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Decision-Support Software for Soil Vapor Extraction Technology Application:

HyperVentilate

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DECISION-SUPPORT SOFTWARE FOR SOIL VAPOR EXTRACTION TECHNOLOGY APPLICATION: HyperVentilate

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, may threaten both human health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural resources to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, toxic substances, solid and hazardous wastes, and other environmental programs. This publication presents information on a corrective action technology tool and provides a vital communication link between the researcher and the user community.

An area of major concern to the Risk Reduction Engineering Laboratory is the selection and use of appropriate and cost-effective corrective action technologies for cleanup of petroleum hydrocarbon releases from leaking underground storage tanks. This document presents an approach for evaluating the feasibility of a specific corrective action technology, soil vapor extraction, through the use of decision-support software developed by EPA and the Shell Oil Company.

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ABSTRACT

The U.S. Environmental Protection Agency (EPA) estimates that 15 to 20% of the approximately 1.7 million underground storage tank (UST) systems containing petroleum products are either leaking or will leak in the near future. These UST systems could pose a serious threat to public health and the environment. Selection of appropriate corrective action technologies that can be rapidly implemented, and that are efficient and cost-effective is essential to minimize the impact of UST releases on the environment and public health. Soil vapor extraction (SVE) is a proven, in situ corrective action technology that can remove volatile organic compounds (VOC) and selected residual petroleum hydrocarbons from unsaturated soils. To assist regulators, investigators, and UST owners in evaluating whether SVE is an appropriate cleanup technology for use at UST sites, decision-support software entitled HyperVentilate has been developed by EPA and Shell Oil Company under a 1990 Cooperative Research and Development Agreement under the Federal Technology Act.

HyperVentilate is an interactive, software guidance system for evaluating the feasibility of using SVE at a specific site based on site and contaminant characteristics. HyperVentilate is designed to (1) identify the level of site data required to evaluate SVE systems, (2) evaluate soil permeability test results, (3) approximate the minimum number of extraction wells likely to be needed, and (4) provide a rough approximation of the system's desired and maximum removal rates.

This document provides guidance in evaluating the use of the IBM-compatible version of HyperVentilate that requires a computer equipped minimum with 80386 processor, 4 MB RAM, DOS 3.1, Microsoft Windows 3x, and Spinnaker PLUS 2.5. An overview of SVE principles and procedures is presented along with the basic model principles and a sensitivity analysis of HyperVentilate. A sample application of the software is also presented using data from an actual UST site. The case study demonstrates how to estimate and determine input parameters, goes through the steps involved in deriving estimates to evaluate if SVE is appropriate, and discusses interpretation of the case study results.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

^oC	-- degree Celsius
^oF	-- degree Fahrenheit
ACFM	-- actual cubic feet per minute
API	-- American Petroleum Institute
atm	-- atmosphere
BCF	-- Block Centered Flow
BTEX	-- benzene, toluene, ethyl benzene, and xylenes
CFR	-- Code of Federal Regulations
cm	-- centimeters
cm^2	-- centimeters squared
cm^3	-- cubic centimeter
CRTC	-- Chevron Research and Technology Company
dim.	-- dimensionless
DOS	-- disk operating system
e.g.	-- example
est.	-- estimate
EPA	-- Environmental Protection Agency
GAC	-- granular activated carbon
GC	-- gas chromatography
HSWA	-- Hazardous and Solid Waste Amendments
ICE	-- internal combustion engine
i.e.	-- explanation
in.	-- inches
JP-4	-- jet petroleum grade 4
K	-- Kelvin
KB	-- kilobytes
K_d	-- soil sorption coefficient
K_h	-- Henry's law constant
kg	-- kilogram
K_{oc}	-- octanol-water coefficient
L	-- liter
lb	-- pound
m	-- meter

LIST OF ABBREVIATIONS AND SYMBOLS
(Continued)

m^3	-- cubic meter
MB	-- megabytes
mg	-- milligrams
min	-- minutes
mm	-- millimeters
MPCA	-- Minnesota Pollution Control Agency
NAPL	-- nonaqueous phase liquid
OUST	-- Office of Underground Storage Tanks
PC	-- personal computer
ppmv	-- parts per million volume
PVC	-- polyvinyl chloride
RAM	-- random access memory
RCRA	-- Resource Conservation and Recovery Act
RF	-- radio frequency
RIR	-- remedial investigation report
s	-- seconds
SCFM	-- standard cubic feet per minute
SVE	-- soil vapor extraction
T	-- temperature
TPH	-- total petroleum hydrocarbons
USGS	-- U.S. Geological Survey
UST	-- underground storage tank
VOCs	-- volatile organic compounds
vs.	-- versus

SYMBOLS

H_2O	-- water
Hg	-- mercury
π	-- "Pi" = 3.1415927
>	-- greater than
%	-- percent
$\approx$	-- approximately
=	-- equals

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This document was produced under the direction of Mr. Robert Amick, IT's Program Director. Mr. Roy Chaudet served as the Work Assignment Manager. Mr. Curtis Kruger from Midwest Research Institute and Mr. John Morse from IT Corporation are the principal authors. Ms. Linda McConnell and Mr. Jerry Day provided editorial support. Ms. Karen Price and Ms. Joanna Engle prepared the manuscript.

SECTION 1

INTRODUCTION

BACKGROUND

Hundreds of thousands of underground storage tanks (USTs) containing petroleum products and hazardous chemicals have been installed in the past 30 to 40 years. Many of these tanks have either been abandoned or exceeded their useful life. In addition, many are leaking and thereby pose a serious threat to the Nation's surface and groundwater supplies and to public health. In response to this threat, the Hazardous and Solid Waste Amendments (HSWA) of 1984 (PL98-616) were enacted to add Subtitle I, Regulation of Underground Storage Tanks, to the Resource Conservation and Recovery Act (RCRA). These amendments required the U.S. Environmental Protection Agency (EPA) to develop and implement a regulatory program to deal with USTs containing petroleum products and hazardous substances. After the passage of HSWA, EPA established the Office of Underground Storage Tanks (OUST) to promulgate final rules (40 Code of Federal Regulations [CFR] 280) in 1988 under Subtitle I to prevent, detect, and remediate UST releases to the environment.

EPA estimates that as many as 15 to 20% of the approximately 1.8 million regulated UST systems nationwide either are leaking or are expected to leak in the near future (EPA, 1991a). Approximately 90 to 95% of the regulated facilities contain motor fuels and petroleum products. The environmental threat from leaking tank systems has a direct impact on public health because approximately half of the Nation's drinking water supply comes from groundwater. Small quantities of gasoline released from UST systems can contaminate millions of gallons of potable groundwater and surface water with suspected carcinogens such as benzene. In addition, the components of petroleum products released in the subsurface can preferentially migrate through underground utility trenches to the basements of homes and businesses and accumulate to explosive levels.

In the first several years following promulgation of the Federal UST regulations, EPA focused on evaluating, developing, and implementing effective release detection techniques. This effort has resulted in the rapid identification of a significant number of past and ongoing releases. By December 1991, 137,000 confirmed releases had been identified; however, less than 40,000 of these releases have been remediated (EPA, 1991b). Effective and efficient corrective action technologies have not been developed, evaluated, or implemented quickly enough to address the increasing number of releases identified and confirmed. EPA has been working with the regulatory community to implement new, modified, or innovative corrective action technologies more rapidly. One of the methods that is proving to be very effective is soil vapor extraction (SVE).

SVE is a proven in situ technology used to remove volatile organic compounds (VOCs) and selected residual hydrocarbons from soils. SVE has gained popularity over the last 5 years because it can be rapidly implemented, it has a potentially high removal rate of VOCs from the subsurface, and it generally costs less than other treatment alternatives. To ensure effective and efficient cleanup, however, many site and contaminant characteristics must be evaluated before SVE can be selected.

A practical approach has been developed for evaluating the selection, design, operation, and monitoring of SVE systems (Johnson et. al., 1990a). Based on this approach, Dr. Paul Johnson and Ms. Amy Stabenau of Shell Development Corporation developed decision-support software entitled HyperVentilate in 1991. HyperVentilate was originally developed for use on Apple Macintosh computers, but it is now available in an IBM-compatible version for use on IBM and IBM-compatible personal computers (PC). This decision-support software was designed to enable regulators, consultants, and owners of UST systems to evaluate site characteristics and determine whether SVE technology is a viable option for remediation of volatile petroleum hydrocarbons.

Since promulgation of the Federal regulations, the number of leaking UST systems being discovered has rapidly outpaced the capabilities and resources of both industry and regulatory agencies to implement and complete corrective actions at these sites. Because the number of unaddressed sites is increasing, decision-support software such as HyperVentilate can be a valuable tool for expediting the process of selecting and implementing effective corrective actions.

The objective of HyperVentilate is to help the user engage in a systematic, iterative evaluation of the feasibility of SVE as a remedial alternative at a given site. The software utilizes data provided by the user to develop a rough approximation of the system's desired and maximum removal rates. At no point does the software give a definitive "yes" or "no" response to the question of feasibility. The software can provide two estimates of the minimum number of vapor extraction wells needed to achieve remediation. The first estimate is developed by simply comparing the anticipated extraction well radius of influence with the radial area of contamination. The second estimate is based on a calculation of the volume of air that needs to be extracted from the soil in order to remove residual contamination. The user is ultimately responsible for deciding if the estimates generated by the software are technically and economically practical for a particular site. HyperVentilate is primarily a software tool for evaluating SVE as a remediation alternative; it is not intended to be a detailed SVE modeling or design tool.

The purpose of this document is to provide technical assistance in evaluating the practical use of the IBM-compatible version of HyperVentilate for examining design and operational parameters in the screening of SVE as an option for site remediation. This document presents practical information on the capabilities and uses of HyperVentilate as a decision-support tool for evaluating SVE as a remedial option. Section 1 provides an overview of the SVE technology, including a brief discussion of the behavior of petroleum contaminants in the subsurface, the SVE process, and SVE system modeling. Section 2 describes the basic model principles and structure of the software application of HyperVentilate. Section 3 describes how actual site data can be used to apply the software to a case study. Section 4 provides an analysis of the sensitivity of the software and a test of the response of different input parameters. Appendices to this document include procedures for installing the IBM-compatible version of HyperVentilate and a copy of the User's Manual developed for the Apple Macintosh version.

SOIL VAPOR EXTRACTION TECHNOLOGY

SVE is a proven, cost-effective technique for removing VOCs and motor fuels from contaminated soil in the unsaturated or vadose zone. This technology is also referred to as vacuum extraction, soil venting, aeration, in situ volatilization, and enhanced volatilization. SVE is the term selected for use in this document.

The following advantages of SVE systems make this technology applicable to a broad spectrum of sites:

- This in situ technology can be implemented with only minor site disturbance. Normal business operations often can be continued throughout the cleanup period.
- Large volumes of soil can be treated at reasonable costs, compared with other available technologies.
- The systems are relatively easy to install, and their use of standard, readily available equipment enables rapid, cost-effective mobilization and implementation of remedial activities.
- VOC concentration in the vadose zone is effectively reduced. This, in turn, reduces the potential for further transport of contaminants as a result of vapor migration and infiltrating precipitation.
- SVE can be an essential element of a complete remedial program, which may include groundwater extraction and treatment.
- Discharge vapor treatment options allow the design flexibility necessary to comply with site-specific air emission regulations.

To determine if SVE is applicable for a particular site as well as the key design and operational limitations, an understanding is needed of the behavior of petroleum hydrocarbons in the vadose zone, the SVE process, and modeling tools that are used to evaluate the effectiveness of an SVE system.

This section provides an overview of the factors that influence contaminant fate and vapor-phase transport in the vadose zone. The basic principles that govern vapor behavior and transport in soils are identified to provide a sound basis for decision making with regard to site investigations; pilot testing; and system design, operation, and monitoring. Specifically addressed are the behavior of hydrocarbon contaminants and the characteristics of soil in the vadose zone, the SVE process, and the SVE system modeling.

Principles of Contaminant Behavior in the Vadose Zone

A fundamental understanding of how hydrocarbon contaminants behave in the vadose zone is necessary to properly interpret the results from HyperVentilate in determining if SVE is an appropriate and effective corrective action technology. The behavior of hydrocarbon contaminants in the vadose zone is determined by the quantity of contaminant released, the time since the release occurred, the physical and chemical properties of the contaminant, and the characteristics of the soils through which these contaminants migrate. SVE can be used to remove volatile constituents present in soil gas as well as free and residual liquid product in the vadose or unsaturated zone. SVE also can treat contaminants dissolved in immobile soil water in the unsaturated zone. Theoretical opinions and field studies indicate that SVE cannot effectively remove constituents trapped in the interior of the soil matrix, however. Because the quantity of such constituents may exceed surface contamination by one to two orders of magnitude (Travis and Macinnis, 1992), SVE cannot be used to return long-contaminated locations to original pristine conditions. This section discusses the physical properties of typical hydrocarbon contaminants and the characteristics of soils in the vadose zone that influence the effectiveness of SVE.

Soil Characteristics--

In this document, soil in the vadose or unsaturated zone is defined as unconsolidated mineral and organic material that extends from the ground surface to the top of the capillary fringe and contains soil vapor and a lesser amount of soil water in the pore space between or on soil solids (API, 1992). The textural classes of soil range from clays to silts to sands. The actual soil types present at any particular site are frequently limited. Fill material is often present in vadose zone soils that are contaminated by petroleum hydrocarbons (API, 1992). Fill materials commonly consist of soil, sand, gravel, or crushed rock. Also present in vadose zone soils are biota and manmade structures. An understanding of the interactions between these naturally occurring and manmade features and the movement of petroleum hydrocarbons is necessary for an effective evaluation of SVE as a remedial option.

Critical to the application of SVE technology is the ability to achieve adequate vapor flow through the contaminated soil. Vapor flow rates in the vadose zone depend in part upon soil characteristics such as air permeability, water content, and the heterogeneity of these properties among different soil types. These properties are briefly discussed below.

Air Permeability--Air permeability is the measure of a porous medium's ability to transmit fluids based on laboratory or field airflow tests. The density and viscosity of vapors combined with the permeability of the porous medium significantly influence the ability of the vapor to flow through the soil. Permeability of soil is perhaps 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 (Johnson et al., 1990b). The permeability of the soil or vadose zone is determined from literature values and laboratory or field testing. Permeability is expressed in terms of "darcys" or cm^2 and has the units of length squared. The literature and laboratory tests usually provide values of intrinsic permeability, which is generally the permeability of the dry soil matrix. Field tests usually yield "pneumatic" permeability, which is the permeability of the soil matrix with soil moisture taking up some of the soil pore space. "Pneumatic" permeability is less than intrinsic but approaches the intrinsic permeability as the soil dries out. This can be important in evaluating and designing SVE systems because the site pneumatic permeability can be expected to increase somewhat as the soil dries out during SVE operation. This, in turn, can increase the flow rate and removal rate.

Soil Heterogeneity--The structure, stratification, type, and size of soil particles that influence contaminant migration are often heterogeneous in vadose zone soils. Soil heterogeneity accounts for differences in permeability in or between different soil layers or horizons. Coarsely textured, highly permeable soils are best suited for SVE. Heterogeneous soils that contain low-permeability layers or lenses require a careful evaluation in the selection and design of SVE systems. SVE has been successfully used to remediate volatile hydrocarbons from clays and silts in interbedded permeable layers and in secondary structures such as joint systems or macropores, which include fractures or expressions of bedrock faults.

Water Content--Soil water content (the percentage of soil pore spaces filled with water) affects the air-filled porosity of a soil and the permeability as discussed previously. A higher water content in the soil generally limits the effectiveness of SVE by reducing air-filled porosity, which decreases the size of the connected pores through which air can flow. SVE is well suited for soils with lower water content because a greater percentage of the pore space is air filled and available for vapor transport and therefore can result in a greater induced airflow for a particular vacuum. If the water content is very low, however, sorption of contaminants to soil increases and competes with the volatilization of constituents into the soil gas (Reible, 1989). A range of 94 to 98.5% relative humidity in soil gas appears to be optimal for SVE (Davies, 1989).

Contaminant Characteristics--

Petroleum hydrocarbons are complex mixtures of many different compounds. The composition of specific petroleum products (e.g., gasoline, diesel fuel) differs widely and therefore behaves differently in the subsurface. Petroleum hydrocarbons are released in the subsurface partition in four phases: (1) nonaqueous phase liquid (NAPL), (2) dissolved phase in water, (3) sorbed phase to soil particles and colloids, and (4) vapor phase. Figure 1 graphically depicts each of these hydrocarbon phases in the subsurface environment.

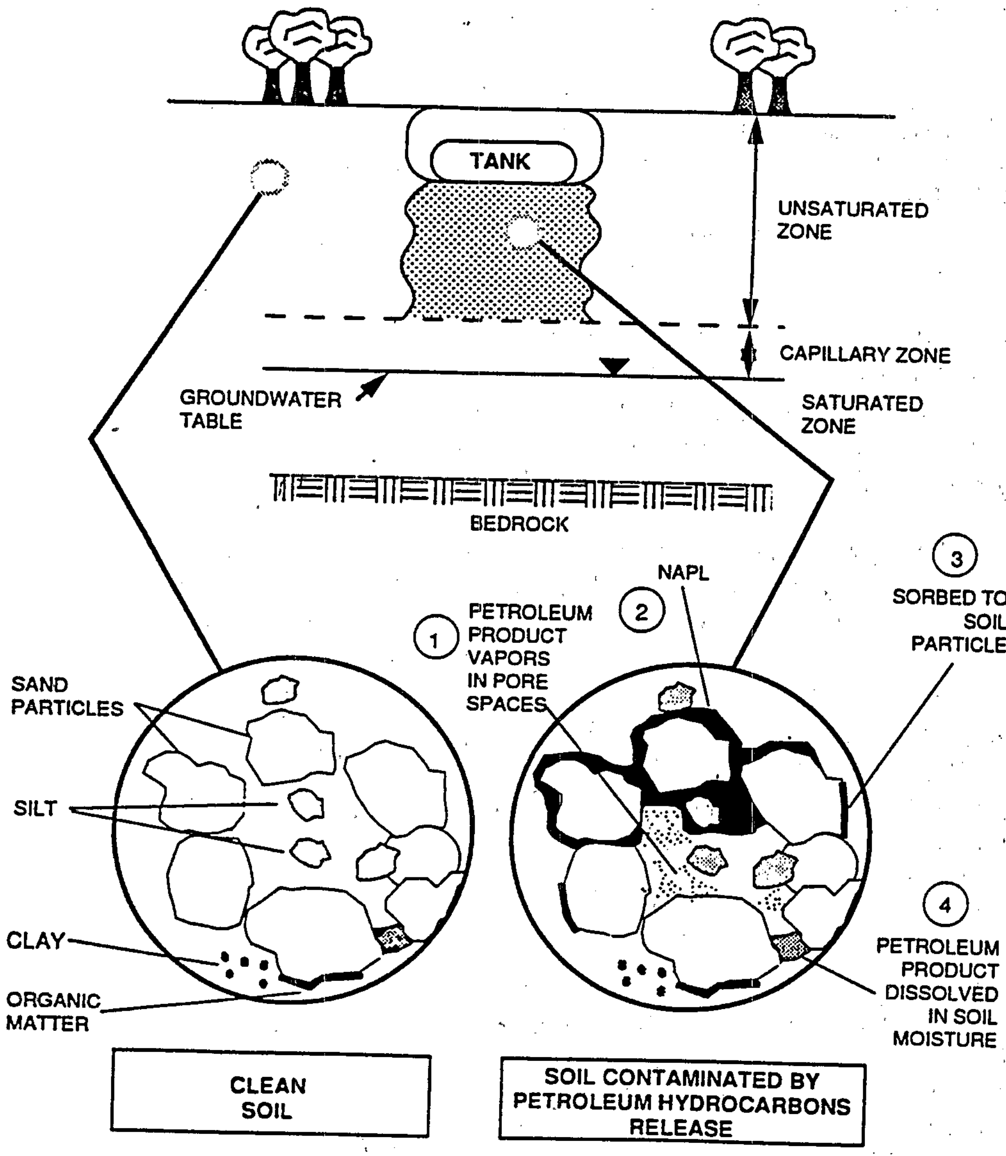


Figure 1. Unsaturated zone contaminant phase.

Source: EPA, 1991c

Petroleum hydrocarbons released in the subsurface are partitioned among the four phases depending on the chemical and physical characteristics of the product, the degree of product weathering that has occurred, and the characteristics of the vadose zone soil. The movement and fate of petroleum products in unsaturated soils are influenced by the following primary physical and chemical properties: vapor pressure, Henry's law constant, solubility, soil sorption coefficient, and chemical composition. Each of these properties is discussed as follows.

Vapor Pressure--The degree to which a constituent transforms from the liquid to the vapor phase is controlled by the vapor pressure according to Raoult's law. Vapor pressure is directly related to the vapor of the chemical constituent in equilibrium with its pure liquid product. For "fresh" or unweathered gasoline releases, the high vapor pressure, lower molecular weight constituents (e.g., butane or pentane) typically account for 75 to 85% of the hydrocarbons in the vapor phase in equilibrium with the gasoline liquid. These constituents can be readily removed by SVE (see Table 1). Temperature has a strong influence on the vapor pressure of a constituent, with the vapor pressure increasing exponentially as temperature increases (three to four times for each 10 ^{o}C). Vapor pressure must always be reported at a specified temperature at which the pressure was measured. Table 1 lists vapor pressures at a temperature of 20 ^{o}C.

There is also an important relationship between a compound's boiling point and vapor pressure. At a compound's boiling point, its vapor pressure equals the vapor pressure of the atmosphere. At sea level the pressure exerted by the atmosphere is 760 millimeters mercury (mm Hg). A decrease in atmospheric pressure results in a reduction in the boiling point. At a pressure of 451 mm Hg, for example, water boils at a temperature of 86 ^{o}C, significantly less than the boiling point at sea level (100 ^{o}C). Inducing a vacuum in the soil reduces the air pressure in the soil pore space. This causes the boiling point to decrease and cause more of the liquid compound to transfer into the vapor phase. The depression of the boiling point due to the induced vacuum is not always a major factor in the volatilization of compounds; however, understanding this phenomenon provides an appreciation of the factors that might influence SVE operation.

Henry's Law--Henry's law constant (K_h) governs the volatilization of a contaminant in aqueous solution, rather than a pure product. Henry's law is an appropriate partitioning constant for evaluating the partitioning of NAPL into the vapor phase, where the contaminant is likely to exist in solution with soil pore water (Stephanatos, 1988). Table 1 lists the Henry's law constant (K_h) for several hydrocarbon constituents. Constituents with Henry's law constants (K_h) greater than 0.01 (dimensionless) will have significant volatility and are amenable to removal by SVE (Danko, 1989; Hutzler et al., 1988). Gasoline is particularly well suited to SVE because of its high composite volatility (for fresh gasoline, K_h = 32). Other petroleum products, such as fuel oil No. 6, are less amenable than gasoline to removal by SVE because of their lower volatility. Researchers have reported, however, successful removal of petroleum products other than gasoline with SVE. For example, DePaoli et al. (1989) reports the successful removal of jet petroleum grade 4 (JP-4) from a site in Utah.

TABLE 1. CHEMICAL PROPERTIES OF HYDROCARBON CONSTITUENTS

Chemical Class	Representative Chemical	Liqud Density (g/cm^3) at 20 °C	Henry's Law Constant (dim.)	Water Solubility (mg/L) at 20 °C	Pure Vapor Pressure (mm Hg) at 20 °C	Vapor Density (g/m^3) at 20 °C	Octanol-Water Coefficient (K_{oc}) (L/kg) at 25 °C
n-Alkanes							
C4	n-Butane	0.579	25.22	61.1	1560	4960	250
C5	n-Pentane	0.626	29.77	41.2	424	1670	320
C6	n-Hexane	0.659	36.61	12.5	121	570	600
C7	n-Heptane	0.684	44.60	2.68	35.6	195	1300
C8	n-Octane	0.703	52.00	0.66	10.5	65.6	2600
C9	n-Nonane	0.718	NA	0.122	3.2	22.4	5800
C10	n-Decane	0.730	NA	0.022	0.95	7.4	13000
Mono-							
aromatics	Benzene	0.885	0.11	1780	75.2	321	38
C6	Toluene	0.867	0.13	515	21.8	110	90
C7	m-Xylene	0.864	0.12	162	6.16	35.8	220
C8	Ethyl benzene	0.867	0.14	167	7.08	41.1	210
C9	1,3,5-	0.865	0.09	72.6	1.73	11.4	390
C10	Trimethylbenzene	0.862	0.19	15	0.697	5.12	1100
	1,4-Diethylbenzene						
Phenols							
Phenol	Phenol	1.058	0.038	82000	0.529	2.72	110
C1-phenols	m-Cresol	1.027	0.044	23500	0.15	0.89	8.4
C2-phenols	2,4-Dimethylphenol	0.965	0.048	1600	0.058	0.39	NA
C3-phenols	2,4,6-	NA	NA	NA	0.012	0.09	NA
C4-phenols	Trimethylphenol	1.037	NA	NA	0.08	0.53	NA
Indanol	m-Ethylphenol	NA	NA	NA	0.014	0.1	NA
	Indanol						
Di-aromatics	Naphthalene	1.025	NA	30	0.053	0.37	690

Note: NA - not available

Source: EPA, 1990

Henry's law constant is highly temperature dependent and increases with an increase in temperature (1.6 times increase for each 10 °C).

Water Solubility--Solubility controls the degree to which a constituent dissolves into groundwater and soil pore water in the vadose zone. Constituents present in petroleum products have widely varying solubilities. As shown in Table 1, pure constituents such as phenols and simple aromatic hydrocarbons (benzene and toluene) are highly soluble compared with the alkane constituents. The solubilities of constituents in a hydrocarbon blend or mixture, however, are different than those for the pure constituents. Differences or large variations in the composition of the hydrocarbon blend can result in a large variation of dissolved constituent concentrations in water. For example, the range of aromatic hydrocarbon concentration dissolved in water can vary over one order of magnitude depending on the composition of the gasoline (Cline et al., 1991). The range in concentrations of aromatic constituents in water, shown in Table 2, reflects the range of equilibrium concentrations that may be found in water saturated with gasoline. Soluble constituents in hydrocarbon blends that are in unsaturated soils are likely to dissolve in widely varying concentrations when precipitation infiltrates through the soil and becomes part of the soil pore water or migrates into the groundwater.

Soil Sorption Coefficient--Sorption of contaminant liquids to soil particles and organic matter controls the distribution of released products in the soil and strongly affects product movement through the vadose zone. A significant portion of the released product often may be sorbed onto the soil. The sorption of a liquid product to soil and organic matter can be described by the contaminant's soil sorption coefficient, K_d. Because values for K_d are not always readily available, the more common octanol-water coefficient, K_{oc}, is often used as a surrogate for the soil sorption coefficient. Table 1 lists the octanol-water coefficients for common hydrocarbon constituents. This table shows the strong relationship between the number of carbon atoms and the octanol-water coefficient; the larger molecules have a much greater tendency to sorb (i.e., K_{oc} is a larger value). This explains in part why compounds such as No. 6 fuel oil, which are high in these "heavy fractions," are very immobile in the subsurface (viscosity is also an important factor).

Contaminant Composition--Petroleum hydrocarbons are the most common products stored in USTs (EPA, 1988) and constitute the majority of confirmed releases. Petroleum fuels are composed of a complex mixture of constituents. Each type of fuel has a different composition and will behave differently in the vadose zone. Contaminants that have a greater amount of lighter, more volatile fractions (e.g., gasoline) are more applicable to rapid SVE removal than those with heavier, less volatile fractions (e.g., diesel or heating oils). Hydrocarbons released into the vadose zone will change composition with time because the more volatile constituents will partition into the vapor phase and the more soluble constituents will preferentially dissolve, thereby leaving the less volatile and less soluble constituents in the soil. The concept of weathering applies to the effectiveness of SVE for removing contaminants and the effect on the residual contaminant. Volatile constituents are first removed at the startup of the SVE system; however, after the system has been operating, the extracted vapor will be depleted in the lighter-end fractions and enriched with heavier-end constituents.

TABLE 2. VARIATIONS IN GASOLINE COMPOSITION AND AQUEOUS-PHASE CONCENTRATIONS OF FUEL COMPONENTS IN GASOLINE[a]

Constituent	Gasoline Composition Weight %			Aqueous-Phase Concentration, mg/L		
	Avg.[b]	(Min.-Max.)[c]	SD[d]	Avg.[b]	(Min.-Max.)[c]	SD[d]
Benzene	1.73	(0.7 - 3.8)	0.68	42.6	(12.3 - 130)	18.9
Toluene	9.51	(4.5 - 21.0)	3.59	69.4	(23 - 185)	25.4
Ethyl benzene	1.61	(0.7 - 2.8)	0.48	3.2	(1.3 - 5.7)	0.8
m-,p-Xylene	5.95	(3.7 - 14.5)	2.07	11.4	(2.6 - 22.9)	3.8
o-Xylene	2.33	(1.1 - 3.7)	0.72	5.6	(2.6 - 9.7)	1.8
n-Propyl benzene	0.57	(0.13 - 0.85)	0.14	0.4	(0.1 - 3)	0.1
3-,4-Ethyl toluene	2.20	(1.5 - 3.2)	0.40	1.7	(0.8 - 3.8)	0.3
1,2,3-Trimethyl benzene	0.8	(0.6 - 1.1)	0.12	0.7	(0.2 - 2)	0.2

[a]After Cline et al., 1991
[b]Avg.= average
[c]Min. = minimum; Max. = maximum
[d]SD = standard deviation

As SVE progresses and volatile fractions are removed, isolated liquid globules may form in soil pores and prove difficult to remove by SVE alone. Depending on a number of operational factors such as flow rate and total treatment time, less volatile constituents may remain in the soil as residuals. Conventional SVE techniques may not remove these residual constituents to an acceptable cleanup level.

Vapor Transport

The flow of vapor through soils can be described by application of Darcy's law. The applied gradients in the soil will dominate the natural gradients under vacuum conditions. Thus, this law can be simplified as follows:

$$q_a = (k/\mu) \nabla P_a \qquad \text{Equation 1}$$

where q_a = airflow per unit area (cm/s)
k = permeability of soil (cm^2)
μ = air viscosity (g/cm-s)
∇P_a = pressure gradient from applied vacuum ([$g/cm\text{-}s^2$]/cm)

The permeability of the soils determines the radius of influence and air discharge rate for a given wellhead vacuum. The soil permeability depends on various soil characteristics such as porosity, structure, grain size distribution, water content, and preferred flow paths. Therefore, SVE applicability is primarily a function of the permeability and the viscosity and density of the air flowing through the soil.

Under ambient conditions, vapor transport can occur by diffusion in response to concentration gradients, density differences in pore gases, meteorological changes in temperature, barometric pressure, and wind speed; infiltration of rainfall; and a fluctuating water table. When a vacuum is applied to the vadose zone, these transport mechanisms are dominated by pressure gradients induced by the vacuum well system. For soils with sufficient permeability, advective flow in response to the applied vacuum is far greater than diffusive flow. For soil layers or lenses with low permeability, the vapor flow is limited by diffusion transport.

Vacuum applied to a well will cause a negative pressure in the zone in the immediate proximity of that well. This zone extends radially from the well and is known as the radius of influence. Within the radius of influence, the vacuum and pressure gradients are strongest at the well and decrease with increasing distance from the well. Wells placed in different soil layers containing distinct permeabilities require applicable vacuum rates, flow rates, and time frames to maintain a similar radius of influence. The interrelationship of these design parameters will be discussed further in Section 4.

Soil Vapor Extraction Process

SVE system equipment consists of commonly used and widely available devices such as polyvinyl chloride (PVC) piping, valves, and pumps. SVE therefore has an advantage over other techniques that require more complex designs or single-purpose equipment. A thorough knowledge of site conditions and SVE processes is still required, however, to achieve maximum system efficiency and contaminant removal.

Site Evaluation--

A detailed site characterization should be performed to obtain data needed for SVE system design. Data obtained from soil borings, soil vapor surveys, and monitoring wells during the site evaluation include soil type and structure, moisture content, air permeability, depth to groundwater, and the source, volume, and type of contaminant. As discussed earlier, permeability of soil is perhaps the single most important soil parameter with respect to the success of SVE. Permeability incorporates the effects of several soil and vapor characteristics. Among the important soil characteristics to be considered are soil type and structure, air-filled porosity, particle size distribution, water content, and the presence or absence of macropores or preferred flow paths. Important contaminant characteristics include contaminant composition, vapor viscosity, and vapor density.

Pilot testing performed along with the evaluation enables specific soil and contaminant properties to be determined for use in the full-scale system design. Although SVE is often implemented without the aid of pilot studies, data obtained through field piloting are invaluable in defining contaminant levels and in developing full system design. In a pilot test, a vacuum (or positive pressure) is applied to a vapor extraction well that is screened in the vadose zone. A pressure distribution is created in the subsurface as a result of the vacuum. Soil pressure measured in probes, or monitoring wells located at various horizontal and vertical distances from the extraction well, is analyzed to measure pressure distribution. Data on soil pressure and extraction well pressure are then used to calculate the soil permeability, radius of influence, and vapor flow rate at different wellhead vacuums. In addition, effluent air samples provide data on expected initial discharge concentrations.

SVE applicability and design can be evaluated from pilot test data using a soil permeability test developed by Johnson et al. (1990a,b). In this test, which is similar to the oil field drawdown gas permeability test, the drawdown (or vacuum pressure) is measured at a monitoring point at a known distance from the vapor extraction well while vapors are regularly extracted. Field data are used to graphically estimate soil permeability. Calculations are made of the slope of the regression line that relates gauge pressure (measured at a sample probe well) to the natural logarithm of the time from which vapor extraction began. The slope of the line is then used to calculate permeability using the known airflow rate and viscosity.

The method developed by Johnson et al. (1990a,b) to determine soil permeability assumes that the time from initiation of SVE increases along with the vacuum pressure in the subsurface (i.e., the absolute pressure becomes more negative). Permeability should be measured over a long enough period to extract at least one pore volume of air, yet at the same time, the time interval should be short enough so as not to be limited by variations in atmospheric pressure. Effective porosity changes can occur after rainfall and when soil-air moisture condenses and evaporates during diurnal temperature changes. A constant vapor extraction rate is often difficult to maintain during SVE operation. Therefore, variations in the vapor extraction rate should be recorded and used when data are evaluated. The sensitivity of the permeability measurement will be reduced as the variations in the vapor extraction rate increase. Permeability should be measured at a number of depths and locations around the vapor extraction well to provide a reasonable estimate of its variability.

System Design--

The objective of the design process is to develop an SVE system that removes the contaminant efficiently, in a timely manner, and cost-effectively. This design requires a knowledge of system effectiveness including contaminant composition and characteristics, vapor flow path and flow rate, and contaminant location with respect to the vapor flow paths (Johnson et al., 1990a,b). In situ SVE systems are designed to increase airflow through the contamination zone. Vertical wells or trenches also are used as extraction points. Wells are used for deep contamination, and trenches are more useful when the water table is close to the surface.

Basic equipment used in SVE systems (see Figure 2) includes pumps or blowers to produce the applied vacuum; piping, valves, and instrumentation to transfer air from the wells through the system and to calculate contaminant concentration and total airflow; vapor pretreatment to remove soil particles and water from the vapors treated; and an emission control device to concentrate or destroy vapor-phase contaminants.

The radius of influence defines the area farthest from the vapor extraction well at which air pressure effects can be measured. The radius of influence is usually estimated as the distance from the vapor extraction well where the air pressure reduction or vacuum is 1.0 inch H_2O. The radius is determined by a site-specific pilot test or is estimated based on permeability. This radius depends mainly on the permeability of the soil, but it is partly dependent on the applied vacuum. The radius of influence can also be controlled by the depth to water, the location of the extraction wells relative to the surface, low-permeability lenses, or an impermeable surface seal. Air inlet or injection wells also affect the radius of influence. Inlet wells enable air to enter the subsurface at specific points, and injection wells force air into the soil.

SVE well systems may be used at sites in which lower permeability soils are interbedded with higher permeability soils. The higher permeability soils help increase the radius of influence and move vapors from the lower permeability soils. Wells in soil layers with lower air permeability (such as 2- to 3-feet thick clays and silts) should be screened across the entire stratigraphic sequence of the targeted contaminated soil zone. Hydrocarbon vapors will tend to diffuse out of the silt-clay layers and into the interlayered sands or gravels. The vapors will then migrate to the extraction well or trench. Remediation of low-permeability soil layers or lenses requires more time because vapor transport is limited by the

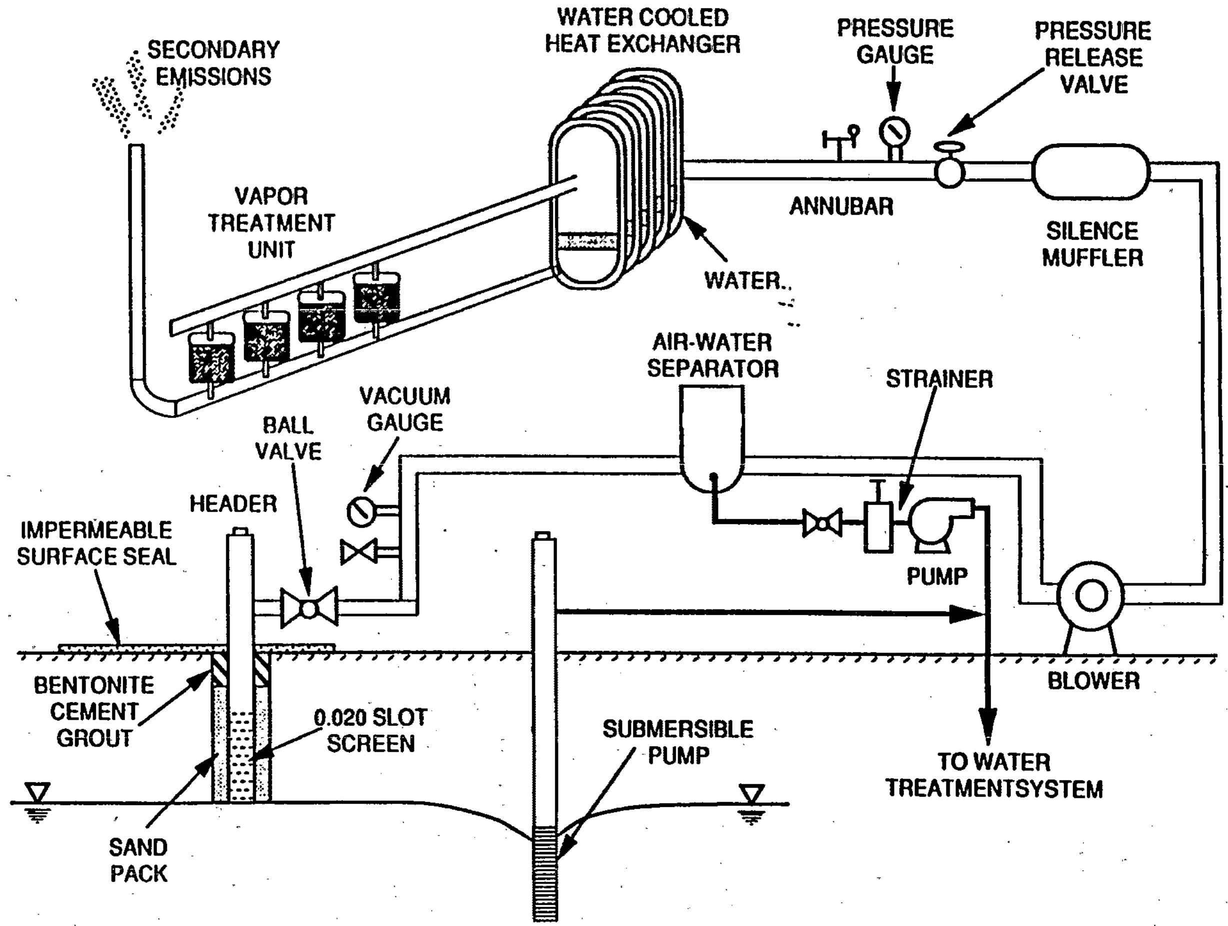


Figure 2. Typical soil vapor extraction system schematic

Source: EPA, 1991c

diffusion of hydrocarbon vapors through low-permeability soils. For thicker clay-silt soil lenses, separate layers with individual wells may be targeted to permit a higher wellhead vacuum and closer well spacings in the lower permeability layers.

The type of blower or vacuum pump selected for use on an SVE system depends on site and contaminant characteristics. The appropriate blower or vacuum pump can be selected after the desired wellhead vacuum and resulting total system flow rate are estimated. In general order of increased vacuum and flow rate, the equipment used includes regenerative blowers, rotary positive blowers, turbo exhausters, multistage centrifuge pumps, and liquid ring vacuum pumps. An air-water separator (condensate-collection tank) often is used on the blower to collect most of the soil moisture condensation. Some condensation also may collect in the extraction piping. Because this air is continually in contact with hydrocarbon vapors, it may contain significant concentrations of dissolved hydrocarbons. Special handling and disposal procedures may also be required. Appropriate equipment is selected based on performance characteristics, mechanical reliability, and cost.

SVE can be operated and controlled automatically via microprocessors, or it can be manually operated. Volume flow rate and vapor concentration are monitored to assess cleanup progress. These data can then be converted to a mass flow rate. Vapor extraction is operated in a continuous or "pulsed" (i.e., intermittent) mode. Pulsed venting is generally more energy efficient.

Vapor treatment can easily double the cost of implementing and operating an SVE system. Hydrocarbons from extracted vapor streams can be removed or destroyed by granular activated carbon (GAC) adsorption, incineration, catalytic oxidation, and internal combustion engines (ICEs). GAC is commonly used to treat vapors because of its ease of implementation and operation, its ability to regenerate spent carbon, and its applicability to a wide range of contaminants, concentrations, and flow rates. Because of the increased costs of carbon regeneration or replacement, GAC generally may not be the most cost-effective option when hydrocarbon concentrations/mass removal rates are high. Incineration, which uses very high temperatures (760 ^{o}C/1400 ^{o}F or higher) to destroy vapor-phase contaminants, is well suited for streams with high concentrations because it can become self-sustaining at vapor concentrations greater than approximately 10,000 parts per million volume (ppmv); below this level, however, supplemental fuel must be used. Catalytic oxidation employs a precious metal formulation as a catalyst to allow the reaction to occur at temperatures of 427 ^{o}C (800 ^{o}F), thereby resulting in reduced fuel costs. The incoming vapor stream concentration is limited to approximately 3,000 ppmv because the heat of combustion will destroy the catalyst at higher concentrations. Results of ICE system tests show that the units reduce hydrocarbon concentrations (>99%); however, a supplemental fuel source is usually required.

Biofilters is another option that is gaining acceptance for treating extracted contaminant vapor. Contaminant vapors from extraction wells are introduced into a sealed soil mound that serves as the medium for microbial degradation. Vapor emissions from these biofilters do not require further treatment.

SVE systems may not require vapor treatment if emission rates are below levels defined by the state or local regulatory agency. This exemption generally occurs when airflow rates or contaminant concentrations in soil are low.

System Performance Monitoring--

Monitoring is performed to determine the amount and movement of pollutants in the subsurface environment before, during, and after remediation (Fan and Tafuri, 1992). An effective monitoring program includes the design of a reliable well network to determine and assess site conditions. The following should be considered in setting up an effective monitoring network:

- At least one well should be placed upgradient or outside the contamination zone so that accurate background levels can be monitored.

- Sufficient downgradient wells should be available to adequately monitor the horizontal and vertical extent of contamination, especially in complex stratigraphy or fluctuating groundwater table areas.

- Wells should be screened in the contamination zone. Special attention should be given to the design of the length of well screens. Longer screens are more likely to intercept the contaminant plume, but may result in diluted soil gas or groundwater samples. Shorter screens provide better concentration estimates, but require more accurate placement to ensure the plume is intercepted.

- Well screen length in the capillary zone must be longer than the total depth of groundwater fluctuations in order to adequately monitor floating NAPL.

- All pathways for potential contaminant migration should be monitored in multiple stratigraphies and aquifers.

The overall objectives of a monitoring program are to: (1) assess site conditions to determine a remediation approach, including the feasibility and requirement of a "no-action" decision; (2) evaluate the progress of in situ treatment; and (3) determine site conditions following treatment.

A field monitoring program should be conducted to select and design the final corrective action approach. Field sampling will be included in the monitoring program to verify soil and site characteristics and to confirm previous assumptions regarding the subsurface. The monitoring well network must be properly designed and operated to determine contaminant movement and to examine passive biodegradation potential. (Naturally occurring biodegradation may be a feasible option for attaining site remediation. To assess this "no-action" alternative and to evaluate decision criteria, the monitoring network should be designed in conjunction with site-specific vapor and groundwater transport modeling.)

After a technology has been selected, designed, and installed, the treatment system performance must be continually evaluated to ensure its effective operation. Remediation of petroleum product releases is often a long process. A treatment technology is usually designed to remove one or more specific constituents to a specified level that conforms to regulatory standards. Performance is then evaluated by measuring the concentrations of each contaminant of concern and comparing those levels to cleanup goals.

SVE performance monitoring of airflow rates and vapor-phase concentrations and composition in extracted vapors directly measures the rate of volatile hydrocarbon removal by the system. Monitoring data typically show that removal rates decrease as the cleanup progresses and the most volatile compounds are removed. Airflow rates and hydrocarbon vapor concentration and composition are monitored at periodic intervals determined by site conditions and SVE system design. Monitoring results can be used to optimize SVE operation and minimize the time and cost of cleanup. Once a sufficiently low rate of hydrocarbon mass removal has been reached, the practical performance limits of the SVE system may have been achieved.

Two basic types of SVE performance categories have been defined by Chevron Research and Technology Company (CRTC) based on soil and site conditions controlling hydrocarbon mass removal rates (CRTC, 1991). These categories are advection and diffusion-limited sites. The rate of hydrocarbon removal at sites where soil subsurface vapor transport is predominantly by advection is primarily a function of hydrocarbon volatilization and airflow rates. Consequently, hydrocarbon removal rates decline toward a near zero asymptote. Once near-zero asymptotic removal rates have been achieved for advection-dominated sites, soil sampling can begin prior to site closure.

Diffusion-limited sites typically contain heterogeneous soils consisting of layers of different air permeabilities in which vapor flows along preferential pathways in soils with higher air permeability. Soils in the airflow pathways are remediated early during SVE operation, whereas hydrocarbon mass transfer from lower permeability soils is controlled by the rate of diffusion of hydrocarbon vapors into the airflow pathways. For these sites, hydrocarbon mass removal rates decrease to a nonzero, diffusion-limited asymptotic value. Diffusion-limited sites may require significantly longer SVE operation to adequately reduce hydrocarbon concentrations in lower permeability soils.

Site remediation is complete once the cleanup goals and cleanup criteria have been met and maintained or when the limits of the corrective action technology have been reached and the remaining contaminants pose no threat to human health or safety. Remediation should not be suspended only because the cleanup criteria have been met. Site monitoring should continue after cleanup because contamination levels can increase even after treatment stops. The following are some of the causes of increased site contamination levels:

- Adsorbed contaminants or contaminants in low-permeability zones can persist in the subsurface but may not be detected at monitoring wells during system operation. These contaminants will tend to disperse after shutdown, increasing contamination levels in soil gas or groundwater.

- Soil gas or groundwater flow patterns created by extraction wells can dilute samples. After pumping stops, normal flow patterns return and concentration levels may increase.

The decision to discontinue monitoring should therefore be made jointly with regulatory officials and experienced professionals to ensure that remediation is actually complete.

Trends in SVE Application

SVE has found widespread application for remediation of soils impacted through the release of gasoline and other petroleum products from USTs. The performance of SVE applications has recently led to improved treatment approaches through use in combination with in situ air sparging (the introduction of air into the subsurface to facilitate volatilization of organic compounds) and in situ bioremediation (referred to as bioventing). SVE has also been used in stockpiled soil mounds to augment bioremediation. SVE systems will find wider application to complex subsurface conditions once a better understanding is gained of vapor flow physics and contaminant fate. Models for predicting subsurface vapor flows will continue to become more sophisticated and provide the required tools to enable an understanding of soil/vapor/contaminant systems. Advances in analytical and field investigation approaches will enable a more accurate assessment of contaminant transport. In addition, a cleanup evaluation will be attained through the use of innovative statistical techniques.

Application of SVE to more restrictive subsurface conditions will be expanded through use of horizontal well systems and high-vacuum techniques. Vacuum-enhanced pumping systems that remove air and groundwater simultaneously are proving very effective for some sites. Subsurface pneumatic fracturing and bioaugmentation will also be used with SVE at future sites. More types of contaminants will be amenable to removal by SVE through steam injection, subsurface radio frequency, or other radiation sources that increase volatilization and use gases other than ambient air. Advances in discharge air treatment technologies will allow SVE to be used in areas where regulatory discharge limitations previously restricted these technologies.

The overall trend in SVE is toward increased sophistication in the assessment of subsurface conditions, simplification of system design, coupling of treatment technologies, and application to increasingly complex sites. Decision-support tools are being developed to assist in selecting and evaluating the design of SVE systems in integrated treatment systems.

Soil Vapor Extraction System Modeling

Models are physically or mathematically constructed to simulate or approximate the behavior of an actual physical process. Models are used as an aid for understanding processes or portions of processes with a high degree of complexity or that cannot be readily understood by direct observation. Models are particularly valuable in evaluating the performance of a soil-vapor-groundwater system prior to construction of a remediation system. Such models also can be used to determine the applicability and effectiveness of a particular corrective action technology and can lower the cost associated with trial-and-error system design and operation.

Effective SVE process modeling has many practical implications. For example, efficient modeling leads to a better examination of process feasibility, a more accurate prediction of potential performance, and the development of system engineering design criteria prior to SVE implementation. This section presents a short summary of the application of microcomputer models for demonstrating how an SVE system influences the soil vapor transport. This section also presents an evaluation of the feasibility of using SVE for site remediation. Table 3 is a summary matrix of general types of models.

The effective design of an SVE system requires an understanding of the mechanisms that control the fate and transport processes and the site characteristics that affect them. SVE is affected by the following major processes: advection, diffusion, dispersion, partitioning, and abiotic and biological transformations.

The results of laboratory SVE column experiments and the results from field-scale implementation of SVE have been analyzed and developed into mathematical models. Subsurface vapor transport models (a larger group of models) were examined to determine their use in evaluating SVE systems. The seven model types within this group include models developed to simulate laboratory column studies, models developed to simulate laboratory pilot (sandbox) studies, SVE screening models, models developed to simulate the field-scale effect of SVE, subsurface flow models for calculating vapor flow rates and pressure distributions, and groundwater flow models modified to approximate vapor flow.

Although each of these types of models has an important application in subsurface vapor transport, only those models that can simulate SVE systems on a personal computer will be discussed.

Column Models--

Column models have been developed to simulate laboratory column studies and to determine the effectiveness of various fate and transport processes under simplified and controlled column conditions. Column studies incorporating computer modeling have been conducted as part of the SVE treatability study and research.

Wilson (1991) developed an SVE column model to simulate one-dimensional flow in laboratory column studies. This model was used to determine the local equilibrium between

TABLE 3. SUMMARY MATRIX OF MODELS

Model Name	Model Type	Developer	Availability	System Requirements	Applications	Input	Output
SVE COLUMN	Lab Column	D. J. Wilson	Beta Test Phase	IBM PC/AT Compatible 640 KB RAM; MS-DOS 2.0 or higher. BASICA	Feasibility of SVE use; qualitative estimates of mass remaining	Flow rate, column dimension, porosity, temperature, time step, sorption isotherms	Mass remaining vs. time
HyperVentilate	Screening	Shell Development Westhollow Research Center	Beta Test Phase	Apple Macintosh, >1 meg of RAM, "Hypercard" 2.0 or newer IBM PC/AT compatible, 386, 4MB RAM, VGA or 8514, DOS 3.1 or higher	Feasibility of SVE use; qualitative estimates of clean-up time and some design parameters	As above plus boiling point data on spill components; desired remediation time	Estimates of flow rates; removal rates; residual concentrations; # of wells required
VENTING	Screening	Environmental Systems and Technologies, Inc.	Available to public $300	IBM PC/AT compatible 512 KB RAM, math coprocessor, hard disk with >1.5 MB	Feasibility of SVE use; qualitative estimate of cleanup times	Airflow/permeability, contaminant characteristics	Mass removal rate curve for each spill component
CSUGAS	3-D Finite Difference Vapor Flow	Colorado State University Civil Engineering Department	Available to public, $125	IBM PC/AT compatible, DOS 2.0 or higher, 640 KB RAM, graphics monitor, math coprocessor	Quantitative estimate of design parameters	Permeability; porosity; initial pressures; topography	Soil pressure distribution; total system flow
Airflow	2-D Finite Element Radial Symmetric airflow	Waterloo Hydrologic Software	Available to public, $700	IBM PC/AT compatible DOS 3.1 or higher, math coprocessor 512K RAM	Quantitative estimate of vapor pressure flow at steady state.	Permeability, initial pressures, gas characteristics, temperature	Soil pressure distribution, total system flow
Airtest	2-D Analytical radial-symmetric airflow	A. L. Baehr C.J. Joss Drexyl University	Test Phase	IBM PC/AT compatible 512K RAM	Quantitative estimate of pressure and flow estimate	Permeability test data, initial pressure, flow rates	Permeability, pressure distribution and flow
MODFLOW	3-D Finite Difference Ground Water Flow (converted for airflow calculations)	USGS	Available to public, $250-$525	IBM PC/AT compatible, DOS 2.0 or higher, math coprocessor, graphics monitor	Quantitative estimate of design parameters	Vapor conductivity, initial pressures	Soil pressure distribution; total system flow

the vapor phase, aqueous phase, adsorbed state, and nonaqueous liquid phase. The model considered the effect of advection and diffusion/dispersion in the vapor and aqueous phases. Biological degradation was also modeled as a first-order process in the aqueous phase. In addition, sorption parameters can be determined based on the test results obtained by use of the Freundlich, Langmuir, and BET adsorption isotherm characteristics.

Screening Models--

SVE screening models are primarily used to semiquantitatively estimate the feasibility of SVE for application at a specific site. These models also may provide estimates of design parameters used to size an SVE system. Johnson et al. (1990a,b) presented a useful screening approach for determining the feasibility of SVE at a particular site. This practical approach makes use of equations that estimate VOC removal rates and pressure distributions for various SVE design parameters. The two models that were developed based on this approach are VENTING and HyperVentilate.

VENTING can be used to estimate the rate of VOC removal from the vadose zone under SVE conditions. This model assumes a steady gas flow, equilibrium partitioning between the free product and vapor phases, and complete mixing of free product and vapor in order to reduce the mass of each contaminant component during the extraction time. The mass balance only considers partitioning from the free-product phase into the vapor phase. It also assumes that the aqueous and adsorbed phases make negligible contributions to the vapor phase. The volumetric gas flow rate is the key parameter that determines the VENTING modeling results. The flow rate may either be input directly based on field measurements or may be estimated based on the permeability of the contaminated soil and the vent pressure. VENTING also provides a method of estimating permeability by use of permeability test data.

HyperVentilate was developed independently from venting and is designed to be used as an instructional tool to identify required site data, decide if SVE is appropriate at a site, evaluate air permeability tests, and estimate the minimum number of wells needed. It is not intended to be a detailed SVE predictive modeling or design tool. The basic model principles and computer software structure are discussed further in Section 2.

Subsurface Vapor Flow Models--

Subsurface vapor transport models calculate the two- or three-dimensional flow of soil vapor through a porous medium as a result of the pressure gradient created by an extraction well. These models do not consider the contaminant concentrations in the soil vapor, but do simulate vapor compressibility. An example of this type model is CSUGAS, a three-dimensional finite difference model that numerically simulates the flow field of a compressible gas in a porous medium as a result of the influence of an SVE system. The finite differences method is used to numerically approximate a solution to the system of equations. This method also allows for use of a heterogeneous and isotropic porous medium with gaseous flow under steady-state or transient conditions. Model applications include selecting design parameters, determining the feasibility of SVE at a particular site, and evaluating proposed modifications to existing SVE systems.

Airflow is a two-dimensional finite element radial-symmetric model that simulates the flow of vapors in the unsaturated zone. It computes vapor pressure distribution resulting from a vapor extraction well at steady state for an ideal, compressible gas in vertical section. Different vapor characteristics can be simulated by using different gas constants, molecular mass, viscosities and temperatures. The model can simulate heterogeneous and anisotropic permeability zones. A variety of boundary conditions can also be imposed.

Airtest is a two-dimensional analytical radial-symmetric model that can be used to estimate permeabilities from test data and/or estimate pressure distribution and flow in soil. The program is currently being tested and documentation is being developed. The program can be run in either interactive or batch mode.

Groundwater Flow Models--

Groundwater flow models are another approach for predicting the pressure distribution and flow of an SVE system for design purposes. Because equations used to describe vapor and groundwater flow in a porous medium are similar, groundwater flow models can be used to approximate the pressure field and flow of a given system design. Use of groundwater models is advantageous because they are readily available, well documented, previously validated, and may already be familiar.

A commonly used groundwater flow model is MODFLOW. The U.S. Geological Survey (USGS) developed this three-dimensional finite difference groundwater flow model to simulate many hydrologic systems (McDonald and Harbaugh, 1985). Several optional features of this model, however, are not applicable for simulating airflow. The model is divided into packages that represent a hydrologic or computational feature. The packages are further divided into module subroutines designed for use in a particular package. The two packages that are the most pertinent for SVE applications are the Block Centered Flow (BCF) Package, which simulates flow within a porous media, and the Basic Package. The Basic Package includes definitions of the number of rows, columns, and layers in the finite difference grid, analysis timing, initial pressures (head for groundwater), boundary conditions, output timing and format, and volumetric balance.

Recent SVE system designs for removing VOCs have mostly been empirically based because of the simplicity of the process and the lack of analytical tools capable of aiding system design. Many numerical models have practical applications in actual field situations that can evaluate the effectiveness of SVE in removing organic vapors. Sensitivity analyses can be used to determine the role of soil moisture, temperature, soil heterogeneity, and other factors in controlling the migration of volatile constituents through the unsaturated zone. The process of contaminant desorption from soil particles involves three consecutive mass transport steps. This process can be used to determine final cleanup efficiency. It also can result in significant differences in removal rates for the various types of soils and volatile organic components.

The focus of this document is on evaluating the practical use of the IBM-compatible version of HyperVentilate as a screening model The principles, structure, and analyses of HyperVentilate are discussed in detail in Sections 2 and 4 of this document. An application using site data is presented in Section 3.

SECTION 2

HyperVentilate

BASIC MODEL PRINCIPLES

HyperVentilate, an interactive, software guidance system, is a useful tool for evaluating the feasibility of using SVE at a specific site. HyperVentilate was designed for use as a guide to achieve the following: (1) to identify the level of site data needed to evaluate SVE systems, (2) to determine if soil venting is appropriate at a site, (3) to evaluate soil permeability test results, and (4) to approximate the minimum number of extraction wells likely to be needed. The basic model principles presented in this part of the document are based on information presented by EPA, 1991, and Johnson et. al., 1990.

Software Characteristics

HyperVentilate Version 1.01 was originally developed for the Apple Macintosh (Plus, SE, Classic, LC, II, Portable, or Powerbook) computer with 2 MB RAM and the Apple Hypercard Software Program (Version 2.0 or higher). HyperVentilate Version 2.0 is now available for IBM compatible PCs equipped with an 80386 processor, 4 MB RAM minimum, VGA or 8514, DOS 3.1 or higher, Microsoft Windows 3.x and Spinnaker PLUS 2.5 or higher. The version of HyperVentilate that will be available through the EPA will have a "run time" version of Spinnaker PLUS sufficient to run only HyperVentilate.

HyperVentilate is composed of a system of multiple stacks of cards in which each computer screen view is called a card. Related cards that follow in sequential order are organized into card stacks, and the main card stack is the soil venting stack. To obtain further explanation of individual cards within this stack, secondary card sets can be accessed through the soil venting help stack. Other supporting stacks include the air permeability test stack, the aquifer characterization stack, the system design stack, and the compound list update stack. The multiple card file system has the flexibility to allow the user to access part of the software without having to work through the entire program.

The HyperVentilate software system uses these stacks to provide card sets with information and calculations on nine major topics associated with implementing SVE. The following sets of cards are used:

- "Is Venting Appropriate?";
- Field Tests;
- System Design;
- About Soil Venting;
- Site Investigation;
- System Monitoring;
- Economics;
- System Shutdown; and
- The "Practical Approach."

The first three card sets listed allow the user to perform calculations related to SVE feasibility, field tests, and design. The other six sets provide technical information on SVE concepts, techniques, and procedures. The following subsections provide information on the basic principles and calculations used in these HyperVentilate stacks.

Venting Applicability

A preliminary estimate of SVE applicability is calculated in the "Is Venting Appropriate?" card set and is based on projected estimates of contaminant characteristics and soil permeability. The first set of calculations is an estimate of ranges of extraction well vapor flows. These ranges are based on input values of the air permeability associated with a given soil type, the radius of the extraction well, the estimated vapor extraction well radius of influence, and the thickness of the subsurface over which vapor extraction is implemented. The following equation is used to estimate the actual horizontal flow rate:

$$\frac{Q_{well}}{H} = \pi \frac{k}{\mu} P_W \frac{[1-(P_{atm}/P_W)^2]}{\ln(R_W/R_I)} \qquad \text{Equation 2}$$

where

Q_{well}	=	actual airflow rate at extraction well (cm^3/s)
H	=	vapor extraction interval thickness (cm)
k	=	soil permeability (cm^2)
μ	=	viscosity of air (1.8×10^{-4} g/cm-s)
P_w	=	absolute pressure at extraction well (g/cm-s^2)
P_{atm}	=	absolute ambient pressure (1.013×10^6 g/cm-s^2)
R_w	=	radius of vapor extraction well (cm)
R_I	=	radius of influence of vapor extraction well (cm)

The units shown in parentheses illustrate that the use of this equation requires a dimensionally consistent set of metric or English units. The flow rate (Q_{well}) obtained from Equation 2 is the flow rate that would be measured under the given wellhead vacuum and soil permeability conditions. To convert Q_{well} to standard volumetric units (Q_S), Q_{well} is multiplied by the ratio of P_W/P_{atm} as follows:

$$Q_{well} \times \frac{P_W}{P_{atm}} = Q_S \qquad \text{Equation 3}$$

Q_S is expressed in standard cubic feet per minute (SCFM) in the HyperVentilate program, and Q_{well} is in actual cubic feet per minute (ACFM).

The "Is Venting Appropriate?" section of the software calculates flow rates in SCFM for five extraction well vacuums ranging from 5 to 120 inches H_2O. Users can also input one vacuum pressure of their choice. In the "System Design" section, the flow rate in SCFM is calculated for the user specified wellhead vacuum.

The second set of calculations in the "Is Venting Appropriate?" card set estimates constituent vapor pressure and vapor concentration. A data base supplied by HyperVentilate is used to determine these vapor estimates for application to gasoline and weathered gasoline. This data base defines the chemical composition of gasoline and the vapor pressures for 62 of the chemical constituents identified in gasoline. The program enables the user to enter mass fractions for these constituents into the data base. The method of estimating vapor concentration is described in Johnson et al., 1990a. The equilibrium or "saturated" vapor concentration is the maximum vapor concentration of any mixture of volatile constituents in extracted vapors. This concentration is easily calculated based on the molecular weight and vapor pressure at the soil temperature for each constituent in the contaminant mixture, the residual soil contaminant composition, and the ideal gas law using Equation 4:

$$C_{est} = \sum_i \frac{x_i P_i^v M_{w,i}}{RT} \qquad \text{Equation 4}$$

where

C_{est}	=	estimate of contaminant vapor concentration (mg/L)
x_i	=	mole fraction of component i in liquid-phase residual ($x_i = 1$) for single compound
P_i^v	=	pure component vapor pressure at temperature T (atm)
$M_{w,i}$	=	molecular weight of component i (mg/mole)
R	=	gas constant = 0.0821 l-atm/mole-K
T	=	absolute temperature of residual (K)

The software adjusts the vapor pressure and concentration estimates to allow for soil temperature changes.

The third calculation estimates maximum removal rates as a function of the maximum vapor concentration and the estimated vapor flow rate:

$$R_{est} = C_{est}\, Q_{well} \qquad \text{Equation 5}$$

where R_{est} = estimated removal rate (kg/day or lb/day)
Q_{well} = flow rate from soil venting operations (ACFM)

Maximum removal rates are estimated based on the range of extraction well flow rates (Q_{well}) previously estimated in Equation 2. A preliminary assessment of SVE feasibility can then be made by comparing the desired removal rate with the estimated range of removal rates. The desired removal rate is calculated by dividing the estimated spill mass (M_{spill}) by the desired remediation time. SVE is considered to be feasible at this point in the evaluation. If the desired removal rate is less than the maximum removal rate at the desired extraction well vapor pressure.

After the desired and estimated removal rates are evaluated, the minimum volume of air required to remove 90% of the residual gasoline in the soil is estimated as $V_{critical}$. The estimate along with previously estimated parameters, is used to determine the number of vapor extraction wells required for site remediation. Johnson et al., 1988, developed a correlation between the gasoline vapor concentration versus the air volume extracted over time. This correlation is used to derive the air volume required to remove a given percentage of residual hydrocarbons in soil. The HyperVentilate software calculates vapor concentration and residual concentrations in 5% increments to estimate $V_{critical}$. The following equation is used to estimate the number of vapor extraction wells required based on $V_{critical}$:

$$N_{wells} = (V_{critical} \times M_{spill})/(Q_{well} \times e \times \Delta\tau) \qquad \text{Equation 6}$$

where additional parameters are:

$V_{critical}$ = minimum volume of air required to remove 90% of residual gasoline
M_{spill} = mass of spill
Q_{well} = flow rate from extraction well
e = efficiency of removal
$\Delta\tau$ = desired remediation time

When Equation 6 is used to provide a preliminary estimate of SVE feasibility, it is assumed that the well efficiency is 1.0 (100%) for initial estimation purposes. In the design stack, the program calculates the number of wells based on $V_{critical}$ using Equation 6 and on area using Equation 7 as follows:

$$N_{wells} = \frac{(R_c)^2}{(R_I)^2} \qquad \text{Equation 7}$$

where R_c = radius of contamination
R_I = estimated radius of influence

The number of vapor extraction wells initially required is best estimated prior to field data collection. This estimate can be used to guide field data collection activities and to approximate the feasibility of implementing SVE at a given site.

Field Test Evaluation

The section of HyperVentilate dealing with air permeability field data evaluations can be found in the Field Tests set of cards. Air permeability tests use airflow and transient air pressure measurements taken from a field SVE test to estimate the permeability of the unsaturated soil matrix. The permeability estimation process follows methodology presented in Johnson et al., 1990a. The resulting permeability measurements can be compared with the values previously estimated for the various soil types found at the site. The permeability calculations in HyperVentilate are independent of the other portions of the software. The user, therefore, can choose the calculated permeability values from this part of the program or the permeability values estimated from the soil type.

System Design

The SVE system design stack of HyperVentilate discusses the number and location of extraction wells needed, well construction, surface seals, groundwater pumping systems, and vapor treatment. The section on the number of extraction wells required is the only section that provides calculation spreadsheets. These spreadsheets or cards essentially repeat the calculation steps (i.e., Equations 2, 4, 5, 6, and 7) used in the "Is Venting Appropriate?" stack. The multiple soil units are evaluated with respect to the total mass of contaminants, critical volume of air needed to remediate 90% of the residual petroleum hydrocarbons, estimated flow rate per vapor extraction well, and minimum number of vapor extraction wells required. In addition, the regional efficiency is provided and the number of extraction wells is estimated. HyperVentilate provides methods for estimating efficiency in two different subsurface cases: (1) vapor flowing past liquid layers floating on the water table and (2) diffusion of vapors from contaminated low-permeability lenses.

COMPUTER SOFTWARE STRUCTURE

HyperVentilate is interactive software with a dual nature. On one level, it is tutorial, intended to help the user understand the nature and distribution of hydrocarbons in the subsurface and to determine if SVE is an appropriate remedial technology at a given site. On another level, it is computational, allowing the user to work through several sequences of operations to determine if SVE is appropriate for use under specific site conditions.

HyperVentilate Multiple Stack Cards

HyperVentilate comprises 100 cards made up of six stacks that provide calculations and information on nine topics as listed on pages 22 and 23. Each topic is handled with a set of cards. The first three sets ("Is Venting Appropriate?," Field Tests, and System Design) take the user through the systematic decision process and evaluation of SVE. The other six sets provide Help cards or technical information on SVE concepts, techniques, and economics. In this subsection, the cards used in the SVE decision process will be discussed sequentially.

Entering HyperVentilate--

Upon opening the HyperVentilate icon, the user finds two disclaimer cards. Clicking on the "NOPE" button will exit HyperVentilate and return the user to the Windows menu. The user must "click" on the "OK" buttons on both cards to proceed into the software. The next card is the main menu or home card that can be used to directly access different stacks. If the user is familiar with the software and wants to access a specific card or stack, the user can click on any of the folder tabs on the right side of the screen. The user should proceed to the next card if unfamiliar with the software. The next card is the equivalent of the software's cover page and table of contents. The fourth card, Card 1 of the soil venting stack, provides an introduction to the software. Cards 2 through 6 and subordinate cards that can be accessed from these cards introduce the user to soil venting and the soil venting system design process.

"Is Venting Appropriate?"--

Cards 8 through 13 contain the first set of cards with computations designed to obtain a rough approximation of SVE feasibility at a specific site. The user should be able to obtain or estimate the required input parameters for these cards from data obtained from a preliminary site investigation. These computations allow the user to estimate the desired system contaminant removal rate. Card 13 has a range of values for the maximum estimated contaminant removal rate. The following scenarios are used to interpret the results and to determine whether to use SVE:

- If the desired removal rate is less than the lower estimate for the removal rate, soil venting is probably a viable remedial technology.
- If the desired removal rate falls between the upper and lower estimates for the removal rate, application of soil venting may not be successful.
- If the desired removal rate exceeds the upper estimate for the removal rate, soil venting is not likely to be appropriate and other treatment alternatives should be considered.

The calculations on Cards 14 through 18 allow the user to refine this initial estimate, taking into consideration anticipated compositional changes in the contaminant mass over the course of remediation. The calculations estimate the minimum number of wells likely to be required to achieve remediation within the specified time. These two initial approximations consider ideal circumstances in which the vadose zone containing contaminants is essentially homogeneous and contaminants are distributed uniformly.

Other Considerations--

Card 19 provides the user with information and equations for four special cases that can affect vapor extraction well efficiency. The cards used to access the four special cases are the "Dilution Effects" or "Ground Water Upwelling" buttons, which are strictly tutorial; the "Liquid Layers" button, which provides an explanation of how the contaminant removal efficiency can be calculated when an NAPL layer is present; and the "Low Permeability Lenses" button, which lets the user access cards that explain how to calculate the removal rate of contaminants in a lens of low-permeability material.

Field Tests--

Cards 20 and 21 deal with field tests that should be performed in support of a soil venting system design. Clicking on the "Aquifer Characterization" button on Card 20 opens a support stack that identifies the circumstances that warrant aquifer characterization, provides a brief description of aquifer characteristics, and identifies useful references on aquifer testing. Clicking on the "Air Permeability Test" button on Card 21 opens a support stack that describes how to conduct and evaluate an air permeability test.

System Design--

Cards 22 through 24 provide a thorough overview of all aspects of the vapor extraction system design. On Card 24, several buttons access cards in the system design support stack. All of these buttons, except "Number of Extraction Wells," open up tutorial cards. The "Number of Extraction Wells" button opens up a sequence of cards (System Design Cards, SD1-4) that allow the user to refine the estimate of the number of extraction wells likely needed to achieve remediation through SVE at the defined site. System Design Cards SD2-4 contain tables that allow the user to subdivide the unsaturated zone interval slated for remediation into eight units, based on stratigraphy and contaminant characteristics. Each of the units identified by the user generates the following: (1) range of flow rates per vapor extraction well, (2) minimum number of wells based on a comparison of the radius of influence with the radial area of contamination, and (3) range for the minimum number of wells based on the estimated volume of soil vapor (in liters) that must be removed to recover each gram of residual contamination.

Tutorial Cards--

Cards 25, 26, and 27 contain tutorial material concerning appropriate system monitoring parameters, system shutdown criteria, and soil vapor extraction economics, respectively. The final card, Card 28, identifies the original intent of the software and acknowledges the contributions of people who have participated in the software's development.

<u>Software Inputs and Outputs</u>

The following input information is required for use of the HyperVentilate software:

- Soil types or permeability range;
- Vapor extraction well radius;
- Estimated radius of influence of the vapor extraction well;
- Thickness of subsurface interval over which vapor extraction occurs;
- Estimated vacuum pressure at extraction wells;
- Contaminant type: gasoline, "weathered" gasoline, or other chemical constituent (molecular weight and vapor pressure at 20 ^{o}C and boiling point at 1 atm needed if a constituent is not in the data base);
- Average subsurface soil temperature;
- Estimated spill mass;
- Desired remediation time;
- Screened interval of vapor extraction well;
- Stratigraphy of contaminated layers: soil types and depth intervals;
- Radius of contaminant layers
- Contaminant distribution thickness;
- Average contaminant concentration;
- Information on air permeability test analysis including:
  - Vapor pressure versus time measurements at vapor monitoring wells based on short-term permeability tests;
  - Distance of vapor monitoring wells from vapor extraction well;
  - Vapor extraction flow rate and vacuum pressure applied during permeability test.

Note: The radius of influence depends on soil permeability, extraction well vacuum, and boundary effects and must be estimated for program input. The equations used in HyperVentilate are not very sensitive to the radius-of-influence parameter; a value of 12 meters or 40 feet is often used for estimating purposes.

HyperVentilate guidance software provides the following output information:

- Estimated range of potential flow rates from a single vapor extraction well;
- Composite contaminant vapor pressure and concentration at a given temperature;
- Desired contaminant mass removal rate;
- Estimated maximum mass removal rate;
- Minimum air volume required to remove 90% of the initial contaminant residual;
- Number of extraction wells required at different measurements of inches of wellhead vacuum pressure;
- Contaminant removal efficiency;
- Permeability based on air permeability site tests;
- Contaminant mass based on average contaminant concentration and extent of contamination;
- Estimated minimum number of extraction wells required with the design vacuum pressure.

Input Parameter Requirements, Data Sources, and Software Constraints

In this section, each input parameter is presented in the order in which it appears on the HyperVentilate cards. When the software calls for a given input parameter, both the source of that parameter and the software constraints on the use of that parameter are addressed. The software constraints are also summarized in Table 4. As indicated earlier, HyperVentilate is available (with minor differences) for both Apple Macintosh and IBM-compatible systems. This evaluation will focus on the IBM-compatible version, but differences between the two versions will be identified. Table 5 presents a summary of the relative importance, effects, and realistic range of values of the different input parameters presented in this section.

Permeability (k)--

Permeability, expressed in darcys, is first required on Card 8 (Flow Rate Estimation). As mentioned earlier, Cards 8 through 18 ("Is Venting Appropriate?" stack) represent a cursory evaluation of SVE feasibility based on data acquired early in the site-investigation process. As such, permeability ranges entered on Card 8 (Flow Rate Estimation) are expected to be determined based on soil type identified from descriptions of soil boring logs or tank excavation sidewalls.

TABLE 4. HYPERVENTILATE INPUT PARAMETER LIMITATIONS

Input Parameter	Value Ranges							
	Card 8 (Flow Rate Estimation) (SCFM)	Card 10 (Vapor Concentration Estimation- Calculation) (mg/L air)	Card 13 (Is Soil Venting Appropriate?)	Card AP3 (Air Permeability Test - Instructions) (darcy)		Card H29 (Help: Boundary Layer Equations - Calculation)	Card H30 (Help: Low Permeability Lenses - Calculation)	Cards SD2-4 (System Design Stack)
	MAC/IBM	MAC/IBM	MAC/IBM	MAC	IBM	MAC/IBM	MAC/IBM	MAC/IBM
Permeability (k in darcys)	$10^{-3} \le k \le 10^{4}$	N/A	N/A	N/A	N/A	$0.14 < k < 6.6E+14$	N/A	$10^{-4} < k < 10^{4}$
Well Radius (R_W in inches)	$10^{-6} < R_W < R_I$	N/A	N/A	N/A	N/A	$10^{-14} < R_W < R_I$	$0.1 < R_W < R_I$	$0.01 < R_W < R_I$
Radius of Influence (R_I in feet)	$R_I > R_W$	N/A	N/A	$4 < R_I < 100$	4-100	$R_I > R_W$	N/A	$R_W < R_I < 4.48R_C$
Interval Thickness (H in feet)	$0.001 < H < 845$	N/A	N/A	N/A	N/A	$0.1 < H < 109$	N/A	$0.03 < H < 7000$
Well Vacuum (P_W in in. H_2O)	$0 < P_W < 406$	N/A	N/A	N/A	N/A	$0.095 < P_W < 406$	N/A	$0 < P_W < 406$
Temperature (T in ^{o}C)	N/A	$-65 < T < 218$	N/A	N/A	N/A	N/A	$-65 < T < 218$	N/A
Spill Mass (M_S in kg or lb)	N/A	N/A	$10^{-5} < M_S < 10^{7}$	N/A	N/A	N/A	N/A	N/A
Desired Remediation Time (in days)	N/A	N/A	$10^{-3} < Time < 10^{5}$	N/A	N/A	N/A	N/A	$10^{-6} < time < 10^{6}$
Radial Width of Contaminated Zone (in feet)	N/A	N/A	N/A	N/A	N/A	$R_W < R_C < 1,067$	$R_W < R_C < 1,102$	$0.19 < R_C < 2,573$

TABLE 5. PRACTICAL RANGE AND RELATIVE IMPORTANCE OF INPUT PARAMETERS

Input Parameter	Practical Range	Relative Importance	Effects
Permeability - k	0.01 to 10 darcys	V	Almost every output variable plus R_I
Well radius - R_w	2 to 24 inches	R	Minor effects on SVE efficiency
Radius of influence - R_I	10 to 20 feet	R	Depends on site K and P_w, 40 ft (12 m) good first estimate
Interval thickness - H	1 to 90 feet	I	Directly affects volumetrically based output calculations
Well vacuum - P_w	10 to 240 inches H_2O	V	Determines system flow rate and related output calculations
Temperature - T	0 to 30 °C	I	Constituent removal rate, critical volume, efficiency, etc.
Contaminant composition	(Data base input)	I	Vapor concentrations and removal rates
Spill mass - M_{spill}	1 to 10 kg	I	Remediation time
Remediation time - $\Delta\tau$	30 to 1,000 days	R	Dependent on other input variables used to evaluate SVE option cleanup time
Boiling point ranges - B_p	Actual values	R	Vapor pressure and distribution of constituents
Radial width of contaminant zone - R_c	0 to 160 feet	I	Spill mass calculations, minimum no. of wells, remediation time

Key: V = very important
I = important
R = required input

The software provides four default permeability ranges on Card 8 (Flow Rate Estimation). Each range is one order-of-magnitude in size. Given the lateral and vertical heterogeneity common to many sites, these ranges may often be too conservative. The user can enter alternative permeability ranges if the available default permeability ranges seem either too broad or too narrow for the site in question, or the soil type is not applicable to these default ranges. If the user's estimated permeability or hydraulic conductivity values are expressed in other units, the nomograph on Card H13 (Help: Soil Permeability) or the computational routine on Card H15 (Help: Unit Conversion [k and K]) can automatically convert the units and/or convert from saturated hydraulic conductivity values to corresponding permeability (intrinsic) values.

When large permeability values outside of the practical range are entered, the resulting flow rate values may exceed the size of the display field provided for them on the card. In these instances, the last digit(s) in the flow rate display are displaced to the next lower line, thereby disrupting the flow rate table. In the Apple Macintosh version, permeability values in the gravel range ($\approx 10^4$ darcys) can result in flow rate values larger than the available flow rate field. In the IBM-compatible version, the flow rate display field is larger, and this problem does not occur until the user enters a permeability value of 10^5 darcys. Because this is an unrealistic value, the problem should not occur for the majority of site permeability values.

The next opportunity to enter permeability values is on Card H29 (Help: Boundary Layer Equations - Calculation). This is the computational card for the "Help 6b, Liquid Layer" special condition (Card 19). At this point in the program, it is likely the user has refined estimates for unsaturated zone permeability. These refined estimates may come from additional drilling, field air permeability testing, or laboratory permeability testing. Although the software automatically defaults to the value range last entered on Card 8 (Flow Rate Estimation), the user can change these values to reflect new permeability estimates. Card H29 computes the relative efficiency of the vapor extraction system in the presence of a liquid hydrocarbon layer. Relative efficiency of the SVE system decreases with increasing permeability. In both versions of the software, the following fairly routine parameter values are entered on this card: (screened thickness = 10 feet, radius of influence = 50 feet, venting well radius = 4 inches, applied vacuum = 120 inches H_2O, and radial width of contaminated zone = 100 feet). The computations will provide unique relative efficiencies for permeability values ranging from 10^{-2} to 10^4 darcys.

The final location for entering permeability values is in the system design stack on Card SD3 (Design Input). Ideally, the values for k entered on this card have been derived from either field or laboratory permeability tests (discussed on Card 21 - Field Tests). The user can input a unique range of k values for each of the defined stratigraphic or contaminant layers that will provide the system designer with a more accurate projection of the number of wells needed to remediate each layer.

Well Radius (R_W)--

As with permeability, the venting well radius is first entered on Card 8 (Flow Rate Estimation) and carried through Card 18 ("Is Venting Appropriate?"). Most vapor extraction wells tend to be constructed of 2- to 4-inch inside-diameter PVC. Because the permeability of the sand- or gravel-packed annular space around the screened interval tends to be significantly more permeable than the formation material, the effective well radius can be considered equal to the borehole radius. This would include the well and sand- or gravel-packed annular space.

As a result, the R_W values that the user should enter on Card 8 (Flow Rate Estimation) will depend on the anticipated design diameter of the well and the drilling method to be used to install the venting well. Boreholes resulting from rotary drilling techniques usually have diameters that closely match the diameter of the drill bit. However, particularly in coarser materials, augered boreholes may have a diameter more than 2 inches larger than the outside diameter of the auger flight. Because the system design process has not begun at this point in the program, the user may use a range of values between 3 and 6 inches on Card 8 (Flow Rate Estimation).

Card H29 (Help: Boundary Layer Equations - Calculation) presents the next opportunity to enter a value for R_W. The software defaults to the value on Card 8 (Flow Rate Estimation); however, because system design may have progressed at this point, the user may have a better idea of the planned venting well radius.

The value R_W is also used in the "Help: Low Permeability Lenses - Calculation" special condition (Card H30). The user must enter the desired value. This card computes the diffusion-limited removal rate for contaminants from a low-permeability layer and the thickness of the low-permeability layer that is "dried out" or depleted of contaminants at various times, up to 1,080 days. R_W has no significant impact on this latter output parameter.

R_W is also entered on Card SD3 (Design Input) of the system design stack. The user can assign a unique venting well radius for each of the defined stratigraphic or contaminant layers and can use these tables to try a variety of venting well radii in each interval to quickly determine optimum well sizes. Conditions discussed regarding Cards 8 (Flow Rate Estimation) and H30 (Help: Low Permeability Lenses - Calculation) continue on Card SD3 (Design Input).

Radius of Influence (R_I)--

The radius of influence, as with permeability and the well radius, is initially required on Card 8 (Flow Rate Estimation). The radius of influence value entered on this card is carried through Card 18 ("Is Venting Appropriate?").

The radius of influence is defined in theoretical calculations as the radial distance from a vapor extraction well, where the gauge pressure measured in the soil during an air permeability test is approximately zero. This is generally identified as the radial distance at which the measurable vacuum is 1 inch H_2O or less. It should be noted that air pressure readings showing a measurable vacuum are no assurance of vapor flow or migration. The radius of influence is a dependent variable that is directly related to soil permeability, applied wellhead vacuum, and boundary conditions such as vertical airflow from the surface and preferential flow paths. Reported R_I values for permeable soils have generally been in the 40- to 120-foot range; tighter soils with lower permeability will cause R_I results to be in the 10-foot or lower range. Because soil vapor extraction pilot tests are rarely performed early in the investigation of a site, the user should experiment with the full range of typical values for this initial evaluation.

The radius of influence is subsequently used in Card AP3 (Air Permeability Test - Instructions) of the air permeability test stack. This card is reached by first clicking on the "Air Permeability Test" button on Card 21 (Field Tests) and then clicking on the "Test Instruction" button on Card AP1 (Air Permeability Tests). Card AP3 is intended to help the user estimate the duration of an air permeability test. First, the user must enter the estimated radius of influence. The card then calculates one pore volume of soil vapor within the radius of influence and the time required to extract one pore volume. The pore volume output box will only display five significant figures. As a result, large input values for R_I (>100 feet) for "Soil Layer Thickness" and "Air Permeability Test Flow Rate" will cause Pore Volume values to exceed the display field, and digits at the end of the value for Pore Volume will not be completely displayed. The user can check for significant figures outside of the display by deleting larger digits from the display box.

Card SD3 (Design Input) is the final location for entering a value for R_I. The user can enter a unique R_I for each of the defined stratigraphic or contaminant layers. For the system design, the user should have air permeability test data from each of these layers.

Interval Thickness (H)--

Interval thickness, as in the preceding input parameters, is first required on Card 8 (Flow Rate Estimation), and the value entered on this card is carried through to Card 18 ("Is Venting Appropriate?"). As used in the software, interval thickness refers to the smaller of either the length of the screened interval or the thickness of the permeable zone in question. Under ideal circumstances, these values will be the same. Typically, values for H will fall in the 5- to 20-foot range. Flow rates vary in direct proportion to changes in interval thickness.

Interval thickness can next be entered on Card H29 (Help: Boundary Layer Equations - Calculation). The software will use the value entered on Card 8 (Flow Rate Estimation) as a default value, or the user can enter a new value. The upper boundary of the relative efficiency output reaches 100% at a minimum interval thickness of 0.1 foot in medium sand and about 1 foot in clayey silt.

Interval thickness is entered separately for each contaminant or stratigraphic layer on Cards SD2 and SD3, respectively. On Card SD2 (Design Input), the user enters a value for H in the "Interval Thickness" column under "Contaminant Distribution" for each defined contaminant or stratigraphic layer. This interval thickness should correspond to the "Depth BGS" interval on the same card. On Card SD3 (Design Input), a value for H is entered in the

"Screen Thickness" column under "Extraction Well Construction" for each defined layer. The values for H entered on these cards should be the same for each layer in order to match the screened interval with the interval of concern. Based on the critical volume measurement (volume of air required to remove 1 gram of contaminant mass), a contaminant interval thickness larger than the screened interval increases the minimum number of wells required. With this design, the remediation of the contaminant interval not intersected by the well screen will depend on contaminant diffusion into the vapor flow path. Based on critical volume, use of a screened interval larger than the contaminant interval thickness will result in a smaller minimum number of wells because of an increased flow rate per vapor extraction well. The user should reduce the well "Efficiency" value entered on Card SD2 (Design Input), however, to accommodate the extraction of uncontaminated vapors with this design. As long as the two H values are changed together, the minimum number of wells based on critical volume will remain constant for any H value because changes in the "Calculated Total Contaminant Mass" are offset by corresponding changes in the "Flow Rate per Vapor Extraction Well." If the two H values (interval and screen thickness) are varied together, the "Flow Rate per Vapor Extraction Well" range is the only output parameter that is sensitive to change.

Well Vacuum (P_W)--

Well vacuum is the last input parameter to be entered on Card 8 (Flow Rate Estimation). The software provides six default well vacuums. In addition, the user can define a well vacuum that may be more appropriate in the field at the bottom of the column. The user should select a value such that $0 < P_W < 406$ inches H_2O. This maximum P_W corresponds to absolute ambient pressure (P_{atm}) or one atmosphere of pressure. All well vacuums appearing on Card 8 are carried to Card 12 (Maximum Removal Rate Estimates). On Card 13 ("Is Soil Venting Appropriate?"), the largest well vacuum from Card 8 (Flow Rate Estimation) is displayed, and the corresponding flow rates and maximum removal rates are used to determine the first estimate of soil venting. On Card 18 ("Is Venting Appropriate?"), however, the software uses a default P_W value of 120 inches H_2O, the associated range of flow rates, and maximum removal rates for determining the first estimate of the minimum number of wells required.

Well vacuum is used next on Card H29 (Help: Boundary Layer Equations - Calculation) to calculate well efficiency in the special liquid-layer condition. The user must enter the appropriate value for well vacuum.

In the system design stack, well vacuum is entered on Card SD2 (Design Input) and automatically displayed on Card SD3 (Design Input). Values for the minimum number of wells, based on critical volume, decrease with increasing well vacuum to reflect greater flow rates and estimated contaminant removal rates.

Temperature (T)--

Temperature, in degrees Celsius, is entered for the first time on Card 10 (Vapor Concentration Estimation - Calculation). The value for temperature entered on this card will be carried through Card 18 ("Is Venting Appropriate?"). This input parameter is defined as the temperature of the vapor in the subsurface. As shown in Equation 2 and on Card H22 (Help: About Calculation), while the user enters the temperature value in degrees Celsius, the software converts the entered value to degrees Kelvin for the calculations. On Card 10 (Vapor Concentration Estimation - Calculation), the calculated output parameters, the "Calculated Vapor Pressure," and the "Calculated Vapor Concentration" are affected by the value of T; the "Sum of Mass Fractions," however, is unaffected by the value for T used.

Temperature is also used in the "Help: Low Permeability Lenses - Calculation" special condition (Card H30). Process variables are input in Step 1 of Card H30. In Step 2 of Card H30, the user should input the values defined and computed on Card 10 (Vapor Concentration Estimation - Calculation).

Contaminant Composition--

Card 10 (Vapor Concentration Estimation - Calculation) provides four ways in which a user can define the composition of a contaminant mass at a given site:

- Default composition for fresh gasoline product,
- Default composition for weathered gasoline product,
- Results of boiling point distribution analysis, and
- Results of detailed gas chromatograph (GC) analysis.

The software provides default compositions for use with fresh and weathered gasoline products. These compositions are based on an analysis of two gasoline samples of 62 representative volatile and semivolatile compounds. The default fresh gasoline distribution is based on a sample of regular unleaded gasoline taken directly from a retail pump. The default weathered gasoline distribution is based on a sample of product recovered from the water table at a site in California. If the user is confident of the age of a site release, the default distributions can be an appropriate means of developing preliminary estimates of recovery rates. Once a site reaches the design stage, however, the user would be advised to revisit Card 10 with site-specific analytical data prior to using the system design stack. Based on these data, Card 10 (Vapor Concentration Estimation - Calculation) should be run by using one of the two approaches on the "Help: Compound List" card, which is accessed through the "Enter Distribution" button.

One approach is to conduct a boiling point distribution analysis. In this approach, a normal GC analysis is run on one or more samples. Rather than calculate the concentration represented by each peak on the GC scan, marker compounds are selected and peaks around these marker compounds are summed and reported as the marker compound. This results in a comparatively inexpensive, reasonably complete generalized profile of vapor composition. Once the laboratory results are available, the user clicks on the "How Do I Measure a Distribution" button located on the bottom left corner of Card 10 (Vapor Concentration Estimation - Calculation) to move to the "Help: How Do I Measure a Distribution?" card. The user then clicks on the "Calculate a Distribution" button located in the bottom right corner of this card. This moves the user to the "Help: Calculate a Distribution" card. The concentrations or areas associated with each of these marker compounds are then entered on this card, and the user clicks on the "Calculate" button. When the calculations are complete, the user clicks on the "Transfer Data to Distribution Card" button. This transfers the user and data to the "Help: Compound List" card. The user checks to ensure the sum of mass fractions equals or is close to one, and clicks on the "Return to Vapor Concentration Estimation Card" button to return to Card 10. Finally, the user clicks on the "Perform Calculations" button to obtain vapor pressure and vapor concentration values.

The second approach is to run a normal GC analysis on one or more samples, and input the analytical results by clicking on the "Enter Distribution" button on Card 10 (Vapor Concentration Estimation - Calculation). This transfers the user to the "Help: Compound List" card, where the user enters the mass fraction of each of the compounds in the analytical results. The user should always click on the "Sum" button to ensure that the sum of mass fractions comes close to equaling one. The user then clicks on the "Return to Vapor Concentration Estimation Card" button to return to Card 10 (Vapor Concentration Estimation - Calculation), and finally clicks on the "Perform Calculations" button.

If the GC analysis contains compounds that do not appear on this card, the user must quit the HyperVentilate file and click on the "Compound List Update" file icon. When the "Compound List Update" card shows on the screen, the user enters the chemical name, molecular weight, vapor pressure at 20 ^{o}C (in atm), and boiling point at 1 atm (in ^{o}C) for the new compound(s) and clicks on the "Insert Compound" button. When all new compounds have been added, the user quits the "Compound List Update" file and returns to the "Help: Compound List" card in the HyperVentilate file to enter the remaining mass fractions.

At a fixed temperature, higher proportions of lower boiling point compounds result in higher calculated vapor pressures and vapor concentrations (with the reverse being true for higher proportions of higher boiling point compounds). Neither extreme will affect the output displays on Cards 10 through 18.

Estimated Spill Mass (M_{Spill})--

The user needs to enter the estimated spill mass on Card 13 ("Is Soil Venting Appropriate?") to calculate a desired removal rate. This input can be one of the most difficult parameters to determine. Under ideal circumstances, the user will know the specific volume of the release and make a simple conversion to either kilograms or pounds. If the contaminant volume is not known, however, other methods are available for estimating the residual spill mass in the unsaturated zone.

The simplest method, at least within the framework of HyperVentilate, is to skip forward to the system design stack. Before clicking on the "Update" button, the user simply enters a radial area of contamination, contaminated interval thickness, and average contaminant concentration within the defined soil volume. The software computes the total residual contaminant mass in either pounds or kilograms; the equation $V = \pi r^2 h$ is used to determine soil volume and soil density in lb/ft^3. The user then enters this calculated value on Card 13.

Another method for estimating the residual spill mass is to use a software routine, such as SPILLCAD. SPILLCAD is a PC-based program designed to calculate the volume (as NAPLs) of hydrocarbons occurring both in the unsaturated zone and on the water table.

Desired Remediation Time--

The user enters the desired remediation time on Card 13 ("Is Soil Venting Appropriate?"). The value selected for this highly subjective input parameter can be driven by such factors as perceived potential impact of contaminant migration on downgradient receptors, demand for action from surrounding property owners, responsible party's and consultant/contractor's relationships with regulator, and responsible party's plans for the site.

A review of the output parameters (desired removal rate versus the range of maximum estimated removal rates) displayed on Card 13 ("Is Soil Venting Appropriate?") often leads to an obvious conclusion of SVE feasibility. The potential flexibility of the desired remediation time comes into play in the gray area when the "Desired Removal Rate" falls between the upper and lower estimates of the "Maximum Estimated Removal Rate." The desired remediation time often can be extended to increase the viability of SVE as a remedial alternative. If the desired remediation time cannot be changed because of external circumstances, the design variable's well radius or well vacuum on Card 8 (Flow Rate Estimation) may be manipulated to achieve the same end. This alteration, however, may require upgrading vapor effluent treatment capabilities. Inasmuch as this card represents the initial evaluation of SVE's potential effectiveness as a remedial technology at the subject site, there is still room for considerable flexibility in the selection of design criteria.

Although the desired remediation time is not entered on Card H30 (Help: Low Permeability Lenses - Calculation), it is useful to compare the projected time frame for remediation to the table displayed on this card. If the target of a site remediation is a low-permeability layer of known thickness, this table can be used to quickly confirm if the entire thickness of the target unit will be "dried out" and, if not, what the anticipated contaminant removal rate will be at that time.

In the system design stack, the desired remediation time is entered on Card SD4 (Design Input). This input parameter will have no bearing on either the "Flow Rate per Vapor Extraction Well" or the "Minimum Number of Wells Based on Area." Changes to the "Time for Clean-up" will have a direct, proportional impact on the estimated "Minimum Number of Wells Based on Critical Volume."

Boiling Point Ranges--

The author of the HyperVentilate users manual (Appendix B, pages 30 and 32), Dr. Paul Johnson, encourages the use of a boiling point distribution analysis as a means of acquiring a comparatively economical profile of the distribution of compounds in the initial subsurface contaminant mass. The software takes the same approach in estimating the residual distribution of compounds over the course of vapor extraction. The initial contaminant distribution is reduced to five boiling point ranges. The following default ranges can be found on Cards 16 (Model Predictions) and H27 (Help: Default Boiling Point Ranges):

(1) Propane to isopentane -50 to 28 ^{o}C
(2) Isopentane to benzene 28 to 80 ^{o}C
(3) Benzene to toluene 80 to 111 ^{o}C
(4) Toluene to xylenes 111 to 144 ^{o}C
(5) Xylenes to methylnaphthalene 144 to 250 ^{o}C.

The boiling points of all 62 compounds on the software's compound list are included in Table 6. This table shows that Boiling Point Ranges 1 and 2 contain only light-end aliphatics. Because state regulators and remedial contractors are particularly interested in benzene, toluene, ethyl benzene, and xylenes (BTEX) constituents, they have been highlighted with boldface type in the table. Benzene and toluene are among the compounds in Boiling Point Range 3, and Boiling Point Range 4 contains ethyl benzene, p-xylene, and m-xylene. Finally, Boiling Point Range 5 contains o-xylene and other compounds not easily recoverable through SVE. After the boiling point ranges have been established, the user clicks on the "Generate Predictions" button. When the screen displays Card 17, the user clicks on the "Import Data" button. This fills the "Saturated Vapor Concentration at time=0" and the "Min Volume to Remove >90% of Initial Residual" boxes and the table.

The default boiling point distribution ranges are effective under normal circumstances. The user may want to adjust those ranges, however, under certain circumstances. For instance, if the regulations in a given locality are tied to residual benzene concentrations, the user can alter the ranges so that the first range extends from -50 to 75 ^{o}C, the second range extends to 85 ^{o}C, and the rest are left unchanged. This change places benzene in the second boiling point range in which the critical volume of air is determined for benzene removal. After clicking on the "General Predictions Button" and the "Important Data Button," the user could scan the columns to 0, and obtain the volume of air moved per gram of residual contamination needed to achieve that goal from the first column. This volume of air may be as little as one-tenth the volume of air cited for removing >90% of the initial residual. If this value is inserted into the "Min Vol..." box on Card 17, an equal or greater reduction in the minimum number of wells required will result on Card 18 ("Is Venting Appropriate?"), thereby making SVE a far more attractive proposition for all concerned. The impact is the same in the system design stack.

Radial Width of Contaminated Zone--

The radial width of the contaminated zone is first required on Card H29 (Help: Boundary Layer Equations - Calculations) to calculate the effect of a liquid layer of petroleum hydrocarbons on recovery well efficiency. At this juncture, the distribution of contaminants at a site should be well delineated either through the use of a soil vapor survey or the drilling and installation of a plethora of borings and monitoring wells. Calculated well efficiencies increase with the radial width of the contaminated zone. Under conventional circumstances (15-foot screened interval, 40-foot radius of influence, 4-inch effective well radius, and a well vacuum of 120 inches H_2O), the upper boundary of relative efficiency reaches 100% in medium sand at a radial width of 1,067 feet.

TABLE 6. BOILING POINT DISTRIBUTION LIST OF COMPOUNDS

B.P. Range	Compound	Boiling Point
1	propane	- 42.07
	isobutane	- 11.40
	n-butane	- 0.50
	trans-2-butene	0.88
	cis-2-butene	3.70
	3-methyl-1-butene	20.00
	isopentane	27.85
2	1-pentene	29.97
	2-methyl-1-butene	31.16
	2-methyl-1,3-butadiene	34.00
	n-pentane	36.07
	trans-2-pentene	36.35
	2-methyl-2-butene	38.57
	3-methyl-1,2-butadiene	40.00
	3,3-dimethyl-1-butene	41.20
	cyclopentane	49.26
	3-methyl-1-pentene	51.14
	2,3-dimethylbutane	58.00
	2-methylpentane	60.27
	3-methylpentane	63.28
	n-hexane	68.95
	methylcyclopentane	71.80
	2,2-dimethylpentane	79.20
3	**benzene**	80.10
	cyclohexane	80.74
	2,3-dimethylpentane	89.80
	3-methylhexane	92.00
	3-ethylpentane	93.50
	2,2,4-trimethylpentane	99.24
	n-heptane	98.42
	methylcyclohexane	100.90
	2,2-dimethylhexane	106.84
	toluene	110.60
4	2,3,4-trimethylpentane	113.47
	2-methylheptane	117.70
	3-methylheptane	118.00
	n-octane	125.66
	2,4,4-trimethylhexane	126.00*
	2,2-dimethylheptane	127.00*
	ethyl benzene	136.20
	p-xylene	138.35
	m-xylene	139.10
	3,3,4-trimethylhexane	141.00*

(continued)

TABLE 6. (continued)

B.P. Range	Compound	Boiling Point
5	**o-xylene**	144.40
	2,2,4-trimethylheptane	147.00*
	n-nonane	150.80
	3,3,5-trimethylheptane	152.00*
	n-propylbenzene	159.20
	2,3,4-trimethylheptane	159.00*
	1,3,5-trimethylbenzene	164.70
	1,2,4-trimethylbenzene	169.35
	n-decane	174.10
	methylpropylbenzene	185.00
	dimethylethylbenzene	189.75
	n-undecane	195.90
	1,2,4,5-tetramethylbenzene	196.80
	1,2,3,4-tetramethylbenzene	205.00
	1,2,4-trimethyl-5-ethylbenzene	208.10
	n-dodecane	216.30
	naphthalene	218.00
	n-hexylbenzene	230.00*
	methylnapthalene	241.05

*This is an approximate value.

In the system design stack, the radial width of the contaminated zone is entered on Card SD2 (Design Input) as one of the values needed to calculate the total contaminant mass. Because the software uses the equation $V = \pi r^2 h$ to determine the volume of contaminated soil, the "Calculated Total Mass" increases by the square of any increase in the "Contaminant Distribution Radius."

SECTION 3

MODEL APPLICATION CASE STUDY

This section presents a sample application of HyperVentilate based on data obtained from a site in Minnesota. It provides examples of how to estimate and determine input parameters from data provided in a remedial investigation report (RIR), defines the steps involved in determining appropriate SVE estimates, and describes how to interpret results. This section also demonstrates the utility of HyperVentilate as an iterative analysis of SVE design in addition to its use as an instructional tool.

BACKGROUND

The Roseville Case Study (Kruger and Carson, 1991) was originally prepared as a demonstration of HyperVentilate for use by the Minnesota Pollution Control Agency (MPCA), Tank and Spill Section. The site was chosen for the study because it is generally representative of the gasoline-station-release scenario commonly faced by the MPCA staff. In this exercise, site data from MPCA files were used to illustrate the value of the software as both an SVE tutorial and an interactive screening tool to help MPCA case managers make better decisions about contractor proposals. The Roseville case also will be more instructive because an operating system at the site has yielded performance data that can be viewed in comparison to the SVE scenarios suggested by HyperVentilate.

This case study demonstrates the process of reviewing a remedial investigation/corrective action plan in order to determine input parameters for HyperVentilate. Initially, the software will help to examine the site from a very basic point of view; the view includes a number of simplistic, but important assumptions about subsurface conditions and contaminant behavior that are explained within the software. Because data needs for this part of the analysis are not rigorous, an iterative approach is encouraged. The software subsequently will be used to revise the initial assumptions, develop better input data, and refine the use of SVE at the site. Users should follow along with this discussion using their own HyperVentilate program and then enter the appropriate data in sequence. Similarly, the user should also read the software text in sequence for further clarification and understanding. Please note that many program inputs are presented in English units for ease of use. The user has a choice of using metric or English units for the outputs.

INITIAL ESTIMATES - IS SOIL VENTING APPROPRIATE?

The user should first review the RIR submitted by the contractor. As part of this review, the user should study the data necessary to run HyperVentilate from the RIR. Two key items needed from the RIR for this study are (1) a site plan showing the locations of wells and vapor monitoring probes as well as the extent of soil contamination (Figure 3) and (2) one or more good representative geologic cross sections with profiles of the distribution of soil contamination (Figures 4, 5, and 6). If the latter are not provided, they should be constructed from the raw data available.

Flow Rates

To begin the first interactive portion of the software program involving Flow Rate Estimation (Card 8), the following are needed:

- Air permeability data (in darcys) or a gross grain size estimate based on soil types that match one of four default categories (medium sand, fine sand, silty sand, or clayey silt) provided in the software,
- Well radius (the borehole radius is used because the packing material around the well is typically much more permeable than the soil formation),
- An estimate of the radius of influence of the extraction well,
- A measurement of the thickness of the screened interval (ideally, this will be the thickness of the contaminated zone), and
- If available, the anticipated well vacuum pressure.

As depicted in Table 7, the contractor has divided the soil profile into four units. The water table is located approximately 65 feet (19.8 m) below grade, below the silt layer. Hydraulic conductivity values from rising water level test data are also provided. Although not ideal, these data can be converted to equivalent permeability values in lieu of air permeability test data; however, they should only be considered representative of Unit 4, if at all.

TABLE 7. STRATIGRAPHY

Unit No.	Thickness (ft)	Lithology	Estimated Permeability (k) (darcy)
Unit 1	3 - 8	Surface Fill	—
Unit 2	45 - 50	Fine to Coarse Sand	—
Unit 3	3 - 5	Silt	—
Unit 4	15+	Fine to Coarse Sand (similar to Unit 2)	0.3 - 0.6

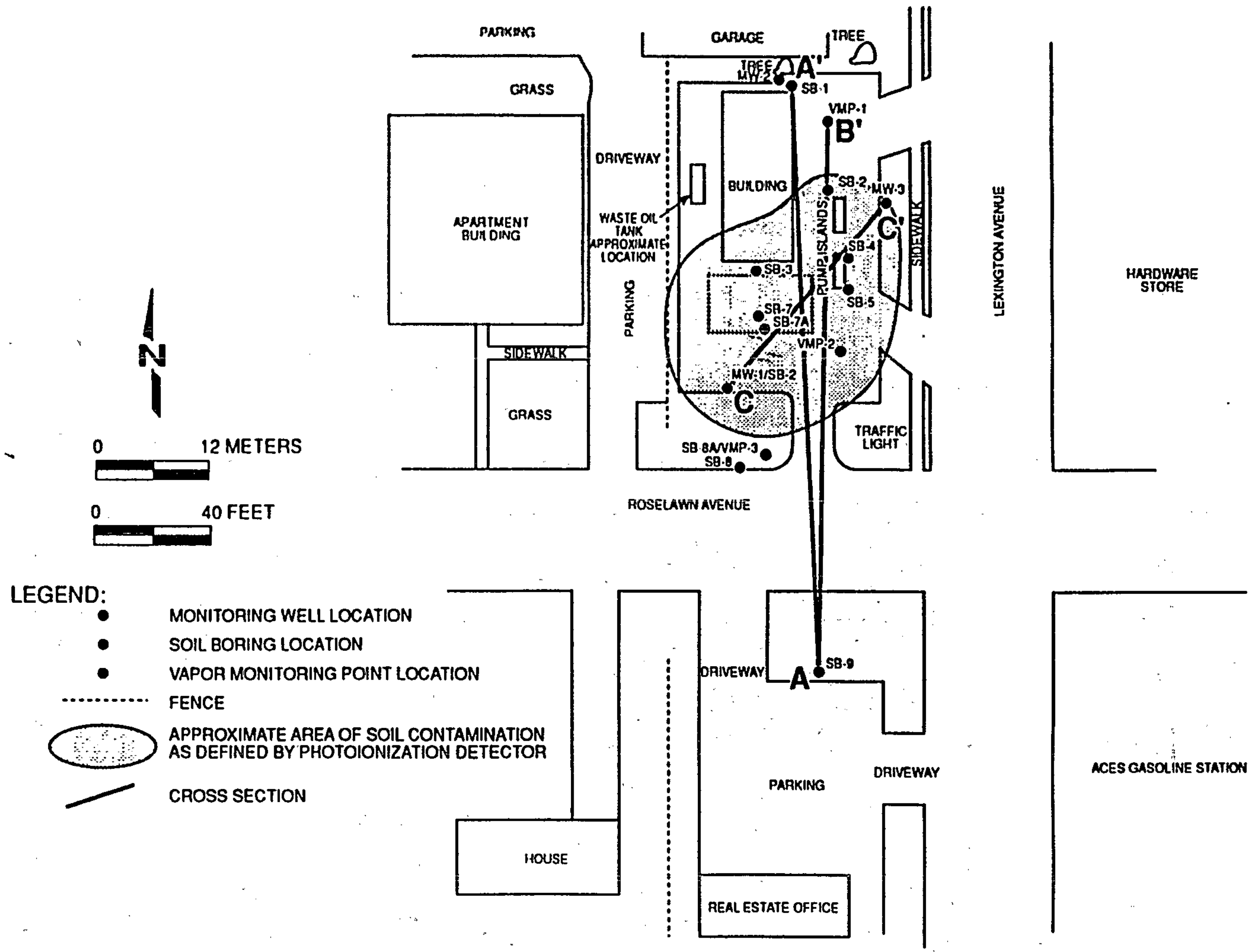


Figure 3. Zone of contamination at the Roseville, MN site.

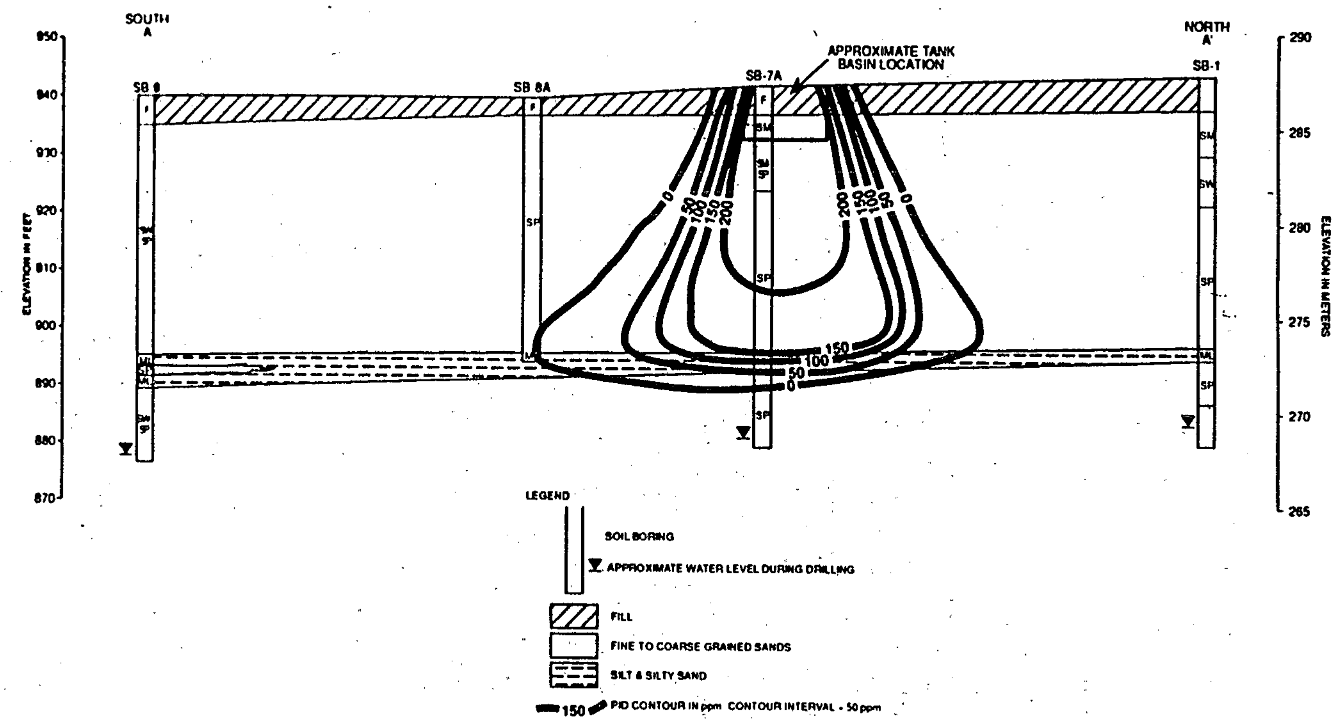


Figure 4. Cross section A - A'.

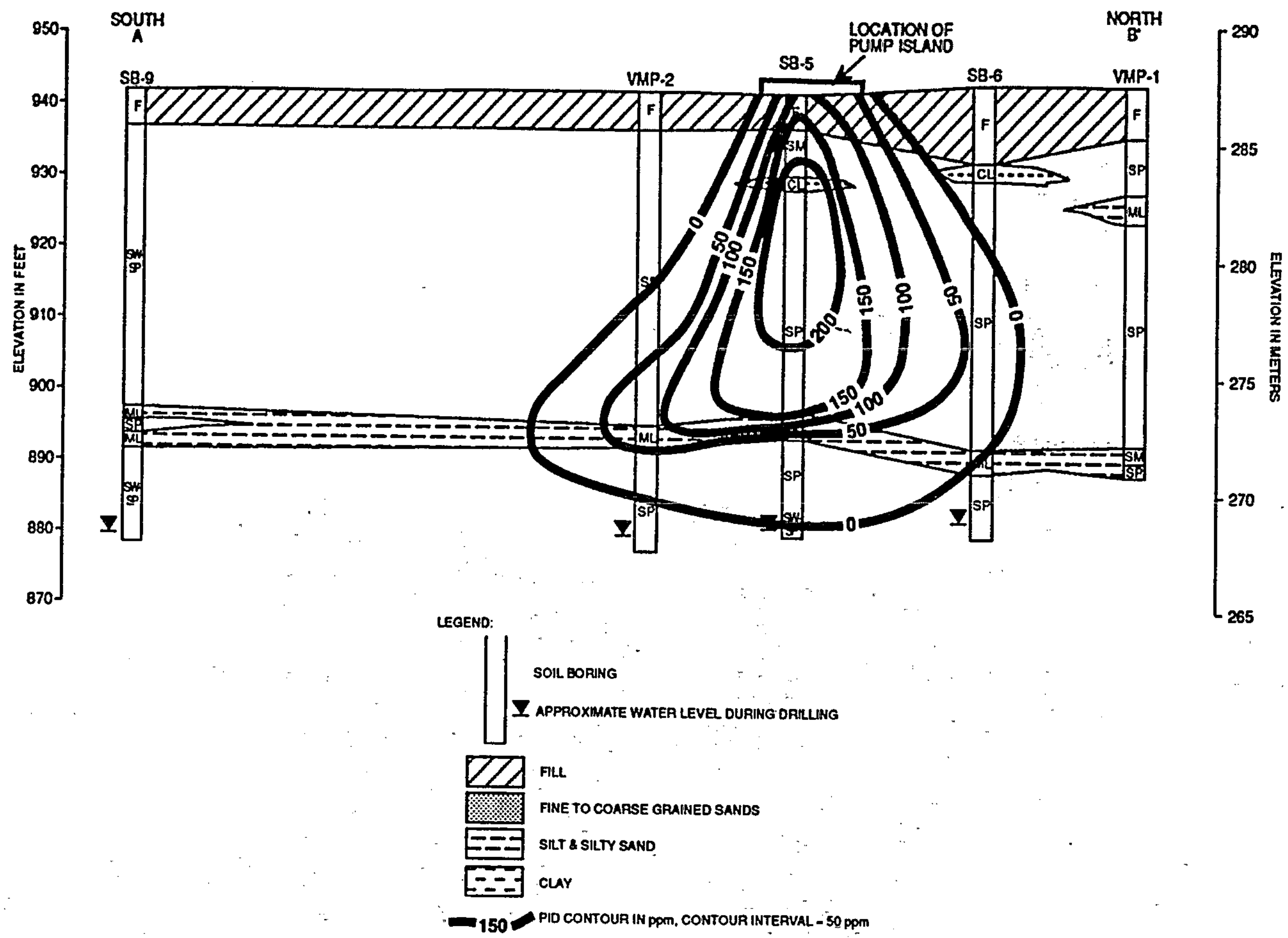


Figure 5. Cross section A - B'.

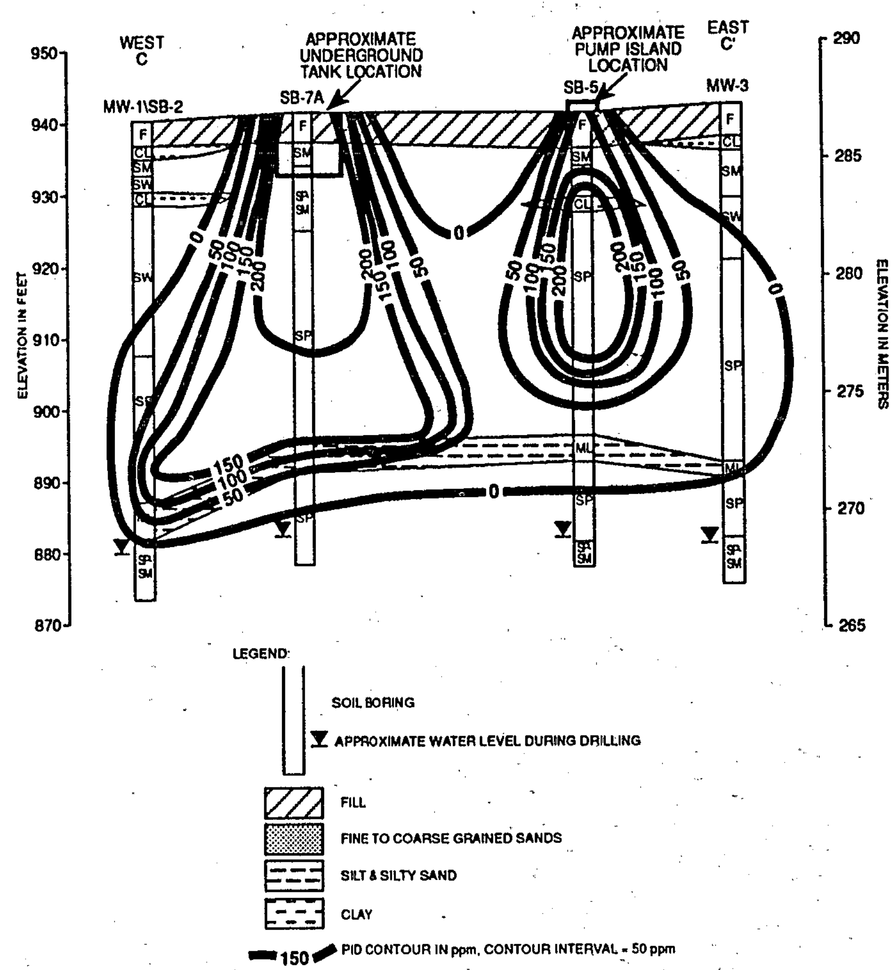


Figure 6. Cross section C - C'.

The geologic cross sections show that the majority of soil contamination is within Unit 2. Therefore, this unit will be the limiting zone and will be the focus of further interest. HyperVentilate can be used to determine a range of permeability values for Unit 2. The fine sand default value (1 to 10 darcys) will be used.

The contractor proposes the installation of both shallow and deep extraction wells screened within the upper and lower portions, respectively, of Unit 2. Combined, the screened depth intervals of the wells span most of Unit 2. The following additional Hyper-Ventilate input data are provided by the contractor's design plans including well schematics (Figures 7 and 8) and a proposed system layout (Figure 9):

- The borehole (well) radii are ~3.5 inches (8.9 cm).

- A minimum radius of influence of 20 feet (6 m) is implied by the proposed well spacing.

- The screened interval for both the shallow and deep wells combined is 35 feet (11 m).

- An anticipated well vacuum pressure is not specified.

Based on these data, HyperVentilate calculates Predicted Flow Rate Ranges of 2.3 to 469.3 SCFM for various well vacuum pressures (5 to 120 inches H_2O).

Vapor Concentration

The next step in the exercise is to calculate a "Vapor Concentration Estimation" (Card 10). Two new input parameters are needed:

- Soil vapor temperature in ^{o}C, and
- Contaminant composition or distribution.

Although neither of these parameters was specifically provided in the RIR, approximations can be made based on general knowledge of soil conditions and petroleum contaminant behavior. In addition, HyperVentilate provides two default contaminant distributions--"fresh" and "weathered" gasoline--just in case actual site-specific data are not initially available. Therefore, one can make the following generalizations:

- Ground temperature at depths below subsoil in midlatitude regions such as Minnesota is approximately 10 ^{o}C.

- Laboratory analytical results reported in the RIR showed that whenever BTEX was detected in soil (3 out of 14 samples), toluene and xylene concentrations greatly exceeded benzene concentrations. This relationship is more typical of a "weathered" gasoline than a "fresh" gasoline.

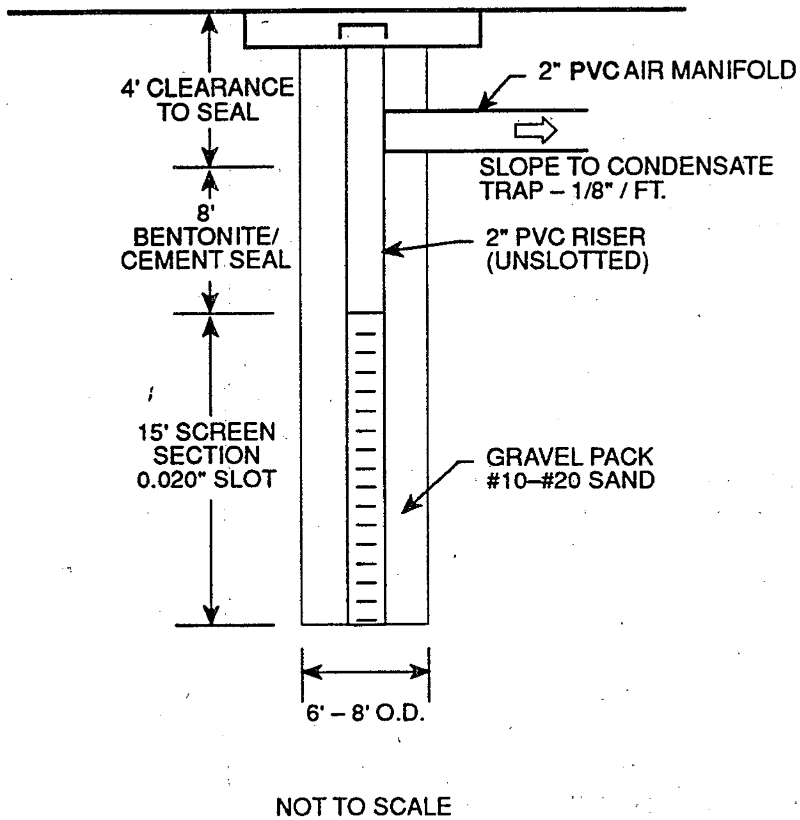


Figure 7. Shallow vapor extraction well schematic.

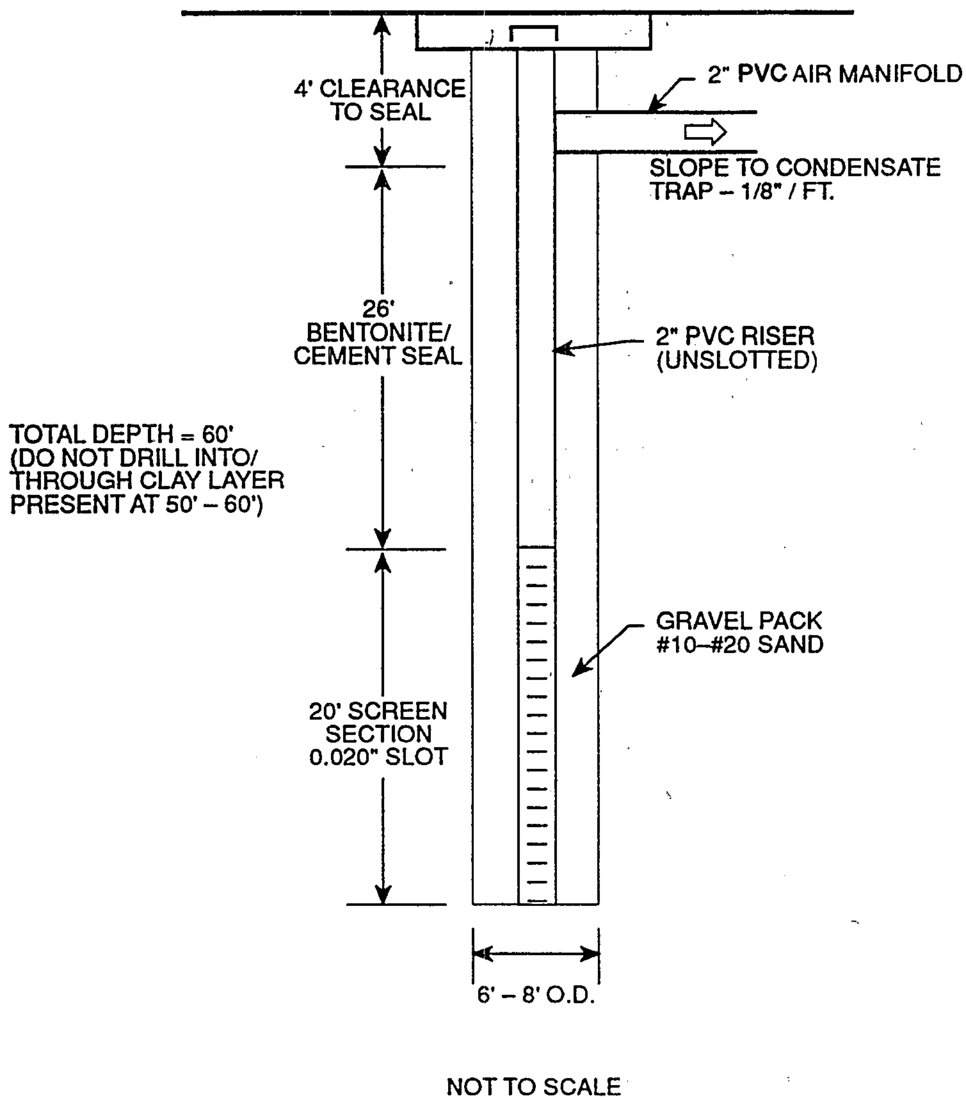


Figure 8. Deep vapor extraction well schematic.

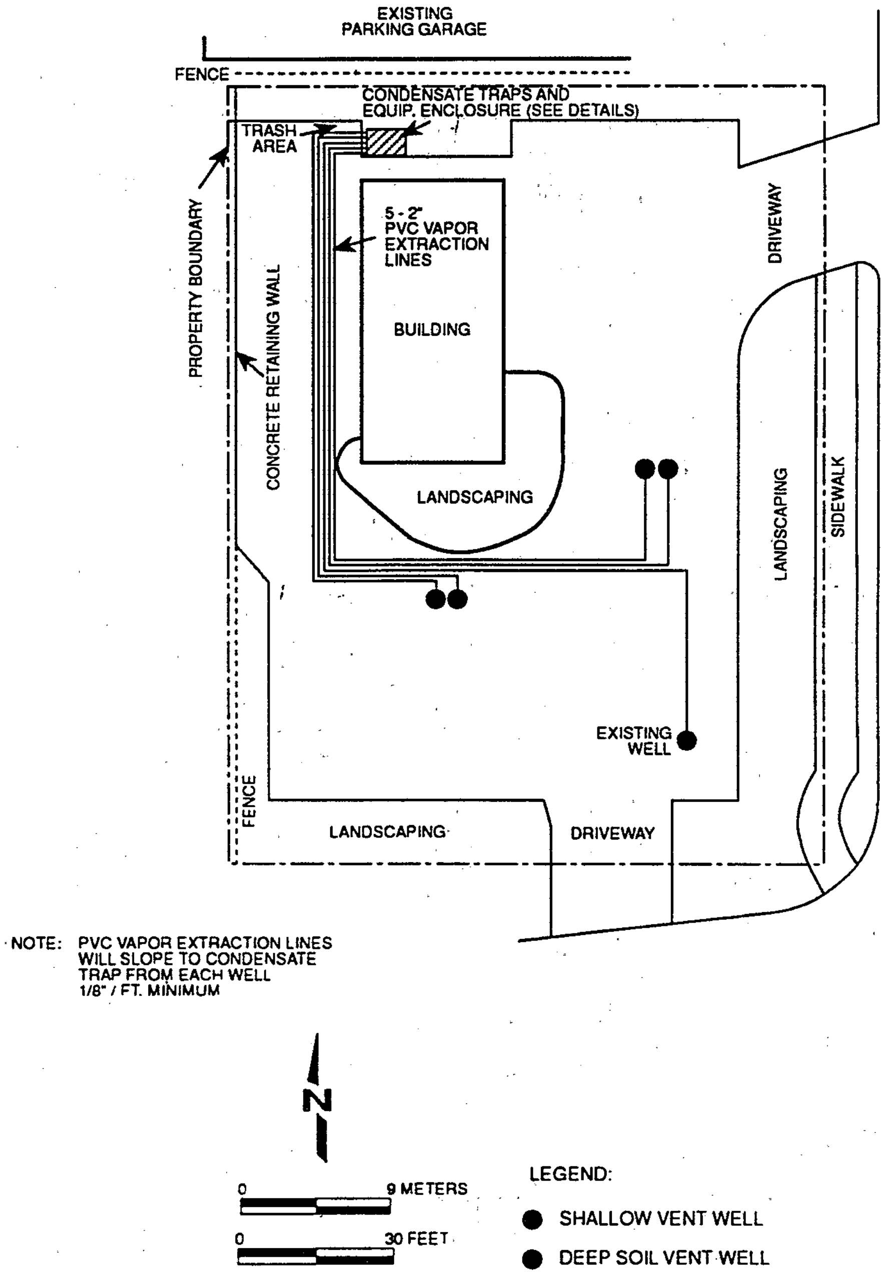


Figure 9. Vapor extraction system layout.

Performing the calculations using these parameters results in a "Calculated Vapor Pressure" of 0.04 atm and a "Calculated Vapor Concentration" of 142.7 mg/L. This estimate is constrained, however, by a lack of detailed information about the contaminant composition. The contaminant may, in fact, be a mixture of gasoline and other petroleum products or an older, more "weathered" product. These and other compositional factors can affect vapor concentration significantly.

Calculated Removal Rate

The predicted flow rate ranges and the calculated vapor concentration can now be used to calculate a "Removal Rate Estimation" (Card 12) for the idealized situation. The estimates suggest that a single well with a 35-foot (11-m) screened interval in Unit 2 would have a "Maximum Removal Rate" of 30 to 8,552 lb/day (13 to 3,874 kg/day) depending upon the vacuum applied (5 to 120 inches H_2O).

Desired Removal Rate

At this point in the exercise, one can begin to ask the question "Is Soil Venting Appropriate?" (Card 13). This is a very rough cut evaluation that depends not only on the "best-case," idealized estimates of contaminant removal rates, but also on two additional and very important input parameters:

- An estimate of the total contaminant or spill mass, and
- The amount of time available for cleanup.

In many situations, it can be very difficult to approximate or anticipate these figures with any reasonable accuracy. Neither of these parameters is provided in the RIR.

It is suggested that 1 year can be picked as an initial timeframe to begin the evaluation of the appropriateness of SVE. A revision of this figure may be warranted if subsequent analyses suggest that this timeframe is overly optimistic. A spill mass is calculated based on available information. Using the site plan (Figure 3) and cross sections (Figures 4, 5, and 6), one can estimate the radius and thickness of the contaminated zone as well as the average contaminant concentration in the zone. HyperVentilate can be used to calculate a total spill mass (Card SD2) based on the following input estimates:

- The maximum (96.5 feet [29.4 m]) and minimum (76.8 feet [23.4 m]) radial dimensions of the irregularly shaped contaminated area were averaged to give an estimated radius of 43.49 feet (13.26 m).

- The bulk of the contaminant mass is within Soil Units 1, 2, and 3 with a total combined interval thickness of ~58 feet (18 m).

- The average of all laboratory analytical results indicating detectable concentrations of total hydrocarbons as gasoline in soil within the contaminated zone is 542 mg/kg.

From these input parameters, one calculates a total spill mass of 19,840 lb (8,987 kg). Note that this is an estimate of the contaminant mass throughout the entire contaminated zone, not just the screened intervals of the proposed wells.

On the basis of the above inputs, one then calculates (Card 13) a "Desired Removal Rate" of 54.3 lb/day (24.6 kg/day). This value can be compared with the maximum removal rate range (at 120 inches H_2O well vacuum) and/or the calculated removal rate range at a design-specified well vacuum. If the desired rate is greater than the maximum or design rate, then one surmises that vapor extraction is probably not an appropriate remediation alternative. In the Roseville case, however, the desired rate is well within the calculated maximum range. Therefore, the application of SVE at this site should be further examined.

REFINED ESTIMATES - HOW APPROPRIATE IS SOIL VENTING?

The next sequence of calculations refines the estimates to determine vapor extraction feasibility. The first interactive portion of this sequence, "Model Predictions" (Card 16), allows a look at changes in residual contaminant composition that occur as a result of vapor recovery. The results provide more details on each progressive stage of the venting process as well as the amount of air that must be moved to accomplish each stage. Ultimately, HyperVentilate will determine a first approximation of the minimum number of wells needed to move the requisite air volume based on previously calculated flow rate ranges.

Critical Volume of Air

No new input parameters initially are needed for the "Model Predictions" (Card 16). The default boiling point ranges can be adjusted (Card H27), however, to include all BTEX constituents within Boiling Point Ranges 3 and 4. This adjustment will make it easier to estimate the point at which all BTEX is removed from the residual. Clicking on the "Generate Predictions" button starts the HyperVentilate computations. Results are then displayed (Card 17); the "saturated vapor concentration at time = 0 is 147.7 mg/L and the "minimum volume of air" estimated as necessary to remove 90% of 1 gram of the initial residual spill mass is 221 L-air/g-residual.

A comparison of Columns 1 and 3 in the table on Card 17 shows that the 221 L-air/g-residual value is more accurately described as the estimate for removing 94.3% of the original spill mass. A rough interpolation shows that only about 165 L-air/g-residual are needed to remove 90% of the original spill mass. By entering 165 L-air/g-residual in the minimum volume box, the user can evaluate a more optimistic estimate for achieving the >90% goal. Alternatively, if the objective were to remove all BTEX components, the user needs to find the minimum volume at which all of the Boiling Point Range 4 residual was removed. In this case, an even more optimistic value (56 L-air/g-residual) is required to remove those constituents.

Finally, a complete summary of the data and results is displayed (Card 18) and the user asks again, "Is Venting Appropriate?". The basis for the evaluation, as provided by HyperVentilate, is an estimate of the number of wells needed to achieve a >90% reduction of the total spill mass in the time desired. Note that this estimate is based on the most ideal circumstances. Nevertheless, it does give a qualitative sense of the feasibility of using vapor extraction at the site. On the basis of the default value of 221 L-air/g-residual (~94% removal), HyperVentilate estimates that 0.2 to 2 vapor extraction wells will be needed to complete remediation in 1 year. Remember that the range in the number of wells reported reflects the range in air permeability values at the default well vacuum of 120 inches H_2O. Alternatively, on the basis of the extrapolated value of 165 L-air/g-residual (~90% removal), HyperVentilate estimates that 0.15 to 1.5 vapor extraction wells are needed to accomplish remediation. If 100% BTEX removal is required and the user inputs 56 L-air/g-residual, an estimated 0.05 to 0.5 vapor extraction wells may only be needed to accomplish remediation in 1 year.

In all of these potential scenarios, the calculated results must be compared with practical considerations such as cost of equipment, available space, etc. In the Roseville case, the results look promising and SVE appears to be a viable option. If these calculated values do not seem practical or realistic, however, vapor extraction may not be an appropriate technology. Alternatively, the user can reevaluate SVE feasibility by revising the expectations of system performance and then recalculate the results. This iterative type of analysis is the key to using HyperVentilate effectively. The program can help the user to explore fully the limitations imposed by both site conditions and vapor extraction technology. "Other Considerations" suggested by the program continue that theme and help to evaluate special cases.

Special Case

The Roseville site exhibits characteristics of the contaminants within Soil Unit 3 under the special case for "Low Permeability Lenses." In this case, HyperVentilate allows an evaluation of the diffusion-limited vapor transport through a soil matrix. To perform the calculations for this case (Card H30), the following parameters must be recalled:

- Borehole (well) radius (3.5 inches [8.9 cm]),
- Radius of the contaminated zone (43.5 feet [13.3 m]), and
- Average concentration of residual contamination in soil (542 mg/kg).

In addition, values for contaminant molecular weight (81.3 g/mole), contaminant vapor pressure (31 mm Hg), and temperature (10 ^{o}C) can be directly imported from previous inputs (Card 10). HyperVentilate can then calculate estimates of gradual reductions in the rate of contaminant removal from the low-permeability lens and estimates of the thickness of low-permeability material that is gradually "dried" or stripped of contamination. The program estimates that the removal rate at Roseville will decline from 53.4 to ≈1.6 kg/day over a period of 365 days, with contamination removed from ≈14.1 feet [4.3 m] of low-permeability material. The full 5-foot (2-m) thickness of Unit 3 could be stripped of contaminants after ≈55 days. Thus, a gross estimate is provided of how removal rates in the low-permeability lens resulting from airflow in the overlying unit might compare with rates estimated for the overlying unit itself. Alternatively, a comparison could be made of removal rates from an imaginary well screened within the low-permeability lens.

Air Permeability Testing

Field tests to determine the soil's permeability to airflow are yet another step in the analysis of site conditions and the accuracy of the program input parameters (Cards AP2 through 4). HyperVentilate allows the user to evaluate air permeability test data easily and quickly (Card AP8). The program calculates permeability values using two methods. These methods are based on a governing equation that predicts a straight line for the logarithmic plot of subsurface pressure versus time. Method A relies on the premise that permeability is proportional to the slope A of the line. Method B relies on the premise that permeability is proportional to the y-intercept B (Cards AP5 through 7). The following parameters must be determined for both methods:

- Airflow rate of the test,
- Screened interval thickness for the test extraction well,
- Radial distances from the subsurface pressure monitoring locations to the extraction well, and
- Air pressure at each monitoring location at various times throughout the test.

Method B can be used when either the airflow rate or screened interval thickness is uncertain.

Actual Test Data

Air permeability tests at the Roseville site were conducted with groundwater monitoring well MW-1 as the extraction well. Monitoring locations included groundwater monitoring wells MW-2 and MW-3 and soil vapor monitoring points VMP-1, VMP-2, and VMP-3 (see Figure 3). Actual test data are provided in Table 8. Unfortunately, the screened intervals for these monitoring locations were not all equivalent. The three soil vapor monitoring points were all screened in Unit 2. Therefore, airflow between MW-1 and these vapor monitoring points had to pass through Unit 3, the low-permeability lens. As a result, permeability estimates based on data from the soil vapor monitoring points cannot be considered representative of any one unit. Alternatively, all three groundwater wells were screened within soil Unit 4. Data from these monitoring locations can be considered representative of Unit 4; however, Unit 2 is the unit of interest. As a compromise, one can assume that because the

TABLE 8. AIR PERMEABILITY TEST DATA

Flow: 57 SCFM

Temp.:
wet bulb = 18°C
dry bulb = 27°C

Test Readings

	Start 1					Start 2								
Time (hr/min)	14:30	14:35	14:50	14:55	15:00	15:07	15:27	15:37	15:47	16:07	16:37	17:07	17:37	17:57
Elapsed Time (min)	0	5	10	15	20	0	20	30	40	60	90	120	150	170
Vent ID#														
VMP-1	0.00	0.00	0.00	0.30	0.25	0.25	0.30	0.25	0.20	0.18	0.18	0.10	0.08	0.07
VMP-2	0.00	0.00	0.00	0.25	0.25	0.25	0.23	0.23	0.18	0.16	0.12	0.06	0.05	0.07
VMP-3	0.00	0.00	0.00	0.26	0.22	0.20	0.22	0.22	0.18	0.14	0.16	0.10	0.07	0.04
MW-2	0.00	0.00	0.00	0.38	0.38	0.31	0.05	0.04	-0.02	-0.08	-0.16	-0.26	-0.35	-0.41
MW-3	0.0	0.00	0.00	0.38	0.31	0.38	0.15	-0.07	-0.21	-0.28	-0.32	-0.55	-0.60	-0.65

lithologic descriptions of Units 2 and 4 are essentially the same, the Unit 4 permeability values can be used for Unit 2.

It is important to run field tests long enough to obtain air permeability values for all types of soils at the site. The extraction of one complete pore volume from the zone of interest generally is sufficient. HyperVentilate conveniently allows the user to calculate the approximate time needed (Card AP3). The user needs the following information to perform the calculation:

(1) Thickness of the soil layer of interest or the extraction well screened interval (10 feet [3 m]),

(2) Estimated radius of influence of the extraction well (~20 feet [6 m]), and

(3) Air permeability test flow rate (57 SCFM).

As a result, one obtains a "pore volume" of 3,768 ft^3 and a "time to extract a pore volume" of 0.05 day (72 minutes). Test data provided show that only one test, No. 2, was run for a sufficient amount of time (170 minutes).

Air Permeability Calculations

After the data are examined to determine any potential problems in its collection, the user is now prepared to calculate air permeability values for Unit 4 (Card AP8). These values are determined from Table 8 data, Items 1 through 3 previously listed, and the following calculations:

(4) Radial distance from MW-1 to MW-2 (109.44 feet [33.36 m]),
(5) Radial distance from MW-1 to MW-3 (86.16 feet [26.26 m]), and
(6) Subsurface pressure versus time data (Table 8).

The resulting air permeability values calculated by Method A are ≈237 darcys and 149 darcys for MW-2 and MW-3, respectively. Results calculated by Method B are 55 darcys and 31 darcys, respectively. These data result in a 0.98 coefficient of correlation with the theoretical pressure drawdown curve (Card AP9). An average range of these values, 193 to 43 darcys, will be used in further calculations.

System Design - Number of Extraction Wells

This final interactive sequence of HyperVentilate provides an overview of all aspects of vapor extraction system design and allows further refinement of the estimated "Number of Extraction Wells" (Card SD1) that are likely to be needed to achieve the specified remediation goals. Inputs and best estimates of critical design parameters for each soil unit can be organized in a series of descriptive tables (Cards SD2 through 4). Up to this point, only Unit 2 has been considered; therefore, the steps previously described for the other soil units must be repeated. This iteration will require that the calculated spill mass be proportioned according to the thickness and average radius of the contaminated zone within each specific soil unit. In addition, because the contractor has proposed both shallow and deep extraction wells within Unit 2, that distinction will be made for the final tabulations. Figures 10, 11, and 12 present the appropriate data inputs for each of the soil units. Note that the total calculated spill mass of 12,224 lb (5,539 kg) is now substantially less than the initial estimate used in Card 13. This discrepancy highlights again the need for sufficient data concerning the distribution of residual contaminants.

The user is now ready to calculate final estimates of the minimum number of extraction wells. For illustration purposes, separate runs are made with each of the critical air volumes (221, 165, and 56 L-air/g-residual) previously calculated (Card 17). A 50% efficiency value is assumed in all cases. The results of each of these trial runs are shown in Table 9.

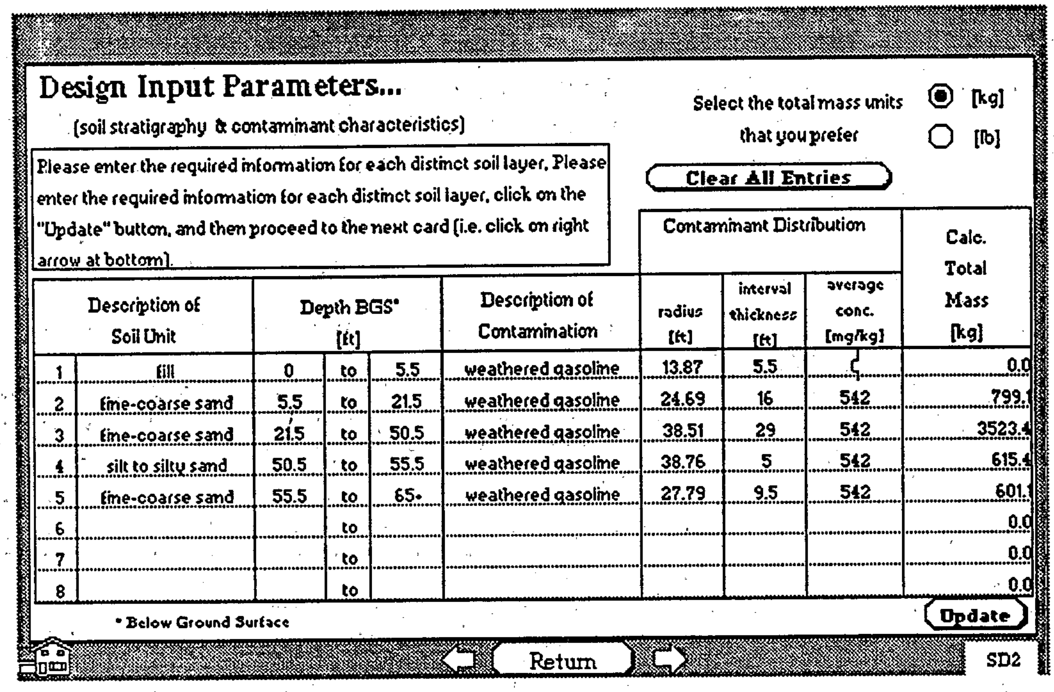
TABLE 9. MINIMUM NUMBER OF WELLS BASED ON CRITICAL VOLUME OF AIR SCENARIOS

Critical Volume of Air (L/g)	Well Vacuum (in. H_2O)	Lithologic Unit	Flow Rate (SCFM)	Number of Wells Based on Critical Volume
221	5	Upper Unit 2	30 - 134	0.2 - 0.8
		Lower Unit 2	30 - 134	0.6 - 2.6
165	5	Upper Unit 2	30 - 134	0.1 - 0.6
		Lower Unit 2	30 - 134	0.4 - 1.9
56	5	Upper Unit 2	30 - 134	0.0 - 0.2
		Lower Unit 2	30 - 134	0.1 - 0.7

The net result is an estimation, based on the critical volume of air constraint, that at least 1 to 3 extraction wells would be necessary to remediate the site effectively in 1 year. As depicted in Figure 9, the contractor proposed four wells, arranged in two pairs of deep and shallow wells. The HyperVentilate-derived minimum number of wells indicates that this approach could be successful; however, the user should consider that one to three wells is a "best-case" estimate and that more than 1 year may be required for the proposed design to achieve complete removal of all but the most volatile fraction of the contaminant mixture.

System Performance

The MPCA eventually approved the construction and operation of a vapor extraction system at the Roseville site with only minor modifications to the proposed design. MPCA personnel have provided system performance data that presents an interesting and instructive critique of the HyperVentilate site review process described. These data covered the first 11



Design Input Parameters...

(soil stratigraphy & contaminant characteristics)

Select the total mass units that you prefer ◉ [kg] ○ [lb]

Please enter the required information for each distinct soil layer. Please enter the required information for each distinct soil layer, click on the "Update" button, and then proceed to the next card (i.e. click on right arrow at bottom).

Clear All Entries

	Description of Soil Unit	Depth BGS* [ft]			Description of Contamination	Contaminant Distribution radius [ft]	interval thickness [ft]	average conc. [mg/kg]	Calc. Total Mass [kg]
1	fill	0	to	5.5	weathered gasoline	13.87	5.5		0.0
2	fine-coarse sand	5.5	to	21.5	weathered gasoline	24.69	16	542	799.1
3	fine-coarse sand	21.5	to	50.5	weathered gasoline	38.51	29	542	3523.4
4	silt to silty sand	50.5	to	55.5	weathered gasoline	38.76	5	542	615.4
5	fine-coarse sand	55.5	to	65	weathered gasoline	27.79	9.5	542	601.1
6			to						0.0
7			to						0.0
8			to						0.0

* Below Ground Surface

Update

Return

SD2

Figure 10. System design card 2

Design Input Parameters...

Please enter the required information for each distinct soil layer, and then proceed to the next card.

Note: - click on any table heading to get more info
- use arrow key to move between cells

- Medium Sand
- Fine Sand
- Silty Sand
- Clayey Silts

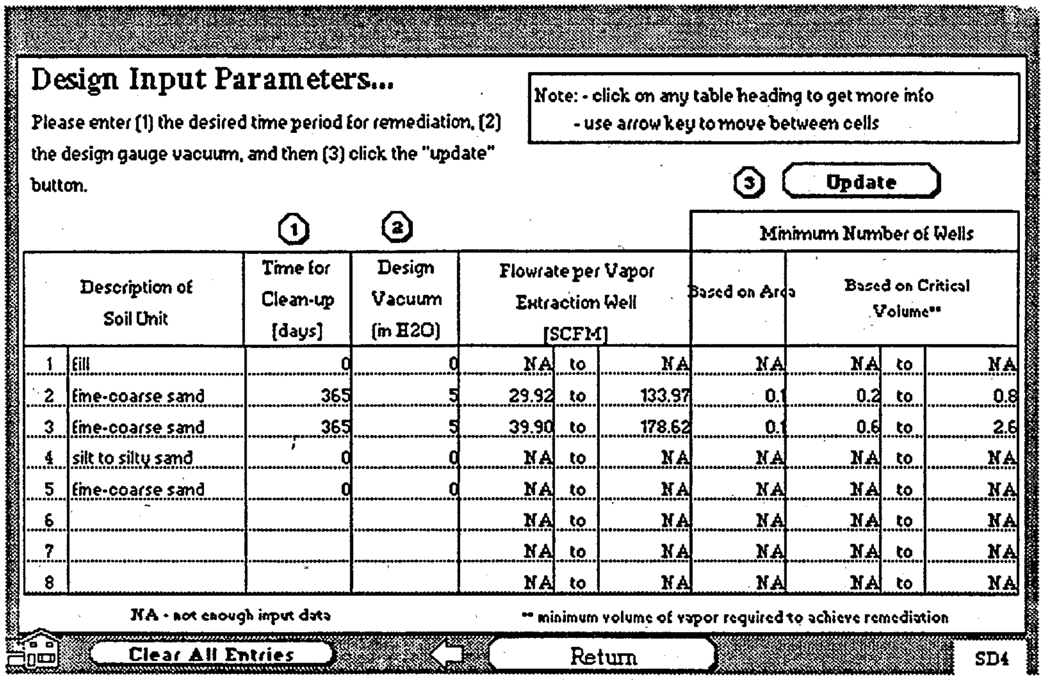
	Description of Soil Unit	Permeability* [darcy]			Design Vacuum (in H2O)	Extraction Well Construction: well radius [in]	screen thickness [ft]	radius of influence [ft]	Critical Volume of Air** [L/g]	Efficiency [%]
1	fill	0	to	0	0	0	0	0	0	0
2	fine-coarse sand	43	to	192.5	5	3.5	15	110	221.5	50
3	fine-coarse sand	43	to	192.5	5	3.5	20	110	221.5	50
4	silt to silty sand	0	to	0	0	0	0	0	0	0
5	fine-coarse sand	0	to	0	0	0	0	0	0	0
6			to							
7			to							
8			to							

* Enter or choose from list at top right

** minimum volume of vapor required to achieve remediation

Clear All Entries | Return | SD3

Figure 11. System design card 3



Design Input Parameters...

Please enter (1) the desired time period for remediation, (2) the design gauge vacuum, and then (3) click the "update" button.

Note: - click on any table heading to get more info
- use arrow key to move between cells

(3) Update

	Description of Soil Unit	(1) Time for Clean-up [days]	(2) Design Vacuum (in H2O)	Flowrate per Vapor Extraction Well [SCFM]			Minimum Number of Wells: Based on Area	Minimum Number of Wells: Based on Critical Volume**		
1	fill	0	0	NA	to	NA	NA	NA	to	NA
2	fine-coarse sand	365	5	29.92	to	133.97	0.1	0.2	to	0.8
3	fine-coarse sand	365	5	39.90	to	178.62	0.1	0.6	to	2.6
4	silt to silty sand	0	0	NA	to	NA	NA	NA	to	NA
5	fine-coarse sand	0	0	NA	to	NA	NA	NA	to	NA
6				NA	to	NA	NA	NA	to	NA
7				NA	to	NA	NA	NA	to	NA
8				NA	to	NA	NA	NA	to	NA

NA - not enough input data

** minimum volume of vapor required to achieve remediation

Clear All Entries

Return

SD4

Figure 12. System design card 4

months of system operation, ending December 20, 1991. As of September 1992, the system was still operating. During the reporting period, the system flow rate was maintained at 140 to 190 SCFM, which was somewhat higher than the range used in the HyperVentilate estimate. The removal rate, however, declined from 469 to 5.9 lb/day. Based on the HyperVentilate analyses, a removal rate of at least 30 lb/day was necessary to achieve full remediation within the 1 year desired. Actual system removal rates decreased below this desired level after only 17 days of operation. This illustrates the importance of viewing HyperVentilate estimates as "best-case" scenarios.

As of the final available monitoring report, a total of 7,369 lb of hydrocarbons (gasoline) had been recovered. Spill mass estimates between 12,225 and 19,840 lb were used in the HyperVentilate analyses. System performance results indicated that between 37 and 60% of the calculated spill mass was removed in 11 months. Once again, this points out the importance of sufficient and good quality data for estimating spill mass prior to initiation of vapor extraction system planning. Otherwise, it is difficult to design the system appropriately and measure success as remediation progresses.

At the start of system operation, the effluent benzene concentrations were reported to be 180 ppmv. The concentrations had decreased to 1 ppmv, however, by the end of the reporting period. The HyperVentilate Model Predictions (Card 17) apparently show that virtually all of the first two Boiling Point Range compounds (propane to benzene) had been removed by that point. HyperVentilate indicates that contaminant removal will be less efficient as system operation continues. The MPCA depicted this phenomenon in a graphical plot of total hydrocarbon removal as a function of time. The plot is very steep in slope during the first 20 days of system operation and then becomes fairly gently sloped, averaging about 330 lb/month for the remainder of the reporting period.

These monitoring data generally indicate that actual system performance is lagging behind the "best-case" scenarios suggested by the HyperVentilate analysis despite operation at significantly higher flow rates than those used in the software calculations. Working back through the software with this hindsight might point to design changes and or operational changes that could be made to improve performance or increase efficiency. For instance, after removal of the initial vapor-phase contaminant concentrations in the unsaturated zone, flow rates could have been slowed down because they apparently greatly exceeded the ability of residual contaminants in the vadose zone to re-establish equilibrium conditions. Similarly, HyperVentilate hindsight can suggest areas where important details may have been overlooked in the system planning and design stages or where information was insufficient to adequately anticipate system performance. For instance, the residual contaminant mass at the Roseville site may have been significantly more degraded or "weathered" than the "weathered" gasoline used by default in the software (i.e., volatiles comprised a lesser fraction of the contaminant mixture at the outset). Therefore, a more qualitative and quantitative analysis of the contaminant mixture probably should have been obtained as part of the contractor's feasibility analysis.

In general, HyperVentilate can be an instructive, functional tool in the critical analysis of a proposed vapor extraction system design. Not only are the important concepts, approaches, processes, and equipment described in an overview along with the tutorial sequences of the program, but the interactive sequences help to direct and expedite a focused iterative review process. Further, the program identifies specific data needs that are critical to good planning and appropriate design and operation. Once a system is deployed, HyperVentilate can continue to be used to troubleshoot performance relative to a standard of what is possible under ideal circumstances. Most importantly, it can provide a useful frame of reference for contractor/site manager discussions and perhaps, as a result, increase their system knowledge.

SECTION 4

MODEL ANALYSIS

A modeling analysis of HyperVentilate was conducted to address two considerations: (1) variations in output parameters were identified over a range of input parameter values, and (2) the sensitivity of each output parameter to changes in input parameter values was addressed. The purpose of this analysis was to identify those site conditions and system design considerations that most strongly affect the potential success of a vapor extraction system at a given site and to identify those parameters over which a system designer can exert some measure of control. This section presents a discussion of these two modeling analyses.

PARAMETER RESPONSE TEST

The parameter response test was conducted to ensure that accurate solutions are generated for all of the equations used in the software. For each parameter analysis, the target input parameter was varied over a sufficient range of values to allow an observable trend in the output parameters. All other input parameters were held constant. The results presented in the tables and text are rounded off. The value for the minimum number of wells was set at the next whole integer.

In this exercise, the following baseline input parameter values were selected to reflect "average" site conditions:

• Permeability	10 darcys
• Venting Well Radius	4 inches
• Radius of Influence	40 feet
• Interval Thickness	10 feet
• Extraction Well Vacuum	120 inches H_2O
• Temperature	20 ^{o}C
• Contaminant Composition	"Fresh" Gasoline
• Estimated Spill Mass	10,000 kg
• Desired Remediation Time	100 days
• Radius of Contamination	60 feet
• Average Contaminant Concentration (in soil)	1,000 mg/kg
• Contaminant Molecular Weight	65 g/mole

• Contaminant Vapor Pressure	366 mm Hg/0.482 atm
• Air Permeability Test Flow Rate	120 SCFM
• Monitoring Point Distance	50 feet
• Critical Volume of Air	37 L/g
• Efficiency	50%

"Is Venting Appropriate?" (Cards 8 through 18)

Permeability--

Permeability was the first parameter tested. As shown in Figure 13, there is essentially a one-to-one correspondence between changes in permeability and changes in flow rate and maximum removal rate. This relationship is expected based on Equation 2. There is an inverse relationship between permeability and the minimum number of wells estimated on Card 18 ("Is Venting Appropriate?"): the number of wells required is reduced by a factor of 10 with every order-of-magnitude increase in permeability. The relationship between permeability and these output parameters is intuitive. Increased permeability allows for greater flow rates, thereby resulting in higher removal rates and the need for fewer wells to achieve the desired result in a fixed amount of time. Subsurface permeabilities at a UST site are generally not applicable to other situations.

Well Radius--

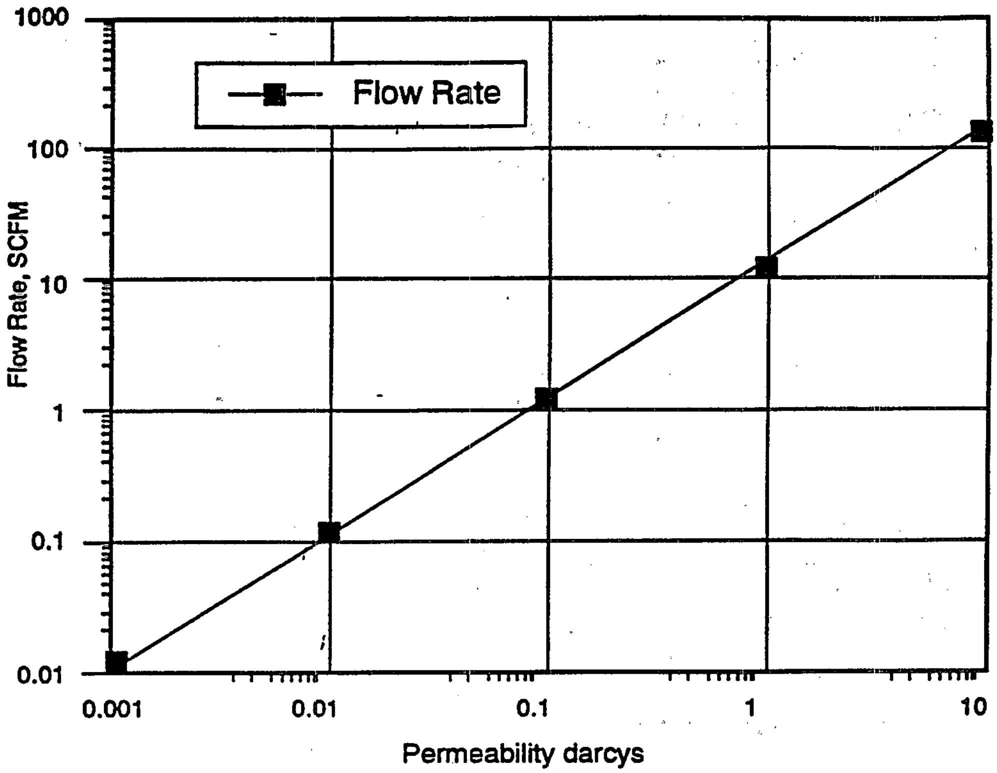
Following permeability testing, the venting well radius was varied. As shown in Figure 14, over an input parameter of 0.25 to 16 inches, flow rate increases by an average factor of 1.16 for every doubling of the venting well radius. Over the range of input parameters used, this factor increases from 1.16 to 1.26 as a natural logarithmic function (see R_W in Equation 2). Based on the range of well radius values used, the minimum number of extraction wells required remains at one. An increase in the radius of the extraction well will result in a slight increase in the flow rate, thus decreasing the time required for remediation. This may result in considerable savings in operation and maintenance costs, depending on the time required to complete remediation.

Radius of Influence--

Radius of influence was the next input parameter tested. Results are shown in Figure 15. Over the range of 10 to 160 feet, flow rate decreased by an average factor of 0.84 for every doubling in the estimated radius of influence. The minimum number of wells required remained at one. The radius of influence is dependent on the air permeability of the site subsurface and, to a lesser extent, the vacuum applied to the vapor extraction well. Larger radii of influence reduce flow rates by distributing the applied well vacuum over a larger volume of material. Although additional wells may be required for sufficient coverage, practitioners may wish to constrain the radius of influence at a site through the use of air inlet wells in order to enhance well efficiency.

Interval Thickness--

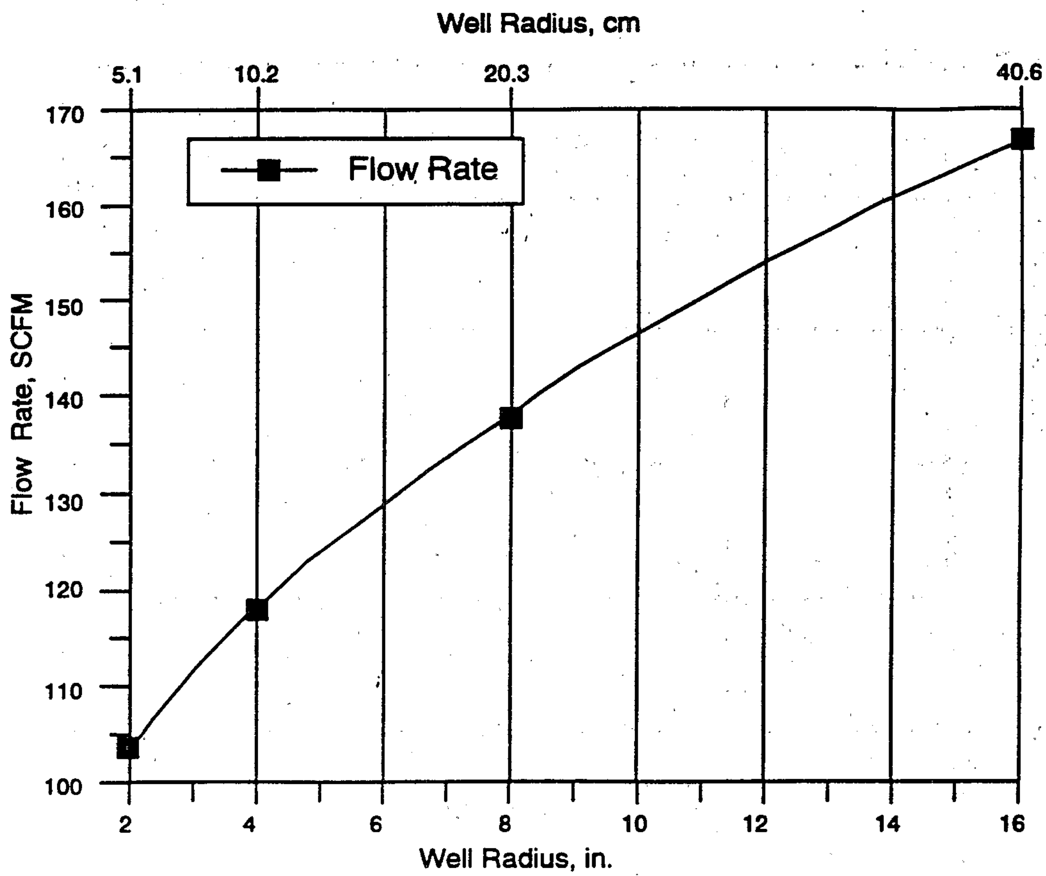
The final input parameter tested on Card 8 (Flow Rate Estimation) was interval thickness. As shown in Figure 16, flow rate doubles with each doubling of the interval



Permeability (darcys)	Flow Rate (SCFM)	Min. No. of Wells
0.001	0.012	6348
0.01	0.12	529
0.1	1.2	54
1.0	11.8	5
10.0	118	0.5

Figure 13. Relationship between permeability and flow rate.

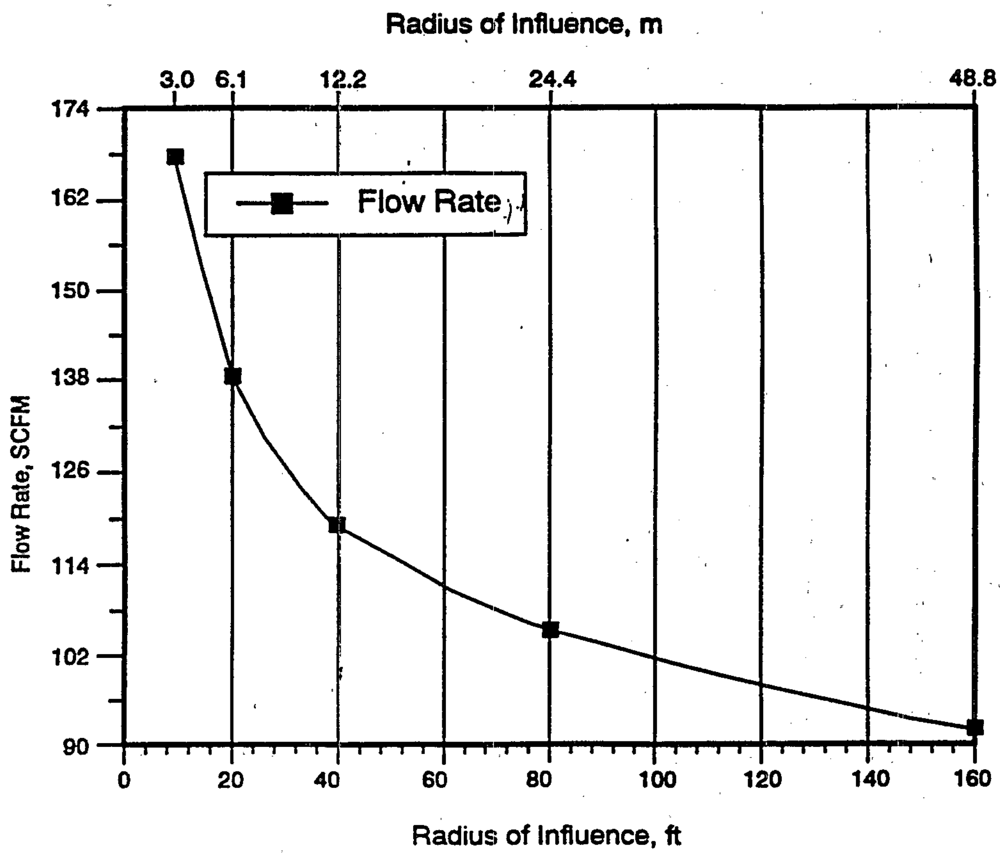
perm/gwts/drw/pc



Well Radius		Flow Rate (SCFM)
cm	in.	
5.1	2.0	103
10.2	4.0	118
20.3	8.0	138
40.6	16.0	166.7

Figure 14. Relationship between well radius and flow rate.

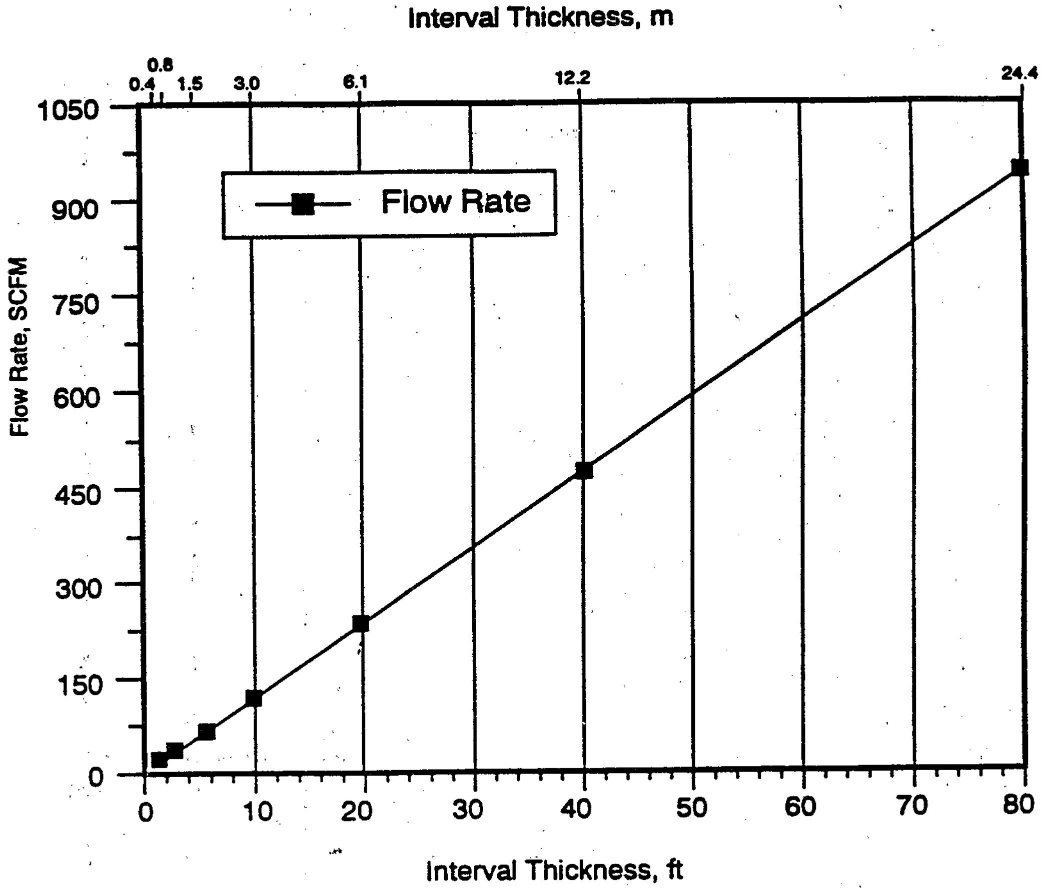
wellrad/gwfe/drw/pc



Change in Radius of Influence		Change in Flow Rate (SCFM)
m	ft	
3.0	10	167
6.0	20	138
12.2	40	118
24.4	80	103
48.8	160	92

Figure 15. Relationship between the radius of influence and flow rate.

radius/gwfa/drw/pc



Interval Thickness		Flow Rate (SCFM)	Min. No. of Wells
m	ft		
0.4	1.25	15	5
0.8	2.5	30	3
1.5	5	59	2
3.0	10	118	1
6.1	20	237	1
12.2	40	474	1
24.4	80	947	1

Figure 16. Relationship between interval thickness and flow rate.

interval/gwfs/drw/pc

thickness from 1.25 to 80 feet. As was the case with permeability, this relationship is expected on the basis of Equation 2. Because this equation generates solutions in terms of the flow rate per unit thickness (Q/H), it assumes uniform distribution of the flow rate over the entire screened interval. In practice, with large screen intervals, flow rates are likely to be variable over the length of the screen, resulting in reduced vapor flow and removal along the length of the screened interval. As a result, the greatest vapor extraction well efficiency is likely to be realized through the use of small screened intervals. Smaller screened intervals, however, may require the installation of additional extraction wells, screened to varying depths, to intersect the entire zone of contamination effectively.

Well (Gauge) Vacuum--

In Card 8 (Flow Rate Estimation), the flow rate is calculated over a range of six vacuum values ranging between 5 and 120 inches H_2O. Users have the option of selecting an alternate well vacuum. With this matrix, users can estimate the flow rate if they knows the optimal well vacuum of the blower or vacuum pump that the contractor normally uses. Alternatively, users can easily determine the well vacuum required to achieve the desired flow rate if they know the capacity of the vapor treatment units or the desired removal rate.

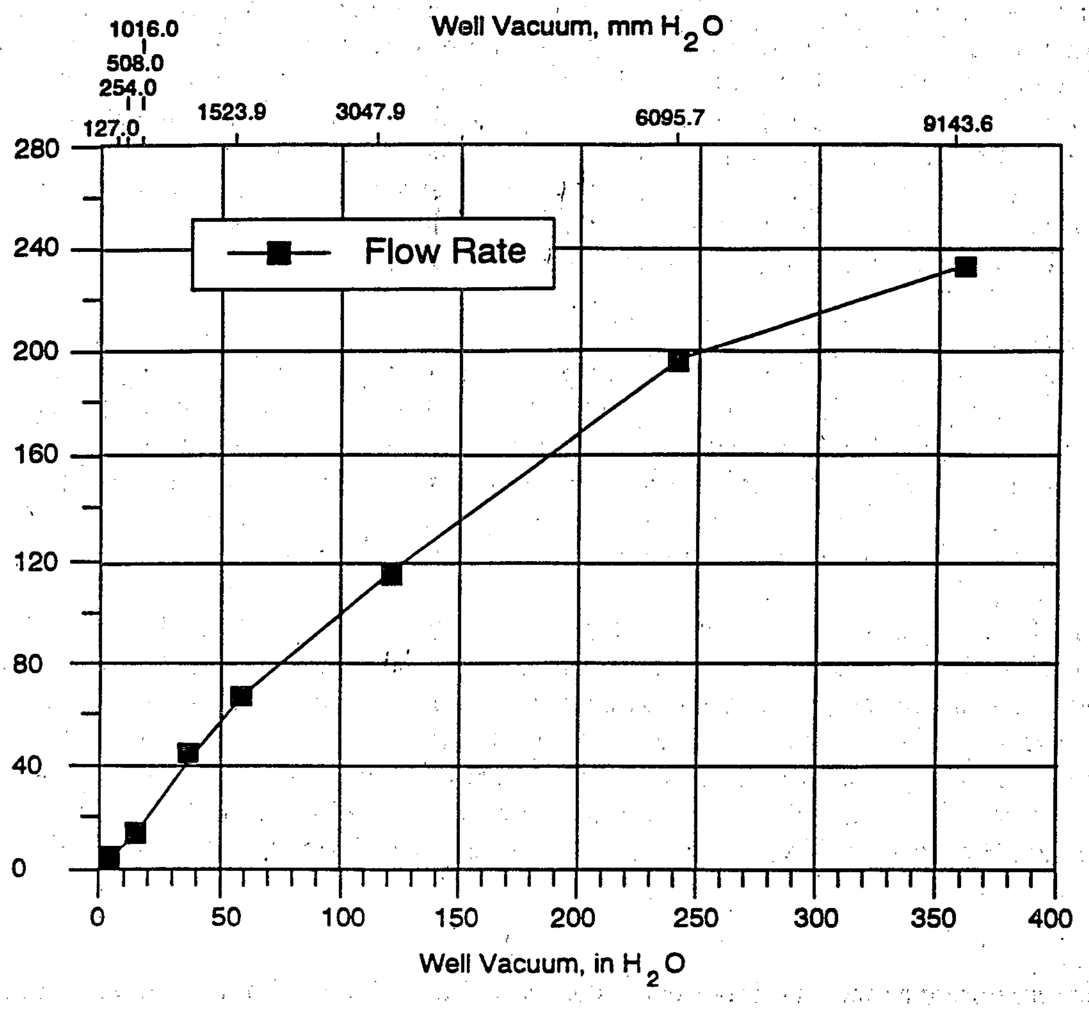
The flow rate increases with increasing well vacuums over a 5- to 360-inch H_2O range, as is shown in Figure 17. The relationship between well vacuum and flow rate is less straightforward than for the previous input parameters. At low well vacuums (<100 inches H_2O), there is a one-to-one correlation between changes in well vacuum and flow rate. As well vacuums are further increased, however, the increase in flow rate lags behind the well vacuum increase. This is due to the larger pressure reduction and resulting difference between actual flow rate (ACFM) in Equation 2 and "standard" flow rate (SCFM) in Equation 3.

Temperature--

Temperature was the first input parameter varied on Card 10 (Vapor Concentration Estimation - Calculation). Table 10 shows that the number of output parameters affected by temperature is much larger than for previous input parameters.

TABLE 10. "IS VENTING APPROPRIATE?" RESPONSE TO TEMPERATURE CHANGES

Temp. (°C)	Calc. Vapor Pressure (atm)	Calc. Vapor Conc. (mg/L)	Sat. Vapor Conc. at Time=0 (mg/L)	Min. Vol. to Remove >90% Initial Residual (L-air/g-residual)	Min. No. of Wells
0	0.23	632	679	199	3
5	0.28	766	807	141	3
10	0.34	922	954	101	2
15	0.41	1,102	1,122	73	2
20	0.48	1,312	1,312	37	1
30	0.67	1,828	1,767	21	1



Well Vacuum		Flow Rate
mm H_2O	in. H_2O	(SCFM)
127.0	5	6
254.0	10	11
508.0	20	23
1016.0	40	44
1523.9	60	64
3047.9	120	118
6095.7	240	196
9143.6	360	232

Figure 17. Relationship between well vacuum and flow rate.

vacuum/gwis/drw/pc

Although temperature was entered in terms of ^{o}C, it is used in Equation 2 in Kelvin. Incremental temperature increases from 5 to 30 ^{o}C (278 to 303 K) resulted in increases in vapor pressure and saturated vapor concentration. At the same time, decreases resulted in the minimum volume required to remove >90% of the initial residual spill mass, the minimum number of wells, the minimum volume value, and the minimum number of wells; thus, temperature changes have a tremendous impact on the effectiveness of system operations.

Contaminant Composition--

This is the last input parameter that impacts multiple output parameters in this stack. As discussed previously in Section 2 under "Input Parameter Requirements, Data Sources, and Software Constraints," the user has three options for testing this parameter. Users may use one of the two default compositions provided in the software, or they may enter a unique distribution based on laboratory analysis of samples taken from a specific site. Table 11 was developed to provide the user with a snapshot of how the various output parameters are affected by contaminant composition. One of the following compounds was selected to represent each of the boiling point ranges used in the software: n-butane, n-hexane, n-heptane, n-octane, and n-nonane.

TABLE 11. "IS VENTING APPROPRIATE?" RESPONSE TO CONTAMINANT COMPOSITION CHANGES

B.P. Range	Calc. Vapor Pressure (atm)	Calc. Vapor Conc. (mg/L)	Min. Vol. to Remove >90% Initial Residual (L-air/g-residual)
1, n-butane	2.11	5,096	0.18
2, n-hexane	0.16	537	1.57
3, n-heptane	0.046	192	4.96
4, n-octane	0.014	67	13.54
5, n-nonane	0.0042	22	40.18

As shown in the table, a change from a lower to a higher boiling point contaminant results in a decrease in vapor pressure and vapor concentration. There is also a corresponding increase in the minimum volume of air required to remove greater than 90% of the initial mass of contamination.

Estimated Spill Mass--

The desired removal rate is the only output parameter affected by estimated spill mass. Both parameters are shown on Card 13 ("Is Soil Venting Appropriate?"). When the desired remediation time is held constant, the desired removal rate increases by the same magnitude as any increase in the estimated spill mass. The realistic range of the spill mass is from 1 to 10^{7} kg or lb.

Desired Remediation Time--

As with the Estimated Spill Mass, the only output parameter this input parameter affects is the desired removal rate. Both parameters are shown on Card 13 ("Is Soil Venting Appropriate?"). When the estimated spill mass is held constant, the desired removal rate decreases by the same magnitude as any increase in the desired remediation time. A reasonable range for remediation time is from 30 to 720 days.

"Other Considerations/Liquid Layers" (Cards 19 and H29)

The cards address the situation in which a layer of liquid hydrocarbons rests either on an impermeable strata or on the water table. Under both of these conditions, the effectiveness of a vapor extraction system depends on the rate at which vapor-phase constituents diffuse out of the liquid hydrocarbon layer. Vapor-phase diffusion will be constrained by the mass transfer resistance between the liquid layer and the unsaturated zone. This mass transfer resistance is best overcome by imposing sufficient airflow rates to ensure that disequilibrium conditions are maintained for vapor-phase constituents between the unsaturated zone and the liquid layer.

Permeability--

This was the first parameter manipulated on Card H29 (Help: Boundary Layer Equations - Calculations). Changing permeability from 0.01 to 100 darcys resulted in a corresponding change in relative efficiency from 100 to 2.2%. Generally there is a 32% decrease in relative well efficiency for every order-of-magnitude increase in permeability. This is a direct result of the position of permeability in Equation 8, which is used to calculate well efficiency. At all permeabilities lower than 0.05 darcy, the program sets the relative well efficiency at 100%.

$$\eta=\frac{1}{3H}(6D^{eff}\mu/k)^{1/2}[\ln(\frac{R_I}{R_W})/(P_{atm}-P_W)]^{1/2}\sqrt{R_2^2-R_1^2} \qquad \text{Equation 8}$$

where η = efficiency relative to maximum removal rate
D = effective soil vapor diffusion coefficient (cm^2/s)
μ = viscosity of air = 1.8×10^{-4} g/cm-s
k = soil permeability (intrinsic) (cm^2)
H = thickness of screened interval (cm)
R_i = radius of influence of venting well (cm)
R_w = venting well radius (cm)
P_{atm} = absolute ambient pressure (1.013×10^6 g/cm-s^2)
P_w = absolute pressure at venting well (g/cm-s^2)
$R_1<r<R_2$ = defines region in which contamination is present.

Screened Interval Thickness--

This parameter was the next input parameter varied on Card H29 (Help: Boundary Layer Equations - Calculations). The interval thickness was varied from 1.25 to 40 feet, which resulted in a change in relative efficiency from 55 to 1.8%. Each increase in screened interval thickness is matched by a corresponding decrease in relative well efficiency. This relationship is shown in Equation 8.

Venting Well Radius of Influence--

The computations on Card H29 (Help: Boundary Layer Equations - Calculations) showed that the relative well efficiency increased in proportion to increases in the venting well radius of influence. The radius of influence was varied from 10 to 160 feet, and the relative efficiency changed from 5.8 to 7.8%. The increase in well efficiency diminishes with progressively larger values of the venting well radius of influence. This characteristic results from the ln (R_I/R_W) component of Equation 8.

Venting Well Radius--

The relationship between venting well radius and radius of influence in Equation 8 is again apparent when this input parameter was varied on Card H29 (Help: Boundary Layer Equations - Calculations). The well radius was changed from 2.0 to 16.0 inches and the relative efficiency from 7.4 to 5.8%. Relative well efficiency decreases with a larger venting well radius, and the decline in the well efficiency accelerates with progressively larger values of the venting well radius.

Applied Well Vacuum--

Increases in the vacuum applied to a well on Card H29 (Help: Boundary Layer Equations - Calculations) reduce the relative well efficiency. The wellhead vacuum was varied from 10 to 360 inches H_2O, and the relative efficiency decreased from 24 to 4%.

Radial Width of Contaminated Zone--

Based on calculations determined using Card H29 (Help: Boundary Layer Equations - Calculations), the user found that when the radial width of the contaminated zone was increased, the relative well efficiency experienced a corresponding increase of equal magnitude. Radial width was varied from 5 to 240 feet, and the corresponding relative efficiency changed from 0.6 to 27.6%.

<u>"Other Considerations/Low Permeability Lenses" (Cards 19 and H30)</u>

These cards address the situation in which residual hydrocarbons are contained in a lens of material that possesses a lower permeability to air than does overlying or underlying materials. This lower permeability layer could be silt within a sand unit, or a fine sand in a gravel. In this situation, vapor flow, resulting from the vacuum on an extraction well, will preferentially pass above and/or below the layer of lower permeability material rather than through the unit. As a result, the removal effectiveness of the vapor extraction system will be limited by the rate at which vapor-phase constituents diffuse out of the lower permeability material. Maintaining disequilibrium conditions for vapor-phase constituents between the lower permeability material and the rest of the unsaturated zone will accelerate vapor-phase diffusion.

On Card H30, process variables employed earlier in the software instructions can be used or adjusted to reflect new information or to test various design options. In contrast, temperature and constituent properties (molecular weight and vapor pressure) are inextricably linked together. As a result of these relationships, the impact of changes in constituent properties on removal rates and the thickness of the "dried-out" layer was not tested by varying one parameter at a time while the other two parameters were held constant. Instead, constituent vapor pressure was allowed to act as a dependent variable while constituent molecular weight was varied. Both constituent molecular weight and constituent vapor pressure were allowed to act as dependent variables while temperature was varied. To accomplish this, contaminant molecular weight and temperature were varied on Card 10 and the calculated outputs from this card were imported to Card H30.

Venting Well Radius--

Increasing the venting well radius on Card H30 (Help: Low Permeability Lenses - Calculations) had no impact on the calculations of the thickness of the "dried-out" layer over time. Incremental increases in the venting well radius from 2.0 to 36.0 inches marginally decreased the Day 1 removal rate from 418.8 to 417.7 kg/day. A similar minuscule reduction in the removal rate is recorded for the Day 1080 removal rate.

Radial Width of Contaminated Zone--

The computations on Card H30 (Help: Low Permeability Lenses - Calculations) showed that increases in the radial width of the contaminated zone had no impact on the thickness of the "dried-out" layer over time. Each doubling in the well radial width of the contaminated zone from 5 to 240 feet resulted in an increase in the Day 1 removal rate from 3 to 6,700 kg/day and an increase in the Day 1080 removal rate from 0.09 to 203 kg/day. When the radial width of the contaminated zone is much larger than the venting well radius, the estimated removal rates will increase by the square of the increase in the radial width of the contaminated zone.

Residual Contaminant Level--

This was the final process variable to be varied on Card H30 (Help: Low Permeability Lenses - Calculations). Each tenfold increase in the residual contaminant level increased the removal rates by a factor of 3. The thickness of the "dried-out" layer at any time becomes smaller by the same factor. Varying the residual contamination level from 1 to 100,000 mg/kg produced the following results:

Removal Rate Day 1: 13 to 4,189 kg/day
Removal Rate Day 1080: 0.4 to 127 kg/day

Thickness of Dried-Out Layer Day 1: 16 to 0.05 foot
Thickness of Dried-Out Layer Day 1080: 518 to 1.6 feet.

Contaminant Molecular Weight and Vapor Pressure--

This was the only contaminant property variable changed on Card H30 (Help: Low Permeability Lenses - Calculations). As shown in Table 12, increases in contaminant molecular weight, imported from Card 10, result in decreased contaminant vapor pressure, removal rates, and thickness of the "dried-out" layer.

TABLE 12. "LOW PERMEABILITY LENSES" RESPONSE TO CONTAMINANT MOLECULAR WEIGHT CHANGES

Contaminant Molecular Weight (g/mole)	Contaminant Vapor Pressure (mm Hg)	Removal Rate on Day 1 (kg/day)	Removal Rate on Day 1080 (kg/day)	Thickness of "Dried-Out" Layer on Day 1 (feet)	Thickness of "Dried-Out" Layer on Day 1080 (feet)
58.10	1603	825	25	0.98	32
65.43	366.6	418.8	12.7	0.5	16.4
86.2	121.6	276.9	8.4	0.3	10.8
95.0	47.9	172.3	5.3	0.21	6.8
100.2	35.0	160.0	4.8	0.19	6.3
114.2	10.6	94.3	2.9	0.11	3.7

Changes in contaminant vapor pressure in response to changes in contaminant molecular weight are the product of Henry's law, the ideal gas law, and Raoult's law. For single-component contaminants, vapor pressure declines exponentially with increases in molecular weight. The mixing effect of multiple components results in a vapor pressure for "fresh" gasoline (molecular weight at 20 °C = 65.43) and "weathered" gasoline (molecular weight at 20 °C = 84.97) that is somewhat lower than would be anticipated from their respective molecular weights. Removal rates, the thickness of the "dried-out" layer, and the contaminant molecular weight all vary by the same amount.

Temperature--

As stated previously, this input parameter directly affects both contaminant properties on Card H30 (Help: Low Permeability Lenses - Calculations). Temperature variations and the resulting calculations imported from Card 10 for use in the Card H30 calculations in Table 13 show that each increase in temperature causes a corresponding increase in the contaminant properties, removal rates, and thickness of the "dried-out" layer.

TABLE 13. "LOW PERMEABILITY LENSES" RESPONSE TO TEMPERATURE CHANGES

Temperature (°C)	Contaminant Molecular Weight (g/mole)	Contaminant Vapor Pressure (mm Hg)	Removal Rate on Day 1 (kg/day)	Removal Rate on Day 1080 (kg/day)	Thickness of "Dried-out" Layer on Day 1 (feet)	Thickness of "Dried- Out" Layer on Day 1080 (feet)
0	60.4	178	290	8.9	0.35	11.4
5	61.7	215	320	9.7	0.38	12.5

Temperature (^oC)	Contaminant Molecular Weight (g/mole)	Contaminant Vapor Pressure (mm Hg)	Removal Rate on Day 1 (kg/day)	Removal Rate on Day 1080 (kg/day)	Thickness of "Dried-out" Layer on Day 1 (feet)	Thickness of "Dried- Out" Layer on Day 1080 (feet)
10	62.9	259	351	10.7	0.42	13.7
15	64.2	309	384	11.7	0.46	15.0
20	65.4	367	418	12.7	0.5	16.4
30	67.0	508	494	15.0	0.6	19.3

The increase in contaminant molecular weight is the only response that seems abnormal. This result is a function of the manner in which the software performs the computations associated with Equation 2. Through the summation process, this equation treats a complex mixture of compounds as a single component in order to calculate an average molecular weight for the mixture. With each temperature change, the vapor pressures of the individual constituents in the mixture do not change equally. As a result, increases in temperature result in a greater contribution from the higher molecular weight compounds in the calculation of the average molecular weight of the mixture.

Air Permeability Test Stack (Cards 21, AP3, and AP8)

Only one of the tables in Card AP8 (Air Permeability Test - Data Analysis [cont.]) was used to evaluate the input parameters in this stack. The hypothetical field data readings used in Table 14 were: 0.1 inch H_2O at 9 minutes, 0.2 inch H_2O at 11 minutes, 0.2 inch H_2O at 15 minutes, 0.4 inch H_2O at 23 minutes, 0.7 inch H_2O at 30 minutes, 1.3 inches H_2O at 40 minutes, and 2.8 inches H_2O at 100 minutes. This set of data was used in the following parameter response analyses.

TABLE 14. "AIR PERMEABILITY TEST" RESPONSE TO SOIL LAYER THICKNESS CHANGES

Soil Layer Thickness (feet)	Pore Volume (ft^3)	Time to Extract a Pore Volume (days)	Air Permeability by Method A (darcys)
2.5	3,768	0.02	395
5.0	7,536	0.04	197
10.0	15,072	0.09	99
20.0	30,144	0.17	49
40.0	60,288	0.35	25

Soil Layer (Interval) Thickness--

This was the first input variable to be manipulated on Card AP3 (Air Permeability Test - Instructions). As shown in Table 14, changes in soil layer thickness result in equal changes in the calculated pore volume and calculated time needed to extract a pore volume. Changes in soil layer thickness also have a direct, inverse impact on air permeability calculated by test analysis Method A on Card AP8 (Air Permeability Test - Data Analysis [cont.]). Soil layer thickness did not affect the air permeability measurements calculated by Method B.

Estimated Radius of Influence--

This input parameter was used only on Card AP3 (Air Permeability Test - Instructions) to compute the pore volume and the amount of time needed to extract a pore volume. It had no bearing on the results of the air permeability test data analysis. Varying the radius of influence from 10 to 80 feet caused the pore volume to change from 942 to 60,288 ft^3 and the time needed to extract a pore volume from 0.1 to 0.35 day. This variation is a direct result of the standard volumetric calculation.

Air Permeability Test Flow Rate--

This was the final input variable to be changed on Card AP3 (Air Permeability Test - Instructions). Changes in the test flow rate have no impact on the calculated pore volume. Any change in the test flow rate did have the expected equal, inverse effect on the calculated time required to extract a pore volume. Changes in the test flow rate were matched by equal changes in air permeability calculated by test analysis Method A on Card AP8 (Air Permeability Test - Data Analysis [cont.]). The test flow rate does not affect the air permeability results calculated by Method B.

Radial Distance of Monitoring Point--

This input variable is unique to Card AP8 (Air Permeability Test - Data Analysis [cont.]). Changes in this parameter had no impact on the air permeability measurements calculated by Method A. Changes in the radial distance of a monitoring point resulted in a change in air permeability calculated by test analysis Method B that is equal to the square of the change in the monitoring point distance.

<u>System Design Stack (Cards 24 and SD2 through 4)</u>

Contaminant Radius--

This is the first Contaminant Distribution input variable on Card SD2 (Design Input). As shown in Table 15, changes in the contaminant radius result in changes in the calculated total mass equal to the square of the change in the contaminant radius. The average contaminant concentration (Average Conc. mg/kg...Card SD2) used for these calculations was 1,000 mg/kg.

TABLE 15. "SYSTEM DESIGN" RESPONSE TO CONTAMINANT RADIUS CHANGES

Contaminant Radius (feet)	Calculated Total Mass (kg)	Flow Rate per Extraction Well (SCFM)	Minimum No. of Wells Based on Area	Minimum No. of Wells Based on Critical Volume
10	151	118	1	1
20	604	118	1	1
40	2,418	118	1	1
60	5,441	118	3	1
120	21,766	118	9	3

Changes in the contaminant radius had no impact on the flow rate of the extraction wells. The relationship between contaminant radius and total mass is simply the standard volumetric calculation.

Changes in the number of wells based on area and contaminant radius are expressed in Equation 5. When the contaminant radius is smaller than the radius of influence, the minimum number of wells will be one. As the value of the contaminant radius becomes increasingly larger, the increase in the minimum number of wells will approach the square of the increase in the contaminant radius. In Equation 4, the relationship between the contaminant radius and the minimum number of wells based on critical volume is tied to the calculated total mass (M_{spill}). When M_{spill} is very small ($\leq$10 kg) relative to the flow rate (Q_{well}), the minimum number of wells will be one. As larger contaminant radius values are used, the minimum number of wells will increase significantly.

Contaminant Interval Thickness--

This is the second of three input variables on Card SD2 (Design Input) for computing total contaminant mass. Changes in the contaminant interval thickness result in equal changes in the calculated total mass. The relationship between contaminant interval and calculated total mass stems from the remainder of the standard volumetric calculation that pertains to the radius. Changes in the contaminant interval thickness have no impact on either the flow rate per extraction well or the minimum number of wells based on area. The relationship between changes in the contaminant interval thickness and the minimum number of wells based on critical volume is again tied to the mass of contaminant.

Average Contaminant Concentration--

This is the final contaminant distribution input variable on Card SD2 (Design Input). Changes in the average contaminant concentration result in equal changes in the calculated total mass. Average contaminant concentration represents a scaling factor applied to the standard volumetric calculation discussed previously. Changes in the average contaminant concentration have no impact on either the flow rate per extraction well or the minimum number of wells based on area. A very small average contaminant concentration (≤100 mg/kg) results in a spill mass relative to the flow rate (Q_{well}), and the calculated minimum number of wells based on critical volume will be one. As larger average contaminant concentration values are used, the minimum number of wells (based on critical volume) will increase at the same rate as the mass of contamination spilled.

Critical Volume of Air--

Although this input parameter on Card SD3 (Design Input) is not a true independent variable, it is displayed on Card 17 as a result of the "more detailed" calculations using temperature and contaminant composition that were performed on Card 16 (Model Predictions). As such, this parameter is used to depict changes in flow rate and the minimum number of wells in the system design stack resulting from changes in temperature and/or contaminant composition. The range of values utilized here is designed to encompass the previously calculated range of values for determining the critical volume of air. Increases in the critical volume of air cause corresponding equal increases in the minimum number of wells. Varying the critical volume of air from 0.1 to 450 L/g results in a change in the minimal number of wells from 1 to 8.

Efficiency--

This is the final input parameter on Card SD3 (Design Input). Although not a true independent variable, efficiency is derived based on an evaluation of special cases utilizing Card 19 (Other Considerations). As such, this parameter is used to adjust the expected effectiveness of the extraction wells as a result of dilution effects, the presence of liquid layers or low-permeability layers, and the potential for groundwater upwelling. Increases in the well efficiency cause corresponding equal and inverse decreases in the minimum number of wells based on the critical volume of air. The minimum number of wells based on area is not affected by changes in well efficiency. A change in the relative efficiency from 1 to 30% resulted in a change in the minimum number of wells from 25 to 1.

Time for Cleanup--

This is the only input parameter on Card SD4 (Design Input) and the final input parameter for the system design stack. Increases in the time allotted for cleanup result in corresponding equal and inverse decreases in the minimum number of wells based on the critical volume of air, which can be an important economic consideration. Neither the flow rate per extraction well nor the minimum number of wells based on area is affected by changes in cleanup time. Varying the cleanup time from 30 to 360 days resulted in a change in the minimum number of wells from 2 to 1.

SENSITIVITY ANALYSIS

The purpose of this section is to focus the user's attention on the sensitivity of each output parameter as it pertains to the final estimate of the minimum number of extraction wells required. This evaluation will also indicate the feasibility of using an SVE system. This section identifies the extent to which each site and system design characteristics affect the feasibility of a vapor extraction system and identifies those parameters over which a system designer can exert some measure of control. Each of the input parameters in the system design stack is addressed with a brief discussion on how to control that parameter's value.

Contaminant Radius--

The minimum number of wells calculated on the basis of area (N_A) and critical volume (N_{CV}) will both increase by the square of the increase in the radius of contamination.

The only control that can be exerted on the radius of contamination is the determination as to what constitutes the limits of contamination. The radius of contamination will have one value if it is defined as the point at which no detectable contamination is found. It will have another value, however, if the radius of contamination is defined as X mg/kg total petroleum hydrocarbons (TPH). This definition could have important economic ramifications on the selection of SVE.

Contaminant Interval Thickness--

Although the number of wells required should not be affected by interval thickness, the flow rate and possibly the wellhead vacuum will be. Once again, the only control that can be exerted over the contaminant interval thickness is the determination as to what constitutes the limits of contamination.

Average Contaminant Concentration--

Essentially, N_{CV} will increase or decrease in direct proportion to changes in the average contaminant concentration (C_{ave}). The relationship between C_{ave} and N_{CV} is tied to the spill mass M_{spill}. Here again, the user can only exert the defined level of control. In this case, the average contaminant concentration will differ only for changes in TPH, total BTEX, benzene, or some other range of constituents.

Permeability--

As shown in the preceding section, the minimum number of wells required at a site, based on the critical volume of air (N_{CV}), is decreased by an amount equal to the increase in permeability. That is, if the permeability value is doubled, N_{CV} will be halved. In Section 1, it was indicated that permeability could vary by as much as several orders of magnitude across a site. Because the appropriate distribution of extraction wells will be strongly influenced by lateral variations in permeability, it is important to know the distribution of these permeability changes.

Design Vacuum--

Design vacuum (P_W) and N_{CV} are joined through flow rate (Q_{well}). At low P_w values, an increase in the design vacuum results in a decrease in N_{CV} by approximately an equal magnitude. The result of the "compressibility effect" (discussed earlier in "Is Venting Appropriate?" (Cards 8 through 18: Well [Gauge] Vacuum) is to progressively accelerate the decrease in N_{CV} as P_W values approach atmospheric pressure (406 inches H_2O).

Because N_{CV} is so closely tied to the extraction well vacuum, it can be a sure means of minimizing the number of wells used at a site. A system's design vacuum initially will be constrained by the capacity of a side waste stream treatment unit for handling the early contaminant vapor concentrations. If extraction well construction can be made suitable to prevent surface breakthrough, the well vacuum probably can be increased gradually to maximize system removal efficiency.

Extraction Well Radius--

The extraction well radius (R_W) is also tied to N_{CV} through Q_{well}. Increasing the well radius results in decreased N_{CV} values. As a result of this natural log function, the well radius has no impact on the minimum number of wells based on area. Because price differentials between well construction materials of different diameters are minimal, the system designer should consider using larger borehole and pipe diameters as an economical means to possibly maximize vapor-phase recovery and minimize the number of extraction wells required.

Extraction Well Screen Thickness--

The extraction screen thickness (H_S) is also tied to N_{CV} through Q_{well}. Increases in H_S result in equivalent increases in the extraction well flow rate. This would cause an equal decrease in N_{CV}. As the software indicates on Card 19 (Other Considerations) and Card H23 (Help: 6a, Dilution Effects [Bypassing]), however, if the thickness of the screened interval is greater than the thickness of the contaminated soil thickness or is not matched to the contaminated interval, then fewer vapors will flow to that part of the screen outside the zone of contamination than will be saturated in vapor-phase contaminants. This effectively reduces the well's efficiency to the percentage of the screened interval in the zone of contamination. Because extraction vapor concentrations tend to run at 10 to 50% of saturation, every effort must be made to accurately match the screened interval to the zone of contamination in order to maximize extraction well efficiency. Screen thickness has no impact on the minimum number of wells based on area.

Critical Volume of Air--

As identified during the system design stack discussion, the critical volume of air required to remove 1 gram of initial residual contamination ($V_{critical}$) is a synthesis of the temperature and contaminant composition input parameters entered on Card 10 (Vapor Concentration Estimation - Calculation). N_{CV} will vary in direct response to and by the same magnitude as changes in $V_{critical}$. An increase in temperature resulted in a decrease in $V_{critical}$. Even at low temperatures (0 to 10 ^{o}C), a 5-degree temperature increase resulted in a 30% reduction in $V_{critical}$, which translates into an equal reduction in N_{CV}. In contrast, $V_{critical}$, and as a result N_{CV}, increases with changes in contaminant composition toward higher boiling point (and higher molecular weight) compounds.

Although designers of vapor extraction systems cannot control contaminant composition, they can control subsurface vapor temperatures or adjust system operations to take into account the impact of temperature. When state regulations permit, one fairly economical means of increasing subsurface vapor temperatures is through the reinjection of vapor extraction system effluent air that has passed through a thermal treatment unit. Alternatively, Sresty et al. (1992) has recently demonstrated the effectiveness of in situ radio frequency (RF) heating in increasing soil temperatures to the 150 to 200 ^{o}C range in order to remove polycyclic aromatic hydrocarbons and phenols. This method is still developmental, however, and it is likely to be several years before it is an economically feasible approach to the use of hydrocarbons. Also, the removal rates of contaminant constituents are dependent on their boiling points. As a result, as vapor extraction proceeds at a site, the residual subsurface contaminant composition becomes increasingly dominated by higher boiling point (less volatile) constituents.

Efficiency--

As mentioned previously in the extraction well screened thickness discussion, factors that can affect well efficiency are addressed on Card 19 (Other Considerations) of the software. Changes that increase well efficiency cause corresponding equal decreases in N_{CV}. Changes to the expected extraction well efficiency have no impact on N_A.

System designers can exert a large degree of control over well efficiencies. In reference to Card 19, designers of vapor extraction systems need to ensure that both horizontal and vertical placement of extraction wells maximizes the percentage of extracted vapors that contain volatile contaminants. Also, in situations where the target zone of contamination is close to the water table, the designers need to consider the potential for groundwater upwelling in response to the extraction well vacuums, and they need to be prepared to offset upwelling with groundwater pumping wells.

Time for Cleanup--

The time allocated for cleanup through SVE affects N_{CV}. Any increase in the allocated time decreases N_{CV} by the same magnitude, with the opposite true for decreases in time. Remediation time has no bearing on N_A.

As discussed in the "Desired Remediation Time" portion of Section 1, the time allocated for site cleanup may or may not be within the control of the system designer. The time frame selected is often driven by the actual or perceived potential impact of contaminant migration to downgradient receptors; demands for action from surrounding property owners; the level of trust between responsible parties, consultant/contractors and regulators; or a responsible party's plans for the site. Few parameters, however, can have as great an impact on the determination of the economic or technical viability of using vapor extraction at the time of cleanup.

REFERENCES

American Petroleum Institute (API). 1992. *A Draft Guide for Assessing and Remediating Petroleum Hydrocarbons in Soils*, API Publication No. 1629, API marketing department, Washington, D.C., April.

Chevron Research and Technology Company (CRTC). 1991. Vapor Extraction System Performance Study. Chevron Research and Technology Company internal document, written for Chevron USA marketing department.

Cline, P. V., J. J. Delfino, and P. S. Rao. 1991. "Partitioning of Aromatic Constituents into Water from Gasoline and Other Complex Solvent Mixtures." *Environmental Science and Technology*, 26(5):914-920.

Danko, J. "Applicability and Limitations of Soil Vapor Extraction." 1989. Presented at the Soil Vapor Extraction Technology Workshop, Office of Research and Development, Edison, New Jersey, June 28-29.

Davies, S. H. 1989. "The Influence of Soil Characteristics on the Sorption of Organic Vapors." Presented at the Workshop on Soil Vacuum Extraction, R. S. Kerr Environmental Research Laboratory, Ada, Oklahoma, April 27-2.

DePaoli, D. W., S. E. Herbes, and M. G. Elliott. 1989. "Performance of In-situ Soil Venting System at Jet Fuel Spill Site." Presented at the Soil Vapor Extraction Technology Workshop, Office of Research and Development, Edison, New Jersey, June 28-29.

Hutzler, N. J., B. E. Murphy, and J. S. Gierke. 1988. State of Technology Review: Soil Vapor Extraction Systems. U.S. EPA, CR-814319-01-1.

Johnson, P. C., C. C. Stanley, M. W. Kemblowski, D. L. Byers, and J. D. Colthart. 1990a. "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil-Venting Systems." *Ground Water Monitoring Review*, pp. 159-178.

Johnson, P. C., M. W. Kemblowski, and J. D. Colthart. 1990b. "Quantitative Analysis for the Cleanup of Hydrocarbon Contaminated Soils by In Situ Soil Venting," *Ground Water*, 28(3):413.

Kruger, C. A., and T. Carson. 1991. "Roseville Site," *Vapor Extraction Systems Course Notebook*, Final Report, EPA Contract No. 68-WO-0015, WA 04, February.

McDonald, M. G. and A. W. Harbaugh. 1988. *A Modular Three Dimensional Finite Difference Ground Water Flow Model*, U.S. Geological Society Book 6.

Reible, D. D. 1989. "Introduction to Physico-Chemical Processes Influencing Enhanced Volatilization." Presented at the Workshop on Soil Vacuum Extraction, R. S. Kerr Environmental Research Laboratory, Ada, Oklahoma, April 27-28.

Sabadell, G. P., J. J. Eisenbeis, and D. K. Sunada. 1989. "The 3-D Model CSUGAS: A Management Tool for the Design and Operation of Soil Venting Systems." In: Proceedings of the 9th Annual Conference on Hazardous Waste and Hazardous Material, New Orleans, Louisiana, pp. 177-182.

Sresty, Guggilam, H. Dev, and J. Change. 1992. *In Situ Treatment of Soil Contaminated with PAH's and Phenols.* Abstract Proceedings of the Eighteenth Annual Risk Reduction Engineering Laboratory Research Symposium, U.S. Environmental Protection Agency, EPA-600/R-92/028, April.

Stephanatos, B. N. 1988. "Modeling the Transport of Gasoline Vapors by an Advective Diffusive Unsaturated Zone Model." In: Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration, Houston, Texas, November 9-11, pp. 591-611.

Travis, C. C. and Macinnis, J. M. 1992. *Environmental Science and Technology*, 26(10):1885-1887.

U.S. Environmental Protection Agency (EPA). 1991a. Strategic Tracking and Results System, 1st Quarter, Fiscal Year 1992.

U.S. Environmental Protection Agency (EPA). 1991b. "Superfund, RCRA, and UST: The Clean-up Threesome," EPA Journal, 17(3):14.

U.S. Environmental Protection Agency (EPA). 1991c. *Soil Vapor Extraction Technology Reference Handbook*, EPA-540/2-91/011.

U.S. Environmental Protection Agency (EPA). 1990. "Assessing UST Corrective Action Technologies: Site Assessment and Selection of Unsaturated Zone Treatment Technologies." EPA-600/2-90/011.

U.S. Environmental Protection Agency (EPA). 1988. "Underground Storage Tanks: Technical Requirements," *Federal Register* 53, No. 185, 23 September 1988, 37082-37212.

Wilson, O. J. 1991. "Movement of a Volatile Organic Compound in a Soil Vapor Extraction Column," (unpublished paper).

APPENDIX A

SOFTWARE INSTALLATION PROCEDURE

SOFTWARE INSTALLATION PROCEDURE

This appendix provides a discussion on how to load both Spinnaker PLUS and HyperVentilate. These directions presume that the user has a working knowledge of Microsoft Windows. The operation of Spinnaker PLUS, and therefore the IBM-compatible version of HyperVentilate requires Microsoft Windows Version 3.0 or higher. If you are using a version of HyperVentilate with a "run time" version of Spinnaker PLUS, skip to the "Loading HyperVentilate" instructions.

Loading Spinnaker PLUS

The Spinnaker PLUS package contains three 3.5-inch and three 5.25-inch diskettes from which to install the program. Use these steps to install the program:

1. Enter Windows.

2. Double-click on the "Main" window icon (if this window is not already open).

3. Double-click on the "File Manager" icon; this will display the "Directory Tree" window.

4. Insert Disk 1 into the appropriate drive (A or B).

5. In the upper left corner of the "Directory Tree" window you will see symbols representing the drives on your system. Click on the drive (A or B) where you just inserted Disk 1.

6. A listing of the files on Disk 1 will appear; double click on the file "plssetup.exe".

7. A window called "Spinnaker PLUS Setup" will appear. Change the path of the installation from "C:\PLUS" to "C:WINDOWS\PLUS" (Note: "C" is a standard drive specification; you should use the letter that designates where Windows is installed on your system). Click on "Continue." The program will

start copying files from Disk 1. Follow the rest of the instructions and prompts on the screen.

8. When the installation has been completed, exit the "File Manager" and exit Windows.

<u>Creating the Spinnaker PLUS Icon and Opening Spinnaker PLUS</u>

1. Re-enter Windows. (Note: exiting and re-entering Windows is a step recommended by the manufacturer of Spinnaker PLUS).

2. Close all windows so that the "Program Manager" window is the only one displayed on your screen.

3. At the bottom of the window, there will be program icons displayed for "Main," "Accessories," and others. Is there a program icon named "Windows Applications?" If yes, double-click on it and go to Step 4. If no, continue with Steps 3a-c to create one.

3a. Click on "File" and drag down to "New." A window called "New Program Object" will appear.

3b. Check to make sure "Program Group" is selected; click on "OK." A window called "Program Group Properties" will appear.

3c. The cursor will be located at the description field. Type in the words "Windows Applications" and click on "OK." An empty window will appear called "Windows Applications."

4. With this window open, click on "File" and drag down to "New." A window called "New Program Object" will appear.

5. Check to make sure "Program Item" is selected; click on "OK." A window called "Program Item Properties" will appear.

6. Click on "Browse." A window called "Browse" will appear.

7. Under "Directories," double-click on "plus."

8. Under "File Name," double-click on the "plus.exe" file. This will bring you back to the "Program Item Properties" window.

9. Click on "Change Icon," click on the icon for "Plus," and click on "OK."

10. You will now be back at the "Program Item Properties" window. Click on "OK."

11. You will now be back to the "Windows Applications" window displaying your "Plus" icon.

12. Double-click on the "Plus" icon to run Spinnaker PLUS.

Loading HyperVentilate

The HyperVentilate package contains one 3.5-inch diskette from which to install the program. The program can be installed from either the DOS prompt or from within Windows. The following procedures are used for both types of installations (Note: For these installation procedures, the 3.5-inch drive from which you will be installing the program is assumed to be the B drive).

DOS Installation

1. Insert the HyperVentilate disk into the appropriate drive.

2. From the C:\> prompt in DOS, type "COPY B:*.*C:\WINDOWS\PLUS".

Windows Installation

1. Follows Steps 1-5 of the "Loading Spinnaker Plus."

2. Click on the B:\ folder icon so that it is highlighted and/or a dotted line appears around it.

3. Click on "File" and drag down to the "Copy" command. The "Copy" window will appear.

4. The curser will be located at the "To" path. Type in "C:WINDOWS\PLUS"; click on "OK."

5. When the installation is complete, exit from the "File Manager."

Opening HyperVentilate

1. Enter Windows.

2. Double-click on the "Windows Applications" icon (if this window is not already open).

3. Double-click on the "Plus" icon.

4. Close the "Home" window.

5. Click on "File" and drag down to "Open." The window "Open Stack" will appear.

6. Either double-click on the "SYS.STA" file or click on "SVS.STA" and then click on "Open." The user is now in HyperVentilate.

<u>Installing Spinnaker PLUS "Run Time" Version with HyperVentilate</u>

1. Create a subdirectory on the hard disk for HyperVentilate and Spinnaker PLUS "Run Time." For example, from the C:\> prompt, type "MD\WINDOWS\PLUS".

2. Copy all the files from both the Spinnaker PLUS "Run Time" diskette and the HyperVentilate diskette to the subdirectory. For example, from the C:\> prompt, type "COPY B:*.* C:\WINDOWS\PLUS".

3. Follow directions in "Creating the Spinnaker PLUS Icon and Opening Spinnaker PLUS" with the following exception: substitute "plusrt.exe" for "plus.exe" in Step 8.

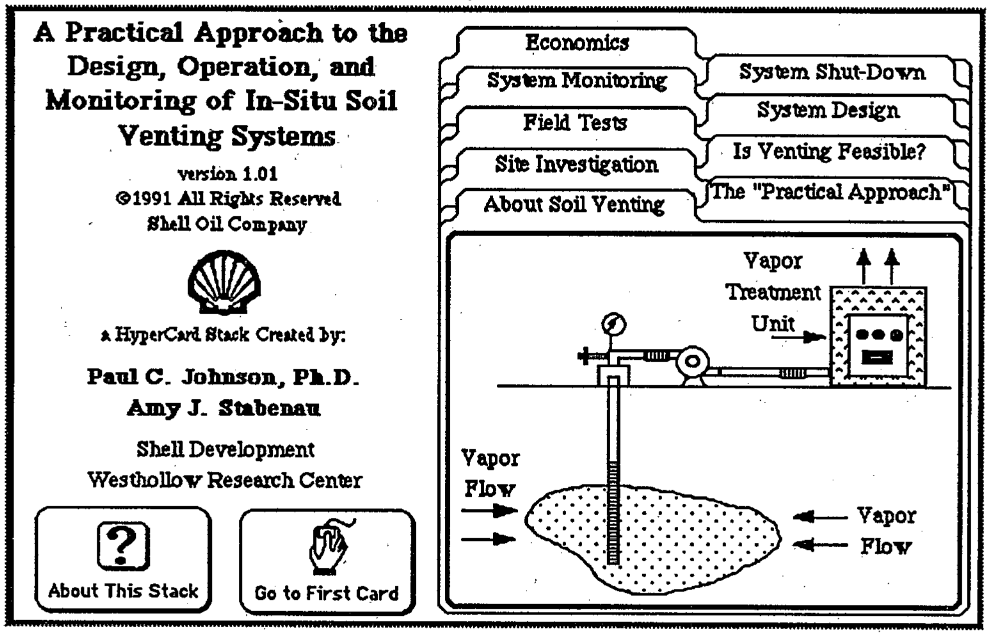
4. Follow directions for "Opening HyperVentilate" to run the program.

APPENDIX B

USER'S MANUAL

HyperVentilate
Users Manual

A Software Guidance System Created for Vapor Extraction Applications



by

Paul C. Johnson, Ph.D.

Apple® Macintosh™ HyperCard™
compatible version 1.01

IBM® PC-compatible
Microsoft® Windows™ version 3.x
Spinnaker PLUS® version 2.5

Disclaimer

The HyperVentilate software package was completed under a Federal Technology Transfer Act Cooperative Research and Development Agreement between EPA and Shell Oil Company, signed in 1990.

EPA is facilitating the distribution of HyperVentilate because the Agency has found the software and manual to be helpful tools, especially in teaching users about in situ soil venting and in guiding them through a structured thought process to evaluate the applicability of soil venting at a particular site. EPA's Office of Underground Storage Tanks advocates the use of innovative cleanup technologies, and in situ soil venting is recognized as an effective remediation alternative for many underground storage tank sites.

HyperVentilate is based on the document titled, "A Practical Approach to the Design, Operation, and Monitoring of Soil Venting Systems" by P. C. Johnson, C. C. Stanley, M. W. Kemblowski, J. D. Colthart, and D. L. Byers, published 1990 by Shell Oil Company. The program asks a series of questions and forms a "decision tree" in an attempt to identify the limitations of in situ soil venting for soils contaminated with gasoline, solvents or other relatively volatile compounds.

EPA and Shell Oil Co. make no warranties, either express or implied, regarding the HyperVentilate computer software package, its merchantability, or its fitness for any particular purpose. EPA and Shell Oil Co. do not warrant that this software will be error free or operate without interruption. EPA and Shell Oil Company do encourage testing of this product.

EPA will not provide installation services or technical support in connection with the HyperVentilate computer software package. Neither will EPA provide testing, updating or debugging services in connection with the enclosed computer software package.

Notes

HyperVentilate is a software guidance system for vapor extraction (soil venting) applications. Initial development of this program occured under the Apple Macintosh HyperCard environment, due to its programming simplicity, ability to incorporate text and graphics, and interfacing with other Macintosh programs (such as FORTRAN codes, etc.). The objective was to create a user-friendly software package that could be both educational for the novice environmental professional, and functional for more experienced users.

HyperVentilate *will not* completely design your vapor extraction system, tell you exactly how many days it should be operated, or predict the future. It *will* guide you through a structured thought process to: (a) identify and characterize required site-specific data, (b) decide if soil venting is appropriate at your site, (c) evaluate air permeability test results, (d) calculate the minimum number of vapor extraction wells, and (e) quantify how results at your site might differ from the ideal case.

HyperVentilate is based on the article "*A Practical Approach to the Design, Operation, and Monitoring of Soil Venting Systems*" by P. C. Johnson, C. C. Stanley, M. W. Kemblowski, J. D. Colthart, and D. L. Byers [Ground Water Monitoring Review, Spring 1990, p.159 - 178]. The software performs all necessary calculations and contains "help cards" that define the equations used, perform unit conversions, and provide supplementary information on related topics. In addition, a 62-compound user-updatable library (to a maximum of 400 compounds) is also included.

HyperVentilate version 1.01 for the Apple Macintosh requires an Apple Macintosh (Plus, SE, SE/30, II, IIX, or portable) computer equipped with at least 1 MB RAM (2 MB preferred) and the Apple HyperCard Software Program (v.2.0 or greater).

HyperVentilate version 2.0 for the IBM-compatible PC requires a personal computer equipped with a 80386 processor and an 80387 co-processor, 4 MB RAM minimum, VGA or 8514 monitor, DOS 3.1 or higher, Microsoft Windows 3.x and Spinnaker PLUS 2.5 or higher.

This manual is not intended to be a primer on soil venting (although the software is) and it is assumed that the user is familiar with the use of an Apple Macintosh or IBM personal computer.

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Spinnaker PLUS is a registered trademark of Spinnaker Software Corporation

Comments/Suggestions?

Comments and/or suggestions about the usefulness of this program can be mailed to:

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Houston, TX 77251-1380

Please do not call the author and/or Shell with questions about the use or interpretation of results from this program.

HyperVentilate Users Manual

Addendum for Microsoft Windows/Spinnaker PLUS Version

Summary

HyperVentilate - the software guidance system created for vapor extraction applications is now available for IBM-compatible personal computers. In general, this new version (v2.0) appears and functions like the original Apple Macintosh HyperCard version. Due to differences in the computer platform and operating environment, however, there are some minor modifications. This addendum to the original users manual identifies those modifications.

HyperVentilate v2.0 is a product of collaboration between Shell Oil Company and U.S. E.P.A., and is still under evaluation. Should you encounter problems that you think are "bugs", please write to the author identifying the problem.

Modifications

- *software platform*
  The original HyperVentilate program was developed and operated under the Apple Macintosh HyperCard software environment, and initially there were no plans to develop an IBM-compatible version. Due to popular demand; however, the author relented and used the least painful method of adaptation to the new platform. This was accomplished through the use of Spinnaker PLUS, a HyperCard-like program that can utilize pre-v2.0 HyperCard stacks and functions on both Macintosh and IBM-compatible platforms. The Microsoft Windows/Spinnaker PLUS version requires the user to have both Microsoft Windows and a “run-time” version of Spinnaker PLUS (Windows 3.0 version). Information on Spinnaker PLUS can be obtained from:

  Spinnaker Software
  201 Broadway
  Cambridge, MA 02139
  (617) 494-1200

- *stack names*
  As listed on p4. of the original users manual, HyperVentilate for the Apple Macintosh consists of eight files. The spinnaker PLUS version contains only seven files. The names are:

HyperCard Version Name	Spinnaker PLUS Version Name
Soil Venting Stack	SVS.sta
Soil Venting Help Stack	SVHS.sta
System Design	SD.sta

Air Permeability Test	APT.sta
Aquifer Characterization	AQ.sta
Compound List Update	CLU.sta
HypeVent	HYPEVENT.exe
f77.rl	none

- *installation*
  All files **must** be copied into the PLUS directory on your hard disk.

- *starting HyperVentilate v2.0b*
  To start HyperVentilate v2.0b, open the Windows "File Manager", navigate to within the PLUS directory, then open (double-click on) the file SVS.sta.

- *printing cards*
  You may experience difficulties with some of the "Print" buttons in the program. Read your PLUS manual to overcome these difficulties.

- *appearance of cards*
  Generally, the cards appear as they are printed in the manual. due to platform differences, however, some text will appear different. This problem is unavoidable with Windows-based systems, as different users will have their computers configured with different screen fonts.

- *tab keys*
  Some cards utilize spreadsheets. In the HyperCard version the "tab" key is used to navigate through these tables. In the PLUS version the "tab" key is not active and you must use the "arrow" keys.

- *speed*
  Due to platform differences, the PLUS version does not operate as smoothly, or quickly, as the HyperCard version. The user will notice that with time the execution speed of the program will slow; therefore, it is recommended that you periodically exit from Windows and restart the system.

  On some machines, when HyperVentilate accesses the external compiled code HYPEVENT.EXE after clicking on the "Generate Predictions" button on card 16 of the SVS.sta stack, there will be a long pause (as long as a few minutes) as PLUS, Windows, and HYPEVENT.EXE fight over available memory. Typically card 17 will eventually be displayed with a shaded rectangle along a portion of it slower base while this battle is occuring. Be patient and wait for the screen to blank out and display the message "HANG ON...." indicating that HYPEVENT.EXE is running. If you have limited memory (<4 MB), or too many applications open, this message will not be displayed, and you will be returned to card 17 as if the program had run. The user needs to be aware that this may occur.

Table of Contents

I. *Introduction*

In situ vapor extraction, or soil venting is recognized as an attractive remediation alternative for "permeable" soils contaminated with "volatile" compounds. As Figure 1 illustrates, vapors are removed from extraction wells, thereby creating a vacuum and vapor flow through the subsurface. Until the residual contamination is depleted, contaminants will volatilize and be swept by the vapor flow to extraction wells. While its use has been demonstrated at service stations, Superfund sites, and manufacturing locations (see Hutzler et al. [1988] for case study reviews), vapor extraction systems are currently designed more by intuition than logic. In fact, many systems are installed at sites where the technology is not appropriate.

"A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems" [Johnson et al. 1990a - see Appendix G] is a first attempt at creating a logical thought process for soil venting applications. The article, which is based on earlier results of Thornton and Wootan [1982], Marley and Hoag [1984], Johnson et al. [1990], and discussions with several of these authors, describes a series of calculations for determining: (a) if soil venting is appropriate at a given site, (b) limitations of soil venting, and (c) system design parameters, such as minimum number of extraction wells and potential operating conditions.

HyperVentilate is a software guidance system based on the Johnson et al. [1990a] article. The software performs all necessary calculations and contains "help cards" that define the equations used, perform unit conversions, and provide supplementary information on related topics. In addition, a 62-compound updatable chemical library (to a maximum of 400 compounds) is included.

Initial development of this program occured under the Apple Macintosh HyperCard environment, due to its programming simplicity, ability to incorporate text and graphics, and interfacing with other Macintosh programs (such as FORTRAN codes, etc.). The objective was to create a user-friendly software package that could be both educational for the novice environmental professional, and a functional tool for more experienced users. The OASIS [1990] system created at Rice University for groundwater contamination problems is another excellent example of the use of HyperCard as a technology transfer tool.

This document is a users manual for **HyperVentilate**. It contains sections describing the installation and operation of the software. During the development of **HyperVentilate**, the goal was to create a guidance system that could be used with little or no instruction. Experienced Apple Macintosh users, therefore, can load and explore the capabilities of this program after glancing at the "*Loading HyperVentilate Software*" section. Those users that are less comfortable about exploring software without a manual are encouraged to read through it once, and work through the sample problem. It is intentionally brief, and a beginner should be able to navigate through the system in less than a couple hours. It is assumed that the user has some previous Macintosh experience. If not, consult a Macintosh users manual for a quick tutorial.

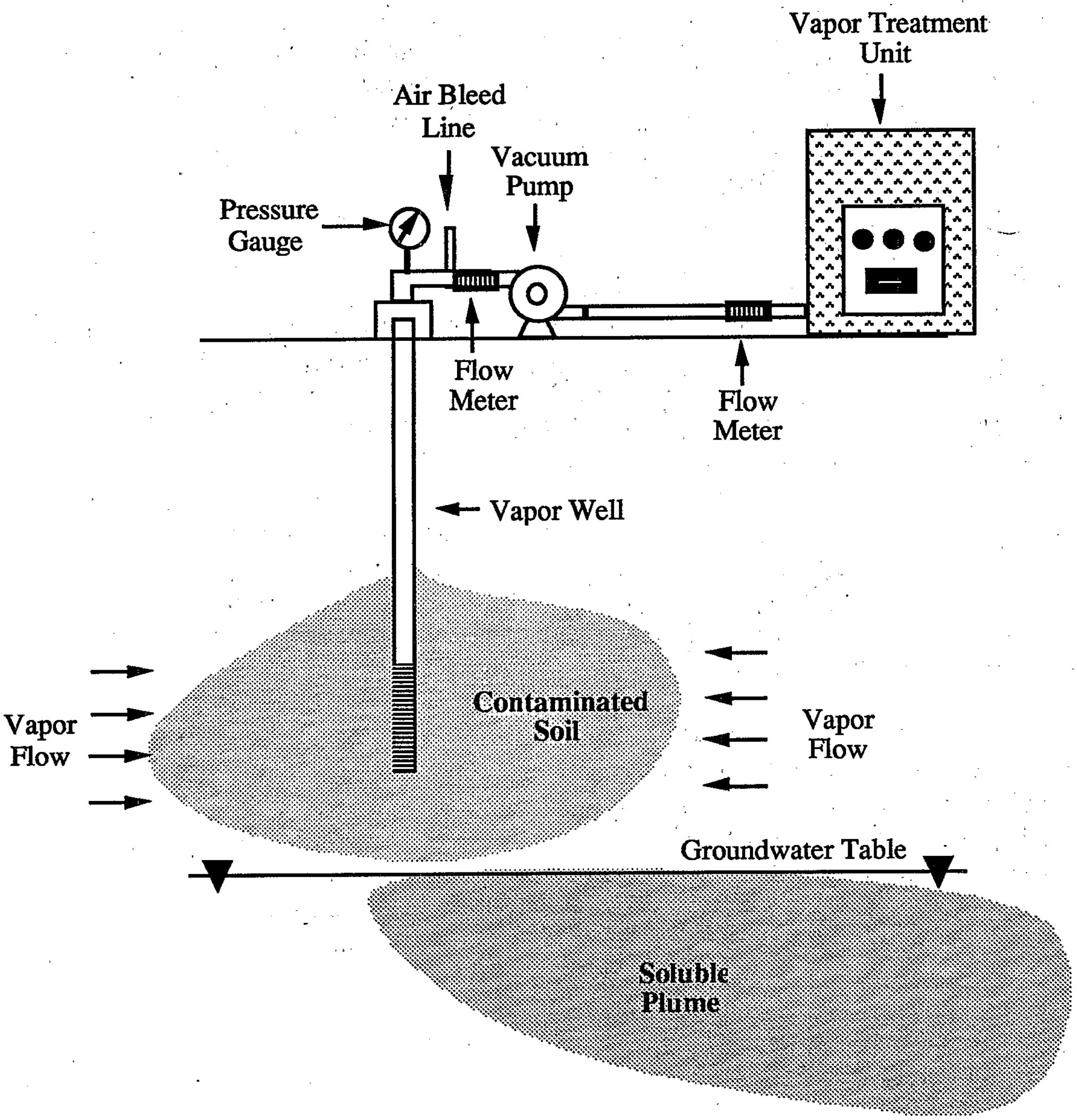


Figure 1. Schematic of a typical vapor extraction operation.

II. *Definition of Some Terms Appearing in this Manual*

button	-	an object on a "card" that causes some action to be performed when "clicked" on
card	-	an individual screen that you view on your monitor
click	-	refers to the pressing and releasing of the button on your mouse
drag	-	refers to holding down the mouse button while moving the mouse
field	-	a text entry location on a "card"
HyperCard	-	a programming environment created by Apple Computer, Inc.
mouse	-	the device used to move the cursor within your monitor
select	-	refers to "dragging" the cursor across a "field"
stack	-	a group, or file, of "cards"

III. *Software/Hardware Requirements*

Apple Macintosh **HyperVentilate** version 1.01 requires an Apple Macintosh (or equivalent) computer equipped with at least 1 MB RAM (2 MB preferable), a hard disk, and the Apple HyperCard Software Program (v 2.0). Check to make sure that your system software is compatible with your version of HyperCard.

IV. *Loading HyperVentilate Software*

HyperVentilate is supplied on an 800 kB double-sided, double density 3.5" diskette. Follow the instructions listed below to insure proper operation of the software.

1) Insert the **HyperVentilate** disk into your computer's floppy drive. The **HyperVentilate** disk should contain the files:

   - "Soil Venting Stack"
   - "Soil Venting Help Stack"
   - "System Design"
   - "Air Permeability Test"
   - "Aquifer Characterization"
   - "Compound List Update"
   - "HypeVent"
   - "f77.rl"

2) Copy these files onto your hard disk. **They must be copied into the folder that contains the "HyperCard" program, or else the software will not operate properly.**

3) Eject the **HyperVentilate** disk

V. *Using HyperVentilate*

The authors of **HyperVentilate** intend it to be an application that requires little pre-training for the user. It is mouse-driven and instructions are included on each card, so please take the time to read them when you first use **HyperVentilate.**

This section of the users manual is divided into three subsections. Start-up instructions are given in the first, basic features of the cards are described in the second, and a sample exercise is presented in the third. For reference, copies of all cards, as well as more details on each are given in Appendices A through F.

V.1. Starting HyperVentilate

1) Those users with color monitors should use the "Control Panel" (pull down the "" menu and select "Control Panel", then click on the "Monitors" icon) to set their monitors to black and white, and two shades of grey.

2) To avoid unnecessary "card-flipping", set the "Text Arrows" option in your "Home" stack "User Preferences" card to on. You can get to this card from within any HyperCard application by selecting "Home" under the "Go" menu. This will take you to the first card in the "Home" stack. At this point click on the left-pointing arrow and the "User Preferences" card will appear on your screen. Then click on the square to the left of "Text Arrows" until an "X" appears in the square.

3) **HyperVentilate** is started by double-clicking on the "Soil Venting Stack" file icon from the Finder (or Desktop), or by choosing "Open" under the "File" menu *(Note that using a more advanced version of HyperCard than the one under which this system was developed (v 2.0) may require you to first "convert" each of the seven HyperCard stacks contained in* ***HyperVentilate***).

4) Your monitor should display the card shown in Figure 2. Note that there are a number of buttons on this card; there are two at the lower left corner, and then each file folder tab is also a button (some cards may contain less obvious "hidden" buttons; try clicking on the authors name on the title card for example). Clicking on any of these will take you to another card. For example, clicking on the "About This Stack" button will take you to the card shown in Figure 3, which gives a brief description about the use of buttons and fields. Read this card well.

5) Explore for a few minutes. Try to see where various buttons will take you, try entering numbers in fields, or play with calculations. Again, just remember to read instructions given on the cards.

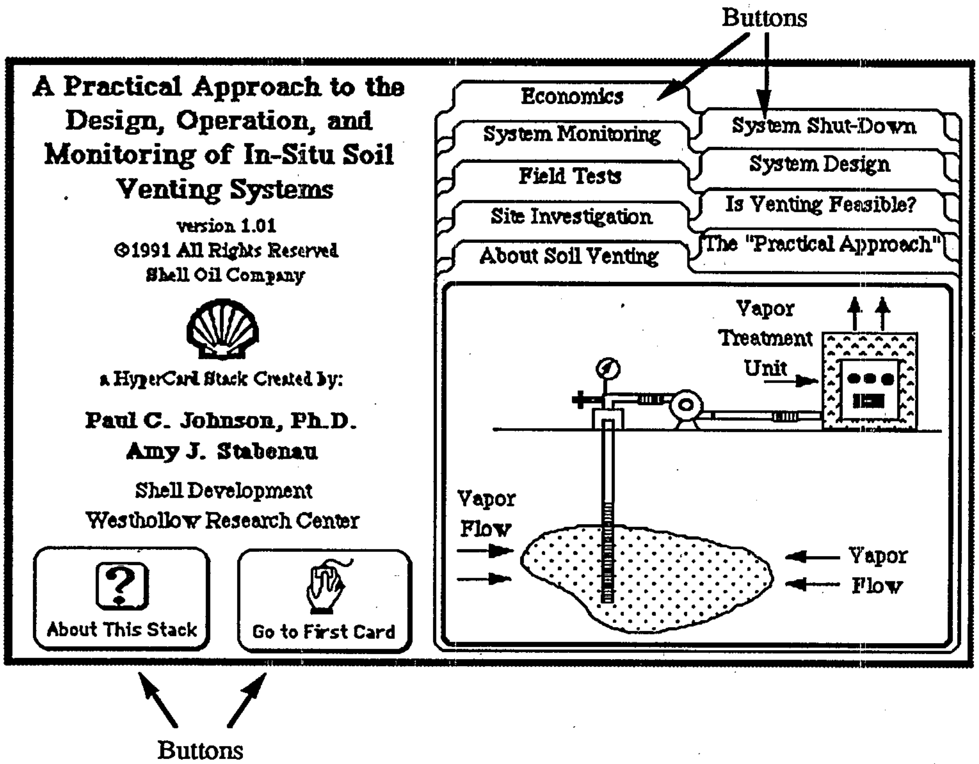


Figure 2. First Card of the "Soil Venting Stack" stack.

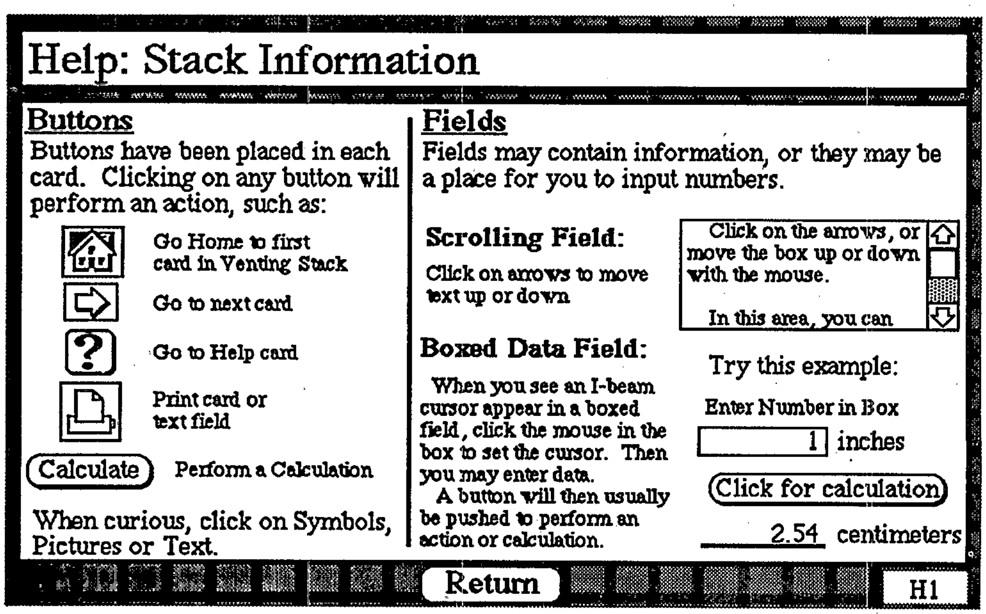


Figure 3. Card H1 of the "Soil Venting Help Stack" stack.

V.2. General Features of Cards

Figures 4 and 5 are examples of cards from the "Soil Venting Stack" stack and "System Design" stack. There are a few general features of these cards that users should understand:

a) Each card (with the exception of the first card of the "Soil Venting Stack" stack) has been numbered for easy reference with the printouts given in Appendices A through F. In the "Soil Venting Stack" these numbers appear in the bottom center of each card (i.e. number "3" in Figure 4). In other stacks these numbers appear at either the top or bottom corners of the card (i.e. "SD1" in Figure 5).

b) Arrow buttons are included at the bottom of some cards. Clicking on right-pointing arrow will advance you to the next card in the stack; clicking on the left-pointing arrow will take you in the opposite direction.

c) The identifying card numbers in the "Soil Venting Stack" stack are also fields into which text can be typed. You can skip to other parts of the "Soil Venting Stack" stack by selecting this field, typing in the card number of your destination (within the "Soil Venting Stack"), and then hitting the "return" key.

d) Many cards have a house button in the lower left corner. Clicking on this button will take you to the first card of the "Soil Venting Stack" stack, which is the card displayed at start-up (see Figure 2).

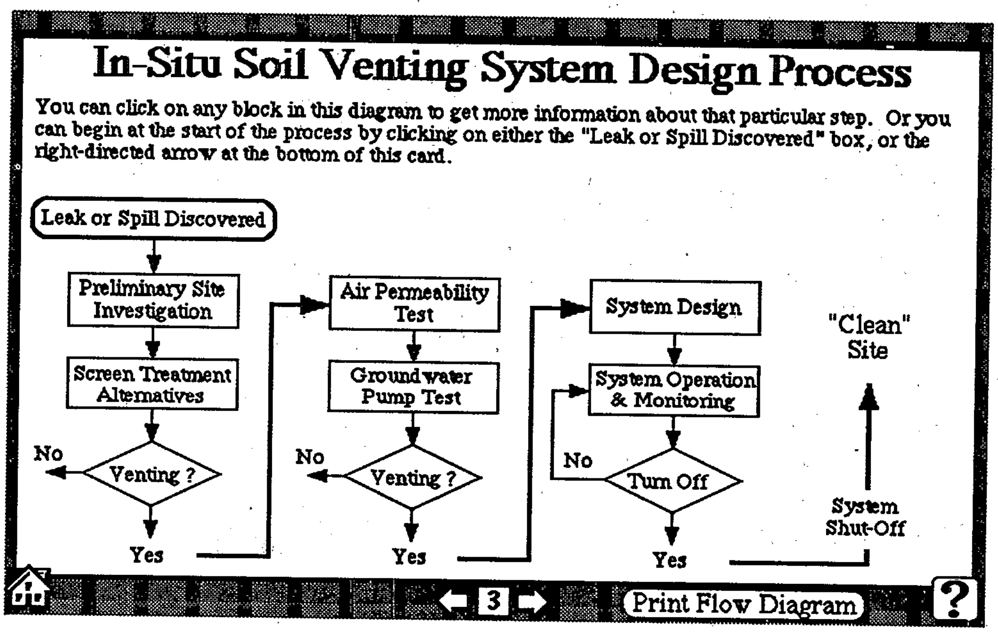


Figure 4. Card 3 of the "Soil Venting Stack" stack.

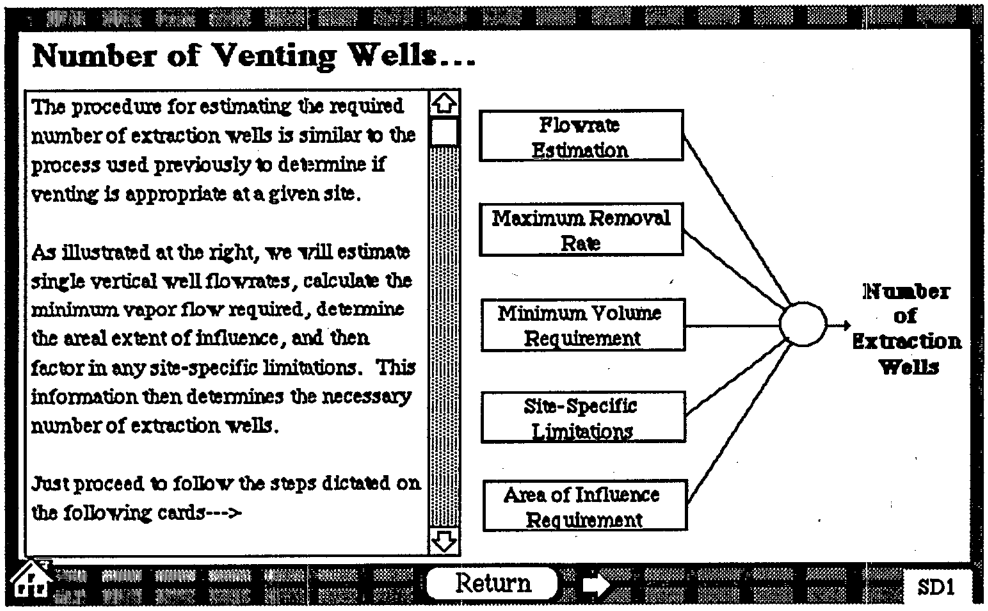


Figure 5. Card SD1 of the "System Design" stack.

V.3. Sample Problem Exercise

In the following a sample problem is executed in excruciating detail. Those not wishing to work along with the example are encouraged to utilize Appendices A through F as references for more details on the less obvious functions of some cards.

This "Sample Problem Exercise" is divided into to four subsections that address: navigating through **HyperVentilate** (§V.3.1), screening sites to see if soil venting is an appropriate technology (§V.3.2), interpreting air permeability test data (§V.3.3), and guidance for designing soil venting systems (§V.3.4).

V.3.1 Navigating Through HyperVentilate

Step 1: Location: The "Desktop" or Finder.
Action: Start-up **HyperVentilate** by double-clicking on the "Soil Venting Stack" icon, or click once on this icon and then choose "Open" from the "File" menu.
Result: **HyperVentilate** will start-up and display the title card (Figure 2).

Step 2: Location: Title Card of the "Soil Venting Stack" stack.
Action: Click on the "About This Stack" button.
Result: You are now at card H1 of the "Soil Venting Help Stack" stack (Figure 3).

Step 3: Location: Card H1 of the "Soil Venting Help Stack" stack.
Action: Play with the buttons and scrolling field. Practice entering a number in the field in front of "inches". Place the cursor in the box. It will change from a hand to an "I-bar" as it enters the field. Hold down the mouse button and drag the I-bar across the entry, which will become hilited. Now type in another number, or hit the delete key. Practice until you feel comfortable selecting text and entering numbers. Then click on the "Click for Calculation" button. When you are done practicing, click on the "Return" button.
Result: Return to the title card of the "Soil Venting Stack" (Figure 2).

Step 4: Location: Title Card of the "Soil Venting Stack" stack.
Action: Click on the "Economics" file folder tab.
Result: You are now at card 27 of the "Soil Venting Stack" stack. Take a quick glance at this card, which is displayed in Figure 6.

Step 5: Location: Card 27 of the "Soil Venting Stack" stack.
Action: Click on the "House" button in the lower left corner.
Result: You are back at the title card (Figure 2).

Step 6: Location: Title card of the "Soil Venting Stack" stack.
Action: Click on the "Go to First Card" button.
Result: You are now at card 1 of the "Soil Venting Stack" stack (Figure 7).

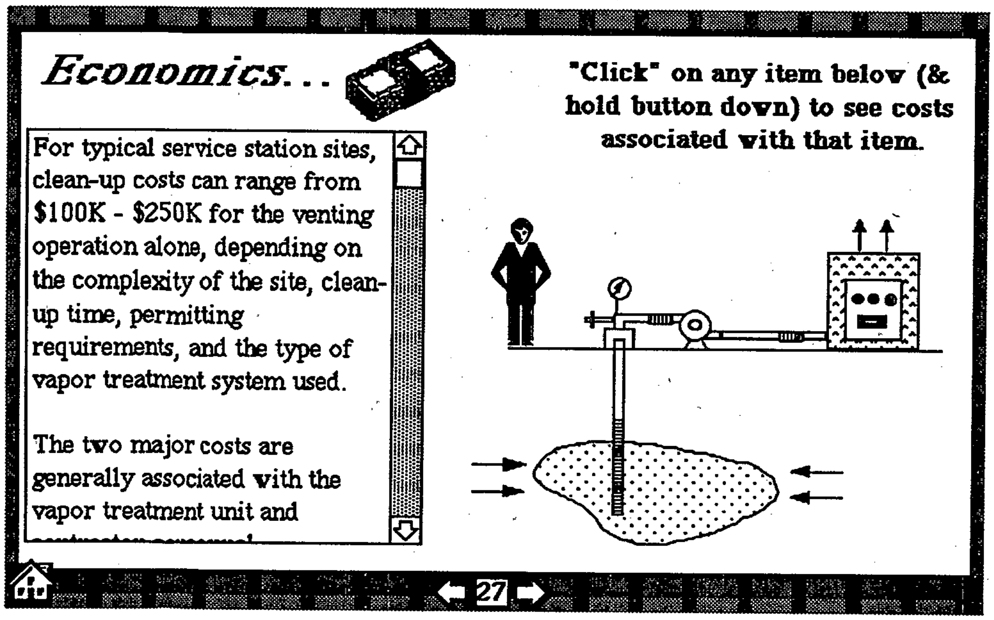


Figure 6. Card 27 of the "Soil Venting Stack" stack.

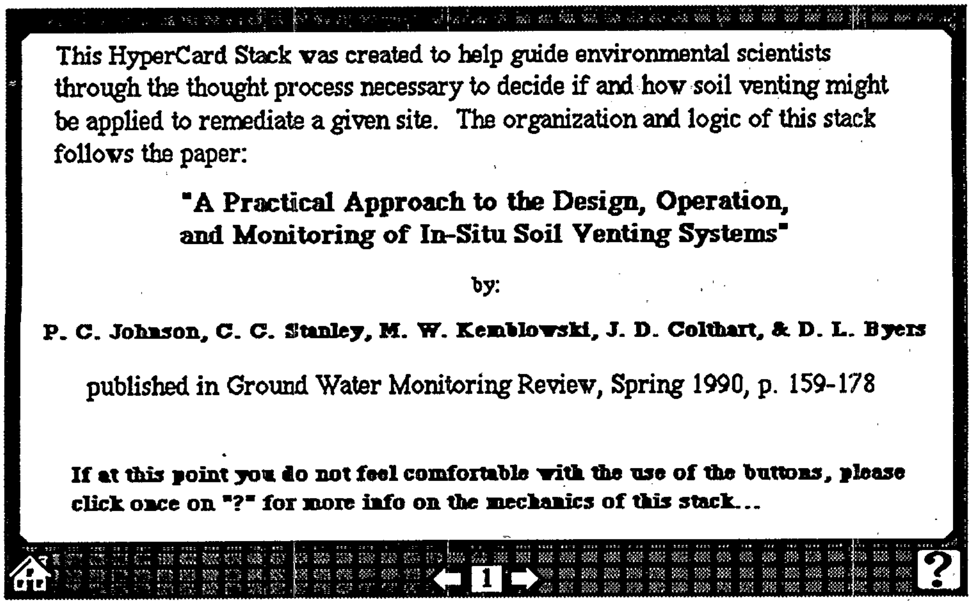


Figure 7. Card 1 of the "Soil Venting Stack" stack.

Step 7: Location: Card 1 of the "Soil Venting Stack" stack.
Action: Click on the right-pointing arrow.
Result: You are now at Card 2 of the "Soil Venting Stack" stack (Figure 8).

Step 8: Location: Card 2 of the "Soil Venting Stack" stack.
Action: Read the text, and click on the "down" and "up" arrows on the displayed text field under "***About Soil Venting...***" to make the field scroll. Then click on the left-pointing arrow at the card bottom.
Result: You are now back at card 1 of the "Soil Venting Stack" (Figure 7).

Step 9: Location: Card 1 of the "Soil Venting Stack" stack.
Action: Click on the right pointing arrow.
Result: You are again at card 2 of the "Soil Venting Stack" stack (Figure 8). By now you should feel comfortable using the left- and right-pointing arrows to travel through the stack.

Step 10: Location: Card 2 of the "Soil Venting Stack" stack.
Action: Click on the "?" button in the lower right corner of the card. This button indicates that there is a "Help" card containing additional information.
Result: You are now at card H2 of the "Soil Venting Help Stack" stack (Figure 9). Scroll through the list of references, then click on the "Return" button to return to card 2 of the "Soil Venting Stack" stack.

At this point you should feel comfortable navigating around in **HyperVentilate**.

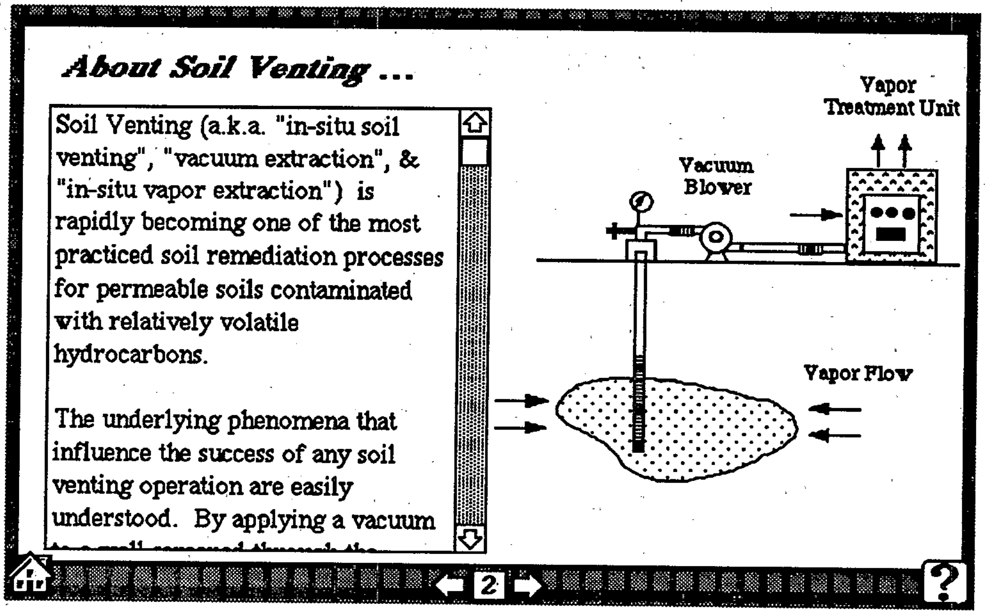


Figure 8. Card 2 of the "Soil Venting Stack" stack.

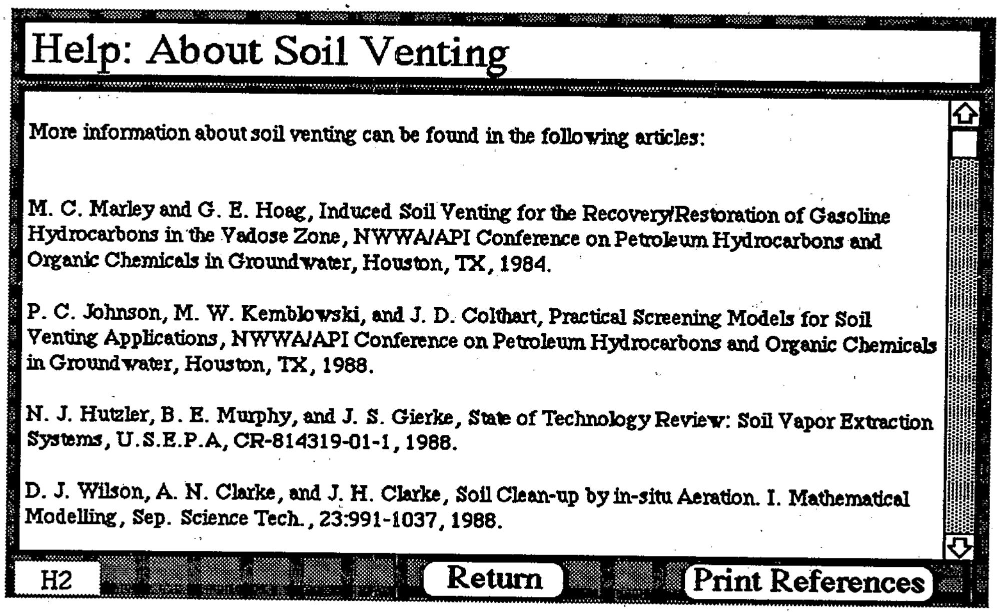
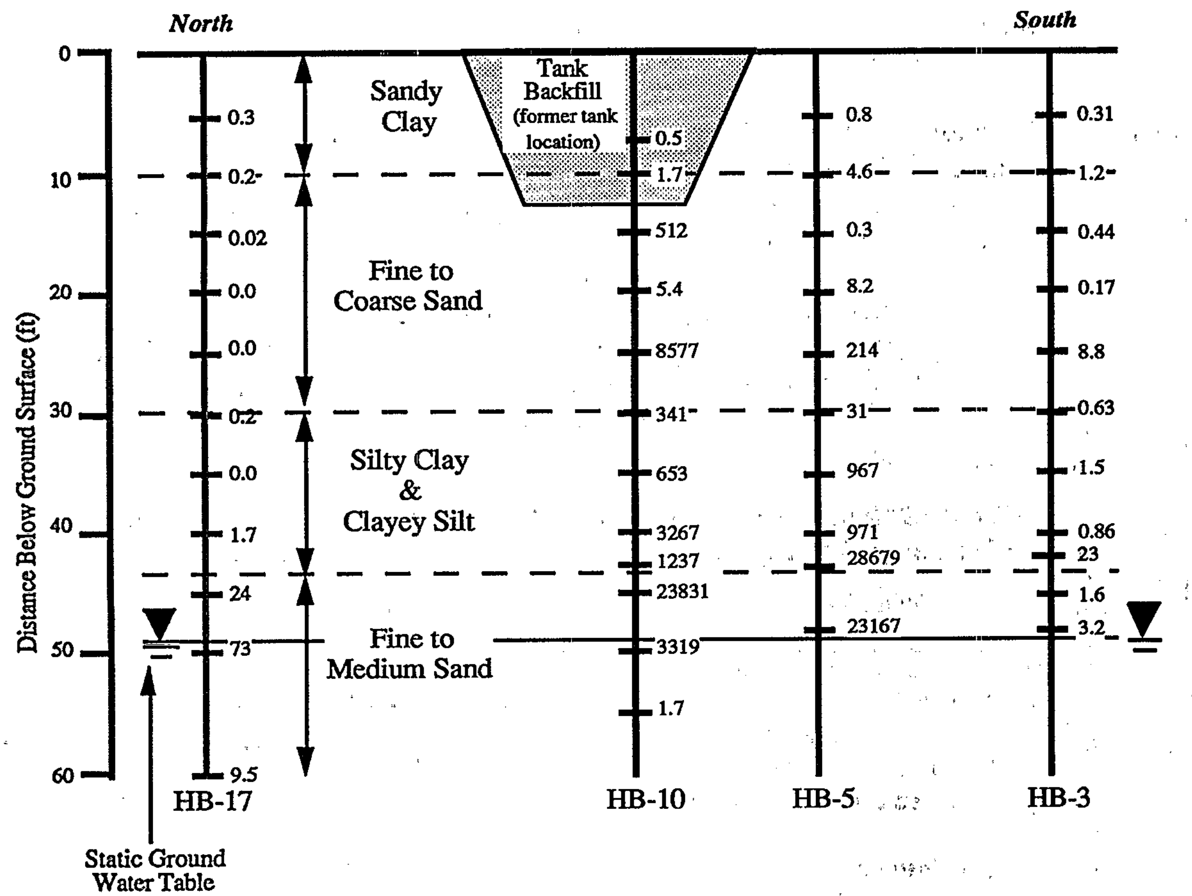


Figure 9. Card H2 of the "Soil Venting Help Stack" stack.

V.3.2 Sample Problem Exercise - Is Venting Appropriate?

In §V.3.2. you will work through an example problem to illustrate how one might decide if venting is appropriate at any given site. For the purpose of this example we will use the example site information given in Figure 10.



Contamination Type: Weathered Gasoline

Figure 10. Sample site data (Johnson et al. [1990a]). Total petroleum hydrocarbons (TPH) [mg/kg] values are noted for each boring.

Using your newly developed navigational skills and the right pointing arrow located at the bottom of each card, slowly step your way through the stack until you reach card 7 of the "Soil Venting Stack" stack (Figure 11). Take your time to read the text and "Help" cards associated with each card along the way.

Step 1: Location: Card 7 of the "Soil Venting Stack" stack.
Action: Read this card. It explains the process that you will use to decide if venting is appropriate. Then advance to card 8 of the "Soil Venting Stack" stack.
Result: You are now at card 8 of the "Soil Venting Help Stack" stack (Figure 12).

Step 2: Location: Card 8 of the "Soil Venting Help Stack" stack.
Action: Read the instructions on this card. Take the time to read the information on the two "Help" cards: "Info about Calculation" and "About Soils (& Unit Conversions)".

Now we will evaluate the efficacy of applying in situ soil venting to the lower soil zone (45 - 50 ft below ground surface) in Figure 10, which is composed of fine to medium sands. It also is the zone of highest hydrocarbon residual levels (>20000 mg/kg TPH in some areas).

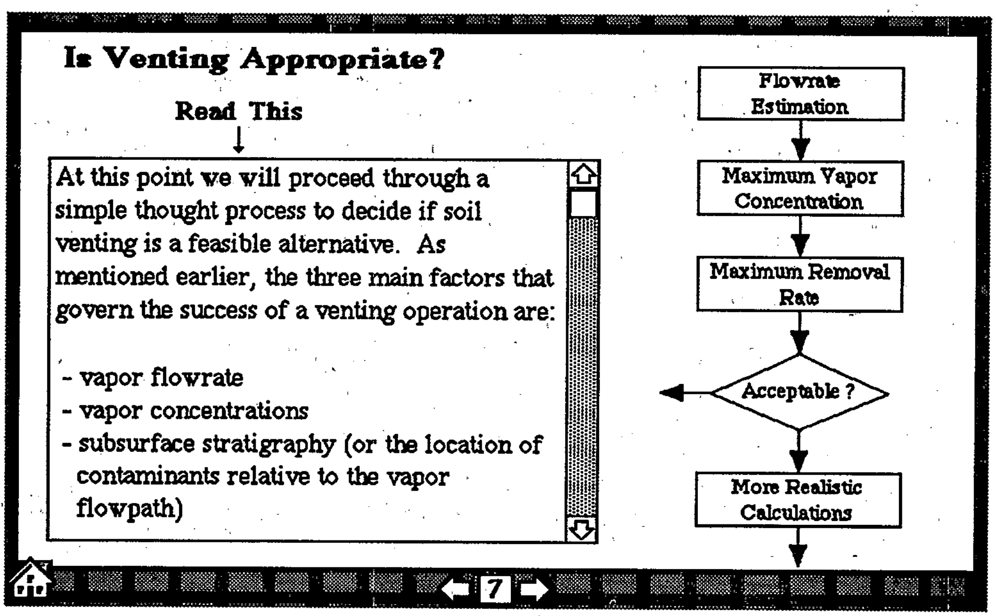


Figure 11. Card 7 of the "Soil Venting Stack" stack.

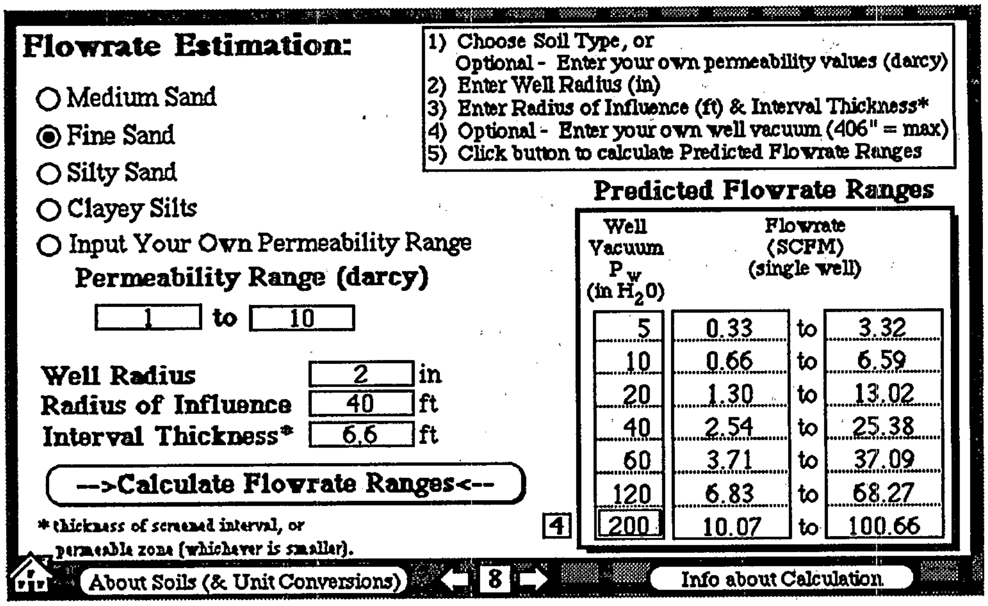


Figure 12. Card 8 of the "Soil Venting Stack" stack.

Step 3:	Location:	Card 8 of the "Soil Venting Stack" stack.
	Action:	Choose the "Fine Sand" soil type, and enter: well radius = 2 in radius of influence = 40 ft interval thickness = 6.6 ft user input vacuum = 200 in H_2O into the appropriate fields, then click on the "-->Calculate Flowrate Ranges<--" button.
	Result:	The flowrate ranges are calculated and displayed. Your screen should now look like Figure 12. The calculated values are estimates of the flowrate to a single vertical well (and are only valid estimates when your conditions are consistent with the assumptions built into the calculation - see Johnson et al. [1990a, b] for more details).
Step 4:	Location:	Card 8 of the "Soil Venting Stack" stack.
	Action:	Click on the right pointing arrow to advance to card 9. Read the information on this card, then advance to card 10
	Result:	You are now at card 10 of the "Soil Venting Stack" stack (see Figure 13).
Step 5:	Location:	Card 10 of the "Soil Venting Stack" stack.
	Action:	Assume that the soil temperature at our sample site is 18° C. Enter this value in the appropriate field, then hit the "return" key. This action clears all values from the other fields.

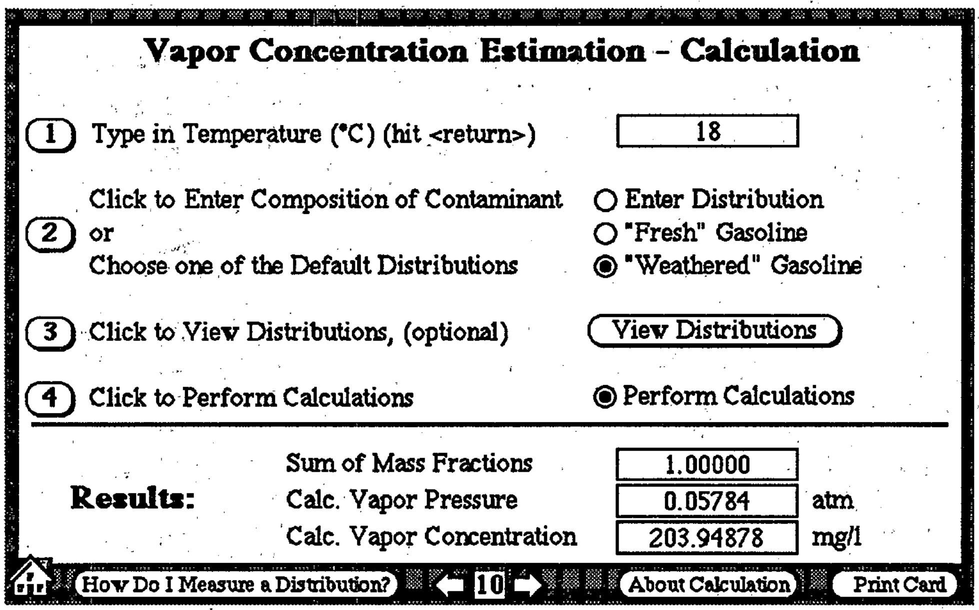


Figure 13. Card 10 of the "Soil Venting Stack" stack.

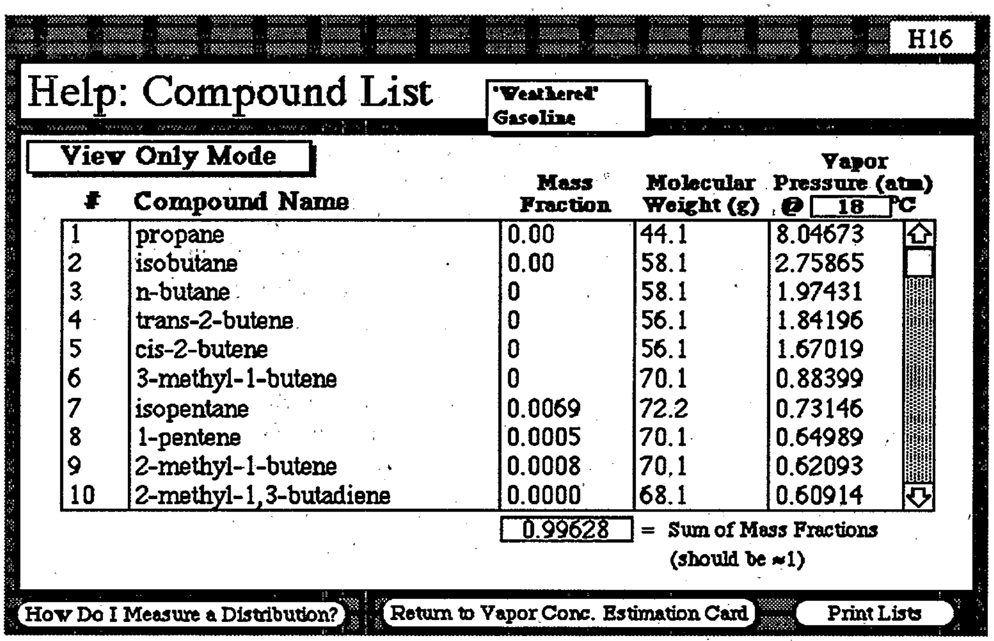


Figure 14. Card H16 of the "Soil Venting Help Stack" stack.

At this site the residual hydrocarbon is a "weathered" gasoline, so choose this selection from the three composition options listed. The "Fresh" and "Weathered" gasoline selections correspond to pre-programmed compositions that are useful for estimation purposes. If you knew the composition of your residual, then you could enter it by selecting the "Enter Distribution" option. Click on the "View Distributions" button to take a look at the compound library and the pre-specified composition of "weathered" gasoline.

Result: You are now at card H16 of the "Soil Venting Help Stack" stack (see Figure 14).

Step 6: Location: Card H16 of the "Soil Venting Help Stack" stack.
Action: View the library and pre-specified composition. If you are interested, explore some of the help cards. Then click on the "Return to Vapor Conc. Estimation Card" button to return to card 10 of the "Soil Venting Stack" stack.
Result: You are now at card 10 of the "Soil Venting Stack" stack (Figure 13).

Step 7: Location: Card 10 of the "Soil Venting Stack" stack.
Action: Click on the "Perform Calculations" button.
Result: **HyperVentilate** calculates the maximum possible vapor concentration corresponding to the specified composition and temperature. The results are displayed in Card 10 of the "Soil Venting Stack" stack, which should now look like Figure 13.

Step 8: Location: Card 10 of the "Soil Venting Stack" stack.
Action: Using the right-pointing arrow button, advance to card 11 of the "Soil Venting Stack" stack. Take the time to read the text, then click on the "Calculate Estimates" button
Result: You are at card 12 of the "Soil Venting Stack" stack. The calculated flowrates and maximum possible removal rates are displayed along with an updated list of the input parameters that you have entered. Your screen should look like Figure 15, if you have chosen the "lb/d" units.

Step 9: Location: Card 12 of the "Soil Venting Stack" stack.
Action: Click on the right-pointing arrow button. You are now at card 13 of the "Soil Venting Stack" stack. Read the text, then enter:
estimated spill mass = 4000 kg
desired remediation time = 180 d
Now click on the "-->Press to Get Rates<--" button

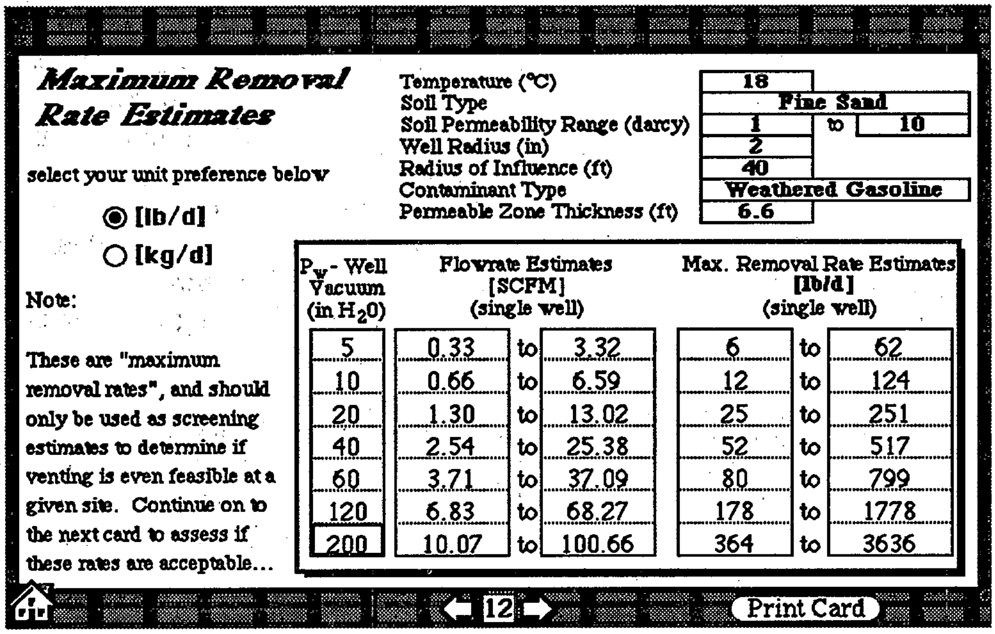


Figure 15. Card 12 of the "Soil Venting Stack" stack.

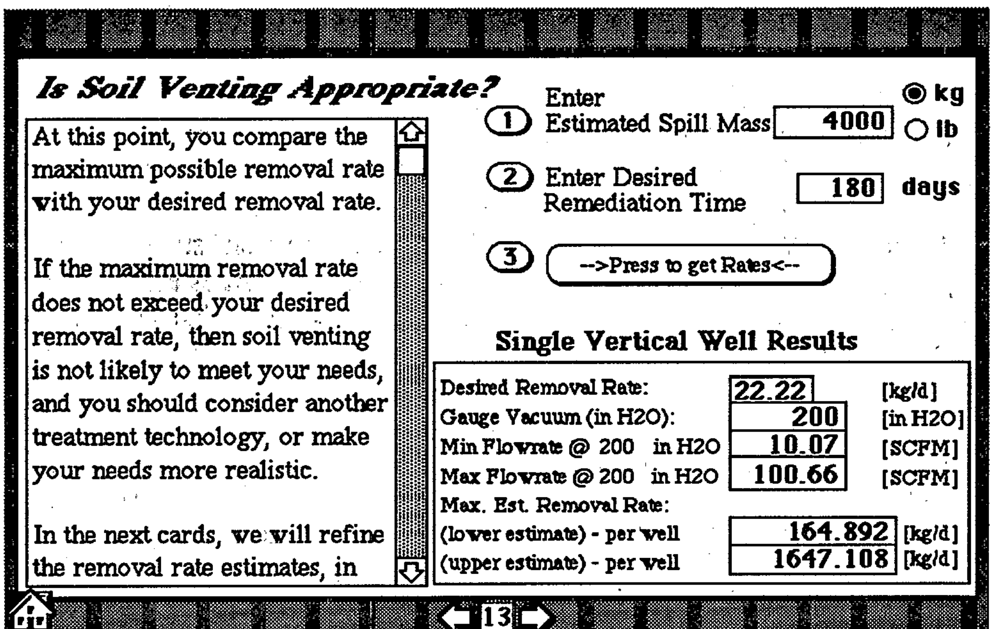


Figure 16. Card 13 of the "Soil Venting Stack" stack.

Result: Your screen should now look like Figure 16. Note that your desired removal rate (=22 kg/d) is less than the estimated maximum removal rates for a single vertical well (=165 to 1650 kg/d). At this point in the screening exercise, therefore, soil venting still appears to be a viable option.

Step 10: Location: Card 13 of the "Soil Venting Stack" stack.

Action: Click on the right-pointing arrow button to advance to card 14 of the "Soil Venting Stack" stack. Read the text, then advance to card 15 of the "Soil Venting Stack" by clicking on the right-pointing arrow button. Again, take the time to read the text, then advance to card 16 of the "Soil Venting Stack" stack. The focus of these cards is the prediction of vapor concentrations and removal rates as they change with time due to composition changes. It is important to try to understand the concepts introduced in these cards.

Result: You are at card 16 of the "Soil Venting Stack" stack (see Figure 17).

Step 11: Location: Card 16 of the "Soil Venting Stack" stack.

Action: This card is used to finalize your input data prior to calculating vapor concentration and residual soil contamination composition changes with time. Read the instructions in the order that they are numbered. Note that the summary table in the upper right corner of the card contains all the parameter values that you have input thus far. The instructions describe how to change these values, but at this point we will retain the displayed values. Because it is difficult to present the behavior of each compound in a mixture composed of an arbitrary number of compounds, the output is simplified by reporting the behavior in terms of "boiling point" ranges. This simply represents a summation of all compounds whose boiling points fall between pre-specified values. Presented in this fashion, the model results can be interpreted much more quickly. Click on the "tell me more about BP ranges..." button, read the help card, then return to card 16 of the "Soil Venting Stack" stack. Click on the "-->Set Default BP Ranges<--" button. Your screen should now look like Figure 17. Click on the "Generate Predictions" button

Result: The message "Sit Back and Relax..." will appear on your screen, followed by a screen on which the following appears:

"Copyright © Absoft Corp 1988
Copyright © Shell Oil Co 1990
HANG ON ----- YOU WILL BE RETURNED TO HYPERCARD...
OF COMPOUNDS IN LIBRARY = 62"

Then card 17 of the "Soil Venting Stack" stack will appear.

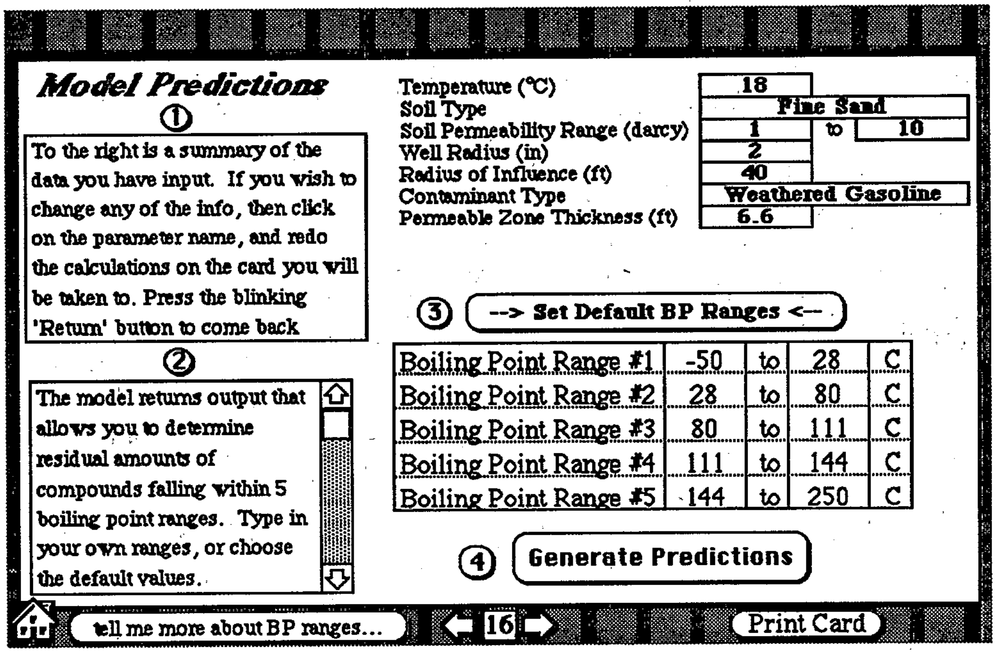


Figure 17. Card 16 of the "Soil Venting Stack" stack.

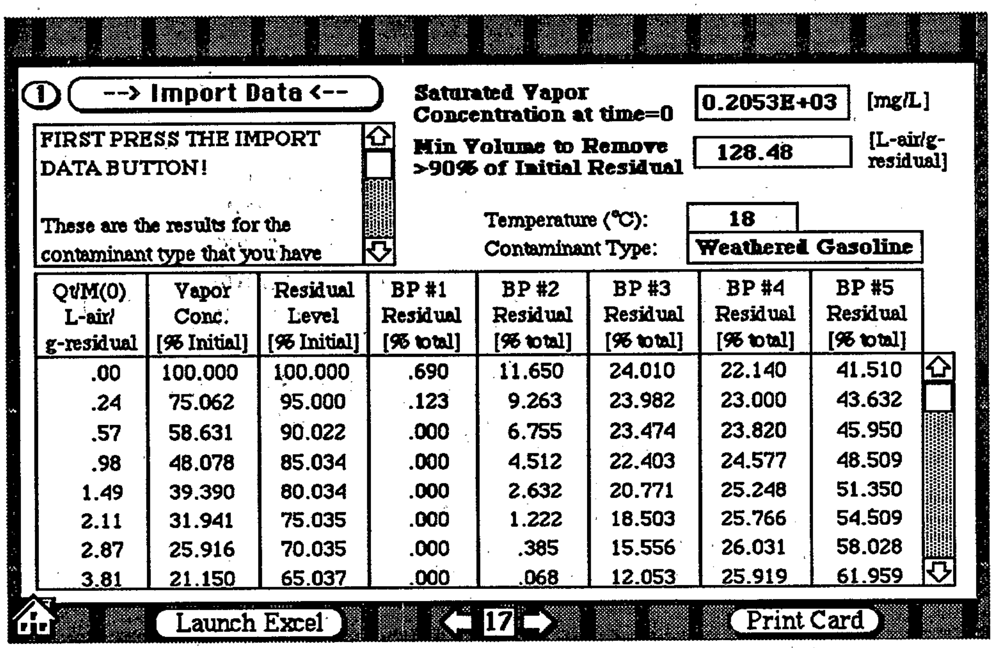


Figure 18. Card 17 of the "Soil Venting Stack" stack.

Step 12: Location: Card 17 of the "Soil Venting Stack" stack.
Action: Read the instructions, then click on the "-->Import Data<--" button.
Result: Your screen should look like Figure 18. The table in the lower part of the card lists model predictions: vapor concentration and residual soil concentration (expressed as a percentage of their initial values), as well as the composition of the residual (expressed as a percentage of the total for each boiling point range) as a function of the amount of air drawn through the contaminated soil. Note that as the volume of air drawn through the soil increases, the vapor concentration and residual soil levels decrease, and the composition of the residual becomes richer in the less volatile compounds (BP Range #5). In the upper right corner of the card are displayed the saturated, or initial, vapor concentration and the minimum amount of air that must be drawn through the soil per gram of initial contaminant to achieve at least a 90% reduction in the initial residual level. This value is used in future calculations as a design parameter.

Step 13: Location: Card 17 of the "Soil Venting Stack" stack.
Action: Click on the right-pointing arrow to advance to card 18 of the "Soil Venting Stack" stack.
Result: You are at card 18 of the "Soil Venting Stack" stack, which should resemble Figure 19. Read the text. A summary of your input parameters appears on the right side of this card. At the bottom appears two calculated values representing the range of the minimum number of wells required to achieve a 90% reduction in the initial residual level in the desired remediation time. These values correspond to idealized conditions, however, they can be used to gauge the efficacy of soil venting at your site. For example, in this case the minimum number of wells ranges between 0.7 - 7, which is not an unreasonable number for a site the size of a service station. If the range had been 100 - 1000, then it might be wise to consider other remediation options.

It is important to recognize that model predictions are intended to serve as guidelines, and are limited in their ability to describe behavior that might be observed at any given site. One should use all the information available, in addition to idealized model predictions to make rational decisions about the applicability of soil venting.

Step 14: Location: Card 18 of the "Soil Venting Stack" stack.
Action: Click on the right-pointing arrow button to advance to card 19.
Result: You are now at card 19 of the "Soil Venting Stack" stack. This card lists several phenomena that can cause one to achieve less than ideal removal rates. Take the time to explore each of these options, then return to card 19 of the "Soil Venting Stack" stack.

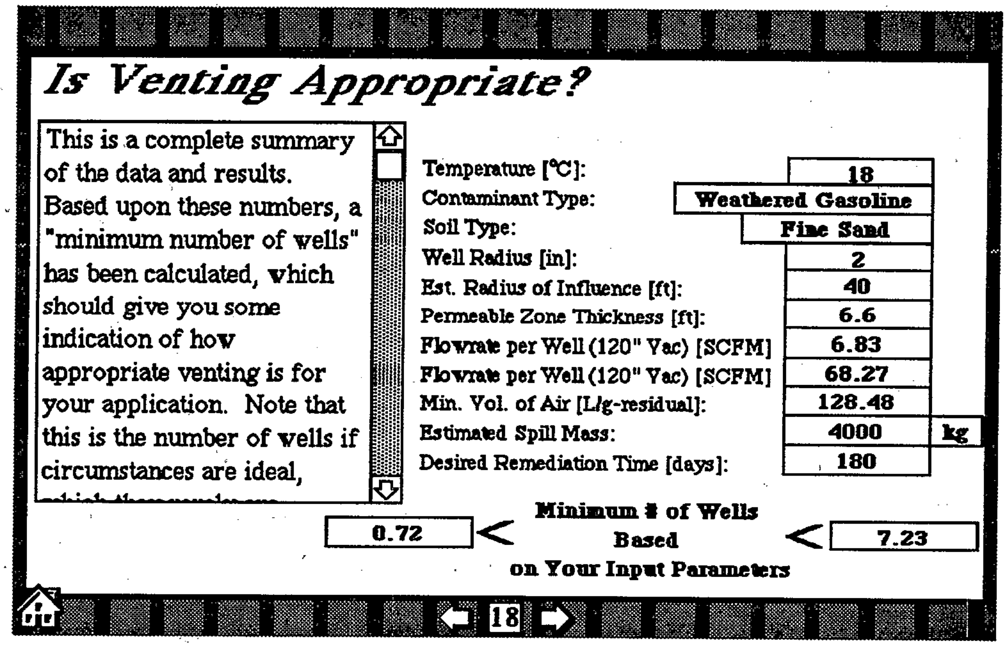


Figure 19. Card 18 of the "Soil Venting Stack" stack.

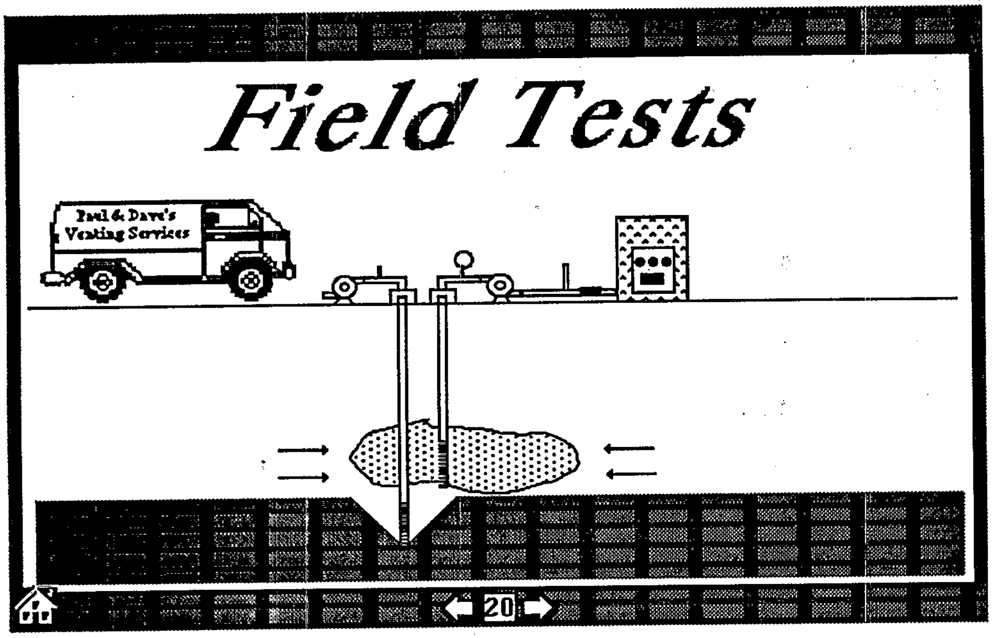


Figure 20. Card 20 of the "Soil Venting Stack" stack.

V.3.3 Sample Problem Exercise - Field Permeability Test.

Note: *It is recommended that you always plot and visually inspect your data prior to attempting to fit it to any theory.*

In this example, we use **HyperVentilate** to analyze air permeability test data from the site pictured in Figure 10. We will focus on results from the lower fine to medium sand zone (45 - 50 ft below ground surface). Advance to card 20 (Figure 20) of the "Soil Venting Stack" stack to begin.

Step 1:
Location: Card 20 of the "Soil Venting Stack" stack.
Action: Using the right-pointing arrow, advance to card 21 of the "Soil Venting Stack" stack. Read the text, then click on the "Air Permeability Test" button.
Result: You are at card AP1 of the "Air Permeability Test" stack.

Step 2:
Location: Card AP1 of the "Air Permeability Test" stack
Action: Read the instructions, then click on the "Show Me Set-up" button. Take a look at the figure, then click the "Return" button to return to card AP1 of the "Air Permeability Test" stack. Now click on the "Test Instructions" button.
Result: You are at card AP3 of the "Air Permeability Test" stack.

Step 3: Location: Card AP3 of the "Air Permeability Test" stack.
Action: Read the text, look at the sample data (click on the "show me sample data" button) then enter the following values for this example:

soil layer thickness	= 6.6 ft
estimated radius of influence	= 50 ft
air permeability test flowrate	= 15 CFM

Click on the "-->Calculate<--" button to estimate how long the air permeability test should be conducted.
Result: Your results should match those displayed below in Figure 21.

Step 4: Location: Card AP3 of the "Air Permeability Test" stack.
Action: Click on the "Return" button to return to card AP1 of the "Air Permeability Test" stack. Then click on the "Data Analysis" button.
Result: You are now at card AP5 of the "Air Permeability Test" stack.

Step 5: Location: Card AP5 of the "Air Permeability Test" stack.
Action: Read the text, then step through cards AP6 and AP7, until you reach card AP8 of the "Air Permeability Test" stack.
Result: You are now at card AP8 of the "Air Permeability Test" stack.

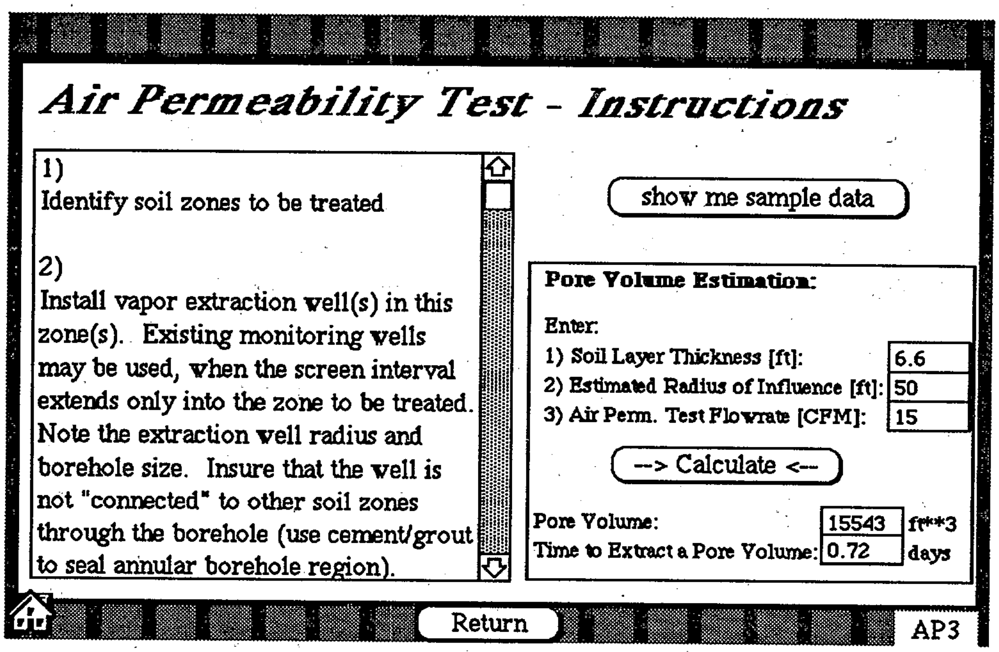


Figure 21. Card AP3 of the "Air Permeability Test" stack.

Step 6: Location: Card AP8 of the "Air Permeability Test" stack.
Action: Read the text, click the "clear" buttons to clear any entries from columns, then enter the following data:

r = 53 ft		r = 32.4 ft	
Time [min]	Gauge Vacuum [in H_2O]	Time [min]	Gauge Vacuum [in H_2O]
9	0.1	4	1.2
11	0.2	7	3.0
15	0.2	9	4.3
23	0.4	12	5.5
30	0.7	16	6.9
40	1.3	24	9.9
100	2.8	30	11
		39	13
		52	16
		77	20
		99	21
		110	23
		121	24.5
		141	25.5

flowrate = 15 SCFM
screened interval thickness = 6.6 ft

While entering the data it is convenient to place the curser in the time column, type in the time value, then use the "tab" key to advance to the vacuum reading column. Enter the corresponding vacuum value, then hit the "tab key again. As you see, this advances the curser to the time column again. Now click the "-->Calculate<--" button.

Result: Your results should match those displayed in Figure 22. Soil permeability values have been calculated by fitting the field data to the theoretical model described in cards AP5 - AP7 of the "Air Permeability Test" stack.

Step 7: Location: Card AP8 of the "Air Permeability Test" stack.
Action: Review the results, then click on the "Explanation & Statistics" button. This advances you to card AP9 of the "Air Permeability Test" stack, which lists correlation coefficients for the data fitting process. These values give an indication of how well the model describes the behavior observed in the field. Values approaching unity indicate a good fit. Your results should match those given in Figure 23.

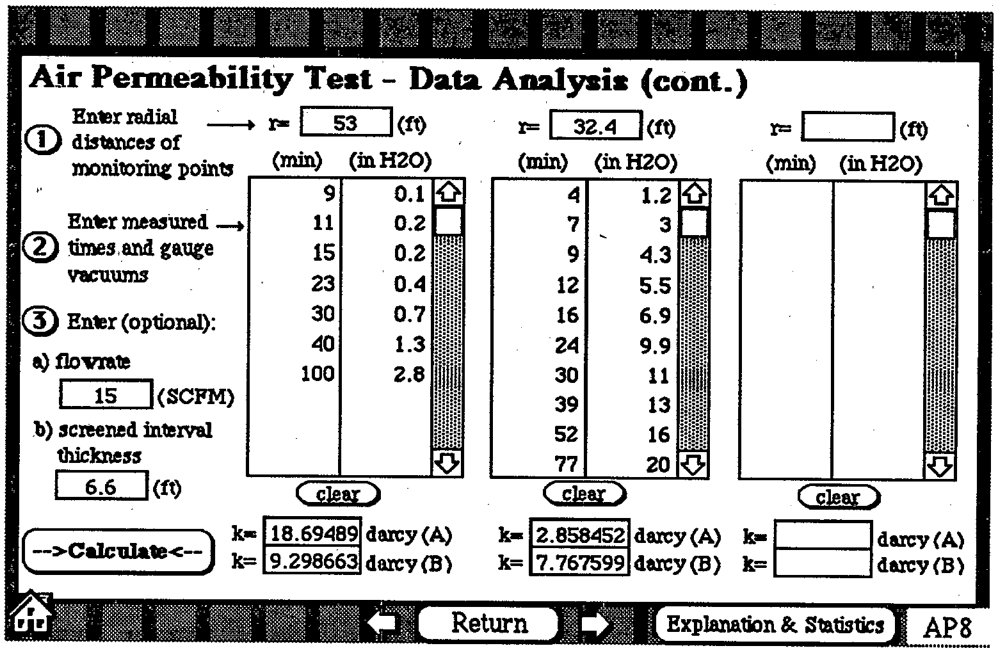


Figure 22. Card AP8 of the "Air Permeability Test" stack.

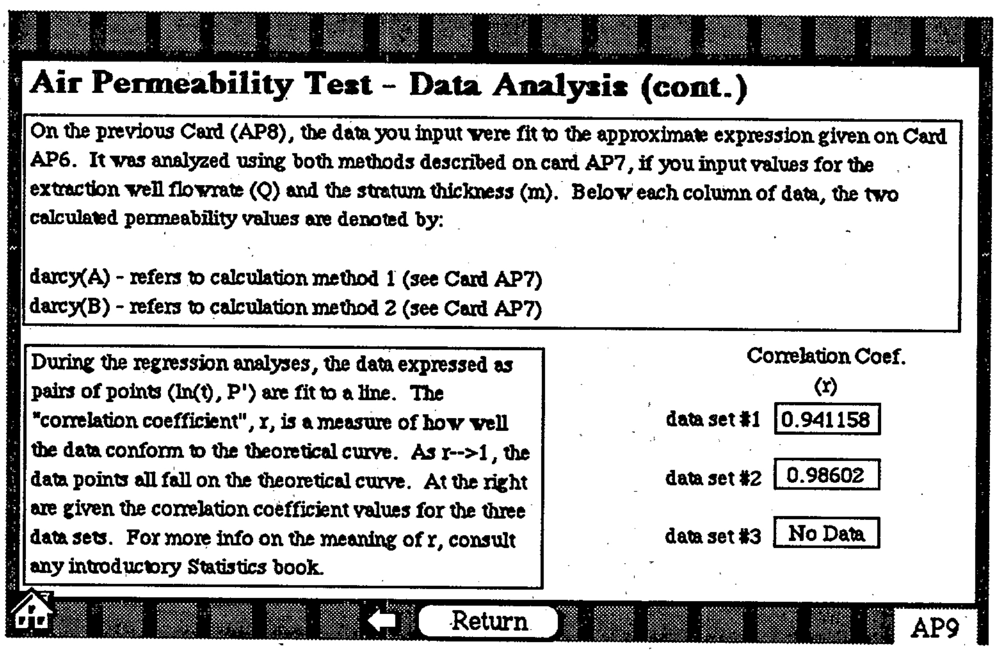


Figure 23. Card AP9 of the "Air Permeability Test" stack.

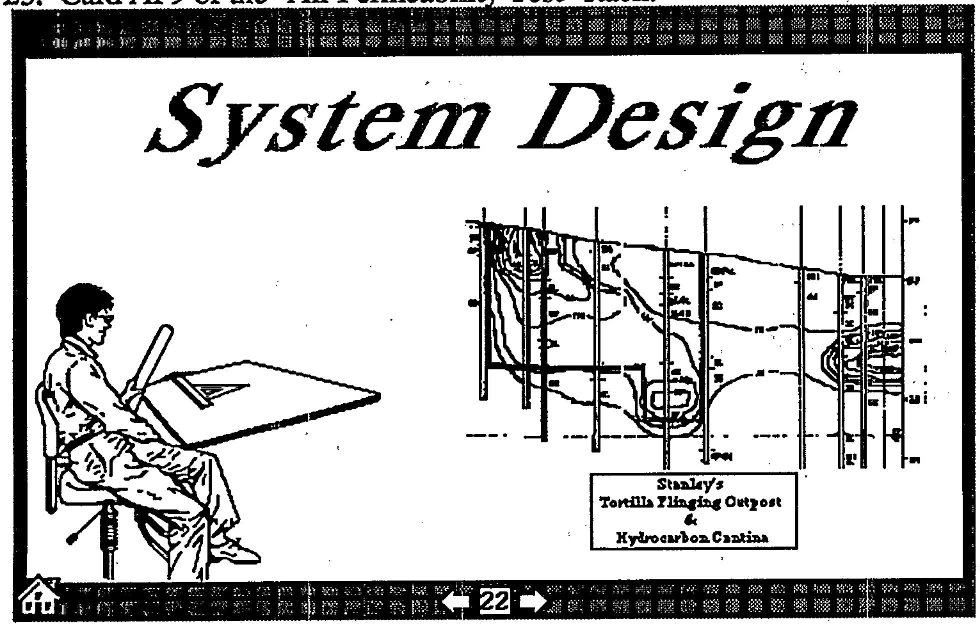


Figure 24. Card 22 of the "Soil Venting Stack" stack.

V.3.4 Sample Problem Exercise - System Design

In this example we illustrate the use of HyperVentilate for system design guidance. As in §V.3.2 and §V.3.3, we use the sample site presented in Figure 10. At this site gasoline was detected in three distinct soil strata: a fine to coarse zone located 10 - 30 ft below ground surface (BGS), a silty clay/clayey silt zone located 30 to 42 ft BGS, and a fine to medium sand zone that extends from 42 ft BGS to the deepest soil boring (60 ft BGS). Groundwater is detected in monitoring wells at about 50 ft BGS.

Advance to card 22 of the "Soil Venting Stack" stack to begin (Figure 24).

Step 1:	Location:	Card 22 of the "Soil Venting Stack" stack.
	Action:	Use the right-pointing arrow to advance to card 23 of the "Soil Venting Stack" stack. Read the text, then advance to card 24 of the "Soil Venting Stack" stack.
	Result:	Card 24 of the "Soil Venting Stack" stack, which appears in Figure 25, should be displayed.
Step 2:	Location:	Card 24 of the "Soil Venting Stack" stack.
	Action:	Read the text, explore using some of the options. You will find that the options: "Well Location", "Well Construction", "Surface Seals", "Groundwater Pumping System", and "Vapor Treatment" provide some useful guidance information on aspects and components of a soil venting system. Return to card 24.

Result: Card 24 of the "Soil Venting Stack" stack should be displayed.

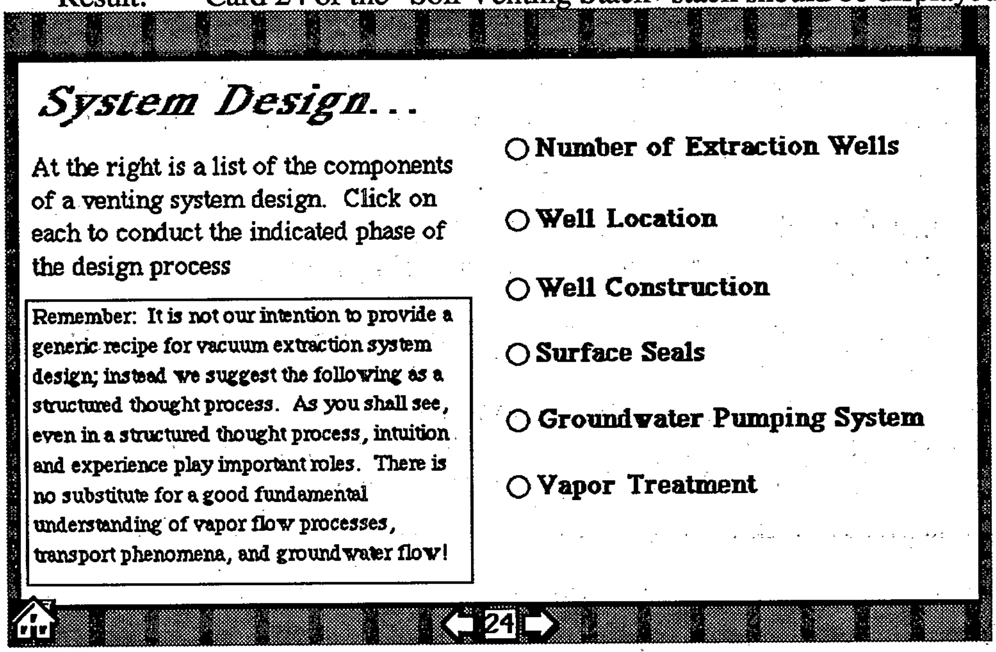


Figure 25. Card 24 of the "Soil Venting Stack" stack.

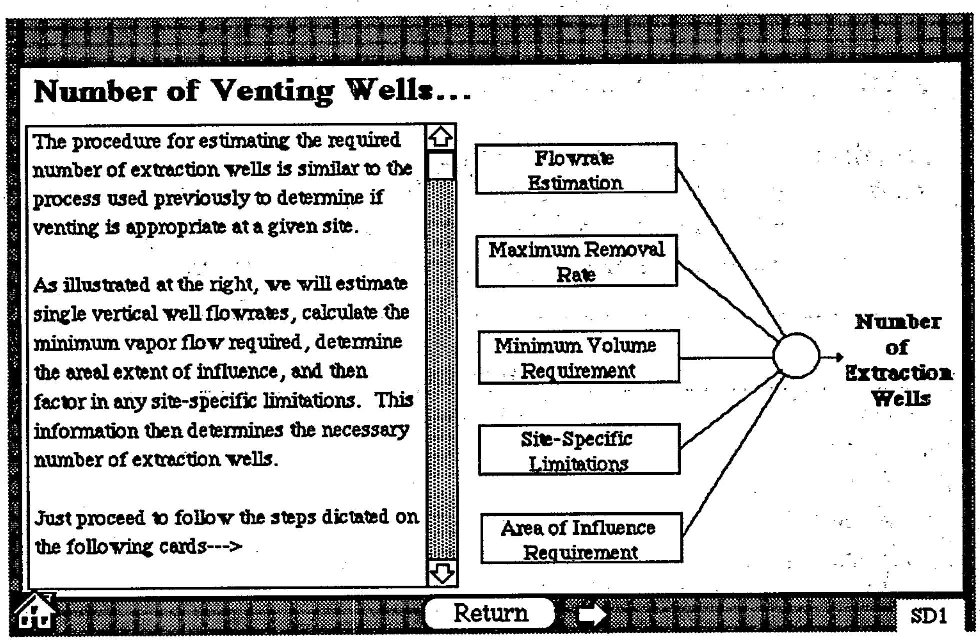


Figure 26. Card SD1 of the "System Design" stack.

Step 3: Location: Card 24 of the "Soil Venting Stack" stack.
Action: Select "Number of Extraction Wells" from the list of options.
Result: Card SD1 of the "System Design" stack should be displayed, as pictured in Figure 26.

Step 4: Location: Card SD1 of the "System Design" stack.
Action: Read the text, then use the right-pointing arrow to advance to card SD2.
Result: Card SD2 of the "System Design" stack should be displayed.

Step 5: Location: Card SD2 of the "System Design" stack.
Action: Read the instructions on the card, enter the following values into the table, then click on the "Update" button:

	Soil Zone		
Parameter	**Medium Sand**	**Clayey Silt**	**Fine Sand**
subsurface interval (ft BGS)	10 -30	30 - 43	43 - 50
description of contaminant	gasoline	gasoline	gasoline
radial extent of contamination (ft)	20	20	20
interval thickness (ft)	20	13	7
average contaminant concentration	100	1000	10000

Result: Card SD2 should now resemble Figure 27.

Step 6: Location: Card SD2 of the "System Design" stack.
Action: Use the right-pointing arrow to advance to card SD3 of the "System Design" stack.
Result: Card SD3 of the "System Design" stack should be displayed.

Step 7: Location: Card SD3 of the "System Design" stack.
Action: Read the text. Note that "clicking" on many of the table headings will take you to "help" cards. Take a few minutes to explore the use of these, then enter the following information:

	Soil Zone		
Parameter	**Medium Sand**	**Clayey Silt**	**Fine Sand**
permeability (darcy)	10 - 100	0.01 - 0.1	1 - 10
design vacuum (in H_2O)	40	40	40
Well Construction:			
Radius of Influence (ft)	40	40	40
Extraction Well Radius (in)	2	2	2
Extraction Well Screen Thickness (ft)	10	5	5

Design Input Parameters...

(soil stratigraphy & contaminant characteristics)

Please enter the required information for each distinct soil layer, click on the "Update" button, and then proceed to the next card (i.e. click on right arrow at bottom).
(the tab key can be used to move between cells)

Select the total mass units that you prefer ◉ [kg] ○ [lb]

Clear All Entries

	Description of Soil Unit	Depth BGS* [ft]			Description of Contamination	Contaminant Distribution radius [ft]	interval thickness [ft]	average conc. [mg/kg]	Calc. Total Mass [kg]
1	Medium Sand	10	to	30	gasoline	20	20	100	120.9
2	Clayey Silt	30	to	43	gasoline	20	13	1000	786.0
3	Fine Sand	43	to	50	gasoline	20	7	10000	4232.3
4			to						0.0
5			to						0.0
6			to						0.0
7			to						0.0
8			to						0.0

* Below Ground Surface

Update

Return

SD2

Figure 27. Card SD2 of the "System Design" stack.

Design Input Parameters...

Please enter the required information for each distinct soil layer, and then proceed to the next card.

Note: - click on any table heading to get more info
- use tab key to move between cells

○ Medium Sand
○ Fine Sand
○ Silty Sand
○ Clayey Silts

	Description of Soil Unit	Permeability* [darcy]			Design Vacuum (in H2O)	Extraction Well Construction: well radius [in]	screen thickness [ft]	radius of influence [ft]	Critical Volume of Air** [L/g]	Efficiency (%)
1	Medium Sand	10	to	100	40	2	10	40	128.48	100
2	Clayey Silt	0.01	to	.1	40	2	5	40	128	100
3	Fine Sand	1	to	10	40	2	5	40	128	100
4			to							
5			to							
6			to							
7			to							
8			to							

* Enter or choose from list at top right

** minimum volume of vapor required to achieve remediation

Clear All Entries

Return

SD3

Figure 28. Card SD3 of the "System Design" stack.

The "Critical Volume of Air" is calculated by the same procedure used previously in §V.3.2 (steps 10 -13). To initiate this calculation, "click" on the "Critical Volume of Air**" heading.

Result: Card SD5 of the "System Design" stack appears on your screen (Figure 29).

Step 8: Location: Card SD5 of the "System Design" stack.

Action: Read the text carefully. The focus of this card is the prediction of vapor concentrations and removal rates as they change with time due to composition changes. It is important to try to understand the concepts introduced in this card. For more information, read the reference article contained in the appendix. Click on the "Do a Calculation" button to advance to card SD6 of the "System Design" stack (Figure 30).

Result: Card SD6 of the "System Design" stack appears on your screen.

Step 9: Location: Card SD6 of the "System Design" stack.

Action: This card is used to finalize your input data prior to calculating vapor concentration and residual soil contamination composition changes with time. Read the instructions in the order that they are numbered, then enter "18" for the temperature and select "weathered gasoline" from the three composition options. Because it is difficult to present the behavior of each compound in a mixture composed of an arbitrary number of compounds, the output is simplified by reporting the behavior in terms of "boiling point" ranges. This simply represents a summation of all compounds whose boiling points fall between pre-specified values. Presented in this fashion, the model results can be interpreted much more quickly. Click on the "tell me more about BP ranges..." button, read the help card, then return to card SD6 of the "System Design" stack. Click on the "-->Set Default BP Ranges<--" button. Your screen should now look like Figure 30. Click on the "Generate Predictions" button

Result: The message "Sit Back and Relax..." will appear on your screen, followed by a screen on which the following appears:

"Copyright © Absoft Corp 1988
Copyright © Shell Oil Co 1990
HANG ON ----- YOU WILL BE RETURNED TO HYPERCARD...
OF COMPOUNDS IN LIBRARY = 62"

Then card SD7 of the "System Design" stack will appear as shown in Figure 31.

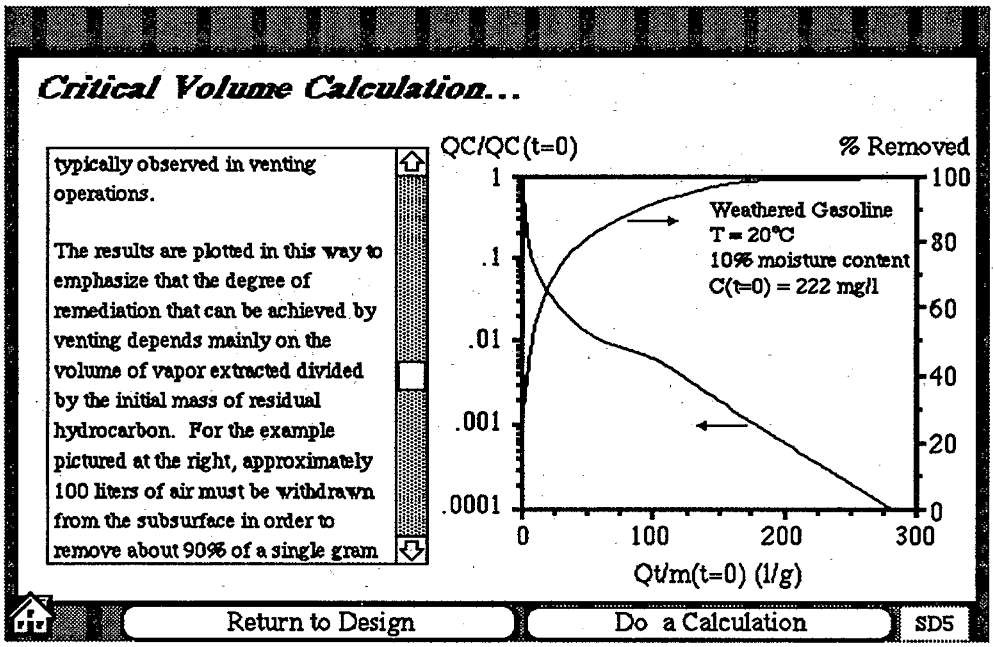


Figure 29. Card SD5 of the "System Design" stack.

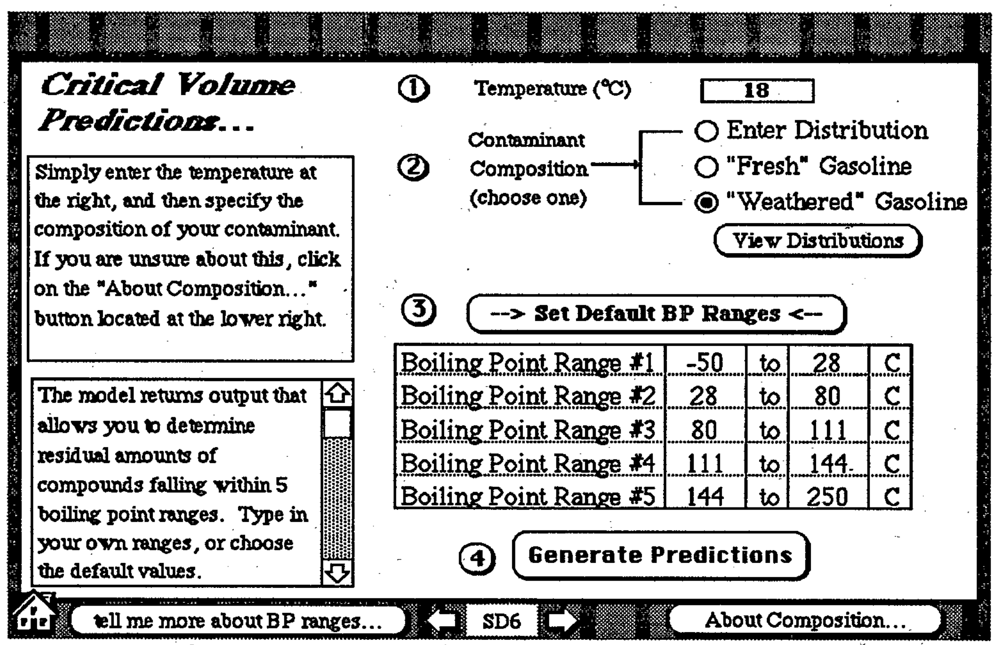


Figure 30. Card SD6 of the "System Design" stack.

Step 10:
Location: Card SD7 of the "System Design" stack.
Action: Read the instructions, then click on the "-->Import Data<--" button.
Result: Your screen should look like Figure 31. The table in the lower part of the card lists model predictions: vapor concentration and residual soil concentration (expressed as a percentage of their initial values), as well as the composition of the residual (expressed as a percentage of the total for each boiling point range) as a function of the amount of air drawn through the contaminated soil. Note that as the volume of air drawn through the soil increases, the vapor concentration and residual soil levels decrease, and the composition of the residual becomes richer in the less volatile compounds (BP Range #5). In the upper right corner of the card are displayed the saturated, or initial, vapor concentration and the minimum amount of air that must be drawn through the soil per gram of initial contaminant to achieve at least a 90% reduction in the initial residual level. This value is used in future calculations as a design parameter.

Step 11:
Location: Card SD7 of the "System Design" stack.
Action: Click on the "Return to System Design" button
Result: A dialog box will appear asking: "Transfer Critical Volume Value?". Click on the "Yes" button. You will now be prompted by another dialog box asking: "What soil unit # is this value for?". Enter "1" into the appropriate place then click on the "OK" button. You will now be transferred back to card SD3 of the "System Design" stack. Note that the value "128.48" has been entered into the "Critical Volume of Air**" column for the medium sand soil unit.

Step 12:
Location: Card SD3 of the "System Design" stack.
Action: Enter "128" into the "Critical Volume of Air**" column for the clayey silt and fine sand soil units. For this example problem enter "100" for the efficiency in all three soil units
Result: Card SD3 should now resemble Figure 28.

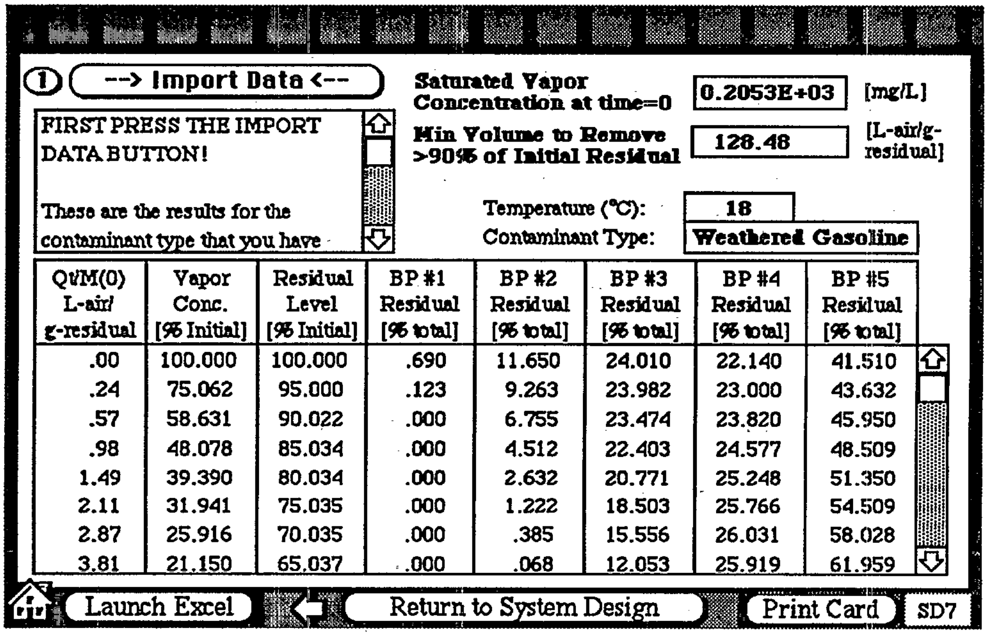
Step 13:
Location: Card SD3 of the "System Design" stack.
Action: Click on the right-pointing arrow at the bottom of the page to advance to Card SD4 of the "System Design" stack.
Result: Card SD4 of the "System Design" stack should appear on your screen.

Step 14:
Location: Card SD4 of the "System Design" stack.
Action: Assume that you wish to remediate this site in 180 days. Enter "180" in the "Time for Clean-up" column for each soil unit. Click on the "Update" button.
Result: **HyperVentilate** calculates a range of flowrates to a single vertical well, then uses this value and other input parameters to determine

the minimum number of wells required based on two approaches. To read about these, click on the "Number of Wells" column heading. Your card SD4 should resemble Figure 32.

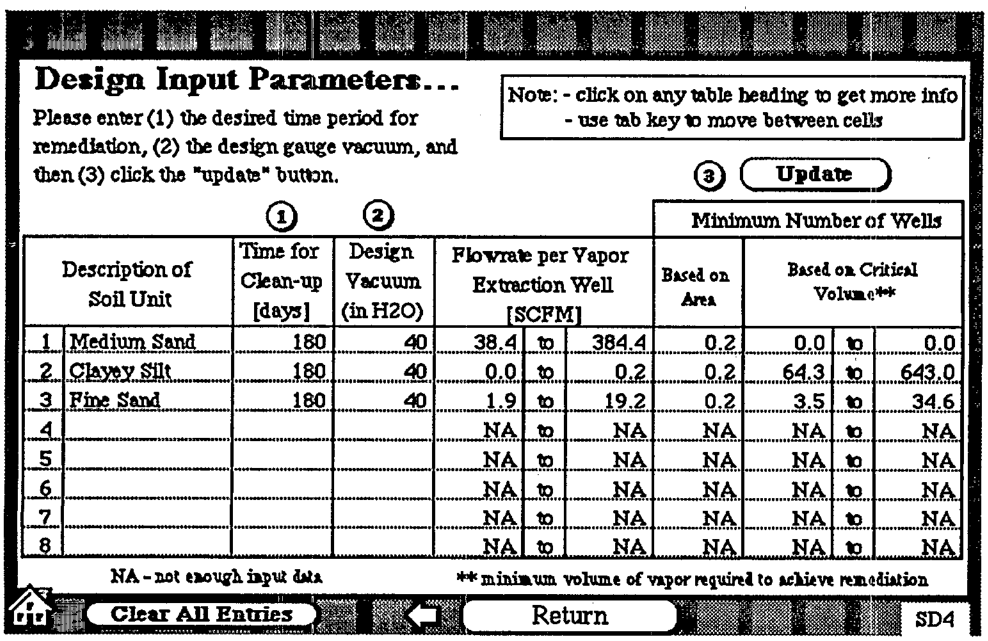
It is important to recognize that model predictions are intended to serve as guidelines, and are limited in their ability to describe behavior that might be observed at any given site. One should use all the information available, in addition to idealized model predictions to make rational decisions about the applicability of soil venting.

You can read about the effect of venting at this site in the article: "Soil Venting at a California Site: Field Data Reconciled with Theory", by P. C. Johnson, C. C. Stanley, D. L. Byers, D. A. Benson, and M. A. Acton, in *Hydrocarbon Contaminated Soils and Groundwater: Analysis, Fate, Environmental Health Effects, and Remediation Volume 1*, P. T. Kostecki and E. J. Calabrese, editors, Lewis Publishers, p.253 - 281, 1991.



Qt/M(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.000	100.000	.690	11.650	24.010	22.140	41.510
.24	75.062	95.000	.123	9.263	23.982	23.000	43.632
.57	58.631	90.022	.000	6.755	23.474	23.820	45.950
.98	48.078	85.034	.000	4.512	22.403	24.577	48.509
1.49	39.390	80.034	.000	2.632	20.771	25.248	51.350
2.11	31.941	75.035	.000	1.222	18.503	25.766	54.509
2.87	25.916	70.035	.000	.385	15.556	26.031	58.028
3.81	21.150	65.037	.000	.068	12.053	25.919	61.959

Figure 31. Card SD7 of the "System Design" stack.



	Description of Soil Unit	① Time for Clean-up [days]	② Design Vacuum (in H2O)	Flowrate per Vapor Extraction Well [SCFM]			Minimum Number of Wells: Based on Area	Minimum Number of Wells: Based on Critical Volume**		
1	Medium Sand	180	40	38.4	to	384.4	0.2	0.0	to	0.0
2	Clayey Silt	180	40	0.0	to	0.2	0.2	64.3	to	643.0
3	Fine Sand	180	40	1.9	to	19.2	0.2	3.5	to	34.6
4				NA	to	NA	NA	NA	to	NA
5				NA	to	NA	NA	NA	to	NA
6				NA	to	NA	NA	NA	to	NA
7				NA	to	NA	NA	NA	to	NA
8				NA	to	NA	NA	NA	to	NA

Figure 32. Card SD4 of the "System Design" stack.

References

Hutzler, N. J., Murphy, B. E., and Gierke, J. S., State of Technology Review: Soil Vapor Extraction Systems, U.S.E.P.A, EPA/600/2-89/024, June 1989.

Johnson, P. C., Kemblowski, M. W., and Colthart, J. D., Practical Screening Models for Soil Venting Applications, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1988.

Johnson, P. C., Stanley, C. C., Kemblowski, M., W., Byers, D. L., and Colthart, J. D., A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems, to appear in Ground Water Monitoring Review, Spring 1990.

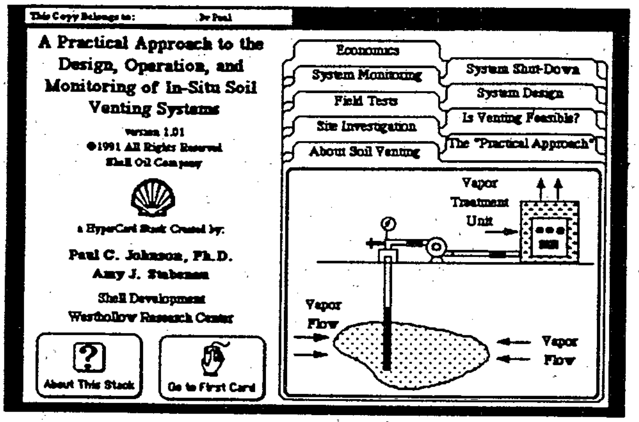
Marley, M. C., and Hoag, G. E., Induced Soil Venting for the Recovery/Restoration of Gasoline Hydrocarbons in the Vadose Zone, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1984.

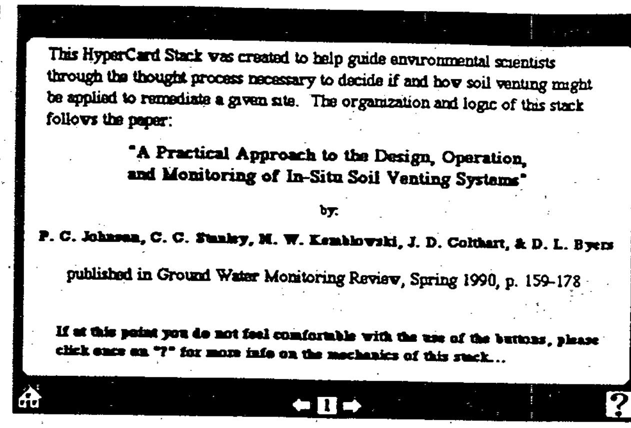
Marley, M. C., Baehr, A. L., and Hult, M. F., Evaluation of Air-Permeability in the Unsaturated Zone using Pneumatic Pump Tests: 1. Theoretical Considerations, in review, 1990.

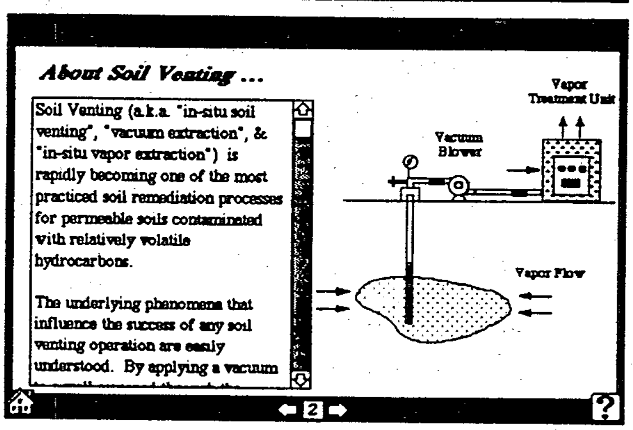
Thornton, J. S. and Wootan, W. L., Venting for the Removal of Hydrocarbon Vapors from Gasoline Contaminated Soil, J. Environ. Sci. Health, A17(1), 31-44, 1982.

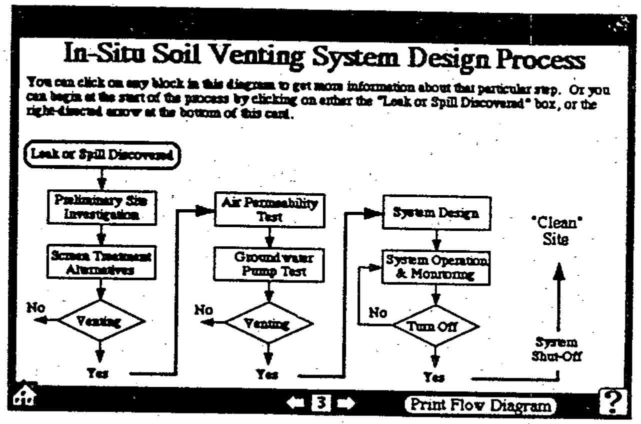
Newell, C. J., Haasbeek, J. F., and Bedient, P. B., OASIS: A Graphical Decision Support System for Ground-Water Contaminant Modeling, Ground Water, 28 (2), 224 - 234, March - April 1990.

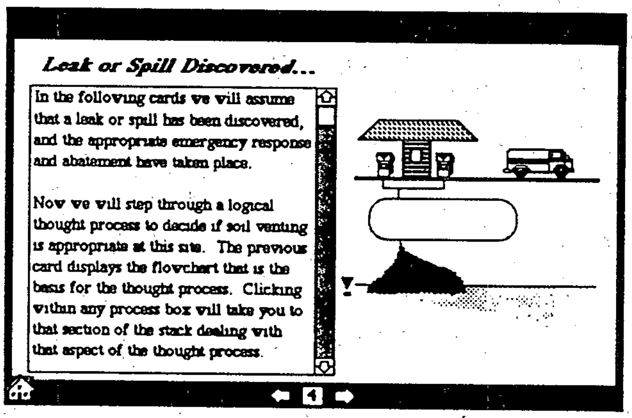
Appendix A: "Soil Venting Stack" stack cards.

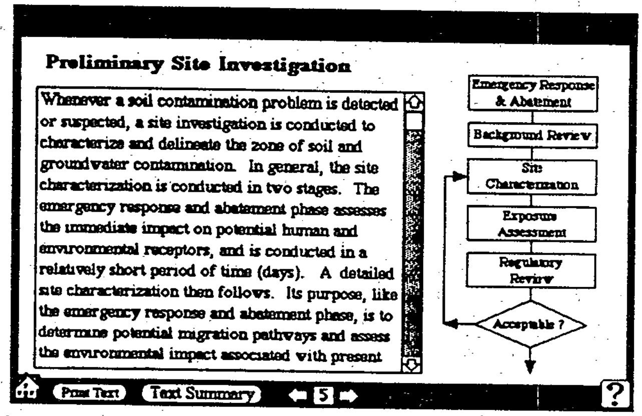

A Practical Approach to the Design, Operation, and Monitoring of In-Situ Soil Venting Systems
©1991 All Rights Reserved
Shell Oil Company
Paul C. Johnson, Ph.D.
Amy J. Stabenau
Shell Development
Westhollow Research Center
About This Stack
Go to First Card
Economics
System Monitoring
System Shut-Down
Field Tests
System Design
Site Investigation
Is Venting Feasible?
About Soil Venting
The "Practical Approach"
Vapor Treatment Unit
Vapor Flow
Vapor Flow

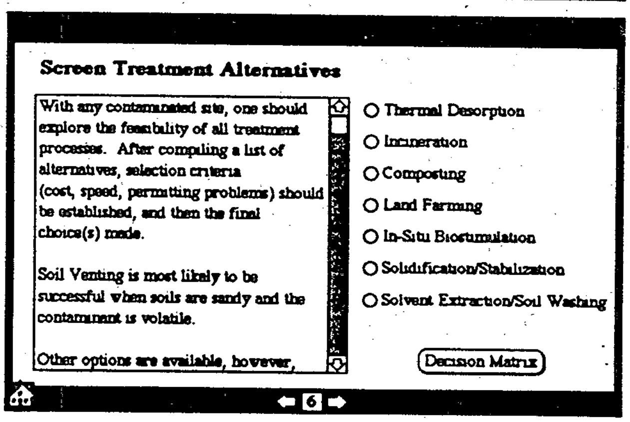

This HyperCard Stack was created to help guide environmental scientists through the thought process necessary to decide if and how soil venting might be applied to remediate a given site. The organization and logic of this stack follows the paper:
"A Practical Approach to the Design, Operation, and Monitoring of In-Situ Soil Venting Systems"
by:
P. C. Johnson, C. C. Stanley, M. W. Kemblowski, J. D. Colthart, & D. L. Byers
published in Ground Water Monitoring Review, Spring 1990, p. 159-178
If at this point you do not feel comfortable with the use of the buttons, please click once on "?" for more info on the mechanics of this stack...
1

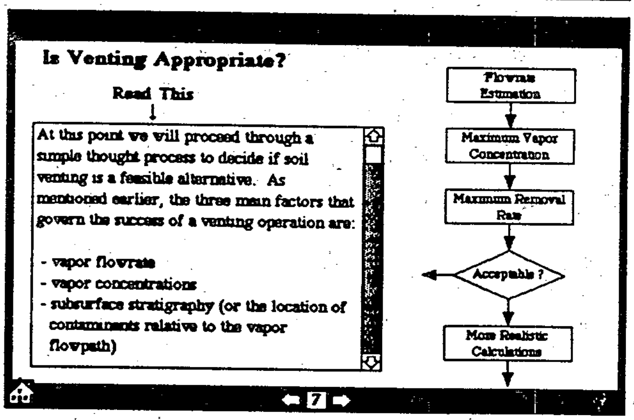

About Soil Venting ...
Soil Venting (a.k.a. "in-situ soil venting", "vacuum extraction", & "in-situ vapor extraction") is rapidly becoming one of the most practiced soil remediation processes for permeable soils contaminated with relatively volatile hydrocarbons.
The underlying phenomena that influence the success of any soil venting operation are easily understood. By applying a vacuum
Vapor Treatment Unit
Vacuum Blower
Vapor Flow
2

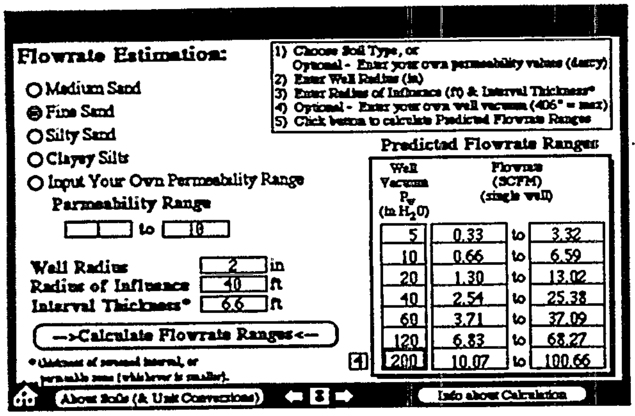

In-Situ Soil Venting System Design Process
You can click on any block in this diagram to get more information about that particular step. Or you can begin at the start of the process by clicking on either the "Leak or Spill Discovered" box, or the right-directed arrow at the bottom of this card.
Leak or Spill Discovered
Preliminary Site Investigation
Screen Treatment Alternatives
Venting
Air Permeability Test
Groundwater Pump Test
Venting
System Design
System Operation & Monitoring
Turn Off
"Clean" Site
System Shut-Off
No
Yes
3
Print Flow Diagram

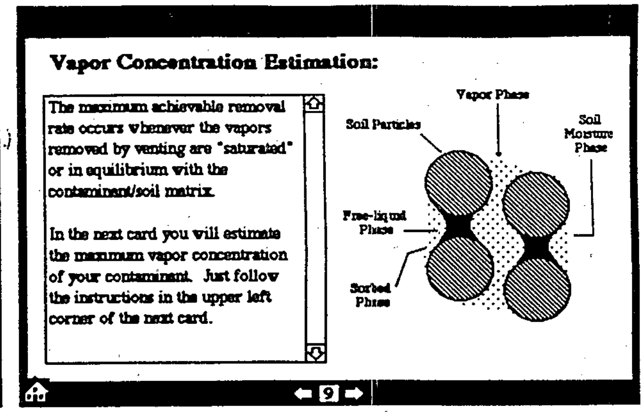

Leak or Spill Discovered...
In the following cards we will assume that a leak or spill has been discovered, and the appropriate emergency response and abatement have taken place.
Now we will step through a logical thought process to decide if soil venting is appropriate at this site. The previous card displays the flowchart that is the basis for the thought process. Clicking within any process box will take you to that section of the stack dealing with that aspect of the thought process.
4

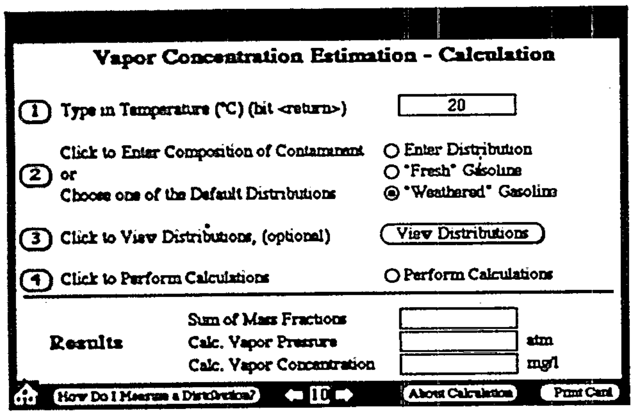

Preliminary Site Investigation
Whenever a soil contamination problem is detected or suspected, a site investigation is conducted to characterize and delineate the zone of soil and groundwater contamination. In general, the site characterization is conducted in two stages. The emergency response and abatement phase assesses the immediate impact on potential human and environmental receptors, and is conducted in a relatively short period of time (days). A detailed site characterization then follows. Its purpose, like the emergency response and abatement phase, is to determine potential migration pathways and assess the environmental impact associated with present
Emergency Response & Abatement
Background Review
Site Characterization
Exposure Assessment
Regulatory Review
Acceptable ?
Print Text
Text Summary
5

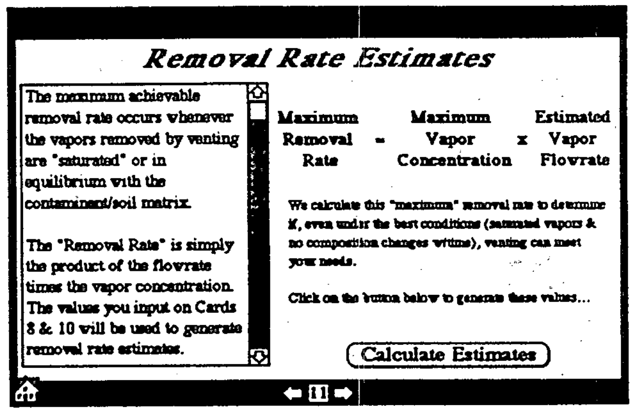

Screen Treatment Alternatives
With any contaminated site, one should explore the feasibility of all treatment processes. After compiling a list of alternatives, selection criteria (cost, speed, permitting problems) should be established, and then the final choice(s) made.
Soil Venting is most likely to be successful when soils are sandy and the contaminant is volatile.
Other options are available, however,
Thermal Desorption
Incineration
Composting
Land Farming
In-Situ Biostimulation
Solidification/Stabilization
Solvent Extraction/Soil Washing
Decision Matrix
6

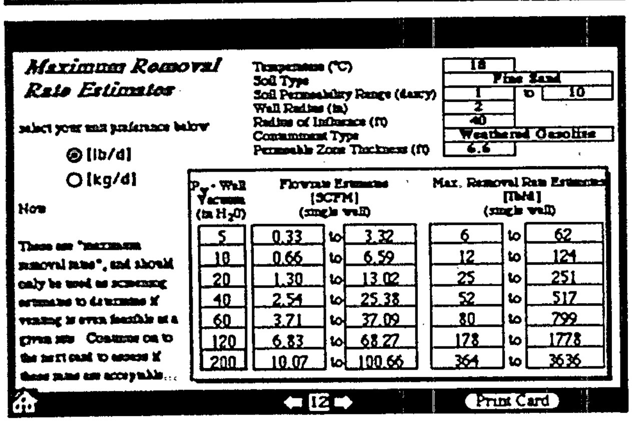

Is Venting Appropriate?
Read This
At this point we will proceed through a simple thought process to decide if soil venting is a feasible alternative. As mentioned earlier, the three main factors that govern the success of a venting operation are:
- vapor flowrate
- vapor concentrations
- subsurface stratigraphy (or the location of contaminants relative to the vapor flowpath)
Flowrate Estimation
Maximum Vapor Concentration
Maximum Removal Rate
Acceptable ?
More Realistic Calculations
7

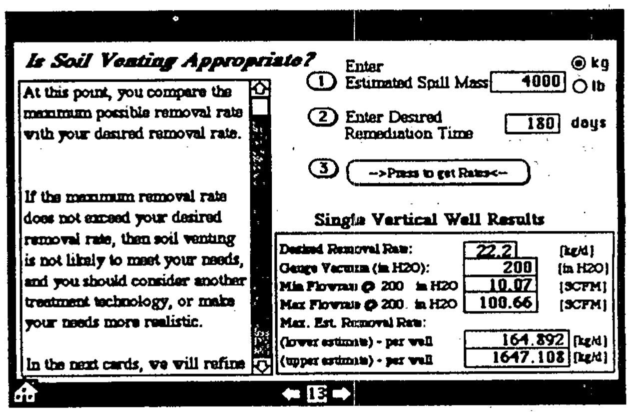

Flowrate Estimation:
1) Choose Soil Type, or Optional - Enter your own permeability values (darcy)
2) Enter Well Radius (in)
3) Enter Radius of Influence (ft) & Interval Thickness*
4) Optional - Enter your own well vacuum (406" = max)
5) Click button to calculate Predicted Flowrate Ranges
Medium Sand
Fine Sand
Silty Sand
Clayey Silts
Input Your Own Permeability Range
Permeability Range
to 10
Well Radius 2 in
Radius of Influence 40 ft
Interval Thickness* 6.6 ft
-->Calculate Flowrate Ranges<--
*thickness of screened interval, or permeable zone (whichever is smaller).
Predicted Flowrate Ranges
Well Vacuum P_w (in H_2O)
Flowrate (SCFM) (single well)
5 0.33 to 3.32
10 0.66 to 6.59
20 1.30 to 13.02
40 2.54 to 25.38
60 3.71 to 37.09
120 6.83 to 68.27
200 10.07 to 100.66
About Soils (& Unit Conversions)
8
Info about Calculation

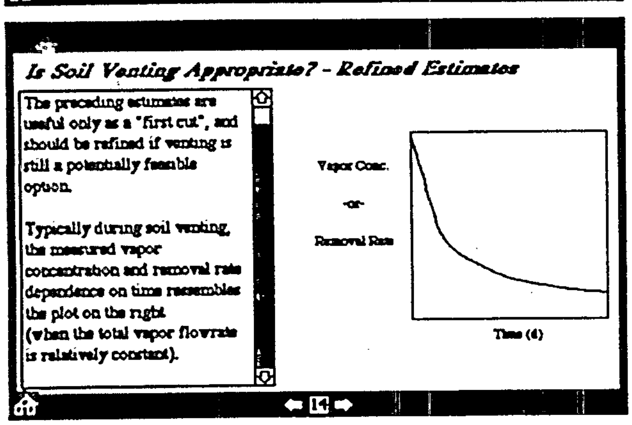

Vapor Concentration Estimation:
The maximum achievable removal rate occurs whenever the vapors removed by venting are "saturated" or in equilibrium with the contaminant/soil matrix.
In the next card you will estimate the maximum vapor concentration of your contaminant. Just follow the instructions in the upper left corner of the next card.
Vapor Phase
Soil Particles
Soil Moisture Phase
Free-liquid Phase
Sorbed Phase
9

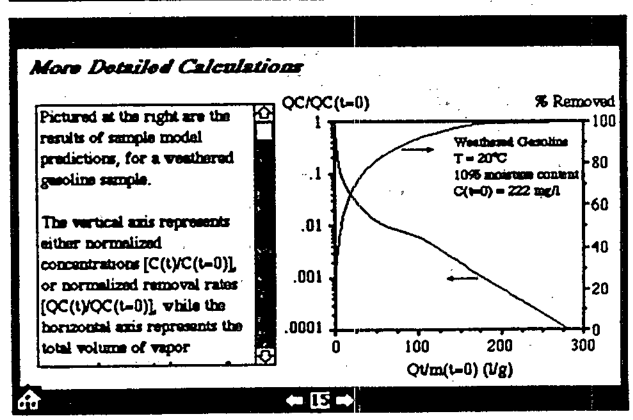

Vapor Concentration Estimation - Calculation
1 Type in Temperature (°C) (hit <return>) 20
2 Click to Enter Composition of Contaminant or Choose one of the Default Distributions
Enter Distribution
"Fresh" Gasoline
"Weathered" Gasoline
3 Click to View Distributions, (optional) View Distributions
4 Click to Perform Calculations Perform Calculations
Results
Sum of Mass Fractions
Calc. Vapor Pressure atm
Calc. Vapor Concentration mg/l
How Do I Measure a Distribution?
10
About Calculation
Print Card

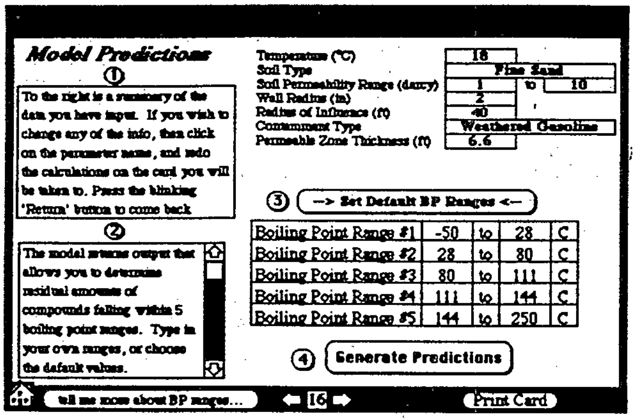

Removal Rate Estimates
The maximum achievable removal rate occurs whenever the vapors removed by venting are "saturated" or in equilibrium with the contaminant/soil matrix.
The "Removal Rate" is simply the product of the flowrate times the vapor concentration. The values you input on Cards 8 & 10 will be used to generate removal rate estimates.
Maximum Removal Rate = Maximum Vapor Concentration x Estimated Vapor Flowrate
We calculate this "maximum" removal rate to determine if, even under the best conditions (saturated vapors & no composition changes with time), venting can meet your needs.
Click on the button below to generate these values...
Calculate Estimates
11

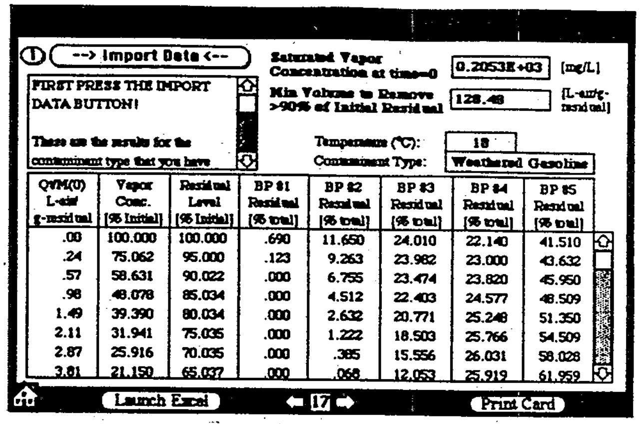

Maximum Removal Rate Estimates
Temperature (°C) 18
Soil Type Fine Sand
Soil Permeability Range (darcy) 1 to 10
Well Radius (in) 2
Radius of Influence (ft) 40
Contaminant Type Weathered Gasoline
Permeable Zone Thickness (ft) 6.6
select your unit preference below
[lb/d]
[kg/d]
Note
These are "maximum removal rates", and should only be used as screening estimates to determine if venting is even feasible at a given site. Continue on to the next card to assess if these rates are acceptable...
P_w - Well Vacuum (in H_2O)
Flowrate Estimates [SCFM] (single well)
Max. Removal Rate Estimates [lb/d] (single well)
5 0.33 to 3.32 6 to 62
10 0.66 to 6.59 12 to 124
20 1.30 to 13.02 25 to 251
40 2.54 to 25.38 52 to 517
60 3.71 to 37.09 80 to 799
120 6.83 to 68.27 178 to 1778
200 10.07 to 100.66 364 to 3636
12
Print Card

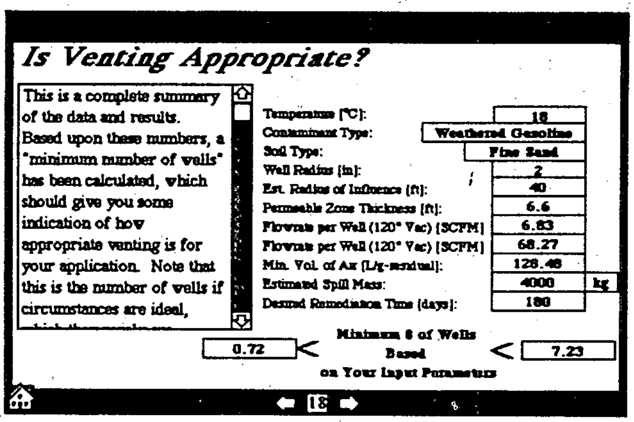

Is Soil Venting Appropriate?
At this point, you compare the maximum possible removal rate with your desired removal rate.
If the maximum removal rate does not exceed your desired removal rate, then soil venting is not likely to meet your needs, and you should consider another treatment technology, or make your needs more realistic.
In the next cards, we will refine
Enter
1 Estimated Spill Mass 4000 kg lb
2 Enter Desired Remediation Time 180 days
3 -->Press to get Rates<--
Single Vertical Well Results
Desired Removal Rate: 22.2 [kg/d]
Gauge Vacuum (in H2O): 200 [in H2O]
Min Flowrate @ 200 in H2O 10.07 [SCFM]
Max Flowrate @ 200 in H2O 100.66 [SCFM]
Max. Est. Removal Rate:
(lower estimate) - per well 164.892 [kg/d]
(upper estimate) - per well 1647.108 [kg/d]
13

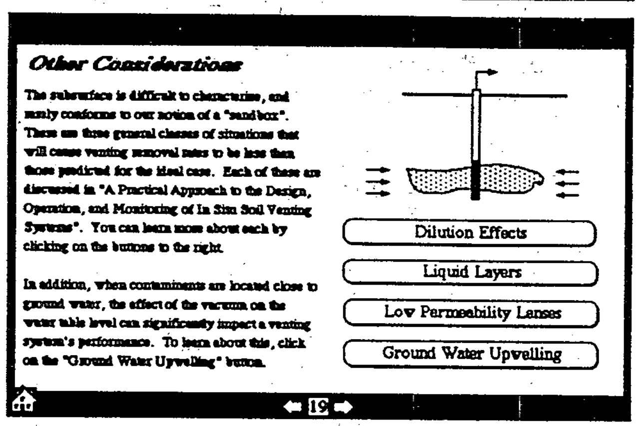

Is Soil Venting Appropriate? - Refined Estimates
The preceding estimates are useful only as a "first cut", and should be refined if venting is still a potentially feasible option.
Typically during soil venting, the measured vapor concentration and removal rate dependence on time resembles the plot on the right (when the total vapor flowrate is relatively constant).
Vapor Conc.
-or-
Removal Rate
Time (d)
14

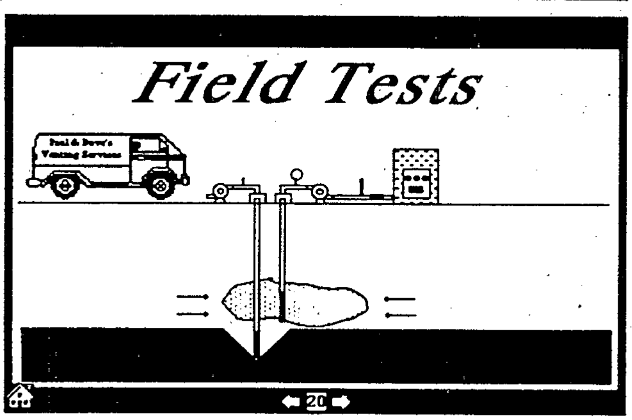

More Detailed Calculations
Pictured at the right are the results of sample model predictions, for a weathered gasoline sample.
The vertical axis represents either normalized concentrations [C(t)/C(t=0)], or normalized removal rates [QC(t)/QC(t=0)], while the horizontal axis represents the total volume of vapor
QC/QC(t=0)
% Removed
Weathered Gasoline
T = 20°C
10% moisture content
C(t=0) = 222 mg/l
1
.1
.01
.001
.0001
0
100
200
300
100
80
60
40
20
0
Qt/m(t=0) (l/g)
15

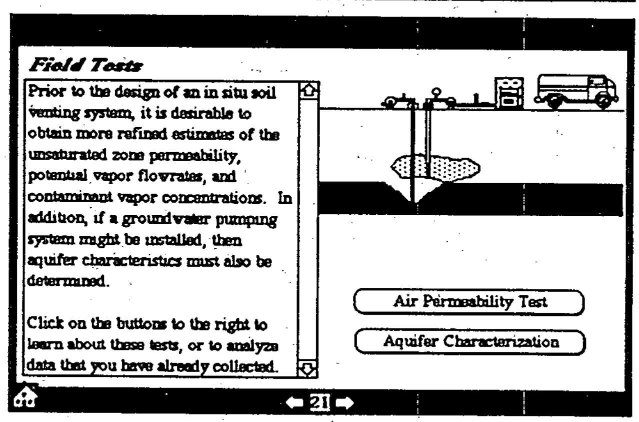

Model Predictions
①
To the right is a summary of the data you have input. If you wish to change any of the info, then click on the parameter name, and redo the calculations on the card you will be taken to. Press the blinking 'Return' button to come back
②
The model returns output that allows you to determine residual amounts of compounds falling within 5 boiling point ranges. Type in your own ranges, or choose the default values.
Temperature (°C) 18
Soil Type Fine Sand
Soil Permeability Range (darcy) 1 to 10
Well Radius (in) 2
Radius of Influence (ft) 40
Contaminant Type Weathered Gasoline
Permeable Zone Thickness (ft) 6.6
③ --> Set Default BP Ranges <--
Boiling Point Range #1 -50 to 28 C
Boiling Point Range #2 28 to 80 C
Boiling Point Range #3 80 to 111 C
Boiling Point Range #4 111 to 144 C
Boiling Point Range #5 144 to 250 C
④ Generate Predictions
tell me more about BP ranges...
16
Print Card

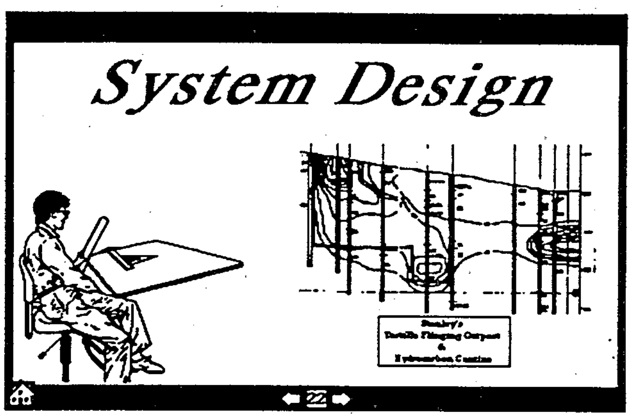

① --> Import Data <--
FIRST PRESS THE IMPORT DATA BUTTON!
These are the results for the contaminant type that you have
Saturated Vapor Concentration at time=0 0.2053E+03 [mg/L]
Min Volume to Remove >90% of Initial Residual 128.48 [L-air/g-residual]
Temperature (°C): 18
Contaminant Type: Weathered Gasoline
Q*t/M(0) L-air/g-residual | Vapor Conc. [% Initial] | Residual Level [% Initial] | BP #1 Residual [% total] | BP #2 Residual [% total] | BP #3 Residual [% total] | BP #4 Residual [% total] | BP #5 Residual [% total]
.00 100.000 100.000 .690 11.650 24.010 22.140 41.510
.24 75.062 95.000 .123 9.263 23.982 23.000 43.632
.57 58.631 90.022 .000 6.755 23.474 23.820 45.950
.98 48.078 85.034 .000 4.512 22.403 24.577 48.509
1.49 39.390 80.034 .000 2.632 20.771 25.248 51.350
2.11 31.941 75.035 .000 1.222 18.503 25.766 54.509
2.87 25.916 70.035 .000 .385 15.556 26.031 58.028
3.81 21.150 65.037 .000 .068 12.053 25.919 61.959
Launch Excel
17
Print Card

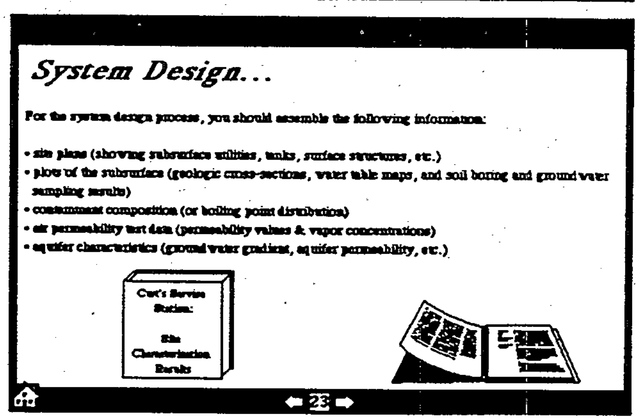

Is Venting Appropriate?
This is a complete summary of the data and results. Based upon these numbers, a "minimum number of wells" has been calculated, which should give you some indication of how appropriate venting is for your application. Note that this is the number of wells if circumstances are ideal,
Temperature [°C]: 18
Contaminant Type: Weathered Gasoline
Soil Type: Fine Sand
Well Radius [in]: 2
Est. Radius of Influence [ft]: 40
Permeable Zone Thickness [ft]: 6.6
Flowrate per Well (120" Vac) [SCFM] 6.83
Flowrate per Well (120" Vac) [SCFM] 68.27
Min. Vol. of Air [L/g-residual]: 128.48
Estimated Spill Mass: 4000 kg
Desired Remediation Time [days]: 180
0.72 < Minimum # of Wells Based on Your Input Parameters < 7.23
18

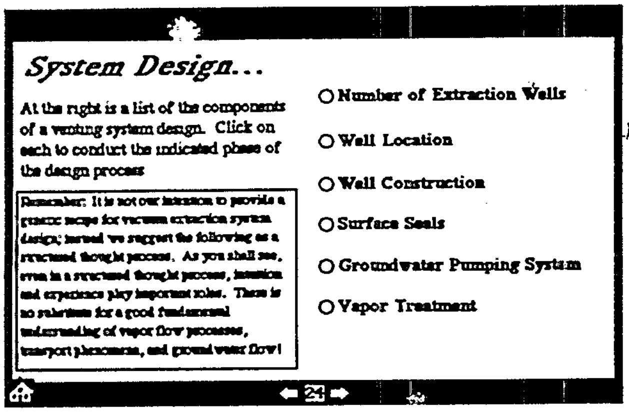

Other Considerations
The subsurface is difficult to characterize, and rarely conforms to our notion of a "sandbox". There are three general classes of situations that will cause venting removal rates to be less than those predicted for the ideal case. Each of these are discussed in "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems". You can learn more about each by clicking on the buttons to the right.
In addition, when contaminants are located close to ground water, the effect of the vacuum on the water table level can significantly impact a venting system's performance. To learn about this, click on the "Ground Water Upwelling" button.
Dilution Effects
Liquid Layers
Low Permeability Lenses
Ground Water Upwelling
19

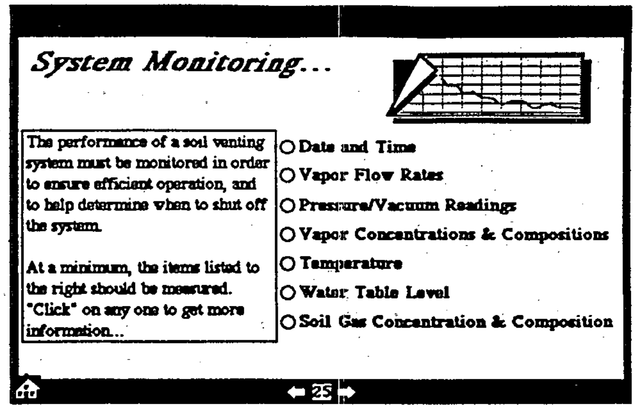

Field Tests
20

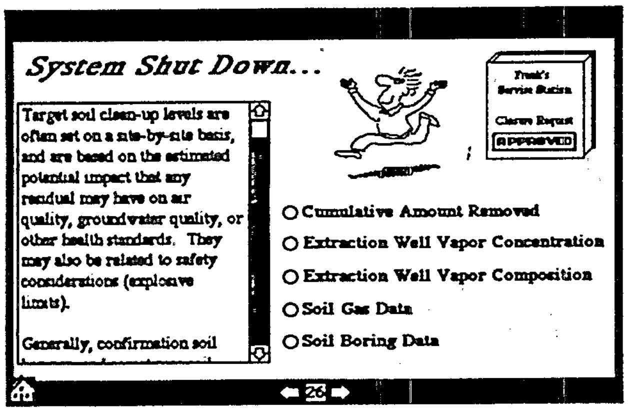

Field Tests
Prior to the design of an in situ soil venting system, it is desirable to obtain more refined estimates of the unsaturated zone permeability, potential vapor flowrates, and contaminant vapor concentrations. In addition, if a groundwater pumping system might be installed, then aquifer characteristics must also be determined.
Click on the buttons to the right to learn about these tests, or to analyze data that you have already collected.
Air Permeability Test
Aquifer Characterization
21

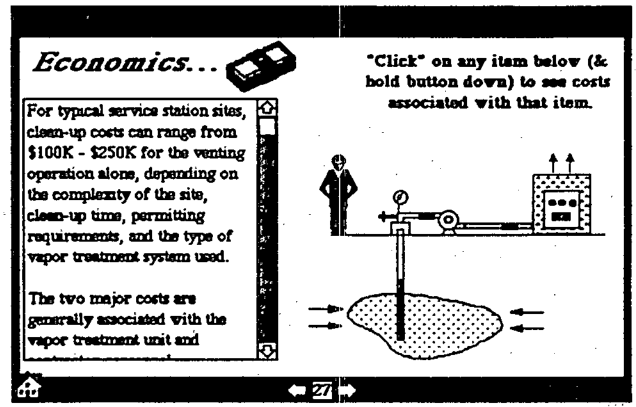

System Design
22

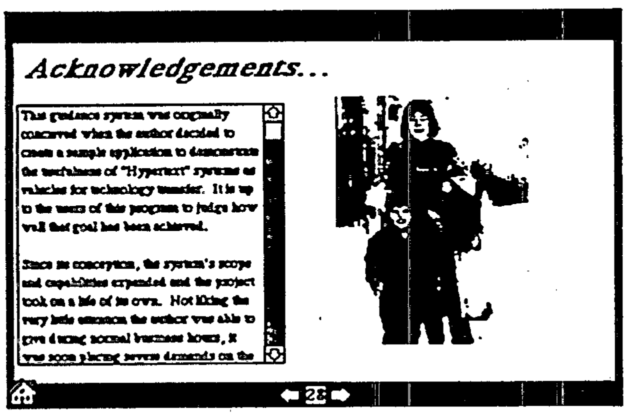

System Design...
For the system design process, you should assemble the following information:
• site plans (showing subsurface utilities, tanks, surface structures, etc.)
• plots of the subsurface (geologic cross-sections, water table maps, and soil boring and ground water sampling results)
• contaminant composition (or boiling point distribution)
• air permeability test data (permeability values & vapor concentrations)
• aquifer characteristics (ground water gradient, aquifer permeability, etc.)
23


System Design...
At the right is a list of the components of a venting system design. Click on each to conduct the indicated phase of the design process
Remember: It is not our intention to provide a generic recipe for vacuum extraction system design; instead we suggest the following as a structured thought process. As you shall see, even in a structured thought process, intuition and experience play important roles. There is no substitute for a good fundamental understanding of vapor flow processes, transport phenomena, and ground water flow!
Number of Extraction Wells
Well Location
Well Construction
Surface Seals
Groundwater Pumping System
Vapor Treatment
24


System Monitoring...
The performance of a soil venting system must be monitored in order to ensure efficient operation, and to help determine when to shut off the system.
At a minimum, the items listed to the right should be measured. "Click" on any one to get more information...
Date and Time
Vapor Flow Rates
Pressure/Vacuum Readings
Vapor Concentrations & Compositions
Temperature
Water Table Level
Soil Gas Concentration & Composition
25


System Shut Down...
Frank's Service Station
Closure Request
APPROVED
Target soil clean-up levels are often set on a site-by-site basis, and are based on the estimated potential impact that any residual may have on air quality, groundwater quality, or other health standards. They may also be related to safety considerations (explosive limits).
Generally, confirmation soil
Cumulative Amount Removed
Extraction Well Vapor Concentration
Extraction Well Vapor Composition
Soil Gas Data
Soil Boring Data
26


Economics...
"Click" on any item below (& hold button down) to see costs associated with that item.
For typical service station sites, clean-up costs can range from $100K - $250K for the venting operation alone, depending on the complexity of the site, clean-up time, permitting requirements, and the type of vapor treatment system used.
The two major costs are generally associated with the vapor treatment unit and
27


Acknowledgements...
This guidance system was originally conceived when the author decided to create a sample application to demonstrate the usefulness of "Hypertext" systems as vehicles for technology transfer. It is up to the users of this program to judge how well that goal has been achieved.
Since its conception, the system's scope and capabilities expanded and the project took on a life of its own. Not liking the very little attention the author was able to give during normal business hours, it was soon placing severe demands on the
28

Appendix B: "Soil Venting Help Stack" stack cards.

Help: Stack Information

Buttons

Buttons have been placed in each card. Clicking on any button will perform an action, such as:

- Go Home to first card in Venting Stack
- Go to next card
- Go to Help card
- Print card or text field
- (Calculate) Perform a Calculation

When curious, click on Symbols, Pictures or Text.

Fields

Fields may contain information, or they may be a place for you to input numbers.

Scrolling Field: Click on arrows to move text up or down

Click on the arrows, or move the box up or down with the mouse.

In this area, you can

Boxed Data Field: When you see an I-beam cursor appear in a boxed field, click the mouse in the box to set the cursor. Then you may enter data.
A button will then usually be pushed to perform an action or calculation.

Try this example:

Enter Number in Box

1 inches

(Click for calculation)

2.54 centimeter

Return H1

Help: About Soil Venting

More information about soil venting can be found in the following articles:

M. C. Marley and G. E. Hoag, Induced Soil Venting for the Recovery/Restoration of Gasoline Hydrocarbons in the Vadose Zone, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1984.

P. C. Johnson, M. W. Kemblowski, and J. D. Colthart, Practical Screening Models for Soil Venting Applications, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1988.

N. J. Hutzler, B. E. Murphy, and J. S. Gierke, State of Technology Review: Soil Vapor Extraction Systems, U.S.E.P.A, CR-814319-01-1, 1988.

D. J. Wilson, A. N. Clarke, and J. H. Clarke, Soil Clean-up by in-situ Aeration. I. Mathematical Modelling, Sep. Science Tech., 23:991-1037, 1988.

H2 Return Print References

Help: In-Situ Soil Venting System Design Process

This is the decision process that one must follow to:

1) decide if soil venting is applicable at a given site

&

2) design an effective soil venting system

It is an abridged version of Figure 2 in *"A Practical Approach to the Design, Operation, & Monitoring of In-Situ Soil Venting Systems"*, by P. C. Johnson, C. C. Stanley, M. W. Kemblowski, J. D. Colthart, and D. L. Byers.

Return H3

Help: Preliminary Site Investigation

More information about site investigation and remediation can be found in the following articles:

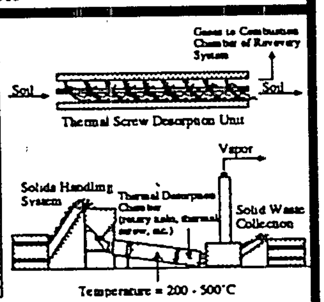
API Publication 1628
"A Guide to the Assessment and Remediation of Underground Petroleum Releases",
American Petroleum Institute, 1220 L Street Northwest, Washington DC, 20005

Return H4

Help: Thermal Desorption

Process Description

In a thermal desorption treatment process, soils contaminated with volatile/semi-volatile organics are heated, and the volatilized contaminants are stripped with air, steam, or combustion products (burner flue gases) at relatively modest temperatures compared with incineration (200-500°C versus 1000-1200°C). The desorbed organic contaminants are

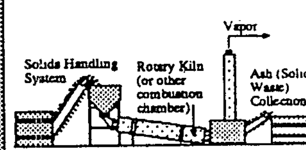


Return H5

Help: Incineration

Process Description

Incineration, or the thermal destruction of wastes, is a complete destruction technology that can be used to treat soils contaminated with a wide range of hazardous organic wastes. Contaminated soils, sludges, or liquid wastes are added to a high-temperature combustion chamber (rotary kiln, fixed hearth, multiple hearth, fluidized bed, liquid

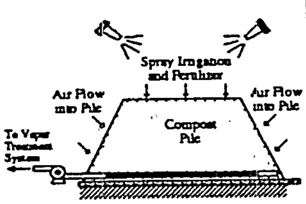


Return H6

Help: Composting

Process Description

Composting is an above-ground soil management technique in which amended soil, containing organic wastes, is placed in large piles and aerated. The aeration enhances microbial degradation by providing oxygen to the soil/waste. With time, the decomposed waste is reduced in weight and volume, and the process produces a stabilized, enriched, humus-like material,

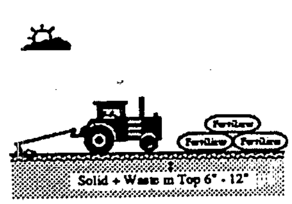


Return H7

Help: Land Farming

Process Description

"Landfarming" refers to the practice of spreading organic wastes over an area of land, then relying on natural microbial action to degrade the waste. It is a widely accepted and cost-effective practice for the treatment of petroleum hydrocarbons, chlorinated compounds, and pesticides. In this process soil-associated microorganisms (bacteria and

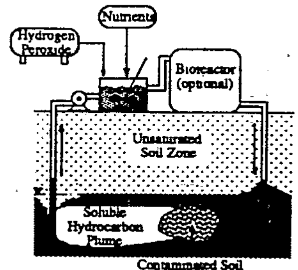


Return H8

Help: In-Situ Biostimulation

Process Description

Treatment of groundwater and soil contamination below the water table ("saturated zone") by in-situ biostimulation involves the addition of nutrients and/or O2 (usually as H_2O_2 or liquid O_2) to an aquifer in order to enhance the degradation of the hydrocarbons by indigenous soil microbes. The nutrients and oxygen are added above ground to



Return

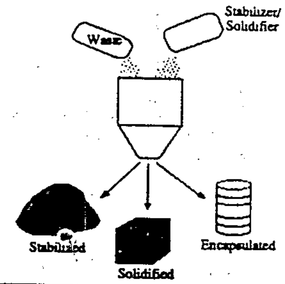
H9

Help: Solidification / Stabilization

Process Description

Stabilization and solidification are treatment processes designed to either improve waste handling and physical characteristics, decrease surface area across which pollutants can leach, or limit the solubility of hazardous constituents. When discussing this technology, the following definitions are common:

Solidification.



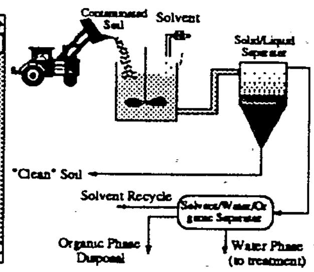
Return

H10

Help: Solvent Extraction / Soil Washing

Process Description

"Solvent extraction" is the process by which contaminants are removed from soils or sludges by mixing them with a solvent into which the contaminants preferentially partition. Which solvent is used for any particular treatment is very dependent upon the type of contaminant present in the soil. The solvent should have a high affinity for the contaminant(s) of



Return

H11

Help: Decision Matrix

● - applicable

◐ - potentially applicable, but not conclusively demonstrated

(1) - Different compounds will vary in their degree of biodegradability. Larger compounds typically have slower degradation rates.

(2) - Free-liquid pumping is only applicable when the residual contamination level is so high that contaminants freely drain from the soil

	Biodegradation (1)	Encapsulation	Excavation	Incineration	Pumping (2) - product recovery	RF Heating/Venting (3)	In-Situ Soil Flushing (4)	Soil Washing/Extraction	Soil Venting	Solidification/Stabilization (5)	Thermal Desorption (6)	Vitrification
Aviation Fuel	●	●	●	●	●	●	◐	●	◐		●	●
Crude Oil	●	●	●	●	●	●	◐	●			●	●
Gasoline	●	●	●	●	●	●	◐	●	●		●	●
Lead		●	●				◐	●		●		●
Metals, Salts		●	●				◐	●		●		●
Petrochemicals	●	●	●	●	●	●	◐	●	●	●	●	●
Pesticides	◐	●	●	●		●	◐	●			●	●
PCB's	◐	●	●	●	●	●	◐	●		◐	●	●
Volatile Solvents	●	●	●	●	●	●	◐	●	●		●	●

Return

H12

Help: Soil Permeability

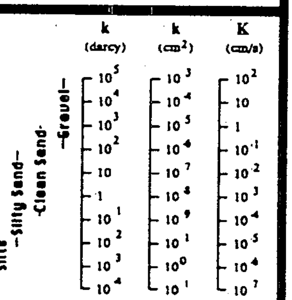
Note that k denotes the "permeability" of a porous media, while K represents the "hydraulic conductivity". The two are related by:

$$K = k\,\frac{\rho_{H_2O}\,g}{\mu_{H_2O}}$$

where:

g = acceleration due to gravity [980 cm/s²]
μ_{H_2O} = viscosity of water [0.01 g/cm-s]
ρ_{H_2O} = density of water [1.0 g/cm³]

When choosing permeability values it is important to keep in mind that k (or K) often varies by several orders of magnitude over small distances. For this



See Conversion Tables | Return to Flowrate Calculation

H13

Help: Vapor Flowrate per Unit Well Thickness

The equation below is the steady-state, one-dimensional, radial flow solution to a vertical well. While simplistic, it generally provides good estimates for vapor flowrates. Its accuracy is, of course, limited by the accuracy of the values you input. In particular, the greatest uncertainty is usually associated with the soil permeability, which can vary by several orders of magnitude over small distances.

$$\frac{Q}{H} = \pi \frac{k}{\mu} P_w \frac{[1 - (P_{Atm}/P_w)^2]}{\ln (R_w / R_I)}$$

k = soil permeability to air flow [cm²] or [darcy]
μ = viscosity of air = 1.8×10^{-4} g/cm-s or 0.018 cp
P_w = absolute pressure at extraction well [g/cm-s²] or [atm]
P_{Atm} = absolute ambient pressure = 1.01×10^6 g/cm-s² or 1 atm
R_w = radius of vapor extraction well [cm]
R_I = radius of influence of vapor extraction well [cm]
H = thickness of well screen interval, or permeable soil zone (choose smallest value)

Return

H14

Help: Unit Conversion (k and K)

1) Enter value of hydraulic conductivity or permeability to be converted
2) Choose initial units
3) Choose final units - (click for each calculation!)

[1] cm² = [9.78374] x 10 [4] cm/s

Convert From	Convert To
○ cm/s	◉ cm/s
○ ft/d	○ ft/d
◉ cm²	○ cm²
○ darcy	○ darcy

Return

H15

H16

Help: Compound List

"Weathered" Gasoline

View Only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 20 °C
1	propane	0.00-	44.1	8.5
2	isobutane	0.00	58.1	2.93
3	n-butane	0	58.1	2.11
4	trans-2-butene	0	56.1	1.97
5	cis-2-butene	0	56.1	1.79
6	3-methyl-1-butene	0	70.1	0.96
7	isopentane	0.0069	72.2	0.78
8	1-pentene	0.0005	70.1	0.7
9	2-methyl-1-butene	0.0008	70.1	0.67
10	2-methyl-1,3-butadiene	0.0000	68.1	0.65

[1.00000] = Sum of Mass Fractions (should be =1)

How Do I Measure a Distribution? | Return to Vapor Conc. Estimation Card | Print Lists

Summary Card: Site Characterization

A complete site assessment must determine the following:

Subsurface Characteristics

- soil stratigraphy
- characteristics of distinct soil layers (permeability estimates, soil types)
- depth to groundwater
- groundwater gradient
- seasonal water table fluctuations
- aquifer permeability (estimate)
- subsurface & above-ground temperature

Contaminant Delineation

- extent of free-phase hydrocarbon
- distribution of contaminant in vadose zone
- distribution of contaminant in saturated zone
- extent of soluble contaminant plume
- composition of contaminant
- soil vapor concentrations (optional)

For more info see: API Publication 1628
"A Guide to the Assessment and Remediation of Underground Petroleum Releases",
American Petroleum Institute, 1220 L Street Northwest, Washington DC, 20005

Print Card

Return H17

Compound List Default Data

#	Compound Name	Molecular Weight (gm)	Boiling Point (°C) @ 1 Atm	Vapor Pressure (Atm) @T=20 °C	New Vapor Pressure (Atm) @T= 20 °C	Mass Fraction Data: All to	"Fresh" Gasoline	"Weathered" Gasoline
1	propane	44.1	-42	8.5	8.5	0.00	0.0001	0.00
2	isobutane	58.1	-12	2.93	2.93	0.00	0.0122	0.00
3	n-butane	58.1	-1	2.11	2.11	0.00	0.0629	0
4	trans-2-butene	56.1	1	1.97	1.97	0.00	0.0007	0
5	cis-2-butene	56.1	4	1.79	1.79	0.00	0.0000	0
6	3-methyl-1-butene	70.1	21	0.96	0.96	0.00	0.0006	0
7	isopentane	72.2	28	0.78	0.78	0.00	0.1049	0.0069
8	1-pentene	70.1	30	0.7	0.7	0.00	0.0000	0.0005
9	2-methyl-1-butene	70.1	31	0.67	0.67	0.00	0.0000	0.0008
10	2-methyl-1,3-butadiene	68.1	34	0.65	0.65	0.00	0.0000	0.0000

Return Print Lists H18

Help: Data for Fortran Program

#	Compound Name	Molecular Weight (gm)	Boiling Point (°C) @ 1 Atm	Vapor Pressure (Atm) @T= 20 °C	Solubility	Organic Carbon Dist. Coeff	Mass Fraction Dist.
1	propane	44.1	-42	8.5	62	73	0.00
2	isobutane	58.1	-12	2.93	49	537	0.00
3	n-butane	58.1	-1	2.11	61	946	0
4	trans-2-butene	56.1	1	1.97	430	204	0
5	cis-2-butene	56.1	4	1.79	430	204	0
6	3-methyl-1-butene	70.1	21	0.96	130	708	0
7	isopentane	72.2	28	0.78	48	1862	0.0069
8	1-pentene	70.1	30	0.7	148	710	0.0005
9	2-methyl-1-butene	70.1	31	0.67	155	525	0.0008
10	2-methyl-1,3-butadiene	68.1	34	0.65	642	323	0.0000

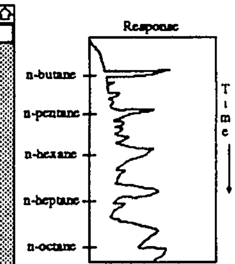
Return H19

H20

Help: How Do I Measure a Distribution?

Determining the exact composition of complex mixtures (such as gasoline) requires specialized analytical techniques. For the purpose of estimating the response to venting, however, an approximate composition can be used with very good results.

To determine an approximate distribution, one must analyze the mixture by gas chromatographic analyses. Prior to the analyses, choose about 6 - 10 marker compounds whose properties are well known. Often a series of straight chain alkanes (n-butane, n-pentane, n-hexane, etc.) is chosen. Then the unknown mixture is analyzed, and the areas of all peaks eluting between the retention times of two known peaks are summed and treated as one of the known peaks, as illustrated on the



Return to Vapor Conc. Calc. Calculate a Distribution

H21

Help: Calculate a Distribution

(1) Perform a GC analyses and sum all peaks whose retention times lie between the known compounds.

(2) Enter the areas or concentrations in the appropriate location in the Table on the right. Then, Click Calculate.

(3) Click the "Transfer Data..." button and your distribution will be copied to the Composition Table.

#	Compound	Concentration or Area	Normalized Distribution
1	propane	0.00	0.00000
2	n-butane	1000	0.07692
3	n-pentane	5000	0.38462
4	n-hexane	7000	0.53846
5	n-heptane	0.00	0.00000
6	n-octane	0.00	0.00000
7	n-nonane	0.00	0.00000
8	n-decane	0.00	0.00000
9	n-undecane	0.00	0.00000
10	n-dodecane	0.00	0.00000

Reset Calculate

Return to Vapor Conc. Calc. Card Return Transfer Data to Distribution Card

Help: About Calculation

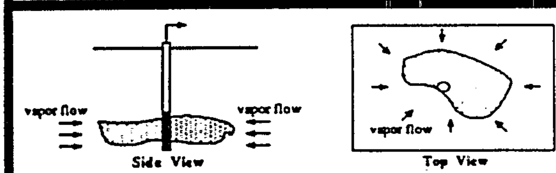
In this estimation of equilibrium (saturated) vapor concentrations, we assume that the contaminant concentrations are great enough (>200 mg/kg TPH) that it is distributed between vapor, sorbed, dissolved-in-soil-moisture, & free-phases. In this case, the equation at the right applies (look for "Raoult's Law" & the "Ideal Gas Law" in any thermodynamics textbook for references). We do correct for

$$C^v = \sum_{i=1}^{i=n} \frac{x_i P_i^v M_{w,i}}{RT}$$

C^v = total vapor concentration [mg/l]
n = number of components
x = mole fraction of component i
P^v = vapor pressure of component i [atm]
M_w = molecular weight of component i [mg/mole]
R = Universal Gas Constant = 0.0821 l-atm/K-mole
T = absolute temperature [K] = T(C) + 273

Return H22

Help: 6a) Dilution Effects [Bypassing]

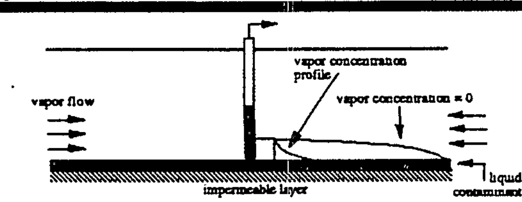


The figure above depicts the case where some vapors "bypass" zones of contamination, and therefore the vapors removed from the extraction well represent a mixture of the vapors obtained from both contaminated and clean vapor flowpaths. One can roughly judge the amount of bypassing by the well placement, screening, and contaminant distribution. Generally, observed vapor concentrations are roughly 10 - 50% of the ideal saturated

Return H23

H24

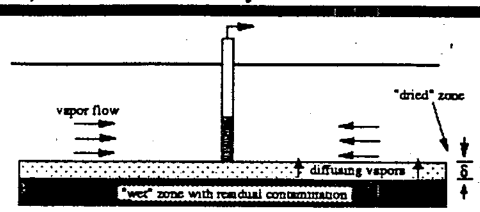
Help: 6b) Liquid Layers



In Figure 6b, vapor flows parallel to, but not through, the zone of contamination, and the significant mass transfer resistance is vapor phase diffusion. This would be the case for a layer of liquid hydrocarbon resting on top of an impermeable strata or the water table. This problem was studied by Johnson et al (1988 - NWWA/API Petroleum Hydrocarbons Conference) for

Show Me Equations Return Let's Do a Calculation

Help: 6c) Low Permeability Lenses



In the situation depicted above, vapor flows past, rather than through the contaminated soil zone, such as might be the case for a contaminated clay lens surrounded by sandy soils. In this case vapor diffusion through the clay to the flowing vapor limits the removal rate (the removal rate actually becomes

Show Me Equations | Return | Let's Do a Calculation

H25

Help: 6c) Low Permeability Lenses - Equations

$$R_{est} = \pi (R_2^2 - R_1^2) \sqrt{\frac{C_{est} D^{eff} C_{soil} \rho_{soil}}{2t}} \qquad \delta = \sqrt{\frac{C_{est} D^{eff} t}{C_{soil} \rho_{soil}}}$$

where:

- R_{est} = estimated removal rate [mg/d]
- δ = thickness of "dried-out" zone [m]
- R_1 = defines region in which contamination is present [m]
- R_2 = defines region in which contamination is present [m]
- C_{est} = estimated saturated vapor concentration [mg/m3]
- D^{eff} = effective soil vapor diffusion coefficient [m2/d]
- C_{soil} = initial residual level of contaminant in soil [mg/kg]
- ρ_{soil} = soil bulk density [kg/m3]
- t = time [d]

Derivations for these equations are given in Johnson, et al - "A Practical Approach to the Design, Operation and Monitoring of In Situ Soil Venting Systems" - 1990.

These Equations are valid for single-component

Let's Do a Calculation | Return

H26

Help: Default Boiling Point Ranges

The Fortran program HYPEVENT will report residual levels of compounds falling between user specified boiling point ranges. The default values have been chosen so that residual levels of compounds with boiling points between the following compounds are grouped together:

Propane - Isopentane (-50 to 28 C)
Isopentane - Benzene (28 to 80 C)
Benzene - Toluene (80 - 111 C)
Toluene - Xylenes (111 - 144 C)
Xylenes - Methylnapthalene (144 - 250 C)

Return

H27

Help: Boundary Layer Equations

$$R_{est} = \eta\, Q\, C_{est}$$

$$\eta = \frac{1}{3H} (6 D^{eff} \mu / k)^{1/2} [\ln(R_I/R_w)/(P_{Atm} - P_w)]^{1/2} \sqrt{R_2^2 - R_1^2}$$

The equation above estimates the removal rate from a layer of liquid product by a single well, based on a Boundary Layer Theory approach to the problem. It is not directly applicable to mixtures, because it

- R_{est} = estimated removal rate
- η = efficiency relative to maximum removal rate
- D^{eff} = effective soil vapor diffusion coefficient (cm2/s)
- μ = viscosity of air = 1.8 x 10-4 g/cm-s
- k = soil permeability to vapor flow (cm2)
- H = thickness of screened interval (cm)
- R_I = radius of influence of venting well (cm)
- R_w = venting well radius (cm)
- P_{Atm} = absolute ambient pressure = 1.016 x 106 g/cm-s2
- P_w = absolute pressure at the venting well (g/cm-s2)
- $R_1 < r < R_2$ = defines region in which contamination is present

Let's Do a Calculation | Return

H28

Help: Boundary Layer Equations - Calculation

(1) Soil Type (choose one)

- ○ Medium Sand
- ○ Clayey Silts
- ○ Silty Sand
- ◉ Fine Sand
- ○ Input Your Own Permeability Range

[1] to [10] (darcys)

(2) Process Variables:

- [6.6] thickness of screened interval [ft]
- [40] radius of influence of venting well [ft]
- [2] venting well radius [in]
- [120] applied vacuum at well [in H2O]
- [40] radial width of contaminated zone

(3) --> Calculate <--

Just enter values into the appropriate fields, then click on the "calculate" button.

The "Relative Efficiency" is the ratio of the predicted removal rate to the removal rate that would be obtained if the extracted vapors were saturated, or in equilibrium with the liquid

Relative Efficiency = (%) [7.457548] to [23.582837]

Return

H29

Help: Low Permeability Lenses - Calculation

(1) Process Variables:
(input values)

- [4] venting well radius [in]
- [150] radial width of contaminated zone [ft]
- [10000] residual contaminant level [mg/kg]

(2) Contaminant Properties:

- [84.2420] contaminant molecular weight [g/mole]
- [43.9584] contaminant vapor pressure [mm Hg]
- [18] temperature (C)
- ○ use values already input from Card 10

Just enter values into the appropriate fields, then click on the "Calculate" button.

(3) --> Calculate <--

Time (days)	Removal Rate (kg/d)	δ (m)
1	3263.553	0.062
7	1233.507	0.164
30	595.841	0.340
60	421.323	0.481
120	297.920	0.681
180	243.251	0.834
240	210.661	0.963
360	172.004	1.179
540	140.441	1.444
720	121.625	1.668
1080	99.307	2.043

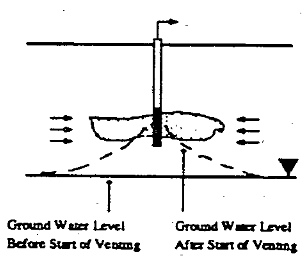
Return

H30

Ground Water Table Upwelling

During venting, the pressure within the radius of influence of the vapor extraction well is lowered, due to the applied vacuum. This lowering of the pressure affects the groundwater level in this zone, and an "upwelling", or local rise in the water table will occur.

The local water table rise can be as great as the gauge vacuum applied at the extraction well



Return

H31

Date and Time...

Generally, the DATE and TIME should be recorded along with any measurement that is made. Given the time scale for venting-related processes, recording the time to the nearest minute should be sufficient.

Sample devices are Rolex watches, hour glasses, sun dials, and timers.

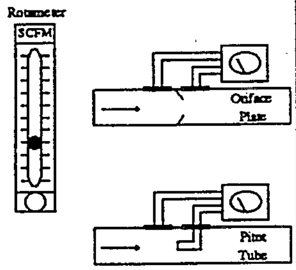
Return

H32

Vapor Flow Rates...

Vapor flow rates from each extraction well and into any injection wells should be monitored.

Sample measuring devices include pitot tubes, oriface plates and rotameters. It is important to have calibrated these devices at the field operating pressures and temperatures

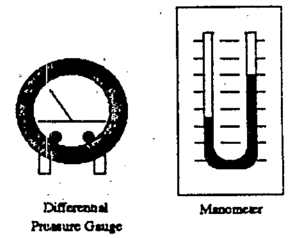


Return H33

Pressure/Vacuum Readings...

Pressures/Vacuums should be measured at each extraction and injection well. In addition, subsurface pressure distributions (measured with vadose zone installations) are useful for determining the zone of influence and vapor flow paths.

Typical pressure/vacuum measuring devices include manometers and differential pressure gauges.

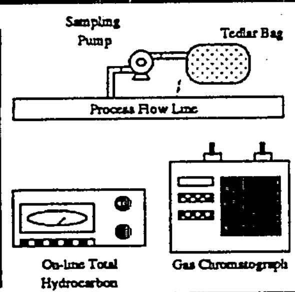


Return H34

Vapor Concentrations & Composition...

The vapor concentration and composition from each extraction well should be analyzed periodically. This data is multiplied by the extraction well flowrate to calculate the removal rate (i.e. lb/day), and cumulative amount of contaminant removed.

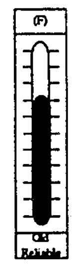
By itself, vapor concentration data does not give a complete picture of the system's performance. Decreases



Return H35

Temperature...

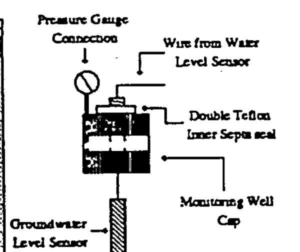
The soil and ambient temperatures can have a significant effect on the performance of soil venting systems. The soil temperature affects the contaminant vapor concentrations, while the ambient temperature controls whether or not condensation, or even freezing will be significant. For future reference, therefore, it is useful to record the ambient and soil temperatures.



Return H36

Water Table Level...(for contaminated soils located near the water table)

Whenever the contaminated zone lies near the groundwater table (within 3 to 5 ft), it is important to monitor the water table level to ensure that contaminated soils remain exposed to vapor flow. Measuring the water table level during venting is not a trivial task because the monitoring well must remain sealed. Uncapping the well releases the vacuum and any effect that it has on the water table level.

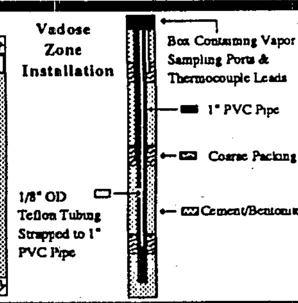


Return H37

Soil Gas Concentration & Composition...

These should be measured periodically at different radial distances from the vapor extraction well(s). Data from soil gas sampling is valuable for three reasons:

(1) by comparing extraction well concentrations with soil gas concentrations, it is possible to estimate the fraction of vapor that is flowing through the contaminated zone (i.e. the "efficiency" of

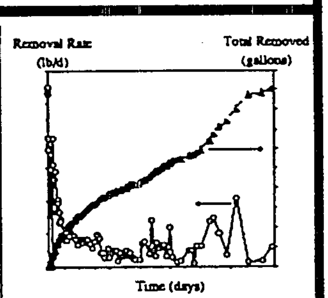


Return H38

Cumulative Amount Removed...

CUMULATIVE AMOUNT REMOVED

is determined by integrating the measured removal rates (flowrate x concentration) with time. While this value indicates how much contaminant has been removed, it is usually not very useful for determining when to take confirmation borings unless the original spill mass is known very accurately. In most cases that

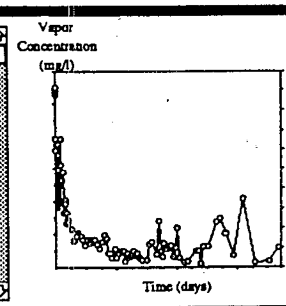


Return H39

Extraction Well Vapor Concentration...

EXTRACTION WELL VAPOR CONCENTRATION

the vapor concentrations are good indications of how effectively the venting system is working, but decreases in vapor extraction well concentrations are not strong evidence that soil concentrations have decreased. Decreases may also be due to other phenomena such as water table level increases, increased mass transfer resistance

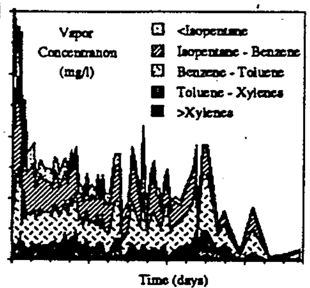


Return H40

Extraction Well Vapor Composition...

EXTRACTION WELL VAPOR COMPOSITION

when combined with vapor concentrations this data gives more insight into the effectiveness of the system. If the total vapor concentration decreases without a change in composition, it is probably due to increased mass transfer resistance (water table upwelling, drying-out of low permeability zones, etc.), and is not



Return

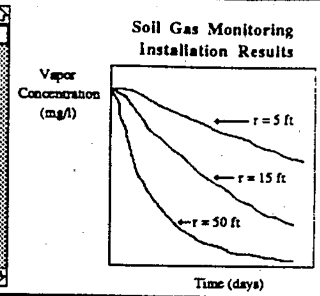
H41

Soil Gas Data...

SOIL GAS DATA

this data is the most useful because it yields information about the residual composition and extent of contamination.

Vapor concentrations can not, in general, be used to determine the residual level, except in the limit of very low residual levels (when vapor concentrations are proportional to soil residual levels).



Return

H42

Soil Boring Data...

SOIL BORING DATA

Generally confirmation soil borings are taken once a system is turned off, and these are often analyzed for TPH (total petroleum hydrocarbons) and volatile residuals.

One should keep in mind that TPH results can often be misleading, since they reveal nothing about the composition of the residual or its

Soil Boring Results

Boring Location	TPH [mg/kg]	BTEX [mg/kg]
Before		
B-1	1200	20
B-2	14000	120
B-3	8600	400
After		
B-4	20	ND
B-5	120	0.1
B-6	5	ND

Return

H43

Appendix C: "Air Permeability Test" stack cards.

Air Permeability Tests...

The purpose of an air permeability test is to obtain site-specific data that will be used in the final system design. It is a way to verify that venting is an appropriate remediation technique for your site.

In particular, one typically tries to get a better estimate of the soil permeability of each distinct soil layer to be treated, and a better estimate of contaminant vapor concentrations

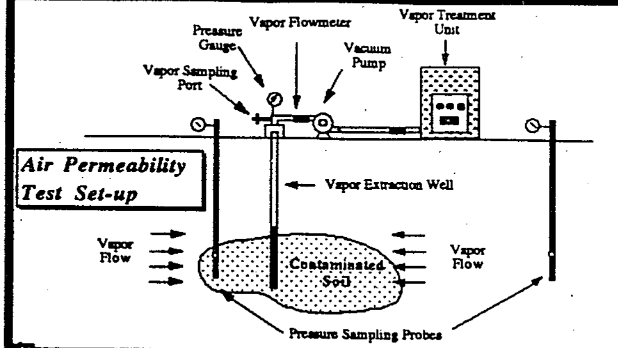
Show Me Set-Up

Test Instructions

Data Analysis

Return to Main Stack - Card 21 | AP1

Air Permeability Test Set-up



Print Card | Return | AP2

Air Permeability Test - Instructions

1)
Identify soil zones to be treated

2)
Install vapor extraction well(s) in this zone(s). Existing monitoring wells may be used, when the screen interval extends only into the zone to be treated. Note the extraction well radius and borehole size. Insure that the well is not "connected" to other soil zones through the borehole (use cement/grout to seal annular borehole

show me sample data

Pore Volume Estimation:

Enter:

1) Soil Layer Thickness [ft]:	6.6
2) Estimated Radius of Influence [ft]:	50
3) Air Perm. Test Flowrate [CFM]:	15

--> Calculate <--

Pore Volume: 15543 ft**3

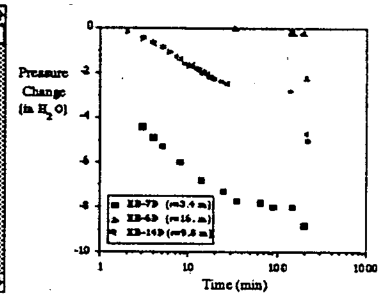
Time to Extract a Pore Volume: 0.72 days

Return | AP3

Air Permeability Test - Sample Data

Pictured at the right are the soil vacuum measurements from an air permeability test conducted in a silty sand.

The specific operating conditions and site characteristics are described in "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems", by P. C.



Return | AP4

Air Permeability Test - Data Analysis

The expected decrease in subsurface pressure (increase in gauge vacuum) P' is predicted by: (see Johnson et al [1990] for derivation)

$$P'(r,t) = \frac{Q}{4\pi m(k/\mu)} \int_{\frac{r^2 \varepsilon \mu}{4 k P_{Atm} t}} \frac{e^{-x}}{x}\, dx$$

- P' = gauge vacuum
- m = stratum thickness
- r = radial distance from extraction well
- k = soil permeability
- μ = air viscosity = 0.018 centipoise
- ε = air-filled void fraction
- t = time
- Q = volumetric flowrate from extraction well
- P_{Atm} = ambient atmospheric pressure

Skip the Explanation | Return | AP5

Air Permeability Test - Data Analysis (cont.)

For $(r^2 \varepsilon \mu / 4 k P_{Atm} t) < 0.1$, the governing equation can be approximated by the expression:

$$P' = \frac{Q}{4\pi m(k/\mu)}[-0.5772 - \ln(\frac{r^2 \varepsilon \mu}{4 k P_{Atm}}) + \ln(t)]$$

This Equation predicts that a plot of P' -vs- ln(t) should be a straight line with slope A and y-intercept B equal to:

$$A = \frac{Q}{4\pi m(k/\mu)} \qquad B = \frac{Q}{4\pi m(k/\mu)}[-0.5772 - \ln(\frac{r^2 \varepsilon \mu}{4 k P_{Atm}})]$$

Return | AP6

Air Permeability Test - Data Analysis (cont.)

The permeability, k, can then be calculated by one of two methods:

① The first is applicable when both Q (flowrate) and m (well screen interval) are known accurately. The calculated slope A is used.

$$k = \frac{Q \mu}{4 A \pi m}$$

② The second approach is used whenever Q or m are not known with confidence. In this case, both the slope, A, and intercept, B, are used:

$$k = \frac{r^2 \varepsilon \mu}{4 P_{Atm}} \exp[0.5772 + \frac{B}{A})]$$

Return | AP7

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points

② Enter measured times and gauge vacuums

③ Enter (optional):

a) flowrate: 15 (SCFM)

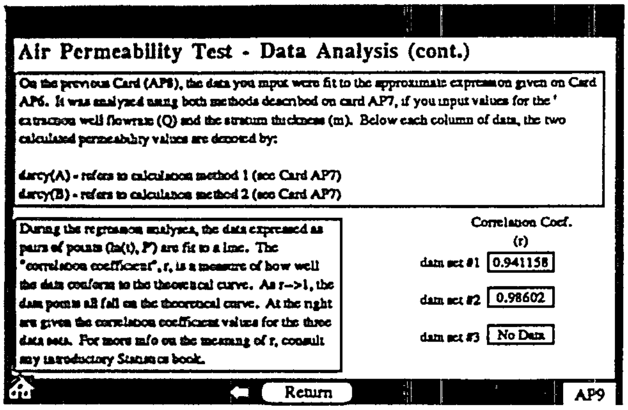
b) screened interval thickness: 6.6 (ft)

r= 53 (ft) (min)	(in H2O)	r= 32.4 (ft) (min)	(in H2O)	r= (ft) (min)	(in H2O)
9	0.1	4	1.2		
11	0.2	7	3		
15	0.2	9	4.3		
23	0.4	12	5.5		
30	0.7	16	6.9		
40	1.3	24	9.9		
100	2.8	30	11		
		39	13		
		52	16		
		77	20		
clear		clear		clear	

-->Calculate<--

k= 18.6948 darcy (A)	k= 2.85845 darcy (A)	k= darcy (A)
k= 9.29866 darcy (B)	k= 7.76759 darcy (B)	k= darcy (B)

Return | Explanation & Statistics | AP8



Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the ' extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)
darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points (ln(t), P') are fit to a line. The "correlation coefficient", r, is a measure of how well the data conform to the theoretical curve. As r-->1, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r, consult any introductory Statistics book.

Correlation Coef. (r)

data set #1	0.941158
data set #2	0.98602
data set #3	No Data

Return

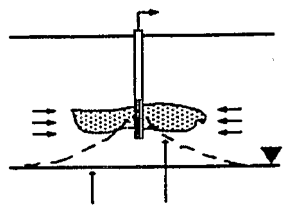
AP9

Appendix D: "Aquifer Characterization" stack cards.

Aquifer Characterization:

To achieve efficient venting, the hydrocarbon-contaminated soil must be exposed to air flow, therefore, in most cases where the residual soil contamination lies close to, or below, the saturated soil zone (groundwater table), it will be necessary to incorporate a groundwater pumping system in the vapor extraction system design.

As mentioned previously, one must always be aware of the groundwater



Return to Main Stack AC1

Aquifer Characterization:

Since most venting systems are installed above "phreatic aquifers" (aquifers with unconfined upper surfaces), the two primary aquifer parameters needed for design are:

K = hydraulic conductivity
S = effective porosity (or specific yield)

The first parameter represents a convenient combination of the fundamental parameters: permeability, density, and viscosity:

$$K = \frac{k \rho g}{\mu}$$

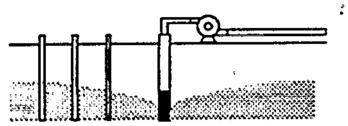
where:

k = permeability
ρ = fluid density
g = acceleration due to gravity
μ = viscosity

Return to Main Stack AC2

Aquifer Characterization:

These parameters (K and S) can be estimated using the results of a standard transient groundwater pump test with a constant pumping rate. The results are then compared against standard "type curves" for specific aquifer situations (i.e. leaky, unconfined aquifers, etc.).



Press the "References" button below for more information on slug tests, bail tests, pump tests, and data analysis.

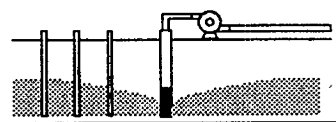
References Return to Main Stack AC3

Aquifer Characterization - References

J. Bear, "Hydraulics of Groundwater", McGraw-Hill, 1979, ISBN 0-07-004170-9, p. 463 - 490.

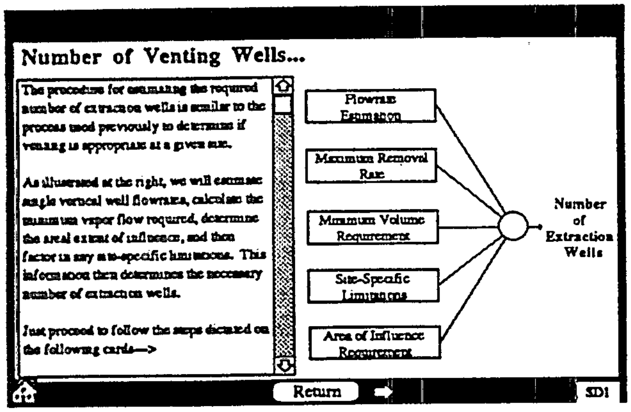
R. A. Freeze and J. A. Cherry, "Groundwater", Prentice-Hall, 1979, ISBN 0-13-365312-9, p. 339 - 352.

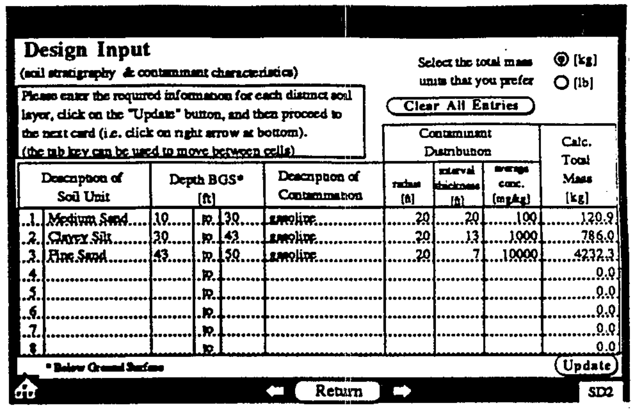
G. R. Chirlin, "A Critique of the Hvorslev Method for Slug Test Analysis: The



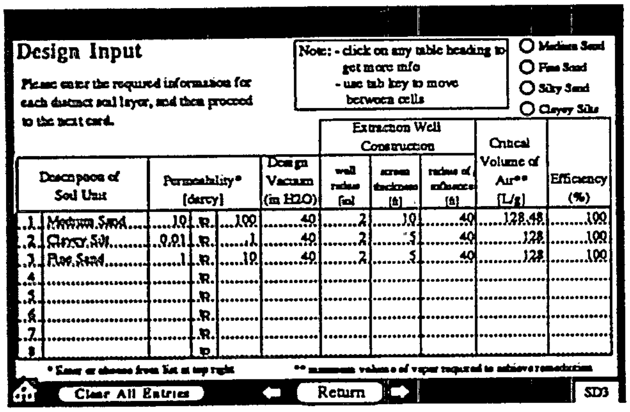
Return AC4

Appendix E: "System Design" stack cards.

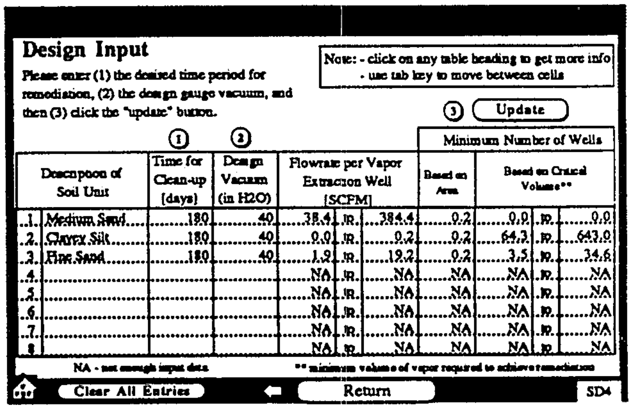




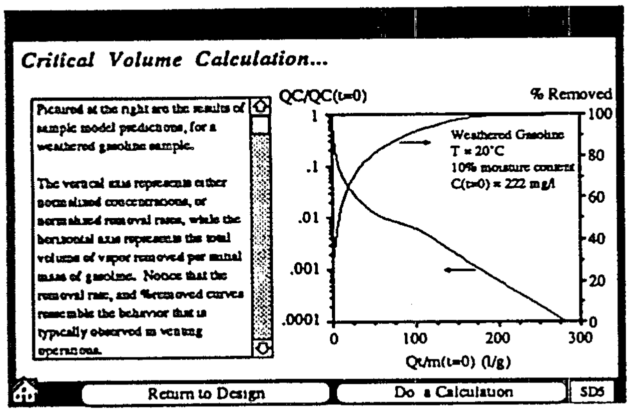
	Description of Soil Unit	Depth BGS* [ft]			Description of Contamination	Contaminant Distribution radius [ft]	interval thickness [ft]	average conc. [mg/kg]	Calc. Total Mass [kg]
1	Medium Sand	10	to	30	gasoline	20	20	100	120.9
2	Clayey Silt	30	to	43	gasoline	20	13	1000	786.0
3	Fine Sand	43	to	50	gasoline	20	7	10000	4232.3
4			to						0.0
5			to						0.0
6			to						0.0
7			to						0.0
8			to						0.0

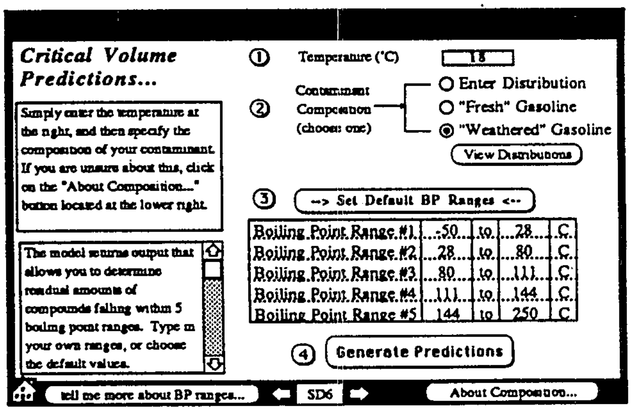


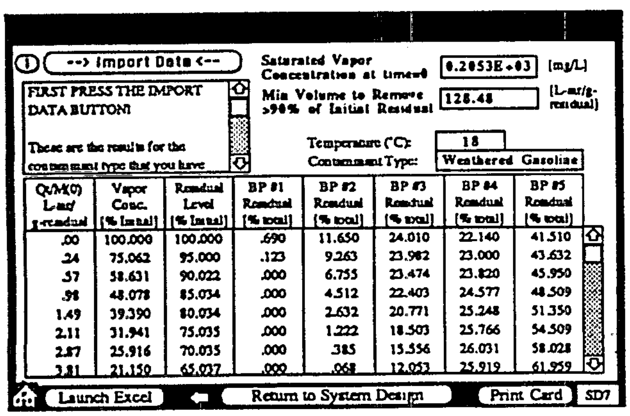
	Description of Soil Unit	Permeability* [darcy]			Design Vacuum (in H2O)	Extraction Well Construction: well radius [in]	screen thickness [ft]	radius of influence [ft]	Critical Volume of Air** [L/g]	Efficiency (%)
1	Medium Sand	10	to	100	40	2	10	40	128.48	100
2	Clayey Silt	0.01	to	.1	40	2	5	40	128	100
3	Fine Sand	1	to	10	40	2	5	40	128	100
4			to							
5			to							
6			to							
7			to							
8			to							



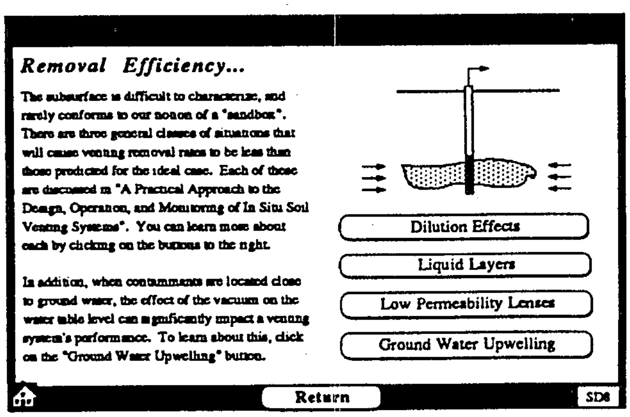
	Description of Soil Unit	(1) Time for Clean-up [days]	(2) Design Vacuum (in H2O)	Flowrate per Vapor Extraction Well [SCFM]			Minimum Number of Wells: Based on Area	Based on Critical Volume**		
1	Medium Sand	180	40	38.4	to	384.4	0.2	0.0	to	0.0
2	Clayey Silt	180	40	0.0	to	0.2	0.2	64.3	to	643.0
3	Fine Sand	180	40	1.9	to	19.2	0.2	3.5	to	34.6
4				NA	to	NA	NA	NA	to	NA
5				NA	to	NA	NA	NA	to	NA
6				NA	to	NA	NA	NA	to	NA
7				NA	to	NA	NA	NA	to	NA
8				NA	to	NA	NA	NA	to	NA







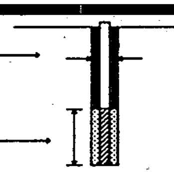
Qt/M(0) L-air/g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.000	100.000	.690	11.650	24.010	22.140	41.510
.24	75.062	95.000	.123	9.263	23.982	23.000	43.632
.57	58.631	90.022	.000	6.755	23.474	23.820	45.950
.98	48.078	85.034	.000	4.512	22.403	24.577	48.509
1.49	39.390	80.034	.000	2.632	20.771	25.248	51.350
2.11	31.941	75.035	.000	1.222	18.503	25.766	54.509
2.87	25.916	70.035	.000	.385	15.556	26.031	58.028
3.81	21.150	65.037	.000	.068	12.053	25.919	61.959



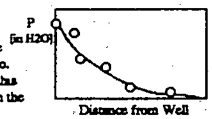
Help: Well Parameters

"Well Radius" - in general will be the radius of the well borehole, because the packing material is typically more permeable than the soil formation.

"Screen Thickness" is the length of the slotted interval of the well, or the thickness of the permeable zone, whichever is smaller.



"Radius of Influence" is the radial distance away from the extraction well, where the gauge pressure measured in the soil is approximately zero. The predictions are not very sensitive to this parameter, and most reported values lie in the range 40 - 120 ft.



Return to Design

SD9

Help: Minimum Number of Wells

The "Minimum Number of Wells" is calculated by the two methods discussed below:

a) Based on Area -

in this approach we estimate the minimum number of wells required to provide air flow through the contaminated zone as you have defined it. If Rc denotes the radial extent of contamination, and Ri denotes the "radius of influence" of an extraction well, then:

$$N_{wells} = \frac{Rc^2}{Ri^2}$$

b) Based on Critical Volume of Vapor -

in this approach we determine the number of wells required to extract the critical volume of vapor from the contaminated soil zone within the desired time frame. In this approach:

$$N_{wells} = \frac{V_{critical} \, M_{spill}}{Q_{well} \, \epsilon \, \Delta T}$$

Vcritical = critical volume of vapor [L/g-residual]
Mspill = spill mass [g-residual]
Qwell = volumetric flowrate from single well [L/d]
ε = efficiency of extraction process
ΔT = time for clean-up [d]

Return to Design

SD10

SD11

Contaminant Composition

Weathered Gasoline

View only Mode

	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 20 C
1	propane	0.00	44.1	8.5
2	isobutane	0.00	58.1	2.93
3	n-butane	0.00	58.1	2.11
4	trans-2-butene	0.00	56.1	1.97
5	cis-2-butene	0.00	56.1	1.79
6	3-methyl-1-butene	0.00	70.1	0.96
7	isopentane	0.00	72.2	0.78
8	1-pentene	0.00	70.1	0.7
9	2-methyl-1-butene	0.00	70.1	0.67
10	2-methyl-1,3-butadiene	0.00	68.1	0.65

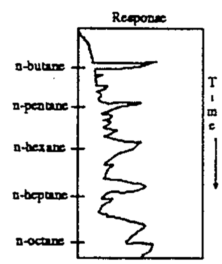
1.00000 = Sum of Mass Fractions

How Do I Measure a Distribution? | Return to Critical Volume Pred. | Print Lists

How Do I Measure a Distribution?

Determining the exact composition of complex mixtures (such as gasoline) requires specialized analytical techniques. For the purpose of estimating the response to venting, however, an approximate composition can be used with very good results.

To determine an approximate distribution, one must analyze the mixture by gas chromatographic analyses. Prior to the analyses, choose about 6 - 10 marker compounds whose properties are well known.



SD12

Calculate a Distribution

Calculate a Distribution

(1) Perform a GC analyses and sum all peaks whose retention times lie between the known compounds.

(2) Enter the areas or concentrations in the appropriate location in the Table on the right. Then, Click Calculate.

(3) Click the "Transfer Data..." button and your distribution will be copied to the Composition Table.

#	Compound	Concentration or Area	Normalized Distribution
1	propane	0.00	0.00000
2	n-butane	0.00	0.00000
3	n-pentane	0.00	0.00000
4	n-hexane	1111	1.00000
5	n-heptane	0.00	0.00000
6	n-octane	0.00	0.00000
7	n-nonane	0.00	0.00000
8	n-decane	0.00	0.00000
9	n-undecane	0.00	0.00000
10	n-dodecane	0.00	0.00000

Reset | Calculate

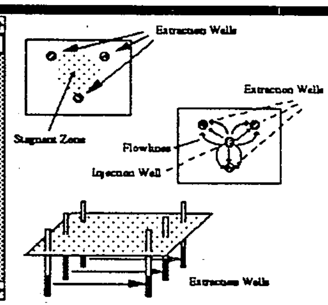
SD13

Return | Transfer Data to Distribution Card

Well Location

To be able to successfully locate extraction wells, passive wells, and surface seals one must have a good understanding of vapor flow behavior. Wells locations should be chosen to maximize vapor flow through the contaminated zone, while minimizing vapor flow through other zones.

If one well is sufficient, it should almost always be placed in the geometric center of the



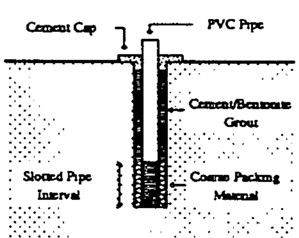
SD14

Return to Design

Well Construction

Wells should be screened only through the zone of contamination, unless the permeability to vapor flow is so low that removal rates would be greater if flow were induced in an adjacent soil layer. Removal rate estimates for various mass-transfer limited scenarios are discussed elsewhere in this stack.

Based on predictive equations, the flowrate is expected to increase by 15% when the extraction well

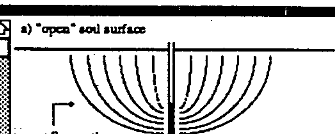


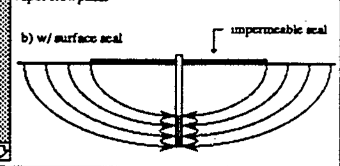
SD15

Return to Design

Surface Seals

Surface seals, such as polymer-based liners and asphalt, concrete, or clay caps, are sometimes used to control the vapor flow paths. Figure 12 illustrates the effect that a surface seal will have on vapor flow patterns. For shallow treatment zones (<5 m) the surface seal will have a significant effect on the vapor flow paths, and seals can be added or removed to achieve the desired vapor flowpath. For



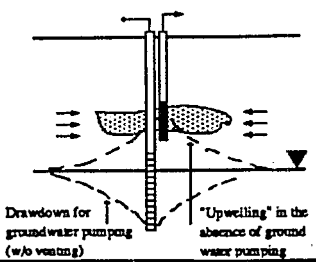


SD16

Return to Design

Groundwater Pumping Systems

In cases where contaminated soils lie just above or below the water table, groundwater pumping systems will be required to insure that contaminated soils remain exposed. In designing a groundwater system it is important to be aware that upwelling (draw-up) of the groundwater table will occur when a vacuum is applied at the extraction well (see the figure at the right).



SD17

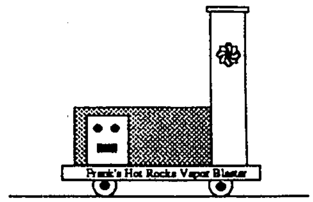
Return to Design

Vapor Treatment Systems

Currently there a four main treatment processes available:

VAPOR COMBUSTION UNITS:

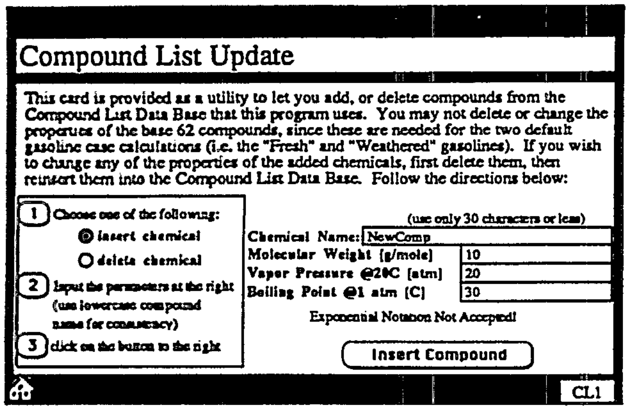
Vapors are incinerated and destruction efficiencies are typically >95%. A supplemental fuel, such as propane, is added before combustion unless extraction well vapor concentrations are on the order of



SD18

Return to Design

Appendix F: "Compound List Update" stack cards.



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