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Remediation of low permeability subsurface formations by fracturing enhancement of soil vapor extraction

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Abstract

This paper describes the Superfund Innovative Technology Evaluation (SITE) of pneumatic and hydraulic fracturing to augment and improve the extraction of volatile contaminants from soil. The fracturing procedures involve a physical pressurization process that creates fissures and channels in soils to enhance fluid or vapor flow in the subsurface. Fractures are placed at specific locations and depths inside the boreholes of wells to increase the effectiveness of in situ remedial technologies, especially soil vapor extraction (SVE). The fracturing technology is primarily beneficial in tightly packed geologic formations having low permeabilities. Results from several demonstrations indicated orders of magnitude increases in subsurface vapor flow and contaminated vapor extraction rates after soil fracturing.

1. Introduction

In 1980, the United States Congress enacted the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or Superfund, the first comprehensive Federal law addressing releases of hazardous substances into the environment. The primary goal of the Superfund legislation was to establish an organized cost-effective mechanism for responding to releases of hazardous substances or to abandoned or uncontrolled hazardous waste sites that posed a serious threat to human health and the environment. The Superfund Amendments and Reauthorization Act of 1986 (SARA) added several important, new dimensions to CERCLA, such as increased emphasis on health assessments and consideration of air releases. One of the most important provisions stipulates rules for the selection of remedial actions, provides for a review of those actions, describes requirements for the degree of cleanup, and mandates conformance with the National Contingency Plan whenever practicable. It strongly recommends that remedial actions use onsite treatment that

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"... permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances ..." and requires selection of a remedial action that is "... protective of human health and the environment, that is cost-effective, and that utilizes permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable".

Several in situ remedial technologies for onsite treatment exist that could meet these requirements. Of these, the most popular is soil vapor extraction (SVE), which is an effective method for the remediation of soil contaminated with volatile organic compounds (VOCs) and petroleum hydrocarbons. SVE has gained popularity because it can treat large amounts of soil at relatively low cost, with some estimates as low as $10 per cubic yard. This compares favorably with virtually every other remediation treatment technology, with cost estimates ranging from $80 for some forms of bioremediation to well over $1200 per cubic yard for hazardous waste incineration [1].

Other advantages of SVE that meet the SARA provisions are that the treatment is permanent and that there is minimal exposure of the public and personnel to the affected contamination zone. SVE is an in situ process that minimizes exposure to both the public and the surrounding environment. There is also minimal disruption to surface activities once the installation is complete, so that normal site functions, e.g., work at loading docks, plant floors, airport runways, may be returned to use quickly and used while the remediation is in progress.

Critical to the application of SVE, however, is the ability to achieve adequate vapor flow through the contaminated soil. SVE is only applicable to sites with soil types that permit the flow of contaminant vapors through subsurface formations for extraction and eventual remediation. It is necessary that air can flow through all of the contaminated soil at a site. Such vapor flow in the vadose zone depends in part upon soil characteristics such as air permeability, water content, porosity and soil homogeneity. Relative to SVE, air permeability is the measure of a soil's ability to transmit fluids based on laboratory or field airflow tests. The density and viscosity of vapors combined with the permeability of soil significantly influence the ability of the vapor to flow through subsurface strata. Permeability of soil is usually the single most important soil parameter to be considered in the successful application of SVE. It is a key parameter not only in deciding if SVE is a feasible remedial option, but also for establishing SVE system design criteria. SVE is typically more applicable to soil types with permeability values greater than 10^{-7} cm/s. This includes subsurface strata of gravel, sand, silty sand and some limestone, basalt and metamorphic rock formations. Sites consisting of igneous rock, shale, clay, dense silt, and glacial till usually are not amenable to SVE. Impermeable soil types exist at many Superfund sites. To address this problem, EPA's Office of Research and Development (ORD), through the Superfund Innovative Technology Evaluation (SITE) program has evaluated pneumatic and hydraulic fracturing techniques for increasing soil permeability. The goal of such evaluations is to promote and accelerate the development of innovative technologies for consideration in the clean-up of Superfund sites across the country. As part of this SITE program, demonstrations are performed to provide reliable engineering and cost data based on field tests of selected technologies. This paper addresses the evaluation of two such technologies, pneumatic and hydraulic fracturing. Although they are not independent remedial technologies, they are designed primarily to operate with and improve the effectiveness of SVE for potential application to sites that currently can only be remediated by more complex and costly ex situ treatment.

Both pneumatic and hydraulic fracturing were evaluated because of the advantages and disadvantages inherent to each procedure. Pneumatic fracturing involves injecting air into a 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 subsurface medium and creates a fracture network radiating from the injection point. Once established, the fractures increase the flow rate of air and vapors through the formation, and make contaminants more accessible. Similarly, hydraulic fractures are created when a fluid is injected into a borehole until a critical pressure is reached and the enveloping soil fractures. Sand, injected as a slurry, acts as a propping agent and holds the fractures open.

The pneumatic process is relatively simple, and can be easily deployed. However, the fractures are not propped open and can sometimes close, requiring re-fracturing. On the other hand, the hydraulic procedure is more complex but provides a more permanent sand propped fracture network. Also, the hydraulic process injects water into the ground which must subsequently be extracted before SVE remediation can be initiated.

2. Method

2.1. Pneumatic fracturing

The SITE program demonstration for pneumatic fracturing was performed in cooperation with Accutech Remedial Systems (ARS), Inc. and the Hazardous Substance Management Research Center (HSMRC) located at the New Jersey Institute of Technology (NJIT) under a Cooperative Agreement (No. CS820795) with EPA. Detailed descriptions and evaluation results are available in EPA reports [2, 3] and Schuring et al. [4]. Pneumatic fracturing was developed by HSMRC as a patented process and is currently marketed by ARS under a service mark as Pneumatic Fracturing Extraction (PFE)^{SM}. Specifically the fracturing is performed by injecting bursts of compressed air at pressures up to 500 psig and in duration of 10 to 20 s, into narrow 0.7 m intervals of one or more wellbores. The air injection is performed using a proprietary injector unit equipped with packers. The packers are inflatable rubber seals that isolate the appropriate interval within the well. Air is then released within the sealed interval through the injector as shown schematically in Fig. 1. The process is repeated for each interval. The fracturing extends and enlarges existing fissures and introduces new fractures, primarily in the horizontal direction. When fracturing has been completed, the formation is then subjected to extraction of contaminant vapors, either by applying a vacuum to all wells or by extracting from selected wells while others are capped or used for passive air inlet or forced air injection.

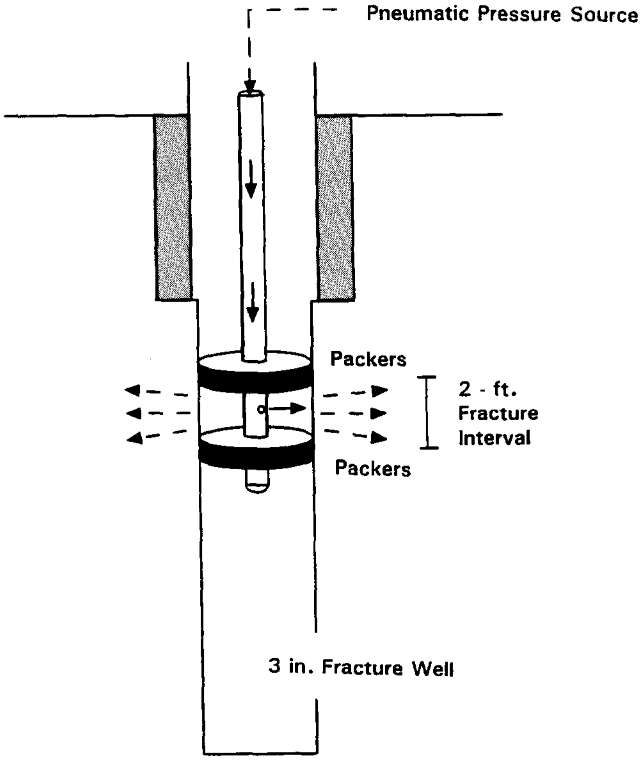

Fig. 1. Schematic of pneumatic fracturing process inside a well borehole.

The ARS/HSMRC equipment used in the SITE demonstration consisted of a 3 m long, open bed SVE trailer fitted with two compressor/blowers, piping, a water knock-out trap, and all associated gauges, valves, and electrical interlocks. The air supply consisted of a bank of 8–12 compressed air cylinders attached to a manifold which was connected to the pneumatic injector and packer system. The injector included an electrically actuated solenoid valve that controlled the actual start and duration of air injection and subsequent fracturing event. Overall, an area of about 15 x 15 m is needed to support the SVE trailer, compressed air supply, monitoring trailer, and auxiliary facilities.

The PFE demonstration was performed at a site in an industrial park in central New Jersey. This site was previously used for small manufacturing and office services for several decades. After a fire, samples taken of surface water indicated the presence of chlorinated organics and petroleum hydrocarbons. Further soil and groundwater testing confirmed the presence of trichloroethene (TCE), and to a lesser extend dichloroethene and perchloroethene, in the groundwater. Benzene, toluene and xylenes (BTX) were more infrequently found. Studies at the site conducted as part of a state cleanup plan helped to define the geological character of the area. Specifically, the site consisted of a glacial till about 1–2 m in thickness underlain by the Brunswick shale formation which is found widely in northern New Jersey and which extends to well below the water table. In spite of the fractured nature of the shale bedrock, pilot testing showed that the permeability of the formation was too low for conventional SVE. Costly excavation and removal of the source area, or encapsulation, were the options under consideration prior to the decision to apply the PFE process.

The well placement and design were based on prior data obtained for the site, best engineering judgement, and practical limitations. The earlier data on groundwater and soil gas analyses at different locations and different depths, as well as the nature of the geology at the site, were taken into consideration. The air injector unit available for performing the fracturing required a 7.6 cm diameter well. To accommodate this requirement, the fracture well was first drilled out 2.4 m deep with an air rotary bit and cased with a 15 cm casing. Next, the well was drilled to a depth of about 6 m with a 7.6 cm hollow bit to provide the 7.6 cm diameter and, simultaneously, a 5 cm core for later geological evaluation by HSMRC.

Combination fracture/monitoring wells were installed at increasing distances radially out from the fracture well. Locations were selected so that data could be generated for the strike and dip directions of the Brunswick formation and for one location for both off strike and off dip. This pattern was selected to evaluate whether fracturing occurred preferentially in a particular direction and how far from the fracture well the effect was detectable. Each monitoring well was 15 cm in diameter and was cased with iron casing down to about 2.4 m ‘below land surface’ (BLS), leaving about 0.6 m of casing above ground for capping and access. Well depths varied slightly in the range of 5.4–6.6 m.

The first test performed was a 1 h passive air inlet predemonstration test to assess the general behavior of the well field. A 4 h pre-fracture SVE test was performed, after the 1 h test, by extracting from the fracture well and keeping all monitoring wells capped. Pressure, air flow rate, temperature, and TCE contaminant concentration data were determined and recorded for background information. This was followed with a ‘restart’ test, which was essentially a repetitive pre-fracture test, carried out after a nominal 24 h period to determine the extent and rate at which TCE concentration levels equilibrate and return to pre-test levels. A post-fracture 4 h SVE test, identical in procedure, was carried out after the fracturing tests were completed. A series of 10 min vacuum extraction tests were also carried out immediately before and after each 0.6 m interval had been fractured to further study the extent of vertical fracture formation and, consequently, cross connections between fracture channels. For each test, vapor extraction was carried out at the fracture well through the injector assembly, usually at about 11 psia (8 in of mercury vacuum). Pressure, air flow rate, and TCE concentration data were then obtained and stored.

2.2. Hydraulic fracturing

Hydraulic fracturing is a technology widely used in the petroleum industry to increase the recovery of crude petroleum from reservoirs with low permeabilities. Consequently, Murdock et al. [5, 6] adopted it to enhance remediation by SVE,

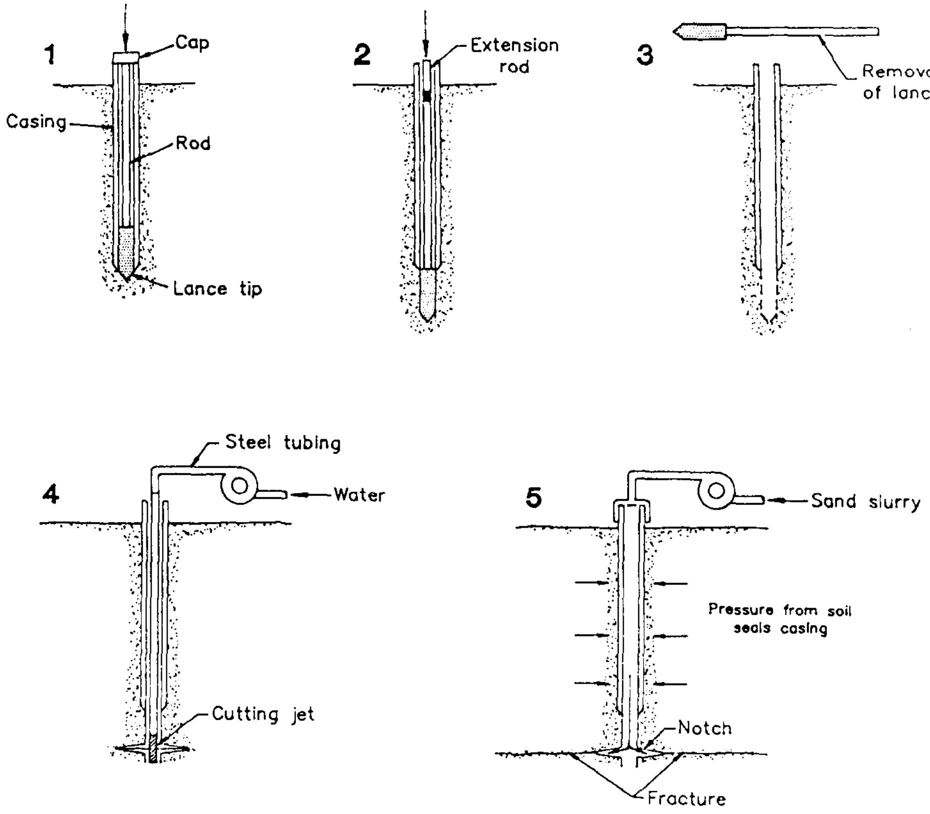

Fig. 2. Schematic of hydraulic fracturing process inside a well borehole.

bioremediation and pump and treat methods. Instead of using air, as in the pneumatic process, hydraulic fracturing involves the injection of water into a sealed borehole until the pressure of the water exceeds a critical value and a fracture is nucleated. A slurry composed of a coarse-grained sand and guar gum gel is then injected as the fracture grows away from the well. After pumping, the sand grains hold the fracture open while an enzyme additive breaks down the viscous guar gum fluid. The thinned fluid is pumped from the fracture, forming a permeable subsurface channel that can be used in conjunction with SVE to enhance the recovery of soil contaminants. The hydraulic fracturing process is shown schematically in Fig. 2. It involves the use of a lance-like device composed of a steel casing and an inner rod that are tipped at one end with hardened cutting surfaces that form a conical point. A drive head on the other end of the lance secures the casing and rod together. Individual segments of the rod and casing are 1.5 m long and are threaded together as required by borehole depth. After the lance is driven to the desired depth in a well, the rod and conical point are pulled out, leaving soil exposed at the bottom of the casing. A high-pressure (24 MPa) water jet is then inserted to the bottom of the casing and rotated, cutting a disc-shaped notch 10–20 cm in diameter. This notch forms the nucleus of the fracture. A simple measuring device, built from a steel tape extending the length of a tube and making a right-angle bend at the end of the tube, is inserted to the bottom of the casing to verify and measure the radius of the slot.

Subsequent to cutting the notch, an injection head outfitted with a pressure transducer is secured to the upper end of the casing to monitor the pressure during the fracturing operation. The onset of pumping is marked by a sharp increase in pressure of the injection fluid followed by a marked decrease as the fracture propagates. Sand is added to the guar gel after the pressure record indicates the onset of propagation. The sand concentration is gradually increased until the ratio of the sand to gel (by volume) is 0.44–0.53. After a fracture is created, the rod and point are reinserted into the lance and driven to a greater depth, where another fracture is created.

The major components of above-ground equipment are a slurry mixer, an injection pump, and gel mixing/storage tanks. The slurry mixer is designed to continuously blend guar gum gel, enzyme additive, and sand. It consists of a sand hopper, reservoirs, a screw auger to introduce the sand to the gel, metering devices, and a mixing tube. The gel is hydrated in 1990 l tanks and pumped to the mixer. The slurry exits the mixing tube and falls into the throat of a positive displacement pump, which injects it into the fracture wells.

The effectiveness of hydraulic fracturing for improving SVE, was evaluated through demonstrations at two sites contaminated with VOCs. An EPA developed technology, these demonstrations were performed through a Contract (No. 68-C9-0031) with the University of Cincinnati. Tests were conducted during 1991 and 1992 at a facility of the Xerox Corporation in Oak Brook, Illinois and at a Mobil retail gasoline station in Addison, Illinois.

The Xerox site was used in past decades for machine conditioning operations using large volumes of organic solvents. Contamination was subsequently discovered in the vicinity of storage tanks under the floor of a building. Soil sampling found contaminants including TCE and other chlorinated VOCs ranging up to 150,000 μg/kg of total halogen content and extending to a depth of 6 m BLS. The site consisted of approximately 4 acres of clayey glacial drift interbedded with lenticular sand deposits. The drift is approximately 12 m thick and can be divided into an upper weathered zone that extends to a depth of 3.7–4.3 m, and a lower unweathered zone. The glacial drift is underlain by dolomite bedrock of Silurian age. The depth to the water table was roughly 9 m, although perched water occurred locally in sand lenses at shallower depths. The permeabilties of the silty-clay ranged from 4×10^{-6} to 7×10^{-7} cm/s. These low permeability values and a treatability study indicated that conventional SVE was not economically feasible. It was estimated that it would require over 300 recovery wells, as well as numerous air inlet wells, to treat the site effectively. The pilot-scale SITE demonstration, utilizing hydraulic fracturing, was therefore initiated. Consequently, a total of six hydraulic fractures were created in two separate boreholes in the contaminated section of the site. Essential details of these fractures are summarized in Table 1.

The gasoline station demonstration site was contaminated by petroleum hydrocarbons from leaking underground storage tanks (USTs). Subsurface samples indicated

Table 1
Details of hydraulic fractures formed at the Xerox and Mobil demonstration sites

Borehole no.	Fracture no.	Depth (m)[a]	Sand (m^3)[b]	Gel (l)[c]	Max. pressure (MPa)[d]	Last pressure (MPa)[e]	Max. rise (mm)[f]	Radius (m)[g]
Xerox site								
1	1	1.8	–	76	0.15	0.14	3	–
1	2	3.0	0.34	492	0.26	0.06	20	4.0
1	3	4.6	0.37	568	0.38	0.23	24	4.9
2	1	1.9	0.17	379	0.17	0.06	26	3.5
2	2	3.0	0.34	530	0.31	0.07	19	4.0
2	3	4.6	0.40	568	0.50	0.24	30	4.7
Mobil site								
1	1	2.0	0.14	379	0.24	0.03–0.10	10.5	5.3
1	2	2.7	0.18	416	0.76	0.05–0.10	11	6.1
1	3	3.6	0.28	492	0.38	0.17–0.28	15	4.6
2	1	2.0	0.17	322	0.34	0.05–0.08	20.5	4.6
2	2	2.7	0.18	397	0.52	0.07–0.10	14.5	5.3
2	3	3.6	0.31	454	0.41	0.12–0.21	21	6.1

[a] Depth below ground surface at point where fracture was initiated.
[b] Bulk volume of sand pumped into fracture.
[c] Volume of guar gum gel pumped into fracture.
[d] Maximum pressure at the point of injection.
[e] Pressure at the end of pumping.
[f] Maximum uplift of ground surface above fracture.
[g] Approximate radius of the uplifted surface area over the fracture.

VOCs to a depth of 3.6 m. Total benzene, toluene, ethylbenzene, and xylenes (BTEX) concentrations exceeded 16,025 μg/kg on 4 out of 11 borings. The site consisted of an inactive service station, including two pump islands, and a gravel backfill area where the USTs were removed. This was underlain by approximately 40 m of gray clayey and silty clay till of the Wadsworth Member of the Wedron Formation. The till uncomformably overlies Silurian age limestone and dolomite. Due to the till's low permeability hydraulic fractures were formed in the contaminated area using two bore holes that were subsequently completed as SVE wells. The fractures were at depths of 2, 2.75 and 3.6 m (Table 1). Two conventional wells were also installed to allow comparisons between the performance of fractured and conventional wells. Parameters measured included well discharge and subsurface pressure distributions.

3. Results

3.1. Pneumatic fracturing

A comparison of the postfracture data with the prefracture data demonstrated an air flow rate increase ranging from 400–700%, and averaging about 600% (Table 2).

Table 2
Extracted air flow, before and after pneumatic fracturing

Test	Pressure (psia)	Air flow (scfm)	Percentage increase	TCE (10^{-6} lb/min)	Percentage increase
Prefracture	11.0	< 0.6[a]		< 10.8 ± 1.0	
Restart	11.1	< 0.6[a]		< 10.8 ± 1.6	
Postfracture	11.4	4.2	600[b]	83.9 + 30.8	675[b]

[a] Developer's test data.
[b] Percent increase = 100(postfracture–prefracture)/prefracture.

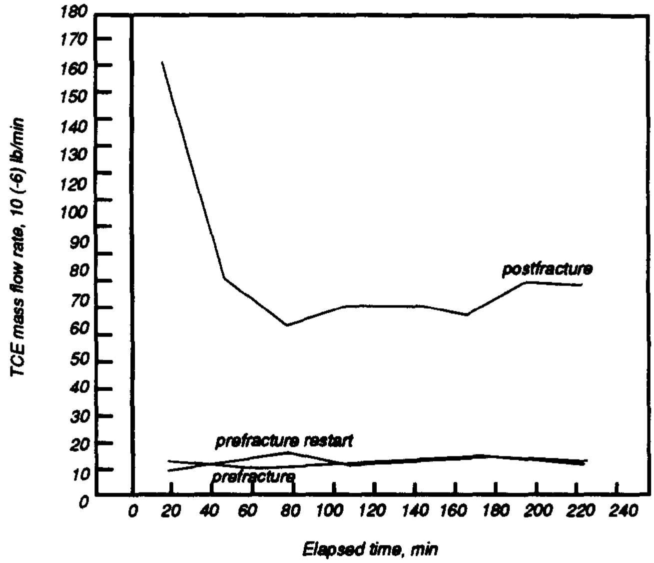

Fig. 3. Comparison of pre- and post-pneumatic fracturing TCE mass removal rates from 4 h extraction tests.

Although TCE concentrations after fracturing were only slightly higher than before fracturing, 58 versus 50 ppmv on average, when coupled with increased air flow rates, the mass removal rate was increased by about 675% as shown in Table 2 and Fig. 3. Also, a more complex gas mixture was extracted after fracturing, with higher concentrations of benzene, chloroform, and tetrachloroethane. Fracturing may have improved connections with pockets of these compounds, making them more accessible for SVE. Extraction at each peripheral monitoring well individually before and after fracturing confirmed that connections were significantly improved even at wells 6 m from the fracture well. Attempts made to determine whether vertical connections existed, or were created by fracturing between adjacent 0.6 m intervals, were inconclusive, probably because of perched water in the vadose zone and the wellbore. Tests carried out by extracting from the fracture well with open monitoring wells indicated that even larger increases in air flow rates and TCE mass removal rates up to 2.270% could be obtained.

3.2. Hydraulic fracturing

At the Xerox site the performance of one conventional unfractured well was compared to the performance of two fractured wells, each containing hydraulic fractures nucleated at depths of 1.8, 3.0, and 4.6 m. Most fractures were shallowly dipping and were confined to the subsurface, except a 1.8 m deep fracture in one of the fracture wells was steeply dipping and reached the ground surface. All three wells were placed in areas of equivalent concentrations of contaminants, according to data obtained from soil samples prior to the test. The wells were evaluated with tri-weekly measurements during 160 days of vapor extraction. The results indicated that vapor discharge from the conventional well averaged 31.1 l/min, whereas it averaged 404.7 l/min and 967.9 l/min from the fracture wells. Some of the difference in discharge between the two fracture wells appeared to be from air that was drawn in from the ground surface through the 1.8 m fracture that reached the surface. However, in general the hydraulic fractures increased the vapor discharge by factors of 13 to more than 20.

The concentration of volatile contaminants was approximately 2 times greater from one of the fracture wells than from the conventional well. The concentration from the other fracture well, was roughly an order of magnitude less. Much of that difference, however, was probably due to dilution of the recovered vapors by air that flowed in through the upper surface fracture and never contacted contaminated soil. The concentration from all of the wells decreases with time as a negative exponential. The decay constants from the three wells were roughly similar, although the decay in concentration from the conventional well was slightly more rapid than from the fractured wells. The mass recovery rate from the fractured wells was 7 to 14 times greater than from the conventional well on average throughout the 160-day-long test. Mass recovery rates also decreased according to a negative exponential. The decay constant for the conventional well was approximately 70% shorter than for the fractured well.

Vacuum was essentially undetectable within a meter of the conventional well, whereas vapor flow was commonly detected 7.6 m from one of the fracture wells. Vacuum measured at piezometers was greatest soon after the piezometers were installed, and decreased markedly over the few months between installation and the period of study. However, vacuum generally increased throughout the duration of the demonstration.

At the Addison site the fractures formed in the silty clay till dipped 20 to 30° towards their parent borehole and ranged in diameter from 7.6 to 10.7 m. During SVE testing, contaminant vapor recovery was prevented by the presence of water in the soil pore space. The fracture wells produced water throughout the study period whereas water recovery diminished after several days at the conventional well, suggesting that the fractured wells influenced a greater area and improved liquid flow through the tight soils.

Vapor recovery from moist silty clay will occur in two stages independent of the presence of hydraulic fractures. During the initial stage, water from the pore space of the soil will be the primary fluid recovered. Air permeability during this period is low and vapor phase recovery will be negligible. During the second stage, the moisture content of the soil in the vicinity of the well diminishes significantly and vapor recovery increases. The results of this SITE demonstration indicated that system operation was confined to the initial stage. The expectation was that if dewatering at the site had continued, vapor recovery from the subsurface would also have increased.

4. Conclusions

Through EPA's SITE program it has been demonstrated that fracturing of impermeable subsurface formations can significantly improve soil remediation by SVE. Pneumatic fracturing increased the extracted air flow rates by 400–700% and TCE mass removal rates by 675% when operating with a single fracture/extraction well and no air inlet sources. Hydraulic fracturing similarly increased the performance of SVE. Volumetric discharge and mass recovery rates from fractured wells were roughly an order of magnitude greater than from conventional wells. In addition, the areas of influence affected increased from less than 1.5 m from a conventional well to more than 6.1 m from a fractured well.

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