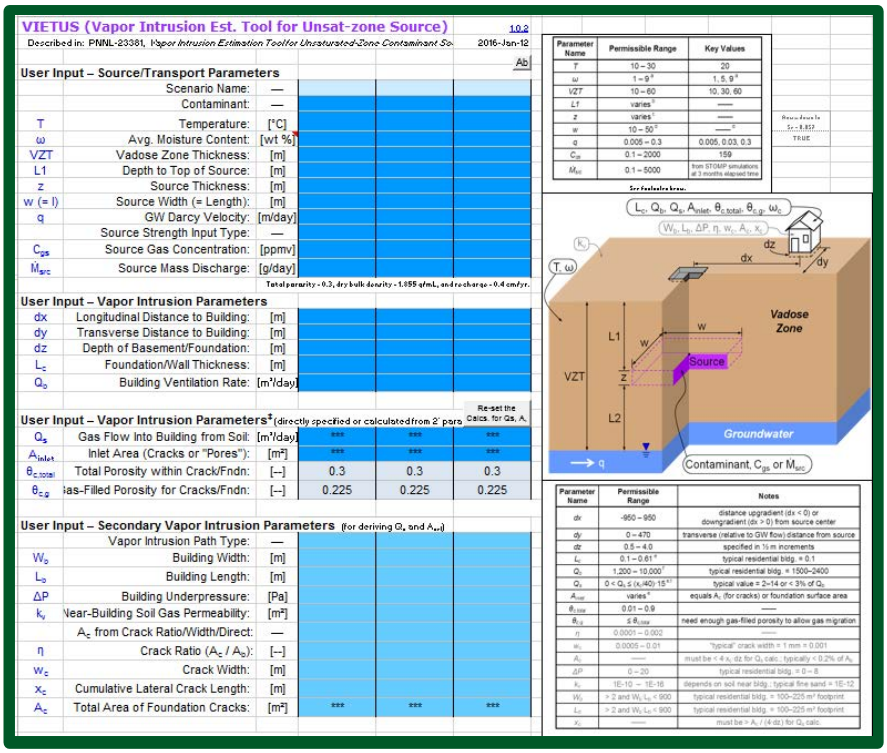
ESTCP
Cost and Performance Report

(ER-201125)



Use of Mass-Flux Measurement and Vapor-Phase Tomography to Quantify Vadose-Zone Source Strength and Distribution

January 2016

This document has been cleared for public release; Distribution Statement A

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

COST & PERFORMANCE REPORT

Project: ER-201125

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY ES-1

1.0 INTRODUCTION 1
- 1.1 BACKGROUND 1
- 1.2 OBJECTIVE OF THE DEMONSTRATION 2
- 1.3 REGULATORY DRIVERS 2

2.0 TECHNOLOGY 5
- 2.1 TECHNOLOGY DESCRIPTION 5
  - 2.1.1 Multi-Stage Vapor-Phase Contaminant Mass Discharge (MS-CMD) 5
  - 2.1.2 Vapor-Phase Tomography (VPT) 8
  - 2.1.3 Chronology of Technology Development 10
  - 2.1.4 Technology Applications 10
- 2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 11

3.0 PERFORMANCE OBJECTIVES 13
- 3.1 PERFORMANCE OBJECTIVE 1: PRODUCE QUANTITATIVE MEASUREMENTS OF CONTAMINANT MASS DISCHARGE 13
- 3.2 PERFORMANCE OBJECTIVE 2: PRODUCE CONTAMINANT MASS DISCHARGE VALUES WITH UNCERTAINTY BOUNDS 13
- 3.3 PERFORMANCE OBJECTIVE 3: ASSESSMENT OF MASS-TRANSFER CONDITIONS 14
- 3.4 PERFORMANCE OBJECTIVE 4: PRODUCE 3D MAP OF CONTAMINANT SOURCE DISTRIBUTION 14
- 3.5 PERFORMANCE OBJECTIVE 5: IMPROVED ANALYSIS OF RISK 14

4.0 SITE DESCRIPTION 15
- 4.1 SITE LOCATION AND HISTORY 15
  - 4.1.1 Tucson International Airport Area (TIAA), Tucson, AZ 15
  - 4.1.2 Site 2, AZ 15
  - 4.1.3 Hill Air Force Base (AFB), south of Ogden, UT 15
- 4.2 SITE GEOLOGY AND HYDROGEOLOGY 15
- 4.3 CONTAMINANT DISTRIBUTION AND REMEDIATION ACTIVITIES 15

5.0 TEST DESIGN 17

6.0 PERFORMANCE ASSESSMENT 19
- 6.1 PRODUCE QUANTITATIVE MEASUREMENTS OF CONTAMINANT MASS DISCHARGE (PERFORMANCE OBJECTIVE 1) 19
- 6.2 PRODUCE CONTAMINANT MASS DISCHARGE VALUES WITH UNCERTAINTY BOUNDS (PERFORMANCE OBJECTIVE 2) 19
- 6.3 ASSESSMENT OF MASS-TRANSFER CONDITIONS (PERFORMANCE OBJECTIVE 3) 20

LIST OF TABLES

Page

6.4 PRODUCE 3D MAP OF CONTAMINANT SOURCE DISTRIBUTION (PERFORMANCE OBJECTIVE 4) 21
6.5 IMPROVED ANALYSIS OF RISK (PERFORMANCE OBJECTIVE 5) 21
6.6 VIETUS TOOL 21
6.7 ESTIMATION OF INITIAL SOURCE MASS 21

7.0 COST ASSESSMENT 23
7.1 COST MODEL 23
7.2 COST DRIVERS 24
7.3 COST ANALYSIS 24

8.0 IMPLEMENTATION ISSUES AND POTENTIAL COST AVOIDANCE 25
8.1 IMPLEMENTATION ISSUES 25
8.2 POTENTIAL COST AVOIDANCE 25

9.0 REFERENCES 27

APPENDIX A APPENDIX A – POINTS OF CONTACT A-1

LIST OF FIGURES

Page

Figure 1. Schematic of Representative Data Set Collected from an MS-CMD Test..... 5

Figure 2. Schematic of a Vadose Zone Source Zone, Associated Mass-Transfer Processes, and a Vapor-Phase Mass Discharge Test. 7

Figure 3. Schematics of the Extraction Well and Four Monitoring Wells. 8

LIST OF TABLES

Page

Table 1. Performance Objectives 13

ACRONYMS AND ABBREVIATIONS

μg/L	microgram(s) per liter
3D	three-dimensional
AFB	Air Force Base
CMD_{ng}	contaminant mass discharge, natural gradient
COC	contaminant of concern
DCE	1,2-dichloroethane
DNAPL	dense non-aqueous phase liquid
DoD	U.S. Department of Defense
ESTCP	Environmental Security Technology Certification Program
g/d	gram(s) per day
kg	kilogram(s)
MS-CMD	multi-stage contaminant mass discharge
OU	Operable Unit
PNNL	Pacific Northwest National Laboratory
SERDP	Strategic Environmental Research and Development Program
SGS	soil gas survey
SSW	south-southwest
SVE	soil vapor extraction
TCE	trichloroethylene
TIAA	Tucson International Airport Authority
VOC	volatile organic compound
VPT	vapor-phase tomography

Page Intentionally Left Blank

ACKNOWLEDGEMENTS

This project was supported by the Environmental Security Technology Certification Program (ESTCP). We would like to thank our collaborators, K. C. Carroll (New Mexico State University) and Mike Truex and Mart Oostrom (Pacific Northwest National Laboratory) for their contributions. We also would like to thank Dr. Candice Morrison and other current and former members of the University of Arizona Contaminant Transport Group for their assistance. Thank you to Fred Brinker of the Tucson International Airport Authority (TIAA) for his support of the project, and Manfred Plaschke, Peter Schwarz, Daniel Ojinaga, and Celia Martinez from CRA, Inc., for their assistance in conducting the test at the TIAA site. Also, thank you to those who assisted in planning and implementation of the test conducted at site 2, and to Dr. Robert Hinchee for alerting us to the Hill Air Force Base data.

Page Intentionally Left Blank

EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The overall goal of this project was to demonstrate that the multi-stage vapor-phase contaminant mass discharge (MS-CMD) test and vapor-phase tomography (VPT) can effectively characterize persistent volatile organic compound (VOC) sources in the vadose zone and measure their associated mass discharge. It is anticipated that these technologies will improve evaluation of vadose zone source impacts on groundwater and vapor intrusion.

The specific performance objectives for this demonstration were as follows:

1. Produce quantitative measurements of contaminant mass discharge
2. Produce contaminant mass discharge values with uncertainty bounds
3. Assess mass-transfer conditions
4. Produce a three-dimensional (3D) map of contaminant source distribution
5. Improve analysis of risk

All five performance objectives were met.

TECHNOLOGY DESCRIPTION

Multi-Stage Vapor-Phase Contaminant Mass Discharge (MS-CMD)

The vapor-phase cyclic or MS-CMD test was recently developed to measure mass discharge for vadose zone sources under both forced gradient and pseudo-natural-gradient conditions (Brusseau et al., 2010). The vapor-phase MS-CMD test consists of three stages: an extended initial extraction stage (identical to a standard CMD test), a rebound stage, and a second extraction stage.

In brief, Stage 1 consists of an initial extraction wherein concentrations of contaminant in the effluent gas are monitored. The extraction continues until quasi-steady-state is attained with respect to effluent concentrations. The purpose of the initial extraction stage is to sweep vapor-phase contaminant from the advective domains. At this point, the extraction is stopped, and the system is monitored to characterize potential rebound (Stage 2). This rebound represents transfer of contaminant from poorly accessible domains to the accessible domain. A second extraction stage is then implemented (Stage 3). Contaminant mass removed during the second extraction stage is tabulated to determine the mass transferred from the poorly accessible domains to the advective domain during the rebound stage.

Vapor-Phase Tomography (VPT)

The VPT method is based on conducting a short-term vapor extraction test at a vertically discrete point, while collecting vapor-phase contaminant concentration data at multiple vertically discrete sampling points surrounding the extraction point. For the test, air is extracted from the vadose zone at a specific point (depth and location). The vapor-phase contaminant concentration (and the gas-flow rate if desired) is measured simultaneously at several other locations. The test is of sufficient length to remove the initial resident volume of contaminant in the local area, allowing interrogation of the source-associated mass flux. In essence, the data collected from the test is analogous to a 3D “snapshot” of the source(s) of the vapor-phase contamination.

DEMONSTRATION RESULTS

Vapor concentrations collected during the MS-CMD test were plotted as a function of elapsed time. The resultant contaminant elution curve was examined to evaluate mass-transfer conditions. The appearance of specific landmarks were evaluated, such as length of the steady-state stage, occurrence of an asymptote, and occurrence of a rebound. This information was used to qualitatively assess the conditions influencing vapor-phase mass transfer and mass removal.

The VPT test produced 3D maps of VOC concentrations and mass flux in which spatial differences were observed, indicating the presence of a vapor source located in the south-southwest (SSW) quadrant of the test area, between the water table and the monitoring well screened interval. These results were consistent with those of the sediment data. In comparison, the standard soil gas survey (SGS) test was unable to identify spatial variability of vapor concentrations or delineate a potential source. Thus, the VPT test provided a more robust source characterization compared to the SGS method. These results illustrate the utility of the VPT test as a higher resolution method for characterizing VOC source distribution in the vadose zone. The analyses of mass-transfer conditions illustrate the ability to use the results of the MS-CMD and VPT tests to evaluate mass-transfer conditions and delineate the presence of persistent contamination.

IMPLEMENTATION ISSUES

Overall, the MS-CMD test has a relatively low implementation cost (modest infrastructure and sampling requirements) and relatively simple data analysis requirements. Therefore, it is expected that this test would be beneficial under many conditions, and applicable for a wide array of sites. In many situations, the cost of implementing the MS-CMD test will be less than the cost of implementing a standard SGS test. The application of a full-scale VPT test (with multiple local extractions) is anticipated to be reserved generally for two scenarios: First, for large or complex sites that have active soil vapor extraction (SVE) operations, and secondly, application of the tomography methods for sites that do not have substantial infrastructure present may be warranted for sites that have a greater degree of complexity or other special circumstances that warrant the additional costs. For other scenarios, a more limited VPT test set could be implemented, thus reducing overall costs.

COST ASSESSMENT

The cost assessment for both technologies is described in detail within the “Decision support tool for application of MS-CMD and VPT technologies”. This decision tool is a Microsoft Excel spreadsheet with two main functions: to provide a summary and guidance for the implementation of each technology, and to be used as a cost assessment tool allowing the user to determine the cost of implementing each technology for several scenarios.

Sample analysis costs are a major component for overall cost estimates for the MS-CMD and SGS tests. In many situations, the cost of implementing the MS-CMD test will be less than the cost of implementing a standard SGS test. The VPT test requires multiple wells, each with multiple screened intervals. In addition, multiple samples are collected for each sampling point. Thus, the costs for implementing a VPT test are in the same range as that of an SGS test. However, the VPT test is designed to be scalable, which allows its use and associated costs to be matched to site-specific conditions and objectives.

1.0 INTRODUCTION

This document serves as the final report for Environmental Security Technology Certification Program (ESTCP) Project Number ER-201125, "Use Of Mass-Flux Measurement and Vapor-Phase Tomography to Quantify Vadose Zone Source Strength and Distribution." It was prepared by the Principal Investigators for this project, affiliated with the University of Arizona, with contributions from subcontractors at Pacific Northwest National Laboratory (PNNL). It was prepared in accordance with ESTCP program guidance (ESTCP, 2012).

1.1 BACKGROUND

The U.S. Department of Defense (DoD) has focused significant effort on characterizing and treating chlorinated solvent sources in groundwater. This demonstration project addresses contaminant sources located in the vadose zone. There are two primary concerns associated with sites that contain vadose zone volatile organic compound (VOC) sources. First, discharge of contaminant vapor from the vadose zone source may impact the underlying groundwater. This could contribute to overall risk posed by the site and delay attainment of groundwater cleanup goals. Second, contaminant vapor from the vadose zone source may migrate to the land surface and transfer into buildings, thereby causing vapor intrusion. The DoD manages thousands of sites wherein the vadose zone is contaminated by chlorinated solvents and other VOCs. Therefore, addressing this issue is of critical importance to DoD for long-term environmental management.

Currently, the decision to require remediation of a vadose zone source zone is typically based on assessing the potential impact of the vadose zone source on groundwater or vapor intrusion (as reviewed in Brusseau et al., 2013). Concomitantly, setting appropriate vadose zone remediation goals once a remedy selection is made, as well as evaluating attainment of these remediation goals, requires evaluating these persistent sources in terms of their impact on groundwater remediation goals or vapor intrusion concerns. These issues are of particular relevance for soil vapor extraction (SVE), which is the presumptive remedy for vadose zone systems contaminated by chlorinated solvents. Standard practices guidance manuals developed by the EPA (2001) and the USACE (2002) outline procedures for assessing transition/closure of SVE systems using several types of analyses, including evaluating the impact of vadose zone source contamination on groundwater. Given the many active SVE systems in operation at DoD and other sites, development of robust methods to support transition/closure decisions is of paramount importance.

Characterizing the impact of vadose zone contaminant sources on groundwater or vapor intrusion requires determination of the contaminant mass discharge from the source. The standard approach for characterizing vapor-phase mass discharge is to measure static contaminant concentrations for vapor (soil gas survey [SGS]) or sediment (borehole cores) samples, and to use them as input for a mathematical screening model to estimate contaminant mass discharge (Johnson and Ettinger, 1991; Rosenbloom et al., 1993; DiGiulio et al., 1999; Hers et al., 2002). This approach has become widely used to evaluate the impact of vadose zone sources on groundwater or vapor intrusion. However, this approach can be subject to considerable uncertainty in the estimates obtained, depending upon the robustness of the input data as well as the simplifications employed in the development and application of the screening model. For example, due to practical and cost limitations on the number of sampling points, the SGS or sediment coring methods often do not provide data of sufficient resolution to accurately characterize the spatial distribution of the contaminant, particularly in the vertical dimension (Rossabi et al., 2003; Feenstra, 2005).

Second, some portion of contaminant mass in the vadose zone is usually associated with regions that are poorly accessible (e.g., low permeability zones). Characterizing mass discharge associated with these regions may often be problematic with the SGS method (DeGroot and Lutenegger, 1998; Thomson and Flynn, 2000; McAlary et al., 2009; Mainhagu et al., 2015). Third, the typical implementation approach for the SGS or sediment coring methods are not able to readily characterize the temporal variability of mass-transfer processes. The potential limitations associated with typical screening models for VOC transport are well documented. As a result of these and other issues, the current standard approach for characterizing vapor-phase contaminant mass discharge can be influenced by a large degree of uncertainty. Developing improved methods to characterize vapor transport from sources in the vadose zone was noted as a critical need by a Strategic Environmental Research and Development Program (SERDP)/ESTCP expert panel (SERDP, 2006).

This project was conducted to demonstrate two vadose zone characterization technologies that can provide more accurate measures of vapor-phase contaminant mass discharge, characterize mass-transfer conditions, and provide a higher resolution characterization of the source distribution. These novel technologies will support improved assessment of vadose zone source impacts on groundwater and vapor intrusion. They will also support improved optimization of SVE systems, as well as support transition/closure decisions for SVE systems.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall goal of this project was to demonstrate that the multi-stage vapor-phase contaminant mass discharge (MS-CMD) test and vapor-phase tomography (VPT) can effectively characterize persistent VOC sources in the vadose zone and measure their associated mass discharge. It is anticipated that these technologies will improve evaluation of vadose zone source impacts on groundwater and vapor intrusion.

The specific technical objectives for this demonstration were as follows:

1. Demonstrate the MS-CMD test as an effective means to quantitatively measure VOC mass discharge in the vadose zone.
2. Demonstrate VPT as a means of characterizing the 3D distribution of persistent VOC sources in the vadose zone.
3. Determine cost performance factors for applying the technologies as a function of site conditions, and compare them to costs associated with standard practices.
4. Develop decision-support tools to assist users in selection and application of the technology.

1.3 REGULATORY DRIVERS

As a result of past operation and disposal practices, chlorinated solvent liquid is present in the vadose zone at many if not most of the chlorinated solvent dense non-aqueous phase liquid (DNAPL) sites managed by the DoD. There are two primary concerns associated with sites that contain vadose zone DNAPL sources. First, discharge of contaminant vapor from the vadose zone source may impact the underlying groundwater. This could contribute to overall risk posed by the site and delay attainment of groundwater cleanup goals. Second, contaminant vapor from the vadose zone source may migrate to the land surface and transfer into buildings, thereby causing vapor intrusion.

Currently, the decision to require remediation of a vadose zone source zone is typically based on assessing the potential impact of the vadose zone source on groundwater or vapor intrusion. Concomitantly, setting appropriate vadose zone remediation goals once a remedy selection is made, as well as evaluating attainment of these remediation goals, requires evaluating these persistent sources in terms of their impact on groundwater remediation goals or vapor intrusion concerns. Characterizing the impact of vadose zone contaminant sources on groundwater or vapor intrusion requires determination of the contaminant mass discharge from the source. This project will demonstrate a vadose zone characterization technology that can provide a more accurate measure of vapor-phase contaminant mass discharge, characterize mass-transfer conditions, and provide a higher resolution characterization of the source distribution. It is anticipated that this technology will improve evaluation of vadose zone source impacts on groundwater and vapor intrusion.

Page Intentionally Left Blank

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Two vadose zone characterization technologies were demonstrated in this project: multi-stage vapor-phase contaminant mass discharge (MS-CMD) test and vapor-phase tomography (VPT). Both are discussed in more detail below.

2.1.1 Multi-Stage Vapor-Phase Contaminant Mass Discharge (MS-CMD)

The vapor-phase cyclic or MS-CMD test was recently developed to measure mass discharge for vadose zone sources under both forced gradient and pseudo-natural-gradient conditions (Brusseau et al., 2010). The vapor-phase MS-CMD test consists of three stages: an extended initial extraction stage (identical to a standard CMD test), a rebound stage, and a second extraction stage (Figure 1). In brief, Stage 1 consists of an initial extraction wherein concentrations of contaminant in the effluent gas are monitored. The extraction continues until quasi-steady-state is attained with respect to effluent concentrations. The purpose of the initial extraction stage is to sweep vapor-phase contaminant from the advective (pneumatically accessible) domains within the treatment zone. At this point, the extraction is stopped and the system is monitored to characterize potential rebound of vapor-phase concentrations (Stage 2). This rebound represents transfer of contaminant from poorly accessible domains to the accessible domain. A second extraction stage is then implemented (Stage 3) once concentrations have stabilized. Contaminant mass removed during the second extraction stage is tabulated to determine the mass that transferred from the poorly accessible domains to the advective domain during the rebound stage.

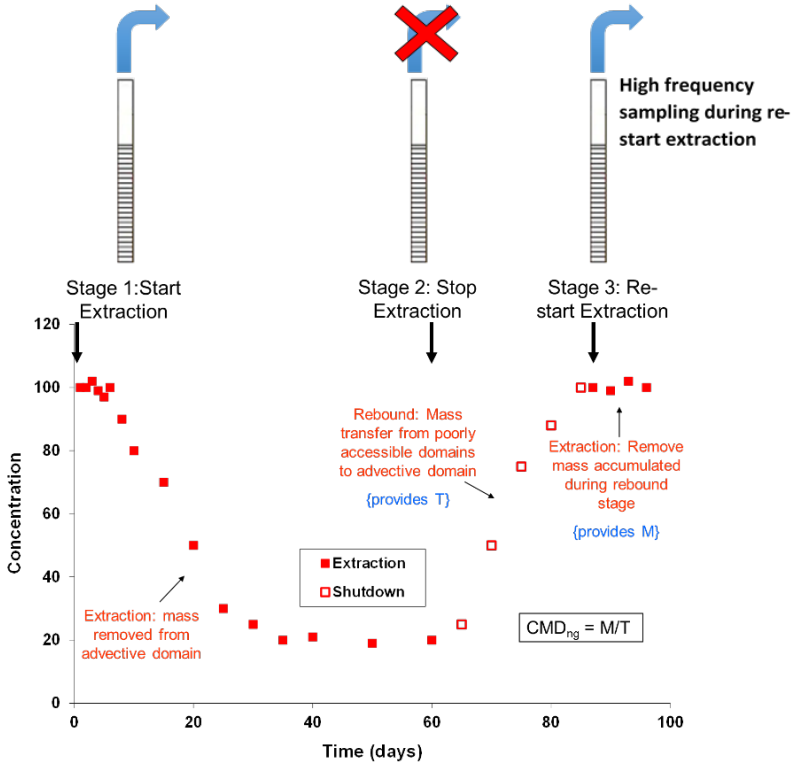


Figure 1. Schematic of Representative Data Set Collected from an MS-CMD Test.

Data collected during the early portion of the initial (or second) vapor extraction stage can be used to quantify the maximum mass discharge obtained under forced gradient conditions. Conversely, data collected at the end of the initial extraction stage (during the steady-state condition) can be used to quantify the asymptotic forced gradient mass discharge. This approach, essentially identical to that employed for analysis of data collected from operating SVE systems (USACE, 2002), can be used to help evaluate SVE performance for sites that have active SVE operations, or to provide data for design and implementation of a new SVE system. The standard (i.e., single-stage) vapor-phase CMD test can be conducted discretely at several locations within a site to characterize the spatial distribution of sources in the vadose zone (Carroll et al., 2013). Samples can also be collected from multiple monitoring points surrounding each extraction point to further characterize spatial distributions (Mainhagu et al., 2014), leading to the concept of a VPT test (Brusseau et al., 2013; Mainhagu et al., 2015).

The CMD values produced under the forced gradient conditions associated with vapor extraction may not be directly representative of values associated with natural gradient conditions, which is the information desired for assessing risk. The innovative component of the vapor-phase MS-CMD test is the ability to measure the CMD associated with the source under pseudo-natural-gradient conditions (CMD_{ng}), with the rebound period serving as a limiting-case representation of mass transfer. This entity is determined from information collected during the second and third stages of the test. First, the mass of contaminant removed is tabulated for typically the first one-to-two equivalent gas pore volumes extracted during the second extraction stage (i.e., after the rebound period). The specific number of pore volumes would depend upon the contributions of dispersion and retardation to VOC transport in the advective domain. The tabulated mass is presumed to primarily represent mass that transferred during the preceding rebound phase from contaminant sources for which mass transfer is constrained. These sources could represent, for example, organic liquid (DNAPL) or sorbed mass in either or both advective and lower permeability domains, or vapor-phase mass retained in lower permeability zones. Second, the mass removed is divided by the time required to attain stable concentrations during the rebound stage to determine CMD_{ng} (M/T). The CMD value determined in this manner is a measure of CMD at the specific time of characterization, which can be used to evaluate impacts of the VOC source on groundwater quality and vapor intrusion. The test can be conducted multiple times at different time points to characterize temporal variability.

The MS-CMD test is designed to actively stress the system by using induced gradient (extraction) conditions. This enhances the accuracy and sensitivity of characterizing mass-transfer constraints and the temporal variability of mass discharge. This is in contrast to the SGS and sediment coring methods, which provide concentrations under static conditions. Furthermore, the method interrogates the entire domain influenced by the extraction well(s), as opposed to the point-sampling basis of the standard methods. Characterization of mass discharge is based on the typical vapor transport behavior observed for natural subsurface environments (see Figure 2). First, the initial vapor extraction phase removes vapor mass primarily from the regions that experience substantial gas flow (the transmissive or “advective” domain). Second, the attainment of a steady-state effluent concentration during extraction represents a condition wherein vapor-phase concentrations in the advective domain are limited by mass transfer from poorly accessible domains (e.g., mass transfer from trapped organic liquid, desorption of mass sorbed by sediment grains, and diffusion from lower permeability units). Third, mass transfer from the poorly-accessible domains during the non-extraction (rebound) stage will re-supply the advective domain. This latter process represents the contaminant mass discharge for the source under natural gradient conditions.

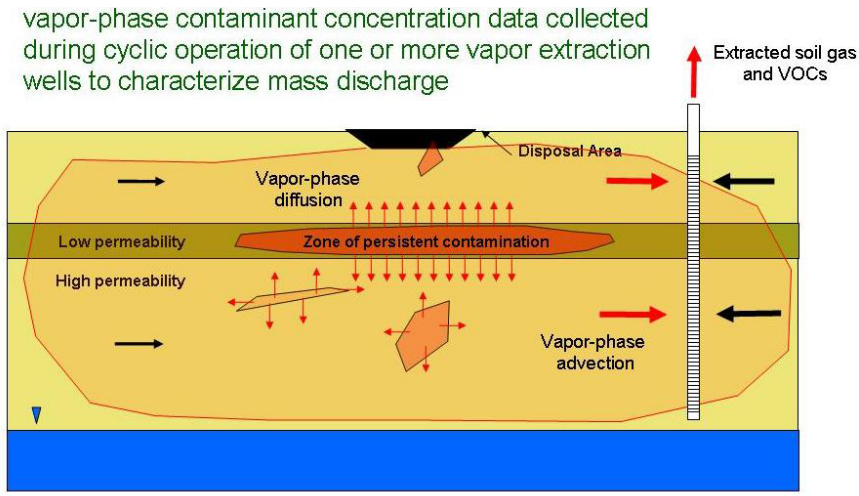


Figure 2. Schematic of a Vadose Zone Source Zone, Associated Mass-Transfer Processes, and a Vapor-Phase Mass Discharge Test.

The data obtained during the vapor-phase mass discharge test can be used to evaluate mass-transfer conditions. Specifically, the resultant contaminant elution curve obtained during the extraction and non-extraction phases can be examined for the appearance of specific landmarks, such as length of the steady-state stage, occurrence of an asymptote, and occurrence of a rebound (Figure 1). This information can be used to qualitatively assess the conditions influencing vapor-phase mass transfer and mass removal. For example, this information can be used to identify potential conditions of rate-limited mass transfer, and the approximate degree of rate limitation.

Implementation requirements and costs for the MS-CMD test are modest and include the following:

- Equipment and infrastructure (completed extraction well, vapor extraction system),
- Data collection (vapor samples, vapor discharge), and
- Data analysis (spreadsheet calculations).

The data collected during the MS-CMD test are used to determine CMD measurements, as follows:

CMD = M/T (mass/time)
CMD = contaminant mass discharge
M = mass of VOC removed during Stage 3
T = rebound time measured in Stage 2

M is determined by integration of the C and Q data collected during Stage 3, where

C = Contaminant of concern (COC) concentration (mass/vapor-volume)
Q = vapor discharge (vapor-volume/time)

N, the number of vapor pore volumes to remove during stage 3, is determined as follows:

$$N = x \times R \qquad \text{Eq. 1}$$

where R = retardation factor for COC
x = factor to account for non-ideal displacement, due to for example dispersion/spreading. This factor may typically range from 1 to 2.

TV, the total volume of vapor to be extracted, is calculated as follows:

$$TV = N \times PV \qquad \text{Eq. 2}$$

where PV = vapor pore volume of the test domain.

2.1.2 Vapor-Phase Tomography (VPT)

This method is based on conducting a short-term vapor extraction test at a vertically discrete point, while collecting vapor-phase contaminant concentration data at multiple vertically discrete sampling points surrounding the extraction point (see Figure 3). For the test, air is extracted from the vadose zone at a specific point (depth and location). The vapor-phase contaminant concentration (and the gas-flow rate if desired) is measured simultaneously at several other locations. The test is of sufficient length to remove the initial resident volume of contaminant in the local area, allowing interrogation of the source-associated mass flux. In essence, the data collected from the test is analogous to a 3D "snapshot" of the source(s) of the vapor-phase contamination. This approach allows determination of location-specific contaminant mass flux, and thus characterization of spatial distributions.

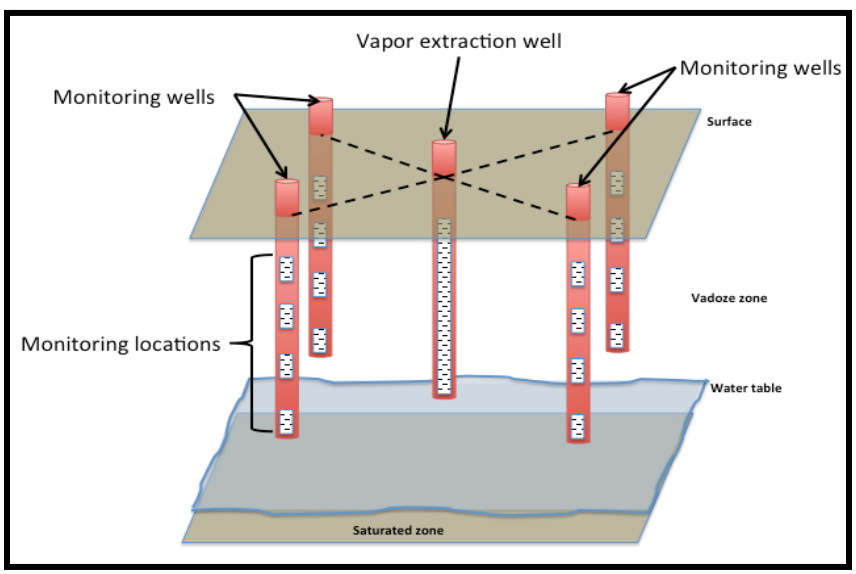


Figure 3. Schematics of the Extraction Well and Four Monitoring Wells.

The VPT test can be repeated at different extraction locations to obtain multiple sets of partially overlapped snapshots of the source distribution. These data are then integrated to enhance resolution of vapor-flux distribution in the subsurface.

Integral to the VPT test design is the collection of COC concentration data under induced gradient conditions. As discussed above for the MS-CMD test, this enhances the accuracy and sensitivity of the measurements compared to standard SGS methods. It is proposed that the final map of the source distribution will be more accurate (higher resolution) than that produced with the current approach based on SGSs.

The VPT method is analogous to the hydraulic and pneumatic tomographic tests that have been developed to characterize permeability distributions in the subsurface. However, for these methods, the parameter directly measured is hydraulic head or pressure. Thus, inverse modeling techniques must be applied to determine the parameter of interest (K). In contrast, the parameter of interest for the VPT test—VOC concentration—is measured directly with the VPT test. This greatly simplifies data analysis, as the use of complex data inversion algorithms and mathematical modeling are not required.

Partitioning tracer tomography has been recently proposed as a means to characterize DNAPL sources (e.g., Yeh and Zhu, 2007). It differs from VPT by requiring the injection of a tracer suite and is applicable only to sources with organic liquids present. The VPT test requires no tracer injection, and is focused on measuring the concentrations and flux of the resident COCs.

Implementation requirements and costs for the VPT test range from modest to moderate, and include the following:

- Equipment and infrastructure (completed extraction well, vapor extraction system, multiple monitoring wells with discrete sampling points),
- Data collection (vapor samples, vapor discharge, vacuum pressure), and
- Data analysis (spreadsheet calculations, 3D rendering).

The data collected during the VPT test are used to determine 3D mass flux measurements. The VOC mass flux is calculated based on the equation below, using known physical parameters and measured data obtained during the experiment:

$$Qc=Ci*(-K(Pb-Pa)i/(\mu*L) \qquad \text{Eq. 3}$$

where Qc = Contaminant mass flux
Ci = COC concentration at a specific location (noted i)
K = Permeability
(Pa-Pb)i = Pressure differential between the sampling location and the extraction well
μ= Viscosity

Values for permeability are required to complete the contaminant mass flux calculation. Any of the several various standard approaches available can be used to obtain the permeability values.

Note that if pressure data are collected during the VPT test, these data can be used as input for a pneumatic tomography application to determine a 3D distribution of permeability.

2.1.3 Chronology of Technology Development

The DoD SERDP program has invested considerable effort in developing an understanding of mass discharge processes in saturated subsurface environments, and in developing methods to characterize and predict mass discharge (e.g., projects ER-1293, ER-1294, ER-1295, ER-1612, ER-1613, ER-1614). The knowledge gained from these efforts was used to help design the technology under demonstration. The MS-CMD test was recently presented by Brusseau et al. (2010), wherein an initial field test was successfully conducted. Similarly, the VPT method builds upon the extensive prior work on developing and testing of the hydraulic, pneumatic, and tracer tomography methods. Data analysis methods for the tomography applications is based in part on methods developed under support provided by SERDP/ESTCP (CU-1367, ER-1365).

2.1.4 Technology Applications

The two technologies are designed to improve existing vadose zone characterization methods by providing three key sets of information for vadose zone contaminant sources:

1. Accurate measurements of vapor-phase contaminant mass discharge,

2. Characterization of mass-transfer conditions (e.g., whether or not mass transfer is rate limited, and to what degree), and

3. Higher resolution characterization of source distribution and source zone architecture.

The standard technique (SGSs and mathematical modeling of flux) produces estimates of contaminant flux based on the application of models; this approach can produce highly uncertain results. In contrast, the MS-CMD test technology provides an actual, direct field measure of VOC mass discharge. In addition, the MS-CMD test can be used to assess mass-transfer conditions, unlike the existing method. The VPT test can produce higher resolution characterizations of source distribution compared to the existing method. The information provided by the new technologies would be used to improve the assessment of vadose zone source impacts on groundwater and vapor intrusion.

Specific applications for the technologies include decisions regarding implementation of vadose zone remediation efforts, setting of remediation goals, optimization of remediation systems, and assessment of remediation system transition or closure. The technologies will be especially useful for enhancing the performance of SVE systems, and for supporting closure assessment for SVE systems. The MS-CMD test and the VPT test can be used to improve and enhance characterization projects for many scenarios. Some illustrative examples are provided below.

Example application scenarios for the MS-CMD Test:

1. Characterizing the impact and associated risk of vadose zone source on groundwater quality.
2. Characterizing the impact and associated risk of vadose zone source on vapor intrusion.

3. Determining the presence of persistent contamination.
4. Supporting decisions regarding the need to implement vadose zone remediation efforts.
5. Supporting measurement of metrics for remediation goals and objectives.
6. Optimizing remediation system operations.
7. Assessing remediation system transition or closure.

Example application scenarios for the VPT Test:

1. Characterizing VOC sources for a contaminated vadose zone with high-resolution 3D.
2. Determining the presence of persistent contamination.
3. Supporting decisions for the need to modify the focal point of vadose zone remediation efforts.
4. Optimizing of remediation system operations.
5. Assessing remediation system transition or closure.

The technologies are designed to be used in a tiered approach that is sensitive to associated cost-benefits, and is responsive to specific requirements of the site.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The technology is designed to improve existing vadose zone characterization methods by providing the three key sets of information for vadose zone contaminant sources:

1. Accurate measurements of vapor-phase contaminant mass discharge.
2. Characterization of mass-transfer conditions (e.g., whether or not mass transfer is rate limited, and to what degree).
3. Higher-resolution characterization of source distribution and source zone architecture.

The standard technique (SGSs and mathematical modeling of flux) produces estimates of contaminant flux based on the application of mathematical models. In addition, the SGS is not sensitive to mass-transfer constraints, thus, the method can produce highly uncertain results. In contrast, the MS-CMD test provides an actual, direct field measure of mass discharge, and the VPT provides a 3D characterization of concentration distribution and mass flux. Both technologies are sensitive to mass-transfer constraints, and adept at characterizing persistent contamination. Thus, the new technologies can be used to assess mass-transfer conditions, which the existing method cannot, as well as produce higher resolution characterizations of source distribution compared to the existing method. Another advantage of the MS-CMD and VPT tests is that their application is generally not limited by site factors such as vadose zone depth, geological media type, contaminant distribution, or other subsurface conditions.

Page Intentionally Left Blank

3.0 PERFORMANCE OBJECTIVES

Several performance objectives were developed to provide a robust assessment of the performance of the technology. Separate objectives were developed for the MS-CMD test and the VPT methods. The performance of the combined technology will be further evaluated using an additional set of technical and cost objectives. The performance objectives are summarized in Table 1 and discussed below.

Table 1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
1. Produce quantitative measurements of contaminant mass discharge	Flow rate and vapor-phase concentration data	Production of improved CMD measurements as compared to SGS results
Qualitative Performance Objectives		
2. Produce contaminant mass discharge values with uncertainty bounds	CMD and other data	Production of contaminant mass discharge values with uncertainty bounds
3. Assessment of mass-transfer conditions	CMD and vapor-phase concentration data	Ability to identify conditions for which mass transfer is constrained
4. Produce a three-dimensional (3D) map of contaminant source distribution	Flow rate, pressure, and vapor-phase concentration data	More accurate source distribution characterization
5. Improved analysis of risk	Data obtained from field demonstration	Improved analysis of risk

3.1 PERFORMANCE OBJECTIVE 1: PRODUCE QUANTITATIVE MEASUREMENTS OF CONTAMINANT MASS DISCHARGE

This performance objective is focused on the production of quantitative measures of vapor-phase contaminant mass discharge. Contaminant mass discharge values were successfully measured. Flow rate and vapor-phase concentration data collected during the vapor extraction and rebound stages were used to determine CMD values. SGS data were used to estimate a CMD value. The MS-CMD test produced more representative CMD values. This performance objective was met.

3.2 PERFORMANCE OBJECTIVE 2: PRODUCE CONTAMINANT MASS DISCHARGE VALUES WITH UNCERTAINTY BOUNDS

This objective is for the vapor-phase mass discharge test. Uncertainty in parameter measurements was applied to the calculation of CMD values to evaluate uncertainty in CMD values. This performance objective was met.

3.3 PERFORMANCE OBJECTIVE 3: ASSESSMENT OF MASS-TRANSFER CONDITIONS

This objective is for the vapor-phase mass discharge test. Vapor concentrations collected during the MS-CMD test were plotted as a function of elapsed time. The resultant contaminant elution curve was examined to evaluate mass-transfer conditions. The appearance of specific landmarks was evaluated, such as length of the steady-state stage, occurrence of an asymptote, and occurrence of a rebound. This information was used to qualitatively assess the conditions influencing vapor-phase mass transfer and mass removal. The results of this analysis were evaluated by using historic SVE operations data and other data sets. This performance objective was met.

3.4 PERFORMANCE OBJECTIVE 4: PRODUCE 3D MAP OF CONTAMINANT SOURCE DISTRIBUTION

This objective is for the VPT test. The performance objective of the VPT demonstration was to produce a high-resolution 3D map of vapor-phase VOC and mass flux distributions. The VOC concentration distribution produced with the VPT method was similar to the high resolution sediment data, indicating the accuracy of the VPT method. The distribution produced with the SGS method was not accurate. This performance objective was met.

3.5 PERFORMANCE OBJECTIVE 5: IMPROVED ANALYSIS OF RISK

This performance objective was to produce data that provides for improved analysis of risk associated with vadose zone contaminant sources for groundwater contamination or vapor intrusion. The new technology produced a more robust characterization of mass discharge and source distribution. The benefit associated with this higher resolution was evaluated by conducting an illustrative risk assessment for groundwater contamination using the data obtained from the technology as input. Data obtained from the SGS was used for a comparative assessment. This performance objective was met.

4.0 SITE DESCRIPTION

4.1 SITE LOCATION AND HISTORY

4.1.1 Tucson International Airport Area (TIAA), Tucson, AZ

The first test site is part of the Tucson International Airport Area (TIAA) Federal Superfund site, which was placed on the National Priorities List in 1983. The site comprises several primary source zones, and a large, several-kilometer-long groundwater contaminant plume that resides in the regional aquifer. Two large-scale pump-and-treat systems and additional smaller-scale systems have been in operation for many years at the site. Full-scale SVE systems have been implemented during different time periods at the source zones. The site consists of a small source area and a groundwater contaminant plume extending approximately 600 meters to the west.

4.1.2 Site 2, AZ

The second test site is a Federal Superfund site, located in Arizona. The site was in operation for 18 months, during which time hazardous wastes were disposed in several unlined pits adjacent to a municipal solid waste landfill. Organic solvents were disposed in a designated area of the site, which will be termed the solvent-disposal area.

4.1.3 Hill Air Force Base (AFB), south of Ogden, UT

The third test site is operable unit (OU) 2 at Hill AFB in Utah. The data for this site were obtained from tests conducted at the site by contractors working for the U.S. Air Force (CH2M HILL, 2009, 2010). The OU2 site, located along the northeastern boundary of Hill AFB overlooking the Weber River Valley, is one of the 13 OUs at Hill AFB in various stages of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process (CH2M HILL, 2010).

4.2 SITE GEOLOGY AND HYDROGEOLOGY

Information available in the full final report.

4.3 CONTAMINANT DISTRIBUTION AND REMEDIATION ACTIVITIES

Information available in the full final report.

Page Intentionally Left Blank

5.0 TEST DESIGN

Information available in the full final report.

Page Intentionally Left Blank

6.0 PERFORMANCE ASSESSMENT

6.1 PRODUCE QUANTITATIVE MEASUREMENTS OF CONTAMINANT MASS DISCHARGE (PERFORMANCE OBJECTIVE 1)

Vapor-phase MS-CMD tests were implemented successfully at three sites, which span the three primary general stages of SVE operations and which represent a variety of site properties and conditions. The results are presented in brief in Section 5.7.1 of the final report and detailed in Appendix B in the final report. The demonstrations showed that the MS-CMD test can successfully produce measurements of CMD associated with vadose zone VOC sources. The representativeness of the measured CMD values was evaluated though analysis of site conditions and other data sources (see Appendix B in the final report).

The results obtained from the SGS test were used to estimate a CMD value for the TIAA site. This was done following the standard approach, wherein the measured soil-gas concentrations of the COC were entered as input into a screening model. The VIETUS tool (see Section 6.6) was used for this purpose. The resultant CMD value obtained is 0.1 grams per day (g/d). This value is much smaller than the value (32 g/d) obtained from the MS-CMD test. The SGS-obtained value is unrealistically low, and inconsistent with site conditions and SVE operations data.

The results of the demonstration indicate that the MS-CMD test produces representative quantitative measurements of CMD. Thus, performance objective 1 was met.

6.2 PRODUCE CONTAMINANT MASS DISCHARGE VALUES WITH UNCERTAINTY BOUNDS (PERFORMANCE OBJECTIVE 2)

There are several sources of uncertainty that may impact the CMD_{ng} values obtained from the MS-CMD test. One source comprises standard “instrument” uncertainty inherent to measurements of concentration and flow rate. These are considered to be relatively small compared to other potential sources. Another potential source is the resolution of the test in terms of the degree to which it captures concentration perturbations, which is relevant for accurate tabulation of mass removed as well as assessment of mass removal behavior. Based on inspection of the test results, it is concluded that the data density is of sufficient resolution to adequately characterize the temporal concentration profiles.

A third potential source of uncertainty relates to the estimation of pore volumes and determination of the number of extracted pore volumes to use for tabulation of the mass removed during the second extraction stage of the test. For the TIAA site, the observed point at which the concentration curve exhibited asymptotic behavior was consistent with the pore volume throughput that was calculated based on the estimated pore volume. This indicates that the method used to estimate pore volume produced reasonable results. The impact of potential uncertainty in determination of the number of extracted pore volumes to use for the mass-removed tabulation was assessed by recalculating the CMD_{ng} value, using 1 rather than 2 pore volumes. This change results in a CMD_{ng} of 19 g/d, compared to the original value of 32 g/d. The significance of this difference can be evaluated by comparing the groundwater concentrations estimated with the nomograph for the two CMD_{ng} values: ~20 micrograms per liter (µg/L) versus ~40 µg/L. This small difference in estimated values has no impact on the overall conclusion that the vadose zone source has minimal impact on current groundwater quality. Similar analyses for the other two sites produced similar results.

A fourth potential source of uncertainty relates to the determination of rebound time. This was assessed by recalculating the CMD_{ng} value, using 2.25 days rather than 4.5 days for the TIAA site. The recalculated value is twice the original value. The new value results in a larger estimated groundwater concentration that is still several times smaller than the measured concentration. For the Hill AFB site, the actual rebound time is unlikely to be significantly shorter than the 178-day estimate used. Use of a time greater than 178 days would result in a smaller CMD_{ng} and a lower estimated groundwater concentration, which would further diminish the apparent minimal impact of the vadose zone source on groundwater quality.

There are also sources of uncertainty associated with the use of the vapor discharge tool, such as those relating to system representativeness and determination of parameters for site-specific conditions. It is important to recognize that this uncertainty is separate from, and has no import for, the MS-CMD test itself. The performance of the combined MS-CMD test and vapor discharge tool can be evaluated to some degree by comparing the results to site conditions. For example, the concentration and mass removal behavior observed for the historic SVE operations data as well as the results of the high resolution sediment coring effort both indicate that a relatively small quantity of trichloroethylene (TCE) remains in the vadose zone at the TIAA site. Thus, it would be expected that the vadose zone VOC source would have small impact on groundwater quality, consistent with the test results and associated interpretation.

The preceding analyses illustrate the ability to evaluate uncertainty for the CMD measurements obtained with the MS-CMD test; thus, performance objective 2 was met.

6.3 ASSESSMENT OF MASS-TRANSFER CONDITIONS (PERFORMANCE OBJECTIVE 3)

The results obtained for the test conducted at the TIAA site indicate the presence of persistent contaminant mass. The results also indicate that there is unlikely to be a significant mass of non-vapor-phase contaminant (e.g., DNAPL, sorbed phase) present in the advective domains, and that most remaining mass is thus likely located in poorly accessible domains. Given the conditions for this site, this remaining mass is hypothesized to be associated with the low permeability (and higher water saturation) region in the vicinity of the saturated zone and capillary fringe. This is supported by the results of a sediment coring effort conducted prior to the MS-CMD test, as well as the data obtained from the historic SVE operations.

The results of the test conducted at the Hill AFB site suggest that non-vapor-phase contaminant mass (e.g., DNAPL) may be present in the advective domains. This is consistent with the results of prior characterization activities conducted at the site. Hence, the asymptotic conditions observed for this site most likely derive from a combination of mass transfer from more accessible DNAPL (and sorbed) phases present in the advective domain as well as mass residing in lower permeability (“non-advective”) regions.

The analyses of mass-transfer conditions, as summarized in the preceding paragraph, illustrate the ability to use the results of the MS-CMD and VPT tests to evaluate mass-transfer conditions and delineate the presence of persistent contamination. As noted above, the results of the SGS did not indicate the presence of mass-transfer processes, nor the presence of persistent contaminant mass.

Thus, the MS-CMD and VPT tests outperformed the SGS test. Based on these results, performance objective 3 was successfully met.

6.4 PRODUCE 3D MAP OF CONTAMINANT SOURCE DISTRIBUTION (PERFORMANCE OBJECTIVE 4)

The VPT test produced 3D maps of VOC concentrations and mass flux in which spatial differences were observed, indicating the presence of a vapor source located in the SSW quadrant of the test area, between the water table and the monitoring well screened interval. These results are consistent with those of the sediment data. In comparison, the SGS test was unable to identify spatial variability of vapor concentrations or delineate a potential source. Thus, the VPT test provided a more robust source characterization compared to the standard SGS method. These results illustrate the utility of the VPT test as a higher resolution method for characterizing VOC source distribution in the vadose zone. Performance objective 4 was met.

6.5 IMPROVED ANALYSIS OF RISK (PERFORMANCE OBJECTIVE 5)

The CMD values obtained from the tests were used in conjunction with a recently developed vapor discharge tool to evaluate the impact of the vadose zone source on groundwater quality. The estimated groundwater TCE concentrations obtained from the assessment were in two cases much lower than the current measured groundwater TCE concentrations. This suggests that for both these sites, the current impact of the vadose zone VOC source on groundwater quality is relatively small compared to the impact of contamination present in the saturated zone. This implication supports consideration of remedy modification or closure for the vadose zone remediation operations for both sites.

These results illustrate the utility of the MS-CMD test for enhancing characterization and risk assessment efforts at sites containing vadose zone VOC sources. Thus, performance objective 5 was met.

6.6 VIETUS TOOL

The spreadsheet-based Vapor Intrusion Estimation Tool for an Unsaturated-zone Source (VIETUS) software program created by PNNL[1] will be useful as another alternative tool available for evaluating the impact of vadose zone VOC sources on groundwater quality and vapor intrusion potential.

6.7 ESTIMATION OF INITIAL SOURCE MASS

The mass estimates obtained with application to the full data sets were reasonably similar to the measured masses removed with the SVE systems for both functions. Additionally, the initial mass was calculated using three different configurations of the exponential function in order to test different convergence criteria. The use of the initial one-third of the data resulted in a higher variation. These results suggest that the method can produce reasonable estimates of initial mass useful for planning and assessing remediation efforts. Source depletion functions have been applied to measured SVE operations data to produce estimates of the initial source zone mass present on the site.

[1] http://bioprocess.pnnl.gov/VIETUS_Request.htm.

Data were collected for several contaminated sites that are close to complete extraction of contaminated mass. The estimates produced with both functions were reasonably similar to the measured mass-removed values. The initial mass estimates resulting from the analysis of the early-time data (initial one-third of the complete data set) had slightly greater variation than on the estimate produced using the total available data sets. This methodology is not limited to SVE remediation sites, and can be applied to groundwater-contaminated sites. The time required to gather one-third to one-half of the full operational data for the latter is significantly longer, rendering this method useful to estimate initial mass after several years of remediation operation.

7.0 COST ASSESSMENT

A decision support tool was developed to provide the end user a simple means to determine the costs required to implement the MS-CMD and VPT tests. This Microsoft Excel tool is named the "Decision support tool for application of MS-CMD and VPT technologies" and is available for download from the ESTCP website.

7.1 COST MODEL

The cost assessment for both technologies is described in detail within the "Decision support tool for application of MS-CMD and VPT technologies." This decision tool is in the form of a spreadsheet with two main functions:

1. To offer a summary as well as a guide for the implementation of each technology; and
2. To serve as a cost assessment tool, allowing the user to determine the cost of implementing each technology for several scenarios.

The cost tool provides the user four different configurations to define and compare several possible scenarios:

Configuration 1: uses existing infrastructure, minimum sampling

This configuration represents a basic lowest-cost implementation scenario. For this scenario, it is assumed that the infrastructure required for the test is in place. In addition, this scenario employs the minimum number of monitoring wells and sampling events required for each technology (see Application tabs).

Configuration 2: well installation necessary, minimum sampling

For this scenario, all required wells need to be installed, with all associated costs incorporated. Costs for renting a vapor extraction system are also included. This scenario employs the minimum number of monitoring wells and sampling events required for each technology (see Application tabs).

Configuration 3: well installation necessary, multiple implementations

This scenario represents a case for which multiple extraction wells are used for an MS-CMD test, or multiple extraction points are used for the VPT test.

Configuration 4: User preset

This configuration is left blank for the user to complete for their desired configuration.

The cost assessment tool for each technology is organized into four sections:

1. *Set-up costs:* This section describes the infrastructure needed to implement the technology.

2. *Technology implementation costs:* This section estimates the number of samples required (including duplicates) and, based on the cost of sample analysis, determines the overall analysis cost.

3. *SGS implementation costs:* This section provides cost determination for implementing an SGS test, the standard characterization method used for comparison.

4. *Comparison of total costs:* This section shows a cost comparison between the deployment of the current technology and the standard technology, as a means to assess either the savings associated with the use of the new technology or, in some cases, the extra cost related to the new technology.

7.2 COST DRIVERS

Depending on the configuration considered, the costs drivers will be the set-up costs, if applicable, and the sample collection and analysis costs. The assessment does not include any personnel costs related to the implementation of the technologies.

7.3 COST ANALYSIS

Sample analysis costs are a major component for overall cost estimates for the MS-CMD and SGS tests. Multiple monitoring wells, each with multiple screened intervals, are used for SGS tests. Conversely, MS-CMD tests require the use of at minimum a single well. Thus, it is evident that the cost for implementing an MS-CMD test will be significantly lower than that for SGS tests for most test configurations. If wells must be emplaced prior to the tests, the cost savings for the MS-CMD test increase significantly compared to the SGS test. Overall, the MS-CMD test has a relatively low implementation cost (modest infrastructure and sampling requirements) and relatively simple data analysis requirements. Therefore, it is expected that this test would be beneficial under many conditions, and applicable for a wide array of sites. In many situations, the cost of implementing the MS-CMD test will be less than the cost of implementing a standard SGS test.

The VPT test requires multiple wells, each with multiple screened intervals. In addition, multiple samples are collected for each sampling point. Thus, the costs for implementing a VPT test are in the same range as that of an SGS test. The exact cost differential between the VPT and SGS tests will depend on the specific configurations employed. This can be tested with the decision support tool. Given that the VPT test has somewhat greater implementation costs, its use is anticipated to be more restricted. However, the VPT test is designed to be scalable, which allows its use and associated costs to be matched to site-specific conditions and objectives. Thus, in many cases, the cost of conducting a VPT test may not be substantially greater than the costs for conducting the standard SGS test. The scalability of the VPT test is based on multiple cost discriminator factors, including the number of discrete local extractions (vapor extractions), the number of monitoring wells, and the number of vertically discrete screened intervals for the monitoring wells. The application of a full-scale VPT test (with multiple local extractions) is anticipated to be reserved for large or complex sites that have active SVE operations. Thus, it is anticipated that tomography applications may be advantageous for such systems to improve assessment of SVE transition/closure. Second, application of the tomography methods for sites that do not have substantial infrastructure present may be warranted for sites that have a greater degree of complexity or other special circumstances that warrant the additional costs.

8.0 IMPLEMENTATION ISSUES AND POTENTIAL COST AVOIDANCE

8.1 IMPLEMENTATION ISSUES

Both the MS-CMD and the VPT technologies use standard infrastructure (monitoring wells, vapor extraction system) and employ standardized data collection methods (vapor sampling). Thus, both tests are simple to conduct and require no specialized equipment or expertise. As a result, there are minimal barriers to general implementation of either test.

Both technologies are capable of being successfully implemented in a wide variety of subsurface conditions. Implementation of both technologies is based on the capacity of a functioning vapor extraction system to generate vapor flow. Thus, they can be implemented for any system for which vapor flow can be generated.

One area of concern is regarding implementation at sites with significant permeability heterogeneity, including the presence of extensive lower permeability units. All three sites used for this demonstration are characterized by the presence of extensive lower permeability zones. The tests were successful for all three sites.

The technologies were not tested for conditions with significant, extensive fracturing. However, it is anticipated that the tests are implementable for such sites, as long as vapor flow can be induced.

The VPT test requires measurements of permeability to produce mass-flux values. Multiple standardized methods are available for characterizing permeability. The method used to characterize the permeability field will partially determine the resultant resolution of the mass-flux map. For example, using standard pneumatic pumping tests (with “fully” screened wells) produces a permeability field that may vary aerially but is vertically homogeneous. This will result in lower resolution for the mass-flux map. At the other end of the spectrum, pneumatic tomography can be used to produce a high-resolution 3D permeability field, which would contribute to a high resolution map of mass flux.

Note that the resolution of the mass-flux map is mediated by the inherent vertical and areal resolution of the concentration data. The resolution of the concentration data is controlled by the number of sampling points employed.

A potential approach to enhance overall resolution would be to combine pneumatic tomography with VPT, with the combined tool providing an integrated characterization of permeability, concentration distribution, and vapor flux, and delineation of migration pathways.

8.2 POTENTIAL COST AVOIDANCE

The cost assessment for both technologies is described in detail within the “Decision support tool for application of MS-CMD and VPT technologies.” This decision tool is in the form of a spreadsheet with two main functions: to provide a summary and guidance for the implementation of each technology, and to be used as a cost assessment tool, allowing the user to determine the cost of implementing each technology for several scenarios.

Sample analysis costs are a major component for overall cost estimates for the MS-CMD and SGS tests. Multiple monitoring wells, each with multiple screened intervals, are used for SGS tests. Conversely, MS-CMD tests require the use of at minimum a single well. Thus, it is evident that the cost for implementing an MS-CMD test will be significantly lower than that for SGS tests for most test configurations. If wells must be emplaced prior to the tests, the cost savings for the MS-CMD test increase significantly compared to the SGS test.

Overall, the MS-CMD test has a relatively low implementation cost (modest infrastructure and sampling requirements) and relatively simple data analysis requirements. Therefore, it is expected that this test would be beneficial under many conditions, and applicable for a wide array of sites. In many situations, the cost of implementing the MS-CMD test will be less than the cost of implementing a standard SGS test.

The VPT test requires multiple wells, each with multiple screened intervals. In addition, multiple samples are collected for each sampling point. Thus, the costs for implementing a VPT test are in the same range as that of an SGS test. The exact cost differential between the VPT and SGS tests will depend on the specific configurations employed. This can be tested with the decision support tool.

Given that the VPT test has somewhat greater implementation costs, its use is anticipated to be more restricted. However, the VPT test is designed to be scalable, which allows its use and associated costs to be matched to site-specific conditions and objectives. Thus, in many cases, the cost of conducting a VPT test may not be substantially greater than the costs for conducting the standard SGS test. The scalability of the VPT test is based on multiple cost discriminator factors, including the number of discrete local extractions (vapor extractions), the number of monitoring wells, and the number of vertically discrete screened intervals for the monitoring wells.

The application of a full-scale VPT test (with multiple local extractions) is anticipated to be reserved generally for two scenarios. First, for large or complex sites that have active SVE operations, the infrastructure necessary for implementing tomography would typically be present, thus greatly reducing set-up costs. Thus, it is anticipated that tomography applications may be advantageous for such systems to assist in optimization of SVE operations and to improve assessment of SVE transition/closure, both of which can be very difficult for complex sites. Second, application of the tomography methods for sites that do not have substantial infrastructure present may be warranted for sites that have a greater degree of complexity or other special circumstances that warrant the additional costs. For other scenarios, a more limited VPT test set could be implemented, thus reducing overall costs.

9.0 REFERENCES

American Petroleum Institute (API) (2003). Groundwater Remediation Strategies Tool. Regulatory Analysis & Scientific Affairs Department, Publication Number 4730, December 2003, Washington, DC.

Bohling, G.C., X. Zhan, J.J. Butler Jr., and L. Zheng (2002). Steady shape, analysis of tomographic pumping tests for characterization of aquifer heterogeneities, Water Resources Research, 38(12), 1324, doi:10.1029/2001WR001176.

Brauchler, R., R. Liedl, and P. Dietrich (2003). A travel time based hydraulic tomographic approach, Water Resources Research, 39(12), 1370, doi:10.1029/2003WR002262.

Brusseau, M.L., N.T. Nelson, Z. Zhang, J. E. Blue, J. Rohrer, and T. Allen (2007). Source-zone characterization of a chlorinated-solvent contaminated Superfund site in Tucson, AZ, Journal of Contaminant Hydrology, 90(1-2), 21-40.

Brusseau, M.L., V. Rohay, and M.J. Truex (2010). Analysis of soil vapor extraction data to evaluate mass-transfer constraints and estimate source-zone mass flux, Ground Water Monitoring and Remediation, 30, 57-64.

Brusseau, M. L., Carroll, K. C., Truex, M. J., & Becker, D. J. (2013). Characterization and remediation of chlorinated volatile organic contaminants in the vadose zone. Vadose Zone Journal, 12(4).

Carroll, K. C., Oostrom, M., Truex, M. J., Rohay, V. J., & Brusseau, M. L. (2012). Assessing performance and closure for soil vapor extraction: integrating vapor discharge and impact to groundwater quality. Journal of contaminant hydrology, 128(1), 71-82.

Carroll, K. C., Truex, M. J., Brusseau, M. L., Parker, K. R., Mackley, R. D., & Rohay, V. J. (2013). Characterization of persistent volatile contaminant sources in the vadose zone. Groundwater Monitoring & Remediation, 33(2), 68-84.

CH2MHILL (2009). Soil Vapor Extraction Evaluation Report for Operable Unit 2 (April 2009).

CH2MHILL (2010). Technical Memorandum: Soil Vapor Extraction Performance Monitoring Evaluation, Operable Unit 2, Hill Air Force Base, Utah (November 18, 2010).

DeGroot, D.J., Lutenegger, A.J. (1998). Reliability of soil gas sampling and characterization techniques. Geotechnical site characterization: Proceedings of the First International Site Characterization Conference, Atlanta, GA. 19–22 Apr. 1998 vol. 1. A.A. Balkema, Rotterdam, the Netherlands, pp. 629–634.

DiGiulio, D.C., V. Ravi, and M.L. Brusseau (1999). Evaluation of mass flux to and from ground water using a vertical flux model (VFLUX): Application to the soil vacuum extraction closure problem, Ground Water Monitoring and Remediation, 19(2), 96-104.

Einarson, M.D. and D.M. Mackay (2001). Predicting impacts of groundwater contamination, Environmental Science & Technology, 35: 67A-73A.

Environmental Protection Agency (EPA) (2001). Development of recommendations and methods to support assessment of soil venting performance and closure. EPA/600/R-01/070. Washington, D.C.: U.S. Environmental Protection Agency, Office of Research and Development.

EPA (2003). The DNAPL Remediation Challenge: Is There a Case for Source Depletion? EPA/600/R-03/143, December.

ESTCP (2012). Final report guidance Environmental restoration projects. https://www.serdp-estcp.org/Investigator-Resources/ESTCP-Resources/Technical-Reports.

Feenstra, S. (2005). Soil sampling in NAPL source zones: challenges to representativeness. Environ. Forensic 6, 57–63.

Gottlieb, J., and P. Dietrich (1995). Identification of the permeability distribution in soil by hydraulic tomography, Inverse Probl., 11, 353–360.

Harper, M. (1994). Novel sorbents for sampling organic vapours. Analyst, 119(1), 65-69. doi: 10.1039/AN9941900065.

Hers, I., R. Zapf-Gilje, D. Evans, and L. Li (2002). Comparison, validation, and use of models for predicting indoor air quality from soil and groundwater contamina- tion. Soil Sediment Contam. 11:491–527. doi:10.1080/20025891107140.

Johnson and Ettinger (1991). Heuristic model for predicting the intrusion rate of contaminant vapors into buildings. Environ. Sci. Technol. 25: 1445-1452.

Johnson, G.R., Norris, D.K., Brusseau, M.L. (2009). Mass removal and low-concentration tailing of tricholoroethene in freshly-amended, synthetically-aged, and field-contaminated aquifer material. Chemosphere 75, 542–548.Karanfil, et al. 2004 p.39.

Liu, X., W. A. Illman, A. J. Craig, J. Zhu, and T.-C. J. Yeh (2007). Laboratory sandbox validation of transient hydraulic tomography, Water Resour. Res., 43, W05404, doi:10.1029/2006WR005144.

Mainhagu, J., Morrison, C., Truex, M., Oostrom, M., & Brusseau, M. L. (2014). Measuring spatial variability of vapor flux to characterize vadose-zone VOC sources: Flow-cell experiments. Journal of contaminant hydrology, 167, 32-43.

Mainhagu, J., Morrison, C., & Brusseau, M. L. (2015). Using vapor phase tomography to measure the spatial distribution of vapor concentrations and flux for vadose-zone VOC sources. Journal of contaminant hydrology, 177, 54-63.

McAlary, T.A., P. Nicholson, H. Groenevelt and D. Bertrand. (2009). A case study of soil-gas

sampling in silt and clay-rich (low-permeability) soils. Ground Water Monitor. Remed. 29: 144-152.

Ni, C.F. and T-CJ. Yeh (2008). Stochastic inversion of pneumatic cross-hole tests and barometric pressure fluctuations in heterogeneous unsaturated formations. Adv. Water Resour. 31, 1708-1718.

National Institute for Occupational Safety and Health (NIOSH) (1994). Trichloroethylene, Method 1022. (2). http://www.cdc.gov/niosh/docs/2003-154/method- 2000.html.

Oostrom, M., Truex, M.J., Rice, A.K., Johnson, C.D., Carroll, K.C., Becker, D.J., Simon, M.A. (2014). Estimating the impact of vadose zone sources on groundwater to support performance assessment of soil vapor extraction. Ground Water Monit. Remed. 34, 71–84.

Rao, P.S.C., J.W. Jawitz, C.G. Enfield, R.W. Falta, M.D. Annable, and A.L. Wood (2002). Technology integration for contaminated site remediation: clean-up goals and performance criteria. Pg 571-578 in: Groundwater Quality-Natural and Enhanced Restoration of Groundwater Pollution, IAHS Publ. 275.

Rosenbloom, J., Mock, P., Lawson, P., Brown, J., Turin, H.J. (1993). Application of VLEACH to an Arizona superfund site. Ground Water Monit. Remed. 159–169 (Summer).

Rossabi, J., Riha, B.D., Eddy-Dilek, C.A., Looney, B.B., Hyde, W.K. (2003). Recent advances in characterization of vadose zone dense non-aqueous phase liquids (DNAPL) in heterogeneous media. Environ. Eng. Geosci. 9, 25–36.

Sanders, P. F., & Hers, I. (2006). Vapor Intrusion in Homes over Gasoline-Contaminated Ground Water in Stafford, New Jersey. Ground Water Monitoring & Remediation, 26(1), 63-72.

Schwarz, R., T. Ptak, T. Holder, G. Teutsch (1998). Groundwater risk assessment at contaminated sites: a new investigation approach. In: Herbert, M., Kovar, K. (Eds.), GQ'98 Groundwater Quality: Remediation and Protection, IAHS Publication, vol. 250, pp. 68– 71.

Straface, S., T.-C.J. Yeh, J. Zhu, S. Troisi, and C. H. Lee (2007). Sequential aquifer tests at a well field, Montalto Uffugo Scalo, Italy, Water Resour. Res., 43, W07432, doi:10.1029/2006WR005287.

Strategic Environmental Research and Development Program (SERDP) (2006). Final Report: SERDP/ESTCP Expert Panel Workshop on Reducing the Uncertainty of DNAPL Source Zone Remediation.

Stroo, H.F., M. Unger, C.H. Ward, M.C. Kavanaugh, C. Vogel, A. Leeson, J.A. Marqusee, Smith, B.P. (2003). Remediating chlorinated solvent source zones. Environ. Sci. Technol. 224A-230A.

Thomson, N.R., Flynn, D.J. (2000). Soil vapor extraction of perchloroethylene from the Borden aquifer. Ground Water 38, 673–688.

Tosaka, H., K. Masumoto, and K. Kojima (1993). Hydropulse tomography for identifying 3-D permeability distribution, in Proceedings of the 4th Annual International Conference on High Level Radioactive Waste Management; Apr 26-30 1993; Las Vegas, NV, USA, High Level Radioactive Waste Management, pp. 955–959, New York, NY, USA: Publ by ASCE.

Truex, M.J., K.C. Carroll, V.J. Rohay, R.M. Mackley, and K.R. Parker (2013). Treatability Test Report: Characterization of Vadose Zone Carbon Tetrachloride Source Strength Using Tomographic Methods at the 216-Z-9 Site. PNNL-21326. Richland, Washington: Pacific Northwest National Laboratory.

U.S. Army Corps of Engineers (USACE) (2002). Engineering design: Soil vapor extraction and bioventing. USACE EM 1110-1-4001. U.S. Army Corps of Engineers, www.usace.army.mil/publications/eng-manuals/em1110-1-4001/toc.htm.

Vasco, D.W., H, Keers, and K. Karasaki (2000). Estimation of reservoir properties using transient pressure data: An asymptotic approach, Water Resources Research, 36 (12): 3447-3465.

Vesselinov, V.V., S.P. Neuman, and W.A. Illman (2001). Three-dimensional numerical inversion of pneumatic cross-hole tests in unsaturated fractured tuff 1. Methodology and borehole effects, Water Resources Research, 37(12), 3001–3017.

White, M.D., Oostrom, M. (2006). STOMP, subsurface transport over multiple phases. Version 4.0. User's Guide, PNNL-15782. Pacific Northwest National Laboratory, Richland, WA.

Yeh, T.-C.J., and S. Liu (2000). Hydraulic tomography: Development of a new aquifer test method, Water Resources Research, Vol. 36, No. 8, p 2095-2105.

Yeh, T.-C.J. and J. Zhu (2007). Hydraulic/partitioning tracer tomography for characterization of dense nonaqueous phase liquid source zones, Water Resour. Res., 43, W06435, doi:10.1029/2006WR004877.

Zhu, J. and T.-C.J. Yeh (2005). Characterization of aquifer heterogeneity using transient hydraulic tomography, Water Resources Research, Vol. 41 W07028, 2005.

Zhu, J., and T.-C. J. Yeh (2006). Analysis of hydraulic tomography using temporal moments of drawdown recovery data, Water Resources Research, 42, W02403, doi:10.1029/2005WR004309.

APPENDIX A – POINTS OF CONTACT

Point of Contact	Organization	Contact Information	Role in Project
Mark Brusseau	University of Arizona	Tel: 520-626-4191 Fax: 520-626-6782 brusseau@email.arizona.edu	Principal Investigator
Jon Mainhagu	University of Arizona	Tel: 520-626-4191 Fax: 520-626-6782 Mainhagu@email.arizona.edu	Postdoc
K. C. Carroll	New Mexico State University	kccarr@ad.nmsu.edu	Collaborator
Michael Truex	Pacific Northwest National Laboratory	Tel: 509-371-7072 mj.truex@pnnl.gov	Collaborator

Page Intentionally Left Blank

ESTCP Office
4800 Mark Center Drive
Suite 17D08
Alexandria, VA 22350-3605
(571) 372-6565 (Phone)
E-mail: estcp@estcp.org
www.serdp-estcp.org