United States
Environmental Protection
Agency

EPA/540/SR-93/509
August 1993

EPA

SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

Technology Demonstration Summary

Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase I

Herbert S. Skovronek

The Accutech Pneumatic Fracturing Extraction(TM) (PFE)(TM) process evaluated in a SITE Program demonstration improves bedrock permeability for vapor extraction of volatile organic compounds by injecting bursts of compressed air into wells in the vadose zone, thereby creating new fractures and/or enlarging pre-existing fractures.

Based on 4-hr tests, fracturing increased the extracted air flow rate 400% to 700%, averaging 600%. With the increased air flow rate and improved accessibility, trichloroethene mass removal rate increased about 675% over that observed in a 4-hr test before fracturing. When extracting from radially located monitoring wells, fracturing increased the extracted air flow rates 450% to 1,400% at wells 10 ft from the fracture well and 200% to 1,100% in wells at 20 ft, providing a significant improvement in the effective radius for extraction. With monitoring wells open as a passive source of air, even larger increases in air flow rate and TCE mass removal rate were achieved. The process is particularly useful where the vadose zone permeability is so low that conventional vapor extraction would not be effective.

Using data developed in the 4-hr postfracture test, the estimated cost for a hypothetical 1-yr cleanup would be $307/kg ($140/lb) of TCE removed, including capital cost amortization. Labor was the major cost factor (29%), followed by capital equipment (22%), collection and disposal of extracted VOCs (19%), site preparation (11%), and residuals disposal (10%).

Experiments to evaluate the effects of injecting heated air (~200 to 250 °F) into the vadose zone gave inconclusive results.

This Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the SITE program demonstration that is fully documented in two separate reports (see ordering information at back).

Introduction

The Superfund Innovative Technology Evaluation (SITE) Program was instituted in 1986 to promote the development and application of innovative technologies to Superfund and other sites contaminated with hazardous wastes. This project was carried out under a New Jersey Environmental Cleanup Responsibility Act (ECRA) Cleanup Plan for an industrial site in Somerville, NJ where the soil and groundwater were found to be contaminated with VOCs, primarily trichloroethene (TCE). The Plan calls for decontamination of the vadose zone by vapor extraction, where the formation is a shale with very limited air permeability.

Process Description

With Pneumatic Fracturing Extraction (PFE), new fractures may be created and existing fractures may be enlarged and/or extended by injecting bursts (10 to 20 sec) of compressed air (up to 500 psig) into narrow (2 ft) intervals of one or more wellbores. Each interval is isolated by a proprietary injector unit equipped with packers during pneumatic injection. The new fractures provide increased connections and an enlarged radius of influence, thus making vapor extraction from the vadose zone more efficient. Vapor extraction can be carried out from all wells, or with some wells either left open to allow passive air introduction or capped to direct the subsurface air flow.

The developer, Accutech Remedial Systems, Inc., also is developing a catalytic oxidation system for the aboveground destruction of chlorinated hydrocarbons, which may be investigated in a Phase II study. Accutech hypothesizes that further improvements in VOC removal rates can be achieved by injecting the hot exhaust gas (600 to 1000 °F) into one or more wells. The catalytic unit is not yet available, consequently a compressor was used in this Phase I study to produce hot air (200 to 250 °F) in order to develop and calibrate a model for hot gas injection and to evaluate the effects of injecting heated air.

Test Program

A series of radially placed, 6-in. diameter monitoring wells, and a central 4-in. diameter fracture well (FW), were drilled to a depth of about 20 ft (Figure 1).

Each well was cased to about 8 ft below land surface (bls) and left open bore for the remaining depth. Approximately 2-ft intervals of the fracture well (FW) were sequentially isolated by packers and fractured by injecting a burst of compressed air (<500 psig) into each interval for 10 to 20 seconds. The packer assembly was then moved to the next interval and the fracturing process repeated.

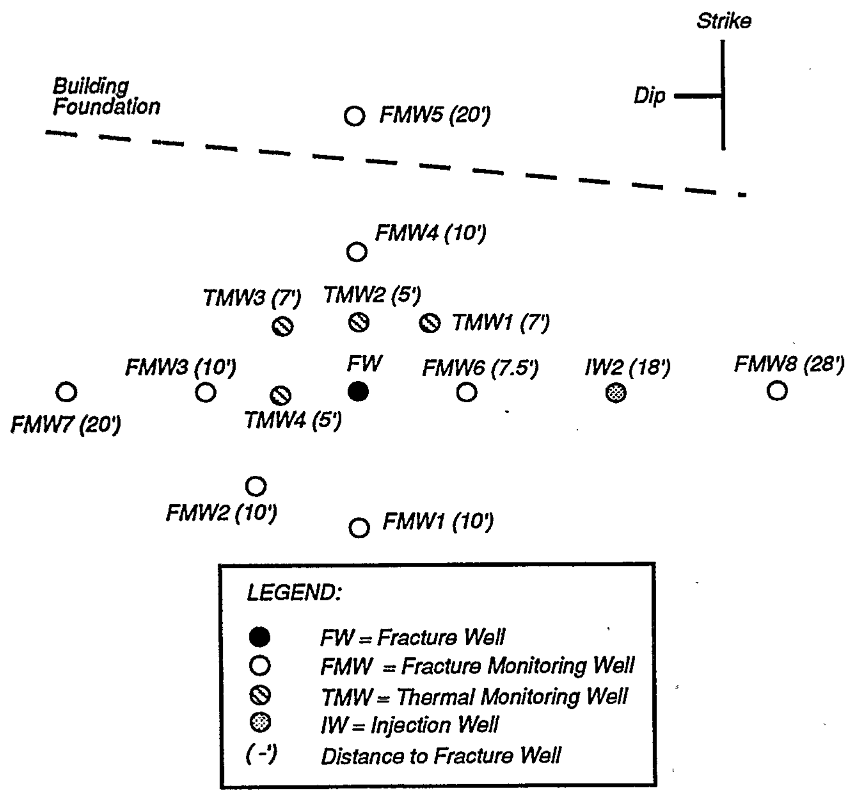

Figure 1. Well location diagram.

Pressures at monitoring wells (capped) and at the extraction well, extracted air flow rates, and TCE mass removal rates were compared before and after fracturing. A second prefracture test was carried out after a 24-hr dormant period to document the recharge effect commonly observed when vapor extraction is interrupted and then restarted. Samples of the extracted gas were collected using EPA Method 18 and analyzed onsite by gas chromatography for TCE concentrations. These values were converted to TCE mass removal rates using the air flow rates. Surface heave during each fracture event was estimated with electronic tiltmeters.

Pressures and air flow rates also were measured while extracting individually from each monitoring well to determine whether fracturing had established connections between the fracture well and the monitoring wells and to provide information on the radius of influence created by fracturing. The effectiveness of passive air inlet was evaluated by uncapping from one to four monitoring wells while extracting from the fracture well. Pressures, air flow rates, and TCE removal rates were determined.

Two experiments were carried out to evaluate the effects of hot gas injection. Compression heated air (~200 to 250 °F) was injected into a central well while extracting from one or more monitoring wells. Temperatures in selected monitoring wells were measured and pressures, air flow rates, and TCE mass removal rates were determined for the extracted air.

Results—Pneumatic Fracturing Extraction Tests

A comparison of the 4-hr postfracture data with the data from the restart test demonstrated an air flow rate increase of between 400% and 700%, averaging about 600%. Although TCE concentrations after fracturing were only slightly higher than before fracturing (58 ppmv vs. 50 ppmv, avg), when coupled with increased air flow rates, the mass removal rate was increased by about 675% (Table 1 and Figure 2).

Table 1. Effects of Fracturing, Capped 4-hr Tests

Test	Pressure, psia	Air Flow, scfm	TCE, lb x 10^{-6}/min
Prefracture	11.0	<0.6*	<10.8±1.0
Restart	11.1	<0.6*	<10.8±1.6
Postfracture	11.4	4.2	83.9±30.8
Increase, %	—	>600#	>675#

* Accutech data indicate prefracture air flow rate <0.6 scfm.

\# % Increase = 100 x (Post - Pre)/Pre.

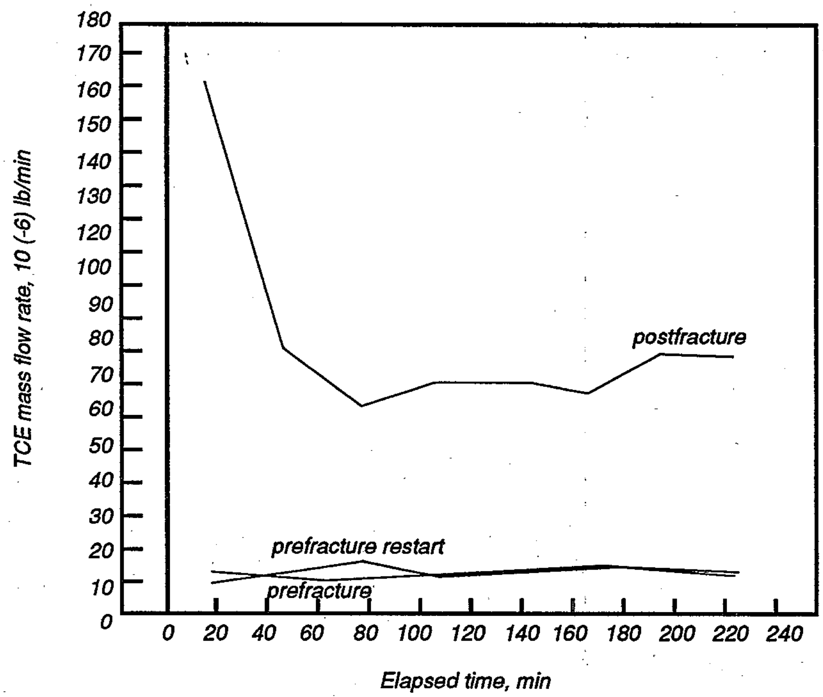

Figure 2. *TCE mass removal comparison—4-hr test.*

It was also found that a more complex gas mixture was extracted after fracturing, with higher concentrations of benzene, chloroform, and tetrachloroethene (Table 2). Fracturing may have improved connection with pockets of these compounds, making them more accessible for extraction.

Extraction at each peripheral monitoring well individually before and after fracturing confirmed that connections were significantly improved even at wells 20 ft from the fracture well, as shown by extracted air flow rates (Table 3).

Attempts were made to determine whether vertical connections existed or were created by fracturing between adjacent 2-ft intervals, but the data were inconclusive, probably because of perched water in the vadose zone and the wellbore.

Additional tests were carried out with monitoring wells left open as passive air inlets while extracting from the fracture well. In these experiments, even larger increases in air flow rates and TCE mass removal rates were observed after fracturing (Table 4).

Table 2. *VOCs in Extracted Air, Before and After Fracturing*

Contaminant	*Concentration, ppmv* Before Fracturing	After Fracturing
Methylene chloride	*1.4*	*26.0*
Chloroform	*3.5*	*108.5*
c-1,2-Dichloroethene	*U* (<3)*	*U (<12.5)*
Trichloroethene	*59.4*	*113.4*
Benzene	*5.4*	*412.7*
Tetrachloroethene	*3.3*	*220.4*
Toluene	*U (<3.3)*	*5.2J#*
Xylene, m/p-	*U (<2.8)*	*U (<11.4)*
Xylene, o-	*U (<2.8)*	*U (<11.4)*

** U = below detection limit.*
 # J = estimated, below quantitation limit.

Results—Hot Air Injection Tests

During the first hot gas injection test (90-hr), temperatures in the monitoring wells remained essentially constant over the first 10 hr at approximately 58°F. At that time the thermocouples were raised from 14 ft bls to 8 ft bls. Elevated temperatures were immediately observed and continued to increase over the next 10 hr before stabilizing (Table 5). It is unknown whether one or more thermocouples was immersed in water in the well at the 14 ft depth.

In addition, only very low concentrations of TCE (~1 ppmv) were found in the extracted air, both before and during hot air injection. Even with the increased air flow rates during injection, the calculated TCE mass removal rate actually decreased during hot air injection (Table 6), possibly due to changes in the subsurface air flow directions when the system configuration was changed from extraction only to extraction and injection.

A second experiment, lasting 24 hr, was carried out in another area of the site where higher TCE concentrations were anticipated. A new hot gas injection well and an additional extraction well were installed (IW2, FMW8). Air was extracted from two wells (FMW6 and FMW8), each 10 ft from the injection well (see Figure 1). Although initial temperatures in the extraction wells were somewhat higher (~65 to 75 °F) than in the first hot gas injection test, well temperatures did not increase further in this case. Compared to an extraction-only pretest, TCE mass removal rate did increase about 50%, reflecting both increased air flow rates and increased TCE concentration in the extracted air (Table 7).

Perched water in the wells may explain some of the inconsistencies in the air flow rate and temperature results from the two hot air injection experiments.

Costs

Operating and capital equipment costs provided by Accutech were coupled with the demonstration study to estimate the cost for remediation of a hypothetical site comparable to the demonstration site, with an estimated area of 100 ft by 150 ft or 15,000 ft². With an effective extraction ra-

Table 3. *Monitoring Well Extraction Tests*

Distance from FW, ft	*Well No.*	*Air Flow, scfm* pre-	post-	*Increase, (post-pre) pre*
*10 s**	*FMW 1*	*<.62#*	*5.15-6.36*	*>7.3 - 9.2*
10 o/s	*FMW 2*	*<.62-.88*	*6.99-5.22*	*>4.9 -10.3*
10 d	*FMW 3*	*<.62*	*5.11-9.35*	*>7.2 -14.1*
10 s	*FMW 4*	*<.62*	*5.7 -8.11*	*>8.2 -12.1*
20 s	*FMW 5*	*<.62*	*5.48-7.46*	*>7.8 -11.0*
7.5 d	*FMW 6*	*<.88*	*4.83-7.1*	*>4.5 - 7.1*
20 d	*FMW 7*	*<.62*	*1.94-1.96*	*>2.1 - 2.2*

** s = strike; d = dip; o/s = off strike and dip.*
 # Some prefracture air flows are based on Accutech data.

Table 4. Passive Air Inlet Tests

Test	Pressure, psia avg	Air Flow, scfm avg	TCE Mass Removed, lb x 10^{-6}/min
Prefracture	10.8	0.39±0.04	4.9±1.4
Postfracture	14.6	76.4±4.8	116±91.0
Increase, %	—	19,500	2,270

Table 5. Hot Air Injection Well Temperatures, 90 hr

Well	Distance from Injection Well, ft	Monitoring Well Temperature, °F Initial to 10 hr @ 14 ft	After 11 hr, @ 8 ft	After 21 hr, @ 8 ft	After 89 hr, @ 8 ft
TMW2	5	59	72	77	75
TMW4	5	58	71	74	73
TMW1	7	57	75	75	72
TMW3	7	58	75	76	74
FMW4	10	57	65	70	71
FMW2	10	56	64	68	69

dius of 25 ft and 15% to 20% overlap, about 15 wells would be needed.

Although serious limitations are recognized with such an approach to a cost analysis, the results of the 4-hr tests were extrapolated to a 1-yr cleanup effort. It was also assumed that the observed TCE concentration and mass removal rate would continue unchanged for a full year, even though a decrease in the rate of removal as the concentration in the formation decreases is more realistic.

Accutech estimates that a fracturing system consisting of two injector/packer assemblies, a bank of 12 air cylinders, a 12-hp compressor to recharge cylinders between fractures, and auxiliary equipment would cost about $7,131/wk for 2 wk while the 15 wells were fractured. A monitoring and analysis system (including a field GC, tiltmeters, datalogger, and supporting microcomputers) would add an additional $6,656/wk.

The vacuum extraction system for simultaneous extraction from 15 wells consists of a 40-hp vacuum blower capable of 500 scfm, associated piping, instrumentation, and a water knock-out vessel. The estimated cost for this system is $1,090/wk, for the entire year of operation.

The cost for pumping perched water out of the formation was included, but the cost of disposal was not since it was assumed that it would be air stripped together with contaminated groundwater and the incremental cost would be very small. Well cuttings and a small amount of protective gear will require disposal. The total cost for dewatering of the vadose zone and disposal of these materials was estimated at $37,200.

Since Accutech's proposed catalytic oxidation unit is not yet available and has not been evaluated, carbon adsorption was selected for the extracted VOCs. The cost to adsorb the calculated 1209 kg (2,660 lb) of TCE to be extracted over the year of operation and to remove and replace the carbon is estimated at about $70,000/yr.

Personnel will be required throughout the year (24 hr/wk for 49 wk) to oversee the ongoing extraction and a more intensive effort (120 hr/wk) will be required during the 2 wk of fracturing. At an average rate of $65/hr, the total labor cost is estimated at $107,640/yr.

The resulting cost for 1 yr of operation, during which 1209 kg (2,660 lb) of TCE would be removed, is estimated at $371,364, equivalent to about $307/kg or $140/lb of TCE removed. Table 8 provides a summary of the costs and the percent each subcategory contributes to total cost.

No cost estimate was developed for the effect of hot gas injection; the planned catalytic oxidation unit was not used as the source of hot gas.

Applicability to Other Sites

Based on the demonstration and other information, the PFE process would appear to be attractive for VOC-contaminated formations with low permeability, such as most clays and shales. Studies have suggested that improvements in VOC extraction rates are also obtained with more permeable formations such as sands and silts, but the effects are not as great.

There is no *a priori* reason to expect a fracture necessarily to intersect a pocket of contamination. And, as observed in this demonstration, fractures do not always propagate in the direction or to the distances expected. Natural and man-made obstacles such as boulders, building foundations, buried pipelines, etc., can affect fracture propagation, provide undesirable paths, or decrease resistance to fracturing. This can result in surface failures during fracturing or the unexpected escape of vapors, as occurred during the SITE demonstration. Perched water also may hamper fracturing and/or interfere with

Table 6. Hot Air Injection Test, 90 hr

Test	Air Flow, Inject.	scfm avg Extract.	TCE Mass Removed, lb x 10^{-6}/min
Pre-hot air	—	11.6±1.5	172±18
Hot air injection (one well extraction)	69.3±5.4	55.8±3.4	20.4±32.0
Hot air injection (four wells extraction)	73.0±3.4	82.6±7.1	31.2±10.3

Table 7. Second Hot Air Injection Test, 24 hr

Test	Air Flow, Inject.	scfm avg Extract.	TCE Mass Removed, lb x 10^{-6}/min
Pre-hot air inject	—	3.7±1.8	63±27
Hot air inject (2 wells)	to 26.1*	9.2±4.7	97±33
Increase, %	—	150	54

** Some data lost due to leak in manifold; measured values ranged from 10.9 to 26.1.*

Table 8. Operating Cost of Full Scale Pneumatic Fracturing Extraction

Cost Item	Total Cost, $	Cost/lb TCE, $/lb	% of Total
Site preparation	42,000	15.79	11.3
Permitting/regulatory	1,750	0.66	0.5
Capital equipment (1.5 yr)	82,074	30.85	22.1
Startup	8,200	3.08	2.2
Labor salary	107,640	40.47	29.0
Consumables/supplies	4,000	1.50	1.1
Utilities	17,000	6.39	4.6
Emission control	70,000	26.32	18.8
Residuals (water, etc.)	37,200	13.98	10.0
Analytical services	N/A	—	—
Repair, replacement	N/A	—	—
Demobilization	1,500	0.56	0.4
Total	$371,364	139.60	100.0

air flow through the formation, thereby decreasing VOC removal rates while increasing cost.

Conclusions

For properly selected formations, PFE can significantly improve vapor extraction effectiveness. The nature of the formation, moisture content, air permeability, uniformity, water table, and the presence of obstacles or potential sources of short circuits must all be considered when evaluating PFE as a remediation option.

In the demonstration, Accutech's claims were far exceeded: fracturing increased extracted air flow rates 400% to 700% and TCE mass removal rates by almost 700% when operating with a single fracture/extraction well and no air inlet sources. With passive air inlets, the air flow rate and the TCE mass removal rate after fracturing are increased even more, 19,000% and 2,300%, respectively, when compared with the prefracture results.

The radius of influence can be increased significantly by fracturing, with 1,100% to 1,400% increases in extracted air flow rates in wells at distances of 10 ft and 200% to 1,100% even in wells at 20 ft.

The estimated cost for PFE remediation of a site such as that in Somerville, NJ, is $307/kg or $140/lb of TCE removed. Labor, capital equipment, and emissions control are the three major cost factors.

The effects of hot air injection are inconclusive. Increases in the temperature of the formation may be produced if sufficient heat is introduced, but this does not necessarily increase the TCE mass removal rate.

☆U.S. GOVERNMENT PRINTING OFFICE: 1993 - 750-071/80050

Herbert S. Skovronek is with Science Applications International Corporation, Hackensack, NJ 07601
Uwe Frank is the EPA Project Officer (see below).
The complete report, entitled "Technology Evaluation Report: SITE Program Demonstration Test—Accutech Pneumatic Fracturing Extraction and Hot Gas Injection—Phase I," (Order No. PB93-216596/AS; Cost: $17.50, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

A related report discusses the applications of the demonstrated technology: "SITE Program Applications Analysis Report: Accutech Pneumatic Fracturing Extraction and Hot Gas Injection—Phase I" (EPA/540/AR-93/509).
The EPA Project Officer can be contacted at:

Risk Reduction Engineering Laboratory
U.S. Environmental Protection Agency (MS-106)
Edison, NJ 08837-3679

United States
Environmental Protection Agency
Center for Environmental Research Information
Cincinnati, OH 45268

Official Business
Penalty for Private Use
$300

EPA/540/SR-93/509

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No. G-35