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**IN SITU SOIL VENTING - FULL SCALE  
TEST HILL AFB, GUIDANCE DOCUMENT,  
LITERATURE REVIEW**

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19 ABSTRACT (Continue on reverse if necessary and identify by block number) The purpose of this project was to demonstrate a full-scale in situ soil venting technology and to carefully document the design, operation and performance of this system so that it could be applied at other Air Force contaminated sites. Although this technology is now commercially available, its ability to fully remediate jet fuel spills had never been proven, nor had the full-scale costs ever been validated when catalytic incineration is used as an emission control method. ESL Technical Report 90-21 is in three volumes. The first volume is a complete literature review of previous soil venting research and field work. Volume II is a guidance manual which provides important design information and describes methods of pilot testing this technology prior to full-scale application. Results of the Hill AFB test are included in Volume III. These publications will provide invaluable information to Air Force engineers responsible for cleaning up chemically contaminated sites.					
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## EXECUTIVE SUMMARY

### A. OBJECTIVE

The purpose of this document is to provide personnel involved in environmental restoration projects with information regarding the technology known as *in situ* soil venting.

### B. BACKGROUND

*In situ* soil venting, also commonly known as soil vapor extraction, is rapidly becoming a widespread technique for the remediation of sites contaminated with volatile compounds. In this process, the soil is decontaminated in place by inducing air flow through contaminated soil zones. The volatile contaminants are vaporized and are removed in the gas stream extracted from the soil. Emissions control devices are often necessary for treatment of the gas stream prior to discharge. *In situ* soil venting has been proven to be an effective and economical decontamination technology in many cases.

### C. SCOPE

This document presents and analyzes the advances which have been made in implementation and understanding of *in situ* soil venting during the past ten years. Section I is an introduction to the technology. Section II provides an overview of the literature, detailing the major points of each article reviewed. Section III discusses how various site conditions will determine the effectiveness of the technology. Section IV describes the variety of system designs in common usage and discusses the impact of each design approach upon results. Section V describes the behavior of soil venting systems and the status of development of methods for predicting contaminant removal. Section VI details cost data obtained from field implementations. The conclusions of this study are listed in Section VII.

### D. CONCLUSIONS

*In situ* soil venting is an attractive and economical remediation technology for many cases of volatile contaminant spills. At this point, the limitations of the technology are not well-defined; however, progress has been made recently in expansion of its applicability. As with any *in situ* technique, projection of the time required for site cleanup and the effectiveness of cleanup is uncertain. Future studies, including lab-scale investigations of contaminant removal mechanisms and well-documented field implementations will improve the understanding of the technology.

PREFACE

This document was prepared by the Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6044, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida, as a partial means of fulfillment of the statement of work entitled "In Situ Soil Venting" in accordance with DOE Interagency Agreement No. 1489-1489 A1. Oak Ridge National Laboratory is operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR214000.

This document details the results of activities performed under Task 4.1 of the statement of work, Literature Review. Related documents completed under the same contract are ESL TR 90-21 Vol. 1, Guidance Document, and ESL TR 90-21 Vol. 2, Technical Report. The AFESC/RDCP Project Officers for this effort were Capt. E. C. Heyse, Capt. M. G. Elliott, Mr. Doug Downey, and Capt. E. G. Marchand.

Mention of trade names or commercial products within this document does not constitute endorsement or recommendation for use.

This report has been reviewed by the Public Affairs office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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## LIST OF ABBREVIATIONS

AFB	Air Force Base
API	American Petroleum Institute
DCP	1,3-dichloropropene
BLS	Below Land Surface
EPA	U.S. Environmental Protection Agency
IT	International Technology Corp.
MWRI	Midwest Water Resources, Inc.
PVC	Polyvinyl chloride
TCAAP	Twin Cities Army Ammunitions Plant
TCE	Trichloroethylene
TRI	Texas Research Institute
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency
VOCs	Volatile Organic Compounds

**LIST OF SYMBOLS  
(CONCLUDED)**

$v$	Velocity, $L t^{-1}$
$v_x$	Horizontal velocity component, $L t^{-1}$
$v_z$	Vertical velocity component, $L t^{-1}$
$x_i$	Liquid-phase mole fraction of component $i$ , dimensionless
$y_i$	Vapor-phase mole fraction of component $i$ , dimensionless

**Greek**

$\alpha$	Compressibility of porous media, $L t^2 M^{-1}$
$\eta_e$	Effective air-filled porosity, dimensionless
$\mu$	Dynamic viscosity, $M L^{-1} t^{-1}$
$\rho$	Gas density, $M L^{-3}$

**Dimensions**

$M$	Mass
$L$	Length
$t$	Time
$T$	Temperature

## LIST OF SYMBOLS

$g$	Acceleration due to gravity, $L t^{-2}$
$H$	Length of screened interval of extraction vent, $L$
$k$	Permeability, $L^2$
$k_x$	Horizontal component of permeability, $L^2$
$k_y$	Vertical component of permeability, $L^2$
$K$	Hydraulic conductivity, $L t^{-1}$
$MW$	Molecular weight, $M mol^{-1}$
$\bar{p}$	Relative permeability tensor, $L^2$
$P$	Pressure, $M L^{-1} t^{-2}$
$P_{atm}$	Atmospheric pressure, $M L^{-1} t^{-2}$
$P^{sat}$	Pure component vapor pressure, $M L^{-1} t^{-2}$
$P_{tot}$	Total pressure, $M L^{-1} t^{-2}$
$P_w$	Pressure at extraction vent, $M L^{-1} t^{-2}$
$\bar{q}$	Specific discharge vector, $L t^{-1}$
$Q$	Source or sink, $M L^{-3} t^{-1}$
$R$	Ideal gas constant, $M L^2 t^{-2} T^{-1} mol^{-1}$
$R_i$	Radius of influence, $L$
$R_w$	Radius of extraction vent, $L$
$T$	Temperature, $T$

# ***IN SITU* SOIL VENTING: A REVIEW OF THE LITERATURE**

## **SECTION I**

### **INTRODUCTION**

Remediation of hazardous spill sites has become a major undertaking of the current generation of environmental scientists and engineers in order to alleviate the increasing threat these spills pose to groundwater supplies. Many spills threatening groundwater contamination have been caused by improper storage, use, and disposal of volatile organic compounds (VOCs), including industrial solvents and fuels.

After a spill, these chemicals travel downward through the soil under the influence of gravity and rainwater. The contaminants become smeared throughout the unsaturated zone soils, becoming adsorbed on the soil particles and in the forms of vapor and free liquid in equilibrium in the soil pore space. Left unchecked, the liquid hydrocarbons may reach the water table if sufficient in volume. Most hydrocarbons, which are less dense than water, will spread out on top of the water table, although some denser hydrocarbons will continue to travel downward. In either case, dissolution of some of the hydrocarbons will result from the contact of the hydrocarbons and water, causing contamination of useable groundwater supplies.

The traditional approach for treatment of this problem is to pump the contaminated groundwater from the area and treat it for removal of the hydrocarbons until all contaminant levels are below prescribed limits. This approach by itself is very inefficient, since it ignores the problems caused by the residual hydrocarbons smeared throughout the unsaturated zone. Vapors from the unsaturated zone may travel relatively large distances by diffusion through the soil, contaminating larger areas of soil and causing hazards in buildings and sewers. Also, some of the residual hydrocarbons in the soil will dissolve each time rainwater percolates through the soil, recharging the groundwater with further contamination, and lengthening the time necessary for groundwater cleanup. A more efficient approach, therefore, is to eliminate the source of contamination in the unsaturated soil zone before it reaches the groundwater.

A promising technology for decontamination of the unsaturated zone is *in situ* soil venting, also referred to as *in situ* volatilization, *in situ* air stripping, vacuum extraction, or vapor extraction. A conceptual picture of *in situ* soil venting is shown in Figure 1. In this technique, the soil is

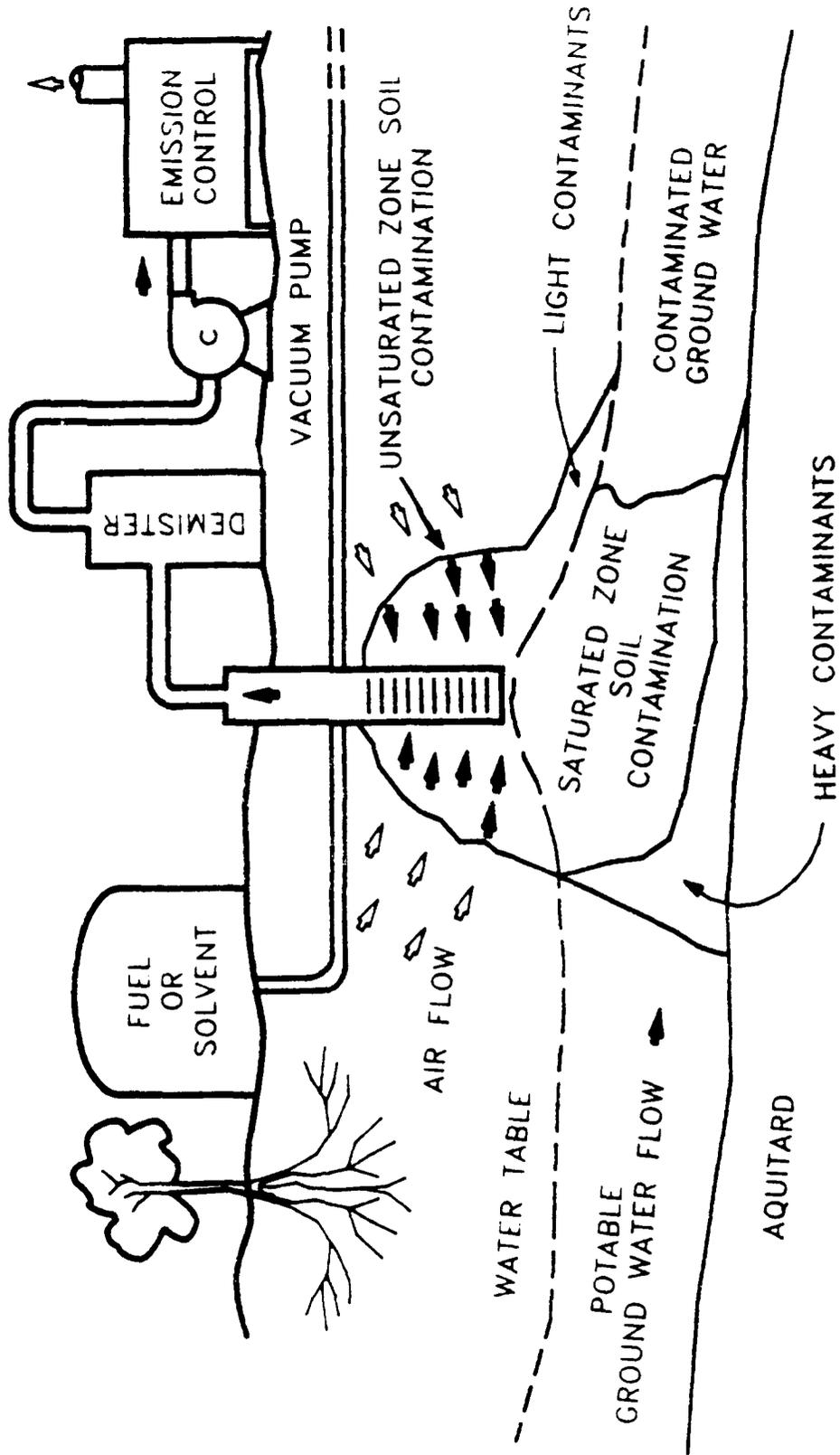


Figure 1. *In Situ* Soil Venting.

decontaminated in place by pulling air through the soil. Air removed from the soil may be resupplied passively by infiltration from the surface or through injection vents, either passively or by pumping. The air flow sweeps out the soil gas, disrupting the equilibrium existing between hydrocarbons sorbed onto the soil, dissolved in soil pore water, as free liquid, and as vapor. This causes volatilization of the contaminants and removal in the air stream.

*In situ* soil venting has proven to be a cost-effective decontamination technology. It is extremely useful in decontaminating unsaturated zone soils, both in preventing the hazards caused by subsurface vapor movement, and in removing the contaminants before they reach the groundwater. Soil venting may also be used in conjunction with pump-and-treat groundwater remediation techniques for complete cleanup of the soil and groundwater in cases where the hydrocarbons have reached the water table.

*In situ* soil venting is a relatively new technology, and as such, the body of knowledge on the subject is growing rapidly. This paper outlines the progression of the technology by review of several studies and demonstrations which have been presented in the literature. Elements of the current understanding of the technology are presented and recommendations are made for future work.

## SECTION II

### OVERVIEW OF THE LITERATURE

During the past decade, the application of soil venting for removal of volatile contaminants from soils has grown from initial exploratory studies through an expansion in application and a modest amount of study to the present, a point in which the technology is in widespread use and the body of knowledge is maturing rapidly. Following is a brief overview of some of the studies, demonstrations, and full-scale operations which have appeared in the open literature in the past several years.

#### A. 1980 TO 1985

Beginning in 1980, Texas Research Institute (for the American Petroleum Institute) undertook two of the earliest studies of soil venting with large-scale tank models simulating gasoline spills in sandy soils. The first study (Reference 1) was performed in a 10x20x4-foot tank in which 75 gallons of gasoline were spilled on washed sand. The results showed extraction of 57 percent of the contamination by venting during the 11-day test and demonstrated *in situ* soil venting to be an effective means for hydrocarbon removal. From measurements of carbon dioxide production, it was also concluded that considerable microbial activity occurred, consuming up to 2 percent of the gasoline. Due to the short duration and ideal nature of the test, the ultimate effectiveness of *in situ* soil venting for site remediation and its applicability to actual sites could not be determined. A second study (Reference 2) used two of the model systems to investigate the effects of venting geometry and types of sand on the rate of removal of gasoline from the soil and the surface of the water table. Geometry of venting was varied by slotting the entire vents in one system, and slotting only the area directly above the model aquifer in the other. Geometry was not found to be a factor in venting effectiveness in this study, but lower removal due to lower flow was noted in less permeable soils. Lighter gasoline fractions were removed more readily, changing relative concentrations in both the soil and extracted gas. Measurement of hydrocarbon concentrations in the model aquifer indicated removal of dissolved hydrocarbons by venting. The equations for an analytical model based on Darcy's Law and Fick's Law were presented for prediction of vapor concentration profiles.

George Hoag and Michael Marley performed venting studies at the University of Connecticut using columns of sand with gasoline at residual saturation. Their results indicated that close to 100 percent removal of gasoline from sand is possible from soil columns over a 1 to 4-day period

(References 3 and 4). By comparison of the column studies to a theoretical model, they determined that vapor phase equilibrium saturation of the induced air stream controlled removal of the hydrocarbons in this case.

By 1984, field applications of the technology began to be described in the literature. L. E. Dunlap, of Standard Oil Company of Indiana, demonstrated the usefulness of venting systems below buildings in soils with hydrocarbon contamination to reduce the hazards from vapor infiltration and buildup in buildings (Reference 5). M. J. O'Connor & Associates, Ltd., reported two cases of *in situ* soil venting systems used to eliminate hazards to the public due to underground gasoline leaks at service stations. Vapor extraction from the spill areas reduced soil vapor concentrations in and around a business in the first case and an apartment building in the second. The systems also drastically reduced the volume of the free gasoline liquid plume (Reference 6).

Terra-Vac® Inc. presented experience in remediation of hydrocarbon spills with soil venting. They proposed a "total approach to decontamination" of a site (Reference 7). This approach utilizes soil venting to first remove contamination from the unsaturated zone, eliminating recharge of hydrocarbons to the groundwater. A second step is venting to remove hydrocarbons from the saturated zone with a lowered water table, followed by groundwater extraction and treatment by air stripping. This approach was proven in the remediation of a shallow water table gasoline spill site. Venting proved capable of removing free product from the water table and residual hydrocarbons and vapors from the unsaturated zone. Coupled with pumping of groundwater and free product, it was reported that the system achieved cleanup to non-detectable levels more efficiently and less expensively than conventional methods.

The Terra-Vac® soil vapor extraction system has also been proposed for use in monitoring gas in soils surrounding underground tanks (Reference 8). The system may then be used for soil venting if hydrocarbons are detected. This system has been used at several sites for detection and cleanup of spills, including a carbon tetrachloride spill, a spill of industrial solvent mixture, and a gasoline spill. Seventy percent of the 15,000-gallon carbon tetrachloride spill was removed in 30 months from depths up to 100 feet (Reference 9).

#### **B. 1985 THROUGH 1987**

By 1985, two well-documented field studies were reported. Radian and Riedel Environmental Services performed a field test of soil venting for the American Petroleum Institute (References 10 and 11). In this study, they operated two sets of test wells on an existing gasoline spill that had reached the aquifer and was spread out upon the capillary zone. During the 36-day test, they

operated at three flow rates, measuring pressure and concentration at several points in the soil. Effluent gas concentrations remained high, 2000 to 4000 parts-per-million-by-volume (ppmv) throughout the test demonstrating high removal capability, but also indicating that the flow rates may have been undersized or the test duration too short to note long-term trends. The results also showed the effect of vapor recharge from the free product layer in the capillary zone and atop the water table. They concluded that soil venting is not only effective for removing hydrocarbons from the unsaturated zone soils, but also can be used in conjunction with conventional methods for aquifer restoration. However, the short test period and unchanging extraction rate did not allow evaluation of the variation of hydrocarbon yield with time or final removal capabilities.

Roy F. Weston, Inc., in conjunction with the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), operated a pilot-scale soil venting test at a solvent dump site at the Twin Cities Army Ammunitions Plant (TCAAP) (References 12 and 13). The test included two systems: (1) a large system in a highly contaminated zone and (2) a smaller system in a less contaminated area. Results indicated soil venting is effective in removal of trichloroethylene, dichloroethylene, toluene, and other solvents from sandy soils. Effluent concentrations in the small system decreased rapidly with time, whereas the effluent from the large system remained at high concentration throughout the test, again indicating a test system that was undersized for the schedule of the test. It was concluded that the technology is applicable for cleanup of both high and low initial concentration contaminated soils. Due to the short term of the tests, it was not clear if the technology continues to be effective after continuing operation has reduced contamination to some lower level. Empirical design relationships of vent pipe spacing and blower sizing for scale-up at the site were developed, and preliminary cost estimates of \$15 to 20 per cubic yard of soil treated were presented.

Further work by George Hoag with Arthur Bachr resulted in the formulation of a one-dimensional mathematical model of *in situ* soil venting based on equilibrium calculations for hydrocarbons in water, air, oil, and adsorbed phases, and on Darcy's Law for flow (Reference 14). Hoag and Mackay presented their perspectives on cleanup of hydrocarbon spills, stating that venting may enhance remediation in many cases. They reported venting results on a 500-gallon gasoline spill, with 90 percent removal in two months, and substantial decontamination of the site in three months (Reference 15).

Two full-scale systems, covering approximately 1 to 3 acres, have since been operated at the TCAAP site. Details of the full-scale operations are reported in Reference 16. These operations included two systems: Site D, including 39 vents in a 130-foot x 200-foot area, and Site G, including

89 vents in a 190-foot x 360-foot area. Initial operation of the systems in early 1986 resulted in the extraction of 20,000 pounds of total VOCs from Site D in 37 days and 24,000 pounds from Site G in 14 days. Due to the high removal rates, extraction from site D was slowed and carbon adsorption emissions control was added to Site G to remain within emissions limits. Estimated total costs for the cleanups were \$2.80/pound for Site D and \$8/pound for Site G. Weston also reported operation of full-scale systems for confidential clients for remediation of a propane tank spill and a solvent spill in an area with high clay content (Reference 17).

Woodward-Clyde Consultants presented several case histories on their operation of soil venting systems for site remediation. A system operated on a spent solvent spill at an electronics firm removed 12,000 pounds of organics, mainly trichloroethylene, from the soil in three years (Referenced 18 and 19). A pilot system was operated on a spill of straight-chain polychlorinated solvents from filter cleaning at an oil reprocessing plant. A full-scale system has been designed and operated from pilot system operation, extracting 100 pounds of hydrocarbons per day from the soil, and removing the threat of further contamination of a water supply (References 20 and 21). Woodward-Clyde's experience with soil venting, including applicability, guidelines, and design considerations, are presented in two articles (References 18 and 22).

Groundwater Technology, Inc., reported removal of 33.5 pounds of hydrocarbons per day from an unsaturated-zone gasoline spill at a convenience store (Reference 23).

Midwest Water Resources, Inc., (MWRI) reported cleanup of three solvent spill sites with their closed-loop venting system, Vaportech®. One system removed 99 percent of spilled perchloroethylene in 35 days, meeting closure guidelines in 90 days at one-fifth of the estimated excavation cost (References 24 and 25). Trichloroethylene (268 pounds) was removed from the other site (Reference 26). Both systems were operated while allowing the existing businesses to remain intact and operating. The third system was operated as an emergency response to a spill of acetone, ketones, toluene, xylene, mineral spirits, and naphtha affecting 6 acres of soil above a well field (Reference 25).

IT Corporation used *in situ* soil venting in conjunction with excavation in remediation of a 15,000-gallon spill of 1,3-dichloropropene from a railroad tank car. The excavation was used to remove much of the highly contaminated soil, but soil venting was necessary to vent the load-bearing soil under the tracks. Fifty percent of the contaminant was removed by excavation, with another forty percent removed by venting. The railroad continued operation throughout the cleanup (Reference 27).

In a related technology, Masood Ghassemi of CH2M Hill presented Toxic Treatment's innovative Detoxifier, a mobile system capable of several soil treatment methods, including an agitated-soil air stripping technique. This system has been demonstrated to reduce soil hydrocarbon concentrations from 5000 to 100 parts-per-million (ppm) quickly and uniformly (Reference 28). Reference 29 presents results of agitated soil air/steam stripping at a fuel spill site. For zones of less than 1000 ppm contamination, 75 to 80 percent removal was achieved in 47 minutes, whereas 90 to 95 percent removal was achieved in 75 minutes from zones of approximately 10,000 ppm contamination. The authors reported the limitations of the technique to be poor removal of higher molecular weight compounds, treatment only to a 60-foot depth, and the need to recompact the soil before construction can be performed at the site.

### C. 1988 TO PRESENT

In the past few years, a great expansion in the soil venting literature has been noted. The more recent articles stress a greater understanding of the factors involved in venting effectiveness and demonstrate successful completions of site remediations.

The results of the IT dichloropropene spill cleanup are analyzed in Reference 30. The authors assessed the effects of varying climate and soil properties, distinguished between periods of convective and diffusive control of extraction rate, and suggested methods to reduce costs. They concluded that higher air temperature and moisture positively affected the rate of removal, whereas wind and barometric pressure did not. Higher temperatures increased the contaminant vapor pressure, while moisture may have competed with the contaminant for adsorption on the soil. Convection controlled extraction rate during the first portion of operation, but diffusion limited removal later. Suggested methods for cost savings included pulsed operation, injection of humidified air, operation only in the warm weather, and reduction of vent spacings in areas of high bulk density to reduce diffusive path length.

AWARE, Inc., (now Eckenfelder, Inc.) has performed experimental and theoretical work on *in situ* soil venting in an attempt to produce a predictive model for venting effectiveness with various contaminants and soil types. Their tests with columns of clean and silty sand contaminated with acetone, trichloroethylene, or chlorobenzene have shown that 45 to over 99 percent removal is possible, depending on contaminant, soil type, and moisture content. They presented simple removal rate models using Henry's Law for pure component equilibrium for 85 compounds. Also presented were models of air flow through test columns and in soil near an extraction vent, which may prove useful in comparison of lab and field data (Reference 31). The progression of their modeling work

was described in Reference 32. In this paper they presented a two-dimensional model for contaminant removal, coupling steady-state flow into a point sink and Henry's Law equilibrium convective mass transport. The model was tested with site data from the Tyson waste site with very good agreement. The authors emphasized the semiquantitative nature of the model results due to heterogeneity and uncertainties in physical constants and transport mechanisms; however, the model is very valuable for general system design and operating guidance. The Eckenfelder work has continued with a one-year field study (Reference 33), consisting of a single 4-inch vent 20-foot-deep surrounded by 38 probes in Cohansey sands. Two blowers in series allowed for extraction of up to 400 ft<sup>3</sup>/minute at a vacuum of 50-inches of water. The moderate to high permeability sand, interbedded with clay and silt, allowed steady state pressure distribution to be achieved quickly (15 minutes). The radius of influence based on pressure was measured to be 150 feet, nearly twice that expected from flow modeling. The progression of temperature fronts in the soil was monitored, as well as water table rise. Extracted gas concentration dropped steadily from an initial 110 to 140 ppm to 60 to 70 ppm. The authors indicate an upcoming report of the field study with comparison to modeling work.

In Reference 34, a three-layer diffusion model was introduced as an attempt to display the effects of diffusion on extraction rate. The simplicity of the model does not allow accurate prediction of extraction in real systems; however, it may be used to give qualitative guidance toward the understanding of extraction behavior. The results obtained with the model show high initial removal rates, followed by a long tail in the curve of concentration versus time. These results were shown to be in qualitative agreement with the field results of three cases. The authors conclude that it is difficult to extrapolate the behavior of vapor extraction systems since the early behavior may be controlled by convective transport and later extraction governed by diffusion. The effects of diffusion should also be taken into account when determining adequacy of cleanup - the site should be allowed to equilibrate before measurements are taken.

Reference 35 presents a case history that emphasized the usefulness of soil gas analyses for directing soil venting applications. Removal of 733 pounds of VOCs in four months is reported from a complex geological setting of till over fractured limestone.

Reference 36 illustrates the usefulness of soil venting for removal of large amounts of contaminants before they impact groundwater, from which contaminant removal is much slower. Their case study of a PCE site showed removal of 1000 pounds of VOCs from groundwater by air stripping over a one-year period. The addition of soil venting at the site resulted in the removal of 1200 pounds of VOCs in 4 weeks.

Reference 37 describes the steps necessary to use soil venting to decontaminate the capillary fringe. Hydraulic control is necessary to dewater the capillary fringe and to offset the water table rise caused by vapor extraction.

Reference 38 presents a case study of remediation of a shallow (4 to 6 feet to groundwater) gasoline spill in tight soil, using trenches containing horizontal vent pipes over the half-acre site. A 5 hp blower capable of 600 ft<sup>3</sup>/minute at vacuums up to 20 inches of water fed the fumes to two on-site regenerable carbon beds. Water table rise was minimized by using many extraction vents rather than a single high-vacuum vent. Polyethylene sheeting spread over the site was pulled tightly to the surface by the induced vacuum to prevent short-circuit air flow. Connor claims that the surface barrier was not necessary in later operation after subsurface flow pathways were cleared. Higher soil and groundwater temperatures in contaminated soil zones were attributed to bioactivity.

Reference 39 presents an innovative self-contained unit for remediation of fuel-contaminated sites. The system combines spray aeration for groundwater decontamination with soil venting. Vapors from the two processes were fed to the inlet of an internal combustion engine with a catalytic converter for exhaust treatment. The engine powered the blower moving the vapors. The system was particularly efficient in the early stages of venting, when the extracted fumes provided most or all of the fuel required for the engine. The system described was capable of removing 120 pounds of fuel hydrocarbons per day, requiring 0.75 gallons of fuel per hour.

Reference 40 reports the successful completion of the three venting systems operated by MWRI (see page 7 of this report). In one of the cases, closure was based upon comparing aqueous phase liquid concentration with drinking water standards. Reference 41 presents a more detailed case study of the MWRI emergency site remediation. During 56 weeks of operation, 8000 pounds of VOCs were removed from 400,000 cubic yards of soil. Associated removal of VOCs from groundwater yielded only 10 pounds. Closure of 70 percent of the site within 10 months was reported.

Reference 42 discusses factors involved in soil venting effectiveness. Contaminant volatility and suction pressure were stated to be major factors in the removal rate. The majority of the paper focused upon a 2-dimensional finite element model for isothermal, incompressible flow through inhomogeneous, anisotropic media. The numerical model was validated using an experimental model system containing sand. Model output for cases of simple, covered, and layered vadose zones were presented, showing pressure and flow fields in the soil due to extraction from a single vent. Relationships of flow rate, pressure distribution, and suction pressure were presented for the simple vadose zone case. The case of a homogeneous vadose zone with a surface barrier showed an increase

in radius of influence and a tendency for the surface barrier to induce more horizontal flow. The layered site case indicated that flow would be less and the radius of influence (based on pressure) would be larger in the less permeable layer. As indicated by an example case of vapor management near an underground structure, the flow model is a useful tool for the prediction of flow fields. The authors foresee coupling of the model with contaminant transport relations for a complete venting model.

Reference 43 describes "bioaugmented soil venting", in which conditions for microbial activity are enhanced during venting. The results obtained with gasoline-contaminated soil columns were presented, showing that higher microorganism levels and greater degradation are possible with greater oxygenation, such as that supplied by venting. They presented three cases of successful removal/destruction of diesel fuel and gasoline from aboveground piles of clay and sand by a combination of venting and, if necessary, addition of nutrients and/or moisture.

References 44 and 45 present the steps involved in a decision to implement soil venting at a chlorinated hydrocarbon spill site, thereby providing general guidelines for deciding whether to use venting for site cleanup. The site characteristics used in making the decision were presented, along with an overview of each technology considered. Because of the listed applicability and cost considerations, and comparison with other successful cases, soil venting was chosen for the specific site remediation.

In a demonstration program (of which this document is a part) the Air Force Engineering and Services Center has sponsored the operation of a soil venting system at the site of a 27,000-gallon JP-4 jet fuel spill at Hill AFB, UT. Reference 46 describes the site characterization and pilot studies which were performed in order to design the full-scale system. The full-scale system is described and initial results are presented. Reference 47 presents results obtained after 6 months of operation at the site. Approximately 70,000 pounds of hydrocarbons were removed from the sandy soils in 42 million cubic feet of soil gas, lowering the gas concentrations from around 40,000 to 2,500 parts-per-million. The extraction results were favorably compared with a simple equilibrium model based on Raoult's Law. Reference 48 documents biodegradation occurring during operation of the Hill AFB soil venting system. Through microbial characterization, isotopic analysis, and measurement of carbon dioxide and oxygen levels in the soil gas and gas extracted from the vents and a background vent outside of the contamination area, the authors concluded that aerobic biodegradation occurred at the site. Biodegradation, enhanced by soil venting, accounted for 28 to 38 percent of the initial hydrocarbon removal, dropping to a steady-state fraction of 15 to 20 percent. On the basis of bench

studies, the authors conclude that this rate could be increased through addition of nutrients and optimization of the extraction flow rate. A complete technical report of the demonstration results through October 1989 will be published in early 1990.

Reference 49 analyzes the results of the EPA site demonstration performed by Terra-Vac® at Groveland, Massachusetts. In the 56-day test begun in December, 1987, they reported removal of 1300 pounds of chlorinated hydrocarbons (mostly TCE) from a complex soil consisting of silty sand, wet clay, and sand and gravel. Removal of hydrocarbons from an initial range of 200 to 1600 ppm to 60 ppm from clay zones was reported. Because of this result, the authors concluded that porosity was the primary variable of concern (rather than permeability) for determining the capability of venting for contaminant removal at this site. Reductions in concentration correlated well as straight lines on semi-log plots with time, consistent with a diffusion-controlled process. Based on these plots, the authors suggest a means of projecting length of operations by plotting concentration versus time and comparing site-specific soil/soil gas contaminant partitioning.

Reference 50 continues the analysis of transport processes governing VOC extraction. The authors show with their equilibrium model that all contamination may be removed from a gasoline spill given ideal conditions; therefore, the major problems with soil venting remain achieving optimum contact of the air flow and the contaminated soil zones. A two-dimensional, radially-symmetric, finite difference flow model was developed for determining air flows in soil given different soil properties and screening geometries. This model may be used for the analysis of test data for *in situ* determination of air-phase permeability. Using the model, the authors calculated the vacuum and power required to achieve various air extraction rates given the air permeability of the soil and vent geometry. The model is extremely useful for system design purposes but, as reported, does not yet include the complexity to model 3-dimensional flows in nonhomogeneous media.

Reference 51 describes the approach to system design used by Vapex, Inc. Their "scientific approach" to design is based on field sampling and analysis and upon computer transport models. They describe the necessary information to be obtained during site assessments and outline their method of feasibility study and design. Site plans, drill logs, soil and water quality measurements, and both deep- and shallow soil-gas surveys may be used for site characterization. A single-vent field test is conducted using a single extraction vent and several pressure probes to determine the *in situ* air permeability tensor. This information is used as input to an air flow model in order to determine design variables.

Joseph Danko (Reference 52) presented a good overview of soil venting that is useful for guidance in the decision process. The advantages, applicability, and limitations of the technology were presented. Several good points were made with respect to cleanup standards, a subject which is not well defined but which is of the highest interest. Guidance was provided on the applicability of soil venting dependence on the type of governing standard.

Two excellent analyses of soil venting applications have been published by Shell Development Co. In the first article, (Reference 53), simple screening models were presented, which may be used to address the three major factors identified in soil venting: flow rate, contaminant composition, and location of air flow relative to contamination. The authors gave simple estimations for the time necessary to achieve steady-state flow, a one-dimensional pressure distribution using radial flow assumption, water table rise, and air conductivity measurements from field data. By means of a diffusive transport equation and typical soil properties, they concluded that equilibrium is reached locally in most simple venting applications. Based upon this result, they described an equilibrium model that ignores mass transfer limitations but includes soil sorption, aqueous solubility, vapor pressure, and the ability to add the effects of bioactivity. The results obtained with the model for fresh and weathered gasoline were presented, showing the relatively rapid removal of BTX compounds but not of residual heavy hydrocarbon fractions. Equations were given utilizing boundary-layer theory that may be used to estimate the relative amount of diffusion control versus equilibrium control in an application.

In their second article, (Reference 54), the authors provided guidance for the applicability of soil venting by listing the steps to follow for deciding upon venting as the remediation technique and for designing an efficient system. They first described the site characteristics that should be evaluated in a site investigation, then they presented factors to be considered when deciding whether or not to use venting. These factors include (1) determinations as to whether air flow and contaminant concentration will be high enough to provide acceptable removal, (2) what residual contamination will be present, and (3) possible negative effects. Methods for determining air permeability and ability to offset water table rise were related, and practical guidance on system design was given. The authors also discuss possible means of determining when to shut down the system and also discuss other important factors. Sample calculations through the entire decision tree were presented.

Neil Hutzler of Michigan Technological University has published a review of the literature, (Reference 55), which presents many case studies and summarizes common features of the technology. His report provides an excellent overview of the technology and is the largest single source of detailed information regarding soil venting studies and field applications.

## SECTION III

### FACTORS IN SOIL VENTING EFFECTIVENESS

Many factors play a role in the effectiveness of *in situ* soil venting for removal of hydrocarbon contamination. The main factors considered here are the amount of induced air flow, geometry of air flow, suction pressure, the nature of the contaminants, soil characteristics, temperature, moisture, and bioactivity.

First, it must be noted that removal efficiency is difficult to measure. Heterogeneity of soils, variable distribution of spills, and transport of contaminants through the soil usually preclude knowing the initial mass of chemical to be removed (Reference 12). Soil gas measurements may help provide a better estimation of volatile contamination; however, they may not accurately ascertain levels of less volatile residual hydrocarbons.

#### A. AMOUNT OF AIR FLOW

A major factor in the effectiveness of *in situ* soil venting is the volume of air drawn through the contaminated soil areas. Increased flow generally increases the removal rate and the zone of influence for a single vent. More flow through an area will sweep away larger volumes of soil gas, causing increased volatilization rates, especially in cases where convective transport of contaminants is based on equilibrium conditions in the soil. For cases where diffusion controls removal rate, higher flow rates will speed removal. Reference 1 suggested that higher flow rates set up steeper concentration gradients, encouraging diffusion of contaminants toward the bulk air flow to the extraction vents. Results of the second TRI study indicated that points directly in the flow path from inlet to extraction vent showed two to twenty times greater soil vapor concentration reduction than the areas outside the direct flow path which are subject to lower flows (Reference 2). Reduction of contamination was shown to increase further as the flow rises geometrically closer to the inlet and extraction vents (Reference 10).

While the amount of air flow has a great effect in soil venting effectiveness, the relationship of removal rate to air flow rate will be linear only in cases where diffusion rates are relatively fast and equilibrium-convection mechanisms control removal rate. Equilibrium will not control removal in soil areas of very high air flow rate or, more commonly, in soil discontinuities such as zones of lower permeability. In these cases, diffusion will control contaminant removal, and an increase in the extraction flow rate will result in a less than proportional increase in contaminant removal rate. Several studies have found diffusion to be the rate limiting factor. Payne, (Reference 24), found air

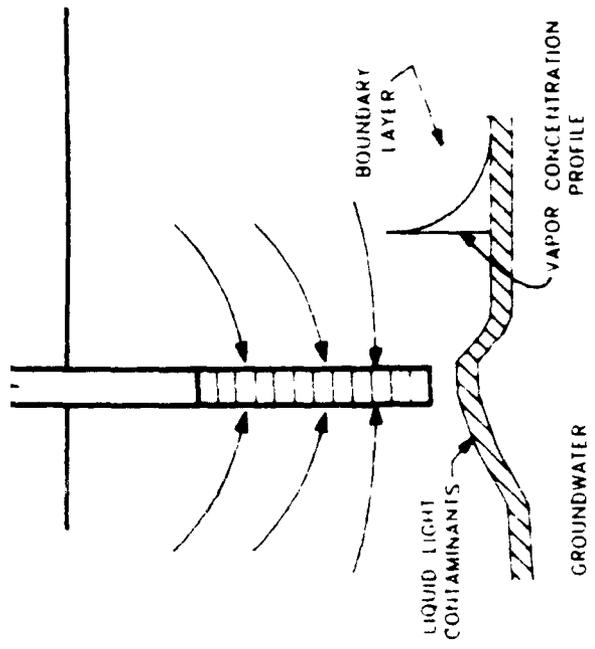
extraction rates in the soil to exceed the volatilization rate of perchloroethylene and showed "restart yield spikes", or sharp increases in extracted gas concentration after a shut-down period, which indicated that contaminants diffused from less permeable zones or zones of low air flow during the shut-down. Re-equilibration of soil gas levels after a pause in venting in the API study at a gasoline spill site was quite slow, (Reference 10), showing that the removal rate was dependant on diffusion of contaminants from the free product layer.

These findings of diffusion control indicate that an optimum venting rate (as defined in terms of mass removal per unit time) exists, above which increasing the air flow rate will not necessarily cause enhanced removal. This optimum venting rate would necessarily be site specific, and highly difficult to predict due to the freedom in extraction vent placement and to uncertainties in geohydrology and contaminant distribution. Another optimal venting rate, based on cost per unit of chemical removed, may result from pulsed operation, as several investigators suggest (References 10, 30, 40, and 55). In this case, although contaminant removal with respect to time will be slower than the rate described above, the cost may be minimized by operating the system at the highest possible gas phase contaminant concentration, thereby lowering specific emissions control and blower costs.

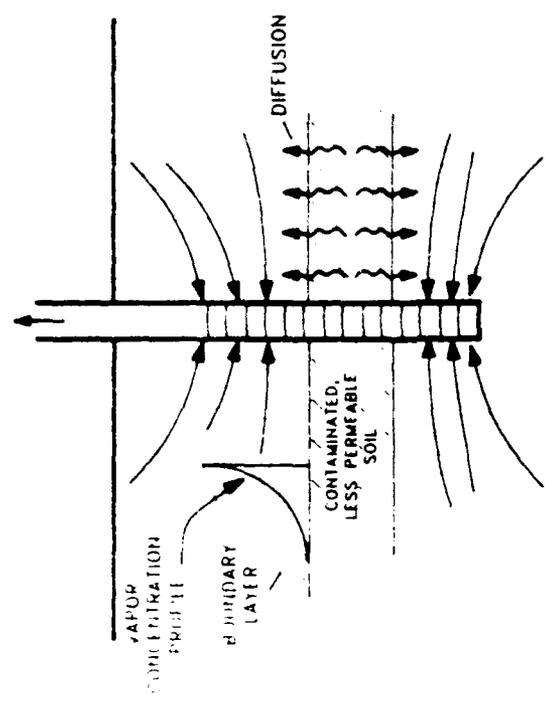
## **B. GEOMETRY OF AIR FLOW**

A factor as important as the amount of air flow induced in a soil venting situation is the geometry of the air flow. In fact, Baehr, et al. (Reference 50), claimed that the primary factor in soil venting effectiveness is establishing the intersection of a significant air flow with the contaminant plume. Conceptual illustrations of problems in establishing good air flow geometry relative to contaminant distribution are presented by Reference 54, showing cases of heterogeneous contaminant distribution, free product resting on a water table, contaminant in a less permeable zone surrounded by more permeable zones (see Figure 2), and vent configurations leading to stagnant regions.

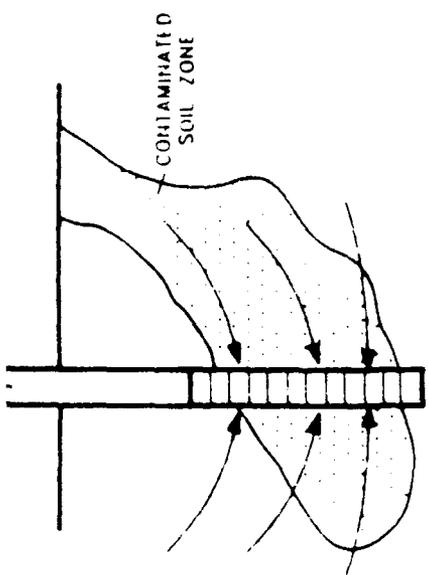
Field reports of problems caused by air flow geometry include cases of diffusion-control of extraction because of free product layers (References 10 and 34) and diffusion from less permeable layers (References 12, 25, and 30). Reference 41 reports a case in which the contaminant concentration in the gas extracted from a set of vents reached a maximum after 3 weeks of operation because of the placement of the vents relative to the contaminant distribution.



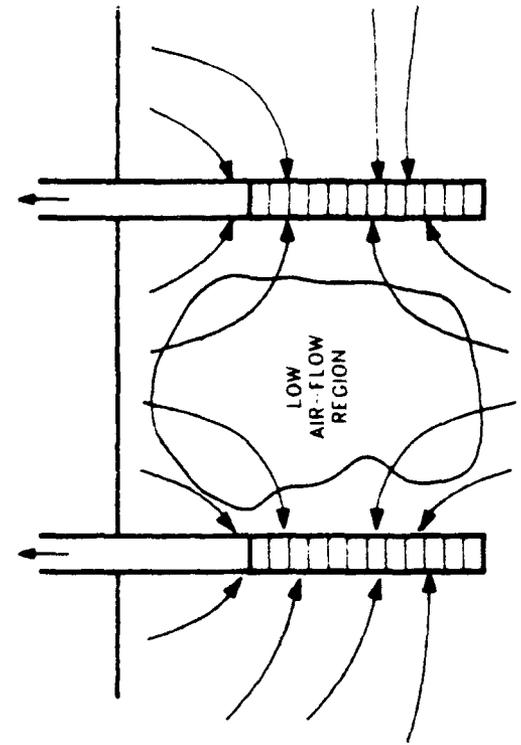
(a) HETEROGENEOUS CONTAMINANT DISTRIBUTION IN SOIL



(c.) DIFFUSION FROM LESS PERMEABLE SOIL ZONES



(b) REMOVAL OF FREE PRODUCT ON WATER TABLE



(d.) STAGNANT ZONES IN VENT OPERATION

Figure 2. Examples of Problems in Establishing Good Air Flow Geometry (adapted from Reference 54).

Several techniques aimed at improving air flow geometry have been suggested. Addition of passive air inlets (References 2, 10, and 18) or forced (References 24 and 41) air injection vents in deeper zones have been suggested to supplement surface air flow. Surface barriers have also been included to minimize surface air flow near the vents for better flow distribution (References 9, 10, 17, 24, and 38). Several authors (References 11, 18, 24, and 32) point out that placing the screened interval of the vents deeper in the soil will offset the effects of short circuiting of air from the surface. Terra-Vac® (Reference 49) and Weston (Reference 17) used nested extraction vents screened in different intervals in order to extract efficiently from different strata. Johnson and Sterrett (Reference 30) recommend smaller vent spacings in areas of high soil bulk density due to the tendency for lower air flow rates in these soils.

A powerful tool for tailoring flow geometry is flow modeling, such as that documented in References 32, 42, and 50. These papers demonstrate the power of modeling for predicting the magnitude of air flow throughout the soil. For instance, Reference 42 shows decreased flow through less permeable zones despite a greater zone of influence as would be measured in the field. Reference 32 uses a flow model coupled with a simple contaminant transport relationship; therefore, the authors may use projections of soil cleanup to drive air flow management design decisions.

### C. SUCTION PRESSURE

The suction pressure applied to the soil will have an effect upon removal rates, with greater vacuum inducing higher removal rates (all else being equal). This has been suggested in discussions (Reference 25), described in modeling work (Reference 31), and indicated in a bench-scale experiment of liquid gasoline volatilization (Reference 42).

The magnitude of the effect of increased vacuum level upon removal may be seen by an investigation of equilibrium relations. For instance, if Raoult's Law is used to describe equilibrium at a point in the soil, the contaminant vapor concentration may be written as

$$y_i = x_i P_i^{sat} / P_{tot} \quad , \quad (1)$$

where  $y_i$  is the vapor phase mole fraction of component  $i$ ,  $x_i$  is the liquid phase mole fraction of component  $i$ ,  $P_i^{sat}$  is the pure component vapor pressure of component  $i$ , and  $P_{tot}$  is the total pressure. In a given situation, increasing the suction, thereby decreasing  $P_{tot}$ , will increase the vapor phase contaminant concentration.

This factor helps to explain the findings of Reference 10, whose authors found higher contaminant removal near the extraction vent. In an isobaric situation, it would be expected that the gas flowing through the soil would become loaded with contaminants on the outer fringes of the contaminated soil, likely reaching conditions at or near equilibrium as it flows toward the vent. In this case, the increased flow near the vent would not cause greater removal rates in that area. The pressure,  $P_{\text{soil}}$ , in the soil actually drops drastically near the vent, shifting the equilibrium and thereby allowing greater removal.

Enhancement of removal by this mechanism is only achieved in a secondary fashion. Suction is usually increased in order to achieve a certain flow rate from a given vent configuration. Also, any enhancements achieved purely by increasing suction are likely to be offset by increased blower operation costs.

#### **D. TYPE OF CONTAMINANTS**

The nature of the contaminants has a large bearing on venting effectiveness. Certainly, the volatility of the contaminant is the single most important factor in removal. Lower molecular weight and more volatile constituents are more easily removed earlier in a soil venting process (References 1, 47, and 53). This has the effect of changing the relative compositions in the extraction gas and in the soil during operation, with heavier and less volatile contaminants possibly remaining in the soil after venting is finished. There is no rigorous method for identifying applicable compounds, but general guidelines listed, state that compounds having a vapor pressure of 0.27 to 0.54 inches of water at 68° F or greater, or a Henry's Law constant of greater than 0.01 liters liquid/liters air are likely to be adequately removed by soil venting (Reference 19). Table 1 shows a list of common compounds which may be removed from soil by *in situ* soil venting. Less volatile contaminants may also be removed, but at a slower rate.

Two other contaminant properties of concern are water solubility and adsorption characteristics. These factors are covered in the discussion of moisture (Section H).

#### **E. GEOHYDROLOGIC VARIABLES**

Table 2 summarizes published hydrologic data for 15 laboratory- and field soil venting studies. In some cases, data have been collected but are not given in the published reports; these are shown in parentheses in Table 2. Blank entries indicate that no data were collected.

TABLE 1. COMMON CONTAMINANTS WHICH MAY BE AMENABLE TO REMOVAL BY *IN SITU* SOIL VENTING

COMPOUND	VAPOR PRESSURE <sup>a</sup> (in of Water)	HENRY'S CONSTANT VOLUME LIQUID/ VOLUME AIR <sup>b</sup>
Vinyl Chloride	1232	0.87
Dichloromethane	189	0.09
Chloroform	104	0.17
Acetone	98	
n-Hexane	64.5	6.53
1,1,1-Trichloroethane	53.6	0.59
Carbon Tetrachloride	48.5	0.98
Cyclohexane	41.3	6.16
Benzene	40.0	0.19
Trichloroethene	31.1	0.35
n-Heptane	18.9	
Toluene	11.6	0.23
1,1,2-Trichloroethane	9.8	0.03
Tetrachloroethene	7.4	0.59
n-octane	5.6	
Chlorobenzene	4.8	0.14
Ethylbenzene	3.8	0.25
p-Xylene	3.8	0.25
m-Xylene	3.5	0.25
o-Xylene	2.6	0.18
n-Nonane	1.7	17.35
n-Decane	0.5	
Naphthalene	0.1	
1,1-Dichloroethene		0.86

TABLE 1. COMMON CONTAMINANTS WHICH MAY BE AMENABLE TO REMOVAL BY *IN SITU* SOIL VENTING (CONTINUED)

COMPOUND	VAPOR PRESSURE <sup>a</sup>	HENRY'S CONSTANT VOLUME LIQUID/ VOLUME AIR <sup>b</sup>
trans-1,2-Dichloroethene		0.35
cis-1,2-Dichloroethene		0.16
1,3-Dichlorobenzene		0.12
1,4-Dichlorobenzene		0.11
1,2-Dichlorobenzene		0.07
Ethylene dibromide		0.02
1,1,2,2-Tetrachloroethane		0.02

<sup>a</sup>Vapor pressure data is from Reference 69 except for 1,1,1,-Trichloroethene which is from Reference 70.

<sup>b</sup>Henry's data taken from Reference 62.

TABLE 2. SUMMARY OF GEOLOGIC DATA OBTAINED FOR SOIL VENTING TESTS

Reference	Conductor of test	Project scale	Borehole geologic logging	Groundwater depth (ft)	Particle size distribution	Total porosity (%)
Crow et al., 1985 (10) AWARE, 1987 (31) Mackay & Hoag, 1986 (15) Baehr & Hoag, 1985 (14) Sterrett et al., 1985 (27)	API AWARE Hoag Hoag IT	Field Lab(column) Field Lab(column) Field	Field/medium sand Soil or sand (homogeneous) Sand (homogeneous) (Conducted)	24-25 NA NA (Determined)	(Determined) (Determined) (Determined) (Determined)	30-47 43
Payne et al., 1986 (24) O'Connor et al., 1984 (6) Agrelet et al., 1985 (9) Malot, 1985 (8)	Midwest Res O'Connor Assoc. Terra Vac Terra Vac	Field Field Field Field	Fine sand Gravel overlying silt Clay/silt; limestone bedrock Sand/silt/clay	30 300 (Determined)		
Thornton & Wootan, 1982 (1) Thornton et al., 1984 (2) Anastos et al., 1985 (12) Anastos et al., 1987 (17)	TRI TRI Weston Weston	Lab(tank) Lab(tank) Field Field	Sand (homogeneous) Fine sand (homogeneous) Fine to coarse sand/gravel (Conducted)	Approx. 3 Approx. 3 165	(Determined)	28
Bennedsen, 1987 (18) Woodward-Clyde, 1985 (21) Payne & Liescecki, 1988 (40) Payne & Liescecki, 1988 (40) EPA, 1989 (49)	Woodward-Clyde Woodward-Clyde Midwest Res Midwest Res Terra Vac	Field Field Field Field Field	Sand/gravel Clacial drift Gravel/sand Silty sand overlying gravel	30 40	(Determined)	40-50

TABLE 2. SUMMARY OF GEOLOGIC DATA OBTAINED FOR SOIL VENTING TESTS (CONTINUED)

Reference	Soil moisture (%)	Hydraulic conductivity (cm/sec)	Lenses/discontinuities	In Situ pressure/flow distribution monitoring points
Crow et al., 1985 AWARE, 1987 Mackay & Hoag, 1986 Baehr & Hoag, 1985 Sterrett et al., 1985	1.7-8.1 Satd. (17,24)	mean = $9.8E(-4)$  (Estimated)	Low perm (fine sand) zones	34; lateral+vertical distribution Column inflow/outflow  Column/inflow/outflow
Payne et al., 1986 O'Connor et al., 1984 Agrelot et al., 1985 Malot, 1985		$E(-5)$ to $(E^{-7})$	Solution cavities in bedrock	1 (adj.well)
Thornton & Wootan, 1982 Thornton et al., 1984 Anastos et al., 1985 Anastos et al., 1987	2.2-13	$4E(-2)$	Oily/stained low perm. zones Clay layers	25; lateral distribution
Bennedsen, 1987 Woodward-Clyde, 1985 Payne & Liescecki, 1988 Payne & Liescecki, 1988 EPA, 1989	20 (mean)	$E(-4)$ to $E(-8)$ $3E(-3)$  $E(-3)$ to $E(-8)$	West clay lens, 14-20-ft BLS	4 wells x 2 depths

In most of the studies, at least qualitative descriptions of soil type are reported (sand, silt, etc., as well as depth to the water table, if present). In some cases, soil particle size distributions, soil porosities, soil moisture content, or hydraulic conductivities are reported. Only four literature citations mention conditions which could cause non-uniform vapor flow, including zones of reduced permeability (i.e., compacted fines, oil cementation, or clay layers) or zones in which the implicit assumption of bulk vapor flow through a uniformly porous medium clearly is not appropriate (e.g., limestone bedrock containing fractures and solution cavities).

The scarcity of published geohydrologic data undoubtedly reflects the empirical nature of most reported soil venting studies, which rely on the minimal amount of subsurface geohydrologic characterization sufficient to anticipate the potential for successful venting and to guide vent placements. In addition, most studies have been oriented toward remediation of a particular site, rather than to increasing the quantitative understanding of the bounds of applicability of the soil venting process. Much of the information on the importance of individual geohydrologic factors comes from laboratory studies and from the few well-documented field studies, principally the API test (Reference 10) and the Weston/USATHAMA study (Reference 12). Information on individual factors is summarized in Table 2.

#### 1. Geologic Medium, Particle Size Distribution, and Hydraulic Conductivity

A parameter which is commonly used to describe the rate of water flow through subsurface material is hydraulic conductivity ( $K$ ). This is a constant with dimensions  $Lt^{-1}$  which is proportional to water flux through material under a unit pressure gradient. Because hydraulic conductivity is related to the properties of the fluid as well as the medium, a related term, the intrinsic permeability  $k$  (dimensions:  $L^2$ ), is sometimes used. Under low pressure gradients (or vacuums) intrinsic permeability is independent of fluid properties, and the following is true,

$$k = K \mu / \rho \quad (2)$$

where  $\rho$  is fluid density and  $\mu$  is dynamic viscosity.

Because intrinsic permeability is independent of fluid type it has been used for decades in the petroleum industry, where flows of water, oil, and gas phases are often evaluated. It is generally expressed in units of darcys ( $1 \text{ darcy} = 10^{-8} \text{ cm}^2$ ).

Although intrinsic permeability, because of its independence from fluid characteristic and more general applicability is inherently a more useful term in describing soil gas dynamics, fluid flow measurements in most soils are determined from well pump tests and results are expressed as

hydraulic conductivities. Soils where venting has been successful have predominantly been sands and gravels, with measured hydraulic conductivities of about  $10^{-3}$  cm/second. Conductivities for coarse to medium sands range from 1 to  $10^{-3}$  cm/second (Reference 56). Silty and clayey soils, with hydraulic conductivities ranging from  $10^{-5}$  to  $10^{-7}$  cm/second were reported to be successfully vented only by Agrelot et al., (Reference 9). Anastos (Reference 17) indicates that Weston has successfully vented soils with conductivities as low as  $10^{-8}$  cm/second, although no additional soil characterization data are given.

Particle size distributions reported in the literature (e.g., Reference 31) generally distinguish among the gravel and sand fractions, which may be obtained by sieve analysis, while silt and clay fractions are combined. This results in analyses which supplement soil descriptions and which are useful in estimating hydraulic conductivities for coarser-grained materials, but which cannot be used to distinguish among soils that may have low to moderate porosities.

## 2. Lenses and Discontinuities

Clearly, soils with high intrinsic permeabilities are more likely to be vented effectively due to both rapidity and uniformity of air flow. In less permeable media, such as weathered bedrock or glacial till, secondary permeability (i.e., fractures) is likely to dominate air flow, possibly resulting in the bypassing of zones of contamination [unless contaminant liquids have accumulated in the fractures; this may explain the successful use of the technique by Agrelot et al. (Reference 9) in limestone, which contains many fractures and solution cavities]. Lateral zones of either high (e.g., gravels) or low permeability (e.g., clays) may also affect venting effectiveness by providing pathways for preferential air movement which may result in bypassing of highly contaminated zones.

Anastos et al. (Reference 17) reported that the presence of clay layers at a field venting site necessitated installation of vents at different depths to adequately ventilate the soil. The thickness and extent of the layers, however, was not reported, and would clearly affect whether or not separate venting systems were necessary.

Crow et al. (Reference 10) observed fine sand zones of apparent low permeability at a depth of 15 to 16 feet adjacent to the pilot venting site and speculated that these layers may have inhibited vapor movement above this depth since gasoline vapor concentrations decreased to barely detectable levels above the 16-foot depth. Anastos et al. (Reference 12) found zones of oily, stained sand within the venting area of the USATHAMA test, which correlated with the zones of highest trichloroethylene contamination. The authors speculated that this oily material may represent areas

of reduced permeability; in fact, a pressure test indicated a possible flow obstruction near a borehole in which a layer of stained soil had been noted. The modification of soil by some contaminants at high concentrations may thus represent a complicating factor, because the zones which must be vented most thoroughly may be those which are least amenable to vapor flow.

In a summary of a field demonstration by Terra-Vac<sup>®</sup>, Foster Wheeler Enviresponse (Reference 49) reported that the technology was able to remove TCE from a contaminated clay lens. Four extraction vents and four vapor-monitoring wells were screened in sand layers at intervals of 3 to 12.6-foot and 19 to 24-foot BLS, directly above and below a wet clay layer (14 to 20-foot BLS). Initial soil samples showed that TCE was present throughout both upper and lower sand layers, as well as within the clay lens. Following vapor extraction over a 58-day period, TCE levels on adjacent borings showed a mean reduction in the four boring locations of 37 percent. Samples collected from within the clay layer adjacent to a boring which had initially shown TCE concentrations as high as 1570 parts-per-million-by-weight (ppmw) showed no concentrations above 62 ppmw. Based on these analyses, the authors conclude that the test demonstrated the successful extraction of TCE from clay and that "permeability of a soil need not be a consideration in applying the vacuum extraction technology." They suggest that the reason for removal from clay is that although permeabilities differ by four or more orders of magnitude, the porosities of the sand and clay strata are approximately equal. A more likely explanation is that the observed TCE reductions in the clay layer at one boring location are a fortuitous result of contaminant variability throughout the vented area; at least one pair of pre- and post-venting samples showed a 96-fold increase in TCE concentration. If the observed reduction is assumed to be real, it may have been due to the high concentration gradient established within the clay layer by the presence of three vapor extraction vents installed within 12 feet of the boring location. These multiple vents undoubtedly reduced the TCE vapor level in the sand immediately above and below the clay layer to far below equilibrium vapor pressure, thus creating the driving force for diffusive transport of TCE both upward and downward from the clay. The results suggest, therefore, that vacuum extraction of clay layers can be successful if (1) vents are placed close enough together to remove air effectively from the soil adjacent to the clay, and (2) venting is continued for a length of time sufficient to permit diffusive transport of contaminant vapors to progress to near-complete contaminant removal.

### 3. Permeability - Effect of Porosity and Moisture Content

The porosity and moisture content of soils are important in that both affect soil vapor permeability. The air-filled porosity, which is the total porosity minus the volumetric water content, is directly related to soil permeability. Total porosities reported in Table 2 from field and laboratory venting tests range from 28 to 47 percent (volume/volume). The only reported field moisture contents were highly variable: 1.7 to 8.1 percent (weight/weight) (Reference 10) and 2.2 to 13 percent (Reference 12). These field moisture values represent water-filled porosities in the range of 4.3 to 25.6 percent (volume/volume), which may in some soil zones represent a significant fraction of the total porosity. Clearly, data on the water-filled porosity of the soil may be important in estimating whether or not soil zones may be only partially vented due to filling of soil pores by water. Water content might change as air is forced through the soil during the venting process, but Anastos et al. (Reference 12) did not find significant changes in water content between core samples collected before and after the USATHAMA test.

Following vacuum extraction recovery of a 15,000-gallon spill of 1,3-dichloropropene (DCP), Johnson and Sterrett (Reference 30) attempted to evaluate qualitatively the effect of soil bulk density on removal efficiency. Low airflow was observed from extraction vents that had high blow counts (the number of blows needed to drive an object into the ground) during installation; the authors infer that these vents were located in an area of high bulk soil density and thus low porosity. They conclude that efficient removal of contaminants in areas of low porosity would require vents spaced closer together.

#### F. TEMPERATURE

Temperature may have a large effect on contaminant removal rates, since vapor pressure and Henry's Law Constants vary with temperature. Increased temperature will cause higher contaminant vapor pressure and generally will cause desorption of contaminants from the soil. Johnson and Sterrett (Reference 30) noted increased removal rates with higher ambient temperatures. The dependence of effective air flow into the soil upon soil temperature was measured by AWARE (Reference 31) in their field study. Their results show that the upper soil layers vary greatly in temperature with ambient air, but lower zones will not change greatly due to the large mass and high heat capacity of the soil. Therefore, the recommendation of Johnson and Sterrett (Reference 30) to suspend venting operations in winter is especially relevant to shallow systems.

Due to the potential enhancement of extraction rates with increased temperature, several authors suggest means for raising soil temperatures (References 12, 13, 28, and 54). Anastos (Reference 12) abandoned plans to heat inlet air due to the high energy requirements for appreciable enhancements. Johnson et al. (Reference 54) suggest radio frequency and conduction heating or injections of exhaust from combustion units. The latter method, mentioned by DePaoli et al. (Reference 47) in plans for further testing, is attractive in that no extra energy is required. Steam injection has also been mentioned for heating the soil (Reference 28), but this technique is less attractive in a soil venting application due to the effect of moisture on air permeability and contaminant transport.

#### G. SIZE OF SPILL

There is a minimum spill size above which *in situ* soil venting becomes an attractive treatment alternative. For spills contaminating less than 500 cubic yards of soil (Reference 24) or at depths less than 10 feet, excavation may be more cost effective. Soil venting is more applicable to spill sites where contaminants have reached greater depths. For example, spill depths of 40 feet and greater definitely favor soil venting over excavation (Reference 18).

In order to use soil venting, the depth of the contamination or the depth to groundwater should be over 10 feet to reduce short-circuiting of air from the surface to the extraction vents. One plan included lowering the water table from 6 feet to 8 feet to 16 feet due to this fact (Reference 57). It should be noted that this depression of the water table will smear the contamination over a larger area, and may increase the amount of dissolved components reaching the groundwater (Reference 7). Connor (Reference 38) described avoidance of short-circuit air flow in remediation of a site with 4 to 6 feet groundwater depth by using horizontal vents in trenches and a polyethylene sheet as a surface barrier.

The size of spill criteria may be waived when considering treatment of soil beneath a building or other valuable structure (Reference 14). In that case, excavation costs would also include the cost of destroying and rebuilding the structure. For example, an *in situ* soil venting remediation of soils at a metals finishing plant cost \$150,000, whereas the costs associated with excavation were estimated to be five million dollars (Reference 26).

## H. MOISTURE

Besides soil moisture's negative effect on soil air permeability, two other competing effects upon contaminant transport have been noted. These factors — aqueous solubility and competitive adsorption on soil between contaminants and water — should be considered when analyzing extraction data, and they must be taken into account when planning such design features as a surface barrier, moisture addition, or steam injection.

Soil moisture provides a sink for water-soluble contaminants, affecting contaminant removal by venting in two ways. Dissolution into water may reduce removal by volatilization, as noted by Regalbuto et al. (Reference 41) and Payne (Reference 40), in the lower but steadier removal rate of acetone from a mixture of other less soluble contaminants. The dissolved contaminants may be removed, however, as groundwater is extracted from the soil. Removal of contaminants by the uptake of large amounts of perched water was reported in Terra-Vac's SITE demonstration (Reference 49) and by Regalbuto (Reference 41) and Payne (Reference 40).

Based on multiple linear regression analysis, Johnson and Sterrett (Reference 30) concluded that air moisture content significantly affected DCP concentration in the vented gas stream. Increases in DCP removal, observed when the relative humidity increased, were attributed to the reduced sorption of DCP to soil particles at higher soil moisture contents. This seems reasonable under the conditions of the venting project: soil moisture was low (2 to 5 percent) and precipitation did not infiltrate the soil, either evaporating or running off the surface. At low moisture contents, the effect of small changes in moisture on sorption of organic contaminants can be considerable (Reference 58). At a site in a more humid region, or where water infiltration is significant, air moisture content may not be a significant determinant of venting efficiency.

## I. BIOACTIVITY

A potentially significant means of hydrocarbon removal due to *in situ* soil venting is enhanced biodegradation. The increased oxygen levels in the soil gas from the infiltration of atmospheric air may stimulate aerobic biological activity to a considerable extent. Enhanced biodegradation was first considered by Thornton and Wootan (Reference 1) in response to their measurement of carbon dioxide generation; however, it has generally remained unquantified (Reference 54). Connor (Reference 38) postulated that higher temperatures in gasoline-contaminated soil zones were due to enhanced bioactivity and further suggested that venting may be initially necessary for inducing enhanced bioactivity by lowering concentrations of hydrocarbons which inhibit microbial growth. Hinchee et al. (Reference 48) have the first documented proof and measurements of biodegradation

associated with a soil venting field operation, measuring a steady-state destruction value of 15 to 20 percent of that removed by volatilization. Brown and Harper (Reference 43) demonstrated the usefulness of enhancing conditions for microbial activity in aboveground soil piles. They supplemented oxygenation by venting with nutrient and moisture addition to achieve removal of heavy components of gasoline and diesel fuel that could not have been easily removed by venting alone. Future studies suggested by Hinchee et al. (Reference 48) will be aimed at increasing the rate of bioactivity relative to volatilization by *in situ* addition of nutrients and by adjustment of flow rates. This approach is attractive in that emissions control costs may be minimized.

## SECTION IV

### ELEMENTS OF SOIL VENTING SYSTEMS

#### A. SOIL VENTING DESIGN STRATEGIES

All *in situ* soil venting treatment operations reviewed thus far utilize the concept of induced air flow in the unsaturated zone of the soil to volatilize and remove hydrocarbon contaminants. However, they differ in the design strategies employed. The six venting strategies listed below are detailed in the paragraphs which follow.

- Forced Injection/Forced Extraction
- Passive Inlet Vents/Forced Extraction
- Forced Extraction Only
- Vapor Extraction with Liquid Pumps
- Horizontal Trenches
- Closed Loop with Agitation

##### 1. Forced Injection/Forced Extraction

This design strategy was used in tests described by Anastos et al. (Reference 12), Koltuniak (Reference 13), and Regalbuto et al. (Reference 41). As shown in Figure 3, this strategy includes an injection blower (and optional inlet air heater) forcing air through a series of injection vents into the soil. The air is pulled through the soil and into a set of extraction vents by an extraction blower, then sent through an emission control device. A subset of this category is the closed loop design described by MWRI (References 24 and 25), in which the extracted vapors are removed by an emission control device and the air is reinjected into the soil at the perimeter of the contaminated zone (see Figure 4).

**Advantages —** Due to capabilities of two blowers, may operate with high flow rates through the soil, allowing shorter decontamination periods.

Higher pressure drop capability of both inlet and outlet blowers may allow application to impermeable soils.

Can direct air flow through contaminated zones via inlet vents.

Forces larger pressure gradients between vents.

Closed loop design does not emit contaminants to the atmosphere.

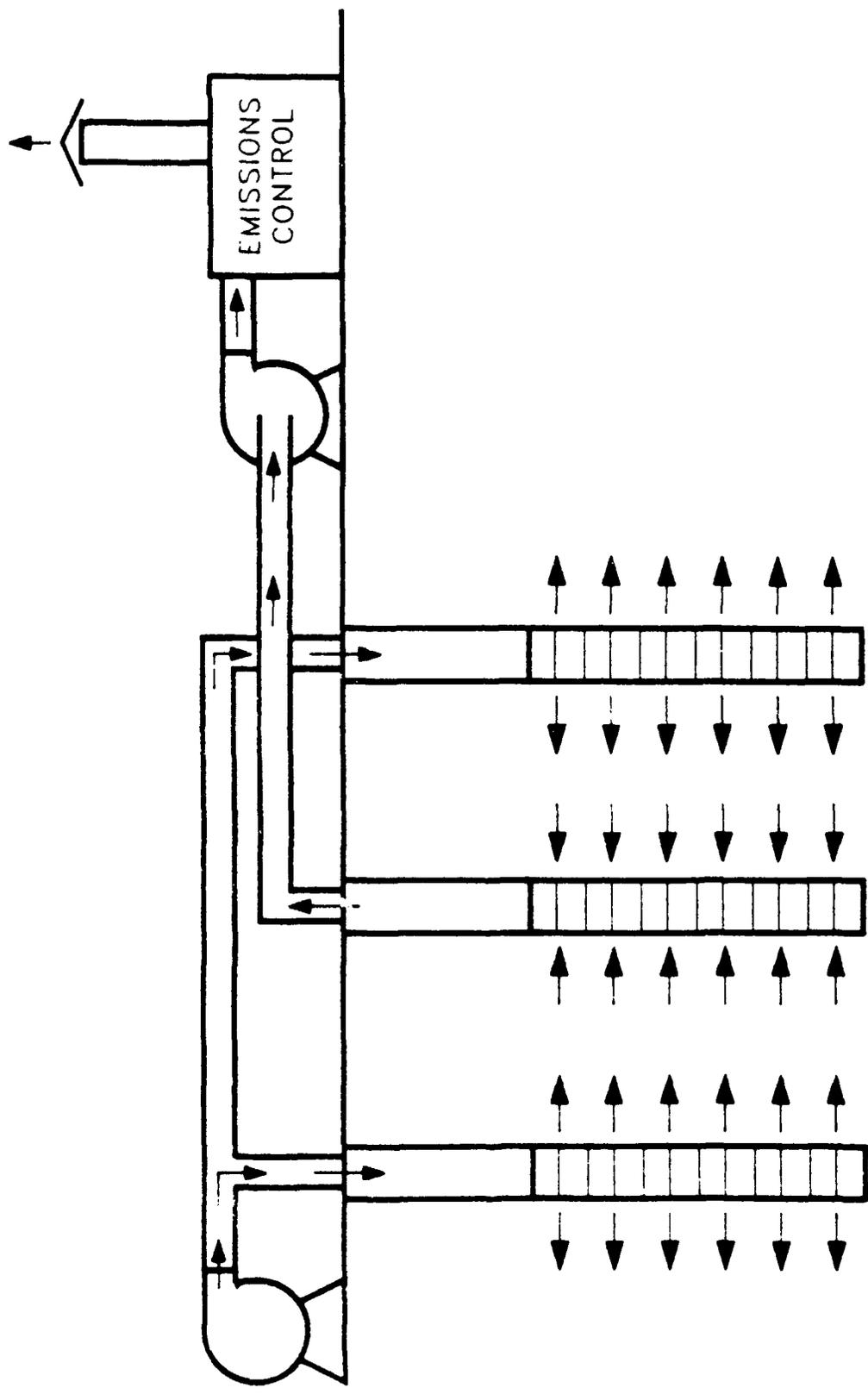


Figure 3. Example of Forced Injection/Forced Extraction Strategy (adapted from Reference 12).

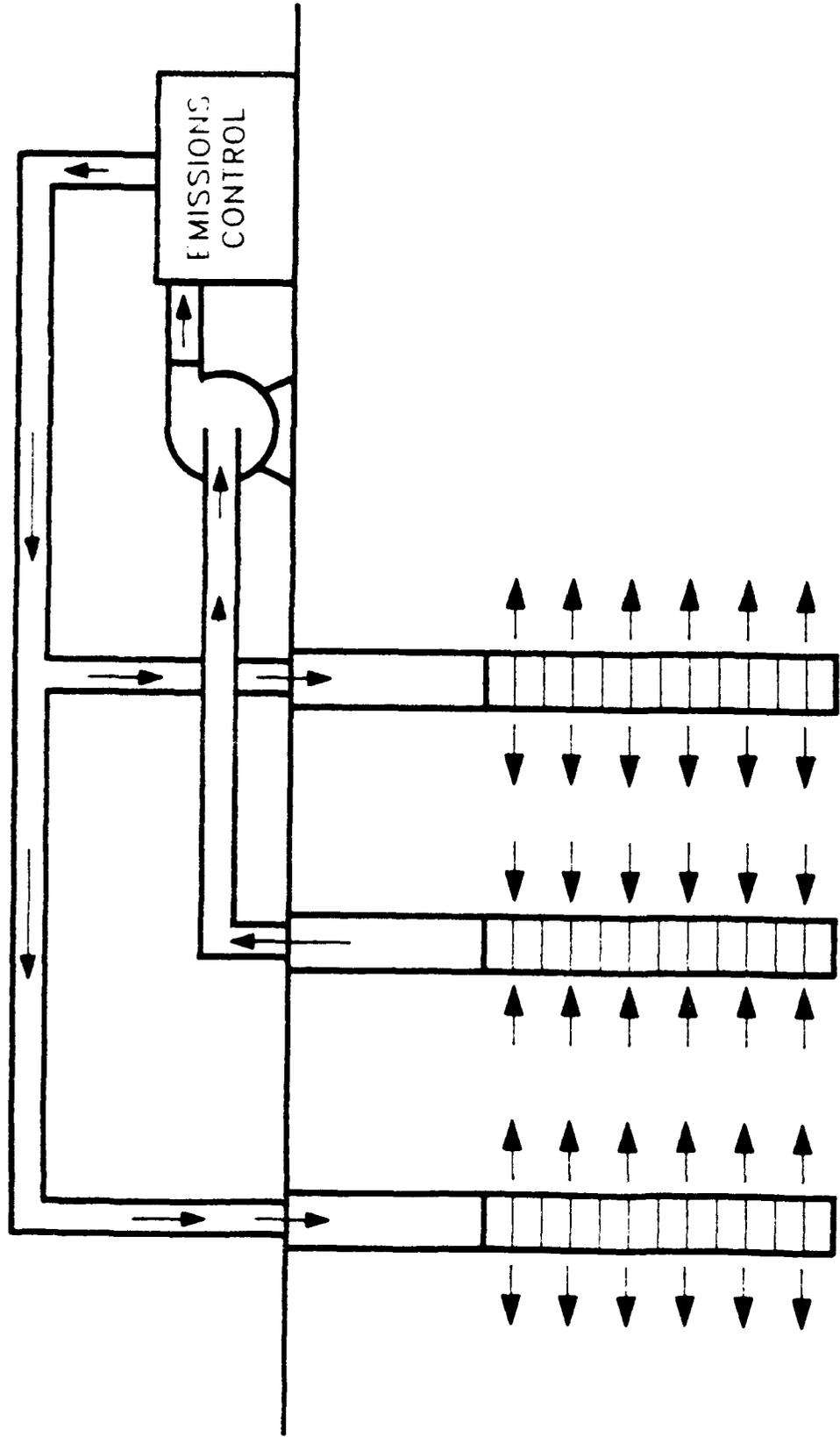


Figure 4. Example of Closed Loop System Design Strategy (adapted from Reference 24).

Disadvantages — Forced inlet air may be unnecessary for efficient removal.

The process involves two resistances due to concentrated flows in the vicinity of vents, leading to increased blower power requirements.

The effect of inlet vents is likely significant only in a localized area around the vent. A large number of inlet vents are probably needed to induce even flow distribution.

Pressurized vents may cause movement of contaminants out of the treatment area.

The forced air inlet may cause depression of the water table (Reference 59).

## **2. Passive Inlet Vents/Forced Extraction**

This design strategy (see Figure 5) was used in tests described by Bennedsen (Reference 18), Bennedsen et al. (Reference 19), Crow et al. (Reference 10), Crow et al. (Reference 11), and Sterrett et al. (Reference 27). This strategy has no injection blower, using instead the vacuum produced by the extraction blower to pull air into the passive inlet vents and through the soil into the extraction vents. Extraction air may be sent through an emission control device prior to discharge.

Advantages — Passive inlet vents allow air to be directed to contaminated soil zones, which is especially useful for deeper contamination.

The inlet vents may offer less flow resistance than the soil, allowing higher flow rates.

Disadvantages — The benefits gained by passive inlet vents may not be economically worthwhile. Two studies saw only 10 percent of the extraction flow pass through the passive inlet vents (References 10, 11, and 27).

## **3. Forced Extraction Only**

This design strategy was used in operations described by Agrelot et al. (Reference 9) Bliss (Reference 23), Oster et al. (Reference 16), and Elliott and DePaoli (Reference 46). As shown in Figure 6, this design strategy includes no inlet vents. Vacuum produced by the extraction blower pulls air from the surface through the soil into the extraction vents. Extraction air may be sent through an emission control device prior to discharge.

Advantages — This design is the simplest, least expensive, and may be completely adequate for site remediation.

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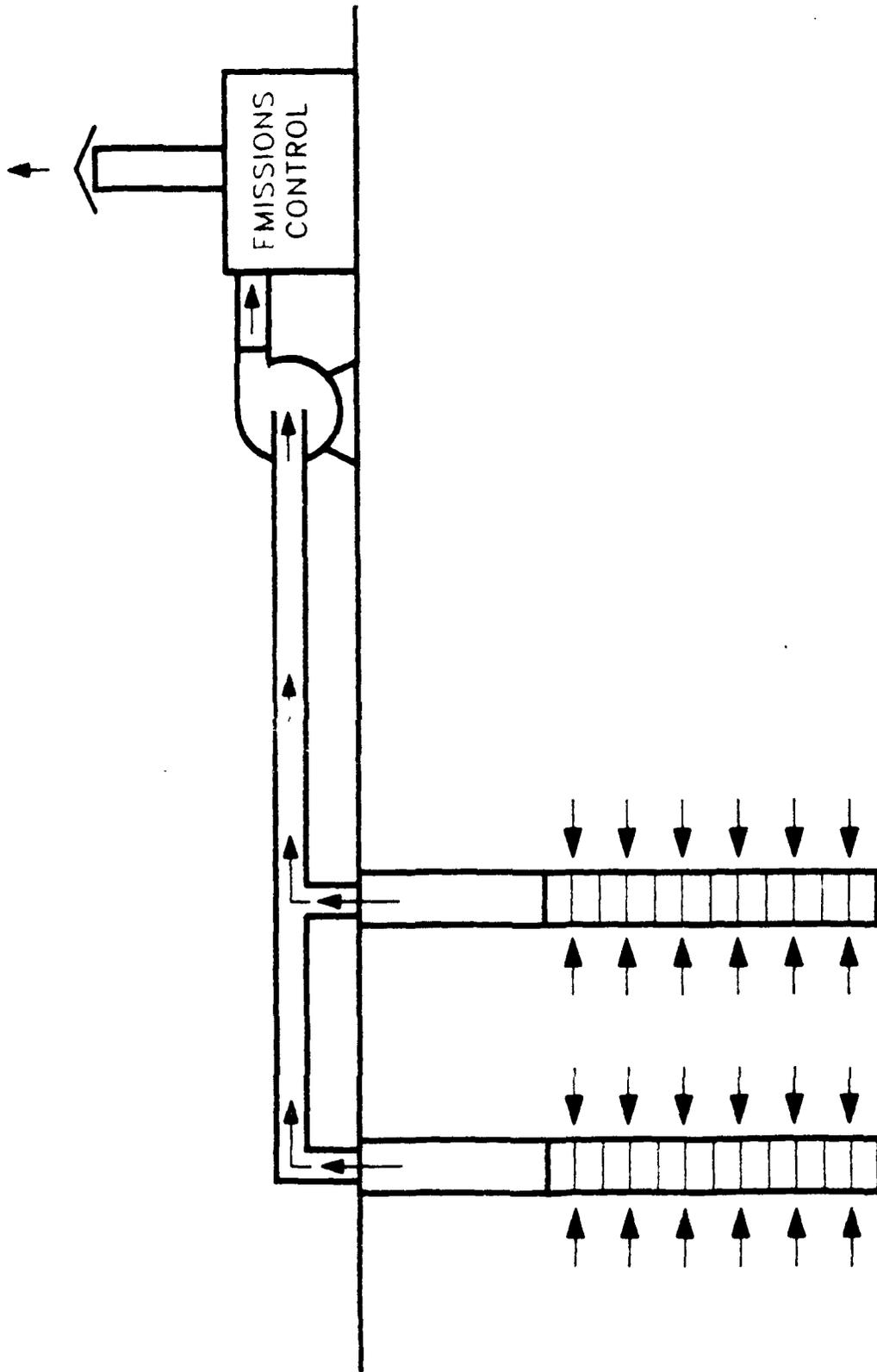


Figure 6. Example of Forced Extraction Only Strategy (adapted from Reference 8).

Disadvantages — Effective area and flow rates achievable may be limited by soil permeability.

Less capability to adjust air flow patterns in the soil, so some zones may not be vented, particularly deeper soil areas.

Short-circuiting of air flow from the surface near the extraction vent may be a problem.

Operation without inlet vents requires alternating modes of vent operation to offset the effects of stagnation zone formation.

#### 4. Vapor Extraction with Liquid Pumps

This design strategy was used in operations described by Malot (Reference 8), Malot and Wood (Reference 7), Nichols and Gibbons (Reference 36), and Batchelder (Reference 37). As shown in Figure 7, this strategy is applicable in cases where free hydrocarbons have reached the water table or where groundwater contamination exists. Combination venting/pumping wells are used to pump liquid from the water table for aboveground treatment and to pull a vacuum on the soil for venting. Extraction air and air from the air stripping operation on the groundwater are combined and treated by an emission control device.

Advantages — The combination pump-and-treat and *in situ* soil venting strategy reduces cleanup time.

Removal of free hydrocarbons from atop the water table will remove a source of soil vapors and will reduce cleanup time as well as reduce the burden on the emission control system.

Disadvantages — The combination vents/wells will be more complicated and costly.

#### 5. Horizontal Trenches

This strategy, first attributed to Knopik (Reference 60), suggested by Bennedsen (Reference 18), and used by Connor (Reference 38), and Elliott and DePaoli (Reference 46), consists of vent pipes placed horizontally in trenches dug in the soil (see Figure 8). This design is most applicable for sites with shallow contamination.

Advantages — Special drilling equipment is not needed for vent installation, reducing costs significantly.

Two-dimensional (possibly approaching one-dimensional) flow patterns may be developed rather than axisymmetric flow. This flow geometry will lead to more even treatment, and may be more suitable for certain situations, such as above an aquifer with floating product.

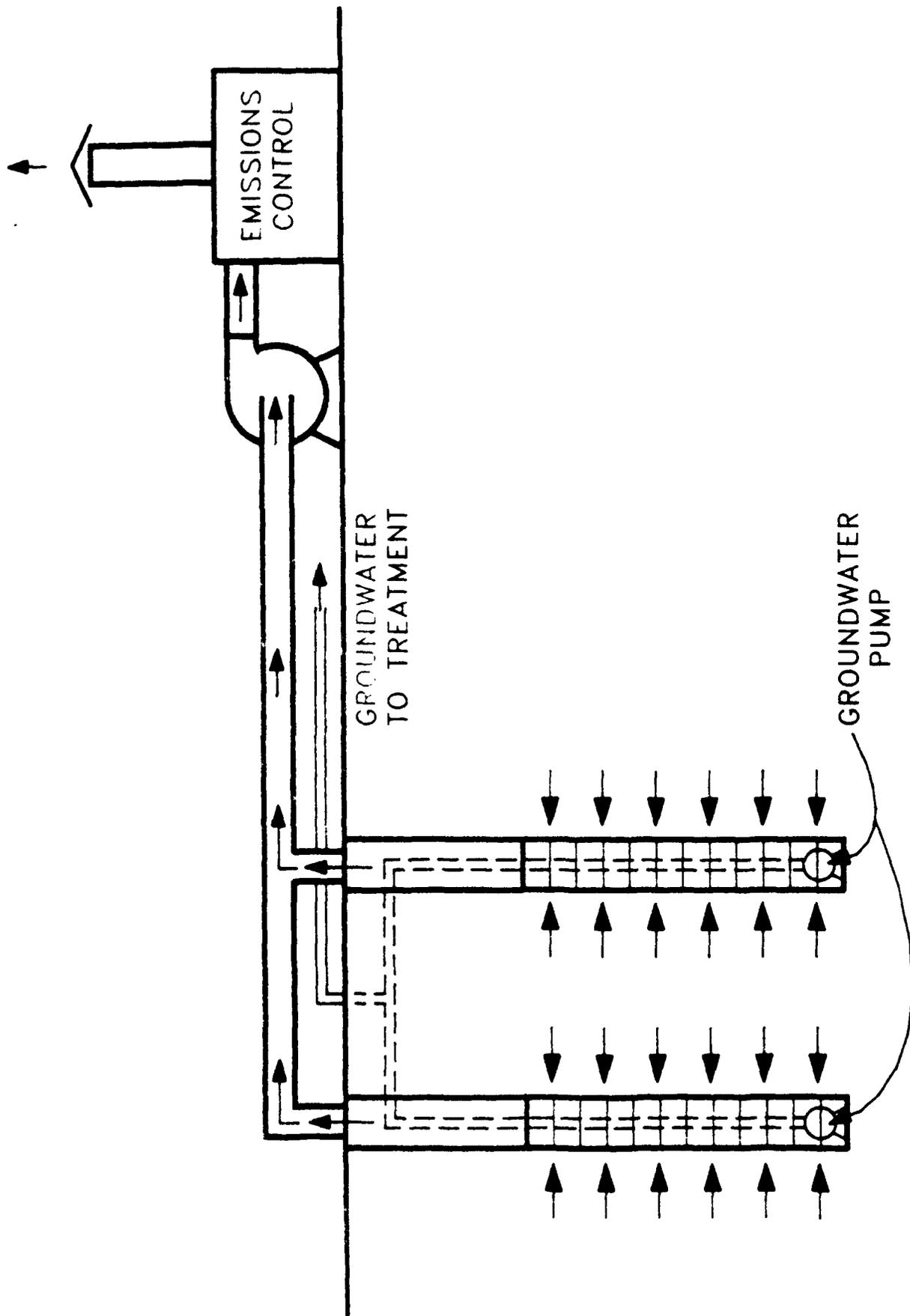


Figure 7. Example of Vapor Extraction with Liquid Pumps.

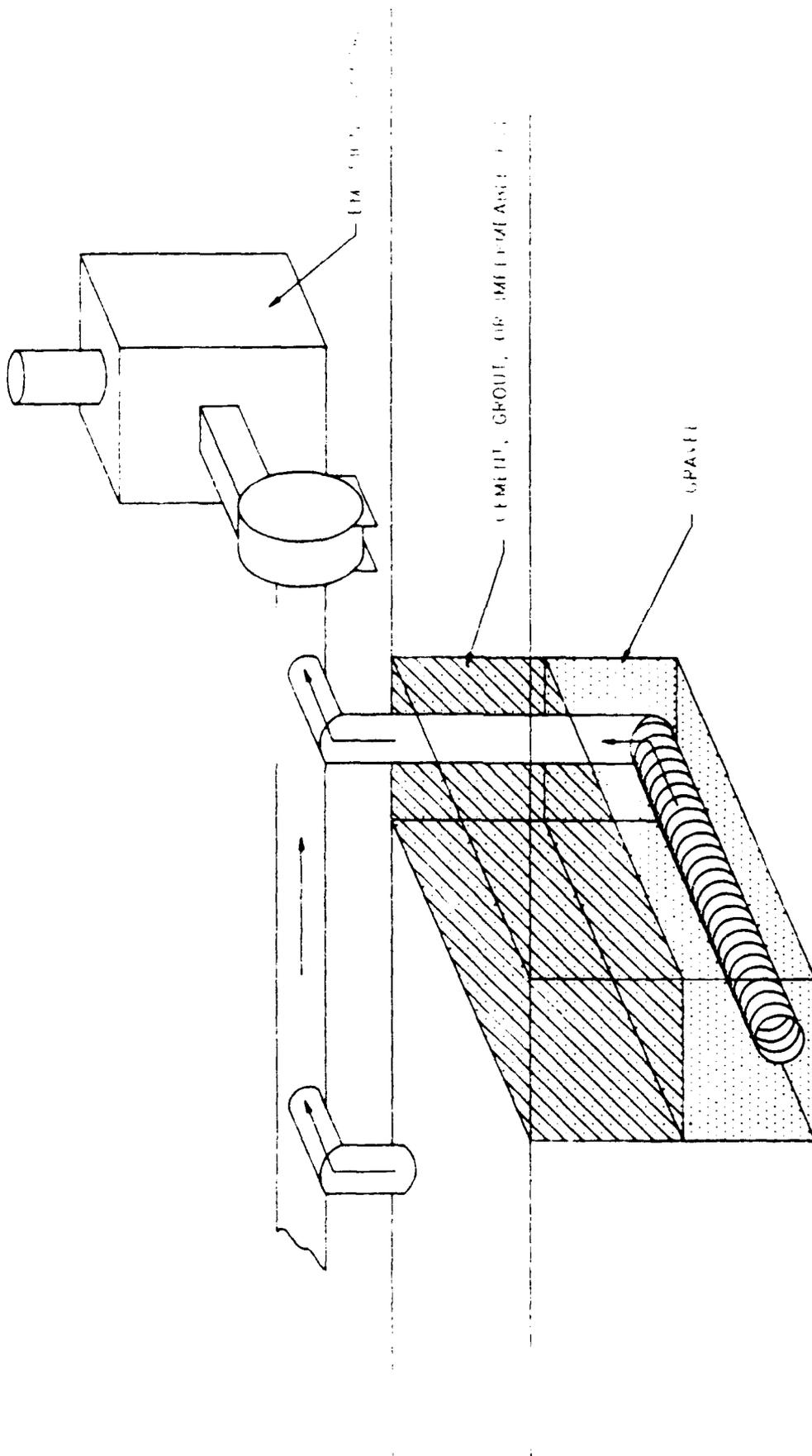


Figure 8. Example of Horizontal Trench Venting Strategy (adapted from Reference 35).

Disadvantages — Limited to depth of trench digging equipment.

Large quantities of contaminated soil may be excavated.

#### 6. Closed Loop with Agitation

This strategy, described by Ghassemi (Reference 28) and Troweck and Wojec (Reference 29), consists of a movable system designed to treat the soil by simultaneous agitation and injection of treatment agents, including hot air and steam. Gas injected during agitation of the drill bits is collected by vacuum in an above-ground shroud, treated for removal of hydrocarbons, and compressed for reinjection.

Advantages — No discharge to atmosphere.

Cleanup may be quick and effective.

Ability to inject treatment agents in liquid and slurry form provides flexibility to treat many different types of spills.

Disadvantages — Appears to be very labor and energy intensive and is expensive.

Limited to depth of drill bits - 60-foot maximum.

#### B. VENT LAYOUT AND DESIGN

An important consideration in the installation of an *in situ* soil venting system is the layout and design of the vents. In most systems, these vents are installed vertically; however, in instances of a shallow water table (10 to 15-ft), it may be preferable to lay horizontal pipes (Reference 19).

Several geometries have been used in the layout of vertical vents. In extraction-only systems, it is optimal to place the vents throughout areas of high concentration in order to take advantage of the high flows near the vents. However, successful systems have been implemented with extraction vents outside of the contamination area due to permanent structures in the contamination area (Reference 7). For systems including inlet and extraction vents, system layouts with extraction vents surrounding inlet vents (Reference 12) and with inlet vents surrounding extraction vents (Reference 24) have been used, with promising results from both. The TRI pilot study showed higher removal in the high flux areas surrounding both the inlet and extraction vents. It is preferable to position the extraction vents in the more highly contaminated zones, however, because of the higher flows at extraction rather than inlet vents (References 10 and 27). In that configuration, the flow draws clean air into contaminated areas, rather than vapor-laden air into clean soil.

In the layout of venting systems, it is wise to include simplicity and flexibility in the design. Consideration should be given to the ability to valve each vent separately at the manifold to allow control of flows throughout the system. This enables the use of a recommended strategy of venting areas of highest concentration first (Reference 12) while adjusting operations periodically to maximize removal (Reference 37). Another feature to be included is valving to allow each vent to be used for either injection or extraction, giving greater ability to direct air flow (Reference 21).

Vertical vents may be placed in holes sunk especially for the purpose, in holes originally used for soil sampling (References 18, 21, and 22), or in groundwater monitoring wells for those systems combining soil venting and pump-and-treat techniques (Reference 36). The vent design generally consists of a lower slotted section with a solid pipe section and grout cap above. PVC pipe is widely used, commonly ranging from 2 to 6 inches in diameter with well screen used for the slotted section. Weston used 2-1/2-inch OD pipe for its ability to be lowered inside standard 6-inch augers. Vents including extra equipment such as pumps or inflatable packers may require larger holes of 8 inches in diameter or above.

The slotted section of pipe is used to direct air flow in or out of the soil. It is usually packed outside with pea gravel to keep the slots free of soil and to provide an area of high permeability in the highest flow area. Although Thornton et al. (Reference 2), concluded that venting geometry (including amount of vent pipe slotted) is not a primary factor in the effectiveness of a soil venting system, the position of slots in the vent pipes will play a role in directing air flow through contaminated soils and should be specified for the particular site after soil monitoring. For cleanup of highly permeable soils with deeper contamination, the slots should be placed low on the pipe to direct flow through the contamination and to reduce short-circuit flow from the surface (References 10 and 24). For less permeable soils, or for more continuous vertical contamination, a higher slotted section may be useful. Regardless of the height of the slotted section of vent pipe, the annular region between the riser pipe and the soil above the screened section should be grouted to prevent short-circuit air flow.

### **C. SURFACE BARRIER**

A design consideration for improving the performance of an *in situ* soil venting system is the addition of an impermeable surface barrier over all or part of the system area. A surface barrier is used to stop rainfall percolation through the soil, thereby retarding the movement of the contaminants, and to prevent short-circuit flow from the surface to the extraction vents. Several materials have been used as surface barriers, including concrete (Reference 9), 6 mil polyethylene

covered with sand (References 10 and 24), and clay (Reference 17). The extent of coverage used ranges from a 5-foot by 5-foot section surrounding each vent to coverage of the entire vented area. A surface barrier may not be necessary in horizontally stratified soil, which limits vertical air flow.

Surface barriers have limited effectiveness in isolating inlet vents as primary air sources. Crow et al. (Reference 10) measured only 9 to 11 percent of the extraction flow passing through the air inlet vents with coverage of the entire venting area, indistinguishable from the 10 percent measured through the inlet vents of the system described by Sterrett et al. (Reference 27) with no surface barrier. Justification for the surface barrier can be made, however, by considering that addition of the surface barrier must shift the air source from the surface near the extraction wells to soil areas outside the barrier, inducing a more horizontal flow pattern through the contaminated area (Reference 42). This type of flow was used exclusively in the extraction-only system design reported by Oster et al. (Reference 16), which included a clay barrier over the venting area and no inlet vents (Reference 12).

#### **D. BLOWERS**

A wide variety of blower types and sizes have been used successfully in *in situ* soil venting demonstration systems. Conventional positive displacement blowers, centrifugal blowers, liquid ring pumps, and rotary vane vacuum pumps were reported for the demonstration systems reviewed, ranging from 10 to 9500 ft<sup>3</sup>/minute capacity and 0.5 inches of water to 29 inches of mercury vacuum.

The selection of a blower for a system is dependent on site specific conditions, such as soil permeability and size of the spill site. If possible, selection of a full-scale blower should be made after a pilot-scale test at the site. General guidelines are for 25 inches of water vacuum for sandy soils and at least 8-inches of mercury vacuum for less permeable high clay content soils. Use of an air flow model (References 42 and 50), normalized plots of vacuum requirements (Reference 50), or analytic equations for radial flow (Reference 54) are helpful for determining blower requirements. It is recommended that blower capacity and vacuum be somewhat oversized. Blowers should be spark-resistant, with explosion-proof motors, or the installation should include flame arrestors and explosive atmosphere detectors. A typical electric drive motor is 10 hp or less (Reference 18); however, the largest blower motor reported was 40 hp (Reference 16).

Most venting applications include a vapor/water separator or demister in the piping before the blowers to remove particulates and/or water droplets. Water uptake may be quite large, as noted by Payne (Reference 28), Regalbuto et al. (Reference 41), and Michaels and Stinson (Reference 61).

## E. EMISSION CONTROL

A necessary part of an *in situ* soil venting system, in many cases, is a process to control emissions of hydrocarbons to meet regulatory discharge limits. Emission control is a major cost factor in *in situ* soil venting systems (Reference 18). If regulations require emissions control, the system can amount to 20 to 50 percent of total installation and operating costs (References 12 and 13).

Due to the nature of extracted gas from these systems, usually of high humidity and varying over several orders of magnitude in contaminant concentration, selection of optimal emissions control processes may be difficult. Processes that are currently technically feasible for use on a soil venting system are carbon adsorption, condensation, thermal or catalytic oxidation, direct discharge to the atmosphere, and other site-specific solutions. Descriptions of these systems follow. Singh and Counce (Reference 62) and Corbin et al. (Reference 63) provide further descriptions and evaluations of these and other technologies.

Carbon adsorption is the most widely used emission control technology for soil venting systems (References 16, 17, 21, 24, 26, 28, 33, 38, and 49). In this process, vapor-laden air is passed through beds of activated carbon to which hydrocarbon molecules adsorb without chemical reaction due to Van der Waals forces. Adsorption of VOCs is dependent on relative humidity, temperature, concentration, type of organic compound, and regeneration steps used (Reference 62). Carbon beds are used until breakthrough of organic constituents occurs. The carbon is then either discarded (if in small quantities) or regenerated. Regeneration can be performed on-site with proper equipment, such as a steam system and condenser; or it may be transported to the vendor.

Because of uncertainties in *in situ* soil venting effluent concentration and composition, it is difficult to estimate carbon consumption before actual operation. Several tests found high carbon usage due to high humidity and/or high concentration in the extracted air (References 12, 24, 26, and 28). Adsorption capacity reports ranged from 0.14 to 0.2 pounds of various vented organic compounds per pound of activated carbon (References 12 and 24). Recommended additions to a carbon adsorption system to reduce carbon consumption included either a demister (Reference 12), a condenser (References 28 and 33), or a preheater upstream to reduce humidity and concentration in the stream feeding the carbon bed.

Carbon adsorption is an attractive choice for emission control since it is a widespread and proven technology; however, the cost of carbon and regeneration may be quite high. Johnson et al. (Reference 54) suggest a guideline of 100 grams/day as the upper contaminant rate for economical use of carbon adsorption. Also, carbon adsorption does not solve final destruction problems, since the hydrocarbons retain their composition even after regeneration.

Condensation is a hydrocarbon vapor reduction step that employs chilled surfaces to liquefy water vapor and organics in an air stream. It is limited by the vapor pressure of each constituent, being most effective with the least volatile compounds. Because of this fact, it is not likely to be successful as the primary emission control step for an *in situ* soil venting system. In order to reach temperatures where emission of hydrocarbons would be greatly reduced, the condenser may encounter operating problems due to freezing of water vapor from the nearly saturated extraction air. A vent system on a carbon tetrachloride spill site discontinued operation of a cold water condenser due to low recovery (Reference 9). Condensation may prove to be economical in high-concentration, high-humidity air streams to reduce the load on other emission control processes, such as carbon adsorption.

Thermal and catalytic oxidation are attractive emission control steps both in terms of economics and final destruction capability. In these processes, the vapor-laden air is heated to a temperature high enough to oxidize the hydrocarbons in the case of thermal incineration or to a much lower temperature followed by contact with specific catalysts in the case of catalytic oxidation.

Thermal oxidation may be considered as a burner in which the vapor-laden air stream is used as combustion air. Koltuniak (Reference 13) reports that a system tested for *in situ* soil venting used propane fuel to incinerate VOC-rich air at 1832°F for two seconds for 99.9 percent removal. Regalbuto et al. (Reference 41) reported successful treatment of fumes at concentrations higher than  $6 \times 10^7$  pounds VOCs/ft<sup>3</sup> using a propane-fired, rich-fume incinerator. The simplicity and high final destruction of volatile organics may be offset by the high energy requirements for this process. Johnson et al. (Reference 54) suggest a lower concentration limit of 10,000 ppmv for the economical use of thermal oxidation.

Catalytic oxidation is a promising process in which a catalyst is used to promote the oxidation of organic compounds. A typical system is usually composed of four basic parts. A preheater is used to raise the temperature of the incoming gas stream to approximately 600°F. The gas then enters a mixing chamber which promotes uniform temperature. The gas then contacts either a fixed or fluidized catalyst bed, which is composed of finely divided precious metal, on metal or ceramic supports. A final heat recovery stage is optional.

Fixed-bed catalytic oxidation devices are widely used in industry due to their simplicity. Potential problems, however, are deactivation of the catalyst due to halogens, sulfur dioxide, or nitrogen dioxide, and fouling by dust. Fluidized-bed systems reduce the fouling and deactivation problems of the fixed-bed systems by replenishment of catalyst and abrasion of the catalyst pellets.

Neither type of catalytic oxidation has been reported in widespread use with *in situ* soil venting systems. A Weston study (Reference 63) found the techniques to be economically attractive. The Hill AFB demonstration (References 46 and 47) has included catalytic incinerators of each type, but no operating or performance data have been published to date. Johnson et al. (Reference 54) suggest an upper limit of approximately 8000 ppmv for these units because of overheating. The extracted gas from the Hill AFB system was diluted during the early phases of operation to account for this problem.

In certain cases, extraction air may be directly discharged to the atmosphere with regulatory agency approval (References 12, 16, 23, 41, 54, and 65). Since the only system requirements are air dispersion stacks, this technique is by far the least expensive. In fact, some systems have been operated below design venting rates in order to stay within discharge limits (References 17 and 51).

Other innovative and often site-specific solutions to *in situ* soil venting emission control problems have been implemented to reduce costs. Extraction air has been piped to on-site boilers to be used as combustion air (References 18 and 64), as in a thermal incinerator. Another system was connected to the existing air scrubber of a building (Reference 21). The self-contained unit reported by Rippberger (Reference 39) not only destroyed the contaminants, but powered the venting process.

## SECTION V

### MODELING AND PROJECTING SOIL VENTING BEHAVIOR

The majority of soil venting applications share the same general removal behavior: high initial contaminant vapor concentrations decreasing rapidly with time, then tailing off over a long period of time. Extracted gas concentrations and removal rates may decrease over several orders of magnitude during operation. This behavior is the result of a complex combination of the many factors in air flow and contaminant transport that may differ in relative importance from site to site. Several attempts have been made to quantify some of the factors involved in order to improve system design and project system behavior. Below is a discussion of these efforts, divided into groups of air-flow modeling and system-behavior projections.

#### A. AIR FLOW MODELING

Air flow through a porous media may be described by Darcy's Law

$$\bar{q} = \frac{1}{\mu} \bar{p} \cdot (\nabla P + \rho g) \quad (3)$$

where  $\bar{q}$  = Specific discharge vector (L/t)

$\mu$  = Dynamic viscosity of air (M/L t)

$\bar{p}$  = Relative permeability tensor (L<sup>2</sup>)

$\rho$  = Air density (M/L<sup>3</sup>)

$P$  = Pressure (M/L t<sup>2</sup>)

$g$  = Acceleration due to gravity (L/t<sup>2</sup>)

$\nabla$  = Vector differential operator (known as "del").

Darcy's Law can be combined with the law of conservation of mass to yield

$$\frac{MW}{RT} (\eta_e + P\alpha) \frac{\partial P}{\partial t} = \nabla \cdot \left[ \frac{\rho}{\mu} \bar{p} \cdot (\nabla P + \rho g) \right] + Q \quad (4)$$

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$$Q = \frac{H \pi k P_w \left( 1 - \left( \frac{P_{atm}}{P_w} \right)^2 \right)}{\mu \ln \left( \frac{r_w}{r_l} \right)} \quad (6)$$

where  $k$  = air permeability ( $L^2$ ),  $\mu$  = gas dynamic viscosity ( $M/Lt$ ),  $Q$  is air extraction rate ( $L^3/t$ ), and  $H$  is the length of the vent screened interval.

Johnson et al. (Reference 53) point out that stratified soils may be approximately modeled by summing the flows for each stratum. Note that the radial flow approach requires the input of a radius of influence; good approximations may be made with reasonable input values.

The radial flow models are simple to use and may be valuable for system design. With input of a permeability value and vent screen length, one may produce a relationship between the amount of air extracted and the suction required at the vent. Conversely, one may analyze the data obtained from a vadose zone pump test to obtain a field air permeability value (Reference 53).

The applicability of radial models is limited. For cases with shallow vent screens, deep vadose zones beyond the depth of the vent, or cases without a surface barrier, the vertical component of flow may be significant. In these cases, a higher dimensional model is more applicable.

Two-dimensional flow models, such as those described by Wilson et al. (Reference 32), Krishnaya (Reference 42), and Baehr et al. (Reference 50) solve equations such as,

$$\nabla^2(P^2) = 0 \quad (7)$$

Metcalf and Farquhar (Reference 67) present the situation as,

$$\partial v/\partial x + \partial v/\partial z = 0 \quad (8)$$

$$v_x = -k_x/\mu \partial P/\partial x \quad (9)$$

$$v_z = -k_z/\mu (\partial P/\partial z + \rho g) \quad (10)$$

where  $v_x$  and  $v_z$  are the velocities in the horizontal and vertical directions,  $k_x$  and  $k_z$  are the permeability in the horizontal and vertical directions, and  $g$  is the acceleration due to gravity.

As Marley et al. (Reference 51) point out in the discussion of a similar flow model used for system design, these numerical flow models may be written to include the effects of anisotropy, the Klinkenberg effect, swelling soils, variable water saturation, the presence of an oil phase, and different strata. Expansion to three dimensions would not be difficult, but would require more input data and much more computer time.

The usefulness of numerical flow models for system design may be seen in Figures 9 and 10, which present the results of Baehr et al. (Reference 50), who calculated the vacuum and power requirements for a given vent geometry with different permeability inputs and the pressure and flow distribution in a stratified system, as calculated by Krishnayya et al. (Reference 42). Application of such models for a given site specific conditions will provide vent design guidance in terms of screening interval and vent spacing.

## **B. PROJECTING SYSTEM BEHAVIOR**

As stated above, several complex and generally unquantifiable factors govern the behavior of soil venting systems. Some attempts that have been made to project behavior are listed below.

The first level of system behavior projection is empirical extrapolation. Foster Wheeler Enviresponse (Reference 49) plotted the results of the Terra-Vac<sup>®</sup> SITE demonstration for removal of TCE as the logarithm of the contaminant vapor concentration versus time, resulting in a reasonably straight line representation as shown in Figure 11. Support for this type of plot may be made in their assertion that transient diffusion processes generally exhibit first order behavior. The authors suggest that the time required for remediation can be predicted by projecting the extracted gas concentration with time and using a field Henry's Law constant to correlate with soil concentrations. The authors of this review have found that the extraction data of the TCAAP pilot study (Reference 12), the TCAAP site D full-scale system (Reference 63), Payne et al. (Reference 24), and Sterrett (Reference 27), plot as a straight-line when the wellhead concentration and cumulative gas volume extracted are plotted on a log-log plot. Plots of the TCAAP data are shown in Figure 12. Each straight-line log plot is for one component or nearly one component spills of chlorinated compounds. The Hill AFB demonstration results (Reference 47) for venting of a petroleum-hydrocarbon mixture may be more closely represented by a semi-log line after an initial startup phase. In the absence of more rigorous models, empirical extrapolations may be useful in rough predictions of system behavior; however, the results obtained are very uncertain.

A second level of projection is the use of equilibrium models. These models assume perfect contact of air flow with the contaminants and instantaneous transport of those contaminants into the vapor phase. These models require the input of the amount and the chemical composition of the contaminant plume prior to venting. Marley et al. (Reference 51), point out that although these models are not valid for heterogeneous distribution of contaminants in the soil pores, less permeable zones, or free-product layers, they may provide good results for systems with uniform distribution in homogeneous soils. With accurate input information, equilibrium models will provide the most

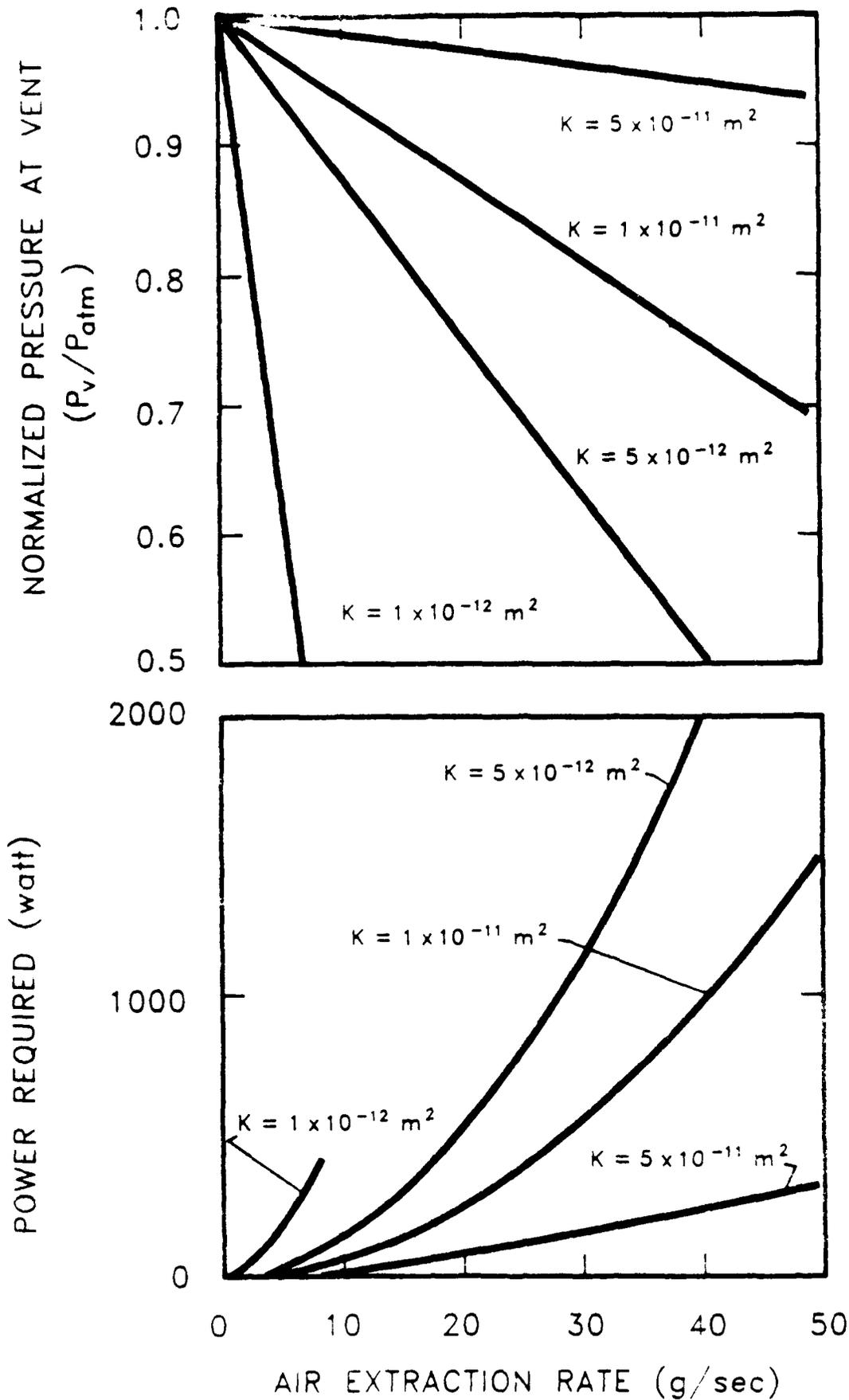


Figure 9. Normalized Vacuum and Power Requirements for a Given Vent Geometry as Calculated by a Two-dimensional Flow Model (adapted from Reference 50)

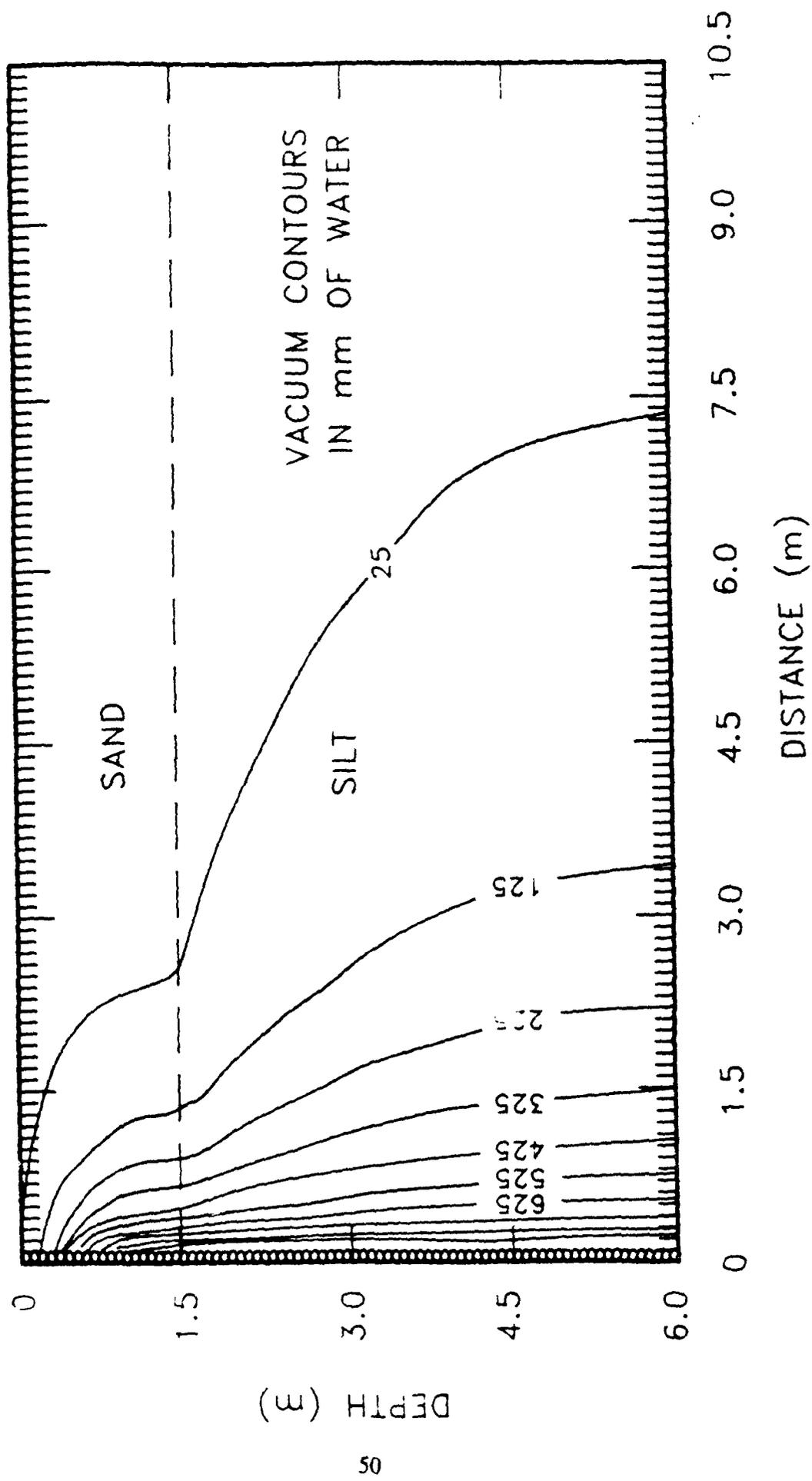


Figure 10. Predicted Pressure and Flow Distribution for a Stratified and Covered System  
(adapted from Reference 42).

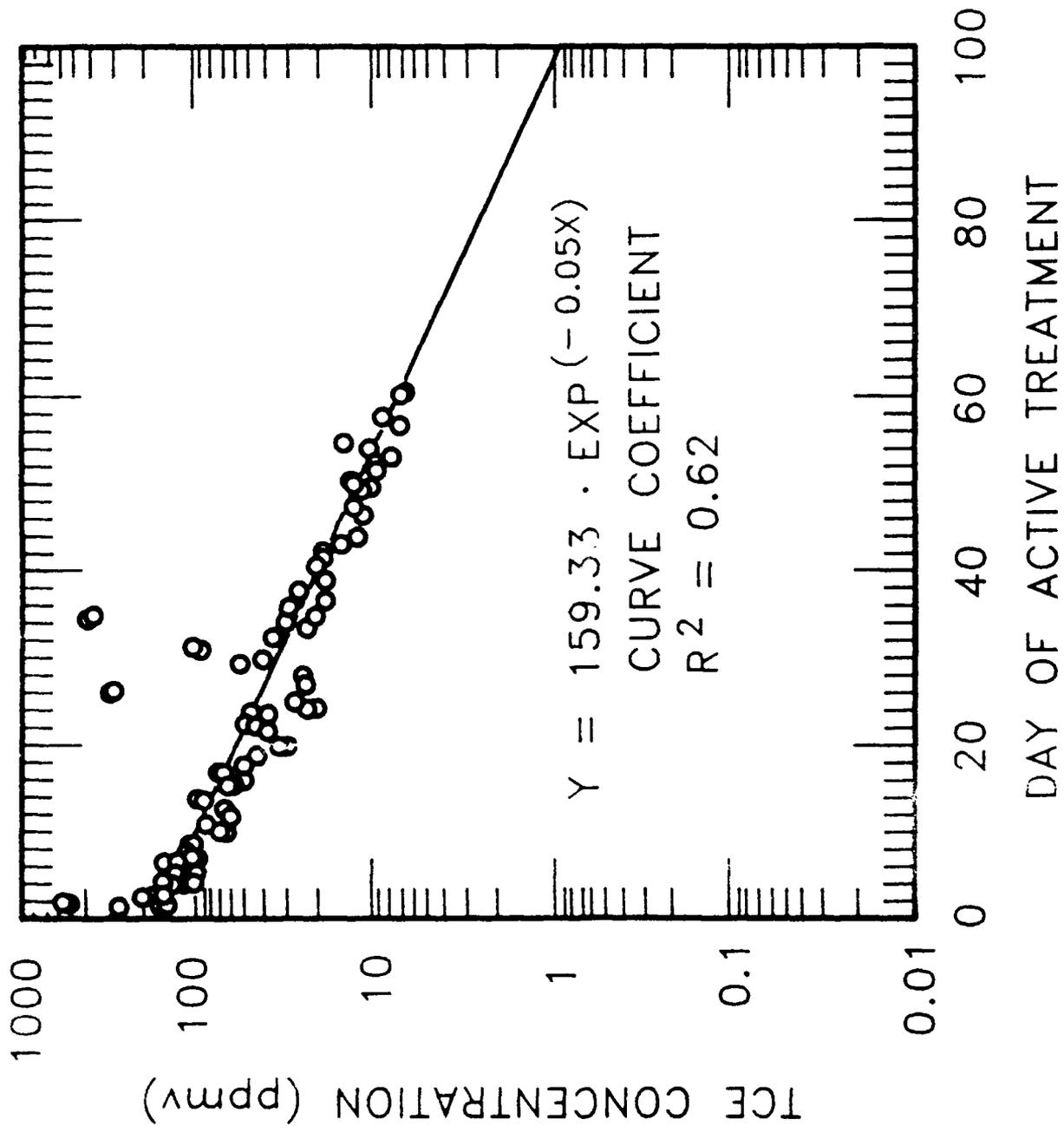


Figure 11. Example of Semi-log Extraction Behavior (adapted from Reference 49).

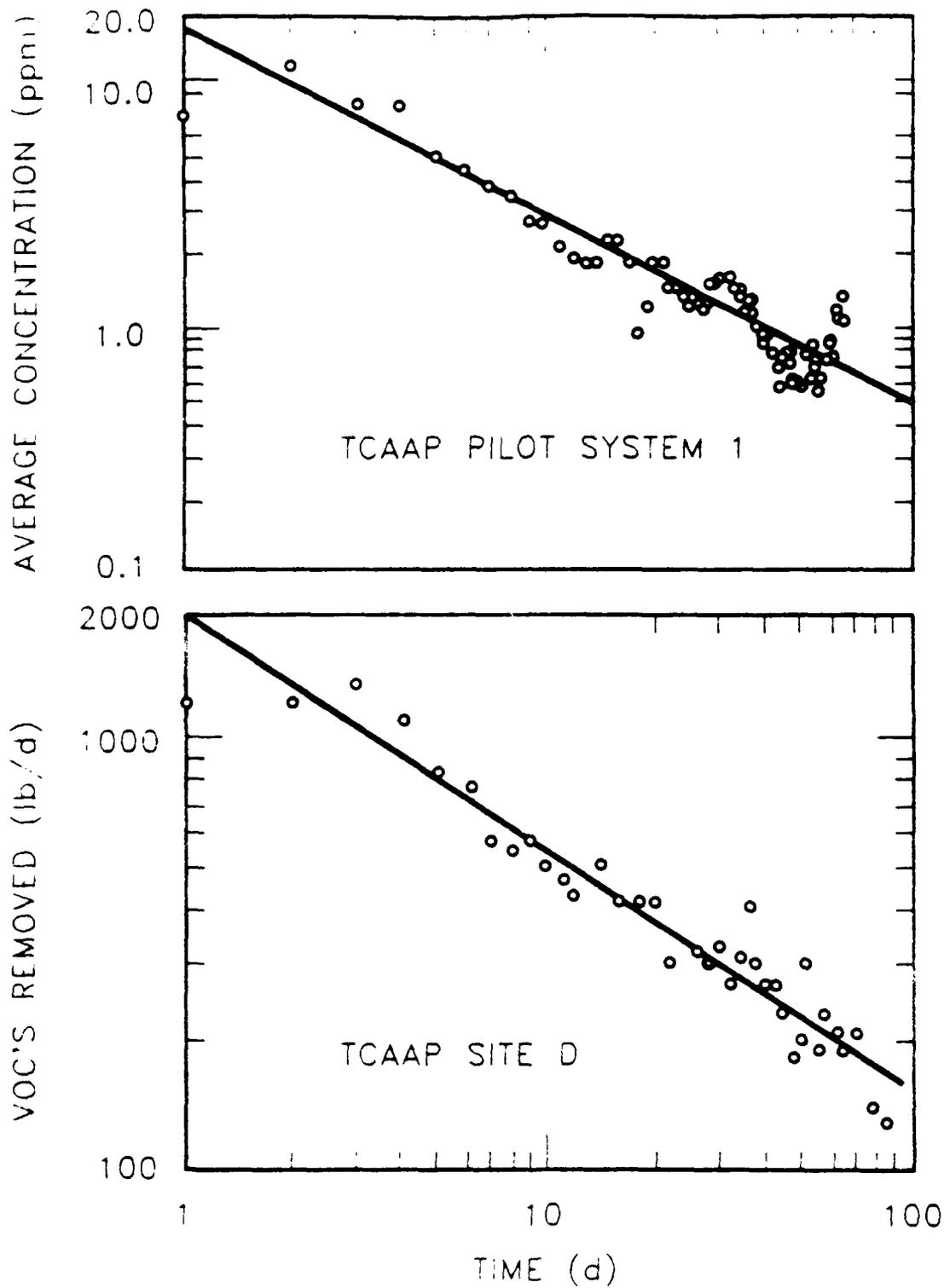


Figure 12. Examples of Logarithmic Extraction Behavior (adapted from References 12 and 63).

optimistic estimate of the time required for remediation. The first equilibrium model reported was that of Marley and Hoag (Reference 3). They modeled gasoline removal from a soil column using Raoult's Law and material balance equations, and they achieved good results. Marley and Hoag stated that a local equilibrium assumption may be valid for air velocities in soil pores of 0.4 to 2.8 inches/second. Another equilibrium model was given by Johnson et al. (Reference 53). This model included provisions for volatilization based on Raoult's Law, sorption of contaminants on soil particles, dissolution in pore-space water, and it may be altered to include bioactivity. Results of this model for gasoline are shown in Figure 13. DePaoli et al. (Reference 47) reported reasonable agreement, given uncertainties in contaminant volume composition and distribution, between a simple equilibrium model including only Raoult's Law volatilization and the results of the Hill AFB demonstration. A simple removal rate model based on Henry's Law was presented by AWARE (Reference 31).

Due to nonuniform flows and contaminant distributions and heterogeneous soils, the simple equilibrium model, with only inputs of air extraction rate and contaminant volume and composition, will likely overpredict the removal rate. A more accurate approach is to derive the air velocity profiles in the soil, which drive convective and diffusive contaminant vapor transport and couple these with transport and mass balance equations.

A useful model with this approach was presented by Wilson et al. (Reference 32). Their two-dimensional model determined steady-state gas flows near a point sink. The amount of contaminant removal from each point in the soil was determined using the magnitude of the gas velocity at that point and Henry's Law equilibrium. Results of the model are shown in Figure 14. Although the model includes great simplifications over actual site conditions and contaminant transport mechanisms, very good agreement was achieved in comparison with field results.

A more advanced treatment was presented by Sleep and Sykes, (Reference 68), who described a multi-purpose contaminant fate/transport model. Their model includes the capability to calculate gas- and water-phase flow patterns; and it considers advection and diffusion (using an overall mass transfer coefficient), with dissolution, volatilization, and gas-liquid partitioning in the calculation of contaminant transport. A sample calculation for a venting situation was presented. Models such as this, which can be used to combine convective and diffusive transport for the soil zones in which they are applicable, show promise for realistic prediction of soil venting behavior.

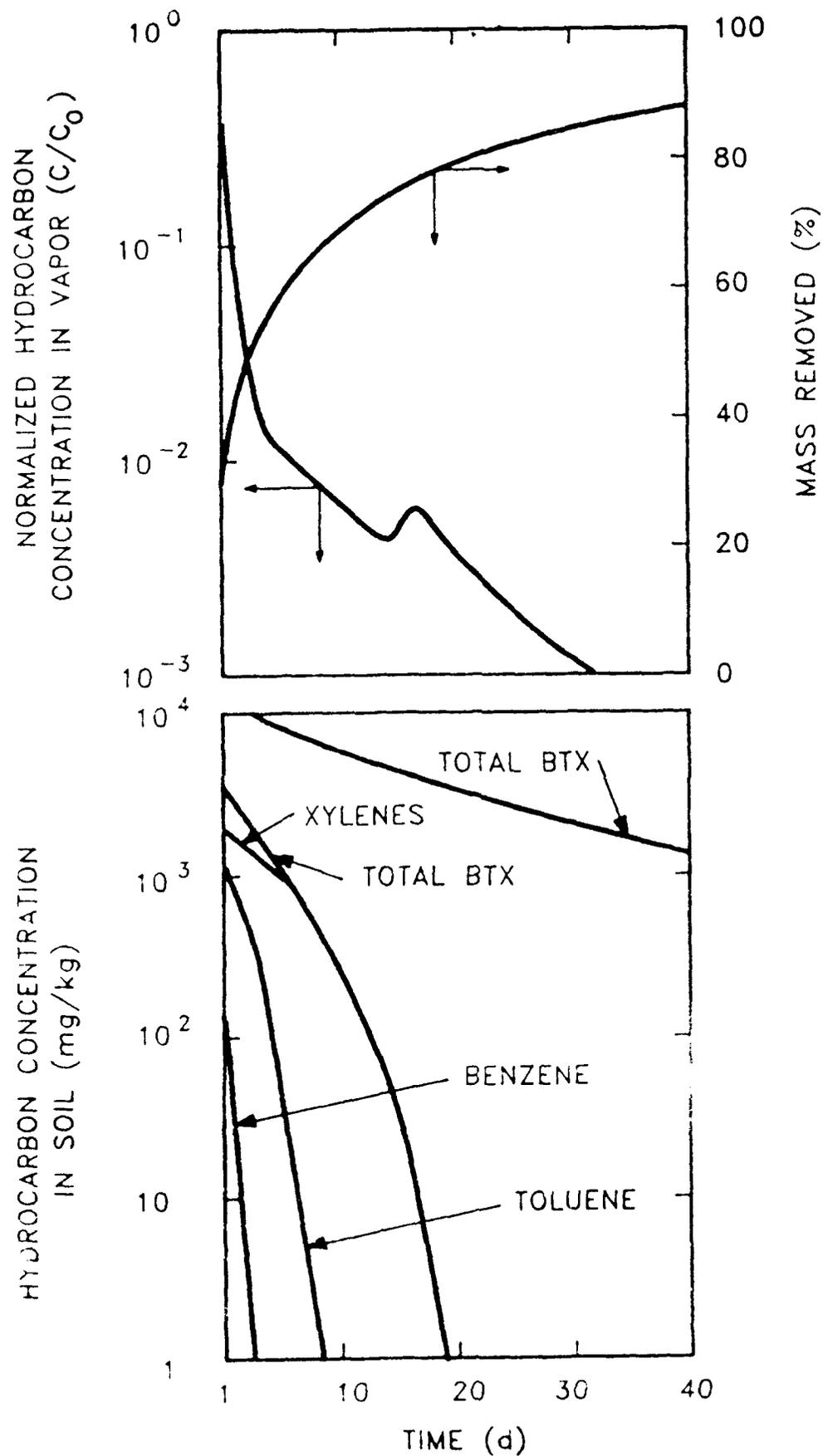


Figure 13. Predictions of Gasoline Removal Using an Equilibrium Model (adapted from Reference 53).

# Concentration Contours of Wilson et al. (Reference 32) Model.

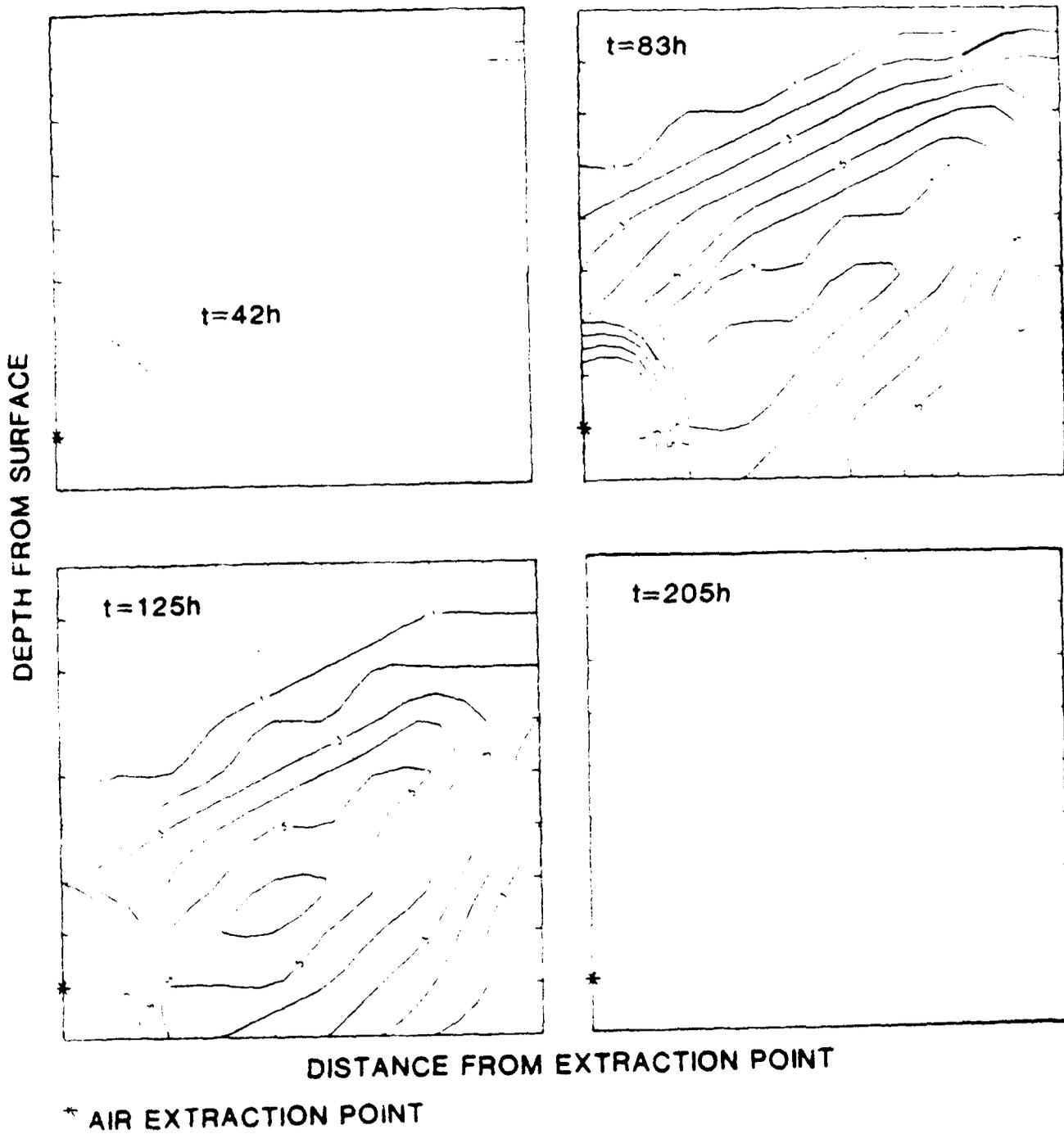


Figure 14. Predicted Contaminant Removal Using a Coupled Flow and Equilibrium Removal Model (adapted from Reference 32).

In conclusion, there has been recent growth in efforts for modeling and prediction of soil venting system behavior. Simple models, such as radial flow equations and equilibrium removal calculations, may be very valuable for system design due to their ease of implementation. Flow and removal models of greater complexity may be more realistic representations and may give better guidance for system design. Coupled flow and contaminant transport models allow calculation of spatial variations of treatment. It must be noted, however, that more complex models, which include several transport mechanisms, may become more difficult to use accurately due to the large number of input variables required; and they may suffer due to the uncertainties prevalent in site characterization.

## SECTION VI

### ECONOMICS

*In situ* soil venting is an economically attractive remediation technology. Compared with conventional techniques such as excavation and pump-and-treat cleanup of groundwater, soil venting may cost one-tenth as much. It is cheaper than pump-and-treat remediation alone, mainly due to the amount of time necessary to complete treatment, as may be seen in the dramatic increase in removal with the addition of soil venting to the pump-and-treat system presented by Nichols and Gibbons (Reference 36). It is estimated that soil venting could remove hydrocarbons 1000 times cheaper than removal from the aquifer (Reference 9), with lower installation costs and higher recovery rates (Reference 7). Markley (Reference 35) stated that soil venting performed in tandem with bioremediation reduced the cost of a site cleanup to 10 to 20 percent of that for bioremediation alone.

Based on excavation costs of \$300 to \$500 per 55-gallon drum of soil and estimates of \$8.33 (Reference 26) and \$15 to \$20 (Reference 12) per cubic yard of soil cleaned by soil venting, soil venting is cost effective when over 500 cubic yards of soil are to be treated (Reference 24), or at depths greater than 20 feet (Reference 19).

The costs of *in situ* soil venting systems are site specific. Capital costs are usually low, with major factors including the number and depth of vents, blower, valving, piping, instrumentation, and air emission control, if necessary (References 8, 18, and 22). Operating costs are usually low, since the systems are not labor-intensive. Major operating costs are sampling, analysis, power, maintenance, and emissions control (References 8, 12, 18, and 22). Emissions control can add up to 50 percent of the total installation cost (References 12, 13, and 19). Other major costs involved in the site cleanup will include preparation of cleanup plans, permitting, and performance monitoring (Reference 58).

Cost figures reported for different soil venting applications are listed below.

A cost breakdown for the TCAAP pilot system estimated 32 percent capital, 54 percent operating, and 13 percent contingency. Of the operating costs, 27 percent was for sampling, 37 percent for carbon adsorption, and 36 percent for system operation (Reference 12). Total cleanup cost was estimated to be in the range of \$15 to \$20 per cubic yard treated.

Oster et al. (Reference 16) reported the costs for the full-scale TCAAP systems. The capital cost for Site D was \$167,000, with \$2000 to \$3000 per month operating costs; whereas Site G, with its carbon adsorption emissions control, had a \$470,000 capital cost and \$20,000 per month operating cost. Total treatment costs were estimated at \$2.80/pound contaminant removed for Site D and \$8/pound for Site G.

Connor (Reference 38) reported a total cost of \$175,000 for removal of 400 gallons of gasoline from a shallow site, including carbon emissions control. The reported cost breakdown was 54 percent equipment, 3 percent installation, 5 percent utilities, 17 percent monitoring and emissions control, 18 percent planning and permitting, and 3 percent miscellaneous.

Johnson and Sterrett (Reference 30) list \$25,000 capital and \$500,000 operating costs for the removal of 90,000 pounds of dichloropropene. Emissions control was not reported with this system.

Marley et al. (Reference 51) list a range of \$10 to \$50 per cubic yard of soil treated by venting.

## SECTION VII

### CONCLUSIONS AND RECOMMENDATIONS

As noted in the literature, there has been a large increase in the application of *in situ* soil venting technology for the removal of volatile organic contaminants from unsaturated-zone soils. Remediation by soil venting may be several times less expensive than excavation for sites of medium-to-large size or depth, and it can eliminate or shorten the time necessary for treatment of groundwater.

Its limitations are not well defined due to the limited number of well-documented experiences with this technology. It is possible that other remediation measures may be necessary, in conjunction with soil venting, to achieve desired levels of certain contaminants.

Each soil venting application is site specific. Although some general guidelines have been published, the body of knowledge is not great enough to dictate the design of a system *a priori*. Bench- and pilot-testing at the particular site, and limited modeling are presently the best means for determining applicability and design parameters. Continued testing at various sites may lead to an adequate data base for usable, universal models for these tasks. However, due to soil and contaminant distribution heterogeneities, there will continue to be uncertainties associated with modeling of field applications; and successful system design may continue to be somewhat of an art.

Recommendations for further tests and demonstrations include the following:

1. Operate soil venting demonstrations for extended periods to determine limits of cleanup effectiveness.
2. Perform venting tests on different contaminants in settings with various soil types or of greater geohydrological complexity. Include detailed site characterization and system monitoring to provide adequate information for application to modeling.
3. Continue lab-scale investigations into the equilibrium between contaminant vapors, free liquid, dissolved species, and sorbed species in soil for different contaminants and soils. Also perform controlled venting experiments that include problems of diffusion-controlled removal, such as contaminated zones of low permeability surrounded by permeable soils. This research into the mechanisms controlling soil venting will prove useful in modeling.
4. Continue demonstrations of innovative enhancements of soil venting, such as soil heating through air/steam injection, radio frequency or microwave heating, optimization of biological activity, and different venting configurations.

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**SUPPLEMENTARY**

**INFORMATION**



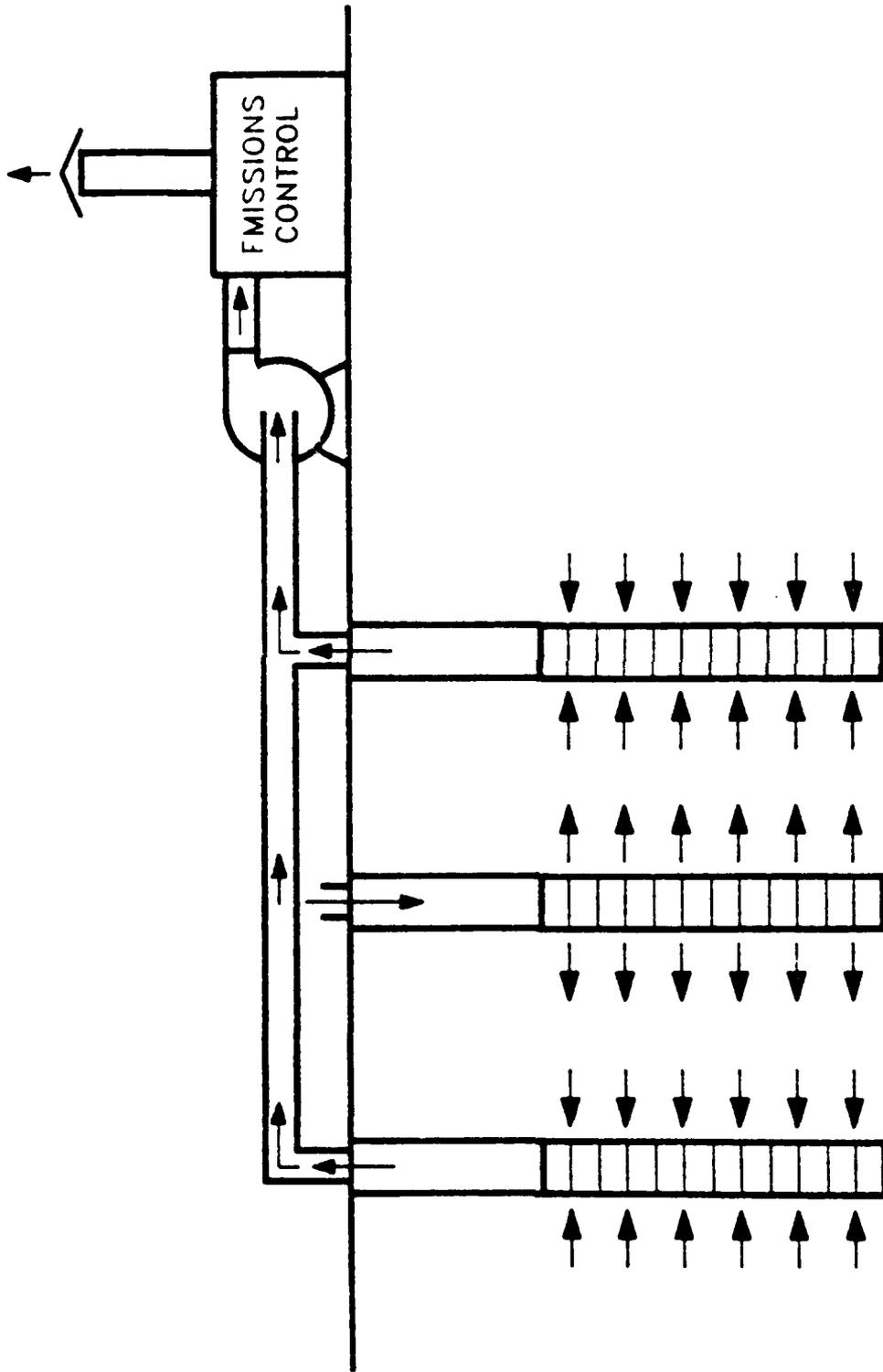


Figure 5. Example of Passive Inlet/Forced Extraction Strategy (adapted from Reference 10).

where  $\bar{M}\bar{W}$  = Molecular weight of air (M/mol)

$R$  = Ideal gas constant ( $M L^2/t^2 T \text{ mol}$ )

$\eta_e$  = Effective air-filled porosity (dimensionless)

$\alpha$  = Compressibility of the porous media ( $L t^2/M$ )

$Q$  = Source/Sink ( $M/L^3 t$ )

$M$  = Mass

$L$  = Length

$T$  = Temperature

$t$  = Time

(Reference 65).

For a strictly valid representation of subsurface air flows, a three-dimensional model including all features of subsurface structure would be needed. However, since the use of such a model would be time-consuming and costly, several simplifications of the above equation have been made for useful approximate solutions. The first is to ignore the effects of gravity and media compressibility, removing the terms  $\rho g$  and  $P\alpha$ . This should have little effect on gas flow (Reference 66). The next simplification is the assumption of an isotropic medium (permeability is the same in all directions), considerably simplifying the tensor representation.

One-dimensional radial flow equations may be solved analytically. The radial flow assumption neglects vertical flows and angular variability.

Johnson et al. (Reference 53) presented the solutions for steady state radial flow as,

$$P(r) = P_w \left( 1 + \frac{\left( 1 - \left( \frac{P_{atm}}{P_w} \right)^2 \right) \ln \left[ \frac{r}{r_w} \right]}{\ln \left[ \frac{r_1}{r_w} \right]} \right)^{1/2} \quad (5)$$

for the radial pressure distribution, where  $P(r)$  is the pressure in the soil at a distance  $r$  from the center of the extraction vent,  $P_w$  is the pressure at the extraction vent having a radius of  $r_w$  and  $r_1$  is the radius of influence, at which the pressure is the atmospheric pressure  $P_{atm}$ . Sterrett et al. (Reference 27) used a similar relation, the Thiem equation. The extraction rate may be expressed as,