

Comparison of Geoprobe® PRT and AMS GVP Soil-Gas Sampling Systems with Dedicated Vapor Probes in Sandy Soils at the Raymark Superfund Site



Comparison of Geoprobe® PRT and AMS GVP Soil-Gas Sampling Systems with Dedicated Vapor Probes in Sandy Soils at the Raymark Superfund Site

Dominic DiGiulio, Cynthia Paul, and Brad Scroggins
U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Ground Water and Ecosystems Restoration Division
Ada, OK

Raphael Cody and Richard Willey
U.S. Environmental Protection Agency
Region I
Boston, MA

Scott Clifford
U.S. Environmental Protection Agency
Region I, New England Regional Laboratory
North Chelmsford, MA

Ronald Mosley
U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Research Triangle Park, NC

Annette Lee and Kaneen Christensen
Xpert Design and Diagnostics, LLC
Stratham, NH

Ravi Costa
The Shaw Group Inc.
Ada, OK

Project Officer
Dominic C. DiGiulio
U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Ground Water and Ecosystems Restoration Division
Ada, OK

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
NATIONAL RISK MANAGEMENT RESEARCH LABORATORY
CINCINNATI, OH 45268

Notice

The U.S. Environmental Protection Agency (EPA) through its Office of Research and Development funded and managed the research described here through in-house efforts and under Contract No. 68-C-02-092 to the Dynamac Corporation. It has been subjected to the Agency's peer and administrative reviews and has been approved for publication as an EPA document.

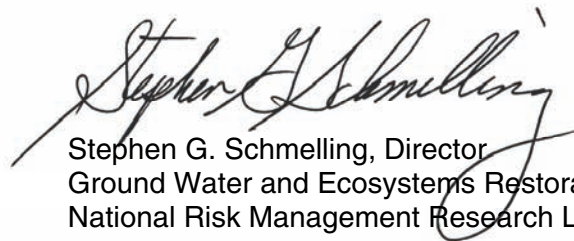
All data generated in this report were subjected to an analytical Quality Assurance Plan developed by EPA's New England Regional Laboratory. Also, a Quality Assurance Project Plan was implemented at the Ground Water and Ecosystems Restoration Division. Results of field-based studies and recommendations provided in this document have been subjected to external and internal peer and administrative reviews. This report provides technical recommendations, not policy guidance. It is not issued as an EPA Directive, and the recommendations of this report are not binding on enforcement actions carried out by the EPA or by the individual States of the United States of America. Neither the United States Government nor the authors accept any liability or responsibility resulting from the use of this document. Implementation of the recommendations of the document and the interpretation of the results provided through that implementation are the sole responsibility of the user.

Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet these mandates, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This report describes the results of an investigation conducted to assist EPA's New England Regional Office in evaluating vapor intrusion in homes and a commercial building near the Raymark Superfund Site in Stratford, Connecticut. Specifically, a study was conducted to compare results of soil-gas sampling using dedicated vapor probes, a truck-mounted direct-push technique, Geoprobe® Post-Run-Tubing system, and a hand-held rotary hammer technique, AMS Gas Vapor Probe kit. Testing revealed some statistically significant differences. However, the magnitude of variation was similar to that due to spatial variability on the scale of testing (1 m). Hence for practical purposes, all three sample systems were considered approximately equivalent. This investigation should provide confidence that the PRT and GVP sample systems are satisfactory for collecting soil-gas samples in sandy soils, such as those present near the Raymark site, to evaluate the potential for vapor intrusion.



Stephen G. Schmelling, Director
Ground Water and Ecosystems Restoration Division
National Risk Management Research Laboratory

Abstract

A study was conducted near the Raymark Superfund Site in Stratford, Connecticut to compare results of soil-gas sampling using dedicated vapor probes, a truck-mounted direct-push technique - the Geoprobe Post-Run-Tubing (PRT) system, and a hand-held rotary hammer technique - the AMS Gas Vapor Probe (GVP) kit. A comparison of VOC concentrations using dedicated vapor probes and the GVP sampling kit indicated that the two methods provided similar results. However, at one location, VOC concentrations were significantly higher for dedicated vapor probes indicating potential leakage with the GVP system. VOC concentrations using the PRT system were higher than VOC concentrations using dedicated vapor probes by an average factor of 1.2. This is the same magnitude observed for spatial variability on a scale of 1 m (median of 1.2 and average of 1.3 for 90 sample pairs). However, this effect did not appear to be due to spatial variability which would result in random scatter not a consistent bias as observed. It is also unlikely that extraction volume or sampling sequence caused the observed bias given the results of extraction volume and sample sequence testing. VOC concentrations using the PRT system were also higher than VOC concentrations using the GVP kit by an average factor of 2.4. Similar to the comparison between probe and PRT sampling systems, the effect did not appear to be due to spatial variability, extraction volume, or sequence of sampling. Thus, utilization of the PRT system resulted in observation of higher concentrations of VOCs compared to the GVP kit and dedicated vapor probes. However, variation in concentration was relatively minor when compared to spatial variability on the scale used for comparison testing. Hence for practical purposes, all three sample systems can be considered approximately equivalent.

Table of Contents

Notice	ii
Foreword.....	iii
Abstract.....	iv
List of Abbreviations	vi
List of Figures	vii
List of Tables	xi
Acknowledgements.....	xiv
Executive Summary.....	E1
1.0 Introduction	1
2.0 Site Description.....	2
3.0 Methods and Materials.....	6
3.1 Soil-Gas Sampling from Dedicated Vapor Probes	6
3.2 Soil-Gas Sampling with the GeoProbe® PRT System	8
3.3 Soil-Gas Sampling with the AMS GVP Kit	11
3.4 On-Site Soil-Gas Analysis and Data Quality	13
3.5 Computation of Pre-Sample Internal Volume Exchange Requirements	15
3.6 Assessment of Extraction Volume on Sample Results	18
3.7 Assessment of Air Extraction at One Location on Another Location.....	21
3.8 Consideration of Spatial Variability on Comparison of Sampling Techniques	22
4.0 Results.....	26
4.1 Results of Testing at MW302SGM.....	26
4.2 Results of Testing at MW514SG.....	27
4.3 Results of Testing at MW523SGS, MW523SGM, and MW523SGD.....	29
4.4 Results of Testing at MW525SG.....	31
4.5 Results of Testing at MW526SGS, MW526SGM, and MW526SGD.....	34
5.0 Discussion of Comparison Testing	38
6.0 Summary.....	41
References	43
Appendix A	45

List of Abbreviations

1,1,1-TCA	1,1,1 – trichloroethane
1,1-DCE	1,1 – dichloroethylene
TCE	trichloroethylene
c-1,2-DCE	cis-1,2-dichloroethylene
O ₂	oxygen
CO ₂	carbon dioxide
CH ₄	methane
ID	inner diameter
VOC	volatile organic chemical
PRT	post-run tubing
GVP	gas vapor probe
PVC	polyvinylchloride
SLPM	standard liter per minute
GC	gas chromatography

List of Figures

Figure 1	Direction of ground-water flow (large arrows) and location of the residential area of investigation near the Raymark Superfund Site (modified from Tetra Tech NUS, Inc., 2000)	2
Figure 2	Location of geologic cross-sections and the residential area of investigation near the Raymark Superfund Site (modified from Tetra Tech NUS, Inc.,2000)	3
Figure 3	Geologic cross-section G – G' (modified from Tetra Tech NUS, Inc., 2000).....	3
Figure 4	Geologic cross-section H – H' (modified from Tetra Tech NUS, Inc. 2000	4
Figure 5	Results of ten shallow single-well hydraulic conductivity tests at the Raymark site (boundary values for sand and gravel taken from Freeze and Cherry, 1979).....	4
Figure 6	Results of a sub-slab air permeability test taken from EPA (2006)	5
Figure 7	Typical construction log for dedicated vapor probes installed at the Raymark Site	6
Figure 8	Photograph of valve used to seal dedicated probes, PVC barbed fitting, and Teflon tubing used for sampling.....	7
Figure 9	Photograph of peristaltic pump, flowmeter, and landfill gas meter used during purging dedicated vapor probes.....	8
Figure 10	Photograph of peristaltic pump and one-liter Tedlar bags (duplicate sample) used for sampling dedicated vapor probes	8
Figure 11	Photograph of truck-mounted PRT system	9
Figure 12	Components of PRT sampling system.....	9
Figure 13	Photograph of an expendable point and expendable point holder.....	9
Figure 14	Photograph of a PRT adapter with an O-ring and associated Teflon tubing.....	10
Figure 15	Photograph of metal rod used to push out the expendable point.....	10
Figure 16	Photograph of connection of PRT adapter to expendable point holder	10
Figure 17	Creation of hole in asphalt prior sampling with GVP kit	11
Figure 18	Photograph of Retract-A-Tip	11
Figure 19	Disassembled view of Retract-A-Tip	11

List of Figures - continued

Figure 20	Photograph of hammering Retract-A-Tip and support pipe using a rotary hammer drill and the GVP extension drive adapter	12
Figure 21	Retraction of Retract-A-Tip prior to sampling.....	12
Figure 22	Proximity of dedicated vapor probe (metal cover surrounded by white concrete at base of Geoprobe unit), PRT, and GVP sampling systems	12
Figure 23	Comparison of EPA Method TO-15 with sample collection using a peristaltic pump and Tedlar bags with on-site GC analysis of 1,1,1-TCA, 1,1-DCE, TCE, and c-1,2-DCE (n = 91, $r^2 = 0.88$).....	14
Figure 24	Purge volume as a function of C_o/C_{in} and C_{out}/C_{in}	16
Figure 25	Vapor concentration as a function of cumulative post-sample extraction volume up to 5.5 liters at dedicated vapor probe MW513SG	17
Figure 26	O_2 , CO_2 , and CH_4 concentration as a function of cumulative post-sample extraction at dedicated vapor probe MW514SG.....	18
Figure 27	Vapor concentration as a function of cumulative pre-sample extraction volume using the PRT sampling system at a depth of 0.76 m near MW525SG	19
Figure 28	Vapor concentration as a function of cumulative pre-sample extraction volume at dedicated vapor probe MW513SG at a depth interval of 2.1 to 2.4 m.....	20
Figure 29	Comparison of first and third samples at dedicated probe, PRT, and GVP sample locations.....	21
Figure 30	Coefficient of variation (%) as a function of mean vapor concentration for first, second, and third samples at dedicated probe, PRT, and GVP sample locations	22
Figure 31	Photograph illustrating five PRT sample locations (orange flags) near MW213	23
Figure 32	Schematic illustrating five PRT sample locations near MW213 in plan view	23
Figure 33a	Vapor concentration at locations S1 through S5 (one sample at each location) at a depth of 0.76 m	24
Figure 33b	Vapor concentration at locations S1 through S5 (one sample at each location) at a depth of 2.3 m	24
Figure 33c	Vapor concentration at locations S1 through S5 (one sample at each location) at a depth of 3.2 m	25

List of Figures - continued

Figure 34	Schematic illustrating the location of sampling systems at MW302SGM in plan view	26
Figure 35	Comparison of mean (3 samples from each sample system) vapor concentrations at MW302SGM at a depth of 2.3 m.....	27
Figure 36	Schematic illustrating the location of sampling systems at MW514SG in plan view	28
Figure 37	Comparison of mean (3 samples from each sample system) vapor concentrations at MW514SG at a depth of 2.3 m.....	28
Figure 38	Schematic illustrating the location of sampling systems at MW523SGS, MW523SGM, and MW523SGD in plan view	29
Figure 39	Comparison of vapor concentrations (1 sample from each sample system) at MW523SGM at a depth of 2.3 m.....	30
Figure 40	Comparison of vapor concentrations (1 sample from each sample system) at MW523SGD at a depth of 3.4 m	31
Figure 41	Schematic illustrating the location of sampling systems at MW525SG in plan view	32
Figure 42	Comparison of mean (3 samples from each sample system) vapor concentrations at MW525SG at a depth of 0.91 m.....	32
Figure 43	Comparison of mean (3 samples from each sample system) vapor concentrations at MW525SG at a depth of 2.3 m.....	33
Figure 44	Schematic illustrating the location of sampling systems at MW526SGS, MW526SGM, and MW526SGD in plan view	34
Figure 45	Comparison of mean (3 samples from each sample system) vapor concentrations at MW526SGS at a depth of 0.76 m	35
Figure 46	Comparison of mean (3 samples from each sample system) vapor concentrations at MW526SGM at a depth of 0.76 m.....	35
Figure 47	Comparison of mean (3 samples from each sample system) vapor concentrations at MW526SGM at a depth of 2.3 m.....	36
Figure 48	Comparison of mean (3 samples from each sample system) vapor concentrations at MW526SGD at a depth of 3.2 m.....	37
Figure 49	Comparison of probe and GVP VOC concentrations – error bars represent one standard deviation from three samples	38

List of Figures - continued

Figure 50	Comparison of dedicated vapor probe and GVP VOC concentrations – error bars represent one standard deviation from three samples39
Figure 51	Comparison of PRT and GVP VOC concentrations – error bars represent one standard deviation from three samples40

List of Tables

Table 1	Depth of Fill Materials and Screened Intervals in Boreholes Containing Dedicated Vapor Probe	45
Table 2	Results of Container Blanks	45
Table 3	Results of Field Blanks.....	45
Table 4	Results of Probe Blanks.....	45
Table 5	Results of Travel Blanks	45
Table 6	Results of Replicate Samples	46
Table 7a	Computation of Internal Volume of PRT Sampling System When Sampling at 0.76 m Near MW525SG.....	46
Table 7b	Computation of Pre-Sample Extraction and Internal Exchange Volumes of PRT Sample System When Sampling at 0.76 m Near MW525SG	46
Table 8a	Computation of Internal Volume Dedicated Vapor Probe MW513SG When Sampling at a Depth Interval of 2.1 to 2.4 m.....	46
Table 8b	Computation of Pre-Sample Extraction and Internal Exchange Volumes of Dedicated Vapor Probe MW513SG When Sampling at a Depth Interval of 2.1 to 2.4 m	47
Table 9a	Computation of Internal Volumes Using the PRT Sampling System at Five Sample Locations at a Depth of 0.76 m Near MW213	47
Table 9b	Computation of Internal Volumes Using the PRT Sampling System at Five Sample Locations at a Depth of 2.3 m Near MW213	47
Table 9c	Computation of Internal Volumes Using the PRT Sampling System at Five Sample Locations at a Depth of 3.2 m Near MW213.....	47
Table 9d	Computation of Pre-Sample Extraction and Internal Exchange Volumes and Sample Results Using the PRT Sampling System at a Depth of 0.76 m Near MW213	48
Table 9e	Computation of Pre-Sample Extraction and Internal Exchange Volumes and Sample Results Using the PRT Sampling System at a Depth of 2.3 m Near MW213	48
Table 9f	Computation of Pre-Sample Extraction and Internal Exchange Volumes and Sample Results Using the PRT Sampling System at a Depth of 3.2 m Near MW213	48
Table 10a	Internal Volumes of Probe, PRT, and GVP Systems at 2.3 m Near MW302SGM.....	48

List of Tables - continued

Table 10b	Cumulative Pre-Sample Internal Exchanges of Probe, PRT, and GVP Systems at 2.3 m Near MW302SGM.....	49
Table 10c	VOC and Gas Concentrations of Probe, PRT, and GVP Systems at 2.3 m Near MW302SGM.....	49
Table 11a	Internal Volumes of Probe, PRT, and GVP Systems at 2.3 m Near MW514SG.....	49
Table 11b	Cumulative Pre-Sample Internal Exchanges of Probe, PRT, and GVP Systems at 2.3 m Near MW514SG.....	50
Table 11c	VOC and Gas Concentrations of Probe, PRT, and GVP Systems at 2.3 m Near MW514SG.....	50
Table 12a	Computation of Internal Volumes of Sample Systems at 0.8 m Near MW523SGS	50
Table 12b	Computation of Pre-Sample Internal Exchanges and VOC Concentrations of Sample Systems at 0.8 m Near MW523SGS.....	51
Table 13a	Computation of Internal Volumes of Sample Systems at 2.3 m Near MW523SGM.....	51
Table 13b	Computation of Pre-Sample Internal Exchanges and VOC Concentrations of Sample Systems at 2.3 m Near MW523SGM	51
Table 14a	Computation of Internal Volumes of Sample Systems at 3.4 m Near MW523SGD	51
Table 14b	Computation of Pre-Sample Internal Exchanges and VOC Concentrations of Sample Systems at 3.4 m Near MW523SGD	51
Table 15a	Computation of Internal Volumes of Sample Systems at 0.91 m Near MW525SG	51
Table 15b	Computation of Pre-Sample Internal Exchanges of Sample Systems at 0.91 m Near MW525SG.....	52
Table 15c	Summary of VOC Concentrations in PRT and GVP Systems at 0.91 m Near MW525SG.....	52
Table 16a	Computation of Internal Volumes of Sample Systems at 2.3 m Near MW525SG	52
Table 16b	Computation of Pre-Sample Internal Exchanges of Sample Systems at 2.3 m Near MW525SG.....	52
Table 16c	Summary of VOC and Gas Concentrations in PRT and GVP Systems at 2.3 m Near MW525SG.....	53
Table 17a	Computation of Internal Volumes of Sample Systems at 0.91 m Near MW526SGS	53

List of Tables - continued

Table 17b	Computation of Pre-Sample Internal Exchanges of Sample Systems at 0.91 m Near MW526SGS	53
Table 17c	Summary of VOC and Gas Concentrations in PRT and GVP Systems at 0.91 m Near MW525SG.....	54
Table 18a	Computation of Internal Volumes of Sample Systems at 0.91 m Near MW526SGM.....	54
Table 18b	Computation of Pre-Sample Internal Exchanges of Sample Systems at 0.91 m Near MW526SGM.....	54
Table 18c	Summary of VOC and Gas Concentrations in PRT and GVP Systems at 0.91 m Near MW526SGM.....	55
Table 19a	Computation of Internal Volumes of Sample Systems at 2.3 m Near MW526SGM.....	55
Table 19b	Computation of Pre-Sample Internal Exchanges of Sample Systems at 2.3 m Near MW526SGM.....	55
Table 19c	Summary of VOC and Gas Concentrations in Sample Systems at 2.3 m Near MW526SGM.....	56
Table 20a	Computation of Internal Volumes of Sample Systems at 3.2 m Near MW526SGD	56
Table 20b	Computation of Pre-Sample Internal Exchanges of Sample Systems at 3.2 m Near MW526SGD	56
Table 20c	Summary of VOC and Gas Concentrations in Sample Systems at 3.2 m Near MW526SGD	57

Acknowledgements

The authors would like to thank the following for their help and support in this project: Mike Jasinski, Ron Jennings, Matt Hoagland, Mary Sanderson, and Don Berger of EPA Region I, and David Burden of NRMRL, Ada, OK.

The authors would like to acknowledge the following for their formal review of this manuscript:

Dr. John E. McCray
Colorado School of Mines
Environmental Science and Engineering Division
1500 Illinois Street
Golden, CO 80401

Dr. Blayne Hartman
HP Labs
432 N. Cedros Avenue
Solano Beach, CA 92075

Dr. Jim Weaver
U.S. Environmental Protection Agency
Office of Research and Development
National Exposure Research Laboratory
Ecosystems Research Division
Athens, GA 30605-2700

Executive Summary

Soil-gas sampling is widely used as a reconnaissance tool to help delineate the areal extent of ground-water contamination and both the areal and vertical extent of vadose zone contamination by volatile organic compounds (VOCs). Soil-gas sampling is often followed by ground-water and/or soil sampling to quantify contamination in these media. Since soil-gas data is generally not used to evaluate the need for corrective action or attainment of remedial goals, quality assurance and control (QA/QC) considerations associated with soil-gas sampling are often less stringent compared to ground-water or soil sampling. However, EPA's recent draft guidance on vapor intrusion (EPA, 2002) allows the quantitative use of soil-gas data along with empirical attenuation factors or the Johnson-Ettinger Model (1991) to directly assess potential exposure from vapor intrusion. Thus, collection of representative soil-gas samples could be critical to this endeavor. Representative soil-gas data refers to collection of a sufficient number of properly located samples within an area and depth of concern subject to adequate QA/QC measures. Implementation of QA/QC measures ensures that observed concentrations reflect true soil-gas concentrations in the vicinity of a probe during sampling.

There are a number of important QA/QC issues relevant to soil-gas sample collection. One issue not addressed in the literature is the equivalence of direct-push/hammer soil-gas sampling techniques with dedicated vapor probes. Dedicated probes are generally considered a reliable method for soil-gas sampling because of the use of a layer of bentonite to isolate a sand-packed screened interval. However, direct-push/hammer soil-gas sampling techniques have become common to support vapor intrusion investigations because they are more convenient (ability to sample the same day as probing) and less expensive compared to installation of dedicated probes. Also, direct-push/hammer techniques allow collection of soil-gas samples close to a building minimizing concern regarding interpolation and extrapolation of soil-gas concentrations beneath a building.

In this investigation, concentrations from soil-gas samples collected using dedicated vapor probes were compared with samples using the Geoprobe Post-Run Tubing (PRT) system and AMS Gas Vapor Probe (GVP) kit. The PRT system is one of the most commonly used truck-mounted direct-push soil-gas sampling systems in the United States. The PRT system can be used to collect soil-gas samples to depths up to 20 m. The hand-held rotary hammer GVP kit is suitable for shallow soil-gas sampling (up to 4 m) but allows access within 1 m of a building. These two methods were selected for evaluation because of their common use.

Soil-gas sampling was conducted at one to three depths at several locations near the Raymark Superfund site in Stratford, Connecticut. Surficial soils in the soil-gas sampling areas are very permeable consisting of sand or a mixture of sand and gravel. A peristaltic pump with Masterflex[®] tubing, variable-area PVC flowmeter, and landfill gas meter were used in line to extract air, measure flow rates, and measure gas (O₂, CO₂, and CH₄) concentrations during purging. A peristaltic pump and one-liter Tedlar bags were used for sampling. Purging and sampling occurred at a flowrate of 0.5 standard liters per minute (SLPM). On-site gas chromatography (GC) analysis was conducted by EPA's New England Regional Laboratory using their standard operating procedure. Air samples from each Tedlar bag were injected into two portable GCs with results compared to ensure consistency. Tedlar bag sampling and on-site analysis provided near real-time data. Detection limits for on-site analysis were 2 – 5 ppbv for VOCs of concern. Container, field, probe, and travel blanks demonstrated that Tedlar bags used to collect samples, coolers used to transport samples, PRT and GVP sample systems used to extract samples, and atmospheric air were not a source of VOCs at detection limits of concern. Replicate samples indicated excellent sample precision.

A mass-balance equation was used to estimate internal volume exchanges necessary to purge dedicated probe, PRT, and GVP systems prior to sample collection. Simulations indicated that if air within a sample system had initially been reduced to zero concentration because of direct exposure to atmospheric air, extraction of 2.2 to 3.0 internal volumes prior to sampling would ensure that VOC concentrations of air entering a sample vessel would be 90 to 95% of VOC concentrations of soil-gas entering a sampling system. This would be the most conservative condition and representative of PRT and GVP sample systems. A zero concentration would not be expected for a dedicated vapor probe which had been sealed for months prior to sampling. Purge testing at a dedicated vapor probe indicated concentration stabilization after only one internal volume exchange. In this investigation, at least 2 internal volumes of air were removed from dedicated vapor probes prior to sample collection. At least 3 internal volumes of air were removed from PRT and GVP sample systems prior to sample collection.

To allow a comparison of dedicated probe, PRT, and GVP sampling systems, it had to be demonstrated that the act of sample collection did not affect sample results at the system being sampled or at other nearby sample locations. Increasing internal volume exchanges or pre-sample air extraction volume in excess of a purging requirement could increase the possibility of collecting a soil-gas sample not representative of some integrated volume of soil around a screened interval. If properly sampled, VOC concentrations should remain relatively constant unless air is drawn in from a nearby region of lower or higher vapor concentration. To evaluate the impact of pre-sample internal volume exchanges on sample results, ten soil-gas samples were collected after various (starting with zero) internal volume exchanges at

one PRT and one dedicated vapor location sampling location. In the test using the PRT system, up to 9 liters of air and 74 internal volume exchanges were extracted with little impact on vapor concentration. In the test using the dedicated vapor probe, up to 103 liters or internal volume exchanges were extracted with little impact on vapor concentration (1 internal exchange equaled 1 liter). Thus, it is unlikely that pre-sample air extraction impacted sample results at the systems being sampled.

To evaluate the potential impact of air extraction at one location on sample results at a nearby location and depth, three samples were taken non-sequentially from each sampling system. For example, at one location, the PRT system was sampled first, followed by the GVP system, followed by sampling at the dedicated probe. The sequence was then changed to sampling at the GVP system, followed by sampling at the dedicated vapor probe, followed by sampling at the PRT system and so on until three samples had been obtained from each system at each depth. A comparison of first and third VOC concentrations for locations and depths where three samples were collected indicated that sample collection at a one location did not impact sample results at another location. Also, coefficients of variation for the three samples were generally below 10% again indicating little impact.

Another potentially complicating factor in comparing vapor concentrations from dedicated probe, PRT, and GVP sampling systems is spatial variability. PRT and GVP sampling locations were positioned relatively close (usually within 1 m) to dedicated vapor probes to minimize the effect of spatial variability on soil-gas concentration. To assess the presence and magnitude of spatial variability at this scale, soil-gas sampling was conducted at three depths at five locations separated by 0.46 m (1.5') in a cross-like pattern using the PRT sampling system. In general, variation in VOC concentration with location at each depth was present but relatively minor.

Sampling systems were compared using data from all locations and depths. A comparison of VOC concentrations using dedicated vapor probes and the GVP sampling kit indicated that the two methods provided similar results ($p = 0.31$ for two-tailed paired t-Test, $p > 0.2$ for two-tailed non-parametric Wilcoxon Signed Rank Test). However, at one location, O_2 , CO_2 , and VOC concentrations were noticeably different for sampling systems indicating potential leakage with the GVP system.

VOC concentrations using the PRT system were not statistically equivalent to VOC concentrations using dedicated vapor probes ($p = 0.009$ for two-tailed paired t-Test, $p < 0.01$ for two-tailed non-parametric Wilcoxon Signed Rank Test). VOC concentrations using the PRT system were higher than VOC concentrations detected using dedicated vapor probes by an average factor of 1.2. This is the same

magnitude observed for spatial variability on a scale of 1 m (median of 1.2 and average of 1.3 for 90 sample pairs). However, this effect did not appear to be due to spatial variability which would result in random scatter not a consistent bias as observed. It is also unlikely that extraction volume or sampling sequence caused the observed bias given results from extraction volume and sample sequence testing.

VOC concentrations using the PRT system were also not statistically equivalent to VOC concentrations using the GVP kit ($p = 0.03$ for two-tailed paired t-Test, $p < 0.01$ for two-tailed non-parametric Wilcoxon Signed Rank Test). VOC concentrations using the PRT system were higher than VOC concentrations detected using the GVP kit by an average factor of 2.4. Similar to the comparison between probe and PRT sampling systems, the effect does not appear to be due to spatial variability, extraction volume, or sequence of sampling.

Thus, utilization of the PRT system resulted in observation of higher concentrations of VOCs compared to the GVP sampling system and dedicated vapor probes. However, the magnitude of variation was relatively minor especially when compared to variation on a scale of 1 m due to spatial variability. Hence for practical purposes, all three sample systems can be considered approximately equivalent.

This testing was conducted in highly permeable soils where the potential for leakage from direct-push/hammer soil-gas sampling systems would be expected to be low compared to less permeable soils such as silt and clay. Thus, the results of this investigation should not be extrapolated to other soil textures where additional investigation is needed. Also, only one direct-push and one rotary hammer method was evaluated for comparison with dedicated vapor probes. Thus, the results of this investigation should not be extrapolated to other direct-push/hammer soil-gas sampling techniques.