site identification number, ST-09. Treatability studies and tests have been conducted at ST-09 for the past four years. In situ technologies tested at the site include free product recovery, bioventing, and vacuum-enhanced free product recovery ("bioslurping.") To date, these treatment methods have had limited success.

Fuel contamination has been observed during drilling operations down to 5 feet in some areas. Oil and grease concentrations up to 12,000 micrograms per gram (ug/g) were found at a depth interval of 9 to 11 feet below grade. Floating product up to 6 feet thick has been observed in one monitoring well. Maximum concentrations of various benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds detected during 1991 investigations include: benzene (9,000 parts per billion (ppb)), toluene (14,000 ppb), and xylene (47,000 ppb). Nickel was also present at 160 ppb, and cadmium was detected at slightly elevated levels.

The site is underlain by the Kirkwood area of the Formation, consisting mostly of fine sandy fill material, but clays, silts, and ash are also present. In the area near a stream, a peat layer underlain by a 12-foot-thick clay layer followed by glauconitic sand was found during drilling operations. This type of formation has a moderate to low permeability. Laboratory testing, completed by NJIT, has demonstrated a permeability of 4 x 10 -5 cm/sec in the BFSA. This type of loosely formed or non-cohesive soil restricts movement of subsurface liquids, namely JP-4, and thus inhibits the performance of bioventing, bioslurping, and free product recovery systems. At McGuire, rates of free product recovery have averaged one gallon per day or less. At such a slow rate, removal of the product to state-required cleanup levels would take roughly 30 years and cost up to ten million dollars.

NJIT was contacted to conduct a pilot test using Pneumatic Fracturing at the BFSA to enhance the free product recovery system. Since the geology of silty fine sand would not be conducive to sustaining fractures formed by Pneumatic Fracturing, Extended Radius Wells (ERWs) were proposed.
A pilot-scale pneumatic fracturing project was performed in 1998.

The theory of creating an ERW is similar to the concept of creating a permeable reaction wall. First, Pneumatic Fracturing is applied to the formation to create the fractures and second, a non-reactive dry media is immediately introduced into the fractures to maintain them. The first step of establishing the ERWs installed at the McGuire site was Pneumatic Fracturing. Initially tested at another site in New Jersey under EPA's S.I.T.E. demonstration program in 1992, Pneumatic Fracturing involves the injection of pressurized air at a high flow rate into boreholes at depth(s) of concern. When the subsurface in situ stresses of the formation are exceeded, "fractures" radiate from the origination point (the borehole.) However, in silty sands, like those found at the Site's BFSA, fractures are "held" very briefly by the "cohesion-less" materials. Fracturing the formation alone would not be an effective long-term method of increasing the recovery of the trapped JP-4. The second step of the ERW method entails delivering spherical ceramic beads down the same borehole to pre-determined depths. The injected media fills the newly produced fractures to create conductive channels or "lenses." These lenses have an appreciably higher permeability than the native soil, and therefore, enhance flow of the trapped product toward the recovery wells .

Two injection nozzles were constructed for the field demonstration. A 15 port helical and a movable nozzle (one in each well) were used to measure each design's impact on surface heave, injection flow rates, and pressure influences. The stationary helical nozzle was designed to create lenses of beads over a three-foot interval through several openings. The movable nozzle was adjusted within the formation such that four injections per interval produced a continuous, conductive channel. Field activities at the BFSA site encompassed borehole drilling, pilot testing of two nozzles (i.e., media injection, including gas flow and media loading adjustments,) recovery well installation and pre-ERW and post-ERW free product recovery system monitoring.

Fractures were injected at depths between 9 and 13 feet below the ground surface, and the estimated maximum radius of influence of the fractures was 4.5 feet, with an average of 2 to 3 feet. Over the course of the 85-day test, researchers injected almost 2,000 pounds of media. They concluded that the radius of influence from an ERW was two to three feet, with a maximum of 4.5 feet. Discrete conductive lenses were created by the injection of media at depths of nine to nearly 13 feet below the ground surface. The average lens thickness ranged from 1/8 to ¼ inch.

Results further indicated free product recovery rate improvement ranging from 225% to 325%. In one ERW, the product recovery rate increased from 0.4 to 1.7 gpd, while the other well's product recovery rate increased from 0.4 to 1.3 gpd. Based on these improved rates, scale-up would entail constructing approximately 165 ERWs in the BFSA. The overall required treatment time would be expected to drop from 30 years to just ten, with an estimated $4 million savings compared to a traditional free product recovery system at the site.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0103

Project Name: Mercury Aircraft Co., NY

City:

State/Province: NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Blast-fractured trenches were installed at this Mercury Aircraft Company manufacturing site in New York by Malcolm-Pirnie in 1993. The blasted bedrock zone, created in shale bedrock beneath 5 feet of overburden, was 200 feet long and 60 feet in depth, corresponding to a sidewall area of 12,000 ft2. Pre/post-blast yields were not available from source.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID: FRAC0041

Project Name: Metal Bellows Metal Finishing Plant, Sharon, MA

City: Sharon **State/Province:** MA

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Barrett, James, K., "Interception of Contaminated Groundwater in Bedrock through Artificial Fracturing", James K. Barrett, Thermo Consulting Engineers/Normandeau Engineers Concord, NH; and,
Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Hydrogeologic investigations of a metal finishing plant revealed TCE, which had been released into bedrock at the site, exceeded its MCL in a municipal water supply well located 1,500 feet offsite. Low hydraulic conductivity (0.3 ft/day) fractured granitic bedrock underlies about 15 feet of glacial till at the site. Poorly interconnected fracture conditions are evidenced by dissimilar analytical results from several monitoring wells including two spaced ten feet apart.

The bedrock was artificially fractured in 1991, using a triple line blasting pattern to create a minimum six feet wide, 20 feet high, 250 feet long interception zone. Aquifer testing indicates hydraulic conductivity was increased nearly 100 times. Uniform drawdowns throughout the length of the fractured zone suggest continuous fracturing results. Declining contaminant concentrations indicate sorption/desorption or other interactions are occurring between bedrock and contaminated groundwater. This artificial fracturing program has created a continuous, high permeability zone that greatly increases the effectiveness of extraction wells to intercept contaminated groundwater in bedrock for treatment.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID: FRAC0021

Project Name: Municipal Landfill, Edmonton, Alberta, Canada

City: Edmonton **State/Province:** ALBERTA

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from Company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2:

A municipal landfill has received approval to increase its capacity of municipal wastes by vertical expansion of the landfill. This approval is conditional upon the recovery and treatment of an estimated 200 million to 600 million litres (52,850,000 gallons to 158,500,000 gallons) of landfill leachate generated from existing wastes. However, conventional recovery wells completed in saturated wastes yield extremely low flow rates and capture zone owing to the low hydraulic conductivity of decomposed, saturated wastes. The project objectives were to evaluate the feasibility of fracturing saturated municipal wastes and assess the performance of fractured wells for enhancing the recovery of landfill leachate.

Fracturing was initiated in saturated wastes at three fracture well locations. The thickness of saturated wastes ranged from 2.8 to 6.6 metres (9.2 to 21.7 feet). The leachate level was approximately 8 metres (26.2 feet) below ground surface. A total of 8 fractures were initiated at the fracture well locations; three fractures at FW1 and two each at FW2 and FW3. Approximately 2,000 litres (528 gallons) of sand-laden fracture slurry was pumped into each fracture. Following the completion of wells at the fracture locations, a 24 hour pump test was conducted to evaluate the performance of fractured wells to unfractured wells. This was followed by a 10 week long pump test on an existing, retro-fractured well to assess long term well yield.

The enhancements in fractured well performance are summarized below:

PARAMETER	UNFRACTURED WELL PTW1	RETRO-FRACTURED WELL PTW1	FRACTURED WELL FW2
Hydraulic conductivity	4.0 x 10-6 m/s 4.0 x 10-4 cm/s	2.1 x 10-5 m/s 2.1 x 10-3 cm/s	6.2 x 10-5 m/s 6.2 x 10-3 cm/s
Flow rate (after 24 hrs)	1.5 L/min (0.40 gal/min)	15 L/min (3.96 gal/min)	30 L/min (7.93 gal/min)
Radius of capture	18.8 m (61.7 ft)	25.0 m (82.0 ft)	46.8 m (153.5 ft)

Based on the results to date, it is estimated that the number of recovery wells required to collect the leachate underlying the landfill can be reduced from 55 conventional recovery wells to 33 fractured recovery wells. This would result in a cost savings of $330,000 U.S. for the installation of fewer recovery wells. Additional savings would also accrue because of fewer pumps and infrastructure required as well as significantly reduced operation and maintenance costs.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

GWRTAC ID: FRAC0068

Project Name: Mustang-Shadow Mountain Gas Station, Grand Lake, CO

City: Grand Lake **State/Province:** CO

Report(s)/Publication(s) (GWRTAC Source):

Foremost Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

Project Summary:

The following text was excerpted from Foremost Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information:

In September 1997 at a former retail gasoline station site in the Colorado mountains, installed three BioNets containing three BioLuxes each were installed to remediate BTEX contaminated soils and groundwater in the source area and a shallow trenched BioWall was installed in September 1998 to prevent off-site migration of contamination. The design and remediation was performed under a State of Colorado approved Corrective Action Plan. The BioNets were installed using hydraulic fracturing techniques and the shallow trench was installed by traditional methods. The Isolite carrier used in both the BioNets and the trench installation was inoculated with BTEX degrading microbes. After one year of remediation, BTEX concentrations in the source area have been reduced 66 percent and all three compliance wells are now below the standards for BTEX. The design and installation cost $130,000.

Report(s)/Publication(s) (Additional Info Source):

Foremost Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

GWRTAC ID: FRAC0014

Project Name: New Jersey Environmental Cleanup Responsibility Act (ECRA) Site in South Plainfield,

City: South Plainfield **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992:

An integrated treatment system incorporating Pneumatic Fracturing Extraction (PFE) and Hot Gas Injection (HGI) has been jointly developed by Accutech Remedial Systems, Inc., and the Hazardous Substance Management Research Center located at the New Jersey Institute of Technology in Newark, New Jersey. The system provides a cost-effective accelerated remedial approach to sites with dense, nonaqueous phase liquid (DNAPL)-contaminated aquifers. The patented PFE process has been demonstrated at several sites to increase and make uniform subsurface airflow within low permeability formations, such as clay and fractured rock, and to enhance contaminant mass removal. The PFE process coupled with an in stiu HGI process is designed to recover residual contamination entrapped in the geological formation. The PFE process applies controlled bursts of high pressure air into a well to create fracture channels. Once the permeability of the formation is increased, hot gas is injected under pressure to elevate the temperature of fracture surfaces and volatilize contaminants within the formation. The extracted vapors are then treated either by activated carbon or catalytic technology. Low concentration process streams are treated by activated carbon, while high concentration process streams are treated by ca0alytic technology. An innovative catalyst developed by Engelhard Corporation, which resists deactivation when treating chlorinated process streams, will be used during the second phase of the demonstration activities.

The system can remediate halogenated and nonhalogentated volatile and semivolatile organic compounds. The integrated treatment system is cost-effective for treating soils and rock when low permeability geologic formations limit the effectiveness of conventional in situ technologies.

This technology was accepted into the SITE Demonstration Program in December 1990. The PFE/HGI Process was demonstrated during July and August 1992 at a New Jersey Environmental Cleanup Responsibility Act (ECRA) site in South Plainfield, New Jersey. Trichloroethylene (TCE) was removed from the fractured Brunswick Shale aquifer. The PFE/HGI process was applied in the unsaturated zone to remove residual DNAPLs near the source. Preliminary results indicated that the PFE/HGI process significantly increased contaminant removal rates over conventional vapor extraction. Demonstration results are being prepared and are expected to be published in the spring of 1993.

The PFE/HGI process was demonstrated using a two-phase approach. The incremental benefit of each integrated technology was evaluated in the first phase. In the second phase, the technologies will be integrated with a groundwater recovery process and the catalytic technology to evaluate long-term cost benefits. A Phase II demonstration is planned for 1993.

Report(s)/Publication(s) (Additional Info Source):

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

GWRTAC ID:	FRAC0106		
Project Name:	New York Air Brake, NY		
City:		***State/Province:***	NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Blast-fractured trenches were installed at this manufacturing site in New York owned by New York Air Brake by EMCON in 1998. The blasted bedrock zone, created in limestone bedrock beneath 16 feet of overburden, was 700 feet long and 15 feet in depth, corresponding to a sidewall area of 10,500 ft2. Pre/post-blast yields were not available from source.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID: FRAC0105

Project Name: New York Air Brake, NY

City:

State/Province: NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Blast-fractured trenches were installed at this manufacturing site in New York owned by New York Air Brake by EMCON in 1998. The blasted bedrock zone, created in limestone bedrock beneath 6 feet of overburden, was 1,500 feet long and 12 feet in depth, corresponding to a sidewall area of 18,000 ft2. Pre/post-blast yields were not available from source.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID: FRAC0059

Project Name: Newark, NJ

City: Newark

State/Province: NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

A pneumatic fracturing project was performed in 1992 at a site in Newark, New Jersey to enhance a soil vapor extraction system. Vadose zone sandy silt beneath the site was impacted with miscellaneous petroleum VOCs. Fractures were injected at depths between 5.3 and 7.3 feet below the ground surface.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0058

Project Name: Newark, NJ

City: Newark ***State/Province:*** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

A pilot-scale pneumatic fracturing demonstration project was performed by the New Jersey Institute of Technology in 1991 at a clean site in Newark, New Jersey. Fractures were injected into sandstone at depths between 9 and 11 feet below the ground surface, and the estimated radius of influence of the fractures was >10 feet.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0049

Project Name: Northeast OH

City: **State/Province:** OH

Report(s)/Publication(s) (GWRTAC Source):

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

Project Summary:

The following text was excerpted from information provided by FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040:

Seventeen sand-filled fractures were created in clay soils underlying a chemical manufacturing facility in northeast Ohio. A mixture of industrial solvents contaminated the soil and groundwater down gradient from an underground storage tank. Remedial processes focused upon soil vapor extraction, then the method of choice for solvent contaminants. As expected, the low permeability of the clay so inhibited flow that SVE required the enhancement of hydraulic fracturing.

Three fractures were created as a pilot test to confirm the feasibility of creating sand-filled fractures and to provided quantitative estimates of the radius of influence of vacuum extraction through fractures. The fractures were created from a nest of individual two-inch wells, more-or-less forming a stack of fractures. One fracture contained minimal sand because the well was not sufficiently sealed into the soil at the target depth. An adjustment to the well installation procedure allowed the other two fractures, which contained 700 and 1100 lb of sand, to extend 15 and 20 feet with apertures of 2 and 3 cm, respectively. Multilevel piezometers were constructed distances of 5, 15, 30 and 45 feet from the nest of wells. Suction applied to the uppermost fracture registered at the same elevation in six out of seven piezometers. Substantially less influence was noted at depth, indicating the fracture effected overlying soil.

The encouraging pilot test results justified additional deployment. Fractures were created at seven locations along a line that intercepted the contaminant plume. Fractures were created just above and just below the water table so that contaminants could be recovered through both vapor and groundwater. Quarterly sampling verified process performance. After two years of operation, the site met standards for risk-based closure.

Report(s)/Publication(s) (Additional Info Source):

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

GWRTAC ID: FRAC0037

Project Name: Petroleum Storage Terminal Site

City: Liege **State/Province:** BELGIUM

Report(s)/Publication(s) (GWRTAC Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

Project Summary:

The following text was excerpted from company Case Studies, FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092:

Hydraulic fracturing of silt soils underlying a petroleum storage terminal in Liege, Belgium. Fractures were subsequently excavated and mapped.

Report(s)/Publication(s) (Additional Info Source):

FracRite Environmental, LTD., 6 Stanley Place S.W. Calgary, Alberta T2S 1B2, phone (780) 620-5533, fax (780) 287-7092, Company Information

GWRTAC ID: FRAC0056

Project Name: Railyard in Birmingham, AL

City: Birmingham **State/Province:** AL

Report(s)/Publication(s) (GWRTAC Source):

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

Slack, W.W., L.C. Murdoch, and D. Butler "Recovering Free Product from Clayey Formations using Hydraulic Fractures", pending publication.

Project Summary:

The following text was excerpted from information provided by FRx, Inc., Cincinnati, OH, and Slack, W.W., L.C. Murdoch, and D. Butler "Recovering Free Product from Clayey Formations using Hydraulic Fractures", pending publication:

Light non-aqueous phase liquids (LNAPL), such as motor fuels or lubricating oil, can be a major threat to both underlying groundwater or nearby receptors. The presence of free product at a site often precludes closure because of this potential threat. Several well designs, including special skimming pumps or in-well separators, have been developed to maximize the recovery of free product. This is typically accomplished by targeting a floating LNAPL separately from the underlying water. The designs are intended to recover free product, while minimizing the simultaneous recovery of contaminated water to avoid the expense of treating the contaminated water until after the NAPL problem has been addressed. The performance of free product recovery systems in clean sands can be quite good, however, those systems perform poorly in clayey sediments largely because the discharge of liquids is minimal.

Hydraulic fractures can improve the performance of wells completed in fine-grained sediments or rock. Sand-filled hydraulic fractures form sheet-like, highly permeable layers in the subsurface that will increase the flow rate to wells in fine-grained formations typically by one to two orders of magnitude. We have used hydraulic fractures with free product recovery systems at several sites, and consistent improvements have been observed.

Two different designs of free product recovery systems that use hydraulic fractures have been utilized. The simplest design uses one hydraulic fracture placed at the bottom of the LNAPL layer. A skimmer pump is installed in a recovery well that intersects the fracture and the pump is operated as normal. As a variation of this concept, additional fractures may be created at overlying or underlying elevations so that seasonal variations in water table can be accommodated. This approach is limited in drawdown to approximately 20% of the thickness of the layer. The limitation arises from the need to preserve uniform head throughout the water zone because the water is static. As a result, water will cone-up wherever the product layer is thinned. The maximum amount of coning can be determined by comparing the head at the extreme limit of the cone to the head at the extraction point. At the extreme limit, the head in the water is the height of product, ho, multiplied by product density, po. At the extraction point, no product exists, so the head must be composed of the height of the cone multiplied by the density of water, pw. Since the two heads are equal, the maximum drawdown, h, of product is

h = h0 (pw-po/pw)

For typical densities of hydrocarbon fuels, the relation evaluates to approximately 20% of the free-product thickness.

Another approach is to use two flat-lying hydraulic fractures stacked one on top of the other. The upper fracture is created in the zone containing LNAPL, whereas other one is in the underlying formation saturated with water. Pumping from both fractures simultaneously will limit the upward migration of the interface between water and NAPL. The approach eliminates, or limits, up-coning of water. Preliminary theoretical analyses of the well design confirm field observations and show that the two-fracture design has merit.

We have previously reported on the use of hydraulic fractures to enhance the recovery of free-phase LNAPL while controlling water coning with an additional fracture (Murdoch et al., 1994). The work was done at one of the many refineries near Beaumont, Texas. In a five-day-long test using the two-fracture design, the fracture created in the LNAPL zone produced LNAPL with negligible amounts of water at a rate more than 20 times faster than a conventional well. The well intersecting the underlying fracture produced water with negligible amounts of NAPL, so that both increased the rate of recovery and separated NAPL and water phases as they flowed to the well. We have since completed a project that implemented the more simple approach of separating the product in the recovery well with a phase-separating pump. The results provide an interesting comparison to the earlier work.

Seventy-one sand-filled hydraulic fractures were created in a railroad yard in Birmingham, Alabama, to facilitate recovery of free-phase petroleum hydrocarbons by skimmer pumps. The contaminants consisted mostly of fuel oil and diesel, which was released from multiple points during the refueling of locomotives. Three of the fractures were created in the fall of 1997 as a pilot test. The remainder were created during the summer of 1998 in order to deploy the recovery technology across the 14-acre site.

The site is underlain by the Conasauga Formation that forms the axis of the Birmingham Anticline. The Conasauga Formation is a highly fractured dolomite/limestone approximately 4 to 8 m below ground surface (bgs). The overlying soil consists of weathered residuum containing silty clay and fragments of limestone and chert. A layer of fill materials covers the residuum. The fill, which contains silty clay, coal, cinders, building scraps and other materials consistent with 100+ years of railroad operations, varies in thickness from ½ to 3 m. Native soil samples collected by Shelby tubes in the interval 3.9 to 4.6 m bgs have greater porosity and lower hydraulic conductivity than samples collected from 1.2 to 1.8 m bgs. Hydraulic conductivity for all samples were consistent with the clay-rich, compacted soils, ranging from 1.9 x 10-6 cm/sec to 1.4 x 10-8 cm/sec.

The installation of numerous monitoring wells over the years has provided insight as to surficial hydrogeology and contaminant transport. Groundwater apparently follows preferential pathways, such as steeply dipping natural fractures and zones of higher permeability in the fill. Surface water infiltrates the fill material and percolates downward, in some places forming perched zones over the underlying native soil. Presumably the contaminants follow similar pathways. Depth to groundwater varies spatially across the site, ranging from less than 2 m to more than 6 m depth. Seasonal variations in water table have also been observed. As a result of the heterogeneous structure of the fill and native soil units and the spatial and temporal variation in water table, wells drilled within a few meters of each other can discharge at extremely different rates.

Hydrological factors frustrated recovery of free-phase hydrocarbons from conventional wells. In a pre-fracture test, recovery of water and hydrocarbon from MW-1S yielded hydrocarbon at a discharge rate of 3 liters per day. Smaller discharge rates were predicted when skimmer pumps were used in the well. Three liters per day was deemed too meager for remediation, and lesser discharge certainly would have proven impractical.

The approach for enhanced free product recovery involved creating sand-filled hydraulic fractures at multiple depths around conventional wells. Presumably, the fractures would provide pathways for migration of hydrocarbon into the well. The depths for the fractures were chosen to optimize the coverage of the then current product and groundwater interfaces while allowing for seasonal fluctuations.

Pilot Test. The recovery approach was first implemented on a pilot scale to evaluate uncertainties about fracture form and the concerns about a fracture intersecting an existing well. Three fractures were created from locations around MW-1S. Fractures were placed at depths spanning the range of water table fluctuations to ensure propagation into current product plume. The wells for fracture creation were placed within an expected fracture radius from MW-1S. The materials planned for each fracture were limited conservatively to quantities that would be contained in a fully subterranean, sub-horizontal fracture, i.e. a more-or-less horizontal fracture that does not vent to the surface.

The desire to have the fractures intersect well MW-1S also carried uncertainties about fracture and well interaction. On one hand, MW-1S could have acted as a pin, inhibiting fracture propagation toward or around it. In such case, the fracture would grow substantially in other directions and could not be expected to be adequately connected to the well to enhance recovery. On the other hand, the fracture could fully enter MW-1S during creation and exit to the surface or adversely interact with the first fractures. If so, the propagating fracture could lose its transport liquid through the screen and consequently be of limited size and utility. Thus the first two fractures were located 3 m from MW-1S. After uneventful creation of two fractures, the third was located 2 m away. Table 1 lists the characteristics of the fractures.

TABLE 1. Specifications for hydraulic fractures created around MW-1S for pilot testing of enhanced skimmer pumping.

Frac ID	Depth (m)	Location Relative to MW-1S	Volume of Sand (m3)	Max/Min Diameter (m3)
IP1	3.73	3 m N	0.25	7.9 / 7.8
IP2	4.64	3 m NE	0.37	8 / 6
IP3	3.1	2 m NW	0.23	8.8 / 7.6

Data collected during creation of the fractures permitted assessment of the form of the fracture and provided a preliminary indication of their function. Pressure logs that follow a typical form, symmetric uplift domes, and absence of vents to the ground surface indicated roughly horizontal hydraulic fractures. The two upper fractures definitely propagated past MW-1S, while the lowest one probably did. Accordingly, existing wells at this site do not act as pins that suppress fracture aperture, especially if the fracture has been nucleated a few meters from the well. In addition, fracture wells presumably could be placed closer to existing wells without suffering limited propagation. Closer placement should also increase thickness of the fracture at intersection with the well, which should improve recovery of contaminants.

In any case, horizontal fractures were created and geological conditions were indicated that favor creation of substantially larger fractures, possible double or triple the diameter and two to three times thicker. Improved performance of fractures as remedial enhancements was expected from larger fractures. .

Following creation of the fractures, a product recovery pump was installed in MW-1S. The pump was designed to separate hydrocarbons internally and pump only hydrocarbon to the surface. The pump was set up to achieve a maximum rate of 180 liters per day. As expected, the rate decreased to substantially smaller rates once the initial volume of hydrocarbon in the well was depleted.

The in-well separator pump was operated in MW-1S over five days for a total of 74 hours of operation. The volume of free product recovered was gauged daily. Based on the final measured pumping rate and the total volume recovered, the well discharged 14.7 liters per day. This represents an increase of over five times the discharge of hydrocarbons from the same well utilizing a total fluids pump in the pre-fracture test. In addition, the pump appeared to be suitably robust for long-term operations. In conclusion, the three fracture pilot test justified implementation of the recovery scheme site-wide.

Full-Field Deployment. The approach for field-wide deployment of fractures was revised according to the lessons learned from the pilot test. Fractures were planned to contain as much as five times the sand used in the pilot test. Pairs of overlying fractures were planned, instead of the trio of overlying fractures created at the pilot test location. Typically these pairs were created at depths separated by 2 m, e.g. 3.5 m and 5.5 m bgs. With these constraints in mind, recovery wells and sets of fractures were located within the periphery of the two plumes. In general, location of a recovery well was selected, and one pair fractures was specified to be created within 1.5 m of it. Additional pairs of fractures were then specified at locations adjacent to the limits of the central fractures. Figure 3 shows an example of how fractures were planned for RW-5. The assumption that subsurface flow among spatially contiguous fractures was made in the interest of operational economy, but did not have any justification from the pilot test.

One minor operational change was introduced to improve the efficacy of fracturing during field-wide deployment. The nominal 2-inch (5 cm) steel pipe through which the fractures were created was recovered by drilling crews after fractures were created and re-used. As a result, less pipe was used, which translated into less life-cycle waste in addition to lower cost, fewer permanent pathways were created, which should limit unwanted penetration of fluids into the subsurface, and no stickups remained to frustrate future land use.

The sixty-eight fractures created as part of the field-wide deployment of the fracture assisted separated product recovery system generally had characteristics predicted by the pilot test. However, in 17 instances, cross-linked gel (usually loaded with sand) reached the ground surface after substantial quantity of slurry had been injected. These vents occurred from 3 to 12 m away from the injection well and at all cardinal directions from the well. Injection was stopped when the venting rate obviously approached the injection rate. In another instance, slurry vented from a nearby recovery well, necessitating premature termination. In all of these cases, sufficient volume of material was injected to create a useable fracture, and no steps were taken to inject additional material to meet design criteria.

Two fractures vented in an adverse form. Both vented within a meter of the injection well and after injection of a modest quantity of slurry. The vent patterns suggested the hydraulic fractures may have intersected undocumented excavations near the wells. These fractures will provide limited enhancement to remedial operations at the particular locations.

One fracture could not be created to desired size. Excessive injection pressures were encountered and injection was terminated. Excessive pressure indicates that loss of gel and packing of injected sand blocked the fracture propagation pathway. Such would occur if the fracture were propagating through extremely permeable media that acted like a filter. Consequently, the fracture probably will serve to connect the recovery well to an existing preferential flow path.

Each fracture contained an average of 1.15 m3 of sand. The shallowest was created at a depth of 3.35 m while the deepest was created at 5.8 m. The pattern of uplift typically formed an slightly elongate dome, which is consistent with flay-lying to gently dipping hydraulic fractures at shallow depths. (Murdoch et al., 1994). The center of uplift, location of maximum uplift, and foci of the ellipse rarely coincide with each other or with the injection well. However, the volume of uplift usually correlates well with the volume of injected slurry. In contrast, the uplift volumes of several fractures were substantially less than would be expected from the quantities of injected material. Such a discrepancy has been encountered at other sites. Either of two factors can cause the effect. First, certain geological conditions can distribute the displacement of soil by the fracture over a large area, rendering measurement difficult. Depth and elasticity of the soil favor this mechanism. Although the fractures at the Birmingham site were not particularly deep, the substantial thickness of overlying fill material represents an elastic and compressible unit that can adsorb the uplift signal. Second, fracture slurry that propagates into a highly permeable zone or a zone with substantial course porosity, such as a sand and gravel bar, will not create a fracture but rather will displace fluid within the media and fill the pore space. Such features can be expected to exist at the Birmingham site either as native material or as the occasional extension of an uncharted excavation or deposit of fill.

Results of fracturing suggested the recovery system would operate successfully. Fractures of suitable size were created at chosen locations throughout the hydrocarbon plume. Fracture sand and decomposed slurry were found upon installation of several recovery wells, confirming sufficient lateral extent of the fractures. Even the variance of fracture form, as discussed in the previous paragraph, suggests a beneficial characteristic: fractures that connect to existing sand lenses will aid in recovery of product from an even greater area of the site. Finally, no deleterious processes were observed during the creation of fractures.

Recovery operations commenced in the summer of 1999. As expected, some of the recovery wells performed better than the pilot test, but average performance was remarkable similar to the pilot test. Long term assessment is not yet possible. During the late summer and fall of 1999 the area endured a drought, and seasonal variation of the water table was extreme. The water table fell below the bottom of several of the recovery wells, and representative data have not been collected in several months.

The recovery of free-phase hydrocarbon from low permeability soils can be enhanced and accelerated by sand-filled hydraulic fractures. The fractures effect the desired enhancement by providing low-resistance flow paths within the target soils.

The greatest contrast between recovery rates of fracture-enhanced systems and conventional fluid recovery systems apparently can be realized if water and LNAPL are recovered from separate fractures. At one site in Beaumont, Texas, te the recovery rate from a pair of fractures was at least 20 time more than conventional wells. At another site where LNAPL was recovered from one well, and no water was recovered, the fractures appear to increase the product recovery rate by about a factor of 5. Other differences, such as the product thickness and the hydraulic conductivity of the native soil may also have contributed to these differences. In practice, the expense of treating the contaminated water recovered using the two-fracture system may out-weigh the efficiency of controlling water coning. Nevertheless, at both sites underlain by fine-grained materials the use of hydraulic fractures caused LNAPL recovery to increase from a meager trickle to rates where remediation was viable.

References:
Murdoch, L. C., D. Wilson, K. V. Savage, W. W. Slack, and J. E. Uber. 1994. Handbook of Alternative Methods for Delivery and Recovery, US EPA EPA/625/R-94/003.

Report(s)/Publication(s) (Additional Info Source):

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

Slack, W.W., L.C. Murdoch, and D. Butler "Recovering Free Product from Clayey Formations using Hydraulic Fractures", pending publication.

FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

GWRTAC ID: FRAC0066

Project Name: Raritan, NJ

City: Raritan **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information:

Investigation activities at a private facility in Raritan, New Jersey have been ongoing since the mid-1980's. The site is located in the Brunswick formation of the Passaic. The geology contains weathered bedrock (fractured shale) from ground surface to approximately 45 to 50 feet below ground surface (bgs). A soil investigation was conducted at the site in 1997, and a groundwater investigation was performed in 1998. Groundwater investigative activities included the installation of temporary bedrock monitoring wells upgradient from an existing monitoring well that has had concentrations of trichloroethene (TCE) up to 140 parts per billion (ppb) for the past ten years. Sampling activities of the temporary bedrock wells have delineated a plume of TCE originating under the facility up to 38,000 ppb and at the site boundary up to 700 ppb.

Since the facility is still in operation and the possible origination of the plume is in a location of the building with sensitive operations, investigative activities under the building have been minimal. Yet, the client has decided to take a proactive approach for addressing the plume near the source to minimize downgradient concentrations of TCE. Remedial options were investigated to determine the most efficient means for addressing the plume in this type of geology.

Because of the tight geology, the option of pneumatically fracturing the site and installing a permeable reactive wall (PRW) was suggested. The PRW could then be coupled with natural attenuation such that downgradient concentrations of the PRW would decrease and meet New Jersey Department of Environmental Protection (NJDEP) standards by the time the plume reaches the site boundary.

Three test wells were installed as part of a pilot test perpendicular to the plume direction. The center well was cored and the two observation wells, located five and ten feet away from the center well were reamed. Tests were performed prior to pneumatic fracturing (pre-fracture tests), following pneumatic fracturing (pre-injection tests), and following pneumatic injection of zero valent iron (post-injection tests). The tests were conducted to determine the effectiveness of the emplacement of the iron media and treatment of the TCE plume. Baseline testing included video logging all three wells to determine fracture locations, slug testing to determine baseline TCE concentrations, and depth-discrete packered interval permeability testing of the center well to determine pre-fracture permeability. Pneumatic fracturing of the well occurred at 11 fracture locations; fractures were injected at depths between 25 and 45 feet below the ground surface, and the estimated radius of influence of the fractures was 10 to 15 feet. Subsequent to fracturing, the permeability tests were run again. Permeability measurements from pre-fracture to post-fracture tests indicated an increase in permeability of one to two orders of magnitude.

Prior to injection of iron, geophysical logging of the wells was conducted to confirm fracture locations (i.e., depth, size). The logging included temperature, density, gamma, spontaneous potential, and induction. Iron injection was performed in the well at 11 fractures and approximately 1,700 pounds of iron was injected into the fractures. Post-injection testing is presently being conducted to determine TCE concentrations, permeability changes, and induction changes. This is the first time iron has been emplaced into fractured bedrock. The client is interested in installing a full-scale PRW in the summer of 2000.

Report(s)/Publication(s) (Additional Info Source):

Company Information, McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0054

Project Name: Retail Gasoline Facility, Lakewood, CO

City: Lakewood ***State/Province:*** CO

Report(s)/Publication(s) (GWRTAC Source):

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

Foremost Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

Project Summary:

The following text was excerpted from information provided by FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, Company Information, and
FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040:

In October 1997, per a Colorado State Oil Inspection Section approved Corrective Action Plan at an operating gasoline retail station in Lakewood, Colorado, a remediation system was installed. Seven BioNets with 31 total BioLuxes were installed up to 20 feet below grade to bioremediate BTEX and TPH compounds in the clay soils and groundwater. The PeRT barrier system was installed in 12 days with hydraulic fracturing methods. Isolite was inoculated with aerobic microbes and then pumped into each of the BioLuxes. After 14 months of operation BTEX concentrations have been reduced in groundwater from 11 ppm to less than 3 ppm. In some cases the concentrations in groundwater were reduced up to 94 percent. The project was designed and installed for $160,000. The passive system is in the monitoring phase of remediation.

Report(s)/Publication(s) (Additional Info Source):

FRx, Inc., P.O. Box 37945, Cincinnati, OH 45222, phone 513-469-6040, fax 513-469-6041, Company Information.

FOREMOST Solutions, Inc., 350 Indiana Street, Golden, CO 80401, phone (303) 271-6117, email foremost@earthlink.net, Company Information.

GWRTAC ID: FRAC0036

Project Name: Rural Test Location, Frelinghuysen, NJ

City: Frelinghuysen **State/Province:** NJ

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 2996-6620; and,
McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information:

A clean site at a rural test location in Frelinghuysen, New Jersey was subjected to pneumatic fracturing extraction (PFE) at a 4.0 to 8.0 foot depth in 1990-1993 by the New Jersey Institute of Technology to measure subsequent changes to a soil vapor extraction system. The estimated radius of influence of the installed fractures was 9 feet. Geologic materials targeted were glacial deposits of clayey silts and sandy silts; the water table was 6 to 10 feet. The natural (pre-fracture) extraction airflow was 0.12 cfm; the post-fracture extraction airflow was 10+ scfm with limited source vacuum.

During pre-fracture air permeability measurements of VW-1, enhancement effects were not measureable due to high precipitation which caused ground water to rise above portions of the fractured zone. As the water table lowered over a 17-week period, air permeability enhancements were observed at VW-1. These permeability enhancements were attributed directly to PFE since no permeability enhancements were observed over the same period at an adjacent well (approximately 50 feet away) VW-4. A pneumatic injection was then applied to VW-4 at a time when the water table was at it's deepest depth and air extraction flowrates increased to more than10 scfm. A period of high precipitation followed, which caused the depth to ground water to decrease. Airflow measurements concurrent to this period resulted again in low air flow measurements as water filled subsurface pathways. Over the course of 27 weeks, permeability enhancements as a result of the application of PFE were observed in both VW-1 and VW-4. Enhancment showed some minor decreases over the period, but still significantly exceeded pre-fracture levels, even after being temporarily located below the water table. Fractures remained open seven years after application.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information.

USGS 14-08-0001-G1739 Document "Removal of Contaminants from the Vadose Zone by Pneumatic Fracturing"

GWRTAC ID: FRAC0006

Project Name: Service Station in Louisiana

City:

State/Province: LA

Report(s)/Publication(s) (GWRTAC Source):

Plaines, A.L., R.J. Piniewski, G.D. Yarbrough, Terra Vac Corporation, USA "Integrated Vacuum Extraction/Pneumatic Soil Fracturing System for Remediation of Low Permeability Soil", Copyright 1992, Hazardous Materials Control Resources Institute, Greenbelt, MD

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC, and
Plaines, A.L., R.J. Piniewski, G.D. Yarbrough, Terra Vac Corporation, USA "Integrated Vacuum Extraction/Pneumatic Soil Fracturing System for Remediation of Low Permeability Soil", Copyright 1992, Hazardous Materials Control Resources Institute, Greenbelt, MD:

Pneumatic fracturing is used to supplement soil vapor extraction in low permeability formations where diffusive flow of soil vapor is poor. Air at high pressure is injected into the zone of low permeability via fracturing probes. The high pressure air fractures low permeability soils, enhancing advective flow by creating microfractures which act as new flow paths through the soil matrix. The additional flow paths enhance the advective mass transfer of volatile contaminants to increase contaminant extraction rates and shorten cleanup time. Injection VacTM is Terra Vac's term for the combination of pneumatic fracturing with soil vapor extraction in low permeability soils. The technology was demonstrated and commercialized beginning in 1990.

At the Louisiana service station in November 1991, pneumatic fracturing was used to enhance recovery of gasoline-range VOCs from firm, plastic clays. Permeability testing of the soil indicated hydraulic conductivities of 10 -8 cm/sec. The clay layer was 23-26 feet thick. Initial air flow rates from a dual vacuum extraction system were 10-15 standard cubic feet per minute (scfm). Injection VacTM operations yielded 16-23 scfm, a 50 to 100 percent increase. VOC extraction rates more than doubled following pneumatic fracturing. The pilot operations removed over 650 kg (1400 lb) of VOCs over 6 days. Full scale operations remediated the site in just over a year. At extraction well DE1, VOC extraction rates increased 240 percent after the initial fracturing (from 94 to 319 ppd). After 20 hours, this rate decreased to 75 ppd, but subsequent fracturing caused significant increases in the VOC extraction rate. At DE2, the VOC extraction rates doubled, increasing from 52 to 111 ppd after fracturing, then decreased to 43 ppd 18 hours later. A second fracturing increased the VOC extraction rate from 35 to 110 ppd. At DE3, VOC extraction rates increased from 40 to 58 ppd after fracturing, and VOC concentrations increased up to 250 percent over Dual Vacuum Extraction TM only operations.

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

Report(s)/Publication(s) (Additional Info Source):

Plaines, A.L., R.J. Piniewski, G.D. Yarbrough, Terra Vac Corporation, USA "Integrated Vacuum Extraction/Pneumatic Soil Fracturing System for Remediation of Low Permeability Soil", Copyright 1992, Hazardous Materials Control Resources Institute, Greenbelt, MD

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID: FRAC0060

Project Name: Service Station, San Francisco, CA

City: San Francisco ***State/Province:*** CA

Report(s)/Publication(s) (GWRTAC Source):

TerraVac Corporation, Pnumatic Soil Fracturing Case Studies, available at www.terravac.com.

Project Summary:

This information was excerpted from TerraVac Corporation, Pnumatic Soil Fracturing Case Studies, available at www.terravac.com:

Free product saturated low permeability strata beneath a service station (property transfer) site in San Francisco, California. TerraVac Corporation utilized an integrated dual vacuum extraction/pneumatic soil fracturing system to remediate the site.

80,000 pounds of super unleaded gasoline have been recovered by the system.
The site was recommended for closure in less than ten months.
The hot air injection increased extraction rates by up to a factor of three over those without hot air injection.

Report(s)/Publication(s) (Additional Info Source):

TerraVac Corporation, Pnumatic Soil Fracturing Case Studies, available at www.terravac.com.

GWRTAC ID:	FRAC0102
Project Name:	Sidney Landfill, NY
City:	
State/Province:	NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Blast-fractured trenches were installed at the Sidney Landfill site in New York by HLA in1998. The blasted bedrock zone, created beneath 20 feet of overburden, was 100 feet long and 60 feet in depth, corresponding to a sidewall area of 6,000 ft2. Pre/post-blast yields were not available from source.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID:	FRAC0009
Project Name:	Site in Bristol, TN
City:	Bristol
State/Province:	TN

Report(s)/Publication(s) (GWRTAC Source):

Murdoch, L.C., D. Wilson, K. Savage, W. Slack, and J. Uber "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/001, 1995, available at www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC; and, Murdoch, L.C., D. Wilson, K. Savage, W. Slack, and J. Uber "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/001, 1995, available at www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html.:

Naturally propped fractures were created at depths of 30.5 to 61 meters (100 to 200 feet) in rock to enhance the recovery of free-phase TCE and other DNAPLs at a site in Bristol, Tennessee. The fractures were created by injecting water into sections of the well isolated by straddle packers. Three wells were drilled to approximately 200 feet. Pumping tests and vapor extraction tests were conducted to evaluate the effects of the fractures. The process was demonstrated with vapor extraction in July 1991.

Sandstone, shale, and limestone underlie the vicinity of the site and form a broad fold and dip about 45 degrees beneath the site itself. The site lies in a local recharge area of a bedrock aquifer characterized by downward vertical hydraulic gradients of approximately 0.5 units. The hydraulic conductivity of the water-bearing formation is approximately 10-6 centimeters per second, based on constant rate tests. The site contains a free-phase plume of TCE, other solvents, and cutting oil that extends to a depth of 100 meters (328 feet). A dissolved-phase plume of primarily TCE extends to greater depths - at least 320 meters (984 feet) from the suspected source. The specific gravity of the free-phase liquid is 1.3. Recovery using a pump and treat system yielded about 3.7 liters (1 gallon) per minute of water per will and fewer than 1.4 kg (3.1 lbs.) per day of DNAPL. These low rates of recovery provided impetus for using hydraulic fracturing techniques to stimulate the wells. The intent was to increase formation permeability that, in turn, would promote liquid flow and possibly permit sufficient air flow into wells for recovery through vapor transport.

Three new wells were drilled to 60 meters (197 feet) with open hole completion, and ther performance of these wells was characterized before and after hydraulic fracturing. Each well was fractured by setting open hole packers 15 meters (49.2 feet) apart and injecting 4,500 to 9,000 liters (1,188 to 2,376 gallons) of clean water; no proppants were injected. Injection pressures ranged between 0.5 and 5 Mpa (73 and 725 psi), and the injection rate was about 280 liters (73.9 gallons) per minute. This approach resembles methods used to increase the discharge of water wells. Injection was terminated when water flowed around the upper packer and began to spill to the surface. In one case, an observation well 2.5 meters (8.2 feet) away, responded with discharge of injected water. The initial discharge was muddy but cleared with continued injection, suggesting that fine-grained particles had been removed from fractures in the formation.

The specific discharge of the three wells increased by factors ranging from 2.8 to 6.2. These effects are typical of naturally propped fractures created by hydraulic fracturing of water wells. Pumping test results indicate that hydraulic conductivity generally increased by factors of 20 or more. (Actual values depend on the method of solution used to analyze the test data.) Vapor extraction appeared to be a feasible remedial technique after fractures were induced. Vapor discharges were on the order of 285 to 700 L/min and suction could be detected 10 meters (32.8 feet) from the recovery well after fracturing. Both discharge and suction had been negligible prior to fracturing. During a two-day test of vapor extraction, DNAPL was recovered at a rate of approximately 82 kg/day (180 lbs per day). Concentrations diminished during this test, probably representing an upper limit of the recovery rate. Nevertheless, the combination of hydraulic fracturing to increase conducivity and suction to induce dewatering and DNAPL recovery appeared to be a viable method of increasing contaminant recovery at this site. Reportedly, the cost to create the fractures used during this project was $1,500 per well.

Report(s)/Publication(s) (Additional Info Source):

Lundy, D.A.; Carleo, C.J.; Westerheim, M.M. "Hydrofracturing Bedrock to Enhance DNAPL Recovery." Proceedings of the 8th Annual NGWA National Outdoor Action Conference, May 1994.

Murdoch, L.C., D. Wilson, K. Savage, W. Slack, and J. Uber "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/001, 1995, available at www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

GWRTAC ID: FRAC0095

Project Name: Stearns & Foster Site, NJ

City: ***State/Province:*** NJ

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information:

Blast-fractured trenches were installed at this manufacturing site owned by Stearns and Foster by ENSR in 1997. The blasted bedrock zone, created in shale bedrock beneath 9 feet of overburden, was 100 feet long and 16 feet in depth, corresponding to a sidewall area of 1,600 ft2. Pre-blast well yields were 1 gpm, with post-blast well yields increasing to 5 gpm, for a ratio of pre/post-blast yields of 5.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Compiled Information.

GWRTAC ID: FRAC0034

Project Name: Steel Manufacturing Facility, Western New York

City: Western New York **State/Province:** NY

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

A pilot-scale test using pneumatic fracturing to enhance conventional soil vapor extraction in an unconsolidated synthetic waste tar pit containing high concentrations of benzene was conducted at a steel manufacturing facility in western New York. There were two main layers of residues present in the pit. The upper layer consisted of approximately six feet of a higher permeable, charcoal and black ash material. Below five feet, this residue was saturated with water and became viscous and sludge-like. This material was underlain by a lower permeable material consisting of multiple waste materials. The pilot test was completed in November 1995 and full-scale remediation is still pending.

Pneumatic fracturing was successfully applied in the lower, less permeable residue in the synthetic waste tar pit. Pneumatic fracturing resulted in increased air permeability and fluids recovery from the pit.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

GWRTAC ID: FRAC0012

Project Name: Storage Tank Site in Beaumont, TX

City: Beaumont **State/Province:** TX

Report(s)/Publication(s) (GWRTAC Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

Sand-filled hydraulic fractures were created in swelling clay to enhance the recovery of free-phase LNAPL at a site in Beaumont, Texas. Fractures were created in July, 1993, and a pilot test was conducted in late February, 1994. Silty clay of the Beaumont formation underlies the site to a depth of 6 to 8m, and fine-grained sand occurs below it. In general, the Beaumont formation consists of kaolinite, illite, calcium smectite and fine-grained quartz. Desiccation cracks are common due to a large decrease in volume of the clays accompanying drying near the ground surface. Wetting and drying cycles have resulted in overconsolidation in the upper 8 to 10 m. Moreover, lateral stress is two to three times greater than vertical stress in the upper few meters, in the interval where hydraulic fractures where created.

At the site, the upper meter is fill composed of silty clay, gravel and shells. From 1 to approximately 3.6 m, the formation is a firm to stiff, dark gray silty clay with reddish to olive yellow mottling. Slickensided partings, which indicate preexisting fractures, are common. A light gray silt to clayey silt occurs at approximately 3.6 m. Fractures were created between 2 and 3.6 m depth, so most of them were initiated in the dark gray silty clay. The deepest fractures, however, were initiated in the light grey clayey silt. The water table is between 1 and 1.5 m depth, so all the fractures were created in saturated conditions.

The area of the test contained gasoline and cyclohexane, which infiltrated from surface spillage. The contaminant occurred as free-phase NAPL from approximately 1.5 to 3 m depth in the vicinity of wells I, C and PW-1, and it thinned to the east toward well G.

The pilot test was designed to compare the performance of two designs of fractured wells to a control well. One of the fractured wells consisted of two casings that access fractures at different depths, one in the LNAPL and the other in the water bearing zone below. The other well only contained one fracture near the bottom of the NAPL zone. The approach of the two-fracture design is to recover NAPL from one fracture and water from another. This should limit upward coning of water, which will both increase the rate of recovery of NAPL and improve the NAPL:water ratio to reduce costs of phase separation compared to recovering from one fracture. Both fractured wells were expected to produce at greater rates than the conventional well.

Sand-filled fractures were created at six locations at the site, but only two, I and C, were used during the pilot test. At I-12, a single sand-filled fracture was created at a depth of 3.6 m. Four fractures were stacked one above the other at well C, but only the deepest two, C-10 and C-12, were used during the test. The fracture at C-10 was initiated at 3.0 m depth, and it curved upward and cut through much of the zone containing NAPL. C-12 was initiated at 3.6 m and most of the fracture was beneath the NAPL zone. The fractures were approximately circular in plan with diameters of 7 to 8 m and average thicknesses of 5 to 6 mm (Table

1). A conventional well, PW-1, was screened from 2 to 4 m depth and used as control. Clusters of multi-level piezometers (depths of 1.2, 2.4 and 3.6 m) with short screens were installed along a line from well I through well C.

Table 1. Specifications of fractures used during the pilot test.

	Depth m	Max. Uplift mm	Ave. sand thickness mm	Ave. Diameter m	Sand volume m3 (ft3)
C-10	3	16	6	7	0.23 (8)
C-12	3.6	24	5.5	8	0.28 (10)
I-12	3.6	22	5.5	8	0.28 (10)

A constant head was maintained approximately 10 cm above each fracture, so that the drawdown was 1.5 to 2 m. Fluid was pumped from the wells to storage drums and was periodically diverted to a graduated cylinder to determine total discharge rate. The proportion of NAPL and water in the beaker was measured to estimate the discharge of each phase.

Both wells containing fractures produced LNAPL at rates roughly an order of magnitude or greater thatn the conventional well (Table 2). The C locations were particularly noteworthy, producing both the greatest NAPL rate and the greatest NAPL:water ratio. C-10 produced a high concentration of LNAPL at a rate that was 19 times greater than the control, whereas C-12 produced liquid that was almost completely water. The combined rate of liquid recovery from the C location was 50 times greater than from the control. The total discharge and the ratea of NAPL recovery are approximately half that from the C well. The average discharges indicate that the two-fracture design improves the NAPL recovery rate.

Table 2. Average discharges and ratios of discharge.

	NAPL L/hr	Water L/hr	Total L/hr	NAPL/Water	NAPL/PW-1	Total/PW-1
C-10	4.33	0.34	4.7	13	19	18
C-12	0.07	8.24	8.3	0.008	0.3	32
C (combined)	4.40	8.58	13.0	--	--	50
I-12	1.85	5.61	7.5	0.3	8	29
PW-1	0.23	0.03	0.26	7	--	--

As an additional test, the rates were measured through time. Water was initially recovered rapidly, presumably as water used to created the fractures drained out, and then water was recovered at a constant rate from C-12 while primarily NAPL was recovered from C-10. The pump in the C-12 fracture was turned off at 116 hours. Discharge from C-10 changed abruptly: total discharge increased, but the recovery of NAPL from C-10 actually decreased. Apparently, turning off the pump in C-12 caused water to flow upwards and reduce the area of C-10 available to recover NAPL.
The distribution of head is consistent with the relatively large NAPL recovery by wells intersecting sand-filled fractures. Bowl-shaped zones of relatively large drawdown occur in the vicinity of the fractures. Significant drawdown, however, occurs throughout the area between wells I and C, and a band of 7 cm drawdown at least 25 m long occurs in the vicinity of the two wells. Drawdown in the vicinity of PW-1 was unavailable, but similar tests in the area have shown that drawdowns are negligible within 1 to 2 m from conventional wells.

It is noteworthy to point out that the fractures caused large vertical head gradients. Multi-level piezometers with short screens (25 cm) were required to characterize the head distribution. Conventional piezometers screened over a large interval would have missed the vertical gradients and resulted in a misleading estimate of the effects of the fractures in the subsurface.

Report(s)/Publication(s) (Additional Info Source):

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC

U.S. Environmental Protection Agency, 1995, "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/003, available at http://www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html.

GWRTAC ID: FRAC0016

Project Name: Toronto, Ontario, Canada

City: Toronto ***State/Province:*** ONTARIO

Report(s)/Publication(s) (GWRTAC Source):

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

Project Summary:

The following text was excerpted from information supplied by McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111:

Pnematic fracturing was used to enhance performance of soil vapor extraction underneath a warehouse floor. Pneumatic fracturing was performed under the concrete slab with no damage to the building. Radius of influence and airflow mobility were improved.

Report(s)/Publication(s) (Additional Info Source):

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111

GWRTAC ID: FRAC0072

Project Name: U.S. DoD Fort Hood, TX

City: Fort Hood **State/Province:** TX

Report(s)/Publication(s) (GWRTAC Source):

J. Dablow, Fluor Daniel GTI, "Remediation of Tight Soils by Hydraulic Fracturing, Steam Injection and Electro-Heating", in U.S. DoD's Advanced Applied Technology Demonstration Facility, AATDF News, Spring 1998, page 7

Project Summary:

The following text was excerpted from Dablow "Remediation of Tight Soils by Hydraulic Fracturing, Steam Injection and Electro-Heating", in U.S. DoD's Advanced Applied Technology Demonstration Facility, AATDF News, Spring 1998, page 7:

Comparative studies of soil vapor extraction (SVE) and soil heating to remediate tight clay soils proposed by the University of Cincinnati were conducted by Fluor Daniel GTI for AATDF at Rice University. Thermal and physical enhancement technologies were chosen to test remediation of clay soils contaminated with JP-8 (jet propellant no. 8) at the Robert Gray Airfield at Fort Hood, Texas. Three test cells were utilized to demonstrate thermal enhancement to reduce viscosity and increase vapor pressure, in combination with physical enhancement to improve air and water flow rates.

Soils within the three test cells (Cells A, B, and C) had pre-test hydraulic conductivities of 10-8 to 10-9 cm/sec. Four horizontal fractures were installed in each test cell at depths of 12,15,18, and 21 feet, and real-time fracture propagation was measured using electral resistivity to ensure the target fracture radii of 15 feet was met. Subsequent evaluation of the fractures by soil coring revealed that the fracture radii had not reached 15 feet; this was attributed to variations in soil resistivity (discovered later) that affected the electrical resistivity monitoring. Those involved in this research effort would advise that a backup system for real-time monitoring, such as tiltmeters, should also be used. Fracture radii achieved were marginal to adequate for steam injection in Cells B and C and not sufficient in Cell A. Therefore the experiment was modified to include electro-heating in Cell A and steam injection in Cells B and C. (Steam heating was later discontinued in Cell B after one month of operation due to dewatering problems related to inadequate fracturing).

In all three test cells, volatilization and vapor flow increased in the upper three fractures after soil heating. Liquid and vapor effluents were treated by oil/water separation, air stripping, and thermal oxidation. An innovative venturi eductor system was designed to control groundwater level in the test cells after heavy rainfall raised the water table ten feet, impacting the hydraulic fractures.

In Cell C, steam injection raised soil temperatures to over 212 deg. F. Early in the project, light (<C10) and medium-weight (C10-C11) hydrocarbons were enriched in the vapor stream. When soil temperatures exceeded 113 deg. F., medium and heavy weight (C12-C13 and >C13) hydrocarbons began to volatilize. After the final temperature of 112 deg. F. was exceeded, vapor-phase composition exhibited a decrease in light hydrocarbons and a strong increase in heavier hydrocarbons. Volatilization of all hydrocarbons in the JP-8 source was indicated by a near normal JP-8 distribution in the vapor stream.

In Cell A, electro-heating raised soil temperature at a relatively constant rate to about 140 deg. F. The vapor stream was enriched in light hydrocarbons throughout the test, and the percentage of medium-weight hydrocarbons increased with temperature. At 113 deg. F., light and medium-weight hydrocarbons volatilized, and heavier hydrocarbons remained in separate and adsorbed phases. Electro-heating rates were consistent and not affected by water table flucuations, in contrast to steam injection, where a higher soil temperature was achieved, but temperature flucuations resulted from the injection rate and groundwater conditions.

In Cells A and C, soil sampling after heating revealed a reduction in TPH concentrations to less than 250 mg/kg. Mass removal mechanisms likely included contaminant volatilization and mobilization, physical displacement of liquid and vapor phases outside the test cells, and possible biodegradation. The steam injection system has been scaled up at the request of the base to remediate the entire site.

Report(s)/Publication(s) (Additional Info Source):

J. Dablow, Fluor Daniel GTI, "Remediation of Tight Soils by Hydraulic Fracturing, Steam Injection and Electro-Heating", in U.S. DoD's Advanced Applied Technology Demonstration Facility, AATDF News, Spring 1998, page 7

GWRTAC ID: FRAC0024

Project Name: U.S. DOE Hanford, WA Facility

City: Hanford **State/Province:** WA

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information.

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

Pneumatic fracturing was integrated with in situ vitrification (ISV) at the U.S. Department of Energy (DOE) Facility in Hanford, Washington, in an uncontaminated area. The ISV process is designed to vitrify soil at intense temperatures, subsequently trapping contaminants within a glass matrix and volatilizing others. An integrated Pneumatic Fracturing injection system utilizing graphite particles was injected into the subsurface to establish a conductive plane by which the ISV process could occur. The geology consisted of a mixture of sand, gravel, and cobbles from the Hanford formation. Field activities were completed in January 1995.

Upon completion of field activities, the vitrified soil was recovered from the subsurface, indicating that the project was a success. The process allowed vitrification of a specific target zone which lowered energy requirements.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

McGonigal, S.T., 1995. "Integration of Pneumatic Fracturing and In Situ Vitrification", MS Thesis, Dept. of Civil & Environmental Engineering, New Jersey Institute of Technology, Newark, NJ

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information.

GWRTAC ID: FRAC0020

Project Name: U.S. DOE Portsmouth Gaseous Diffusion Plant, X231-A Land Trmt Site, Piketon, OH

City: Piketon **State/Province:** OH

Report(s)/Publication(s) (GWRTAC Source):

Siegrist, Robert L., Kathryn S. Lowe, Lawrence C. Murdoch, Traci L. Case, and Douglas A. Pickering, "In Situ Oxidation by Fracture Emplace Reactive Solids", Journal of Environmental Engineering, May 1999

Siegrist, R.L., K.S. Lowe, L.D. Murdoch, W.W. Slack, and T.C. Houk, "X-231A Demonstration of In Situ Remeidation of DNAPL Compounds in Low Permeability Media by Soil Fracturing with Thermally Enhanced Mass Recovery or Reactive Barrier Destruction", Oak Ridge National Laboratory, ORNL/TM-13534, March 1998

Project Summary:

The following text is excerpted from Siegrist, et. al. "In Situ Oxidation by Fracture Emplace Reactive Solids", Journal of Environmental Engineering, May 1999, and,
Siegrist, R.L., K.S. Lowe, L.D. Murdoch, W.W. Slack, and T.C. Houk, "X-231A Demonstration of In Situ Remeidation of DNAPL Compounds in Low Permeability Media by Soil Fracturing with Thermally Enhanced Mass Recovery or Reactive Barrier Destruction", Oak Ridge National Laboratory, ORNL/TM-13534, March 1998:

In low permeability but naturally fractured media, vertical leaching or volatilization of toxic organic compounds can lead to high exposures and unacceptable human health or environmental risk. A field test was completed to evaluate in situ remediation at such sites by using hydraulic fracturing to emplace iron metal (Fe0) and permanganate (KMnO4) solids in the subsurface to chemically treate TCE. At an olde land treatment site, two test cells were installed in silty clay soils with hydraulic fractures filled witih either iron metal or permanganate solids at 1.8, 2.4, and 3.6 m depths. Fracture emplacment was monitored, and soisl and groundwater conditions characterized.

Test cell installation features were as follows:

Iron-filled fractures for dechlorination

Fracture Depth	Proppant	Amount
1.2 m	Sand	0.14 m3
1.8 m	Fe0	1,000 kg
2.4 m	Fe0	3,000 kg
3.6 m	Fe0	2,600 kg
5.0 m	Sand	0.57 m3

Fracture trend direction - SE
Test cell volume 148 m3

Permanganate-filled fractures for oxidation

Fracture Depth	Proppant	Amount
1.2 m	Sand	0.14 m3
1.8 m	KMnO4	400 kg
2.4 m	KMnO4	600 kg
3.6 m	KMnO4	600 kg

5.0 m	Sand	0.57 m3

Fracture trend direction - NW
Test cell volume 148 m3

After 3, 10, and 15 months of emplacment, continuous cores were collected and morpohologic and geochemical data were collected across the fracture zones. Controlled degradation tests were completed using site ground water with TCE concentrations near 53, 144, and 480 mg/L equivalenet to 0.5, 1.2, and 4.1 g TCE per kg media, respectively. The iron-filled fractures formed a discrete reactive seam less than 1 cm thick, wherein the Eh decreased and reductive dechlorination could occur, but effects in the adjacent silty clay soils were negligible. Though the emplaced iron exhibited some surface corrosion after extended emplacement in the subsurface, its reactivity was unaffected. Iron from the fractures degraded TCE at efficiencies of as much as 36% after 24-48 hrs of contact, which is consistent with Fe0 packed bed degradation half lives of 1 to 2 hrs. The permanganate-filled fractures yielded a diffuse reactive zone that expanded over time, reaching 40 cm in thickness after 10 months. Throughout this oxidizing zone, the degradation efficiency was >99% after 2 hours of contact for dissolved TCE at 0.5 and 1.2 mg TCE per g of media. When exposed to higher TCE loadings (i.e. 4.1 mg per g), degradation efficiencies after 10 months dropped to 70% as the TCE load exceeded the oxidant capacity remaining. These efficiencies and rates are consistent with oxidation stoichiometry and previously determined half-lives of <2 min for permanganate oxidation of TCE. In both test cells there were no marked effects on the chemisty of contamination levels in the ground water beneath the cells. Though the results of this research are pomising for emplacement of horizontal treatment zones, further work is required to support full-scale application.

At this same site, in December 1997, field activities were completed on a demonstration focusing on soil fracturing to increase mass recovery by thermally enhanced soil vapor extraction as well as to achieve in place destruction through emplacement of reactive horoizontal barriers. The active demonstration phase began in August 1996 when four primary test cells (A-D) were established using hydraulic fracturing methods. Each test cell encompassed a subsurfacee region of about 30 feet in diameter and up to 18 feet below ground surface (bgs) and each was composed of a set of stacked horizontal fractures. Test cell A consisted of sand-propped fractures for steam injection and vapor extraction via overlying and underlying fractures. Test cell C contained iron-metal propped fractures to create a set of horizontal permeable barriers for interception and in situ destruction by reductive dechlorination. Test cell D was composed of fractures that were emplaced and propped with a new permanganate particle grout. These stacked horizontal fractures were used to create a set of permeable reactive barriers that provided interception and in situ desctruction by oxication of organic compounds.

Pre-operational site characterization revealed that concentrations of TCE and related hydrocarbons were highly variable within the test site with concentrations ranging from non-detectable levels to about 100 mg/kg. Free product was encountered in one of the ground water piezometers adjacent to Test cell B.

Active operation of test cells A and B began in October 1996. To establish baseline ambient air flushing characterisitics, the initial 15 day operation consisted of ambient air injected into a sand-propped fracture at 8 ft bgs with active vapor extraction occurring via sand-propped fractures at 4- and 12-ft bgs. After this initial baseline operation, cells A and B were converted to hot fluid injection with down-hole steam generation/injection (test cell A) or down-hole hot air generation/injection (test cell B) and operated approximately 60 days. Rates of vapor extraction averaged about 4 cfm from the shallow fractures at 4 ft bgs and about 1 cfm or less from the deeper fractures at 12 ft bgs. Off-gas VOC concentrations were in the 3000 to 5000 ppmv range from the shallow fractures and 20,000 to >100,000 ppmv from the deeper fractures. Additional preliminary analysis of the off-gas from the deep fractures indicated up to 17% methane and >800 ppmv of TCE at test cell B. Rates of removal of volatile constituents gradually declined during ambient air passive inlet. The rate of removal increased when hot fluid injection began, followed by a gradual decline.

In December 1996, the X-231A demonstration site was sampled and put in passive mode for the winter. Continuous cores were collected and degradation tests completed with soil cores collected from the reactive fracture barriers in test cells C and D. Samples of the reactive fractures and soil within a 30-cm thick zone above or below the fractures were batch-tested for TCE degradation potential. Results indicated hightly reactive zones were present in these two cells after 3 months of emplacement. In the permanganate barrier cell the TCE degradation efficiencies were >99% after 24 hours of reactive throughout a 10-cm thick soil zone, and in the iron metal barreir cell the efficiencies were eonly about 35% and only within the iron-filled fracture itself. Assuming pseudo first-order kinetics with respect to TCEe concentration and normalizing the degradation rates based on a solid:solution ratio representative of the reactive solids in a fracture, these degradation rates observed were equivalent to half-lives in the range of 40 minutes for the iron.

In July to September 1997, further process operation and performance evaluation were carried out. In test cells A and B input temperatures and flow rates were elevated to enhance subsurface heating. In hot air cell B subsurface temperatures were elevated to nearly 60 deg. C, with maximum subsurface temperatures of 100 deg. C around the deep fracture at 8 ft bgs. To assess more active operation of test cells C and D, tapwater with a conservative tracer was injected into the shallow sand-filled fractures in each test cell for about 45 days. Infiltration and percolation of the tapwatear and tracer downward through the underlying reactive-fracture zone was evaluated. Also, a second round of continuous coring and reactive fracture examination of test cells C and D corroborated the December 1996 findings. The reactive iron metal barrier in test cell C was still reactive at about the same level of 35% degradation (about 1 g TCE per kg of iron particles) after 24 to 48 hours of contact. Only the iron metal itself, not the surrounding soil, was reactive. The permanganate grout barrier of test cell D exhibited greater degradation over a larger zone than earlier tests. Degradation on the order of 3 g TCE/kg of permanganate-effected soil occurred over a 2 hour contact period.

In September 1997, tests were completed and the site restored. A final set of continuous cores was collected from test cells C and D in December 1997. Examination of the reactive fractures corroborated and extended the findings of the December 1996 and July 1997 work. In the iron-filled fractures the redox potential remained highly reducing with little effect on the surrounding soil. Kinetic tests with the iron metal and different concentrations of TCE indicated reductive dechlorination was still viable. However there was some concentration dependency related to the initial TCE concentration. In the permanganate fracutre zones, there were still hightly oxidizing conditions present after 15 months of emplacement and high concentrations of permanganate were still present in the subsurface in zones that were nearly 90 cm thick.

The hot air flushing and permanganate grout barriers appear most promising for further focused demonstration and implementation. A proof-of-principal document that summarizes the applicability of permanganate grout barriers for vadose zone VOC removal at PORTS was issued in April 1998.

Report(s)/Publication(s) (Additional Info Source):

Siegrist, Robert L., Kathryn S. Lowe, Lawrence C. Murdoch, Traci L. Case, and Douglas A. Pickering, "In Situ Oxidation by Fracture Emplace Reactive Solids", Journal of Environmental Engineering, May 1999

Siegrist, R.L., K.S. Lowe, L.D. Murdoch, W.W. Slack, and T.C. Houk, "X-231A Demonstration of In Situ Remeidation of DNAPL Compounds in Low Permeability Media by Soil Fracturing with Thermally Enhanced Mass Recovery or Reactive Barrier Destruction", Oak Ridge National Laboratory, ORNL/TM-13534, March 1998

GWRTAC ID: FRAC0023

Project Name: U.S. DOE Portsmouth Gaseous Diffusion Site, Piketon, Ohio

City: Piketon **State/Province:** OH

Report(s)/Publication(s) (GWRTAC Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

McLaren Hart, Inc., 25 Independence Boulevard, Warren, NJ 07059, phone (908) 647-8111, Company Information.

Project Summary:

The following text was excerpted from Company Information, ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620 or www.arstechnologies.com:

Pneumatic fracturing was used to increase aquifer hydraulic conductivity in a clean (uncontaminated) formation consisting of two aquifers at a U.S. Department of Energy (DOE) Site in Ohio at pilot scale. The uppermost aquifer was a silt formation commonly interbedded with clay and sand lenses. The lower aquifer consisted of sand and gravel. Pneumatic Fracturing was applied in each of these formations to increase the hydraulic conductivity and transmissivity of those aquifers. The treatability study was conducted in a clean area to evaluate feasibility of utilizing the technology in contaminated zone at facility. Fracturing was performed in 1994 for the purpose of demonstrating its impact on pump and treat performance. Fractures were injected between 8 and 23 feet below the ground surface.

Pneumatic fracturing was effective for doubling the hydraulic conductivity of the upper silt formation, and increasing the hydraulic conductivity of the lower formation by 60%. Pneumatic fracturing was also shown to substantially increase the "dewatering" of the site, which can be used to increase the unsaturated zone depth. This application can improve the effectiveness of SVE/DVE applications at contaminated portions of the site.

Report(s)/Publication(s) (Additional Info Source):

ARS Technologies, Inc., Cass Street at Highway 35, Keyport, NJ 07735, phone (732) 296-6620, Company Information.

McLaren Hart, Inc. Warren, NJ, phone (908) 647-8111, Company Information.

GWRTAC ID: FRAC0091

Project Name: U.S. DOE, UMTRA, Tuba City, AZ

City: Tuba City **State/Province:** AZ

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, Rochester, NY, Project Summary Information:

This project involved a pilot test of blast fracturing to attempt improvement of a proposed groundwater pump & treat system. The proposed system would deploy 200 wells on an orthogonal grid to recover a groundwater plume containing elevated levels of uranium, sulfate and nitrate. These compounds resulted from a uranium processing tailings pile generated at the site from 1956-1966. The blast fracture pilot study was intended to evaluate the feasibility of creating better interconnection between stratigraphically separated saturated, permeable units and create linear blast-fractured zones that could be drained with fewer wells than the about 200 proposed. The pilot study was conducted in 1997 but was not taken to full-scale design.

Bedrock at this location is Navajo Sandstone consisting of fine to medium-grained, cross-bedded aeolian sandstone cemented with calcium carbonate and silica. It is overlain by an average of 30 feet of dune sand, pediment gravel and clay. A pilot trench 50 feet in length and 70 feet deep was blasted at the site, corresponding to a sidewall area of 3,500 ft2. Relatively minor increase in yield was observed in pre- and post-blast well testing. Pre-blast well yields were 0.5 gpm, with post-blast well yields increasing to 1 gpm, for a ratio of pre/post-blast yields of 2. It is believed that the lack of significant yield enhancement was related to the poorly consolidated, friable nature of the local Navajo Sandstone. The blasting appeared to turn a poorly cemented sandstone back into un-lithified sand, rather than create a consistent zone of higher permeability rock "rubble" as had been observed at other sites.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0010

Project Name: Xerox Corporation Site, Oak Brook, IL

City: Oak Brook ***State/Province:*** IL

Report(s)/Publication(s) (GWRTAC Source):

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC.

Project Summary:

The following text was excerpted from U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992;
Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994; and,
U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC:

The hydraulic fracturing techology entered the SITE Demonstration Program in July 1991, and the demonstration took place over 21 weeks beginning in July 1992. The Oak Brook Site contains solvents that were spilled during the filling of a storage tank. The contaminants consist of trichlorothene (TCE), 1,1,1-trichlroethane (TCA), 1,1-dichloroethane (DCA), tetrachloroethene (PCE), and other solvents, and are present in silty clay till to depths of 6 m (20 feet) bgs. Hydraulic conductivity varies from 10-7 to 10-8 cm/sec. The low conductivity hinders vapor extraction. In order to improve extraction rates, hydraulic fractures were created at depths of 1.8, 3, and 4.6 (6, 10, and 15 feet) bgs at two locations. Ground surface uplift measurements showed a maximum thickness of 2.5 cm and indicated a lateral extent of about 6 m. Multi-level recovery wells, Wells No. RW3 and RW4, were installed to connect each fracture individually to a two-phase vapor extraction system. The vapor recovery rates from these two wells were compared to rates from similarly screened zones in unfractured Well No. RW2. A multi-level monitoring system consisting of as many as six pneumatic piezometers per borehole was installed at radial distances of 1.5, 3, 4.6, and 7.6 m from each recovery well.

The vapor flow rates and contaminant concentration were measured using variable area flow meters and gas chromatography. Other parameters of interest included water discharge from the vapor extraction system, soil moisture content, and soil vacuum at the recovery wells and the monitoring holes.

Vapor discharge rates from Well Nos. RW2, RW3, and RW4 are presented in Table 1. The average discharge rates from the fractured wells, RW3 and RW4, were 15 to 20 times greater than unfractured Well No. RW2. Discharge from fractured wells tended to flucuate, while that for Well No. RW2 was more consistent. The fluctuation may have been due to changes in the subsurface caused by precipitation events.

Table 1. Vapor Discharge Rates at the Oak Brook Site

Well No.	Range of Rates liter/sec	Ave Rate liter/sec	Fraction discharged from 1.68 to 1.98 m bgs	Fraction discharged from 2.90 to 3.20 m bgs	Fraction discharged from 4.42 to 4.72 m bgs
RW2	0.047-2.2	0.52	0.47	0.27	0.24
RW3	1.0-10.4	6.7	0.61	0.09	0.30
RW4*	13.2-20.1	16.1	0.34	0.36	0.23
RW4**	8.1-14.0	10.7	Not Appl	Not Avail	Not Avail

* The 1.8 m fracture at Well No. RW4 vented to the surface. Data for this line include discharge when suction was applied simultaneously to all three fractures.
** This line shows data from when suction was applied to the 3 m and 4.6 m fracture only; hence, well discharge was less than when suction was applied to all three fractures.

Mass recoveries for ten targeted compounds were computed for each well from concentration and discharge measurements (Table 2). Mass recoveries from hydraulically fractured wells were approximately one order of magnitude greater than that from the unfractured well. Mass recovery rate from all wells decreased through time.

Table 2 Recovery of Contaminants from Oak Brook Site

Well No.	Time (days)	Mass of VOCs Recovered (Kg)	Time (days)	Mass of VOCs Recovered (Kg)	Time (days)	Mass of VOCs Recovered (Kg)
RW2	60	2.3	110	2.7	160	2.7
RW3	60	10.4	110	16	160	19
RW4	60	3.6	110	7.3	160	8.6

Suction head measurements provide insight into the extent of influence of a well. Suction head decreased abruptly with distance from the unfractured well, from 670 cm of water suction in Well No RW2 to a few millimeters (mm) of water at a piezometer 1.5 m away. On the other hand, suction head decreased gradually with distance from the fractured wells, ranging through pressures of 40, 33, 1, and 0.5 cm of water at distances of 1.5, 3, 4.6, and 7.6 m from the well, respectively.

Report(s)/Publication(s) (Additional Info Source):

Proceedings, Fifth Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Chicago, IL, May 3-5, 1994.

U.S. Environmental Protection Agency, 1992: The Superfund Innovative Technology Evaluation (SITE) Program: Technology Profiles, Fifth Edition, U.S. EPA, Office of Solid Waste and Emergency Response, Washington, DC, Office of Research and Development, Washington, DC, EPA/540/R-92/077, November 1992.

U.S. Environmental Protection Agency. Technology Evaluation and Applications Analysis Reports: University of Cincinnati/Risk Reduction Engineering Laboratory: Hydraulic Fracturing Technology. EPA/540/R-93/505, September 1993.

U.S. Environmental Protection Agency (EPA), April 1995: Status Report: Hydraulic and Pneumatic Fracturing, EPA 542-K-94-005, U.S. EPA Office of Solid Waste and Emergency Response (5102W), Technology Innovation Office, Washington, DC.

U.S. Environmental Protection Agency, 1995, "Alternative Methods for Fluid Delivery and Recovery", USEPA/625/R-94/003, available at http://www.epa.gov/ordntrnt/ORD/WebPubs/fluid.html.

GWRTAC ID: FRAC0096

Project Name: Xerox Corporation, Micheldean, England

City: Micheldean ***State/Province:*** ENGLAND

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Project Summary:

The following text was excerpted from Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information:

Blast-fractured trenches were installed at this Micheldean, England manufacturing site Haley & Aldrich, Inc. The blasted bedrock zone, created in sandstone/shale bedrock beneath 21 feet of overburden, was 120 feet long and 50 feet in depth, corresponding to a sidewall area of 6,000 ft2. Pre-blast well yields were <0.1 gpm, with post-blast well yields increasing to 6.6 gpm, for a ratio of pre/post-blast yields of 66.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

GWRTAC ID: FRAC0015

Project Name: Xerox Corporation, Webster, NY

City: Webster **State/Province:** NY

Report(s)/Publication(s) (GWRTAC Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Smith, L.P., W. Davidson, and J.E. Loney, "Linear Blasting for Migration Control in Low Permeability Formations"

Project Summary:

The following text was excerpted from Smith, L.P., W. Davidson, and J.E. Loney, "Linear Blasting for Migration Control in Low Permeability Formations", and Haley & Aldrich of New York, Rochester, NY, Project Summary Information:

An application of controlled blasting to create fractured rock trenches was conducted at a Xerox Corporation facility in Webster, New York, where individual pumping wells were not successfully controlling contaminant migration. At the site, shallow bedrock was contaminated with solvents over several hundred acres. The concentration of the contaminants ranged from low ppb to over 1,000 ppm. The site is underlain by relatively flat-lying interbedded sandstone and shale, with permeabilities ranging from 10-5 to 10-7 cm/second. Groundwater flow and contaminant transport is controlled primarily by bedrock joint patterns oriented in northeasterly and northwesterly directions. Prior to blasting, pumping well yields ranged from 0.1 to 1.5 gpm, and the average radius of influence of a single pumping well was about 50 feet.

A system of individual pumping wells and blasted rock trenches was installed at the site to provide an effective means of controlling contaminant migration. A series of recovery wells have been installed in 8 blasted-bedrock zones to enhance remediation processes in place at source areas (2-PhaseTM Extraction), by controlling the migration of groundwater plumes and shrink selected areas of plumes. Initial release discovery was in 1984 during the removal of underground spill containment tanks and waste transfer tanks. Blasted trench installation started in 1987; several subsequent trenches were installed in later years until the most recent in 1998. Straight line trench or orientations were selected for downgradient areas of the plume where migration control was the primary objective. Y-shaped trenches were selected for interior areas of the plume to allow for a reduction of contaminant concentrations and further enhancement of migration control.

Soil overburden on site consists of lacustrine sand and glacial till overlying bedrock, ranging from 6 to 25 feet in thickness at trench locations. Bedrock consists of interbedded sandstone, siltstone and shale. Groundwater depth ranges to from about 5+/- to 20 feet below ground surface. The trenches installed at the site ranged in length from 300 to 850 feet, and in depth from 20 to 30 feet below the top of bedrock. The sustained yield of the trenches vary seasonally and average between 12 and 50 gpm, in contrast to the 0.05 to 1 gpm prior well yields.

The dimensions of the eight blasted bedrock zones (Trenches 1 through 5 were installed at Salt Road and Trench 6 was installed at Micheldean Road), and corresponding bedrock type and overburden depths were as follows:

Trench 1 (Length x Depth, Sidewall Area): 700 x 25 ft, 17500 ft2 in sandstone/shale beneath 6 feet of overburden;
Trench 2 (Length x Depth, Sidewall Area): 675 x 25 ft, 16875 ft2 in sandstone beneath 12 feet of

overburden;
Trench 3 (Length x Depth, Sidewall Area): 800 x 20 ft, 16000 ft2 in shale beneath 25 feet of overburden;
Trench 4 (Length x Depth, Sidewall Area): 600 x 25 ft, 15000 ft2 in sandstone beneath 9 feet of overburden;
Trench 5 (Length x Depth, Sidewall Area): 330 x 25 ft, 8250 ft2 in shale beneath 6 feet of overburden; and,
Trench 6 (Length x Depth, Sidewall Area): 500 x 24 ft, 12000 ft2 in sandstone beneath 11 feet of overburden.
Trench 7 (Length x Depth, Sidewall Area): 300 x 30 ft, 9000 ft2 in sandstone beneath 12 feet of overburden.
Trench 8 (Length x Depth, Sidewall Area): 450 x 47 ft, 21150 ft2 in sandstone beneath 8 feet of overburden.

The pre-blast and post-blast well yields in each trench, and the ratio of the pre- and post-blast yields were:

Trench 1 (Pre-blast yield, Post-blast Yield, Ratio): 0.1 gpm, 15 gpm, 150;
Trench 2 (Pre-blast yield, Post-blast Yield, Ratio): 0.1 gpm, 40 gpm, 400;
Trench 3 (Pre-blast yield, Post-blast Yield, Ratio): <0.1 gpm, 50 gpm, 500;
Trench 4 (Pre-blast yield, Post-blast Yield, Ratio): 1 gpm, 30 gpm, 30;
Trench 5 (Pre-blast yield, Post-blast Yield, Ratio): <0.1 gpm, 12 gpm, 120;
Trench 6 (Pre-blast yield, Post-blast Yield, Ratio): <0.5 gpm, 20 gpm, 40;
Trench 7 (Pre-blast yield, Post-blast Yield, Ratio): 0.1 gpm, 15 gpm, 150; and,
Trench 8 (Pre-blast yield, Post-blast Yield, Ratio): <0.5 gpm, 10 gpm, 20.

Since trench installation at the site, over 120 million gallons of groundwater have been withdrawn, representing about ten times the known volume of contaminated groundwater at the site. The contaminant distribution in groundwater has been altered by five years of pumping. The blasted trench technology resulted in a reduction of over 90 percent in the dissolved phase contaminant concentration and more than a 50 percent reduction in the areal extent of contamination.

At this same site, a migration control trench and recovery well system was installed in 1989 on the site of a closed industrial landfill. Use of the industrial landfill occurred between 1960 and 1971. NYSDEC reports the landfill was used for disposal of solid industrial waste, including drummed sludge. Groundwater contaminants include trichloroethylene, tetrachlorothylene, cis-1,2-dichloroethylene, and toluene.

Overburden soil on site consists of lacustrine sand and glacial till overlying bedrock. The overburden averages 20 feet thick at the trench location. The bedrock consists for sandstone, siltstone, and shale of the Ordovician Queenston Formation. Groundwater depth ranges from 6+/- to 15 +/- feet below ground surface. The blasted bedrock zone length is 850 feet to a depth of 26 feet below top or rock, for a sidewall area of 22,100 ft2. Well yield prior to blasting was 0.1 gpm, and this increased to 10.0 gpm after blasting, for a ratio of pre- to post-blast yield of 100.

Report(s)/Publication(s) (Additional Info Source):

Haley & Aldrich of New York, 189 North Water Street, Rochester, NY 14604-1151, phone (716) 327-5507, Company Information.

Smith, L.P., W. Davidson, and J.E. Loney, "Linear Blasting for Migration Control in Low Permeability Formations"