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AN EVALUATION OF VAPOR EXTRACTION OF VADOSE ZONE CONTAMINATION

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Executive Summary

An in-depth analysis of vapor extraction for remediation of soils contaminated with volatile organic compounds (VOC's) was conducted at 13 sites. The effectiveness of vapor extraction systems (VES) was evaluated on the basis of soil concentrations of VOC's and soil-gas concentrations of VOC's. The range of effectiveness was found to be 64%-99% effective in removing organic contaminants from soil. At nine of the 13 sites studied in this report, vapor extraction was found to be effective in reducing VOC cooncentrations by at least 90%. At the remaining four sites studied, vapor extraction was found to reduce VOC concentrations by less than 90%. Vapor extraction is ongoing at two of these sites. At a third, the ineffectiveness of the vapor extraction is attributed to the presence of "hot spots" of contamination. At the fourth site, where performance was found to be relatively poor, the presence of geological tar deposits at the site is thought to be a major factor in the ineffectiveness.

Vapor extraction is a complex process that is influenced by two categories of parameters: those that affect the ease of air flow through the soil matrix, and those that influence the vapor concentration of contaminant in the soil. Specifically, these categories include the soil type, soil porosity and permeability, soil moisture content, the volatility of the contaminant, and operational parameters such as the location and number of extraction wells and the implementation of an impermeable "cap" over the area of contamination.

The intrinsic limitation of vapor extraction is the character of chemical interactions with soils. Non-polar organic contaminants are thought to reside in five different phases in the soil matrix. The free-liquid, vapor, and surface-sorbed phases are all amenable to vapor extraction technology, and contaminants present in these phases will be removed using this remediation technology. The aqueous phase of contaminant can also be removed using vapor extraction but will require prolonged pumping times. Studies show that that portion of contaminant entrapped inside the soil matrix cannot be removed using vapor extraction. In long-contaminanted soils, a substantial portion of the soil contamination is thought to be located in the interior of the soil matrix. This internally-sequestered fraction of contaminant poses the greatest challenge to current remediation methods.

We conclude that *in-situ* vapor extraction is very effective in removing organic contaminants located in the pore space of the soil matrix and which are adsorbed to accessible surfaces of soil aggregates. In cases of long-standing soil contamination, a certain amount of contaminant may have diffused into the interior of the soil matrix and may be inaccessible for removal by vapor extraction. This remediation technology is not effective in removing the sequestered fractions of VOC's. Consequently, although vapor extraction is effective in removing a large fraction of the VOC's from contaminaed soils, this technology cannot be relied upon to return contaminated sites to their original pristine condition. Nonetheless, we strongly support its use for removal of the major portion of subsurface soil contamination.

1.0 INTRODUCTION

The Superfund Amendments and Reauthorization Act of 1986 (SARA) requires that remedial alternatives be "protective of public health and the environment" and "significantly and permanently" reduce the toxicity, mobility, or volume of contaminants. Several innovative technologies have been developed in order to meet these requirements. In particular, *in situ* technologies have seen a steady increase in use because of their ability to treat areas of contamination without further disruption of the environment. However, the trend toward seeking permanent *in situ* remediation solutions began before the current technologies revealed permanent remediation capabilities, and the effectiveness of on-site treatment techniques has only recently come under scrutiny. *In situ* vapor extraction is one such treatment technology now widely used to remove volatile organic compounds (VOC's) from subsurface soils. Since its introduction in 1984, use of vapor extraction systems (VES) has increased markedly; VES now comprises 18.1% of the selected remedies for Superfund sites, and this number continues to grow (EPA, 1990b). Advantages of VES are that it causes only limited disturbance of the ground water, is constructed of standard equipment, and can treat volumes of soil much greater than can be reasonably excavated. Moreover, with VES there is a potential for recovery of extracted contaminants (Hutzler *et al.*, 1990).

As of August, 1991, there were approximately 50 full-scale vapor extraction projects at Superfund sites: 36 in predesign or design phase, 13 being installed or already operational, and one completed (EPA, 1991). The current growth in VES implementation prompts questions concerning the effectiveness of this remediation technology. Our objective in this report is to provide a base of knowledge regarding the applicability, performance, and limitations of VES. This study consists of an in-depth overview and analysis of vapor extraction based on performance records for pilot- and full-scale operations.

Table 1 lists the sites considered in this study. Analysis was limited to the source operable units at the sites; however, in some cases, relevant information regarding ground water contamination and/or remediation was incorporated into the evaluation. Information was obtained from pertinent literature, remedial action documentation, support documents, post-remedial monitoring data, and several existing databases. Site identification and current sampling data were obtained through interviews with regional U.S.

Environmental Protection Agency (EPA) personnel and contractors.

Table 1

Vapor Extraction System Sites Reviewed

Site	Contaminant
Belleview, FL	BTEX
Custom Products, MI	TCE
Groveland, MA	TCE, PCE
Hill AFB, UT	JP-4 fuel
Lawrence Livermore, CA (LLNL)	gasoline, TCE
Nuremberg, FRG	VOCs
Ponders Corner, WA	TCE, PCE
Scherwiesen, FRG	VOCs
Study Site, NJ	VOCs
Twin Cities AAP, MI	TCE
Tysons Lagoon, PA	VOCs
Upjohn, PR	CCl_4
Verona Well Field, MI	VOCs

2.0 VAPOR EXTRACTION TECHNOLOGY DESCRIPTION

Vapor extraction is an *in-situ* soil cleaning process designed to remove volatile organic compounds (VOCs) from the unsaturated (vadose) zone of soil (i.e., the subsurface zone between the surface soil and ground water) in order to minimize the amount of contamination that enters the ground water (Visser *et al.*, 1986). Large quantities of VOCs can remain in the vadose zone as free liquids held in the soil matrix, as solutes in the soil moisture, as mass adsorbed to soil particles, as vapor in the soil pore spaces, and entrapped in internal micropores within soil particles (*vide infra*).

In general, VES removes VOCs from the contaminated subsurface by providing a moving airstream that volatilizes contaminants and thereby provides a vector for their removal as the contaminated air is mechanically drawn to the surface. The air flow produced by the vacuum sweeps out the soil gas, disrupting the equilibrium existing between the contaminant adsorbed to the soil and its vapor phases. This promotes further volatilization of the contaminant on the soil and subsequent removal in the airstream. After the VES removes volatile organics from subsurface media in the unsaturated zone, the system can be designed to then collect, treat, or otherwise dispose of the extracted contaminant (Visser *et al.,* 1986). While individual systems and site conditions vary considerably, the typical vapor extraction system is comprised of one or more *extraction* wells and one or more *inlet* or *injection* wells. Inlet or injection wells provide fresh air to the subsurface. Placement of these wells at the edge of a site also helps to enhance air flow through zones of maximum contaminant concentration. Inlet wells or vents are a passive means for allowing air to enter the subsurface at specific locations whereas injection wells force an airstream into the ground. Both well types facilitate horizontal air movement and thus enhance volatilization. Vacuum pumps or air blowers create the air stream that exits at the extraction well.

The extraction well is comprised of plastic pipe, vented or slotted along the sides, with a vacuum-tight seal at the soil surface. The well can be either open or capped at the bottom. Permeable packing surrounds the well, which is buried vertically in the area of contamination. If the water table is fairly close to the surface or if contamination is restricted to near-surface soil (<10-15 ft.), then extraction wells may be placed horizontally. A column or trench is dug for installation. Usually, the surface is grouted to enhance air movement through zones of contamination by preventing direct air flow from the surface (along the well casings) or through the well trench. Piping connects the extraction well to an optional vapor/liquid separator. The separator condenses the moisture in the vapor and strips any liquid VOCs from the water. Depending on the contaminant type and concentration, however, the condensate may consist of hazardous wastes that require special handling and disposal. Otherwise, the vapor portion is transported to air emissions controls, the requirements for which vary with state and contaminant. Typically, emissions control is in the form of carbon adsorption, although aeration, ultraviolet (UV) photolysis, and catalytic oxidation are other

alternatives.

Proper contaminant characterization (including vapor pressure), proper subsurface characterization, and the number and sizes of the vacuum extraction wells used are factors that affect the treatment time and overall effectiveness of the VES operation (Visser *et al.,* 1986). A potential complication in any VES operation is that the vacuum causes a pressure reduction in the vadose zone and may induce a rise in the level of the underlying aquifer (Johnson *et al.*, 1990b). If this occurs when the water table lies just below the contaminated zone, which is often the case, then the ground water will be drawn into the contaminated area, the vadose zone may become water-saturated, and the VOC mass removal rate will be reduced. To combat this problem, most vacuum extraction systems operate a simultaneous dewatering system, (i.e., a ground-water pumping well which maintains the water level below the contaminated vadose zone (Johnson *et al.*, 1990b).

3.0 DEFINITION OF EFFECTIVENESS

3.1 EVALUATING EFFECTIVENESS

The 1990 National Contingency Plan (NCP), EPA's primary Superfund policy directive, specifies that treatment technologies should achieve reductions of at least 90% to 99% in the concentration or mobility of contaminants. In addition, the NCP specifies that treatment technologies achieve site-specific cleanup goals for contaminated soils based on site-specific risk assessments. Thus, for purposes of the present study, effectiveness was evaluated by determining (1) whether the technology can reduce contaminant concentrations by at least 90%, and (2) whether the technology can reduce concentrations to achieve health-based cleanup goals when applicable. We determined health-based cleanup goals by comparing post-treatment concentrations to the cleanup levels established at specific sites (when provided) or by comparing removal efficiencies to those required to achieve health-based cleanup goals for indicator chemicals at an average Superfund site.

3.2 INDICATORS OF VES EFFECTIVENESS

Effectiveness of vapor extraction as a treatment remedy is primarily defined and measured in one or more of the following ways: (1) comparison of pre- and post-treatment soil concentrations; (2) comparison

of pre- and post-treatment soil-gas concentrations; and (3) comparison of the mass of contamination *removed* to the mass of contamination *lost* to the environment. We briefly review these measures of VES effectiveness and comment on their limitations.

3.2.1 Soil Sampling

Direct measurement of contaminant concentrations in subsurface soil samples is the best method of characterizing the concentration and location of contamination within the subsurface. Soil sampling therefore provides the best and most direct method for evaluating the effectiveness of VES; however, this method does have inherent limitations. At large sites with varying soil types, direct soil sampling is difficult to perform uniformly, and hot spots or zones of elevated contamination levels may go undetected. A site with a series of thin interbedded layers of varying soil types requires that samples be taken from each layer at every borehole or well. In addition, this measurement technique is difficult to implement over extended areas. Perhaps the most significant problem with soil sampling techniques is that it may not detect all of the contamination present in the soil. One common technique is "purge-and-trap," which measures only a portion of the total VOC concentration in the soil (Sawhney *et al.*, 1988). Two other methods that are commonly used but also give low recoveries of VOC's in contaminated soils are sonication-extraction and Soxhlet extraction. The most rigorous but least used method of soil sampling is hot solvent extraction, where the contaminant is removed by heating the affected soil at elevated temperatures in solvents such as methanol, acetone, or acetonitrile, and the extract is analyzed using gas chromatography. Despite limitations in determining accurate soil concentrations, soil sampling remains the method of choice for assessing the effectiveness of VES.

3.2.2 Soil Gas

A comparison of pre- and post-treatment soil-gas concentrations is the most common method of evaluating the effectiveness of VES. Soil-gas concentrations can be determined either from wellhead-gas samples or by obtaining soil-gas samples using vapor probes. Vapor probes are inserted to a specified depth within the unsaturated zone and are used to collect soil-gas samples using a vacuum pump. Gas chromatography is used on-site to analyze samples from both wellhead-gas and subsurface gas for VOC

concentrations. The fixed position of the well limits wellhead-gas measurements whereas vapor probes are more versatile and can be used throughout a site.

Soil gas surveys are not only limited by the method of obtaining air samples; the reliability of soil-gas measurements is also influenced by the porosity, pore size, and moisture content of the soil as well as the volatility of the contaminant (Clarke *et al.*, 1990). A recent study by Marks and Singh (1990) evaluates the accuracy of soil-gas measurements by comparing the results of soil-gas surveys to "chemically-analyzed" soil and ground water. Data compared were soil-gas, soil, and ground water samples of benzene and toluene from 25 sites in California. Marks and Singh found that soil-gas readings result in both false negative and false positive measurements when compared to actual soil sample measurements. False positives occurred when there were measurable concentrations of VOC in the soil-gas but the corresponding soil sample did not have measurable concentrations. False positives occurred in 36% of the samples of benzene and 28% of the samples of toluene. False negatives resulted from soil-gas concentrations recorded below detection limits when the soil or ground water sample contained measurable concentrations of contaminants. False negatives can occur when extrapolating a soil-gas result over distance; one to eight feet was the maximum range of distance from the detector (wellhead or probe) in which the presence of toluene or benzene could be predicted with any accuracy using soil-gas surveying, depending upon the soil type. False negatives occurred in 57% of samples for benzene and in 46% of the samples for toluene. The study concludes that soil-gas readings are only about 64.5% reliable in predicting soil contamination and that this level of accuracy is achieveable only when the soil and soil-gas samples are taken within close proximity to each other (Marks and Singh, 1990).

A comparison of wellhead-gas and soil concentrations for VOCs at the Groveland Wells site (EPA, 1989d) supports the results of the Marks and Singh (1990) study. Wellhead gas and soil samples were taken at seven locations at the Groveland Wells site. Wellhead-gas measurements resulted in both false negative and false positive measurements, and did not yield accurate results for any of the seven samples at this site.

These limitations prevent soil-gas surveys from providing accurate and reliable predictions of soil contaminant concentrations. Therefore, soil-gas cannot serve as an accurate indicator of VES effectiveness.

Groveland Wells, MA

Comparison of Wellhead Gas to Soil Samples for TCE Concentrations (ppm)

Extraction Well	Wellhead Gas*	Soil	Accuracy
1S	0.1	55	false negative
1D	0.1	7	false negative
2S	0.2	nd	false positive
2D	0.2	20	false negative
3S	1.5	20	false negative
3D	0.7	18	false negative
4S	12.5	9	false positive

* Measured wellhead gas concentration in parts per million by volume (ppmv) were converted to corresponding soil concentrations in parts per million by weight (ppmw) using Henry's Law.

nd non-detectable reading

Reference (EPA, 1989d)

3.2.3 Mass Removal

A frequently-used method of assessing the effectiveness of VES is to compare the mass of contamination removed to the mass of contamination lost to the environment. Initially, an estimate of the contaminant mass present in site soils is used for determining VES design, including factors such as the necessary number of wells and the most cost-effective type of emissions treatment. As site remediation progresses, pounds or gallons extracted are recorded by measuring vapor concentrations and airstream flow at the wellhead. Several limitations are associated with the use of mass removal as a basis for evaluating the effectiveness of VES.

The overriding limitation of a mass removal comparison is that of inaccurate estimates of initial contaminant mass. Table 2 lists the sites reviewed, the initial mass/volume estimate, and the mass/volume extracted to date. At three of the sites reviewed (Ponders Corner, Verona Well Field, and Upjohn), the initial mass or volume of contaminant was underestimated. Originally, Ponders Corner was estimated to contain five pounds of tetrachloroethylene (PCE). To date, more than 750 pounds have been extracted using VES. For Verona Well Field, 1,700 pounds of VOCs were initially estimated to be present at the site; to date, more than

40,000 pounds have been removed. At the Upjohn site, the initial estimate for CCl_4 was 15,300 gallons; at the time of site VES termination, approximately 17,900 gallons of CCl_4 had been extracted from site soil.

Table 2 Mass Removal at Reviewed Sites

Site	Projected Mass/Vol	To-Date Mass/Vol
Belleview, FL	unknown	>30,000 lbs
Custom Products, MI	unknown	>1,671 lbs
Groveland, MA	3,000-30,000 lbs	1,297 lbs
Hill AFB, UT	27,000 gal	ca. 70,000 lbs
LLNL,CA BTEX spill	17,000 gal	ca. 6,150 lbs
Nuremberg, FRG	nda[1]	2,700 lbs
Ponders Corner, WA	5 lbs	>750 lbs
Scherweisen, FRG	nda	>5,000 kg
Study Site, NJ	318 lbs	110 lbs
Twin Cities AAP, MN	unknown	117,650 lbs
Tysons, PA	290,000 lbs	>90,000 lbs
Upjohn, PR	15,300 gal	17,871 gal
Verona Well Field, MI	1,700 lbs	>40,000 lbs

[1] No data available

A second complication associated with a mass removal comparison arises when the mass or volume of contaminant lost to the environment cannot be estimated and is consequently unknown. This was the case for three of the sites studied. For example, at the Twin Cities Army Ammunitions Plant (AAP), Site D was used for open burning of solvents and fuel for more than a decade. In such cases, the amount of contaminant within the soil is considered unknown.

Due to these limitations, mass removal comparisons cannot serve as a basis for evaluating the effectiveness of vapor extraction. Mass removal does provide an estimate of the amount of contamination

removed from an area; however, inaccurate or unavailable estimations of total contaminate released prevent mass removal comparisons from being a reliable indicator of VES effectiveness.

4.0 SITE STUDIES

The following site descriptions provide a short introduction to the sites included in this report. For each site, the studies supply background information describing the types of facilities and practices that led to site contamination.

Belleview, FL

The Belleview site is a gas station in Marion County, Florida. A leaking underground storage tank (LUST) and its pipeline caused extensive subsurface VOC contamination. Initial concentrations were 29 ppm benzene, 97 ppm total BTEX (benzene, toluene, ethylbenzene, xylene), and 335 ppm total petroleum hydrocarbons, with the highest concentrations located in a 10 to 20 foot range just above the clay layer (Applegate *et al.*, 1987). Soil layers are clayey sand, clay, and silty sand over limestone (EPA, 1989e). Cleanup goals consisted of reducing soils to non-leachable concentrations that were not specified (Malmanis, 1991).

Custom Products, MI

Custom Products is a manufacturing facility in Stevensville, Michigan with less than 5,000 cubic yards of soil contaminated with tetrachloroethylene (PCE). The contamination resulted from discharge from a sludge tank. Initial concentrations of PCE are a maximum of 5,600 ppm. Soil is homogeneous, dry sand. No cleanup goals were documented for this site (Payne and Lisiecki, 1988).

Groveland, MA

In 1987, EPA selected the Groveland Wells site in Massachusetts for a Superfund Innovative Technology Evaluation (SITE) demonstration project. Leaking underground storage tanks and mishandling of wastes and solvents contaminated the machine shop, soil, and ground water on and around the property of Valley Manufacturing. The company, operating since 1964 to produce valve parts, used trichloroethylene (TCE), PCE, methylene chloride, and trans-1,2-dichloroethene (DCE) as part of the operation of screw

machines. An estimate of total contaminant mass was between 3,000 and 30,000 pounds. Initial concentrations were reported to be 2,500 ppm TCE, 40 ppm PCE, and 12 ppm DCE. Toluene and metals, primarily copper, arsenic, and lead, are also present at the site. Soil at Groveland is comprised of layered fine to coarse sand, silt, clay, and gravel. Cleanup goals for soil at the site are 6.3 ppb TCE and 18.2 ppb PCE. Cleanup goals and treatment methods are not specified for metals (EPA, 1989d).

Hill Air Force Base (AFB), UT

The Hill AFB site in Utah is the location of a 27,000 gallon JP-4 jet fuel spill. An automatic underground tank filling system malfunctioned and spilled JP-4 jet fuel on soil surrounding the tanks. JP-4 jet fuel consists of naphtha, gasoline, and kerosene. The initial concentration of aviation fuel was greater than 13,000 ppm in medium- to fine-grained sand interlayered with clay. The sand is underlain by a clay layer extending to depths of 600 feet. The Delta aquifer is present at a depth of 600 feet and constitutes a major water source for the area. Soil borings indicate that the majority of contamination resides at a depth of 10 feet. The purpose of the VES operation is not to attain specific cleanup goals, but rather to demonstrate the applicability of VES for remediating aviation fuel spills (DePaoli *et al.*, 1989).

Lawrence Livermore National Laboratory (LLNL), CA

At LLNL in Livermore, California, a vapor extraction system operates in the gasoline spill area near Building 403. The spill site is where 17,000 gallons of leaded gasoline (BTEX), lost between about 1952 and 1979, leaked from an underground tank and contaminated soil to concentrations of 4,800 ppm (CERCLA, 1990; McConachie, 1989). Calculations of hydrocarbon mass indicate that as of 1988, about 6,000 gallons existed in the vadose zone, about 10,000 gallons were present in saturated sediments, and about 100 gallons were dissolved in ground water. The soil at LLNL consists of gravel, sand, silt, and clay. The objectives at this site are demonstration of VES technology and remediation.

Nuremberg, FRG

The Nuremberg site is an old oil recycling plant that was closed in the early 1970's. PCE and TCE have contaminated site soil and ground-water, with concentrations in soil of 8 ppm. The VES design at this site has been integrated to treat both soil and ground water contamination. Soil at the site is very sandy. The

cleanup goal is complete remediation (Bohm and Rost, 1990).

Ponders Corner, WA

Ponders Corner is a site in Lakewood, Washington, where PCE and TCE were poured on the surface soil behind the Plaza Cleaners dry cleaning facility. In addition, leaking waste-water storage tanks contaminated a 2,000 square foot area around Plaza Cleaners. The site is underlain by several layers of soil, gravel, silt, and clay. Contamination migrated through the gravel layer, consisting predominantly of sands and gravel, to the Vashon Till, a layer of clays and silts that are generally unsaturated but contain discontinuous saturated zones. The migration continued to the Calvos Sand layer, a layer of poorly graded silty clay and clayey silt approximately 150 feet thick (EPA, 1989a). Initial concentrations of PCE, TCE, and 1,2-trans-DCE were 3.88 ppm, 3.6 ppm, and 9.6 ppm, respectively. Soils are composed of layered sand, gravel, silt, and clay. The goal of VES is to reduce vapor concentrations to 670 mg/m^3 PCE, 540 mg/m^3 TCE, and 790 mg/m^3 DCE (Ecova, 1989).

Scherwiesen Site, FRG

The Scherwiesen Site in Germany is a landfill where various industrial, animal processing by-products, and municipal wastes were disposed from 1967 to 1980. In 1980, a one meter thick clay cap was installed over the site following its closure. Soil at the site is heavy clay contaminated with volatiles with a concentration of 8,000 ppm. Cleanup goals include site remediation, but no specific goals are provided (Bohm and Rost, 1990).

Study Site, NJ

The test site chosen for a pilot scale evaluation of *in-situ* vapor extraction is a former manufacturing facility in New Jersey. The site contained volatile organic compounds including TCE, PCE, 1,1,1-TCA, and methylene chloride. This site was chosen in order to study VOC removal by VES at relatively low concentrations, simulating the latter phases of a remediation. Total VOCs averaged 13.3 ppm in soil of low and high permeability. No cleanup goals were specified for the site (Clarke *et al.*, 1990).

Twin Cities Army Ammunitions Plant (AAP), MN

Until 1970, Site D at the Twin Cities Army Ammunitions Plant (TCAAP), Minnesota, was used for

open burning of various solvents and fuels. Soil conditions at Site D are sandy with intermittent layers of highly stained and contaminated soil (USATHAMA, 1985). The operational goals are demonstration of VES technology and remediation of the site.

Tysons Lagoon, PA

In 1973, the Tysons Lagoon Dump Site, located in Montgomery County, Pennsylvania, was ordered to be closed after operating for seven years as a disposal site for industrial, municipal and chemical waste. The VES was installed to treat 30,000 cubic yards of contaminated soil. The concentrations of the primary contaminants were as follows: (1) toluene: 600 ppm; (2) ethyl benzene: 1,100 ppm; (3) p, m-xylene: 11,700 ppm; (4) o-xylene: 3,700 ppm; and (5) 1,2,3-TCP: 2,600 ppm. The soil is sandy but clumpy with tars. The remediation goal is to achieve a level of 0.05 ppm for the primary contaminants after two years of operation, based on a $1x10^{-6}$ cancer risk (EPA, 1988b).

Upjohn, PR

The Upjohn site is a tank farm along the north coast of Puerto Rico where approximately 15,300 gallons of CCl_4 leaked from underground storage facilities and migrated north for a distance of two miles, contaminating 4,400,000 cubic yards of soil as well as on- and off-site ground-water (EPA,1989b). Soil sampling showed carbon tetrachloride (CCl_4) concentrations as high as 2,200 ppm, and soil gas concentrations of 10,500 ppmv (EPA, 1989e). The site is underlain by fine grained material in blanket sands of variable thickness, silty clays, and clayey silts. The cleanup goal was to acheive 0.05 ppm CCl_4 in wellhead gas (Soil Tech, 1987).

Verona Well Field, MI

Verona Well Field is a municipal well field consisting of 30 wells and a major pumping and water treatment station located approximately one-half mile northeast of Battle Creek, Michigan. The Verona Well Field provided drinking water for approximately 50,000 Battle Creek residents, two major food processing industries, and a variety of other commercial establishments. A total of 56,246 cubic yards of soil requires treatment. Initial soil concentrations were as follows: (1) methyl chloride: 60 ppm; (2) 1,2-dichloroethane (DCA): 27 ppm; (3) 1,1,1-TCA: 270 ppm; (4) TCE: 550 ppm; (5) PCE: 1,800 ppm; (6) toluene: 730 ppm; and

(7) xylene: 420 ppm. Soil at Verona Well Field is layered sand, silt, clay, and pebbles over sandstone, shale, and limestone. Cleanup goals are to decrease total VOC soil concentrations to no greater than 10 ppm, with no more than 15% of soil samples greater than 1 ppm total VOCs. The original timeframe to reduce VOCs to one ppm was three years, ending by March 1991 (Guerriero, 1989).

5.0 VES EFFECTIVENESS

Calculation of the percent reduction in contaminant concentrations determines the performance of vapor extraction systems. Section 5.1 consists of an evaluation of VES performance based on initial and resulting (to date) *soil sample* concentrations. Section 5.2 contains an analysis of VES performance based on pre- and post-treatment (to date) *soil-gas* concentrations.

5.1 VES EFFECTIVENESS BASED ON SOIL CONCENTRATIONS

Soil sample concentrations provide the most accurate basis for evaluating the effectiveness of vapor extraction systems (*vide supra*). The following VES sites were been evaluated using this method, and Table 3 lists the percent reduction in contaminant concentrations achieved using VES.

Belleview, FL

Terra Vac, in association with the Florida Department of Environmental Regulation, installed the VES and extracted over 30,000 pounds of total hydrocarbons during a pilot study from January 29, 1987, to August, 1987 (Applegate *et al.*, 1987). The goal of the operation was to evaluate the effectiveness of VES.

Table 3 Performance Based on Soil Sampling Data

Site	Status	%Concentration Reduction
Belleview, FL	completed	98.66%
Custom Products, MI	completed	99.9997%
Groveland Wells, MA	incomplete	70.4%
Lawrence Livermore,CA BTEX Spill	ongoing	91.66%
Ponders Corner,WA[a]	ongoing	98.87%
Study Site, NJ	completed	64.5%
Twin Cities AAP, MN[b]	ongoing	99.5%
Verona Well Field, MI	ongoing	50%
Upjohn, PR[c]	completed	99.997%

[a] Average reduction excluding hot spot not detected during sampling
[b] Average reduction to depths of 35 feet, does not include deep contamination not detected during initial sampling
[c] Based on Soil Tech (1987) soil samples; ROD (EPA,1988) states that contamination remains in deep blanket sands.

Operations at the Belleview site underwent a second phase. In September 1988, the EPA reactivated the system and operated the VES for approximately 32 days. The VES removed additional contaminant mass during this operating period; however, the system did not operate long enough to reduce the hydrocarbon concentrations within the soil matrix. In the final soil sampling data, the mean concentration for each individual BTEX component was in the range of 0.2 to 1.3 ppm. The reduction in BTEX concentrations from the initial levels to 1.3 ppm resulted in an effectiveness of 98.66% (EPA, 1989e)

Custom Products, MI

The VES installed at the Custom Products site in Michigan treated approximately 2,000 cubic yards of soil contaminated with perchloroethylene (PERC), trichloroethylene (TCE), BTEX, and paint solvents (Payne *et al.*, 1986). The treatment system consisted of one extraction well and six air injection wells in a closed-loop design. The site was capped with 6-mil polyethylene sheeting. After 45 days of operation, the VES reduced concentrations of PERC in soil samples from 5,600 ppm to 0.64 ppm. A stagnation period of

45 days followed. When the system was restarted, concentrations did not rebound beyond the 1% of the initial mass removed with the VES (Payne and Lisiecki, 1988). After 280 days of operation, soil sampling showed PERC levels at 0.017 ppm, reaching a 99.9997% reduction in PERC soil concentrations.

Belleview, FL

SITE TYPE:	gasoline
CONTAMINANTS/ CONCENTRATIONS:	Benzene/29ppm BTEX/97ppm THCs/335ppm
SOIL VOLUME:	10,000-30,000 cy
SOIL MASS/VOL:	22,252 lbs
SOIL TYPE:	clayey sand, gumbo clay, silty sand, limestone
DURATION:	6-7 months
NO. OF WELLS:	6
WELL SPACING:	14-50 feet
CAP:	existing pavement
STATUS:	completed

Custom Products, MI

SITE TYPE:	manufacturing facility
CONTAMINANTS/ CONCENTRATIONS:	PERC/5,600 ppm
SOIL VOLUME:	<5,000 cy
SOIL TYPE:	dry, sandy
DURATION:	280 days
NO. OF WELLS	1
AIR FLOW RATE:	10.2 cfm
CAP:	6-mil-polyethylene
STATUS:	completed

Groveland, MA

Table 4 describes the wide variations of soil types and the VOC concentrations present at the site. Although site remediation is incomplete, post-demonstration soil sampling for Groveland indicate that VES is capable of removing TCE from layers of clayey soil. The VES effectiveness at this site is 74.4%.

Groveland, MA

SITE TYPE:	machine shop
CONTAMINANTS/ CONCENTRATIONS:	TCE/2,500 ppm PCE/40 ppm DCE/12 ppm arsenic/460 ppb lead/61,800 ppb copper/4,890 ppb
SOIL VOLUME:	ca. 30,000 lbs
SPILL VOL/MASS:	1353 lbs
SOIL TYPE:	sand, clay, glacial till
DURATION:	demo--56 days cleanup--3-10 yrs
NO. OF WELLS:	8
WELL SPACING:	20 feet
AIR FLOW RATE:	3-800 cfm
CAP:	none
STATUS:	incomplete

Table 4 Percent Reduction of TCE Concentrations in Soil at Groveland Wells (ppm)
(Post-Demonstration, using soil-sampling)

Monitoring Well 3 TCE Concentrations

Depth Range ft	Soil Type	Initial Conc.	Resulting Conc.	% Effectiveness
0-2	med. stiff fine sand	10.3	0.005*	99.95
2-4	med. stiff fine sand	8.33	800	-96
4-6	soft fine sand	80	84	-0.05
6-8	fine sand	160	0.005*	99.996
8-10	stiff fine silty sand	nd	63	-12.59
10-12	not recorded	—	2.3	—
12-14	soft silt	316	0.005*	99.998
14-16	wet silty clay	195	0.005*	99.997
16-18	wet silty clay	218	62	71.6
18-20	wet silty clay	1570	2.4	99.8
20-22	silt, gravel, rock frag.	106	0.005*	99.995
22-24	stiff med. sand	64.1	0.005*	99.992

Extraction Well 4 TCE Concentrations

Depth Range ft	Soil Type	Initial Conc.	Resulting Conc.	% Effectiveness
0-2	med sand w/ gravel	2.94	0.005*	99.8
2-4	fine sand	29.90	0.005*	99.9
4-6	med. stiff fine sand	260.0	39	85
6-8	soft fine sand	303.0	9	97
8-10	med. stiff sand	351.0	0.005*	99.998
10-12	stiff med. sand	195.0	0.005*	99.997
12-14	stiff fine sand w/ silt	3.14	2.3	26.7
14-16	stiff clay w/ silt	nd	nd	—
16-18	soft wet clay	nd	nd	—
18-20	soft wet clay	nd	nd	—
20-22	stiff med. coarse sand	nd	nd	—
22-24	stiff med. coarse w/ gravel	6.71	0.005*	99.93

Average Percent Reduction of TCE Concentrations in Post-Demonstration Soil (ppm)

Well	Average % Effectiveness
M3	60.2
E4	88.5
	74.4

* EPA recorded a non-detect level; a detection limit was set for TCE at 0.005 ppm (EPA, 1989d) for non-zero effluent purposes when TCE was detected in the initial soil sample but not in the second.

nd Non-detectable reading (EPA, 1989d)

Lawrence Livermore Nat'l Laboratory, CA

In 1988, a pilot study designed to treat each contaminated medium with vapor extraction was proposed (Nichols *et al.*, 1988). The system's design included volatilization of BTEX from the vadose zone while dewatering the saturated sediments. A "downhole skimmer" was used to extract a floating product layer from the water surface. As of 1990, a full-scale system was not yet operational (LLNL, 1990a). During testing, a total of 5,000 gallons were removed from the soil, and 150 gallons were removed by the skimmer. BTEX concentrations were reduced from 4,800 ppm to 400 ppm (LLNL, 1990b; McConachie, 1989). During pilot-scale operations, contaminant concentrations within the soil were reduced by 91.66%.

Lawrence Livermore, gasoline spill, CA

SITE TYPE:	BTEX spill
CONTAMINANTS/ CONCENTRATIONS:	BTEX/4,800 ppm
SPILL VOL:	17,000 gal
SOIL TYPE:	gravel, sand, silt and clay
DURATION:	2 yrs
NO. OF WELLS	1
AIR FLOW RATE:	50-60 cfm
CAP:	none
STATUS:	incomplete

Ponders Corner, WA

Soil remediation began in September 1987, and was to operate for six months (Ecova, 1989); however, the extent of contamination was underestimated, and the time for site remediation has been extended. To date, the VES has extracted more than 775 pounds of PCE from the soil (the original estimate of mass was five pounds) (Ecova, 1989).

Presently, the Ponders Corner site is in a state of partial remediation. An area of local contamination continues to manifest itself in the storage tank area. A hot spot, undetected in the original sampling, contains

a PCE concentration of 1,200 ppm and TCE concentration of 34 ppm (CH_2M Hill, 1991). Under these circumstances, a percent concentration reduction that includes the local hot spot of contamination would not provide an accurate assessment of the ongoing VES effectiveness. However, excluding the hot spot, the average, current percent reductions for VOC's are as follows: PCE, 97.97% reduction (from 3.88 to 0.0787 ppm); and TCE, 99.76% reduction(from 3.6 ppm to 0.00875 ppm); total average VES performance is 98.87%.

Ponders Corner, WA

SITE TYPE:	dry cleaners
CONTAMINANTS/ CONCENTRATIONS:	PCE/3.88 ppm TCE/3.6 ppm DCE/9.6 ppm
SPILL VOL/MASS:	>750 lbs
SOIL TYPE:	sand and gravel , clay and silt
DURATION:	3.5 yrs
NO. OF WELLS:	10
AIR FLOW RATE:	630-690 cfm
WELL INFLUENCE:	20 feet
CAP:	none
STATUS:	ongoing

Study Site, NJ

Pre- and post-treatment VOC concentrations were 13.3 ppm and 4.6 ppm, respectively (removal efficacy of 65.4%). An estimated 750 pounds of volatile organics were present in site soils, of which 485 pounds were removed through non-continuous treatment for 227 days, pumping four hours per day.

Study Site, NJ

SITE TYPE:	manufacturing
CONTAMINANTS/ CONCENTRATIONS:	VOC's/13.3 ppm (avg)
SPILL VOL/MASS:	317.1 kg
SOIL TYPE:	low and high permeable soil
DURATION:	1 year study, 227 operating days
NO. OF WELLS:	1
AIR FLOW RATE:	800 cfm
WELL INFLUENCE:	25 meters
STATUS:	completed

Site D, Twin Cities Army Ammunitions Plant, MI

In 1985, a vapor extraction system was used on a pilot-scale in order to evaluate VES effectiveness in TCE-laden soils, and later, the VES was increased to full-scale. The pilot-scale testing unit consisted of two separate systems that differed slightly in design. System 1 covered an area of 2,500 square feet and addressed soils with TCE contamination under five ppm. System 2 covered an area of 10,000 square feet and addressed TCE soil concentrations between 100 ppm and 8,000 ppm.

System 1 operated for 67 days, extracting 0.880 kg of TCE from 8,000 cubic feet of soil. Initially, the system extracted 70 mg of TCE per day, although these levels decreased to less than 10 mg per day prior to ceasing operations. System 2 operated for 78 days, extracting a total of 730 kg of TCE from 50,000 cubic feet of soil. The system averaged a daily extraction rate of 11 kg per day (EPA, 1989b).

At this location, the pilot study results show that removal efficiencies of 99.99% are possible for VES in areas free of oily hydrocarbons (USATHAMA, 1985). However, an analysis of post-treatment pilot-scale soil samples shows higher concentrations of contamination in soils *after* treatment than before treatment. Removal efficacies for Site D are 61% (System 1) and -4.7% (System 2) when based upon pre- and post-treatment pilot-scale soil sampling. These poor removal efficacies and rising concentrations are attributed to

contaminant migration within the subsurface, local hot spots that were originally undetected, and insufficient operating duration.

The pilot study continued as a full-scale operation and has run almost continually since July 1986, extracting between eight and 32 pounds of VOCs per day, for a total removal of 117,647 pounds of VOCs. In May 1989, mid-operational samples were collected and recorded. The reduction in TCE concentration in the soil samples indicates that the VES operation at Twin Cities is effective in soils to depths of 35 feet. The VES has succeeded in reducing TCE concentrations by 99.55% in relatively shallow soil.

In response to contamination found in deep soil borings, a deep vent was installed in May 1990, to reach contamination to depths of 170 feet. Once deep vent removal rates stabilize, a pulsed approach will be applied to the system (Fuller, 1990). Table 5 lists the pre- and post-treatment TCE soil concentrations at Twin Cities AAP, MN.

Twin Cities Ammunitions Plant, MI

SITE TYPE:	fire testing area
CONTAMINANTS/ CONCENTRATIONS:	TCE/1,000 ppm
SOIL VOL:	3,800-33,000 cy
SPILL VOL/MASS:	ca. 1,600 lbs
SOIL TYPE:	loamy sand over stained sand and sediments
DURATION:	System 1--67 days System 2--78 days Full scale-- 4 yrs
NO. OF WELLS:	System 1--9 System 2--9 Full scale--39
WELL SPACING:	System 1--20 ft System 2--50 ft
AIR FLOW RATE:	System 1--40-55 cfm System 2--220 cfm reducing to 50 cfm
CAP:	18 in. clay
STATUS:	pilot completed, full ongoing

Table 5 Pre- and Post-Treatment Soil Concentrations (ppm) at Twin Cities AAP, MN

Average Soil Boring Sample Concentrations[a]

Depth Range 0-10 Feet			Depth Range 11-20 Feet			Depth Range 21-35 Feet		
Initial	Resulting	% Effectiveness	Initial	Resulting	% Effectiveness	Initial	Resulting	%Effectiveness
2060	0.0085	99.9999	672	0.004	99.999	nd	nd	
231	0.002	99.999	80.3	0.029	99.96	nd	nd	
nd[b]	nd[c]		nd	nd		nd	nd	
nd	nd		nd	nd		nd	nd	
nd	nd		nd	nd		nd	nd	
nd	nd		100.2	0.001	99.999	0.4	0.0053	98.67
nd	nd		nd	nd		nd	nd	

Average Percent Reduction of TCE Concentration in Soil

Depth Range	% Effectiveness
1-10 Feet	99.999
11-20 Feet	99.986
21-35 Feet	98.67
45-172 Feet	-1204

Deep Soil Boring TCE Concentrations (ppm)

Depth Range	Initial	Resulting	%Effectiveness
45-47 Feet	10	6.7	33.0
61-63 Feet	1000	0.001	99.9999
135-142 Feet	400	1510	-2775
150-172 Feet	nd[b]	9.11	-2177.5

[a] initial sampling data (Weston, 1984); resulting sampling data (Weston, 1989)
[b] non-detect reading from 1984 soil borings when nd = 0.4 ppm.
[c] non-detect reading from 1989 soil borings when nd = 0.001 ppm.

Verona Well Field, MI

Of the 1,700 pounds of VOCs originally estimated to be present at the site, VES has removed over 40,000 pounds of VOCs (Guerriero, 1989). The source of this unexpected excess volume may be a floating free-liquid layer that had previously not been detected during initial sampling (Guerriero, 1989). Now, because of the extensive VOC contamination, over 400,000 pounds of carbon are required for complete treatment of effluent vapor. This underestimation of the extent of contamination has prompted changes in the duration of and procedures for site remediation. Because of frequent replacement of the carbon canisters (used for treatment of VOC vapor in the air extracted from the soil), the system has been operational for only five to ten days each month, totaling 100 operating days in an 18-month period (Guerriero, 1989). Originally, the site was scheduled to close during summer 1990; however, the cleanup has not reached completion.

	Verona Well Field
SITE TYPE:	municipal well field
CONTAMINANTS/ CONCENTRATIONS:	methyl chloride/60 ppm 1,2-DCA/27 ppm 1,1,1-TCA/270 ppm TCE/550 ppm PCE/1,800 ppm toluene/730 ppm xylene/420 ppm
SOIL VOL:	56,246 cy
SPILL VOL/MASS:	>40,000 lbs
SOIL TYPE:	sand with silt, clay and pebbles over sandstone, shale and limestone
DURATION:	2.5 years
NO. OF WELLS:	23
WELL INFLUENCE:	>50 ft average
CAP:	none
STATUS:	ongoing

Upjohn, PR

A total of 17,781 gallons of CCl_4 has been recovered from the soil. Of approximately 160 soil boring samples taken, no samples revealed detectable levels of CCl_4. The source of contamination at the Upjohn site is no longer in operation; however, results of the soil sampling for the Record of Decision or ROD (1988d) do not provide conclusive evidence that all of the CCl_4 has been removed from the unsaturated zone (EPA, 1988d). CCl_4 exists in a separate, free-liquid phase, and sorbed into the soil particles, pocketed deep within the sandy soil matrix. This sorbed phase is a continuous source of contamination which will slowly leach out of the interior of soil particles into the pore spaces between particles in the soil matrix (EPA, 1988d). There is no clear-cut assessment of the VES effectiveness at Upjohn. For relatively shallow sands, the reduction in concentration is 99.997%; however, CCl_4 contamination continues to exist at greater soil depths at the site.

Upjohn, PR

SITE TYPE:	tank farm
CONTAMINANTS/ CONCENTRATIONS:	CCl_4 / 2,200 ppm
SOIL VOL:	4,400,000 cy
SPILL VOL/MASS:	232,000 lbs
SOIL TYPE:	silty clays and clayey silts over limestone
DURATION:	3.5 yrs
NO. OF WELLS:	19
AIR FLOW RATE:	18-150 cfm
STATUS:	completed

5.2 VES EFFECTIVENESS BASED ON SOIL-GAS MEASUREMENTS

Soil-gas is the most common form of sampling data for sites where vapor extraction systems operate; nevertheless, as discussed in Section 3.2.2, this method is not a good quantitative indicator of soil VOC

concentration. Studies by Marks and Singh (1990) show that soil-gas measurements are only 64.5% reliable when compared with results of analytical chemistry determinations of benzene and toluene soil concentrations at 25 sites in California. Soil characteristics and contaminant volatility influence the accuracy of the soil-gas sampling method. When soil sampling is not available or was not conducted, the less quantitative method of soil-gas sampling can be used as a basis for evaluating the effectiveness of vapor extraction. Table 6 lists the percent reductions in contaminant concentrations in soil-gas samples taken at seven VES sites. As this method has been found to be only 64.5% accurate, an error of 35.5% has been calculated for the effectiveness of VOC concentration reduction. Thus, the error provides a range of values for evaluating the effectiveness of VES using soil-gas measurements.

Table 6 VES Performance Based on Soil-Gas

Site	Status	Effectiveness[a]	Basis
Belleview, FL	completed	64.05-99.3%	wellhead-gas
Hill AFB, UT	ongoing	37.73-58.5%	soil-gas
LLNL Gas Spill, CA	ongoing	60.47-93.75%	wellhead-gas
Nuremberg Site, FRG	ongoing	60.47-93.75%	wellhead-gas
Scherweisen Site, FRG	ongoing	64.09-99.37%	wellhead-gas
Tysons Lagoon, PA	ongoing	29.75-46.12%	wellhead-gas
Upjohn,PR	completed	64.49-99.9995%	wellhead-gas

[a] Performance is evaluated with 64.5% error with the upper bound of the range representing 100% accuracy of gas sample.

Belleview, FL

Wellhead vapor concentrations showed a decrease of 95.9% to 99.99% for hydrocarbons and 99.3% to 99.999% for benzene (Applegate *et. al.*, 1987). The VES at Belleview has an efficacy range of 64.05 to 99.3% based on soil-gas measurements.

Hill AFB, UT

In the initial response to the spill, approximately 1,000 gallons of fuel were recovered. This action was followed by excavation of the storage tanks as well as all soil with contaminant levels greater than 10,000 ppm. A concrete pad now supports the storage tanks, and the excavated soil was collected in a mound nearby. To date, more than 70,000 pounds of fuel have been recovered using VES. The full-scale VES system is comprised of three parts: vertical piping system in the spill area, a lateral extraction system in the area of the concrete dike, and a lateral system in the soil pile. Two catalytic oxidation units control air emissions by transforming the fuel into carbon dioxide and water.

Operating from February to June of 1989, the vapor extraction system at Hill AFB demonstrated removal efficacies ranging from 64% to 97.93%, with an average effectiveness of 84.58%. These evaluations are based on soil-gas effluent decreases over the four-month period. Soil sampling results from tests conducted in October 1989 are not yet available.

Hill AFB, UT

SITE TYPE:	fuel spill
CONTAMINANTS/ CONCENTRATIONS:	JP-4 jet fuel/ >10,000 ppm
SPILL VOL/MASS:	27,000 gal
SOIL TYPE:	medium to fine grained sands with clay layers
DURATION:	2 yrs
NO. OF WELLS:	30
AIR FLOW RATE:	200 cfm
CAP:	none
STATUS:	ongoing

Table 7 Percent Decrease of Soil-Gas Concentrations at Hill AFB, UT

Initial	Resulting	%Effectiveness
15,720	1,451	90.75
9,956	1,009	89.87
8,908	1,585	82.21
524	79	85.0
5,240	1,886	64.0
13,100	1,703	87.0
23,499	3,354	85.7
19,519	3,982	79.6
21,877	4,323	80.24
12,838	1,349	89.49
5,633	969	82.8
3,799	79	97.93
524	79	85.0
Average % Effectiveness	84.58%	

Lawrence Livermore National Laboratory, CA (LLNL)

Total vapor concentrations reached a maximum of 16,000 parts per million by volume (ppmv). To date, soil-gas concentrations are approximately 1,000 ppm, yielding a reduction in contaminant concentration by 93.75% (LLNL, 1990b). For this site, the effectiveness range is 60.47 to 93.75%.

Nuremberg Site, FRG

In 1979, nine ground water monitoring wells were installed to monitor potential ground water contamination of the lower aquifer; however, the ground water already was heavily contaminated to depths of 33 feet. Ten years later, in November 1988, one of the monitoring wells was converted to a vapor extraction well for soil remediation. The air pumping rate was approximately 175 cfm and operated with a radius of influence greater than 50 feet. The VES operated for 13 months, and in December 1989, had reduced concentrations of contaminants by 93.75%, to yield a resulting concentration of 500 ppb (Bohm and Rost, 1990). A range of effectiveness for this site is 60.47 to 93.75%.

Nuremberg, FRG

SITE TYPE:	oil recycling
CONTAMINANTS/ CONCENTRATIONS:	TCE,PCE/ 8 ppm
SPILL VOL/MASS:	5,940 lbs.
SOIL TYPE:	very sandy
DURATION:	13 months
NO. OF WELLS:	1
AIR FLOW RATE:	176 cfm
WELL INFLUENCE:	>50 feet
CAP:	none
STATUS:	ongoing

Scherwiesen Site, FRG

Initially, only ten vapor extraction wells were installed in the landfill at the Scherwiesen site; however, after one year of operation, the impermeable character of heavy clay necessitated the addition of 20 wells. To date, recorded soil vapor concentrations range between 30 and 50 ppmv, whereas the initial concentrations were 8,000 ppmv. This yields a reduction in chlorinated hydrocarbon concentration of between 99.37% and 99.63%. The VES at this site is unusual because there are only two carbon filter canisters which are used alternately. In this way, the VES can operate continuously without interruption. All of the solvents recovered at Scherwiesen are 99% pure and are then either recycled or disposed of properly, as is the treatment water which is used to condense the vapor extracted from the soil. During the first year of VES operation, over 6,600 pounds of solvents were recovered from clay soil (Bohm and Rost, 1990). For this site, the range of performance is 64.09 to 99.3%.

Scherwiesen, FRG

SITE TYPE:	landfill
CONTAMINANTS/ CONCENTRATIONS:	solvents/8,000 ppmv
SPILL VOL/MASS:	>12 lbs
SOIL TYPE:	heavy clay
DURATION:	2.5 years
NO. OF WELLS:	30
AIR FLOW RATE:	147 cfm
WELL INFLUENCE:	10-16 feet
CAP:	clay
STATUS:	unknown

Tysons Lagoon, PA

On closing this septic and chemical waste site, the landowners performed minimal site remediation, consisting of removal and off-site storage of lagoon liquid waste, backfilling, and vegetating the lagoon. An Immediate Removal Measure (IRM) resulted in the installation of a leachate collection and treatment system, drainage controls, a site cover, and perimeter fencing of the lagoons. The Remedial Investigation (RI) by the leading potentially responsible party (PRP), Ciba-Geigy (CGC), resulted in the selection of an innovative VES technology to remove organic contamination from the lagoon soils and sediments.

Since bench-testing in June 1988, VES at Tysons has operated at full-scale(EPA, 1989b). Thus far, of the 290,000 pounds of VOCs suspected to be present in site soil, 90,000 pounds of VOCs have been extracted through VES. Site remediation has been hampered by a "tar phenomenon" that has clogged extraction wells, requiring decane (hydrocarbon) treatments to re-establish air flow. Scrubbing and resting periods followed the decane treatments which appear to reduce the tar interference, although the decane itself requires special handling and safety precautions. The original time estimated to reach VOC concentrations

of 50 ppb was two years (EPA, 1988b). The tar has both reduced the operating efficiency of the VES and extended the operating duration for site cleanup. As of November 20, 1989, the VES had decreased wellhead vapor concentrations by an average of 46.1%. VES effectiveness is 78% for the East Lagoon, and 14.2% for the West Lagoon. The range of effectiveness for the entire site is 29.75 to 46.12%.

Tysons Lagoon, PA

SITE TYPE:	lagoon disposal
CONTAMINANTS/ CONCENTRATIONS:	toluene/600 ppm ethylbenzene/1,100 ppm m,p-xylene/11,700 ppm o-xylene/3,700 ppm 1,2,3-TCP/2,600 ppm
SOIL VOL:	30,000 cy
SPILL VOL/MASS:	290,000 lbs/ 90,000 to date
SOIL TYPE:	sandy and clumpy with tars
DURATION:	2.5 yrs
NO. OF WELLS:	99
AIR FLOW RATE:	9,000 cfm
WELL INFLUENCE:	40 ft
CAP:	none
STATUS:	ongoing

Table 8 Percent Reduction of VOC Wellhead Concentrations (ppm) at Tysons Lagoon, PA

Former East Lagoon				Former West Lagoon			
Well	Initial	Final	%Effect -iveness	Well	Initial	Final	%Effect -iveness
VE-01	56	0.98	98.3	VE-37	47	3.0	93.6
VE-02	514	7.59	98.5	VE-39	562	101	82.0
VE-03	325	39.9	87.7	VE-41	14	17.4	-24.3
VE-04	76	80.1	-5.4	VE-42	99	37.7	61.9
VE-05	7.4	1.14	84.6	VE-43	260	24.7	90.5
VE-06	156	15.2	90.3	VE-45	116	11.8	89.8
VE-07	64	6.05	90.5	VE-46	18	8.4	53.4
VE-09	61	79.5	-30.3	VE-47	2640	48.5	98.2
VE-13	1830	95.1	94.8	VE-50	136	562	-313.2
VE-14	196	20.0	89.8	VE-51	146	186	27.4
VE-15	248	65.8	73.5	VE-52	21	10.4	50.4
VE-16	656	9.85	98.5	VE-54	77	183	-137.7
VE-17	482	169.0	64.9	VE-73	1540	788	48.8
VE-18	1250	11.1	99.1	VE-78	652	963	-47.7
VE-19	58	26.6	54.1	VE-79	1560	1250	19.2
VE-20	1290	22.1	98.3	VE-91	211	20.3	90.4
VE-22	209	8.16	96.1				
VE-71	1340	19.7	98.5				
VE-74	299	18.3	93.9				
VE-81	1320	211.0	95.0				
VE-82	971	122.0	87.4				
VE-89	671	110.0	83.6				
VE-90	863	308.0	64.3				

Average Percent Reduction in VOC Concentrations, 11/20/89

Former East Lagoon	78.0 %
Former West Lagoon	14.2 %
	46.1%

Upjohn, PR

Apparently VES has attained the remediation goal of achieving a CCl_4 concentration of 0.05 ppm. Optimum performance of VES resulted in a reduction in contaminant concentration of 99.9999%. Since soil gas measurements were used, we consider the range of effectiveness to be between 64.49% and 99.9999%.

6.0 FACTORS INFLUENCING EFFECTIVENESS

It is important to understand the physical factors influencing the effectiveness of soil venting. While a broad spectrum of site-specific factors influence the performance of vapor extraction systems, two major categories of parameters play a critical role in the determining the effectiveness of this technology: those that affect the ease with which air flows through the soil matrix (e.g., soil type, soil moisture content, soil permeability and porosity), and those that influence the vapor concentration of the contaminant (e.g., volatility of the VOC, temperature of the soil).

The ease with which air flows through the soil matrix is primarily determined by soil type and soil permeability. For example, clays are relatively impermeable, while sandy soils are more permeable. Hence, clays are relatively more difficult to remediate using vapor extraction than soils which are predominantly sandy in character. An additional component such as the presence of tar may interfere with soil permeability (e.g., the "tar phenomenon" at the Tysons Lagoon site reduced the operating performance of the VES and increased the time-scale for site remediation).

Another factor that influences air flow through the soil (and hence vapor extraction efficacy) is the amount of water present in the soil matrix. Excessive moisture may impede the flow of air through the soil matrix by occluding openings in the soil through which the air would otherwise flow. Moisture can be acquired from natural rainfall, or may be introduced into the vadose zone from the water table. According to Smith *et al.* (1990), when soil moisture is bound to the mineral surfaces of the soil particles, contaminants are displaced by water molecules and may partition into organic soil matter where they become entrapped. Further, the carrying capacity of the air for VOC's is diminished by the presence of water vapor, which

displaces VOC's from the air stream. Moisture in the vapor can saturate the carrying capacity of the air stream, rendering it incapable of effectively removing VOC's from the soil.

During vapor extraction, pressure in the vadose zone may be reduced as a consequence of the presence of the vacuum which draws air out through the top of the area. In many cases, the water table is sufficiently shallow that this decrease in pressure will draw water from the aquifer up into the soil above it, causing the contaminated zone to become saturated with water and contaminating the aquifer itself. Under these conditions, the effectiveness of the system will be diminished. A preventative measure used in most VES is the operation of a pump which maintains the level of the aquifer below the contaminated vadose zone (Johnson *et al.*, 1990b). In addition, many sites precede vapor extraction with a soil dewatering treatment.

The second major factor influencing effectiveness of vapor extraction is the volatility of the contaminant. The more readily a chemical forms a vapor, the easier it is to remove the chemical from the soil. Volatility is a both chemical and temperature specific. As the volatility of a compound increases with increasing temperature, so should the effectiveness of vapor extraction. However, according to Clarke *et al.* (1990), the temperature within the subsurface remains relatively constant due to the insulative properties of the top soil, and to the soils inherent ability to absorb heat without undergoing an increase in temperature. According to Johnson (1990b), large changes in subsurface temperature (e.g., from 0°C to 40°C) would result in a seven percent change in vapor flow rate.

As in any remediation process, a number of operational parameters can effect the performance of vapor extraction. The system may be designed to include a relatively non-permeable "cap" that regulates the air flow into the contaminated area and controls the air flow through the subsurface (EPA,1989b). Three of the sites reviewed (Belleview, Custom Products, and TCAAP) had caps installed over the treatment area. In the case of the Custom Products site, a cap was installed for the purpose of promoting air flow in a radial distribution through the contaminated area. Other operating variables that can influence effectiveness of vapor extraction are air flow rate, operating duration, and well-spacing. Vapor extraction design must consider the number of wells necessary for adequate air flow and the number of vacuum pumps required to operate the system at optimum air flow rates. The air flow rates determine the radius of influence for each well, which

is an important factor optimizing the well-spacing.

7.0 ABILITY OF VES TO MEET STANDARDS

The present study considered reduction of VOC contamination at 13 sites as a result of vapor extraction operations. To measure the effectiveness of the vapor extraction operations at these locations, the reduction in contaminant concentrations was compared with two standards: (1) whether the operations resulted in at least a 90% reduction in concentrations and (2) whether the operations resulted in final soil concentrations compatable with current health-based standards. ORNL has compiled a database (CRM,1991) on health-based cleanup goals for ten indicator chemicals at Superfund sites, most of which were taken from ROD's. Using both the initial concentrations at the site and cleanup goals, a mean was calculated from which a reduction percentage was calculated for each chemical to satisfy the mean cleanup goal. For example, TCE has a mean *initial* concentration of 15 ppm (range of 2.8 to 34,250 ppm). The mean cleanup *goal* for TCE is 0.1 ppm. To attain this goal, VES would have to reduce contaminant concentrations in the soil by 99.33%. For sites where cleanup goals have not been announced, the ORNL database has been used to provide a hypothetical endpoint.

Nine of the 13 sites considered in this study utilized the technique of soil sampling during some of their operations. At least five of these sites (Belleview, Groveland, Hill AFB, LLNL, and Upjohn) also used soil-gas sampling during part of their sampling operations. Table 9 presents the results of our analysis on the effectiveness of VES for all 13 sites.

At eight of the 13 sites studied, vapor extraction was found to be effective in reducing VOC concentrations by at least 90%. At the remaining five sites, vapor extraction was found to reduce VOC concentrations by less than 90%. Vapor extraction is a complex process which can be adversely affected by many parameters. Ineffectiveness at the Study Site is caused by the presence of "hot spots" of contamination, which are spatially removed from the location of the extraction wells. At Verona Well Field, Groveland Wells, and Hill AFB, three additional sites where performance was found to be relatively poor, remediation

using vapor extraction is ongoing. At Tyson's Lagoon, the poor performance may be attributed to the presence of tar deposits in the soil that has interfered with the VES.

Table 9 Meeting Criteria for VES Effectiveness

					Criteria Achieved	
Site	Scale/Status	Contam.	%Effectiveness	Required %Effectiveness	Health Based	> 90 % Reduction
Belleview	full/complete	BTEX	98.66	99.97[b]	no	yes
Custom Products	full/complete	PCE	99.9997	99.95[b]	yes	yes
Groveland Wells	pilot/incomplete	TCE	70.4	99.9998[a]	no	no
LLNL, BTEX Spill	full/ongoing	BTEX	91.66	99.97[b]	no	yes
Ponders Corner[c]	full/ongoing	PCE	98.87	99.95[b]	no	yes
Study Site	pilot/complete	VOC's	65.4	99.75[b]	no	no
Twin Cities AAP[d]	full/ongoing	TCE	99.6	99.33[b]	yes	yes
Upjohn[e]	full/completed	CCl_4	99.9997	99.9997[a]	no	yes
Verona Well Field	full/ongoing	TCE	34.1	99.97[a]	no	no
		PCE	58.1	99.97	no	no
		TOL	56.8	99.97	no	no
		XYL	75.3	99.97	no	no
Hill AFB[f]	full/ongoing	jet fuel	84.58[g]	ns[h]	no	no
Nuremburg[f,i]	full/ongoing	PCE/TCE	60.47-93.75	ns	no	yes
Scherweisen[f,i]	full/unknown	VOC's	64.09-99.63	ns	no	yes
Tysons Lagoon[f,i]	full/ongoing	VOC's	29.75-46.12	99.9997	no	no

[a] The effectiveness required to reach health-based cleanup goals provided by the Record of Decision or other site records.
[b] The effectiveness required to reach hypothetical health-based cleanup goals based on ORNL database when health-based cleanup goals were not provided by site records.
[c] Effectiveness does not include a hot spot.
[d] Results are for depths to 35 feet; contamination exists below this depth.
[e] Results according to 1987 sampling data; 1988 sampling data detected deep contamination.
[f] Determined using soil-gas measurements.
[g] Average value.
[h] Not specified.
[i] Range of effectiveness based on reported value (upper value) and 64.5% of that value (lower value).

8.0 CHEMICALS IN A SUBSURFACE ENVIRONMENT

The degree of success of environmental remediation using VES is influenced by the character of the soil matrix where the contamination resides. One can picture the soil matrix as a collection of permeable aggregates of particles, which are, in turn, comprised of a network of successively smaller and more tortuous crevices and micropores. Organic chemical contaminants can reside in five different phases within this soil matrix: (1) a free-liquid phase between the soil particles; (2) the vapor phase; (3) dissolved in soil moisture; (4) adsorbed to the surface of soil particles (under conditions of low relative humidity); and (5) sequestered inside the tiny micropores within the soil particles or entrapped in the organic soil matter. The first three phases of the subsurface contamination (free-liquid, vapor, and surface-sorbed), are all amenable to vapor extraction. Contaminant dissolved in ground water is also potentially removable by VES, but may take much more time. The most difficult portion of the total soil contaminant concentration to remediate is that sequestered inside the soil particles themselves. This inaccessible component is thought to be present in two forms. Molecules of the contaminant may diffuse into the small internal micropores of the soil where they become entrapped. In addition, these nonpolar organic contaminants may diffuse into the interior of the soil organic matter. Diffusive transport of the VOC's into the soil is very slow; however, when organic contaminants have been in contact with soils for a long period of time (years), a substantial quantity of contaminant can be found inside the soil matrix. This fraction of contaminant material poses the greatest challenge to current remediation technologies.

9.0 CHEMICAL BONDING TO SOILS

The traditional view of contamination in subsurface soil environments is that a rapidly-obtained, completely reversible equilibrium exists between the organic fraction of soil and groundwater. This view implies that organic contaminants can be easily removed from soils using vapor extraction and groundwater pumping. As pumping (either vapor or water) reduces the concentrations in the pores between soil particles,

the chemical rapidly desorbs from the soil particles to reestablish equilibrium. This simplistic view ignores the fraction of contaminant entrapped in the interior of the soil matrix. A considerable body of literature is becoming available that suggests that these long-held assumptions of dynamic equilibrium and complete reversibility of chemical sorption are inaccurate. These data indicate that adsorption from the soil matrix is actually a two-phase process. The first phase involves a rapid desorption from the organic fraction of the soil matrix (the readily assessible portion of the soil) into the soil vapor (or water) component. The second phase involves a much longer desorption on the time scale of days to years, in which the VOC's slowly diffuse from the interior of the soil matrix where they have become entrapped (Steinberg *et al.*, 1987; Pignatello, 1990a,b; Pavlostathis and Jaglal, 1991; Ball and Roberts, 1991a,b, Pavlostathis and Mathavan, 1992).

Recent studies show that contamination trapped inside the soil matrix is nearly inaccessible to removal by VES or groundwater pumping. Studies of vapor extraction of 1,2-dibromoethane (EDB) long-sorbed to agricultural soils show that this contaminant is highly resistant to desorption (Steinberg *et al.*, 1987). This organic material is moderately soluble in water, volatile, readily biodegradable, and consequently would be expected to disappear rapidly from the soil, but was found to persist in the soil matrix 19 years after its last application. In a laboratory setting, passing approximately 750,000 pore volumes of dry nitrogen through a soil sample (assuming a soil porosity of 0.2) removed only 8% of the EDB sorbed into the soil. Pignatello (1990a, 1990b) confirms this observation and notes that only the most extreme extraction procedure could produce significant EDB recoveries from long-contaminated soils.

Similar phenomena have been thought to occur in groundwater pumping. For example, Travis and Doty (1990,1991) evaluated 16 sites where contaminated groundwater pumping and treating has been implemented for more than one year (ranging from two to 13 years). These authors concluded that groundwater pumping is ineffective at removing VOC's from the subsurface environment.

Travis and Doty attribute the *perceived* success of groundwater pumping to the following: As aquifer pumping begins at a site, contaminated ground water is removed from the subsurface and nearby uncontaminated water is drawn in to replace it. This water mixes with the remaining dissolved contamination to lower the overall groundwater concentrations; this condition persists for the duration of pumping activity.

As long as the removal rate of contaminants from the aquifer by pumping exceeds the rate at which contaminants desorb from the soil matrix, the observed contaminant concentrations will drop. However, this decrease in groundwater contaminant concentration results from dilution of groundwater contaminants with fresh water rather than from an actual reduction of the total contaminant mass in the aquifer. In fact, a substantial portion of the contaminant mass remains nearly irreversibly-sorbed into the soil matrix and is not removed by pumping. Contaminants in the soil matrix continuously diffuse into the aqueous phase, and when pumping is discontinued, water concentrations will increase until they reach pre-pumping levels.

Several additional studies have addressed the tenacity of organic contaminants entrapped inside the soil matrix. Trichloroethylene, the most common contaminant found at hazardous waste sites, is very resistant to desorption in long-contaminated soils and even repeated extractions fail to recover significant quantities (Pignatello, 1990a,b; Pavlostathis and Jaglal, 1991). Smith *et al.* (1990) studied the sorption of TCE to soil in the unsaturated zone above a contaminated aquifer at Picotinny Arsenal in Morris County, N.J. where TCE-containing wastewater had been discharged to unlined ponds for over 20 years. In spite of the continued influx of clean groundwater into the contaminated aquifer over the last ten years, the groundwater TCE levels have not appeared to decrease. This observation indicates that the slow desorption of TCE from the soil serves as a continual source of aquifer and soil-gas contamination. In addition, they found that TCE concentrations in the soil were one to three orders of magnitude higher than predicted from standard distribution coefficients, indicating that a large quantity of contamination was inaccessibly trapped in the interior of the soil matrix. In related work, the desorptive behavior of TCE that had resided in soils for at least 18 years at a hazardous waste site was studied by Pavlostathis and Jaglal (1991). These researchers found a high persistence level of TCE contaminant in the soil, indicating that the contaminant was undergoing slow diffusion from inside the soil matrix.

In addition, the sorption of tetrachloroethene (PCE) and 1,2,4,5-tetrachlorobenzene (TeCB) was investigated by Ball and Roberts (1991a, 1991b). These researchers estimated that the time required for these contaminants to equilibrate between the soil matrix and the soil moisture was approximately three years, indicating that contaminants were slowly diffusing from the internal matrix of the soil. In addition, these

workers found the long-term sorption of PCE and TeCB to the soil was over 10 times greater than that predicted on the basis of traditional organic partitioning, which ignores that portion of VOC entrapped inside the soil matrix.

10.0 WHY IS VES EFFECTIVE ?

The primary factor controlling the effectiveness of VOC removal from contaminated soils is the velocity at which air or water can be removed by pumping. Vapor extraction is more effective in removing VOC's from the soil pore space than ground water pumping is in removing contaminated water because air extraction rates used in vapor extraction are higher than ground water pumping rates.

Based upon formulas from Johnson *et al.*(1990b), we estimate that the time required for removal of 30 L of homogeneously-distributed TCE from a $1m^3$ wedge of soil is *89 days*. In our projection, we assumed that the vapor was moving at a velocity of 31.97 meters/day in a sandy soil matrix. This time-scale for removal of TCE using VES is much shorter than the *120 years* estimated by EPA hydrologists for dissolution of 30L of TCE into ground-water under natural ground-water flow conditions (flow rate of 0.03 meters/day) (Mercer *et al.*, 1990). This disparity in TCE removal times is a consequence of the higher pumping rate used in vapor extraction.[1]

Table 10 presents vapor extractabilities based on a similar table published by Angell (1992). In these calculations, several assumptions were used: (1) contaminants instantaneously desorb from the soil into the soil vapor to create a soil vapor concentration determined by the contaminants vapor pressure; (2) vapor molecules were assumed to behave independently and to be noninteracting (exhibiting ideal behavior); and (3) soil vapor was extracted at a rate of 100 cubic feet per second. For each compound listed, the number of

[1] Although TCE is volatile (Henry's Law Constant of 0.01) and therefore has a relatively high vapor pressure, it is approximately twice as soluble in water (1.1 g/L) as it is in air (0.520 g/L). Therefore, the greater effectiveness of vapor extraction relative to groundwater pumping for removal of TCE from contaminated soils cannot be attributed to the increased solubility of TCE in air versus water, but rather to the higher air flow rate that is characteristic of vapor extraction.

pounds of material that can be extracted per day with an air flow rate of 100 cubic feet per second was calculated using the Ideal Gas Law at 40°C. These calculations, which ignore interactions of the contaminants with the soil, provide the maximum rate of vapor extractability. Note that the rate of extractability is directly proportional to the contaminants vapor pressure.

Table 10 Maximum Vapor Extractability

Compound	Vapor Pressure @ 40°C (mm Hg)	lb/day @ 100 SCFM
Benzene	28.0	1134
Chlorobenzene	3.8	154
Chloroform	77.0	3119
1,1- DCA	89.0	3605
Methylene Chloride	198.9	8055
Naphthalene	0.1	405
PERC	7.5	304
1,1,1-TCA	4.6	186
TCE	28.0	1134
Toluene	9.0	365
Xylenes	3.0	122

11.0 CAN VES BE USED TO REACH HEALTH-BASED STANDARDS?

The goal of VES is to achieve a level of soil contamination that is compatible with human health. As previously-mentioned, our analysis of VOC studies indicates that vapor extraction is 64-99% effective in removing organic contaminants from soil, depending on the VOC under consideration. However, this result is in contradiction to the results of groundwater pumping studies (Doty and Travis 1990,1991) where, because of the slow leaching of organic contaminants from the internal micropores in the soil matrix, ground water

pumping was shown to be ineffective in removing groundwater contamination. Assuming that the soil structure and properties are the same for both vapor extraction and groundwater pumping sites, the entrapment and slow release of VOC's should also be an underlying pathology in VES. However, the data for VES indicates a measured *decrease* in soil contaminant concentrations.

The resolution of this apparent paradox lies in the method used to determine the concentration of VOC's in the soil. The EPA-preferred method is "purge-and-trap," in which an inert gas is passed through the soil, driving organic contaminants from the pore spaces and external soil surfaces. The contaminant is then trapped and concentrations are subsequently measured using a gas chromatograph. However, recent studies indicate that the purge-and-trap method does not remove contamination from the soil that has diffused into the internal micropores *inside* the soil. Steinberg *et al.* (1987) and Sawhney *et al.* (1988) have proposed extraction of organic contaminants from soils using solvents (methanol, acetonitrile, acetone) at elevated temperatures, followed by analysis of VOC concentrations using gas chromatography. In studies measuring the concentrations in soils using both purge-and-trap and hot solvent extraction, these researchers found that the latter method removed approximately 10 times more contamination from the soil than did purge-and-trap. Thus, under the conditions of these studies, the purge-and-trap method only identified less than 10% of the total soil contamination.

We hypothesize that purge-and-trap *is* effective at removing some fraction of surface contamination from soil, but is ineffective in removing contaminants trapped in the interior of the soil matrix. Since in long-contaminated soils the majority of contamination is found in the interior of the soil matrix, purge-and-trap is measuring only a small fraction of the total contamination within the soil. Desorption of entrapped materials is dependent on diffusion rates out of the soil matrix, which can be up to three orders of magnitude slower than diffusion in water (an already slow process) (Ball and Roberts, 1991).

The VES demonstrations studied in this report used purge-and-trap as the method for determining the effectiveness of the technique in lowering soil contaminant concentrations. They indicated that the soil concentrations as determined by this method dropped by 95-99% from the initial contaminant concentration levels. However, since purge-and-trap is measuring only the *surface* contamination and pore space

concentrations, the measured drop in the concentrations as determined by this method does not indicate that VES has been effective in removing contaminants from the *interior* of the soil matrix (see Section 9.0).

In conclusion, we believe that the available evidence indicates that VES is very effective in removing free-liquid and vapor-phase contamination from the exterior surfaces of soil particles. However, both theoretical considerations and field studies indicate that VES will not be effective in removing contamination trapped in the interior of the soil matrix. Since the quantity trapped in the interior of the soil matrix may exceed the surface contamination by one to two orders of magnitude, VES may not be effective in reducing soil contamination to health-based standards.

12.0 CONCLUSIONS

We have reviewed the vacuum extraction technologies used at 13 sites and have found that vacuum extraction was effective in removing contamination from the vadose zone. Measurement of concentrations obtained from soil borings at six sites, and soil-gas measurements performed at three other sites, indicate removal efficiencies in the range of 84.6% to 100% for nine of the 13 sites--all within a short period of time (ranging from 7 months to 4 years, and averaging 2.2 years).

We conclude that *in-situ* vapor extraction is very effective in removing organic contaminants located in the pore space of the soil matrix and adsorbed to accessible surfaces of the soil aggregates. In cases of long-standing soil contamination, a certain amount of contaminant may have diffused into the interior of the soil matrix and be inaccessible for removal by VES. Vacuum extraction is not effective in removing the sequestered fractions of VOC's. Consequently, although VES is effective in removing a large fraction of the VOC's from contaminated soils, vapor extraction cannot be relied upon to return contaminated sites to their original pristine condition. We strongly support its use, however, for removal of the major portion of subsurface contamination.

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