United States Air Force
Environmental Restoration Program

FINAL

Guidance on
Soil Vapor Extraction Optimization

June 2001

Prepared For

Air Force Center for Environmental Excellence
Brooks AFB, Texas

EXECUTIVE SUMMARY

During this decade, the Department of Defense will spend over one billion dollars per year on the operation, maintenance, and monitoring of environmental remediation systems. This document was written to assist Air Force environmental managers and consulting engineers who are responsible for the operation and monitoring of soil vapor extraction (SVE) systems, and to promote the closure of sites where SVE systems have achieved cleanup goals. Practical guidance is provided on performance monitoring and the optimization of SVE systems so that remediation goals can be achieved in a cost-effective manner. This document was prepared by Parsons Engineering Science Inc. under the direction of the Technology Transfer Division of the Air Force Center for Environmental Excellence (Contract No. F116323-94-D0024, D.O. 39).

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LIST OF ACRONYMS AND ABBREVIATIONS

AFCEE	Air Force Center for Environmental Excellence
BESST	Best Environmental Subsurface Sampling Technology, Inc.
bgs	below ground surface
BRAC	Base Realignment and Closure
C	Degree Celsius
CPT	cone penotrometer technology
CSM	conceptual site model
DAF	dilution attenuation factor
DoD	Department of Defense
DNAPL	Dense non-aqueous phase liquid
DPE	dual-phase extraction
DQO	Data quality objective
ECD	electron capture device
EPA	Environmental Protection Agency
ER	electrical resistance
FID	flame ionization detector
Hg	Mercury
MCL	maximum contaminant level
MCLG	Maximum contaminant level goal
mS/m	milliSiemen per meter
mg/kg	milligram per kilogram
µg/L	microgram per liter
MIP	membrane interface probe
mm	millimeter
MPE	multi-phase extraction
NAPL	non-aqueous phase liquid
O&M	Operations and maintenance
PID	photoionization detector
ppmv	Parts per million, volume per volume
Praxis	Praxis Environmental Technologies, Inc,
PVC	Polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
RF	Respirable fraction
RFH	radio frequency heating
RI/FS	remedial investigation/feasibility study
ROD	Record of decision
RPO	remedial process optimization
SPLAT	SimulProbe® Latch Activated Tip
SSL	soil screening level
SSTL	site-specific target limit
STOP	SVE Termination or Optimization Process
SVE	soil vapor extraction
SVOC	Semivolatile organic compound

TBD	Technical Background Document
TCE	trichloroethene
USACOE	United States Army Corps of Engineers
UST	underground storage tank
VMP	vapor monitoring points
VOC	volatile organic compounds
VW	Vent well

SECTION 1

INTRODUCTION

1.1 PURPOSE AND ORGANIZATION

This document was written for Air Force environmental managers and consulting engineers who are responsible for the operation and monitoring of soil vapor extraction (SVE) systems, and eventual closure of sites where SVE systems are in use. The purpose of the document is to provide practical guidance on the optimization of these systems so that remediation goals can be achieved in a cost-effective manner. Five primary topics will be presented. Section 2 describes the importance of accurate site characterization and how new characterization methods can enhance and redefine the conceptual site model and basis of design. Section 3 underscores the importance of a clear understanding of site closure requirements and provides ideas for defining remediation cleanup goals. Section 4 describes standard methods for monitoring the performance of SVE systems. In Section 5, common performance problems are discussed as well as methods of improving and optimizing the performance of these systems. Finally, Section 6 discusses various approaches for obtaining site closures.

1.2 BACKGROUND

1.2.1 Technology Description

Soil vapor extraction is the application of a vacuum to unsaturated (vadose zone) soils to induce soil vapor flow toward extraction vent wells and remove volatile and some semi-volatile contaminants from the soil (Figure 1.1). Once removed from the soil, volatile organic compounds (VOCs) can either be released directly to the atmosphere or removed/destroyed using an aboveground treatment process. On many sites, a vapor/ liquid separator is required to remove condensed water to protect the blower and improve the operation of vapor treatment units. The need for vapor treatment is based on local air

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Figure 1.1

BASIC IN-SITU SOIL VAPOR EXTRACTION SYSTEM

Vapor Treatment Unit/GAC

Vacuum Pump or Blower

Vapor Liquid Separator

Flow Meter

Pressure Gauge

Multi-Level Vapor Monitoring Points

Difficult to Remediate Capillary Fringe

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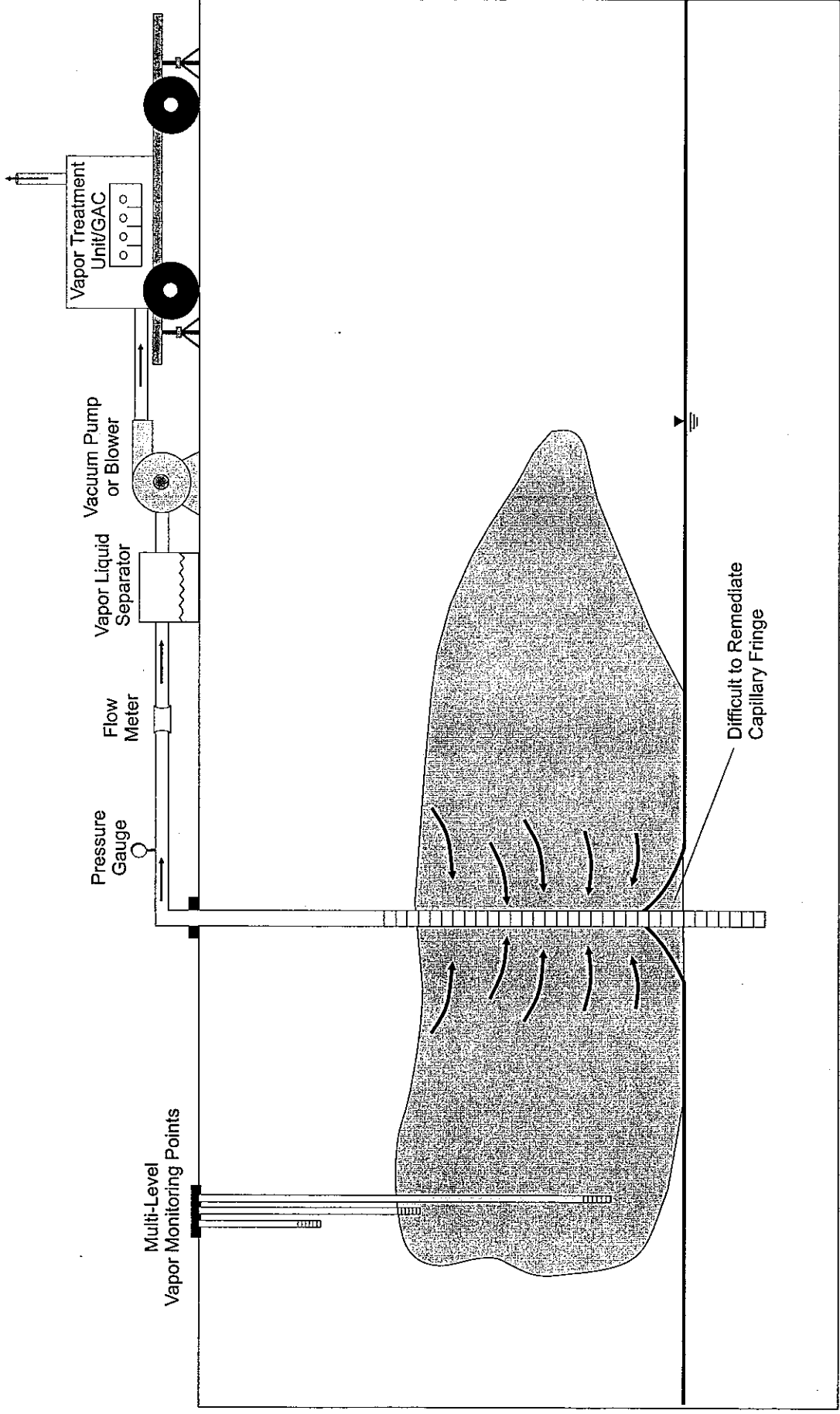
discharge regulations. The progress of vadose zone remediation is normally monitored using strategically placed soil vapor monitoring points or VMPs.

When air is drawn through the soil, it passes through soil pore spaces, and primarily through pathways of low resistance (high permeability soils). Air that is drawn through soils containing VOC vapors will remove these vapors and continue to vaporize adsorbed and non-aqueous phase liquids (NAPLs). This is known as removal by advection and will continue until all of the volatile adsorbed and liquid-phase contaminants are removed from higher permeability soils. Contaminants in lower permeability soils will not be removed by advection because soil vapors will preferentially flow through higher permeability soils. Contaminants in lower permeability silts and clays must desorb and diffuse into an advective flow path before they can be removed by the SVE system. If the rate of diffusion is slow, the timeframe for removing VOCs will be significantly extended (Environmental Protection Agency [EPA], 1991). Figure 1.2 illustrates how contaminants are removed via advection and diffusion processes in the subsurface.

1.2.2 Proper Application of SVE

The proper application of the SVE technology is based on an evaluation of three primary criteria: the risk mitigation requirement, contaminant properties, and soil properties. Although a complete discussion of these design criteria is beyond the scope of this document, a brief summary is provided here.

Risk Mitigation – The proper application of SVE requires a clear understanding of the risks that require mitigation. The SVE system must be designed and operated to accomplish one or more of these risk mitigation goals. There are three common risks that could lead to a regulatory or voluntary cleanup of soils.

- A risk from direct contact with soils or soil vapors such as the exposure to a utility installation worker to contaminated soils.

- A risk to groundwater based on the leaching of contaminants from soils.

1-3

Figure 1.2

VOLATILE ORGANIC FATE
AND TRANSPORT PROCESSES

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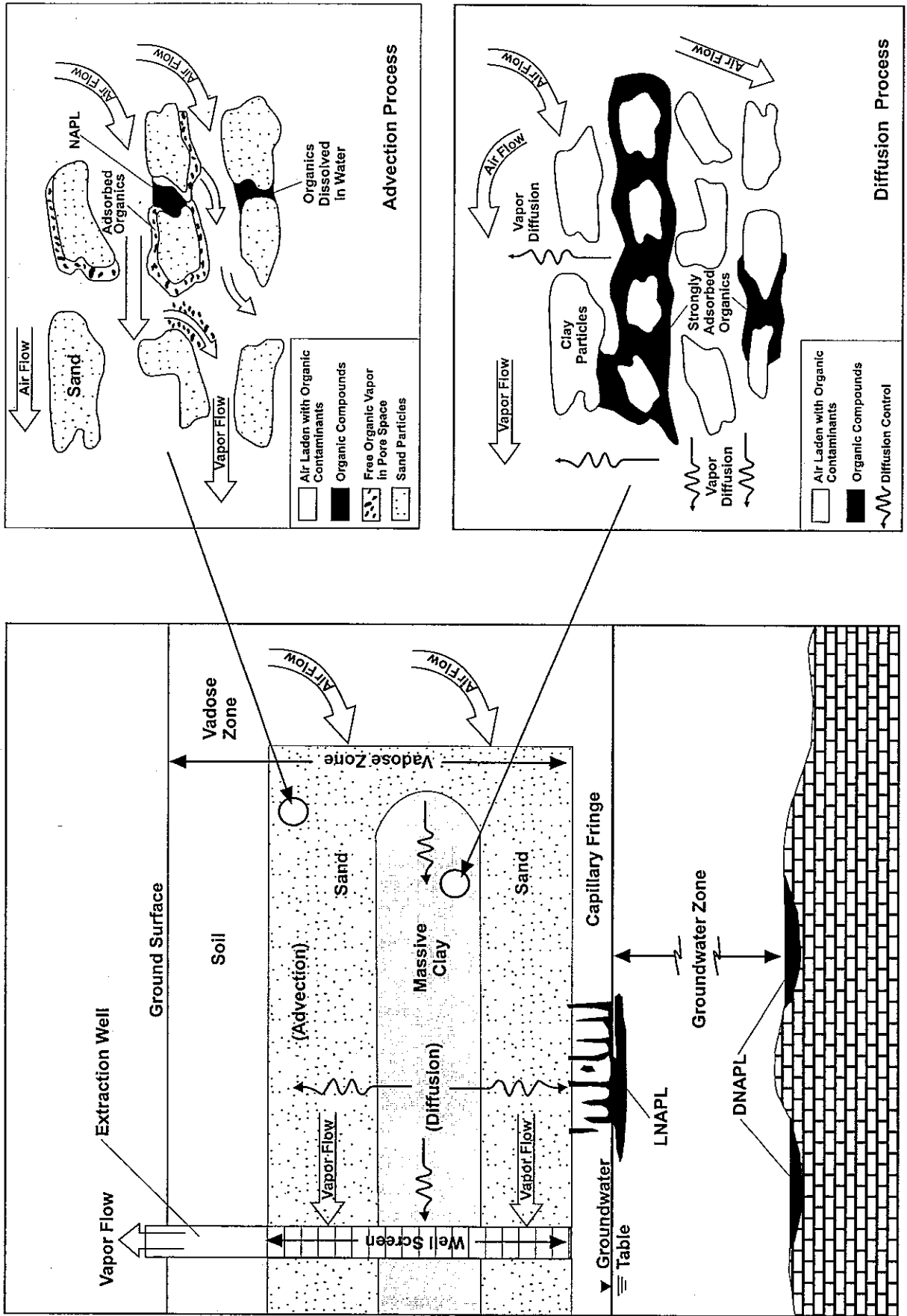
- An explosive risk in nearby structures and underground utilities from high levels of volatile organics.

Contaminant Properties – SVE is generally effective for removing organic contaminants with a vapor pressure greater than 0.5 mm mercury (Hg) at 20° Celsius (C). This includes common chlorinated solvents, gasoline, and many of the more toxic compounds found in jet fuels. Chlorinated solvents, such as trichloroethene (TCE) are the primary targets of most Air Force SVE systems. Due to the biodegradability of gasoline, jet fuels and other petroleum products, the Air Force recommends that bioventing (air injection to promote aerobic biodegradation) be considered the default technology for this family of hydrocarbons. Bioventing is generally less expensive because no off-gas treatment is required. One important exception is when air injection could lead to dangerous vapor migration into buildings or underground utilities. At these sites, SVE is recommended because it provides a positive control on vapor migration until soil vapor levels are sufficiently reduced.

Soil Properties - Soil grain size distribution, soil moisture, and the distribution of contaminants within various soil types are primary factors influencing SVE effectiveness. Soil grain size distribution and soil moisture determine the air-filled porosity of the soil, which in turn determines the air permeability of the soil and the amount of advective and diffusive contaminant removal that will take place. Generally, silt/clay soils with a median grain size of less than 0.075 mm (No. 200 sieve) and a moisture greater than 50 percent of field capacity will be unlikely candidates for successful SVE. (This assumes that contaminants have penetrated these fine-grained soils.) Even sandy soils will be difficult to remediate with SVE if the contamination is centered in the capillary fringe where higher soil moisture prevents soil gas flow. These soils must be dewatered before SVE can remove contaminants (See Section 1.3). A detailed review of contaminant and soil properties, and the theory of soil vapor flow, is provided in the US Army Corps of Engineers publication " Engineering and Design Soil Vapor Extraction and Bioventing" (United States Army Corps of Engineers [USACOE], 1995) available on the web at: www.usace.army.mil/inet/usace-docs/eng-manuals/em.htm.

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1.3 ENHANCEMENTS TO SVE

Several SVE enhancements have been developed to overcome limitations caused by less than optimum contaminant and soil properties. This section provides an overview of commonly applied SVE enhancements that have the potential to accelerate mass removal and extend the application of this technology to semi-volatile contaminants and lower permeability or saturated soils. Figure 1.3 illustrates several common enhancements to SVE. The use of these enhancements to improve SVE effectiveness is also discussed in Section 5.

1.3.1 Thermal Enhancements

Thermal enhancements for SVE include a number of technologies that increase the volatilization of VOCs and semivolatile organic compounds (SVOCs), increase the air permeability of the soil, and enhance gas-phase diffusion process. By increasing the vapor pressure of a contaminant, the volatilization rate from liquid phase to vapor phase accelerates, increasing the mass available for extraction by SVE. An increase in the air permeability of the soil is due to the drying effects of heat, enhancing the vaporization and extraction of moisture from the subsurface, and resulting in increased advection. Gas-phase diffusion is typically much slower than advection and is often a rate-limiting step in SVE. In diffusion-limited formations, increased temperature enhances the rate of vapor transport from low permeability zones to regions of higher permeability. These mechanisms allow thermal enhancement of SVE to increase overall mass removal of contaminant or to shorten remediation times. Thermal processes will generally increase the unit cost for mass removal.

Thermal enhancement technologies include steam or hot air injection, radio frequency heating (radio frequency heating [RFH]), electrical resistance (ER) heating, and thermal conduction heating. Steam injection technologies push contaminants ahead of a condensate front. The steam continues to remove contaminants after the condensate front has passed and heated soil vapor is removed with standard extraction wells. Soils of medium to high permeability are required to allow the condensate front to move freely. Hot air injection is similar to steam injection except the dry hot air removes moisture

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Figure 1.3
ENHANCEMENTS TO SVE

Thermal Enhancements

→ SVE System

Resistive or
Radio-Frequency
Heating

System
Injection

Dual-Phase Extraction

Vapor Treatment ← → Groundwater Treatment

Exposed
Capillary Fringe

Dewatering Pump

Soil Fracturing

Pneumatic/Hydraulic
Fracturing Points

→ SVE System

Increased Advective
Flow
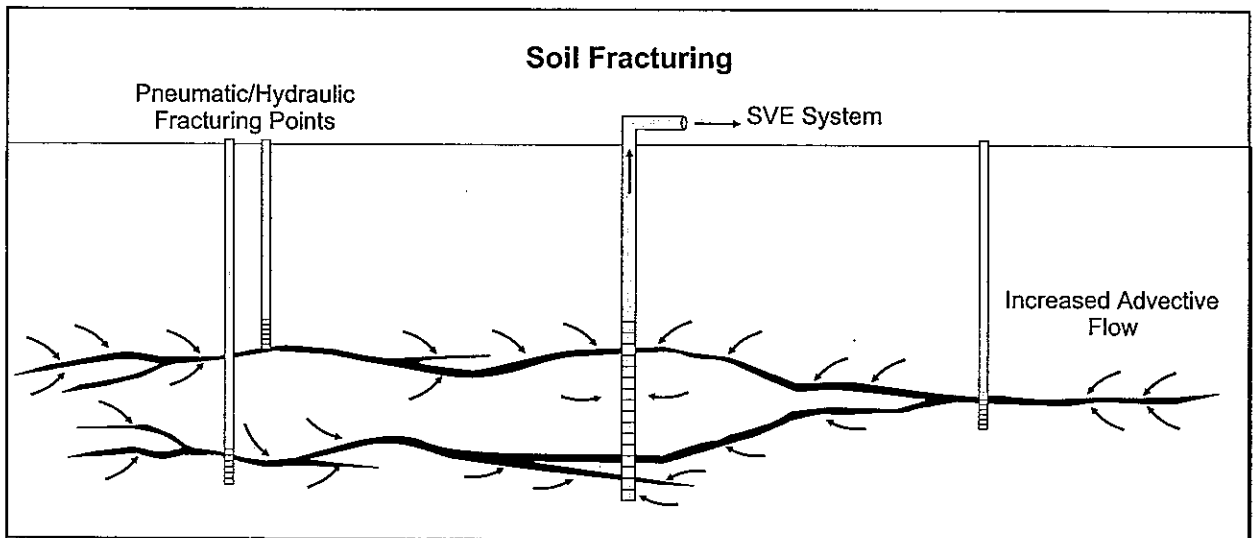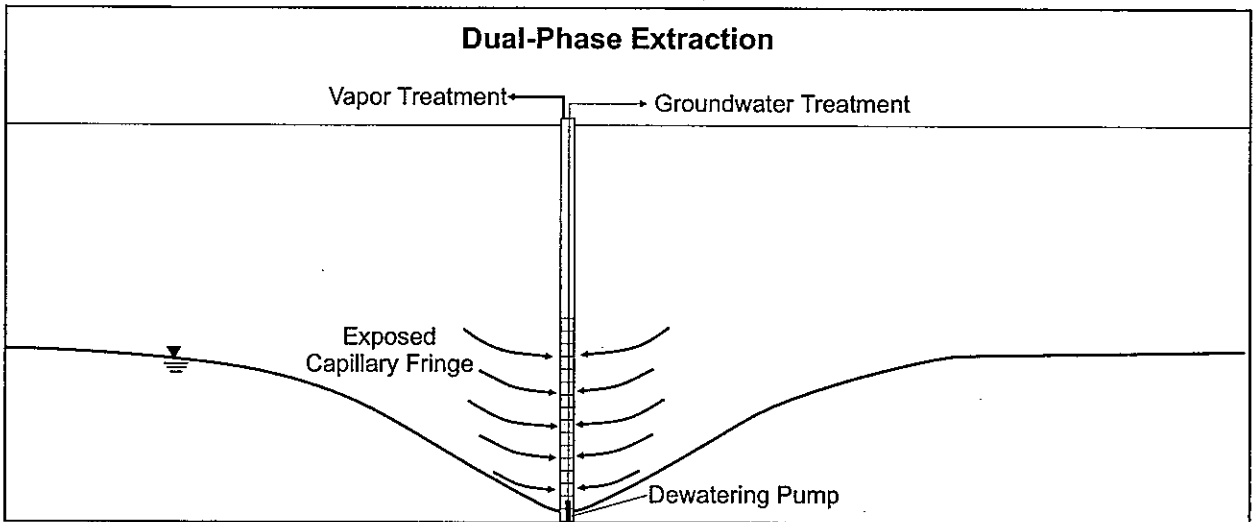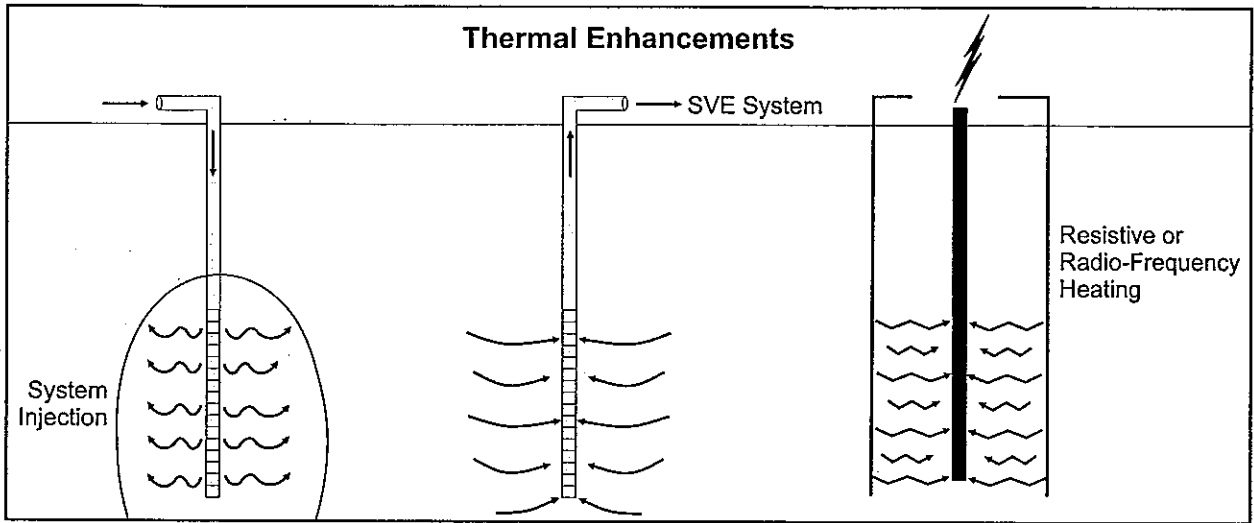
from the soil, increases air permeability, while volatilizing contaminants. RFH uses antennae or electrodes that emit radio frequency waves to increase molecular motion (similar to a kitchen microwave) and produce volumetric heating of the soil. ER heating uses the soil as a conduction path for electrical current and the resistance of the soil is used to create heat. Six-phase heating is the most common form of electrical resistance (ER) heating applied to remediation sites. This method may be effective for low-permeability soils in the vadose zone. As the native soil moisture is driven off, the conductivity of the soil decreases, limiting the maximum temperature to approximately 100°C. Thermal conduction heating uses a heat source such as inserted hot metal rods to directly transfer heat to the soil. Although this is a very simple method, it can be slow and inefficient for large soil volumes. A more detailed discussion of thermal enhancement is available in the EPA Analysis of Selected Enhancements for Soil Vapor Extraction (EPA, 1997).

1.3.2 Dual-Phase Extraction

Dual-phase extraction (DPE) is the removal of contaminated soil vapor and groundwater from a common extraction well. DPE enhances SVE by dewatering the capillary fringe and smear zones and allowing air flow through previously moist or saturated soils. In addition, simultaneous groundwater extraction prevents upwelling typically associated with SVE. The lack of upwelling allows higher vacuums to be applied and increases extraction rates of groundwater and soil vapor. The increased groundwater extraction rates can also accelerate the removal of non-aqueous phase liquid (NAPL) and dissolved groundwater contamination. Well and pump combinations that also remove NAPL as a separate phase are defined as multi-phase extraction (MPE) systems. The Air Force developed "Bioslurping" as an effective MPE method for free product fuel recovery and vadose zone remediation. A more detailed discussion of DPE and MPE enhancements of SVE is available in the EPA Analysis of Selected Enhancements for Soil Vapor Extraction (EPA, 1997) and the "Engineering Evaluation and Cost Analysis for Bioslurper Initiative Final Report" (Air Force Center for Environmental Excellence [AFCEE], 1997).

1.3.3 Soil Fracturing

Soil fracturing enhances SVE by creating high permeability pathways in low-permeability soils. These preferential flow pathways allow the effects of the applied vacuum to propagate further from the extraction well, increasing the advective flow zone round the well. Pneumatic and hydraulic fracturing are the primary methods that have been used to enhance SVE. Pneumatic fracturing involves the injection of highly pressurized air into the subsurface and is effective at enhancing existing fractures and increasing the secondary fracture network. Hydraulic fracturing involves the injection of water or slurry into the subsurface. The injected slurry may contain sand or other granular materials used to hold open the new fractures. A more detailed discussion of soil fracturing is available in the EPA Analysis of Selected Enhancements for Soil Vapor Extraction (EPA, 1997).

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SECTION 2

REFINED SITE CHARACTERIZATION

2.1 OBJECTIVES OF CHARACTERIZATION

This section describes additional site characterization techniques that can be used to refine our understanding of the subsurface conditions that relate to the performance of SVE systems. Standard methods of site characterization are not discussed in detail. Instead, this section will focus on several specialized techniques that have the potential to improve SVE performance. The objectives of SVE site characterization can be grouped into three general statements:

- To define the source, the contaminated volume of soil, and the nature of contamination (non-aqueous phase liquid or vapor).

- To define the capacity of the contaminated soil volume to transmit air and to identify the permeability variations due to soil type and soil moisture.

- To use this information to create a conceptual site model that can be updated as the SVE process moves forward.

2.1.1 Key Elements of SVE Site Characterization

The following site characterization information is required for all effective SVE systems:

1. The volume of contaminated soil must be bounded by clean samples including bottom samples that determine the extent of soil contamination below the water table. Many SVE systems are ineffective at reducing groundwater contamination because a significant fraction of the soil contamination is below the water table.

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2. The source area containing NAPL contamination must be identified and differentiated from areas with only vapor contamination. Locating extraction wells near the center of the NAPL volume is a key to effective SVE.

3. The soil lithology must be defined by multiple boring logs to identify sand and fine-grained layering. Soil samples should be analyzed for moisture content. Grain size and soil moisture to determine the air permeability of the soil.

2.1.2 Developing Detailed Cross-Sections

This fundamental site information should be translated into several cross-sections of the contaminated source area and any resulting smear zone. Figure 2.1 illustrates a detailed cross-section for a TCE-contaminated site. Detailed cross-sections provide the foundation of the conceptual site model described in Section 2.3.

2.2 ADVANCED SITE CHARACTERIZATION TOOLS

Many SVE systems can be successfully installed and operated based on the fundamental site characterization information described above. Sites with permeable sands and minimum silt/clay layering are generally predictable in their response to SVE and are frequently remediated with a high degree of uniformity. Unfortunately, uniform treatment is uncommon at many Air Force bases located on flat sedimentary deposits that are characterized by soil layers of varying permeability.

Many SVE sites can benefit from the use of new and improved characterization tools described in this section. One or more of these tools should be used during initial site characterization, particularly at sites with layers of high and low permeability soils. The additional site characterization information provided by these tools is also useful for updating site conceptual site models and optimizing and improving existing SVE systems. Some tools provide real time information and leave no permanent monitoring points, making them useful for the initial characterization and filling in critical data gaps in the conceptual model. Other tools provide permanent monitoring points or wells that provide a standard reference for updating the conceptual site model or evaluating the performance of a remediation system (Section 4.0).

2-2

Figure 2.1

DETAILED CROSS-SECTION FOR SVE SITE CHARACTERIAZTION
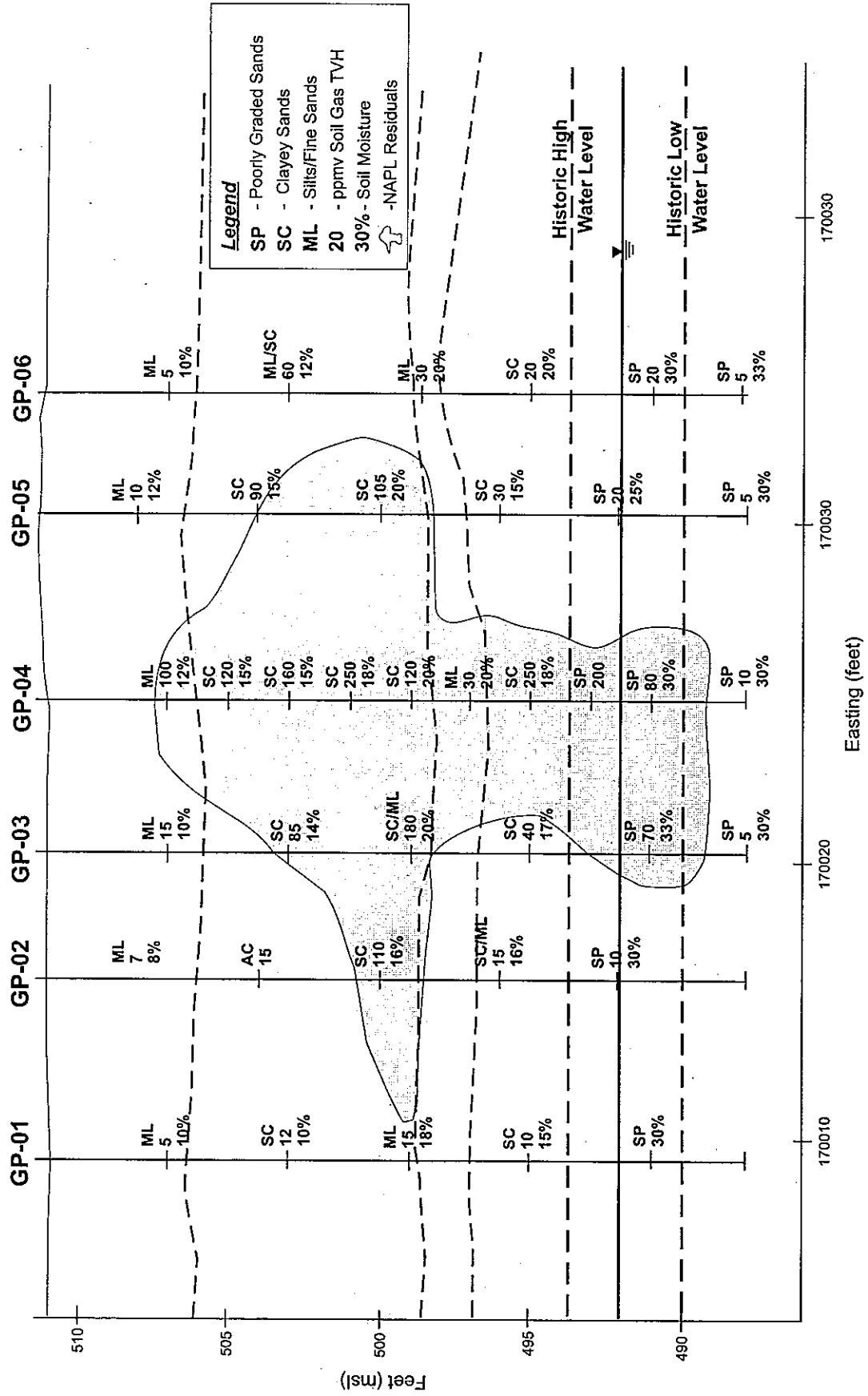
2.2.1 Direct Push Soil and Soil Gas Sampling Methods

Direct push soil sampling tools such as the Geoprobe[®] and the cone penotrometer technology (CPT) units can be used to sample soil, soil gas, and install permanent vapor monitoring points. Direct push technologies use hydraulically driven rods to advance special soil or soil gas sampling tools to a desired depth. These tools can rapidly collect soil cores or extract soil gas without creating soil cuttings that may require special handling and disposal. In general, this equipment is smaller and is less labor intensive than traditional drilling methods. Geoprobes[®] have traditionally been mounted on ¾ to 1-ton pickup trucks and have been successfully applied at sites with sandy, low density soils where penetrations are required in the upper 100 feet of the soil. CPT rigs are larger and heavier and are capable of pushing to greater depths through silt and clay soils. Cobble and rock layers will significant limit the use of any type of direct push technology. For shallow applications, direct push technologies can generally characterize 2 to 3 times the number of boring locations per day as compared to traditional hollow-stem auger rigs.

Direct push units can collect a 2 – 4 foot soil core per rod stroke and can rapidly collect a continuous soil core at each location. The continuous core provides an accurate definition of varying grain sizes and moisture conditions and can be used to estimate air permeability and improve SVE design and operations. At the surface, soil samples are generally logged, screened for contamination using a flame ionization detector (FID) or photoionization detector (PID), and selected samples packaged for laboratory VOC analysis.

Modifications to the rod configuration of direct push equipment allows the collection of soil gas samples in addition to soil cores. Special sampling tips with small-screened sections are driven to the desired depth. A soil gas sample is then collected through tubing that runs from the open borehole or screened tip to a small vacuum pump and sampling device at the surface. Figure 2.2 is an example of a soil gas sampling tool. Other direct push tools, such as the SimulProbe[®], can be used to collect several samples within the same hole (see Section 2.2.2). The soil gas sample can be analyzed using a

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Figure 2.2
SINGLE USE DIRECT PUSH SOIL GAS SAMPLING POINT

Probe Rod

Tubing

PRT Adapter

O-Ring

PRT Expendabe Point Holder

O-Ring

Expendabe Drive Point
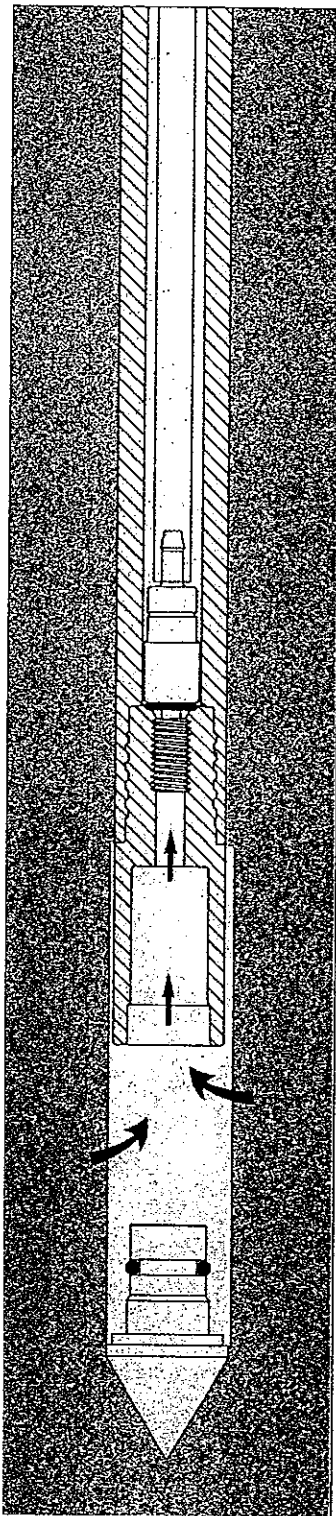
A cross section of the PRT System showing how soil gas (arrows) is drawn through the inner tubing system.
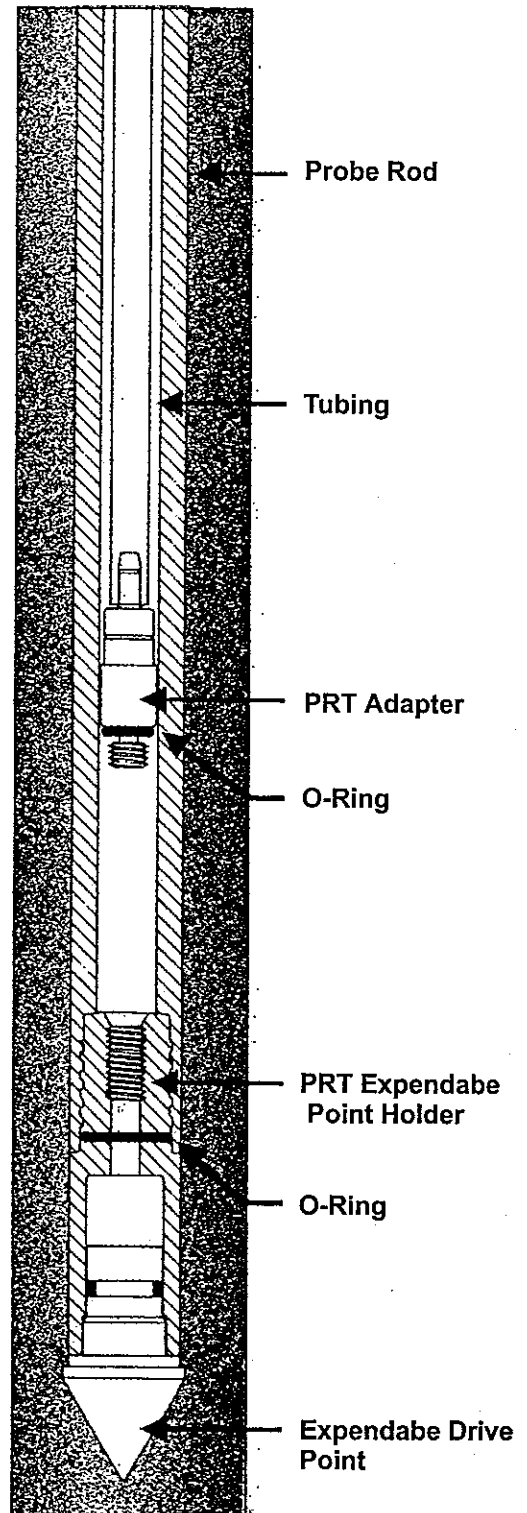
A cross section of probe rods that are being driven to depth and then retracted to allow for soil gas sampling. The PRT adapter and tubing are now fed through the rods and rotated to form a vacuum-tight connection at the point holder. The result is a continuous run of tubing from the sample level to the surface.

Source: GEOPROBE, 2000.

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handheld gas analyzer (FID or PID) or submitted for more specific analysis at a laboratory.

Discrete soil gas monitoring points (Section 2.2.5) can be permanently installed using direct push equipment. The monitoring points generally consist of a 0.5 to 0.75-inch polyvinyl chloride (PVC) tube with a 6-inch soil gas collection screen at the bottom. The entire VMP is installed inside of the hollow steel push rod. As the steel push rods are withdrawn, the VMP remains in place. If direct push units cannot penetrate soils, more traditional (and expensive) drilling methods can be used to install these points (see Section 2.2.3). Discrete soil gas monitoring points are generally installed at various depths within various soil types to determine the uniformity of SVE treatment. VMPs are also installed in contaminated soils at varying distances from the vent wells (VWs) to determine the radius of venting influence. Permanent VMPs are used to measure long-term changes in vapor-phase contaminant concentrations, soil gas chemistry, and pressure/vacuum response through the soil profile and across the site (Section 2.2.5).

2.2.2 Continuous VOC and Permeability Logging

In the past, continuous VOC logging required the field screening of split-spoon soil cores (Section 2.2.3) and the laboratory analysis of selected samples. This method of continuous VOC logging is relatively slow and the integrity of VOC samples taken from open split spoons is always in question. Relative permeability was identified by analysis of soil cores for grain size and moisture content. Recently, technologies have been developed to continuously log VOC contamination and relative permeability in the subsurface using direct push tools or logging tools that can be used with traditional drilling techniques. These technologies provide either quantitative or qualitative results depending on the tool and sample analysis method. The availability of this "high resolution" data can provide important insights into the design of vent wells, subsurface airflow patterns, and the progress toward cleanup. AFCEE recently completed an evaluation of direct push and well logging tools and reported the results in "Final Results Report for Soil Vapor Extraction Optimization Tools" (AFCEE, 2001).

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Geoprobe's® membrane interface probes (MIPS) technology provides continuous logging from a Dipole Conductivity Probe (determines soil conductivity) and a MIP (determines volatile organic concentration) with respect to the probes depth. Figure 2.3 shows the configuration of the MIPS. The MIPS is driven into the ground at a rate of one foot per minute using a Geoprobe® push rod. While the probe is being driven, the dipole conductivity probe measures the soil conductivity (detectable range of 5 to 400 milliSiemen/meter [mS/m]). In general, these conductivity readings can be interpreted as sand (low conductivity) or silts and clays (high conductivity). However, factors such as soil moisture and cation/anion concentrations can also affect conductivity readings. Dipole conductivity probe results can be compared to actual soil types (from boring logs) to develop a correlation between soil conductivity and known lithology features.

The MIP consists of a heated section of stainless steel probe with a permeable membrane that enhances VOCs partitioning across the membrane surface. After partitioning across the membrane, the carrier gas transfers the VOCs to the detector at the surface. The MIP system can be used in the saturated zone to detect residual NAPLs that cannot be detected with standard soil gas techniques. The FID or PID detector readout is semi-quantitative and is useful for determining relative VOC concentrations in the sub-surface. The information provided by the conductivity probe and the MIP can be used to develop a vertical profile of soil type and contaminant concentration zones for each Geoprobe® push location. Figure 2.4 illustrates the results of a typical MIP profile compared to a known boring log. Note the increase in conductivity indicating a less permeable silty layer from 5 to 20 feet below ground surface (bgs). Note the increase in VOCs (PID and electron capture device [ECD] readings) detected at 15 to 22 feet, indicating that the silty sand layer at this interval is the primary source of residual VOCs in this soil column. This information is very useful for designing vent well screens and creating subsurface air flow that will result in minimum clean air dilution and maximum VOC recovery.

The SimulProbe®, produced by Best Environmental Subsurface Sampling Technology, Inc. (BESST), can be used to collect soil gas samples and permeability information

Figure 2.3

**MEMBRANE INTERFACE PROBE
SYSTEM DIAGRAM**

Gas Flow →

Gas Flow →
To Detector

Regulated
Carrier Gas
Supply

Carrier Gas
Return Tube

Carrier Gas
Supply Tube

Polymer
Membrane

Membrane
Contact Zone

Soil Conductivity
Measurement Tip
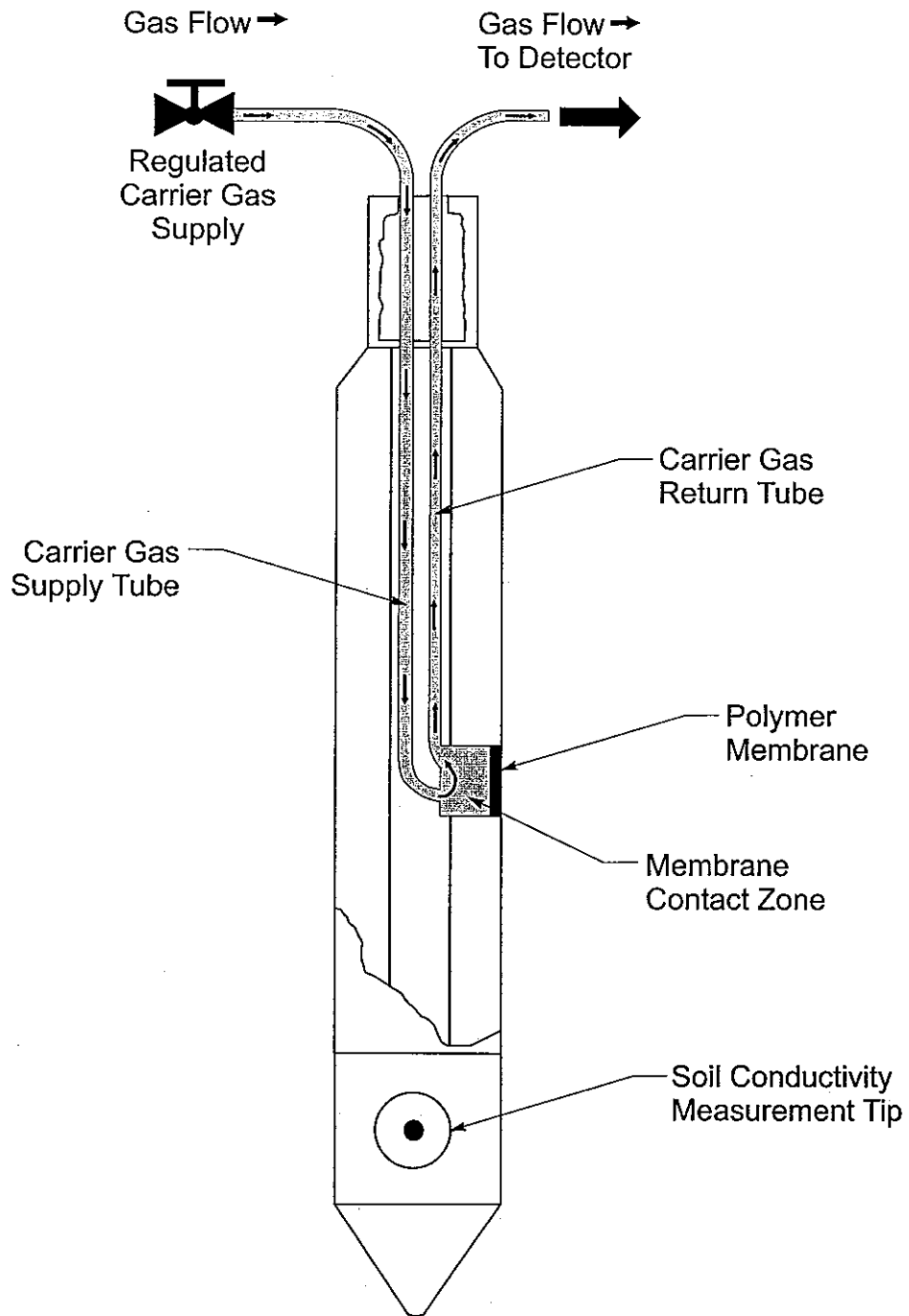
Figure 2.4

VERTICAL PROFILE OF VOCs AND SOIL CONDUCTIVITY PRODUCED BY MIPS
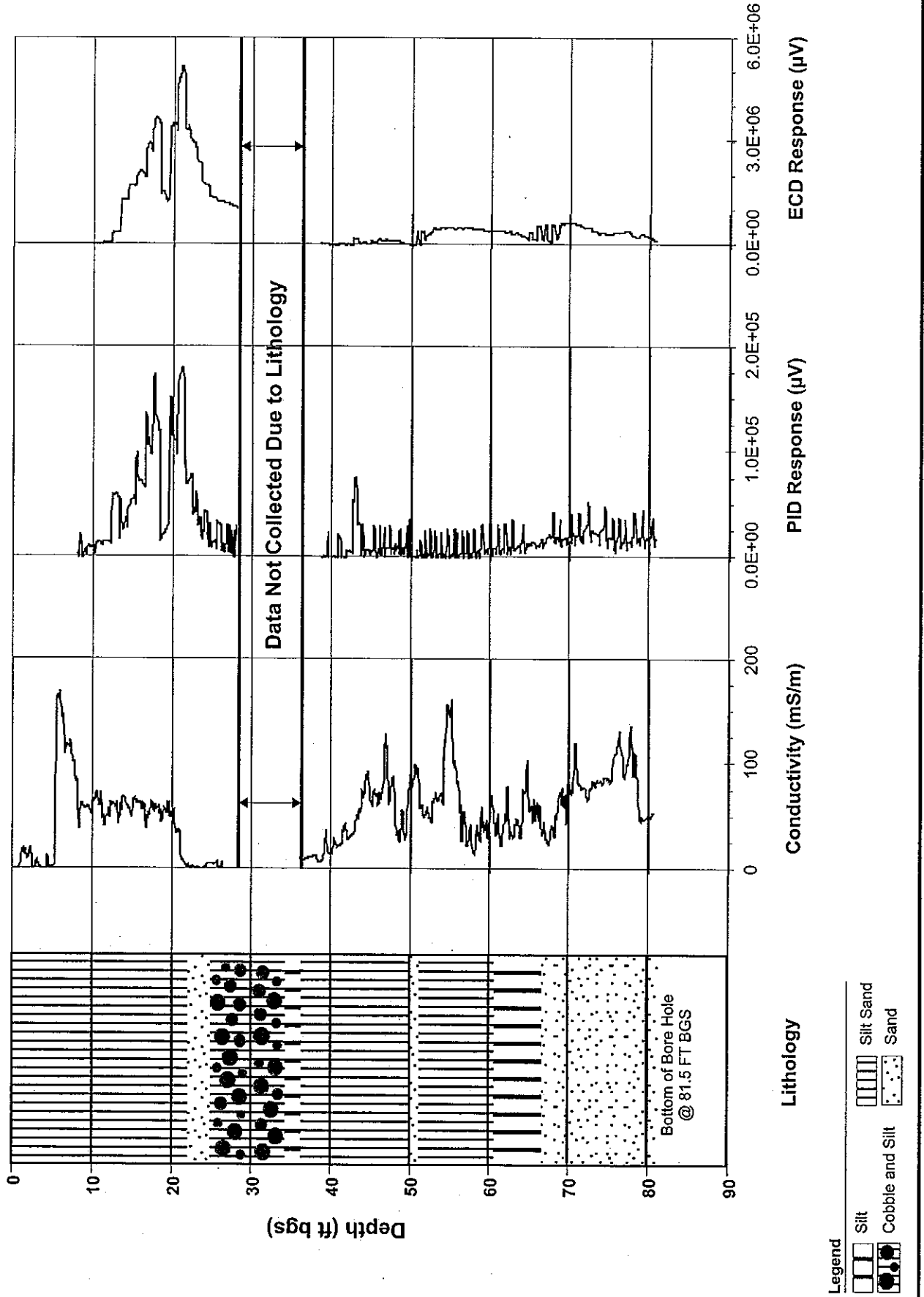
throughout the vertical soil profile with a CPT rig or traditional drilling methods. The SimulProbe® can be pushed to depth by the CPT rig or used like a traditional split spoon with a drill rig. The SimulProbe® can be pushed to depth, opened to expose the screen and then used convey soil gas to the surface through a drop tube (Figure 2.5). The sample is collected at the surface and can be analyzed in the field or at a laboratory for qualitative or quantitative results. The SimulProbe® can operate in three modes useful for site characterization. These modes are:

- Soil and Soil Gas Sampling - soil gas is transported to the surface for analysis and soil samples are collected from the same stratigraphic horizon.

- Continuous Soil Gas Sampling - device is driven continuously collecting soil gas samples at multiple intervals and transporting them to the surface for analysis.

- SPLAT (SimulProbe® Latch Activated Tip) - device is driven continually collecting multiple soil gas samples and transporting them to the surface. A single soil sample can be collected by unlatching the tip after which the device must be retrieved.

In addition, permeability can be calculated by closely monitoring the pressure response at the start of a soil gas extraction purge cycle with data logging pressure transducers (Johnson, 1990). The SimulProbe® can operate in conjunction with a CPT rig or conventional drilling techniques making it more applicable for sites with deep contamination or difficult soil stratigraphy.

2.2.3 Conventional Drilling Methods

Site characterization using conventional drilling methods has traditionally involved driving a split spoon prior to a casing or auger. Soil samples are retrieved from intervals in front of the casing/auger and field screened at the surface (frequency of sampling varies by site). At the surface, the samples are logged for lithologic features and screened for VOCs. Based on the results of the field screening, samples are collected for laboratory analysis, analyzed for potential contaminants, grain size, and moisture content.

2-10

Figure 2.5
SimulProbe® SCHEMATIC FOR
CASED BORE HOLE SOIL GAS SAMPLING

Vacuum Gauge

Flow Meter

Vacuum Pump

Gas Collection Tube

Rods

Hollow Stem Auger
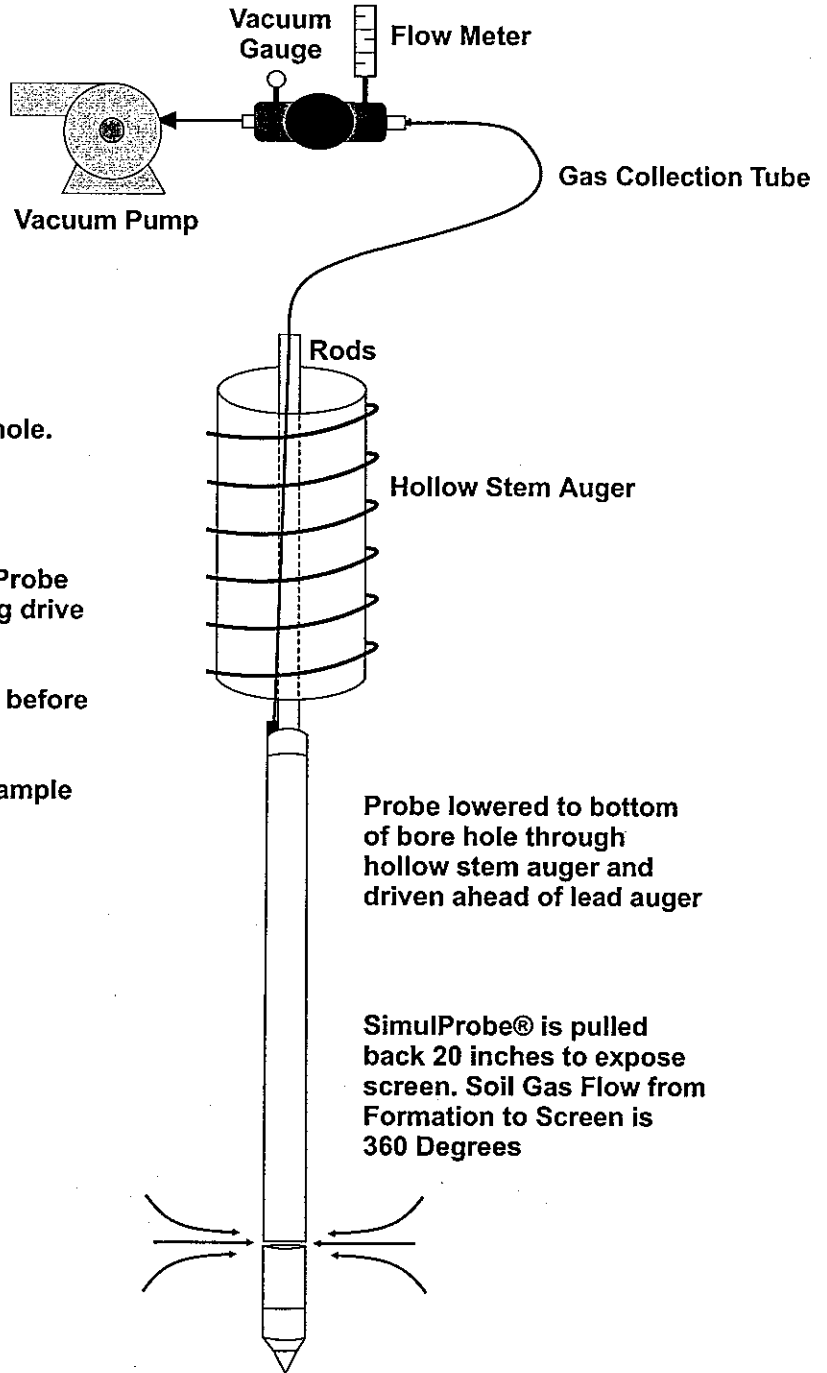
- SimulProbe® lowered inside of bore hole.

- Use down-hole wire line hammer or up-hole hammer rods.

- When drive distance is reached, pull Probe back one to two inches to open sliding drive shoe - to expose screened entry port.

- Turn on vacuum pump and purge line before sampling.

- After line is purged, collect soil gas sample or field screen.

Probe lowered to bottom of bore hole through hollow stem auger and driven ahead of lead auger

SimulProbe® is pulled back 20 inches to expose screen. Soil Gas Flow from Formation to Screen is 360 Degrees

Although the costs of conventional drilling are substantially higher then direct push methods, these rigs can go deeper and overcome adverse soil conditions, including cobbles and bedrock. Conventional drill rigs can quickly install nested VMPs and 2 to 4-inch diameter VWs during the same mobilization.

2.2.4 Permanent Nested Vapor Monitoring Points

Nested VMPs that are screened at various discrete depths have traditionally been installed with conventional drill rigs and used to measure vertical variations of vapor-phase contaminant concentrations and pressure/vacuum response (and indirectly, permeability) along the soil profile. Nested VMPs are constructed by installing several, relatively short-screened intervals (vapor probes), separated by bentonite seals, within a single borehole. Figure 2.6 shows a typical construction detail for a nested VMP. Soil vapor chemistry is determined at each depth by withdrawing and analyzing soil vapor samples collected from each interval. Relative soil permeability is indirectly indicated by the vacuum required to extract soil vapor from each VMP at each depth interval. Higher vacuum response indicates depth zones with relatively low permeability to airflow. Relative permeability can be estimated by closely monitoring changes in soil gas chemistry and the vacuum response at the start of soil gas extraction (Johnson, 1990). The primary advantage of using VMPs is that they can be installed as permanent protected points that are available for assessing soil vapor chemistry and long-term remediation progress.

2.2.6 Vent Well Profiling

The profiling of pilot test vent wells or existing vent wells can provide valuable information for vent well design or redesign to optimize full-scale SVE operations, and to verify closure criteria. Vent well vertical profiling information can now be provided using PneuLog®, a technology developed by Praxis Environmental Technologies, Inc. (Praxis).

PneuLog® technology (Praxis, 1999a) can be used during pilot testing at any site, but the greatest benefit will come from sites with at least 15 feet of contaminated interval and

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FIGURE 2.6 - VAPOR MONITORING POINT TYPICAL CONSTRUCTION DETAIL

FLUSH—MOUNT WELL HEAD PROTECTOR

CONCRETE COLLAR

1/4" BALL VALVE WITH 3/16" HOSE BARB

METAL TAG LABLED WITH VAPOR PROBE DEPTH

SILICA SAND

HYDRATED BENTONITE OR GROUT 2' MIN THICKNESS

BOREHOLE

SAND PACK 2' THICKNESS TYPICAL

1/4" DIA. SCH 80 PVC CASING
OR
3/8" DIA. POLYETHYLENE TUBING

1" DIA. x 6" LONG PVC SCREEN, 0.02" SLOT
OR
3/8" DIA. x 6" LONG STAINLESS STEEL SCREEN

UNDISTURBED SOIL

VARIABLE
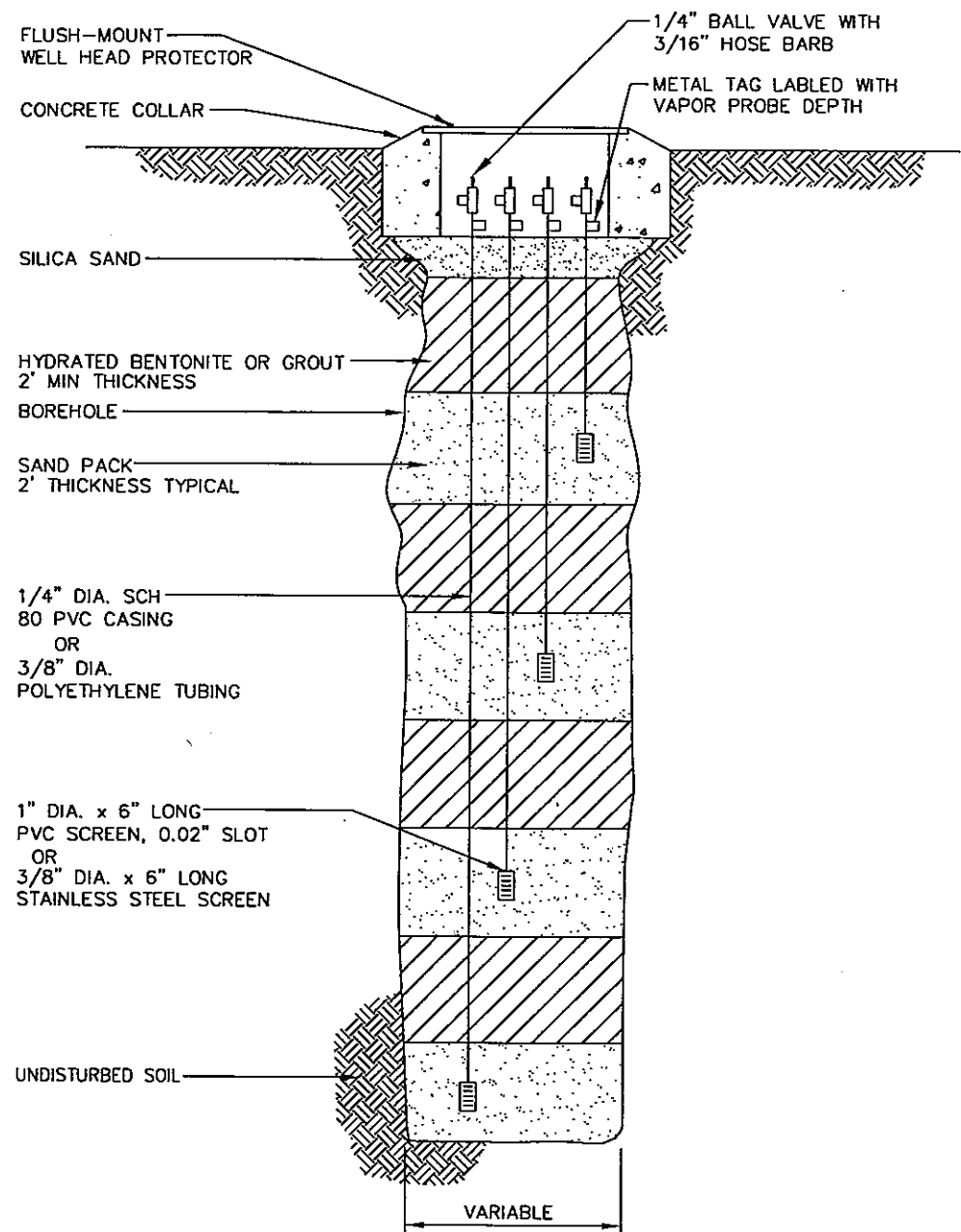
NOTE: NUMBER AND DEPTHS OF VAPOR MONITORING PROBES WITHIN EACH VAPOR MONITORING POINT WILL VARY BY SITE.

layers of varying soil permeability. Pilot vent wells should be constructed with long screens that extend through the entire contaminated interval. At existing SVE sites, PneuLog® will be most useful for analyzing VWs with screened intervals of 10 feet or more.

PneuLog® provides a continuous log of VOC concentrations and flow entering the VW. PneuLog® data can be collected with the SVE system operating or at the end of equilibration tests. Figure 2.7 is a diagram of the PneuLog® system. The flow sensor and vapor sampler are raised and lowered within the well using an automated cable real while a vacuum is being applied to the well. As the flow sensor moves through the well, changes in flow can be attributed to specific soil intervals. The vapor sampler collects vapors from just above the flow sensor. A Teflon sampling tube conveys a continuous vapor sample to the surface were it is analyzed using a (PID. A mass balance is used to determine the VOC production for each vertical interval within the well by analyzing the change in flow and the change in contaminant concentration.

AFCEE has recently tested and used the PneuLog® technology at ten sites to develop detailed lithologic and contaminant cross-sections. Figure 2.8 illustrates a vertical profile of VOC concentrations and flow entering three screens installed in a nested vent well. These profiles are particularly useful for identifying productive and unproductive flow intervals in the subsurface and for designing or redesigning vent wells to maximize VOC removal while minimizing unwanted dilution air. Praxis has also developed numerical models to assist site managers in interpreting equilibrium/rebound test data and for predicting the timeframe required to remediate diffusion-limited zones. The use of PneuLog® to optimize existing systems is also discussed in Section 5.

2.3 UPDATING THE CONCEPTUAL SITE MODEL

An accurate conceptual site model (CSM) is critical to evaluating and optimizing SVE systems and evaluating the degree of treatment (risk reduction) required. A complete CSM should include a visual representation of contaminant source and release information, site geology and hydrology, contaminant distribution, fate and transport parameters, and risk assessment features such as current and future land use and potential

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Figure 2.7

PneuLog™ SCHEMATIC

Cable Alignment Assembly

Data Acquisition System and Real-Time View of Data

Cable Real

Vacuum on Wellhead Applied by Blower

Vacuum Pump

PID

Existing SVE Well

Existing SVE Well

Undisturbed Soil

Tube for Vapor Sample Transfer

Soil Vapor Velocity Sensor

Sand Pack

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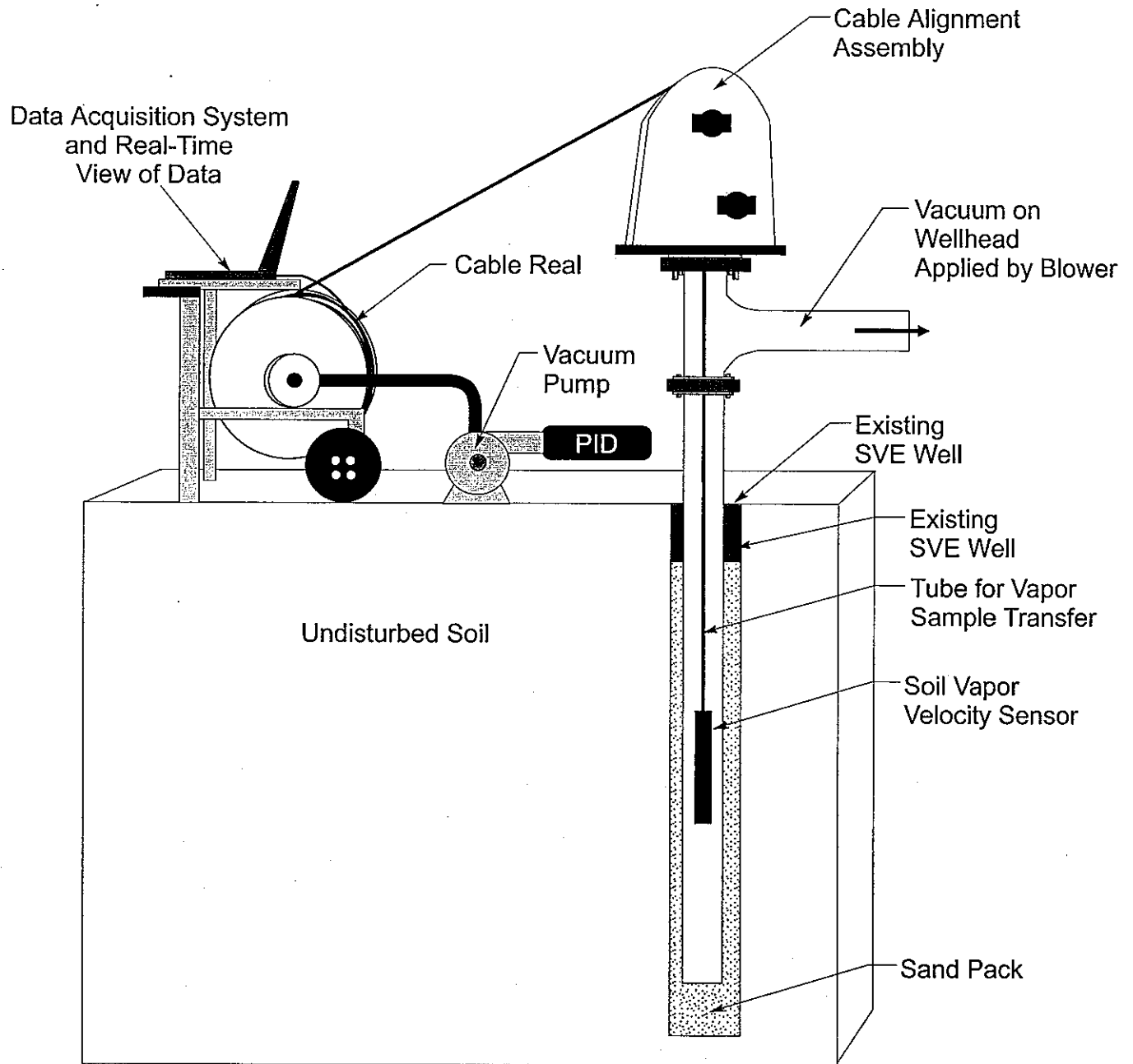
Figure 2.8

PneuLog® VERTICAL PROFILE OF VENT WELL VOC AND PERMEABILITY ZONES
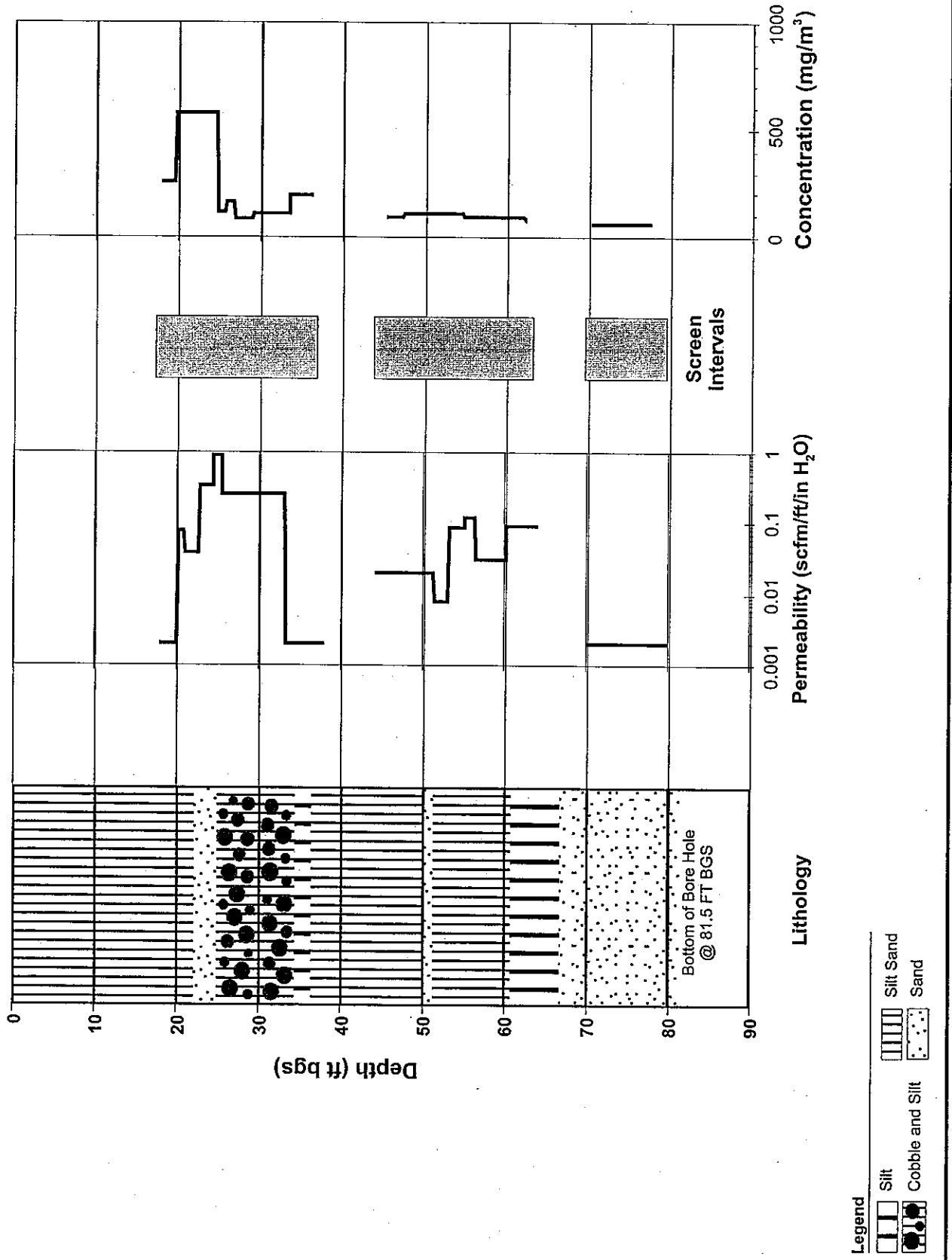
exposure pathways and receptors. The CSM serves as the foundation for evaluating the restoration potential of the site and the effectiveness of operating remediation systems. A detailed CSM is also required to make informed decisions regarding SVE performance criteria and evaluating the system effectiveness. AFCEE recommends that every site manager prepare a visual CSM for each site they are responsible for. Figure 2.9 illustrates an outline of a typical CSM for a chlorinated-solvent-contaminated site.

The CSM will generally be developed as a part of the site investigation or feasibility study phase of site remediation. Many SVE systems have been installed and are operating without a well-defined CSM. Other SVE systems were designed based on an initial CSM that requires updating based on recent operations and monitoring data. Changes in land use, or changes in the enforcement of institutional controls, can also alter the exposure and risk assumptions of the CSM. The CSM is intended to be a dynamic representation of site conditions based on a continual influx of information from the site. This section provides an overview of the key elements of a CSM, with emphasis on SVE optimization.

2.3.1 Source and Release Information

The CSM should include a description of the source of contamination and what is known about the timing and quantity of the release. Most site characterizations begin by locating areas where contamination was released to the subsurface. In many cases, the distinct source of contamination is known to be a former underground storage tank (UST), disposal pit, fire training area, etc. However, many industrial source areas are dispersed and difficult to find. For example, oil/water separators, and sanitary and storm sewers have historically received chlorinated solvents from aircraft and other maintenance shops. At these sites, it is often impossible to install an effective SVE system because the source of contamination cannot be determined. Soil gas surveys can be used to locate these dispersed source areas at sites with sandy, permeable soils. However, at sites with low permeability soils, locating dispersed sources will often require excavation and removal of contaminated soils along underground utilities.

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FIGURE 2.9
ELEMENTS OF A CONCEPTUAL SITE MODEL (CSM)

Background Information

- Location of water supply wells.
- Ground-water classification.
- Nearby wellhead protection areas or sole-source aquifers.
- Locations of potential receptors exposure points.
- Hazardous soil vapor impacts.

Contaminant Source and Release Information

- Location, nature, and history of previous contaminant releases or sources.
- Locations and characterizations of continuing releases or sources.
- Locations of subsurface sources (e.g., NAPLs).
- Flux of contamination from NAPL.

Risk Assessment

- Current and future receptors.
- Exposure scenario's.
- Completed pathways?
- Exposure concentrations.

Geologic and Hydrologic Information

- Description of regional and site geology.
- Physical properties of subsurface materials (e.g., moisture porosity, bulk density).
- Stratigraphy, including thickness, lateral extent, continuity of units, and presence of depositional features, such as channel deposits, that may provide preferential pathways for, or barriers to, contaminant transport.
- Geologic structures that may form preferential pathways for NAPL migration or zones of accumulation.
- Depth to ground water.
- Hydraulic gradients (horizontal and vertical).
- Hydraulic properties of subsurface materials (e.g., hydraulic conductivity, storage coefficient, effective porosity) and their directional variability (anisotropy).
- Spatial distribution of soil or bedrock physical/hydraulic properties (degree of heterogeneity).
- Groundwater/surface water interactions.
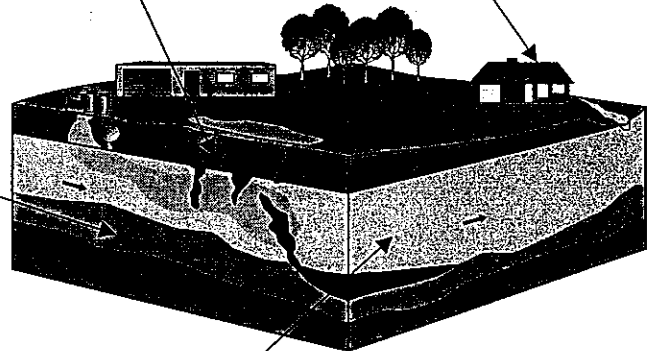
Contaminant Distribution, Transport, and Fate Parameters

- Properties of NAPLs that affect transport (e.g., composition, effective constituent solubilities, density, viscosity).
- Phase distribution of each contaminant (gaseous, aqueous, sorbed, free-phase NAPL or residual NAPL) in the unsaturated and saturated zones.
- Spatial distribution of subsurface contaminants in each phase in the unsaturated and saturated zones.
- Estimates of subsurface contaminant mass.
- Temporal trends in contaminant concentrations in each phase.
- Partitioning coefficients and migration rates.
- Contaminant natural attenuation processes (destructive and non-destructive).
- Geochemical Indicators (aerobic/anaerobic).

Source: Adapted from EPA, 1993.

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The timing and the amount of contaminant released are difficult to estimate. Historical records on chemical use are difficult to obtain, and if they exist are generally found in Phase I Installation Restoration Program documents developed in the early 1980's. TCE was used by the Air Force for approximately 40 years before it was phased out in the early 1980s. TCE has not been widely used at Air Force facilities for nearly 20 years. This fact is important when evaluating the fate and transport of chlorinated solvents.

2.3.2 Geologic Characterization

The CSM should include a complete description of the site geology. At a minimum, the CSM for an SVE site should include:

- A general description of site geology including major soil strata that are impacted by or influence the migration of contaminants. Strata thickness, lateral extent, continuity and depositional features should be described.

- Physical and chemical properties of subsurface materials such as sieve analysis, bulk density, moisture, air porosity, and total organic carbon.

- Geologic or manmade features which may provide preferential migration of dense non-aqueous phase liquids (DNAPLs), solvent vapors, or dissolved contaminants.

- Depth to groundwater, seasonal variations, recharge and discharge information including interactions with surface waters.

The CSM should be updated to reflect current estimates of these properties based on site remediation experience. For example, the air permeability and radius of vapor extraction can be more accurately estimated after a SVE system has operated for several months. Changes in vapor concentrations may not occur during short-term pilot testing, but will become very apparent after a few months of SVE operation.

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2.3.3 Contaminant Distribution, Transport and Fate

In addition to describing the source of contamination, the CSM should include a summary of the chemical, physical, and biodegradation properties of key contaminants of concern and describe their distribution, movement, and fate in the subsurface environment. Existing vent wells and vapor monitoring points can provide valuable insights into the movement and persistence of VOCs in various soil layers. If data gaps remain, such as an understanding of where contaminants remain in the subsurface, this data should be collected using the advanced characterization tools described in Section 2.2. At a minimum, the CSM should include:

- Chemical and physical properties of chlorinated compounds that impact subsurface transport (e.g., partitioning coefficients, solubility, vapor pressure, Henry's Constant, density, viscosity)

- An estimate of the phase distribution of each contaminant (free-phase DNAPL, sorbed, in soil vapor, or dissolved) in the saturated and unsaturated zone.

- A fate and transport model that describes how soil contaminants enter groundwater and how SVE is intended to reduce leaching to groundwater (if appropriate).

- A description of what areas of the site or soil layers are most likely to create diffusion-limited VOC removal constraints which will slow the site cleanup. Equilibrium testing described in Section 5 can provide insights into where diffusion limited removal is occurring.

- Evidence of contaminant natural attenuation processes (primarily biological destruction).

2.3.4 Risk Assessment Site Model

Although the complexity of risk assessment will vary from one site to another and one regulatory environment to another, there are several common elements that should be included in every CSM:

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- An analysis of potential receptors (current and future) that could be impacted by contamination.

- An analysis of potential exposure pathways that could allow contaminants to impact receptors.

- A determination of what level of contaminant exposure will present an unacceptable risk to impacted receptors (risk-based cleanup goals).

- Measurement of contaminant concentrations at potential exposure points or estimation of exposure point concentrations using fate and transport models. These exposure concentrations are then compared to risk-based cleanup goals.

The reader is referred to other documents that have been developed to describe the risk assessment process and how to develop risk-based cleanup goals for fuel and chlorinated solvent sites (REF). The goal of site remediation is generally to find the most cost-effective method of reducing present and future risk by combining three risk reduction techniques:

- **Chemical Source Reduction** - Achieved by engineered removals such as excavation and soil vapor extraction.

- **Chemical Pathway Elimination** - Examples include the vapor collection systems installed around buildings, natural attenuation of a groundwater plume, or pumping to stop the migration of contaminants toward downgradient receptors.

- **Restrict/Protect Receptors** - Land use controls such as site fencing, surface capping, digging restrictions, protective clothing, and groundwater well restrictions can eliminate chemical exposure until SVE can reduce the chemical source.

2.3.5 SVE for Protection of Workers

On most Air Force installations, the greatest potential for exposure to contaminated soil and groundwater will occur during new building construction or utility repairs or replacement. Soil vapor extraction provides a useful method of reducing the risk from the

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most common Air Force soil contaminants, such as benzene and TCE. Application of SVE near inhabited buildings and utility corridors can provide for the positive control and collection of hazardous vapors. It is also important for supervisors of utility shops and base construction planners be informed of the known areas of contamination so that any excavation in these areas can be completed with careful air monitoring and proper protective clothing.

2.3.6 Institutional Controls for Realignment and Closure Bases

On installations that are scheduled for closure or realignment, the question of future land use becomes more critical. The future land use may differ from the current land use. In such situations the most conservative expected land use should be used to complete the site model. *Industrial or commercial land use should be assumed unless residential land use is specifically included in a future land use plan.*

While most flightline areas on closure bases will remain in industrial/commercial land use, formal deed or lease restrictions must be in place to ensure that the new landowner (private or public) understands the extent of remaining contamination and the need to restrict certain future activities or land uses. In general, Air Force Base Realignment and Closure (BRAC) officials should seek risk-based closures of contaminated sites that make maximum use of deed or lease restrictions to minimize the potential for future human exposure to contaminants. The BRAC Environmental Program Fact Sheet (Department of Defense [DoD] Policy on Institutional Controls) provides an overview of institutional controls and how they can be applied during BRAC land transfers. This guidance is available on the DoD BRAC Environmental Homepage at http://www.dtic.mil/envIrodod/envbrac. mil.

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SECTION 3

UNDERSTANDING SITE CLOSURE CRITERIA

3.1 REVIEW OF REMEDIATION GOALS

A clear understanding of the goals and objectives of a remediation project is an essential first step in the SVE optimization process. Remediation projects often lose continuity due to staff turnover in Air Force and regulatory agencies and changes in operating contractors. Because it is impossible to judge the success or failure of a remediation project without clearly defined goals, the SVE optimization process must clearly identify these goals.

An understanding of the original remediation goal by the site manager and the operation and maintenance (O&M) contractor is required to evaluate the merit of these goals in light of changing conceptual site model (CSM) and new regulatory approaches. An understanding of site cleanup goals is essential for SVE performance monitoring and system optimization. Before initiating systems optimization, the site manager should carefully review the key decision documents for the site. These could include remedial investigation/feasibility study (RI/FS) reports, risk assessment summaries, remedial action plans, record of decisions (RODs), Resource Conservation and Recovery Act (RCRA) corrective action program records, and correspondence between the regulatory community and the Air Force.

Regulatory Participation - Site remediation goals are closely tied to the regulatory framework under which site remediation is being implemented. A good working relationship with local regulators will be an important component of a successful SVE project. If significant changes to remediation goals or the remedial approach are needed, a technical expert from the responsible regulatory agency should be consulted along with Air Force experts.

3.1.1 Cleanup Goals Based on Groundwater Protection

The most common and conservative soil remediation criteria are generally based on the protection of groundwater. These criteria are based on the assumption that soil contaminants will eventually leach into groundwater or surface water and degrade water quality. The goal of groundwater protection is generally to prevent an aquifer from being contaminated above drinking water maximum contaminant levels (MCLs). Although many EPA regions and states have adopted groundwater protective cleanup goals for soils, these goals are overly conservative if they "protect" unproductive shallow aquifers or aquifers which are not considered drinking water resources. A less stringent risk-based standard may be more appropriate for shallow aquifers that are not used for drinking water.

The EPA has developed a standard approach for determining soil remediation criteria based on protection of groundwater. The approach is described in the Soil Screening Guidance: Technical Background Document (EPA, 1996) and provides default cleanup criteria for soil. These default criteria are based on extensive modeling and verification using EPA's soil and groundwater database from over 300 sites across the United States.

The soil type, depth to groundwater, and size of site are all site-specific factors influencing soil cleanup criteria. Table 3.1 - Scenario 3 lists conservative soil-to-groundwater screening levels for several common Air Force contaminants assuming residential use of groundwater. For the most conservative residential exposure scenario, groundwater is used both for drinking and showering. Under this exposure scenario, the soil cleanup goal for TCE would be 0.060 milligrams per kilogram (mg/kg).

3.1.2 Cleanup Goals Based on Commercial/Industrial Site-Specific Risks

Soil cleanup goals can also be based on the protection of excavation workers who come into direct contact with contaminated soils, shallow groundwater and soil vapors. These risk-based goals are also known as site-specific target limits (SSTLs) and are generally calculated by risk assessment specialists using conservative exposure scenarios for the site. Table 3.1 - Scenario 1 provides SSTLs assuming that a non-intrusive

TABLE 3.1
EXAMPLE SCREENING LEVELS FOR CHLORINATED SOLVENTS

Chemical	Scenario 1 Nonintrusive Site Worker Soil: ingestion, dermal, inhalation Groundwater: inhalation Exposure: 250 day/year; 25 year			Scenario 2 Intrusive Site Worker Soil: ingestion, dermal, inhalation Groundwater: inhalation and dermal Exposure: 60 day/year; 1 year			Scenario 3 Resident Soil: ingestion, dermal, inhalation Groundwater: ingestion and inhalation Exposure: 350 day/year; 30 year		
	USEPA R9[a] Soil (mg/kg)[b]	Soil-to-Groundwater (mg/kg)	Groundwater (µg/L)[c]	Soil (mg/kg)	Soil-to-Groundwater (mg/kg)	Groundwater (µg/L)	USEPA R9 Soil (mg/kg)	USEPA R9 (20 DAF)[d] Soil-to-Groundwater (mg/kg)	USEPA R9 Tap Water (µg/L)
1,1,1-Trichloroethane (N)	1.40E+03	8.05E+05	8.36E+07	2.88E+04	2.47E+03	2.57E+05	7.70E+02	2.00E+00	7.90E+02
1,1-Dichloroethene (C)	1.20E-01	2.32E+01	2.83E+03	3.46E+01	1.03E+01	1.26E+03	5.40E-02	6.00E-02	4.60E-02
1,2-Dichloroethene (C)	7.60E-01	1.98E+02	4.15E+04	2.10E+02	1.22E+02	2.55E+04	3.50E-01	2.00E-02	1.20E-01
1,2-Dichloroethene, total (N)	1.50E+02	2.79E+04	4.58E+06	1.34E+03	1.08E+03	1.78E+05	4.30E+01	4.00E-01	6.10E+01
Carbon tetrachloride (C)	5.30E-01	1.25E+02	9.53E+03	1.34E+02	2.50E+01	1.90E+03	2.40E-01	7.00E-02	1.70E-01
Tetrachloroethene (C)	1.90E+01	4.84E+03	4.19E+05	2.21E+03	2.52E+01	2.18E+03	5.70E+00	6.00E-02	1.10E+00
Trichloroethene (C)	6.10E+00	2.30E+03	2.01E+05	1.24E+03	6.03E+02	5.27E+04	2.80E+00	6.00E-02	1.60E+00
Vinyl chloride (C)	4.90E-02	1.04E+01	1.56E+03	1.43E+01	7.63E+00	1.15E+03	2.20E-02	1.00E-02	2.00E-02

[a] R9 = USEPA Region 9
[b] mg/kg = milligrams per kilogram
[c] µg/L = micrograms per liter
[d] DAF = Dilution Attenuation Factor

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maintenance worker (such as a landscape technician) spends 250 days a year and 25 years working over a contaminated site. Using these site-specific exposure assumptions, the TCE cleanup goal for Scenario 1 is 6.1 mg/kg. Scenario 2 describes an excavation worker who has a one-time exposure to soils and dermal contact with shallow groundwater for 60 days. The short-term excavation worker scenario requires a TCE cleanup goal of approximately 60 mg/kg. Based on this example, an additional 2 to 3 order-of-magnitude reduction in TCE is required if soil contamination represents a valid threat to drinking water. Unfortunately, many Air Force bases with shallow, unproductive, or non-potable aquifers have agreed to these unnecessary soil-to-groundwater cleanup goals for their SVE systems. For existing SVE sites, where groundwater is clearly not impacted, or the aquifer is not of drinking water quality, AFCEE encourages site managers to review the basis of SVE cleanup goals and to work with local regulatory officials to establish goals based on realistic site-specific risks.

3.1.3 DEVELOPING A CLOSURE STRATEGY

The purpose of a site closure strategy is to layout a logical sequence of monitoring events and performance criteria that will result in the required risk reduction and eventual shutdown of the SVE system. Figure 3.1 illustrates a typical site closure process for SVE systems. Many Air Force SVE systems have been installed and are operating without a coordinated closure strategy. Site managers are encouraged to use the information in this document to develop a draft site closure strategy and to contact regulatory officials and begin a dialogue on this important subject.

A site closure strategy begins with a written agreement with regulatory agencies stating the final soil concentration desired for each contaminant of concern. Once numeric cleanup goals have been established, the site closure strategy should define **how** the SVE system will be monitored to determine progress toward cleanup goals (performance monitoring discussed in Section 4), and **how** the soil will ultimately be sampled to verify compliance with numeric cleanup goals (Section 6). Whenever possible, these details should be discussed with regulatory agencies during the design

Figure 3.1
SVE SITE CLOSURE PROCESS

Define Cleanup Goals and Site
Closure / Sampling Procedures
in Remediation Decision Document

↓

Collect Performance Data to Track
Cleanup Progress Including Annual
Equilibrium / Rebound Testing

↓

Do Equilibrium Soil Gas Levels Exceed Target Soil Gas Cleanup Levels ?

No → Use Soil Gas Data or Actual Soil Samples to Demonstrate Cleanup Has Been Achieved

Yes ↓

Use Advanced Characterization
and/or System Optimization
Methods to Identify and Improve
Remediation of Remaining VOCs

↓

Has System Optimization Improved VOC Removal ?

Yes (loops back to Collect Performance Data)

No → Continue to Operate System While Seeking Alternate Cleanup Goals or Technical Infeasibility Assessment

phase of the SVE project so that vapor monitoring points and pre-venting (baseline) sampling can be coordinated with vent well installations.

As shown on Figure 3.1, the primary indicator of remediation progress for SVE systems are equilibrium soil gas levels collected during equilibrium/rebound tests. These tests are extremely useful in measuring remediation progress and for identifying areas of the site requiring additional characterization and optimized treatment.

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SECTION 4

SYSTEM PERFORMANCE MONITORING

The performance of SVE systems can be monitored using a variety of direct and indirect measurements of subsurface contaminant removal. The most direct method, soil sampling and analysis, is generally too expensive to be used for intermediate measurements and is reserved for a final determination of suitability for site closure (See Section 6). Fortunately, there are several less intrusive and expensive methods for determining SVE remediation progress. This section discusses several common methods for SVE performance evaluation including: the rate and composition of extracted soil gas, changes in soil gas chemistry indicating treatment influence, equilibrium/rebound testing of soil gas VOCs, and in situ respiration testing to account for biodegradation of petroleum hydrocarbons. Finally, this section will briefly discuss performance monitoring for aboveground vapor treatment systems. More general process monitoring such as condensate control, blower and filter performance indicators, and vapor emission testing are not covered in this document but should be covered in O&M manuals for the system.

Table 4.1 defines a minimum level of performance monitoring that is recommended for proper operation of SVE systems and is necessary to evaluate optimization opportunities. Additional information on SVE performance monitoring can be found in the Air Force Remedial Process Optimization Handbook (AFCEE, 1999), and the US Army Corps of Engineers publication " Engineering and Design Soil Vapor Extraction and Bioventing" (USACOE, 1995) available on the web at: www.environmental.usace. army.mil/library/guide/reschk/rsechk.html.

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TABLE 4.1
SVE PERFORMANCE MONITORING REQUIREMENTS

Measurement	Recommended Method	Frequency
Total Extracted Flow Rate	Flow Meter or Blower Curve	Monthly
Extracted VOC Concentrations	Collect Vapor Sample for Lab	Monthly
System Effluent VOC Concentrations	Collect Vapor Sample for Lab	Monthly
Flow Rates From Each VW	Thermal Anemometer	Semi-annual
VOC Concentrations Each VW	Handheld Gas Analyzers	Semi-annual
Vacuum at Each VW	Vacuum Gauge	Semi-annual
$TVH/O_2/CO_2$ At VMPs	Handheld Gas Analyzers	Semi-annual
Equilibrium/Rebound Test Using VWs/VMPs	Handheld VOC Analyzer Collect Final Sample for Lab Analysis	Annual
Respiration Testing at VMPs*	Handheld O_2/CO_2 Analyzer	Annual

*Recommended for sites with petroleum hydrocarbons and mixtures of chlorinated and non-chlorinated hydrocarbons.

4.1 FLOW AND COMPOSITION OF EXTRACTED SOIL GAS

The most common method of assessing SVE performance has been to monitor the flow and VOC concentrations in extracted soil gas. By collecting flow and extracted concentration data over time, several conclusions can be drawn concerning the success of mass removal and general performance of an SVE system. Most SVE systems have three phases of performance: the initial pore volume removal characterized by relatively high VOC levels, the evaporation phase characterized by removal of NAPL from more permeable soil volumes, and the diffusion-limited phase characterized by low recovered concentrations as VOCs slowly diffuse from low-permeability soils (AAEE, 1994). Figure 4.1 shows concentration vs. time data for two sites with different SVE performance profiles. Site A illustrates VOC removal from a site where the vast majority of the NAPL is present in high permeability soils. Site B illustrates a site where low

Figure 4.1
VOC REMOVAL vs TIME PLOTS

Site A

(Chart: VOC Concentration (ppmv) vs Days. Phases labeled: Initial Pore Volume Removal, Evaporation Phase)

Site B

(Chart: VOC Concentration (ppmv) vs Days. Phase labeled: Diffusion Limited Removal)
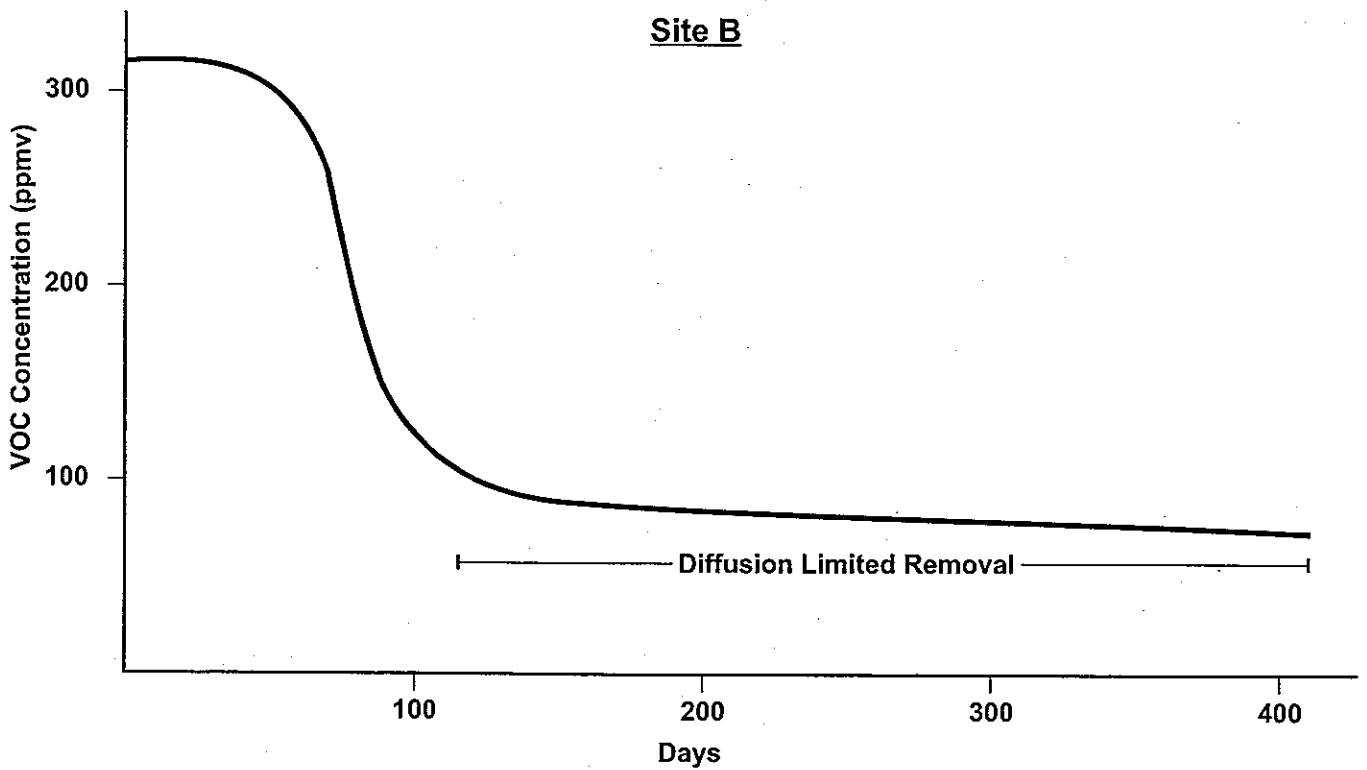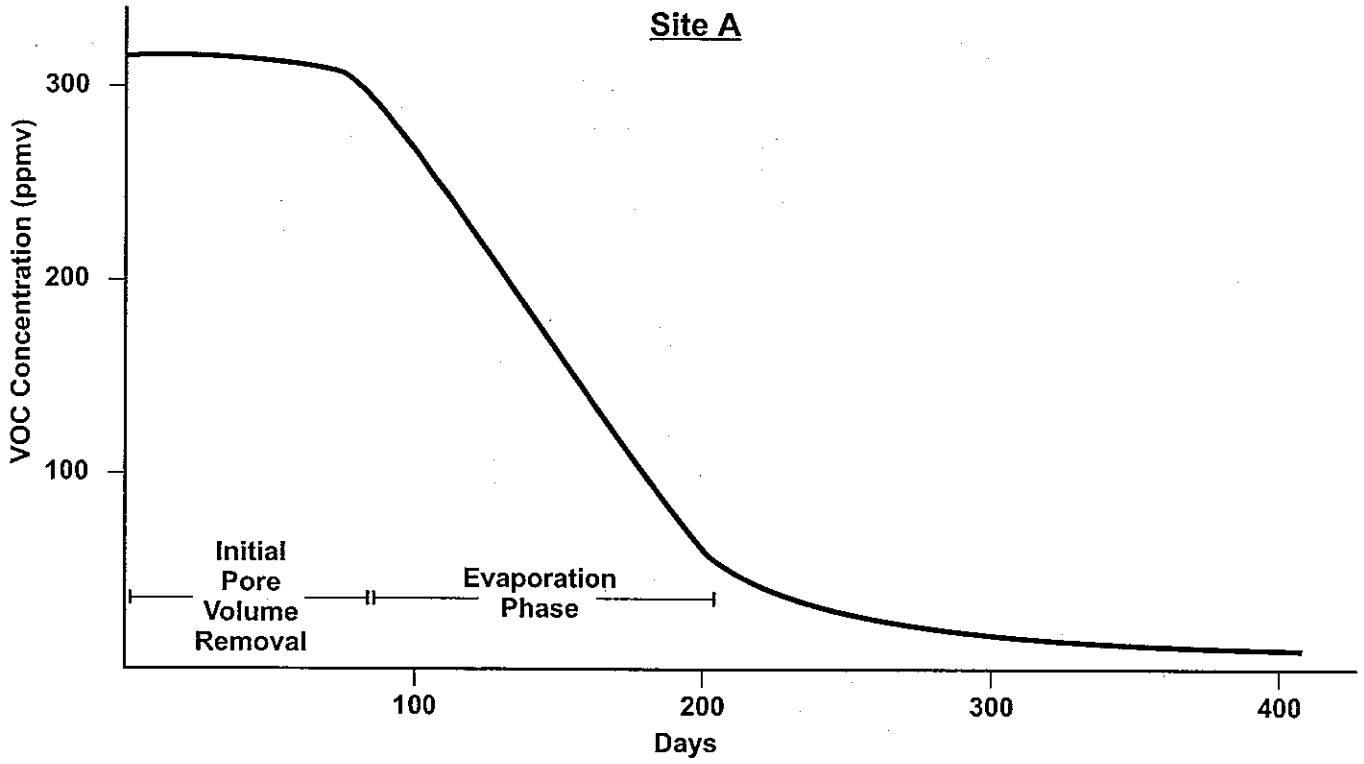
permeability layers are creating slow, diffusion-limited removal. When concentration vs. time data is combined with soil gas chemistry data and equilibrium/rebound testing from specific VMPs and VWs, the unremediated (diffusion-limited) soil volume can often be distinguished from the remediated areas of a site. Sections 4.2 and 4.3 provide additional information on these techniques. Figure 4.2 provides a simple logic diagram for optimizing extraction rates and monitoring the performance of individual vent wells. This procedure will assist site managers in reducing overall flow rates to better match diffusion limited VOC removal which occurs on most sites.

Overall, mass removal is generally calculated by multiplying average monthly flow rate times the average monthly total VOC concentration. Flow rates can be measured by pitot tubes, orifice plates, or by referring to the manufacturer's blower curve for a given pressure across the blower. VOC concentrations can be estimated using handheld gas analyzers such as a FID, PID, or an ECD. For non-chlorinated hydrocarbons, the FID is preferred. For chlorinated hydrocarbons the PID or ECD is preferred. In addition to total VOC concentrations, indicator compounds are frequently selected to monitor system performance. The selected indicator compound is generally the compound that is expected to take the longest time to achieve its respective cleanup goal. A laboratory analysis of extracted gas is required for determining concentrations of individual indicator compounds such as benzene or TCE.

4.2 RADIUS OF TREATMENT INFLUENCE BASED ON VACUUM AND SOIL GAS CHEMISTRY

Determining the volume of the subsurface that is being treated by an SVE system can be difficult. The most common method of estimating treatment influence has been to measure the induced vacuum created in soils surrounding an extraction well. The vacuum influence is measured at a number of discrete VMPs located at varying distances and in varying soil types (layers). Vacuums are measured with the SVE system off and then the system is turned on and vacuum increases are measured in VMPs overtime until steady state is achieved. This method can provide good approximations of the radius of vapor capture. Analytical and numerical flow models such as Hyperventilate™ and

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Figure 4.2
VENT WELL FLOW OPTIMIZATION LOGIC DIAGRAM

Measure extracted VOC's and flow rate from each VW on the site

For each VW, has the extracted VOC concentration decreased by less than 10 percent in the past 6 months?

No → Continue to operate this VW at current extraction rate

Yes

Reduce extraction flow by 50% at this VW and operate for 6 months

Are VOC concentrations at the VW and nearby VMPs stable or decreasing?

Yes → Continue to operate at reduced extraction rate

No

Return to 75% of original VW extraction rate

Have VOC concentrations decreased by less than 10 percent in past 6 months?

No

Yes

When these asymptotic conditions exist at the majority of VWs, complete equilibrium/rebound testing by turning off the entire system

The soil near this VW(s) appears to be remediated to required levels and this VW can be turned off. Proceed with this evaluation process for each VW until all VWs achieve cleanup standards or a decision is made to pursue a technical and economic feasibility assessment to justify system shutdown

Yes ←

Is the final rebound VOC concentration at one or more VWs less than the target soil gas level?

No

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VENT2D/VENT3D (USEPA, 1995) have been used to estimate and design the radius of influence and flow rates for multiple vent well systems.

The use of vacuum data for vent well spacing and air permeability calculations and flow design has come under criticism (DiGiulio and Varadhan, 2000). The authors have recommended that numerical models be used to design a critical pore gas velocity (not vacuum) throughout the soil volume. This approach requires the estimation or measurement of 8 soil parameters within each soil type impacted by contamination. While this method can provide more accurate SVE designs, it will require extensive site characterization and additional costs for numerical modeling. However, the authors also suggest a more rigorous approach consisting of a site-specific field-scale test. This test requires the implementation of SVE for a sufficient duration to yield a decay in the extracted concentration and decreases in concentration in surrounding VMPs. Typical durations are on the order of weeks. Hence, the adequacy of well spacing can be assessed after the initial operation of an SVE system, or an extended SVE pilot test, using the performance data listed in Table 4.1, without excessive site characterization or numerical modeling.

The Air Force recommends a combination of vacuum and soil gas chemistry monitoring at multiple discrete VMPs as the most practical indication that a volume of soil is being treated by an SVE system. Changes in vacuum and soil gas chemistry can be easily measured in discrete VMPs located at varying distances and in varying soil types. This method has been widely applied at bioventing sites and has been found to be more reliable than vacuum methods alone in confirming the area of treatment influence. To use this method, multiple VMPs should be in place before the SVE system is turned on. Soil gas concentrations of oxygen, carbon dioxide and total volatile hydrocarbons should be measured in each VMP before starting the extraction system. Once the system is started, these measurements should be taken at 2, 4, 8, and 16 hours and then daily intervals until soil gas chemistry stabilizes. At most waste sites, initial soil gas oxygen will be depleted and carbon dioxide is elevated above levels found in clean background

soil gas (Background oxygen in soil gas is generally 18 – 20 percent. Background carbon dioxide in soil gas is generally < 1 percent.)

Figure 4.3 illustrates a typical soil gas chemistry response for VMP-3 near the NAPL source, and a VMP-6 outside of the NAPL source. In this case the SVE system is clearly influencing both VMPs. More rapid changes in soil gas chemistry indicate areas of relatively high permeability and pore gas velocity. Note that oxygen and carbon dioxide will not be useful indicators if site contaminants are pure chlorinated solvents such as TCE, which are resistant to aerobic biodegradation. This is an uncommon situation since most chlorinated solvents were spilled with some non-chlorinated and highly degradable hydrocarbons.

4.3 EQUILIBRIUM/REBOUND TESTING

Perhaps the most important indicator of SVE performance is the equilibrium/rebound test. To collect equilibrium data, the treatment system must be turned off so that contaminants that are sorbed or trapped within the soil matrix have an opportunity to equilibrate with surrounding soil gas. Equilibration data provide the only accurate assessment of soil remediation progress. Once an SVE system is operating, soil gas concentrations at VMPs and VWs become diluted with soil gas from clean soils and give an overly optimistic estimate of remaining concentrations. Even in contaminated soils, desorption and diffusion are relatively slow processes and released contaminants become highly diluted in the advective flow. Only when the soil vapor stops flowing can equilibrium VOC levels be reestablished and compared to pre-venting VOC concentrations.

The time period required to reach equilibrium is contaminant and soil-type specific. Sandy soils will generally reach equilibrium in several weeks, while several months may be required for highly-layered soils. Annual equilibrium testing is recommended. The best time to complete an equilibrium test is when it can be scheduled concurrently with system maintenance/modifications. The site-specific equilibration period can best be determined by turning the system off and then using a handheld VOC analyzer to collect

Figure 4.3
TYPICAL SOIL GAS CHEMISTRY
RESPONSE CURVES

VMP-3 (Near Source)

VMP-6 (Outside NAPL Source)
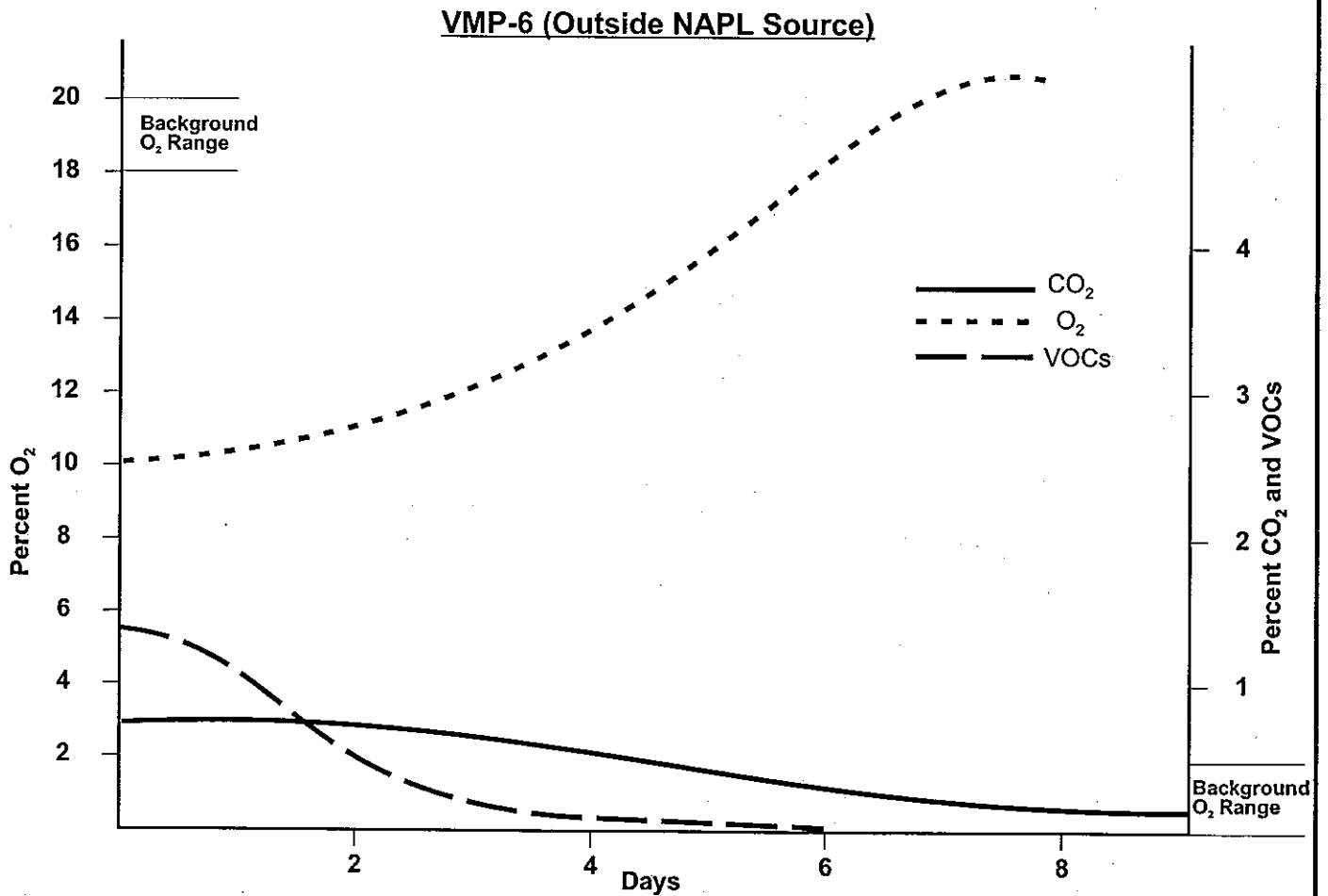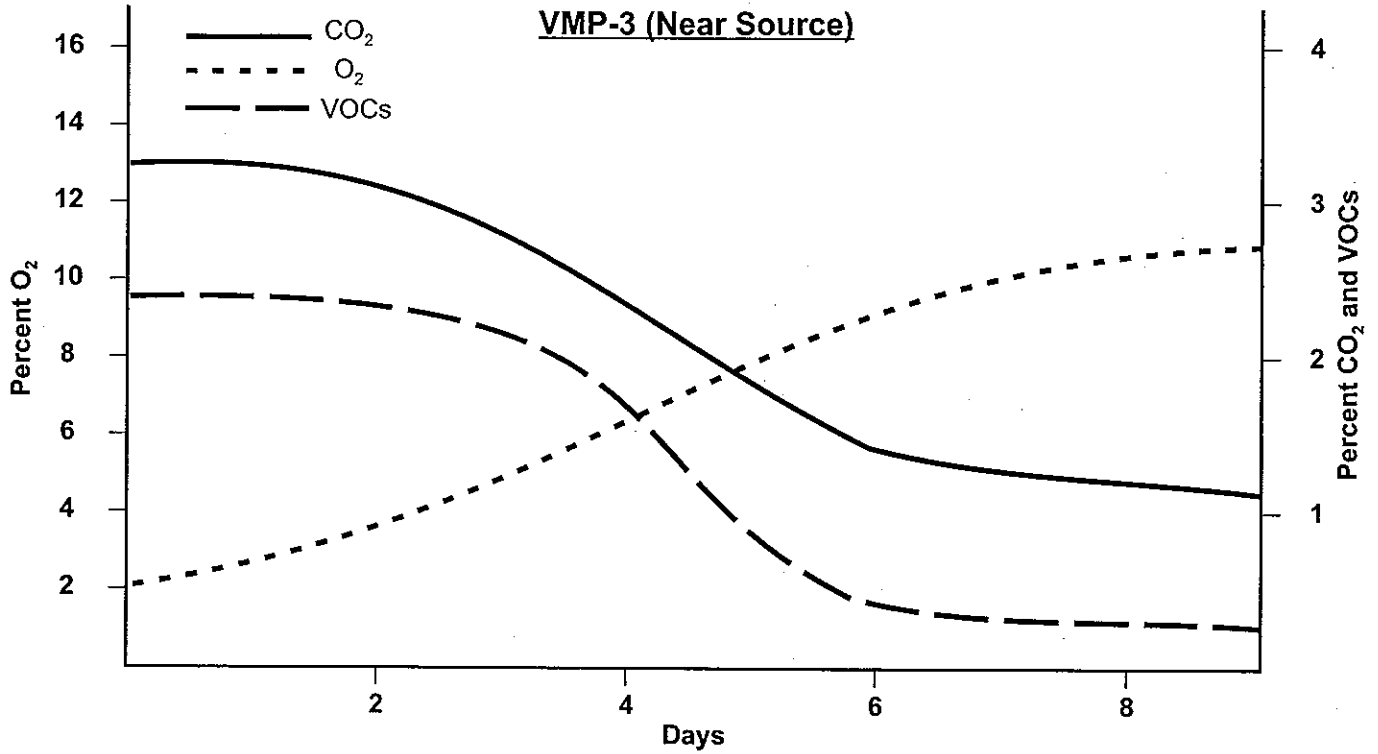
weekly or bi-weekly VOC readings from each VW and VMP until concentrations level off. Figure 4.4 illustrates data collected at three VMPs during a valid equilibration test.

When combined with mass removal data, equilibrium/rebound data provide significant insights into the real progress of soil remediation and can clearly delineate areas of the site that are controlled by diffusion limited VOC removal. The relatively high and stable TCE concentration at VMP-3 indicates that this VMP is located in a highly-contaminated, low permeability soil. The rapid decline and then significant (>50 percent) rebound approaching initial concentrations, indicates that VMP-2 is located in a more permeable zone adjacent to a highly-contaminated low permeability zone that is releasing VOCs through diffusive processes. VMP-1 is located in a soil volume that is no longer influenced by residual NAPL. Additional information and techniques for interpreting rebound data to estimate residual mass can be found in Appendix G of the USACOE Manual (Stewart, 2001).

4.4   RESPIRATION MEASUREMENTS

Respiration measurements are useful in estimating the mass of contaminants that are being biodegraded and removed from the soil during SVE operations. This is particularly important for petroleum hydrocarbon sites where air injection bioventing is employed but is also important at sites where SVE has been selected to remove more volatile fuels. (Note bioventing is normally recommended for jet fuels and diesel fuels, while SVE may be required for more volatile gasoline spills). The reader is referred to the Air Force Bioventing Principles and Practice Manual (Leeson, 1995) for complete details on respiration test methods.

There are two methods of estimating hydrocarbon biodegradation at SVE sites. In situ respiration testing can be completed by measuring the uptake of oxygen at individual VMPs and VWs either prior to starting the SVE system or during an equilibration test. The rate of oxygen uptake at each point is directly related to hydrocarbon biodegradation in surrounding soils.

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Figure 4.4

RESULTS OF EQUILIBRIUM / REBOUND TEST
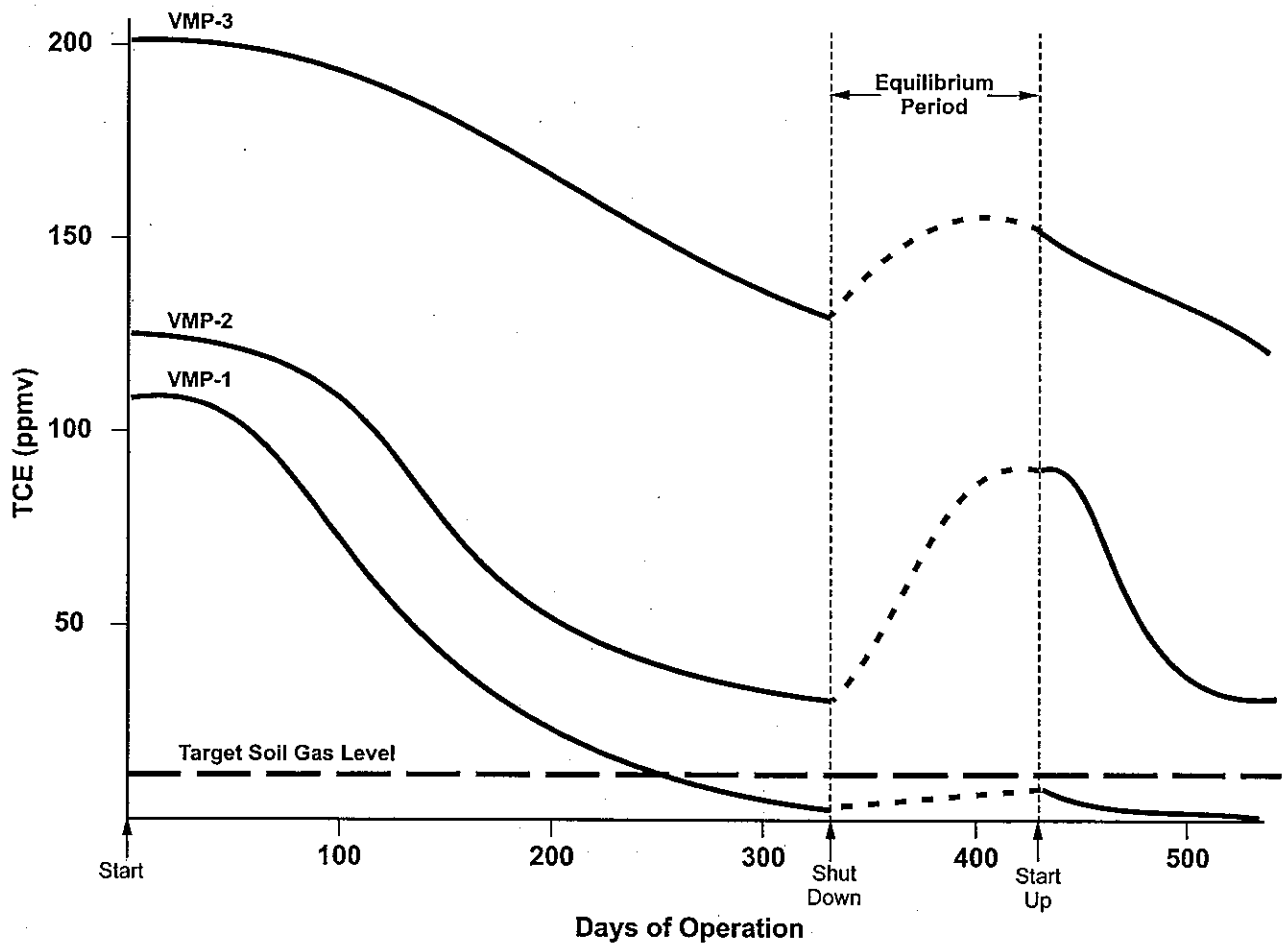
The second method of estimating biodegradation is completed with the SVE system operating and requires 2-3 VMPs located in clean soils around the perimeter of the site to provide background soil gas oxygen concentrations. By measuring the oxygen in the extracted soil gas, and comparing it to the background soil gas oxygen levels, the steady-state oxygen consumption in the contaminated soil volume can be estimated (Figure 4.5). The Air Force Bioventing Principles and Practice Manual provides complete equations for estimating the mass of hydrocarbon being degraded based on both respiration test methods.

4.5 VAPOR TREATMENT PERFORMANCE MONITORING

Although not directly related to the removal of contaminants from the subsurface, aboveground vapor treatment is often the most expensive component of the SVE system. Vapor treatment can be accomplished via thermal technologies, activated carbon, or biofilters. A complete understanding of the manufacturer's performance monitoring requirements is recommended. This section will discuss only the general performance monitoring requirements of vapor treatment systems.

4.5.1 Basic Emission Testing

Basic emission testing requires that the treatment system effluent meet daily mass limits such as pounds of total VOCs per day or pounds of TCE per day. Influent and effluent gas sampling is often required on a weekly basis during the first month of operation to determine the ability of the process to achieve emission limits. Monthly monitoring is normally required once the initial treatment effectiveness is verified. Gas samples are normally collected in a Summa canister or other heat resistant container and can be analyzed with a total VOC analyzer or sent to a laboratory for specific compound quantification.

4.5.2 Destruction Efficiency

Some regulatory agencies require that vapor treatment technologies attain a specified destruction efficiency. Influent and effluent gas sampling is may be required on a daily basis during the first week of operation to determine the ability of the process to achieve

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Figure 4.5
ESTIMATION OF BIODEGRADATION AT SVE SITES
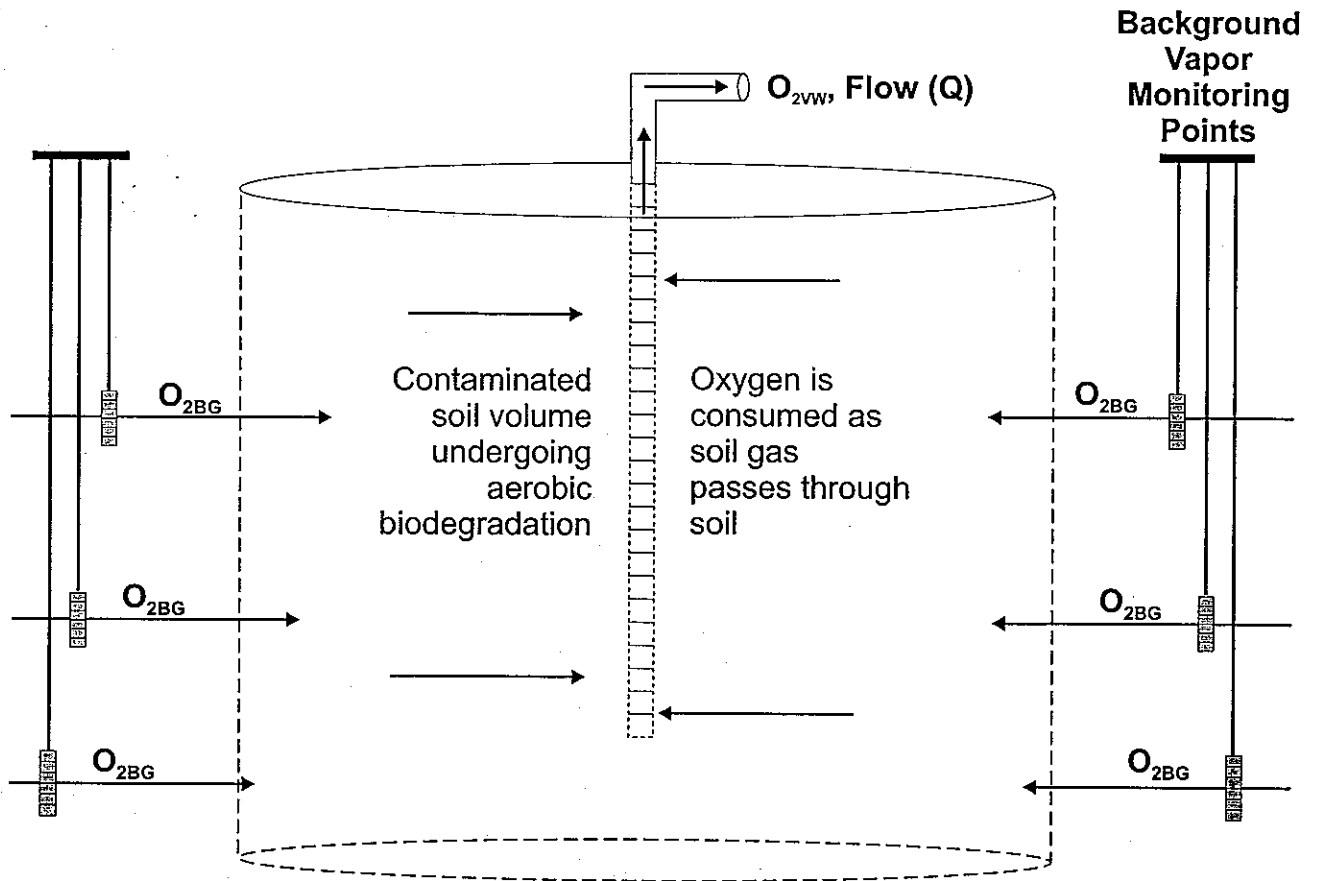
Formula for Estimating Pounds of Hydrocarbons Biodgraded Each Day

$$M_{bio} = 34\ Q\ \frac{(O_{2BG} - O_{2VW})}{100}$$

M_{bio} = mass of hydrocarbons biodegraded (lbs/day)

Q = air extracted flow rate (ft^3/min)

O_{2BG} = % oxygen in background soil gas (averaged)

O_{2VW} = % oxygen in extracted soil gas

Note: Aerobic biodegradation is normally associated with non-chlorinated hydrocarbons

$O_{2BG} - O_{2VW}$ is generally 1-5%

This formula has been simplified for sea-level conditions and assumes
that 3.5 pounds of oxygen are required to degrade one pound of
hydrocarbon. Additional information is found in (Leeson, 1995).

the desired destruction efficiency. Monthly monitoring of influent and effluent is normally required once the initial destruction efficiency is verified. Gas samples are normally collected in a Summa canister or other heat resistant container and can be analyzed with a total VOC analyzer or sent to a laboratory for specific compound quantification. For thermal systems, the temperature of the combustion chamber and flow rates through the system may be required to maintain conditions that ensure the specified destruction efficiency.

4.5.3 Unit Cost Effectiveness

The vapor treatment system should be evaluated to determine if it is the most economical technology for the current flow and influent concentrations. As influent concentrations decrease at SVE sites, the performance of most thermal technologies will decline and greater amounts of auxiliary fuels will be required to maintain combustion temperatures. Each month, the cost per pound of VOC destroyed should be calculated so that this unit cost can be compared to the low-maintenance activated carbon option. Carbon suppliers can provide timely quotes of the capital and O&M cost for a specific influent VOC mixture. Activated carbon is often the most economical vapor treatment method once a site enters the diffusion-limited phase of VOC removal.

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SECTION 5

OPTIMIZATION OF EXISTING SYSTEMS

All SVE systems can benefit from some degree of optimization, and most optimization opportunities are relatively easy to identify if the conceptual site model is accurate (Section 2), cleanup goals are established (Section 3), and the appropriate performance monitoring data has been collected (Section 4). The extent of optimization analysis will vary based on the difficulty and the expected cost to achieve cleanup. For example, a SVE system with three VWs, operating at a gasoline station where natural attenuation has been selected as the groundwater remedy, will likely require 2 to 3 years of operation and have relatively low O&M expenses. While some degree of optimization (such as varying flow between VWs) will reduce treatment time, these small systems do not generally require a separate remedial process optimization (RPO) project. In contrast, a system with 20 vent wells, operating to reduce chlorinated solvent contamination entering a drinking water aquifer, will likely require 5 to 15 years of operation and have much higher O&M expenses. A more comprehensive RPO project may be justified for these complex and expensive SVE systems.

The purpose of this section is to provide a variety of optimization methods that can be applied to several of the most common performance problems. Not all optimization methods will apply to an individual site. Additional details on the overall RPO process are contained in the Air Force RPO Handbook (AFCEE, 1999) available on the AFCEE website: www.afcee.brooks.af.mil/er/toolbox.htm.

The performance monitoring described in Section 4 will provide the necessary data to determine if an SVE system is achieving or failing to accomplish its design goals. Common performance problems can generally be defined by one or more of the following conditions:

- Inadequate treatment of contaminated soil volume.

- Unacceptably slow treatment of low-permeability soils.

- Submerged NAPL and slow groundwater cleanup.

- Inefficient or mismatched vapor treatment systems.

The following sections describe general indicators of these common performance problems and actions to improve or optimize the system when these problems occur.

5.1 INADEQUATE TREATMENT OF THE CONTAMINATED SOIL VOLUME

5.1.1 Indicators

- Some VMPs do not indicate a vacuum response during system startup

- Soil gas chemistry at some VMPs does not change during the first weeks of extraction

- A high vacuum is required to retrieve a soil gas sample from a VMP

- Equilibrium/rebound testing indicates little or no decrease in VOC concentrations when compared to initial concentrations at that VMP

- Large quantities of mobile NAPL are known to exist at the site above the water table.

5.1.2 Optimization Actions to Take

- Check the VMP boring log to determine soil type and moisture content. If this is a low-permeability soil, and it is difficult to retrieve a soil gas sample, the soil may be too wet to transmit air. If soil moisture is associated with the capillary fringe, dual-phase extraction may be needed to dewater the soil.

- If soil moisture is not associated with groundwater, and the entire low-permeability layer is contaminated and greater than 2 feet thick, a thermal enhancement such as respirable fraction (RF) or resistive heating may be required to dewater and release VOCs.

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- For a low-permeability layer that is less than 2 feet thick and surrounded by permeable soils, advective flow may be able to slowly dry the soil and increase both advective and diffusive processes in the low-permeability soils.

- If this level of site characterization detail is unavailable, consider completing a direct push Geoprobe/MIPs or equivalent survey to determine soil type, soil moisture and VOC distribution at multiple depths and locations across the site.

- If it is not difficult to retrieve a soil gas sample and initial soil moisture was less than 15%, it is possible that the nearest VW is either too far from the nonresponsive VMP or the flow rates are too low to impact this VMP. Increase the extraction rate at the nearest VW and see if this creates a vacuum response or soil gas chemistry change.

- It is possible for stagnation zones to form in areas that are under equal vacuum influence of two or more VWs. To determine if a stagnation zone exists, turn off one or more of the VWs that surround the nonresponsive VMP. If stagnation was occurring, this should result in soil gas flow and vacuum and chemistry changes at the VMP. Leaving the VMP open to the atmosphere during normal operations may provide an air injection point and eliminate stagnation. Pulsing flow rates in the surrounding VWs can also reduce stagnation.

- If the site is capped and shallow VMPs are the only ones not responding as desired, the cap may be creating a stagnation zone at the surface and preventing flow in the shallow vadose zone. Consider removing the cap.

- Use a Pneulog® or equivalent device to provide a vertical profile of the flow and VOC concentration entering VWs at the site. Determine if vent well design is creating short-circuiting that is directing flow away from the nonresponsive VMP. Use a packer system to reduce VW short-circuiting to direct more of the flow to the nonresponsive depth interval. If necessary, install a new VW closer to the area of concern or a VW that is screened at a more appropriate interval.

5-3

- The presence of mobile NAPL in any soil type will delay site remediation using SVE. The process of volatilizing contaminants at ambient soil temperatures is time consuming. Higher air flows to NAPL areas will accelerate volatilization but the relationship is not linear. NAPLs located in perched lenses above the water table can be remediated much faster using soil heating enhancements if the cost can be justified by the shortened remediation time. Most thermal applications require less than six months to complete. NAPLS at or below the water table are addressed in Section 5.3.

5.2   SLOW TREATMENT OF LOW - PERMEABILITY SOILS

5.2.1   Indicators

- Slow changes in vacuum readings and soil gas chemistry at VMPs when the SVE system is started up.

- Concentration vs. time plots at one or more VWs indicate asymptotic behavior associated with diffusion-limited removal.

- Equilibrium/rebound testing of a VW or VMP located near or in low permeability soils indicates that concentrations are still increasing weeks after system shut-down. (A rapid rebound is more indicative of the normal volatilization of NAPLs in soil.) Figure 5.1 illustrates the equilibrium rebound that could be expected from low-permeability diffusion (VMP-3) and a NAPL source in higher permeability soils (VMP-2).

- Lower volatility compounds such as naphthalene and higher volatility compounds such as benzene seem to rebound in the same relative concentrations as pre-venting concentrations.

5.2.2   Potential Optimization Actions

- If low-permeability zones are not well-defined, consider the use of advanced site characterization tools such as Geoprobe® MIPs, SimulProbe, or equivalent push tool, to create a vertical profile of soil types and VOC concentrations vs. depth.

Figure 5.1
EQUILIBRIUM / REBOUND INDICATORS
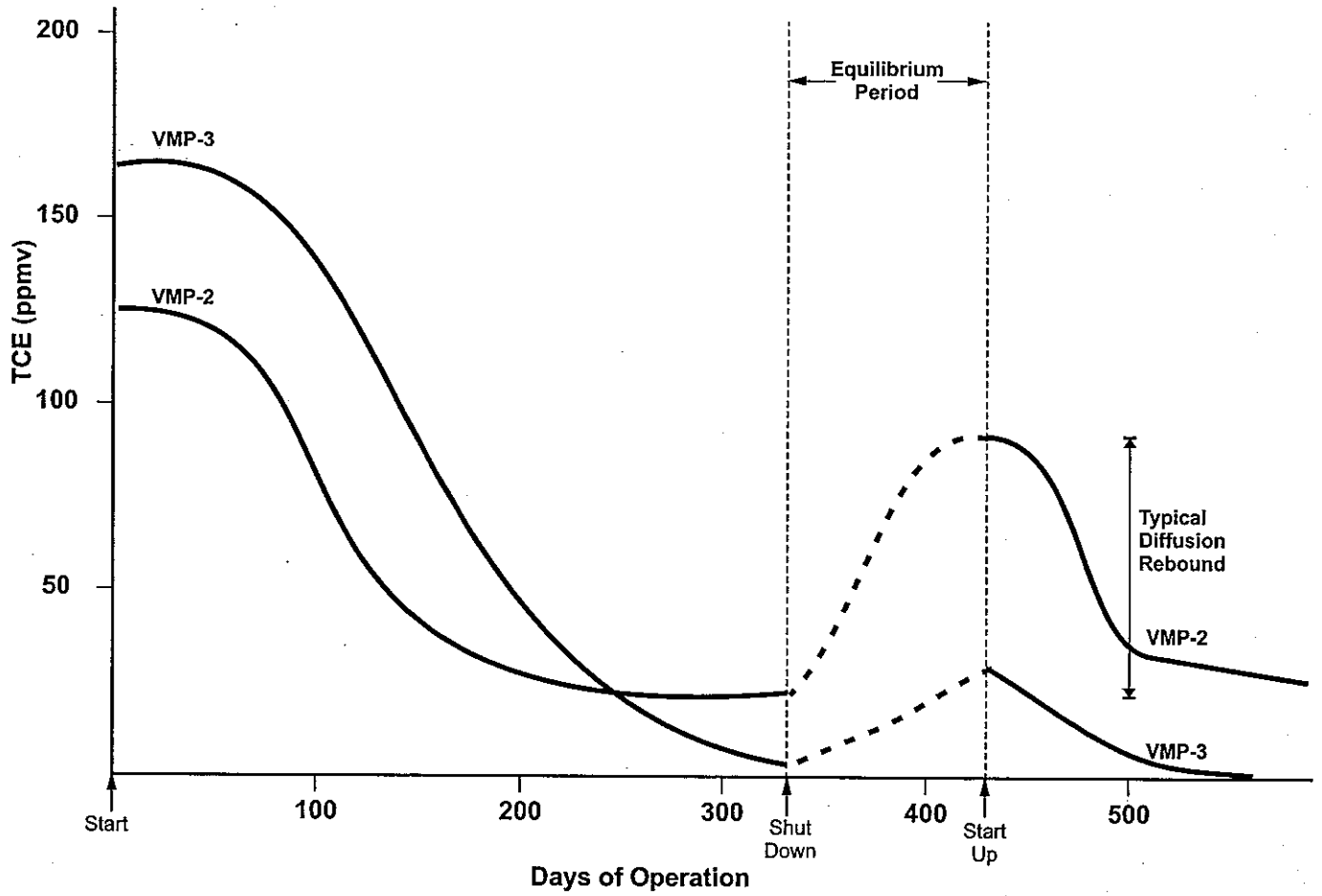
- Consider the use of Pneulog or equivalent device for vertical profiling of existing VWs during system operation and during an equilibrium/rebound test. This information can be used to determine the vertical profile of advective and diffusive layers. Additional short-screened VWs can be placed above or below diffusion-limited zones and low flow rates used to minimize dilution.

- Without SVE enhancements such as soil heating or a successful fracturing effort, most sites with significant low-permeability layering will require 5 to 10 times the treatment time as sandy soils. Generally, the thicker and higher the moisture or VOC levels in the silt or clay layer, the longer the remediation will take.

- If the soil is accessible by excavation, this option should always be reconsidered. Smaller sites with less than 1000 cubic yards of NAPL impacted soils, and sites that can be excavated without destroying high-cost structures, are often remediated at a lower overall cost through excavation using aboveground soil treatment or disposal.

- Higher flow rates or vacuums will generally not improve removal from low-permeability soils. In fact, sites with relatively thin layers (<2 ft) of low permeability soils surrounded by high-permeability sands can be more efficiently remediated by using smaller blowers and lowering the flow rates. Accepting longer operating times at lower flow rates with less frequent monitoring and sampling and, if acceptable, no vapor abatement is often the most cost-effective strategy for these sites.

- Alternating between VWs is another method of reducing the power and vapor treatment requirement for these sites. Diffusion limitations will require extended remediation times and lower flow rates may provide a more cost effective cleanup.

- Soil heating using steam will be difficult in low permeability soils due to the negative impact of additional moisture. RF, resistive, and conductive heating are all potential methods of increasing soil permeability and increasing VOC removal

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rates. These methods are expensive and should only be considered after significant feasibility testing.

• If diffusion is shown to be very slow, consider justifying closure with institutional controls based on the low, site-specific risk of mass reaching a receptor (e.g., groundwater) at an unacceptable rate. This approach has been used successfully within the EPA (DiGiulio et al., 1998).

5.3 SUBMERGED NAPL AND SLOW GROUNDWATER CLEANUP

5.3.1 Indicators

Although mass removal from an SVE system may be significant compared to the initial estimate of contaminant mass at the site, the following indicators are common at sites where NAPL is present in the capillary fringe and/or below the water table or where dissolved groundwater concentrations are high:

• Equilibrium/rebound testing indicates that the greatest relative rebound is occurring in VMPs located near the groundwater.

• Groundwater concentrations in the source area seem unaffected by mass removal in the unsaturated zone.

5.3.2 Possible Optimization Actions

• SVE is only effective in unsaturated soils and must be modified to extend treatment below the water table. Additional site characterization using a Geoprobe® MIPS or equivalent system is recommended to locate NAPL layers. VMPs exhibiting unusual equilibrium rebound may be located over partially submerged NAPL zones.

• Since light NAPLs generally reside at or slightly below the water table, multi-phase extraction systems, such as Bioslurping, will be required to dewater and expose light NAPLs to air flow. Multi-phase extraction will be most effective in soils with moderate permeability, where air flow is possible and groundwater can

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be drawn down without excessive pumping rates. The "Engineering Evaluation and Cost Analysis for Bioslurper Initiative Final Report" (AFCEE, 1997) provides details on testing, design and operation of MPE systems.

- Dense NAPLs located below the water table can be treated using dual-phase extraction (DPE) systems if the soil volume can be adequately dewatered. The effectiveness of DPE is limited to relatively shallow DNAPL penetrations and to aquifers which produce significant drawdowns without excessive pumping rates. Additional information on DPE can be found in the USEPA publication, "Multi-Phase Extraction: State or Practice" (USEPA, 1999).

- Steam injection, RF and resistive heating have all been applied to DNAPL zones below the water table. Heat is applied to the point where groundwater is boiled away creating a steam front which can sweep VOCs from the soil (EPA, 1997). These systems are most successful when applied in the upper five feet of the aquifer, although deeper applications are possible. Rapid groundwater recharge can absorb heat energy as fast as it can be applied resulting in limited steam formation.

- The relationship between the unsaturated zone DNAPL, saturated zone DNAPL, and groundwater contamination must be well-described before any high-cost thermal or dewatering options are considered. There are sites where submerged DNAPL is unrecoverable with available technologies, and SVE will have little or no impact on long-term groundwater contamination.

5.4 INEFFICIENT OR MISMATCHED VAPOR TREATMENT

5.4.1 Indicators

- System VOC concentrations vs. time indicate asymptotic, diffusion limited mass removal

- One or more of the VWs are producing very low VOC concentrations.

- Auxiliary fuel use is increasing for thermal treatment units

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- Granulated activated carbon is reaching breakthrough prematurely due to excessive flow

- Unit cost for VOC treatment is too high or increasing

5.4.2   Possible Optimization Actions.

- Reduce extraction rates at VWs producing low levels of VOCs if equilibration rebound testing indicates the VW is treating a diffusion-limited area.

- Turn off VWs that are producing low levels of VOCs and no longer produce a rebound during equilibration tests.

- Increase flow at VWs that are producing higher VOC levels indicative of NAPL impacted soils.

- Reduce the overall flow rate by using a smaller blower (assuming all NAPL impacted soils can be influenced with the lower flow rate).

- After optimizing VW and overall flow rates, review the discharge limitations for the site to determine if the current VOC removal rate qualifies as a de minimis discharge that does not require treatment.

- If treatment is still required, determine if the existing vapor treatment system is still appropriate for the new VOC concentration and flow rate.

- Evaluate the activated carbon option. Activated carbon may be cost effective for many diffusion-limited sites with total VOC removal rates of less than 5 pounds per day. Contact an activated carbon vendor with your flow and VOC concentration data to obtain a quote on the capital and carbon replacement costs. Carbon generally requires 20-30 percent of the maintenance labor as thermal systems.

- On fuel-contaminated sites with significant NAPL contamination, the use of internal combustion engines has proven to be more efficient than other thermal

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options when VOC levels remain above 10,000 parts per million, volume per volume (ppmv) (AFCEE, 1994).

- If thermal oxidation or catalytic oxidation appears to be the most economical system, ensure that any thermal system is properly sized for anticipated average flow and VOC concentrations. Never size a unit based on maximum initial VOC loading. When VOC levels are high, the flow rate should be reduced to provide an average mass loading to the unit. As VOC concentrations drop the flow rate can be increased to maintain the average VOC loading.

5.5   OTHER PERFORMANCE PROBLEMS

The performance of SVE systems can be impacted by changing site conditions such as removal of an asphalt or concrete cover, excess precipitation, or a rising water table. Each of these conditions can radically change soil moisture conditions and temporarily impact the air permeability of the soil. A steadily rising water table may require that a dual phase extraction systems be installed if soils at the water table require additional treatment. In many western states, the water table may be dropping due to municipal or agricultural water use. SVE systems in these areas will generally benefit from drier soil conditions. The US Army Corps of Engineers publication "Engineering and Design Soil Vapor Extraction and Bioventing" (USACOE, 1995) includes additional details on many of the common performance problems caused by malfunctioning or improperly sized equipment.

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SECTION 6

SVE SHUTDOWN LEADING TO SITE CLOSURE

Site closure is an elusive goal for many remediation projects. At sites where SVE systems are installed to prevent or reduce groundwater contamination, soil cleanup criteria can be very difficult to achieve. While numerical soil standards may be included in site decision documents, final soil sampling procedures and statistical methods for determining compliance are rarely specified. Proving that soils have achieved a certain level of cleanup can be an expensive and time-consuming task requiring regulatory coordination and approval. This section will review key performance and site closure data required for the closure process and explore several options for soil sampling and for confirming cleanup.

6.1 DATA REQUIREMENTS

6.1.1 Establishing Target Soil Gas Concentrations

Because of the extreme difficulty in collecting representative samples for VOC analysis and the loss of VOCs during all collection and analysis procedures, equilibrium soil gas levels of VOCs measured at permanent or temporary VMPs provide the most accurate estimate of VOC residuals in soil. Although recent advancements in soil sampling, such as the EPA Method 5035 (Encore® or equivalent method), have improved VOC retention, soil gas samples provide an average VOC concentrations for one cubic foot or more of soil while individual soil samples only provide information on only a few cubic inches of soil.

In light of the improved VOC detection associated with *in situ* soil gas measurements, AFCEE and most regulatory agencies are recommending that target soil gas concentrations be established to serve as indicators or to confirm soil cleanup criteria have been achieved. At equilibrium, the concentration of contaminants of concern in the soil can be estimated by their concentrations in soil gas. Appendix A provides an

example of the calculation that can be used to relate soil cleanup criteria to target soil gas concentrations.

Soil gas concentrations can be monitored inexpensively throughout the life of an SVE project and can be substituted for expensive soil sampling for the final confirmation of cleanup goals. Additionally, use of site-specific analytical results that are based on simple equilibrium partitioning relationships to estimate residual contamination in soil, particularly that which may pose a threat to underlying groundwater, is in keeping with the technical basis of the soil screening levels (SSLs) developed by the USEPA (1996a, b, and c). The SSLs are based on simple linear equilibrium partition equations, which are used to estimate how much contaminant could migrate into overlying air exposure points or into underlying groundwater. In practice, most risk-based numerical cleanup standards will be based on similar conservative, simplifying assumptions. Consequently, soil gas analytical data will generally provide the best approximation of the site conditions used to develop most risk-based numerical cleanup standards. A more detailed summary of the technical basis of the SSLs, as relevant to sampling for closure, is presented in subsequent discussions in this section.

6.1.2 Evaluating System Performance Data

Much of the performance data described in Section 4 will be extremely useful for developing the case for turning off an SVE system. Figure 6.1 shows a concentration versus time curve for an SVE system that operated at a PCE-contaminated site for over four years. This curve illustrates a nearly 1,000-fold decrease in PCE concentration at a VW that was centered in the NAPL contaminated soil. Three equilibrium/rebound tests were completed at this VW. Note that each post-rebound concentration was smaller than the previous rebound test and the final equilibrium concentration remained below the target soil gas concentration.

Figure 6.2 illustrates equilibrium soil gas levels of PCE measured in the three rebound tests in four separate VMPs located at two depths. VMPs 1 and 2 are located in a silt layer and VMPs 3 and 4 are located in a deeper sand layer. Data indicate that soils near

Figure 6.1

HISTORY OF PCE EXTRACTION AT VENT WELL

- - - - Equilibrium / Rebound Tests

PCE ppmv

Days of Operation
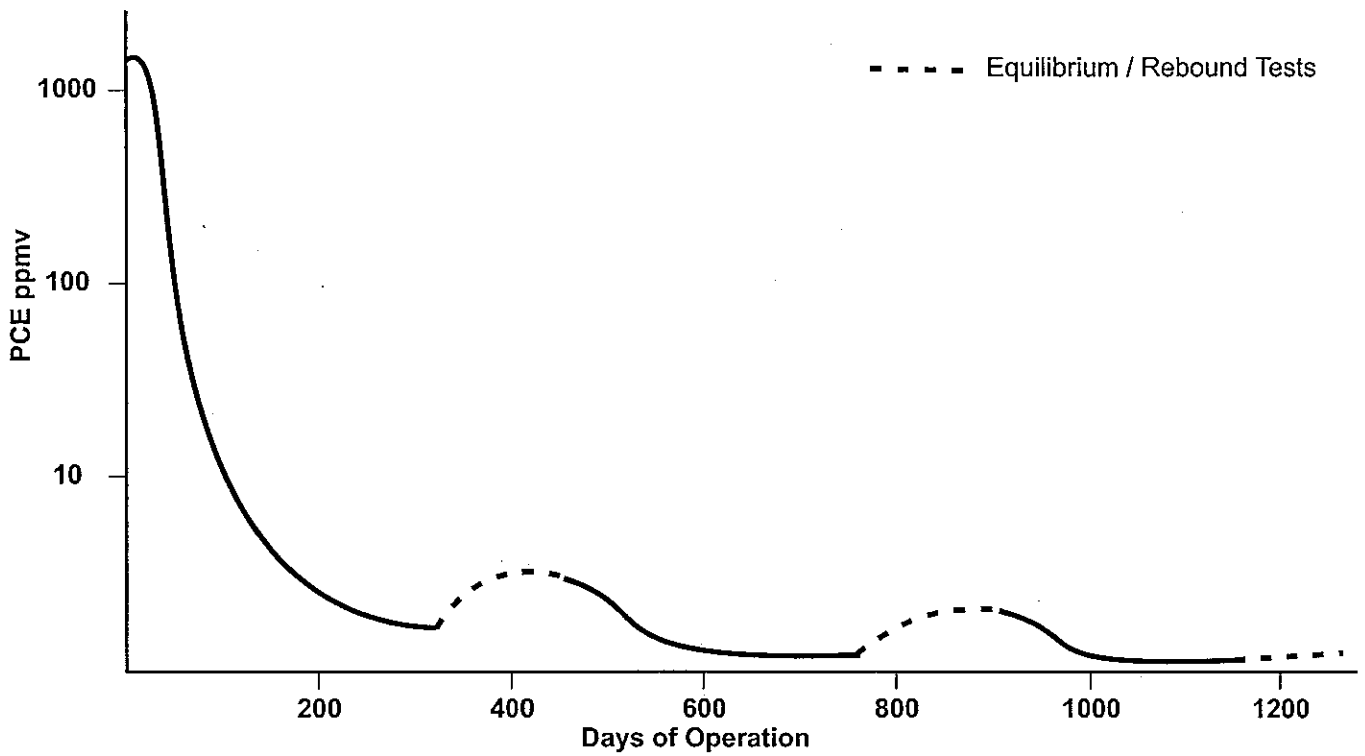
Figure 6.2

HISTORY OF PCE CONCENTRATIONS AT VMPs

VMP-1

VMP-2

VMP-3

VMP-4

- - - - Equilibrium / Rebound Tests

PCE ppmv

Target Soil Gas Level

Days of Operation

draw\svehandbk5.cdr aee p3 4/13/01
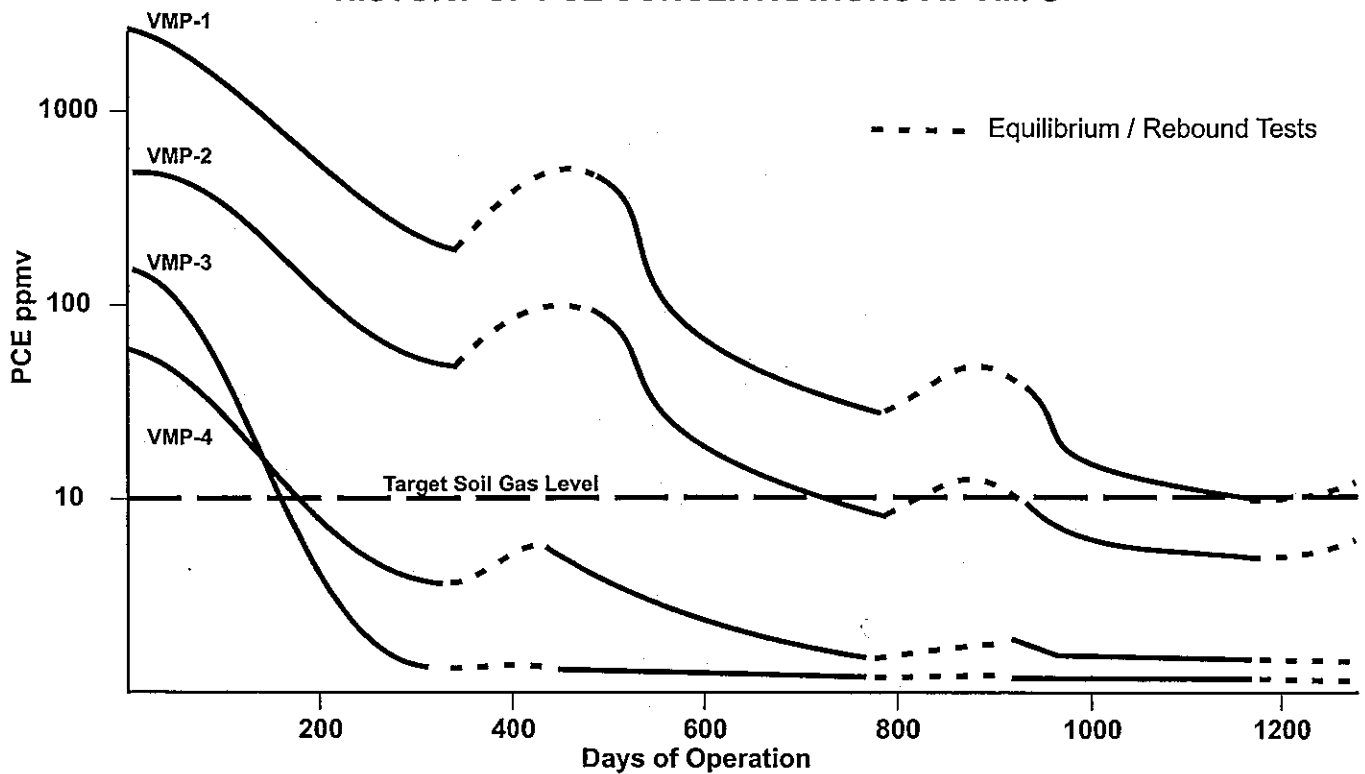
VMPs 3 and 4 were remediated during the first two years of SVE, while soils near VMPs 1 and 2 are at or slightly above the target soil gas concentration. These data are typical for sites with a layer of lower permeability soil. Note that cleanup in the silty soil is occurring but at a lower (diffusion-limited) rate than sandy soils. Based on these data from the extracted soil gas and VMPs, regulatory officials could be notified that the soils are approaching cleanup standards and final sampling plans could be discussed.

6.1.3 Final Soil Gas or Soil Sampling

If the final measure of cleanup will be based on analytical results from soil samples, target soil gas concentrations also should be collected to monitor progress toward and likely achievement of specific numerical cleanup criteria prior to soil sampling. Irregardless of what type of sampling data are to be used to demonstrate compliance with final cleanup criteria (e.g., soil gas data, soil sampling data), the final sampling event should be planned with regulatory officials to ensure that the data are representative of the targeted remediation area and are sufficient to support final decisions.

As part of the technical background material to the SSL guidance, the USEPA developed information on sampling strategies designed to provide site-specific analytical data suitable for direct comparison to "trigger levels" (e.g., action levels, SSLs, preliminary remediation goals [PRGs]). The overall decision rule used to guide these simplified comparisons is identical to that usually applied to demonstrate closure, namely: if site-specific analytical data that are representative of the average exposure concentration falls below the targeted numerical criteria, no additional remediation or action is generally warranted (i.e., closure is a defensible option). Thus, the sampling strategies recommended by the USEPA as part of the SSL guidance can be used to summarize reasonable options for designing and optimizing a closure sampling plan for a SVE-remediated site; however, final closure sampling plans will need to incorporate site-specific data quality objectives (DQOs) and other requirements.

The first step in planning to sample for closure is defining the limits on decision errors. To minimize the sampling intensity necessary to accurately determine the mean

concentration of subsurface soil contamination within a source with a specified level of confidence (e.g., 95 percent), USEPA recommends the use of an operational decision rule based on average concentrations within individual soil cores taken purposively in the source and randomly across the treatment area. For each soil core (or VMP gas sample), the mean concentration is defined as the depth-weighted average concentration within the zone of contamination (USEPA, 1996c). Note that this is not a statistically-based decision rule, which means that it will not be possible to statistically define decision errors.

For subsurface soils, USEPA recommends characterizing the mean contaminant concentration from each soil boring (or VMP gas sample) for direct comparison to targeted numerical criteria (USEPA, 1996a). Characterizing the mean contaminant concentration is the appropriate objective for subsurface sampling strategies because the exposure potential associated with subsurface soils is limited by contaminant transport upward into air or downward into groundwater. In cases where each VMP represents the same subsurface soil interval, the average concentration is the simple arithmetic average of the concentrations measure across the monitored zone. However, if the intervals are not all the same length (e.g., due to complex stratigraphy), then the calculation of the average concentration in the total core (or VMP) must account for the different lengths of the intervals. Thus, the analytical data should be depth-weighted (USEPA, 1996c). Simple equilibrium partitioning equations can then be used to estimate average residual soil concentration. Figure 6.3 illustrates the difference between using maximum and mean concentrations for risk-based cleanup decisions at a TCE-contaminated site.

Any site analytical data collected to demonstrate closure should be based on knowledge of likely contamination patterns and subsurface conditions. This usually means that samples should be collected from source areas targeted during SVE treatment. At least 2 or 3 individual soil borings (or VMPs) should be used to estimate the mean residual soil concentration within the SVE treatment area. However, closure sampling should not be limited to purposive sampling in the source area, as such a sampling strategy will interject bias into the data set; this bias could result in an overestimate of

FIGURE 6.3

MAXIMUM vs AVERAGE SOIL EXPOSURE CONCENTRATIONS FOR TCE
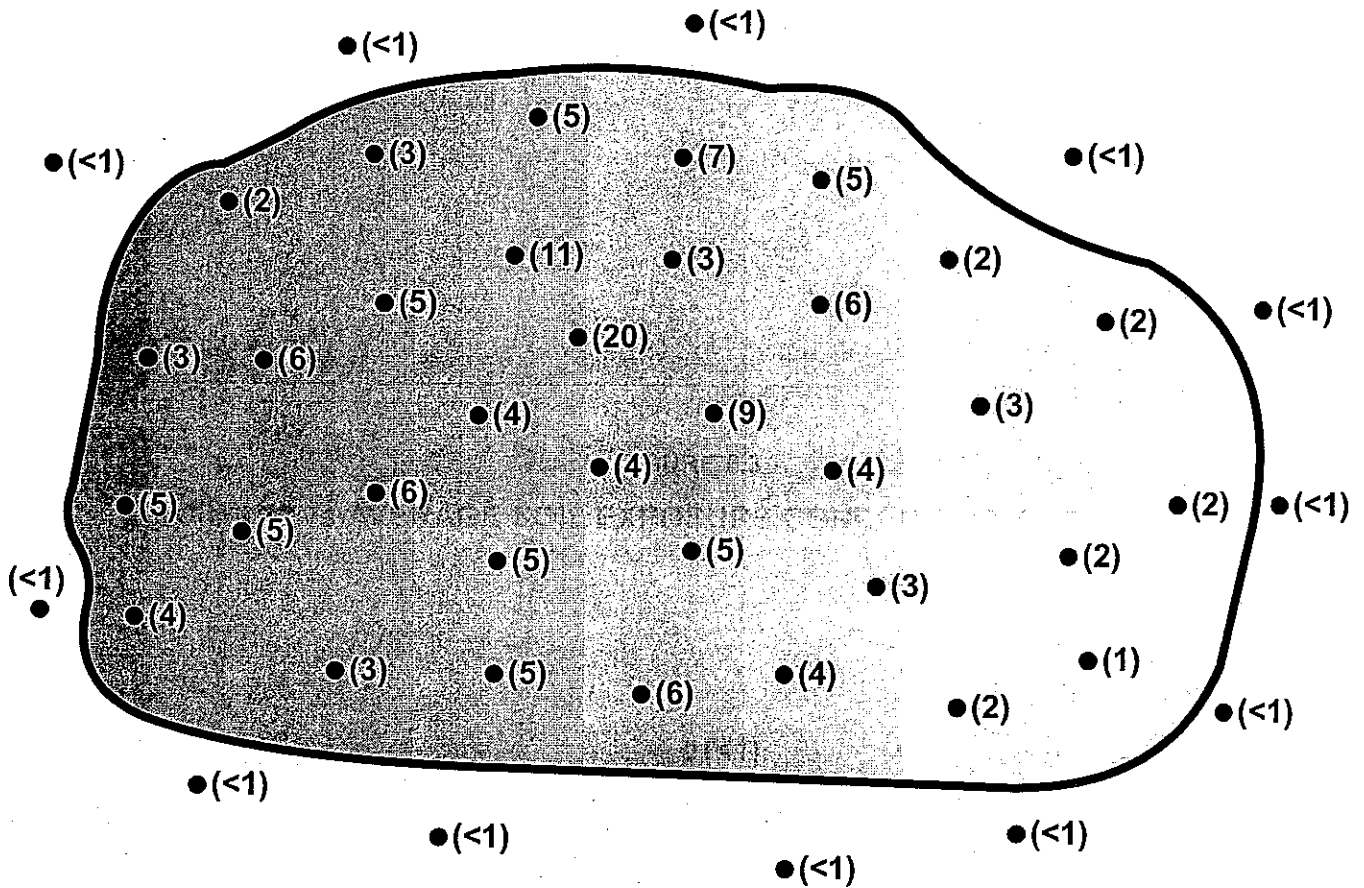
Legend

●   Sample Locations (depth 6-10 feet bgs.)

(3)   TCE Soil Concentration in mg/kg

Maximum Soil Concentration   -   **20 mg/kg**

Average Soil Concentration
at 95% UCL*   -   **5.9 mg/kg**

Non-Intrusive Site Worker
Risk Based Screening Level   -   **6.1 mg/kg**

* Based on normal distribution

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potential risks, should a more detailed risk evaluation be completed in support of closure at a site. In addition to other relevant DQOs, analytical quantitation limits should be less than the most stringent targeted cleanup criteria.

6.2 Evaluating Contaminant Transport to Groundwater

In some cases, more detailed evaluations of the potential impact of remaining contaminant residuals on underlying groundwater quality may be required. For example, soil gas sampling may indicate that significant mass removal has taken place and that most soil layers have achieved target soil gas levels. Unfortunately, a single low permeability layer may contain residual contamination that causes the <u>mean</u> concentration for that sampling location to be above targeted cleanup standards. Rather than continue to operate the unproductive SVE system for additional years, a site-specific evaluation of the potential effects of residual soil contamination on groundwater quality may play an important role in the remedial decision process for the site. This site-specific evaluation may be as simple as modifying the generic assumptions usually imbedded within the soil-to-groundwater cleanup goal to be more representative of actual site conditions, to as complex as constructing and completing a site-specific soils-to-groundwater leaching model.

The soil-to-groundwater SSLs (also referred to as the migration to groundwater SSLs) developed by the USEPA (1996c) incorporate both release of a contaminant in soil leachate and transport of that contaminant through the soil and groundwater to a potential receptor point. The SSL methodology incorporates a standard linear equilibrium soil/water partition equation to estimate contaminant release in soil leachate and a simple water-balance equation that calculates a dilution factor to account for dilution of soil leachate in an aquifer. SSLs are then back-calculated from "acceptable" groundwater concentrations (i.e., non-zero maximum contaminant level goals [MCLGs], MCLs, or health-based levels).

The generic SSL methodology can be revised, as needed, to reflect more site-specific information regarding the release and transport of contaminants in the subsurface. The

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equations used to derive the migration to groundwater SSLs can be updated to reflect site-specific values that are more representative of actual conditions than the default, conservative parameter assumptions. Additionally, more complex unsaturated zone fate-and-transport models can be used to define protective soil concentrations as more detailed site-specific information is available. These more complex models are particularly important when subsurface conditions are not adequately addressed by simple equations (e.g., deep water tables; clay layers or other unsaturated zone characteristics that can attenuate contaminants before they reach groundwater). Applying these more complex models will more accurately define the risk of exposure via the migration to groundwater pathway, which could lead to higher target cleanup criteria that provide the desired degree of protection. However, these complex models can increase remediation-related costs by increasing the effort needed to collect input data and complete the more detailed site-specific evaluations.

The equations used to develop the generic soil-to-groundwater SSLs are based on several conservative, simplifying assumptions – an infinite source, contamination extending throughout the soil column, no biological or chemical degradation, and no adsorption. There are several unsaturated zone models that are commercially available that may be appropriate to more accurately represent more complex site conditions (and amend subsurface cleanup goals, as necessary). Unsaturated models that could be used to evaluate subsurface VOC transport include MULTIMED, VLEACH, and SESOIL. The applications, assumptions, and input requirements for these (and other) models are fully described in the Technical Background Document (TBD) to the SSL guidance (USEPA, 1996c); the following summaries are based on that information.

MULTIMED can be used to simulate direct infiltration to the unsaturated or saturated zones. Transport in the unsaturated zone considers the effects of dispersion, adsorption, volatilization, biodegradation, and first-order chemical decay. The saturated transport module is one-dimensional, but considers three-dimensional dispersion, linear adsorption, first-order decay, and dilution to recharge. This model can be configured to consider a finite source assumption.

VLEACH is a one-dimensional, finite difference model developed to simulate the transport of contaminants displaying linear partitioning behavior through the vadose zone to the water table by aqueous advection and diffusion. Linear equilibrium partitioning relationships are used to determine chemical concentrations; the model can be configured to address a finite source.

SESOIL is a one-dimensional, finite difference model developed to evaluate the transport of contaminants through the vadose zone. The model can be used to estimate the rate of vertical contaminant transport and transformation through the soil to the groundwater table. Fate processes that can be incorporated for VOCs include adsorption, diffusion, volatilization, first-order chemical decay, and biodegradation.

Additional modeling solutions have been developed to estimate quantities of remaining contamination based on equilibrium/rebound data (Stewart, 2001). These models are useful in estimating remediation timeframes and the potential impact of remaining VOC residuals on underlying groundwater.

6.3 Technical and Economic Feasibility Assessments

In some states, including California, very conservative soil-to-groundwater cleanup standards have been enforced at Air Force SVE sites. After 5 to 10 years of operation, many of these sites have failed to achieve these standards and are expecting additional years of diffusion-limited recovery before standards can be achieved. Regulatory policies have been written that allow sites with low VOC recovery rates to be turned off if certain criteria are met. For example, if a groundwater system is expected to operate at a site for decades, the additional leaching of low levels of VOCs may not add to the total groundwater cleanup time. In this case the cost of continuing to operate the SVE system may not be justified given the marginal benefit of VOC removal. In this case the additional soil contaminant removal may be technically feasible but not economically prudent. Under these circumstances, some regulatory agencies have allowed system shutdown without reaching cleanup criteria. The Air Force is normally required to demonstrate that the cost of removing additional VOCs from the soil is high compared to

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the negligible benefit to groundwater quality. This approach known as SVE Termination or Optimization Process (STOP), is being used at the former Castle AFB, CA, and is provided in Appendix B.

SECTION 7

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APPENDIX A

CALCULATE SOIL GAS CONTAMINANT MASS

CALCULATE SOIL GAS CONTAMINANT MASS

- Apply the following factors to convert concentrations of µg/L in soil gas to mg/kg mass in soil:

  1. TCE   0.001316
  2. PCE   0.001445
  3. Cis-1,2-DCE   0.001397
  4. CTCL (carbon tetrachloride)   0.000583
  5. VC (vinyl chloride)   0.000257
  6. BZ (benzene)   0.001418
  7. BZME (toluene)   0.002677
  8. Xylenes   0.002559
  9. 1,1-DCE   0.000488
  10. BDCME (bromodichloromethane)   0.002193

- Calculate contaminant mass for each of the depth zones (0 to 10 feet bgs, 10 to 20 feet bgs, etc.) using the following general equation:

  Mass (in grams) = conversion factor (above) x plume area x thickness of depth zone x soil gas concentration in depth zone x soil bulk density x appropriate unit conversion factors.

- Calculate total contaminant mass by summing the calculated mass in each of the depth zones.

Example: Conversion Factor for TCE

Soil Gas Equation

$$C_t = 0.001 C_g \left(\frac{F_{oc} K_{oc} \rho_b}{H} + \frac{\theta_w}{H} + \theta_A \right) \Big/ \rho_b$$

For soils and TCE:

C_t =   Total contaminant concentration (mg/kg).

C_g =   Soil gas contaminant concentration (µg/L).

F_{oc} =   Organic carbon fraction (dimensionless).

K_{oc} =   Water/organic carbon partition coefficient (ml/kg).

ρ_b =   soil bulk density (g/cm^3).

H   =   Henry's law constant (0.363 dimensionless).

Θ_w =   Soil Water-filled porosity (dimensionless).

Θ_A =   Soil Air-filled porosity (dimensionless).

APPENDIX B

SVE TURN OFF CRITERIA

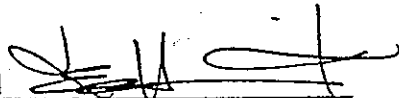MEMORANDUM FOR SEE DISTRIBUTION LIST

FROM: Castle Remedial Project Managers

SUBJECT: Revision to SVE Turn-Off Criteria

1. Attached is revision 2 to the SVE Termination or Optimization Process (STOP). The STOP was completed by the RPMs on 26 June 1999 and forwarded to our respective supervisors for comment. Comments have been received and incorporated into this document. We plan on applying this process at Discharge Area 8 (DA-8) to determine its practicality.   If proven successful at DA-8, this process should be used at Castle to close all SVE sites.
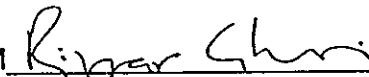
2. If you have any questions or concerns, please feel free to contact any of the Castle RPMs.
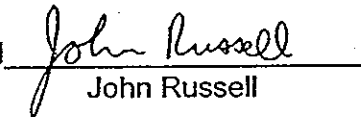
US EPA/RPM _____   CA DTSC/RPM _____
                  Lisa Hanusiak   Rizgar Ghazi

AFBCA/RPM _____ CRWQCB/RPM _____
                  Steve LaFreniere   John Russell

Attachments:
SVE Termination or Optimization Process (STOP)
Distribution List

SVE TURN-OFF CRITERIA
SVE Termination or Optimization Process
Castle AFB

Introduction

The cleanup goal for the sites to be remediated using soil vapor extraction (SVE) is the lowest cleanup level technically and economically achievable to protect human health and the environment, including groundwater quality. The sites to be evaluated at Castle AFB overlie contaminated groundwater which is addressed in the final Comprehensive Base wide Part 1 Record of Decision, signed in 1997. The need to continue operation of an SVE system shall be evaluated at each site or group of sites. This evaluation will be called an SVE Termination or Optimization Process (STOP) and will be considered a primary document under the Federal Facilities Agreement and it may formally document site closure.

The STOP should be conducted after all the parties agree that:
- The site has been adequately characterized;
- The site does not pose an unacceptable risk to human health;
- The SVE system has been optimally designed;
- Performance monitoring indicates that the site conceptual model is accurate;
- Contaminant removal rates have stabilized and approached asymptotic levels, following one or more temporary shutdown periods; and
- The SVE system has been optimized to the greatest extent possible.

The decision to continue operation for an SVE system will depend upon the analysis of the three criteria listed below. It is always technically possible to remove more mass, but eventually whether to continued operations requires evaluating the tradeoff between certain monetary expenditure and uncertain environmental benefit. If the remaining contaminant mass in the vadose zone will not reach the groundwater, additional remediation will not be warranted. If the contaminant concentration in the leachate entering the aquifer from the vadose zone is below the aquifer cleanup level (MCLs), the aquifer will not be unacceptably degraded further. Lower cleanup levels may be achievable, but the additional cleanup required to reach them would likely not be justified. Several lines of evidence must be used to make this professional judgment since measuring actual leachate concentrations may be technically impractical and predicting leachate concentrations via modeling might be inaccurate.

This process represents a compromise of the various parties' policies and should be used as a guide in preparing the SCOU Part 2 Record of Decision.

Decision Criteria

The decision to continue SVE will be based on scientific, economic, and engineering judgment using the following criteria in sequence. The Air Force and the regulatory agencies acknowledge that there is uncertainty inherent in all of the elements used in the STOP, and that consensus is necessary to determine the levels of uncertainty that are acceptable in each of the elements.

I. Will the residual mass in the vadose zone reach the groundwater?

   To answer this question, STOP elements "a" through "f" must be addressed.
   - If the answer is "no", then proceed with site closure.
   - If the answer is "yes" or "unknown", then proceed to criterion II.

II. Will the residual mass in the vadose zone cause the contaminant concentrations in the leachate to exceed the aquifer cleanup level?

   To answer this question, STOP elements "a" through "g" must be addressed.
   - If the answer is "no", then proceed with site closure.
   - If the answer is "yes", or "unknown", then proceed to criterion III which requires a complete STOP.

III. Based on an evaluation of all of the elements, is it appropriate to permanently shut-off the SVE System?

   To answer this question, all STOP elements must be addressed.
   - If the answer is "yes", then shut off the SVE system and proceed with site closure.
   - If the answer is "no" continue SVE operation or develop alternate remedial strategy.

Elements of the STOP

The following elements should be applied to evaluate the criteria listed above.

a. What is the estimated residual contaminant mass and areal and vertical extent of the remaining vadose zone contaminant plume? Include contaminant isoconcentration maps

and plume cross-sections to illustrate the contaminant concentrations and distribution in the subsurface.

b. Do the data indicate migration towards the groundwater? Qualitative answers to this question may be either "yes", "no" or "unable to make a determination". Evidence for migration towards groundwater may include such lines of evidence as: 1) increasing contaminant concentrations in onsite monitoring wells; 2) pre-remediation soil gas profiles from nested wells to estimate the contaminant's propensity for migration; and 3) post-remediation time-series profiles of soil gas concentrations in nested wells.

c. What is the lithology of areas that do and do not demonstrate rebounds in soil gas concentration? Use site-specific information, and include as much information as possible, such as porosity, moisture content and carbon content of soil, etc.

d. What are the actual site specific infiltration and percolation rates? If site specific data are not available, what are the predicted rates?

e. Are there sufficient historical groundwater monitoring data for wells at or adjacent to the site to determine whether the vadose zone plume has or has not impacted the groundwater? (This determination may not be possible due to active groundwater extraction in the area.)

f. Are there any other site specific factors that should be considered in the evaluation such as site history and physical characteristics (e.g. organic carbon, biodegradation)? Factors to consider for this element include: 1) the nature of the release (for example: one-time spill or continued release over time?; how long ago the release occurred or ceased?; was the release to surface soil, or through a conduit to the subsurface such as a French drain, dry well, or leaking sewer line?, etc.) and 2) any site-specific physical characteristics that may enhance or retard the contaminants subsurface migration (such as unusual presence or absence of low permeability layers, high carbon content of soil, etc.).

g. What is the actual or predicted concentration and mass flux rate of leachate leaving the vadose zone?

h. What was the mass removal rate prior to SVE shutdown?

i. What are the VOC concentration and cumulative mass removed expressed as a function of time?

j. How much money has been spent to date on the site's remediation?

k. Are further enhancements to the SVE systems predicted to be technically- or cost-effective?

l. What are the locations and capture zones of operating groundwater extraction wells relative to the vadose zone contaminant plume? Will the existing wells effectively capture the contaminants from the site? If not, what are the additional costs to add groundwater wells?

m. What is the incremental cost over time of vadose zone remediation compared to the incremental cost over time for groundwater remediation provided that the underlying contamination has not reached aquifer cleanup levels? In other words, will the residual mass in the vadose zone significantly prolong the time and increase the cost to attain the aquifer cleanup level?

To implement this element, the following costs need to be calculated:
- The cost to reach the aquifer cleanup level *without* the additional impact from the site (GW_0);
- The cost to reach the aquifer cleanup level *with* the additional impact from the site (GW_1);
- The cost to reach the aquifer cleanup level *with* the additional impact from the site after an additional period of SVE operation (GW_2); and
- The cost of the additional SVE operation (SVE_1).

These costs can be calculated following the steps outlined below:

1. Estimate the predicted time required for the groundwater extraction system to reach aquifer cleanup level(s) in the vicinity of the site *without* additional impact from the site.
2. Estimate the monthly cost to continue operation of the groundwater extraction system in the area impacted by the site?
3. Calculate the cost to reach the aquifer cleanup level (GW_0) in the vicinity of the site *without* the additional impact from the site by multiplying the results of step 1 above by the results of step 2 above.   (GW_0 = step 1 x step 2).
4. Using the measured residual soil gas concentrations at the site, calculate the mass of the residual contaminant in the vadose zone (same as element "a").
5. Estimate the site's potential impact to groundwater using appropriate vadose zone and groundwater fate and transport models.
6. Estimate the time to reach the groundwater aquifer cleanup level using the modeling results obtained in step 5 above.
7. Estimate the monthly cost to continue operation of the groundwater extraction system in the area impacted by the site?
8. Calculate the cost to reach the aquifer cleanup level *with* the additional impact from the site (GW_1) by multiplying the results of step 6 by the results of step 7. (GW_1 = step 6 x step 7).
9. Estimate the monthly cost of continuing to operate the SVE system based on historical costs (including operation and shutdown periods for the site).

10. Estimate the cost to run SVE system for an agreed-upon length of time that is based on site-specific conditions, such as 6 months (SVE_1), by multiplying the agreed upon length of time by the results of step 9. (SVE_1 = length of time x step 9).

11. Estimate what the predicted residual soil gas concentrations would be if the SVE system was operated for the additional agreed-upon length of time.

12. Estimate the impact to groundwater from the site based on the results of step 11. This estimation can be conducted similarly to step 5 above.

13. Estimate the predicted time required for groundwater extraction system to reach aquifer cleanup level *with* the additional impact from the site after operation of the SVE system for an additional period of time.

14. Calculate the cost to reach the aquifer cleanup level (GW_2) *with* the additional impact from the site after operation of the SVE system for an additional period of time. This cost is calculated by multiplying the results of step 13 by the results of step 2. (GW_2 = step 13 x step 2).

15. Compare the costs of groundwater extraction *without* additional SVE at the site to the costs of groundwater extraction *with* additional SVE at the site. Is the cost of groundwater extraction without additional SVE at the site greater than or equal to the cost of groundwater extraction with SVE at the site plus the additional SVE costs.? Is this cost savings to the GW system worth the expense of continued SVE for an additional amount of time? Mathematically, this can be expressed as:

$$\text{Is} \quad (GW_1 - GW_0) \leq (SVE_1) + (GW_2 - GW_0)?$$